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FORECAST OF JET ENGINE EXHAUST EMISSIONS FOR FUTURE HIGH ALTITUDE COMMERCIAL AIRCRAFT

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ABSTRACT

Projected minimum levels of engine exhaust emissions that may be practicably achievable for future commercial aircraft operating at high altitude cruise conditions are presented. The forecasts are based on: (1) current knowledge of emission characteristics of combustors and augmentors; (2) the current status of combustion research in emission reduction technology; and (3) predictable trends in combustion systems and operating conditions as required for projected engine designs that are candidates for advanced subsonic or supersonic commercial aircraft. Results are presented for cruise conditions in terms of an emission index, g pollutant/kg fuel. Two sets of engine exhaust emission predictions are presented: the first, based on an independent NASA study and the second, based on the consensus of an ad hoc committee composed of industry, university, and government representatives. The consensus forecasts are in general agreement with the NASA forecasts.

SUMMARY

This report provides forecasts of exhaust emission levels that may be realistically predicted for future commercial aircraft cruising within the upper troposphere and stratosphere. The forecasts are based on current knowledge of the emission characteristics of combustors and augmentors, the current status of combustion research in emission reduction technology, and predictable trends in combustion systems and operating conditions as required for jet engines that might be developed for future subsonic and supersonic commercial aircraft. Results are presented for cruise conditions in terms of an emission index, g pollutant/kg fuel. Emission forecasts include estimates for oxides of nitrogen, carbon monoxide, total hydrocarbons, particulates (soot), sulfur dioxide, total trace elements, carbon dioxide, and water. Two sets of engine exhaust emission predictions are presented: the first, based on an independent NASA study and the second, based on the consensus of an ad hoc committee composed of industry, university, and government representatives. The consensus forecasts are in general agreement with the NASA forecasts.

INTRODUCTION

This report provides forecasts of projected levels of exhaust emissions that may be realistically applied to future commercial aircraft operating at high altitude cruise conditions. Such predictions are needed by the Department of Transportation as input to the Climatic Impact Assessment Program (CIAP). The purpose of the CIAP effort is to provide an assessment, by 1974, of 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, pp. 2-12). One of the principal efforts of the overall program concerns the preparation of six monographs that will discuss: (1) the natural stratosphere of 1974; (2) the nature of propulsion effluents; (3) the perturbed stratosphere; (4) the perturbed troposphere; (5) biological effects; and (6) economic effects. The engine emission forecasts that are summarized in this report are to be used as part of the input to the second monograph. These emissions will be combined with projections of fuel consumption rates during cruise for future aircraft, routes, and frequency of travel to determine the rate of introduction of engine effluents into the stratosphere from advanced subsonic and supersonic commercial aircraft.

Current NASA-Lewis pollution technology investigations, both small-scale and full annular combustor test efforts, are aimed at initiating and evaluating potentially attractive techniques for reducing exhaust emissions from jet aircraft (refs. 2 to 19). These efforts will provide an estimate of the extent to which current and future combustor emission levels can be reduced. Some examples of techniques being evaluated include air atomizing, premixing, and prevaporizing fuel injection systems; multi-zone fuel distribution; fuel staging, variable geometry for airflow and/or fuel distribution control; exhaust gas recirculation, reduced reaction zone dwell-time, rapid reaction zone mixing, and the use of alternate fuels. In addition, engine cycle study information is being used to forecast the operating constraints that may be imposed on the combustor. The above mentioned study elements are combined to make an NASA forecast described in detail in reference 20 of practicably achievable low-emission engine technology for the time-periods of 1980-1985 and for 1990 and beyond. These forecasts are made on the premise that conventional JP fuel would continue to be the only aircraft fuel that is used until the late 1990's. The use of substitute fuels such as liquefied natural gas (LNG), and hydrogen has also been considered in reference 20 for the time-period beyond the late 1990's; however, the discussion in this report is limited to JP-fueled aircraft.

Exhaust emissions predicted for propulsion systems for future commercial jet aircraft are presented for both minor and major redesigns of the combustor using low emission technology. In addition, theoretical minimum emission limits were determined from chemical kinetics calculations for a combustor burning premixed-prevaporized fuel. The emission forecasts are presented for cruise conditions in terms of an emission index, g pollutant/kg fuel. Emission forecasts include estimates for oxides of nitrogen, carbon monoxide, total hydrocarbons, particulates (soot), sulfur dioxide, total trace elements, carbon dioxide, and water.

Supplementary emission forecasts are presented that were prepared by an ad hoc committee which combined the opinions of several representative engine manufacturers with the independent NASA projections. A consensus of the most likely engine cycles, combustion technology, and cruise emission levels anticipated for the time-periods of 1980-1985 and for 1990 and beyond was obtained by means of a joint evaluation of the independent forecasts prepared by each of the manufacturers and by NASA. The engine manufacturers that contributed to this effort were Detroit Diesel Allison Division of General Motors Corporation, General Electric Company, and Pratt & Whitney Aircraft Division of United Aircraft Corporation. Each of these manufacturers prepared their own independent assessments and then participated with NASA in arriving at a joint consensus of estimated emissions. Representatives from the Department of Transportation, the Environmental Protection Agency, and the University of California, Berkeley, also served on the committee. The members of the Ad Hoc Committee are listed in the appendix. There was general agreement that JP or hydrocarbon type fuels would probably be the only fuel used by commercial aircraft until far beyond 1990; therefore, the consensus forecasts were limited to the use of JP fuel.

I. PROJECTED ENGINE CYCLES

Both the NASA and the Ad Hoc Committee studies conclude that future commercial subsonic jet aircraft will be equipped primarily with advanced high-bypass turbofan engines. The Ad Hoc Committee study predicts that either a duct-burning turbofan or a nonaugmented (dry) turbojet may be the most likely engines for future advanced supersonic transports, as compared with the NASA study which selects only a duct-burning turbofan engine. Both studies conclude that JP-type fuels would probably be the only fuel used by commercial aircraft until far beyond 1990.

NASA Study

Engine designs were selected for both a subsonic and a supersonic mission that resulted in minimum values of aircraft takeoff gross weight (TOGW) for a given payload and range, and a specified noise constraint. Airplane economics are improved as TOGW is reduced. Takeoff gross weight varies as the engine design parameters (turbine inlet temperature, overall pressure ratio, fan pressure ratio, and bypass ratio) and engine size are varied. The values selected for these engine design parameters are influenced by the noise constraint which penalized TOGW. However, the values selected for these engine design parameters were not constrained by engine exhaust emission limits. It has been assumed that engine exhaust emissions would be minimized by means of low-emission combustor technology.

A reduction in the NO_x emission index might be achieved by a lowering of the overall pressure ratio below the values selected in this study. A moderate reduction in overall pressure ratio might be tolerable but a large reduction in overall pressure ratio would seriously penalize TOGW. Similarly, a small reduction in NO_x might also be obtained by reducing the turbine inlet temperature, but, again, not without penalizing TOGW. For the supersonic mission, NO_x might be reduced by minimizing cruise flight speed. None of these emission constraints have been considered in this study.

Tables I and II describe commercial aircraft systems and cruise operating conditions, respectively, for both subsonic and supersonic missions which are forecast for the time period of 1980-1985 and for 1990 and beyond. For the subsonic CTOL (conventional takeoff and landing) aircraft, it is assumed that production or growth versions of aircraft such as the 747 or DC-10 will continue to be in service up to, at least, 1990; and that advanced turbofan engines utilizing low NO_x combustor technology could be incorporated into these aircraft between 1980 and 1985. An Advanced Technology Transport (ATT) fueled by JP could be operational in the early 1990's. For the supersonic mission, it is forecast that the Concorde would enter service in 1975 and that growth versions of the Concorde would remain in service up to, at least 1990. Detailed information is lacking on the Tupolev TU-144, which is expected to become operational in 1974; however, its operating characteristics should be similar to the Concorde. A JP-fueled Advanced Supersonic Transport (ASST) might be operational in the early 1990's. The analytical data presented in tables I and II for the future subsonic (ATT) and supersonic (ASST) aircraft are based on mission-analysis calculations (performed by James F. Dugan, Jr., of NASA Lewis Research Center) similar to those described in references 21 and 22, respectively. Although these mission analyses consider information and comments from aircraft engine and airframe manufacturers, and airlines, they do not indicate any commitments that future aircraft and engines will match these predictions. These indicated engines and aircraft statistics are, however, the best information available to the authors at this time.

Advanced Technology Transport (ATT). - An airframe with a supercritical wing was selected. At the design cruise conditions of Mach 0.85 and 12 200 meters altitude, the nominal lift-to-drag ratio was 20. The design range was 5560 km with a payload of 200 passengers for a transcontinental mission. An intercontinental mission with a design range of about 10 200 km has also been considered, but has not been included in table I, since the combustor operating conditions do not differ greatly from the transcontinental mission; thus, the exhaust emission indices would be similar. Takeoff gross weight of the advanced subsonic aircraft is about 113 000 kg. Three high-bypass turbofan engines are specified for the advanced subsonic mission. The engines selected resulted in a noise level of 96 EPNdB (effective perceived noise decibels) which is 10 EPNdB below the FAR (Federal Air Regulation) 36 requirement. The bypass ratio during cruise is 7.8. An advanced turbine cooling scheme (full-coverage film cooling) was assumed and up to 13 EPNdB of fan machinery noise suppression. The total fuel flow rate per engine during cruise is 1610 kg/hr. As shown in table II(a), at cruise operating conditions, the operating conditions selected for the ATT has combustor inlet temperature and pressure that are slightly lower and a combustor exit temperature that is somewhat higher than a representative production turbofan engine.

Advanced Supersonic Transport (ASST). - The duct-burning turbofan engines for the ASST were selected to meet an FAR 36 sideline noise constraint (108 EPNdB). Bypass ratio and fan pressure ratio were determined by considering the jet exit velocities (and hence jet noise) of the two streams which, when added, produce 108 EPNdB without suppression. The engines were sized for a maximum dry (i.e., nonduct-burning) takeoff with acceptable field length and community noise requirements (at 6.5 km, from start of roll). Turbine-inlet temperature and cooling bleed were selected as being suitable for advanced full-coverage film cooling. The airplane used in this evaluation cruised at Mach 2.7 at an altitude of 19 800 meters. Initial cruise altitude was optimized to maximize the L/D (lift to drag ratio) over sfc (specific fuel consumption) quotient. An L/D of 9.9 was typical for the JP-fueled airplane. The cruise duct-burner temperature was reduced from the climb setting so that operation was near the minimum point on the sfc-versus-thrust curve. A design range of 7400 km was obtained in an all-supersonic-cruise mission (i.e., with no subsonic cruise leg) with 250 passengers. Takeoff gross weight for the ASST is about 382 000 kg. The cruise bypass ratio is 2.36. The combustor fuel flow rate per engine during cruise is 10 750 kg/hr. A small degree of augmentation is required during cruise that results in a duct-burner fuel flow rate of 4200 kg/hr. The total engine fuel flow rate during cruise is 14 950 kg/hr. As shown in table II(b), at cruise operating conditions, the operating conditions selected for the ASST has combustor inlet temperature and pressure that are slightly lower, but a combustor exit temperature that is much higher than the corresponding design conditions of the Olympus 593 engine.

Ad Hoc Committee Study

The consensus forecasts are based on a more general range of operating conditions for future jet engines as compared with the NASA forecasts which are based on specific operating conditions determined from several projected engine cycles for future jet aircraft.

Subsonic aircraft engines. - The Ad Hoc Committee agrees that many of the current turbofan engines presently being used for CTOL aircraft will continue to be in service at least up to about 1990. Aircraft engines such as the CF-6, JT9D, and RB 211 manufactured after 1978 will require modifications in order to meet proposed EPA emission standards (ref. 23). Growth versions of these engines and advanced high-bypass turbofan engines for ATT aircraft would begin to enter service between 1980 and 1985. After 1990, commercial aircraft would be equipped primarily with advanced high-bypass turbofan engines. The sea-level takeoff

(SLTO) thrust of these advanced turbofan engines might vary from 110 000 to 360 000 newtons (25 000 to 80 000 lbf) depending on their use in either short or long haul aircraft. For comparison, the SLTO thrust of current high-bypass turbofan engines ranges from about 180 000 to 240 000 newtons (40 000 to 53 000 lbf). The projected values for the overall pressure ratio for the advanced engines range from about 25 to 37 compared to current values of 20 to 30. The differences in the cruise operating conditions between the advanced and current engines would result in combustor inlet pressures and temperatures, and exit temperatures ranging from current to modestly higher values.

Supersonic aircraft engines. - The Concorde and Tupolev TU-144 or growth versions of these aircraft will probably continue to be in service by the 1980 to 1985 time period; however, advanced supersonic transports (ASST) of greater size and range would be expected to enter service in the time period beyond 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.

The sea level takeoff (SLTO) thrust of these advanced engines could range from 220 000 to 370 000 newtons (50 000 to 82 000 lbf). The SLTO thrust of the Olympus engine used for the Concorde is about 170 000 newtons (38 000 lbf). The projected overall pressure ratio (SLTO) could range from 12 to 25 with a turbine inlet temperature as high as 1600 to 1800 K.

II. PROJECTED EMISSION REDUCTION TECHNOLOGY

Each study considers several categories of advanced combustor technology to attain varying degrees of NO_x emission reductions. In addition, the NASA study predicts a theoretical minimum NO_x emission level based on chemical kinetics calculations for a combustor burning a premixed-prevaporized fuel.

NASA Study

Along with emission controls, there are a number of critical performance factors that must be considered in the design of any aircraft gas turbine combustor; for example, combustion efficiency, total pressure loss, durability, exit temperature profile, and altitude relight. Combustor size and weight are important because they influence the overall weight of the engine. Combustor length affects the turbine shaft length and the bearing requirements. Reducing combustor length also reduces the amount of air required to cool the combustion liner by reducing liner surface area and may also be desirable for reducing NO_x emissions by reducing reaction zone dwell time.

Proposed Federal regulations designed to control noise limits and air quality are expected to have a significant impact on the design of future aircraft engines (ref. 24). To offset the economic penalties of low noise, engines must be lighter and more efficient; thus further emphasizing the requirement for compact engine components such as combustion systems.

Proposed regulations on aircraft emissions include limits on gaseous pollutants (CO, total hydrocarbons, and NO_x) which are produced during a defined landing-takeoff cycle (ref. 23). This cycle covers all aircraft operations below an altitude of 915 meters. A limit on smoke emissions sets a maximum value on the SAE smoke number. Meeting these aircraft emission regulations requires that improvements be made in combustor design to reduce hydrocarbons and carbon monoxide during engine idle and taxi, and to reduce NO_x and smoke during takeoff. Many of the techniques being investigated to reduce NO_x during takeoff are also applicable to the reduction of NO_x during cruise; however, the techniques being studied to reduce CO and THC at engine idle by improving combustion efficiency during idle are generally not required for cruise conditions since the combustion efficiency is already near 100 percent at cruise. Some of the techniques used to minimize idle CO and THC pollutants may adversely affect the formation of NO_x or smoke at higher power conditions; therefore, future combustor designs might require variable geometry for the control of primary airflow distribution and/or fuel distribution to minimize pollutant formation over a wide range of engine operating conditions.

All of the above factors must be considered in arriving at the combustor technology requirements for the projected engine cycles included in table II. The combustion efficiency during cruise of future combustors designed for either ATT or ASST aircraft should be virtually the same as for present production combustors which are very near 100 percent. It may be feasible to design either turbojet afterburners or turbofan duct-burners with combustion efficiencies near 100 percent during cruise by means of effective fuel atomization and fuel-air mixing. Optimum fuel-air mixing might be attainable by variable geometry to control airflow and/or fuel flow distribution.

Satisfactory reignition capabilities are required to allow startup of the engine in the event of a flame blowout at altitude. The technique of leaning-out the primary zone to minimize NO_x may adversely affect altitude relight; therefore, special procedures may be necessary to regain relight capabilities lost due to design changes for reduced emissions.

The discussion of combustor design techniques will accentuate those concepts which may effect a reduction in NO_x emissions during cruise operation. As indicated in table III, two levels of combustion system design changes for reducing cruise emissions are considered: (Class 1) minor retrofits to existing production engines or minor improvements to growth versions of these production engines, and (Class 2) major redesign (advanced state-of-the-art emission reduction technology) based on current experimental emission reduction programs such as the NASA "Experimental Clean Combustor Program." For comparative purposes, lower emission limits determined by chemical kinetics calculations for a premixing-prevaporizing combustor are also included. The two levels of design improvement, in turn, represent increasing design complexity and a greater departure from conventional design methods, and the theoretical minimum represents a goal to strive for in practical combustor design by approaches that have not yet been determined.

It is judged that the technology required for a Class 1 modification to a JP-fueled combustor should be available within 1 to 2 years; however, an additional 3 to 5 years would be required for implementing the modification and obtaining the necessary engine certification. Approximately 3 to 5 years should be required to evolve the technology for a Class 2 modification to a JP-fueled combustor. After demonstrating the Class 2 technology, an additional 4 to 5 years should be required to implement this modification into an advanced engine design.

The projected combustor technology that might be utilized in the advanced propulsion systems listed in tables I and II are based on a projection of the emission reduction technology summarized in reference 20. A description of the predicted levels of design improvement or "Class Change" is discussed below.

Class 1 engine modification. - The simplest modification to the combustor that may be envisioned would be a retrofit or redesign of the fuel injection system to improve the atomization and carburetion of the fuel. The concept of air atomization discussed in reference 10 may be capable of providing a more uniform fuel-air mixture than possible with the conventional pressure atomized fuel injector. Air atomizing fuel injectors are currently under evaluation in several engine development programs. Further research on air atomizing fuel injectors is required to evolve designs that (1) operate well over a wide range of fuel flows, (2) demonstrate good durability, and (3) satisfy altitude relight requirements.

Class 2 engine modification. - A "Class 2 Change" is defined as a major redesign of the combustor based on advanced emission reduction technology. Projections for the "Class 2 Change" will be based on the multizone (swirl-can) combustor concepts described in reference 6 which provide uniform reaction zone temperature and a relatively quick quenching of the reaction by the dilution air. The emissions of oxides of nitrogen (NO_x) for two different multizone combustors (one, a swirl-can and the other, a double annular) are shown in figure 1. Also shown on this figure are data from a single-annular combustor (ref. 25). 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 number of fuel injection sources for each combustor is indicated in the figure. 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 2 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. At an inlet-air temperature of 750 K the swirl-can combustor produces only about 60 percent as much NO_x as the more conventional single-annular combustor.

The swirl-can combustor is just one of the concepts being evaluated in the NASA "Experimental Clean Combustor Program" described in reference 2. The goal of this program is to develop and demonstrate technology to decrease pollutant emissions of modern gas turbine engines. This technology is mainly applicable to advanced CTOL aircraft with engine compressor pressure ratios of approximately 20 to 35. However, the combustor technology generated will also be applicable to engines for supersonic aircraft. The program will be conducted in three phases. Contracts for the first phase were awarded by NASA-Lewis Research Center to both General Electric and Pratt & Whitney Aircraft. In this first phase of the program, both contractors will conduct experiments in combustor test facilities to screen combustor concepts for reducing emissions. Each contractor will evaluate the NASA-Lewis swirl-can concept in addition to several of their own concepts. The primary emphasis of these contracts will be to demonstrate a reduction in NO_x emissions to approximately one-fourth of the current levels for production engines. There is also a requirement to significantly reduce emissions at engine idle conditions. Addendums to this program have also been included to reduce the NO_x emission index to a level of 5 g NO_2/kg fuel during cruise for supersonic commercial aircraft.

In the second phase of the program, further tests will be conducted to develop the best designs of Phase I and to demonstrate satisfactory combustor performance including uniformity of exit temperature profile, altitude ignition capabilities, and durability. In the third program phase, the best combustor concepts will be evaluated in a high compressor-pressure-ratio engine demonstration test. This technology may be available to engine designers during the 1980 to 1985 time period. Other types of low NO_x combustor concepts being investigated in this program as described in reference 2 may prove to be as attractive or even better than the "swirl-can" concept.

Minimum engine emissions. - Experimental research is just beginning in an attempt to evolve combustor concepts that may significantly lower the NO_x emission index to levels of the order of a factor of ten below the current goals of the "Experimental Clean Combustor Program." The NO_x emission projections for the premixing-prevaporizing combustor presented herein will be based on analytical calculations described below. The results of these calculations should be interpreted cautiously because: (1) the analytical model used is an extreme simplification of the combustion process, (2) additional improvements in the chemical kinetic equations that are used may be warranted as new chemical kinetics data become available, and (3) the degree to which this theoretical result may be approached by practical combustor hardware is uncertain. Many problems may be envisioned in the evolution of premixed-prevaporized combustors including the design of a satisfactory vaporizer of JP fuel, and the control of flashback.

The theoretical flame temperature is shown plotted against equivalence ratio, ϕ, for JP fuel in figure 3. Equivalence ratio is defined here as the ratio of the fuel-air ratio in the primary (reaction) zone to the stoichiometric fuel-air ratio. These data were obtained from the computer program of reference 26 for combustor inlet conditions (800 K, 5 atm) simulating supersonic cruise. The theoretical flame temperature for JP reaches a peak at an equivalence ratio of about 1.1. For these inlet conditions, the maximum flame temperature of JP is 2560 K. Nitrogen oxide formation may be minimized by maintaining the lowest flame temperature possible in the reaction zone. Because of the lean flammability limit, the minimum flame temperature for a uniform mixture of fuel and air is shown to be about 1900 K ($\phi = 0.5$) for the specified inlet conditions.

NO_x emission indices for a premixing-prevaporizing combustor were determined from an "Equilibrium Hydrocarbon Model" by using a modification of the chemical-kinetics computer program given in reference 27 as described in detail in reference 20. In this model, concentrations of all species of combustion products were assumed to be initially at equilibrium, and only the kinetics of the nitrogen-oxygen reactions were considered. Results from computations at a combustor inlet temperature and pressure of 800 K and 5 atmospheres, respectively, and a reaction dwell time of 2 milliseconds are shown in figure 4, in which NO_x emission index is plotted against equivalence ratio in the primary (reaction) zone. Recent experimental results (unpublished data by David N. Anderson, NASA Lewis Research Center) obtained at the same operating conditions with a laboratory burner using premixed-prevaporized propane (described in ref. 17), and limited calculations based on a theoretical well-stirred reactor model (ref. 28) which includes the kinetics of the combustion reaction are also shown in figure 4 for comparison.

The two theoretical models agree well with experimental results near an equivalence ratio of 1.0. At lower equivalence ratios, the Equilibrium Hydrocarbon Model predicts NO_x values of an order of magnitude below the experimental results, whereas the single data point from reference 28 is in good agreement with experimental results at an equivalence ratio of 0.5. Thus, the Equilibrium Hydrocarbon Model may not be applicable at low equivalence ratios.

Within the reaction zone, the concentration of oxygen atoms can overshoot the equilibrium value by several orders of magnitude at low temperatures (ref. 29). Because the oxygen atom is an important part of the nitric-oxide-producing scheme, the Equilibrium Hydrocarbon Model which assumes equilibrium values for combustion products may not predict nitric oxide concentrations accurately. Also, a recent study of premixed hydrogen flames showed that measured values of NO_x concentrations were higher than predicted when equilibrium levels for the oxygen atom concentration were assumed (ref. 30). Thus, this assumption can lead to as much as an order of magnitude difference between measured and computed NO_x concentrations at low equivalence ratios.

In applying figure 4 to predictions of the lower NO_x emission limit presented in the next section, the curve faired through the experimental data and the data from the theoretical kinetics model of reference 28 will be used. These results provide only a preliminary indication of the lower limit for NO_x emissions. In actual practice, combustor performance limits such as combustion stability, degree of mixing, and uniformity of reaction zone temperature may significantly alter these estimates.

Ad Hoc Committee Study

The present belief is that the state-of-art of low emission combustor technology available by the 1980 to 1985 time period will be motivated by the need to meet the proposed 1979 EPA emission standards (ref. 23). These emission standards presently pertain only to subsonic aircraft; however, additional standards for supersonic aircraft are anticipated. In addition, the proposed standards are currently only applicable to aircraft operations below 900 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. However, if the EPA NO_x regulation cannot be achieved by combustor redesign alone, it may become necessary to obtain a portion of the NO_x reduction through the use of water injection. This approach would not be acceptable for NO_x reduction at cruise because of the impracticality of using water injection 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. It is conceivable that the necessary combustor redesign may require staged combustion or variable geometry for the control of airflow and/or fuel flow in order to obtain low emissions at both low power (idle) and high power (takeoff) conditions.

After developing the required low emission combustor technology, a substantial amount of development time and testing will be required to translate this experimental technology into production technology that fulfills the safety, reliability, and economic requirements of a commercial aircraft.

A possibility exists that NO_x might be reduced to levels lower than the proposed EPA limits by means of a more advanced technology based on the evolution of a premixed-prevaporizing combustor. However, the probability of translating this more advanced concept into production technology by the 1980 to 1985 time period is considered to be relatively low and would more likely not be achieved until beyond 1990.

III. PROJECTED EMISSIONS

NASA Study

The projected engine-exhaust emissions at cruise conditions are based on the advanced subsonic ATT and advanced supersonic ASST missions described in Section I and table II. Projected emission levels are presented in terms of an emission index, grams of constituent per kilogram of fuel burned.

Emissions affected solely by fuel composition. - The emission levels for constituents that are primarily affected by the composition of the fuel that is used are listed in table IV. In general, the emission indices for these constituents are independent of engine operating conditions. Despite the lack of quantitative data, the quantity of carbon in the exhaust during cruise should be quite small. The estimate for carbon was obtained from reference 1. The estimate for SO_2 was obtained from reference 31, and is based on the current sulfur composition of commercial jet fuels. Total trace elements are defined to include metallic elements in the fuel in addition to a relatively smaller quantity of eroded metal from engine components. The estimate for total trace elements was obtained from reference 31. The estimate for the quantity of lubricating oil lost from the engine lubricating system was also obtained from reference 31.

Emissions affected by engine operating variables. - The CO, total hydrocarbons, and NO_x emission forecasts presented herein for future commercial jet aircraft are based on the projected combustor technology described in Section II. As discussed previously, these forecasts are divided into two categories of advanced combustor technology representing different degrees of NO_x emission reductions. The first level designated as a "Class 1 Engine Modification" assumes a moderate change or retrofit to existing combustion system designs. Emission forecasts for a "Class 1" change are based on current emission reduction research data for air atomizing and vaporizing fuel injectors described in references 10 and 11. The second level designated as a "Class 2 Engine Modification" assumes a complete redesign of the combustion system. Emission forecasts for a "Class 2" change are based on current experimental data for multizone combustors (swirl-cans) described in Section II. In addition, a theoretical NO_x emission level is predicted that represents an estimate of the lower limit. Theoretical minimum emissions are based on theoretical kinetics calculations for a premixing-prevaporizing combustion system assuming a reaction zone dwell time of 2 milliseconds. A "Class 1 Change" represents: (1) the least alteration to the engine design; (2) a moderate reduction in emissions; and (3) the highest probability of being technically feasible without penalizing combustor performance. A "Class 2 Change" represents: (1) a major redesign of the engine's combustion system; (2) a significant reduction in emissions; and (3) a medium probability of being technically feasible without penalizing combustor performance. To approach "Theoretical Minimum Emissions" would entail: (1) an extremely innovative redesign of the combustion system; and (2) a very low probability of being technically feasible without penalizing combustor performance.

For each level of change, the major motivation for the indicated modifications to the engine's combustion system is to reduce nitrogen oxides. Except for the case of the ASST duct-burner, no reductions in the combustor's CO and total hydrocarbon emissions are projected below the best levels currently being observed for production engines because (1) these emissions levels are already quite low during cruise, and (2) it is difficult to envision improvements in combustion efficiency of the core combustor, which is already as close to 100 percent as can be measured experimentally.

Procedures for NO_x emission index data extrapolations. - In many cases, it was necessary to extrapolate available experimental emission data for NO_x to the combustor or augmentor operating conditions specified for the advanced engines described in table II. These extrapolations were performed to correct for the proper inlet and exit temperatures, and inlet pressures for the engines in table II by using the data correlation methods described in reference 5. Inlet pressures are adjusted to the proper levels by applying a square root correction. An exponential adjustment is applied to the inlet temperature by using the correlating parameter $e^{(T/T_d)}$ where T is the inlet temperature (K) and T_d is a constant correlating factor evaluated to be 288 in reference 5. Variations in exit temperature are adjusted by applying a linear correction. Velocity or dwell-time corrections were not used because the combustor velocities of the experimental data available were judged to be representative of the requirements for the combustion systems of table II.

No attempt was made to correct for differences in inlet-air humidity between test facility conditions and conditions at cruise altitude. Reference 32 indicates that the NO_x emission index increases with decreasing inlet-air humidity at a constant exponential rate of e^{19H} (where H is the humidity, g (H_2O)/g dry air). Typical values of inlet-air humidity for combustor test facilities vary from 0.0007 to 0.006 g (H_2O)/g dry air; thus the application of combustor test data to a near zero humidity at cruise altitude results in an underestimation of the cruise NO_x emission index of from 1 to 12 percent.

Baseline production engines. - The NASA exhaust emission estimates during cruise for representative production engines for both a subsonic and supersonic commercial aircraft are tabulated in table V. The cruise emission estimates for the JT9D engine are extrapolated from average takeoff emission indices for the JT9D given in reference 33. The JT9D takeoff emission indices for CO and total hydrocarbons are judged to be representative of cruise emissions because combustor inlet pressure and temperature for either condition is high enough for the combustion efficiency to be independent of operating conditions (ref. 20). These emission indices for CO and total hydrocarbons are also used to characterize combustor emissions for the advanced engines tabulated in table VI. Emission estimates for the Olympus 593 engine were obtained from reference 1 (pp. 173-179). The Olympus 593 engine does not use afterburning during steady-state cruise.

Class 1 engine modification. - The NASA emission forecasts for a "Class 1 Change" for both an ATT and ASST mission are tabulated in table VI. The Class 1 emission forecasts indicated for the ATT using JP are related to the operating requirements of the advanced turbofan engine (table II) but should also be applicable to retrofitted production engines.

A reduction in the NO_x emission index of 30 percent below the baseline levels for the JT9D and Olympus 593 engines (table V) is based on the assumed availability of improved air atomizing fuel injector technology similar to that described in reference 10. The NO_x emission estimates shown in table VI have also been corrected for differences in operating conditions (inlet pressure and temperature, and exit temperature) between the baseline and advanced engines. This correction for differences in combustor operating conditions results in an additional NO_x decrease of about 21 percent for the ATT combustor and a NO_x increase of 8 percent for the ASST combustor (core engine) relative to baseline conditions. This 21 percent reduction in NO_x for the ATT is mainly due to the lower projected values for combustor inlet temperature and pressure (table II). The 8 percent increase in NO_x for the ASST combustor is mainly due to the higher projected value for combustor exit temperature (table II). Thus, the net reduction of the NO_x emission indices for the Class 1 ATT and ASST combustors relative to the baseline engines is about 45 and 24 percent, respectively, as shown by comparing table V with table VI.

The NO_x emission indices for the ASST augmentor (duct-burner) are estimated from the data of figures 1 and 2 for a single annular primary combustor (corrected to duct-burner operating conditions). This approach is considered justifiable because the combustion characteristics of a duct burner would be expected to be similar to a primary combustor running at the same operating conditions. The predicted NO_x emission index for the augmentor is significantly lower than that for the combustor because the inlet temperature and pressure, and exit temperature for the augmentor are much lower (table II(b)). The predicted NO_x emission index (overall) for the ASST engine, calculated from the independent emission indices and fuel flow rates for the combustor and augmentor, is about 43 percent lower than the corresponding baseline engine.

The ASST augmentor (duct-burner) combustion efficiency was estimated to be about 98 percent at the cruise operating conditions of table II by means of a correlation with operating conditions presented in reference 34 and by assuming that duct-burner performance would be similar to the experimental full-scale duct-burner described in reference 34. With these assumptions the duct-burner's contribution to CO and total hydrocarbons is significantly greater than the contribution from the primary combustor in the core engine.

Class 2 engine modification. - The NASA NO_x emission forecasts for making a "Class 2 Change" in either the ATT or ASST engines as tabulated in table VI are based on present swirl-can combustor data (figs. 1 and 2) and goals set for the NASA Experimental Clean Combustor Program. A NO_x emission index of 6 was calculated for the ATT combustor using JP fuel by correcting values obtained from figures 1 and 2 to cruise operating conditions. This represents about a 45 percent reduction in the NO_x emission index as compared with "Class 1" engines (69 percent reduction compared with present "baseline" engines). Based on the NASA Experimental Clean Combustor Program goal of reducing NO_x emission indices by about one-fourth that of the "baseline" engines, a forecast value of 4 was obtained. Thus, a NO_x emission index between 4 and 6 is forecast for the ATT combustor. Similar calculations were made for the ASST combustor, which gave a NO_x emission index forecast between 5 and 9. The NO_x emission prediction for the ASST augmentor was also based on the swirl-can combustor data of figures 1 and 2. The predicted NO_x emission index (overall) for the ASST engine was calculated to be between 3 and 7, representing an average reduction of about 73 percent compared to the baseline engine.

An improvement in duct-burner efficiency for the "Class 2" ASST engine from 98 to 99 percent is arbitrarily judged to be attainable by the introduction of variable geometry to control airflow and/or fuel flow distribution.

Minimum engine emissions. - The minimum NO_x emissions forecast for the premixing-prevaporizing ATT or ASST combustor as tabulated in table VI are obtained from the kinetics data of figure 4 which include the effect of "oxygen overshoot" as discussed in Section II. These data were also corrected to the proper cruise operating conditions. The upper value shown in table VI represents a more conservative estimate of the minimum attainable NO_x emission index for an assumed minimum primary zone equivalence ratio of 0.6 and an assumed reaction zone dwell time of 2 msec. The lower NO_x estimate (table VI) might be attainable by operating with a minimum primary zone equivalence ratio of 0.5. In any event, as discussed in section II, these preliminary analytical results should be interpreted cautiously. Minimum NO_x emission indices could conceivably be estimated more accurately when more realistic computer models are evolved and when more fundamental experimental data of the type obtained in reference 17 becomes available.

The ASST duct-burner emission indices for CO and total hydrocarbons are assumed to be equal to the emission levels for the primary combustor.

Effect of variations in cruise altitude and Mach number. - The emission forecasts presented in table VI are based on the constant cruise operating conditions for the projected engines given in table II. These forecasts may be adjusted to a varying cruise flight envelope such as presented in references 1 (pp. 169-172) and 35 by applying corrections for variations to combustor or duct-burner operating conditions. In general, the CO and total hydrocarbon emission indices for either the ATT or ASST primary combustor are not sensitive to normal variations in combustor operating conditions during cruise such as presented in references 1 and 35. Significant increases in the CO and total hydrocarbon emission indices for the ASST duct-burner may occur during transonic acceleration because of lower inlet temperature and pressure; however, the quantity of fuel consumed during transonic acceleration is considered to be relatively small in comparison to the total quantity of fuel used during cruise. If required, the duct-burner combustion efficiency predictions presented in table VI may be corrected for varying operating conditions by using the correlation of reference 34.

Projected NO_x emission indices may be corrected for varying cruise operating conditions by applying the corrections described in the section "Procedures for NO_x emission index data extrapolation." The largest correction to the NO_x emission index would be due to variations in flight Mach number. The projected NO_x emission indices would be expected to decrease exponentially with decreasing inlet temperatures as flight Mach number is reduced. Because of the large uncertainty of the forecasts presented in table VI, it is doubtful that cruise altitude and Mach number corrections would necessarily improve the accuracy of these emission index projections; however, large variations in cruise fuel flow rates will result in proportionate variations in the projected emission rates.

Ad Hoc Committee Study

The consensus on the exhaust emissions possible using projected technology are summarized in table VII. The emission indices listed that are based on "Current Technology" 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.

Two emission estimates are shown for both CTOL and ASST aircraft engines representative of either retrofitted engines or advanced engines entering service after 1978. The first estimate designated as "Anticipated Emission Reduction Technology" assumes that the low NO_x combustor technology generated to meet the proposed 1979 EPA emission standards covering the landing-takeoff cycle for CTOL aircraft could be applicable to the reduction of emissions during cruise for both CTOL and ASST. It is understood that this estimate assumes that the NO_x reduction will be obtained by means of combustor redesign. The NO_x emission index for the ASST engine should generally be higher during supersonic cruise than at takeoff because combustor inlet temperature increases with increasing cruise Mach number to a level exceeding the inlet temperature at takeoff conditions. Expected emission standards for the landing-takeoff cycle for commercial supersonic aircraft would require a NO_x limit at takeoff but not at cruise. "Anticipated Emission Reduction Technology" implies that technology will be evolved to reduce NO_x emissions for the ASST engine during supersonic cruise as well as at takeoff. If cruise emission standards were not established, and if water injection should be required to obtain a portion of the required NO_x reduction during takeoff;

then, the projected emission index for NO_x would be expected to approach a level somewhere between the value shown for "Anticipated Emission Reduction Technology" and the value indicated for "Current Technology" engines. The second estimate designated as "Advanced Emission Reduction Technology" is a more optimistic projection, and is based on the evolution of a more advanced technology such as a premixing-prevaporizing combustor aimed at even lower NO_x emission levels.

The projected emission index for carbon monoxide for both CTOL and the nonaugmented SST are somewhat higher than the lowest levels that might be achieved because of the assumption that efforts to reduce NO_x by means of both fuel-lean-combustion and reduced dwell time may result in increasing carbon monoxide levels. The CO emission index based on advanced technology could be reduced to as low as 0.5 if allowances were made for a somewhat higher NO_x level; however, one engine manufacturer stated that a CO emission index of 1 could be attainable for a corresponding NO_x emission index of 3 using advanced technology.

The projected emission index for total hydrocarbons based on anticipated emission reduction technology is as great as about 5 times current values to allow for the expected tradeoff necessary for obtaining reduced NO_x; however, two manufacturers believe that this value could be reduced to about 0.1. The NO_x emission indices shown for the two ASST engines based on anticipated emission reduction technology are not much lower than the value shown for the current Olympus 593 (Concorde) or NK-144 (Tupolev TU-144) engines. This is attributed to the expectation that future ASST aircraft will cruise at higher flight speeds than the current models. Combustor inlet temperature may be higher at the higher flight speeds; therefore, the NO_x formation rate will tend to be greater. The projected NO_x emission index for both the nonaugmented and augmented ASST that is based on advanced technology assumes that the required turbine inlet temperature will be less than about 1750 K. For advanced technology SST engines requiring turbine inlet temperatures greater than about 1750 K, the estimated NO_x emission index might be as high as 6 for the dry turbojet and as high as 5 for the duct-burning turbofan. The estimated emission index for soot is based on the accumulated mass of all particles in the exhaust that are greater than about 0.1 micron.

The Ad Hoc Committee study considered two categories of emission reduction technology: "Anticipated" and "Advanced" whereas, the NASA study considered two categories of emission reduction technology (Class 1 - Minor Combustor Modification and Class 2 - Major Combustor Redesign) in addition to a theoretical minimum based on chemical kinetics calculations for a completely premixed-prevaporized combustor. NO_x emissions predicted for the NASA "Class 2" - Major Combustor Redesign - fall within the range of the consensus predictions designated as "Anticipated" and "Advanced Emission Reduction Technology." The NASA emission index predictions for total hydrocarbons are in good agreement with the consensus predictions, and the NASA emission predictions for carbon monoxide are somewhat below the consensus predictions. The consensus study did not consider a category comparable to the NASA "Class 1" - Minor Combustor Modification - because of the opinion that minor combustor modification would not be sufficient to meet proposed clean air standards. Also, the consensus forecast did not include predictions of theoretical minimum emission levels since they were not within the scope of the ad hoc committee study of practicably achievable emission reduction technology.

CONCLUDING REMARKS

Forecasts were made in this study by predicting technological advances in reducing exhaust emissions of future commercial aircraft operating at high altitude cruise conditions. Emission characteristics were determined for future jet engines that were selected for both subsonic and supersonic missions based on minimizing the aircraft take-off gross weight for a given payload and range, and a specified noise constraint. High bypass turbofan engines were specified for an advanced subsonic aircraft, and duct-burning turbofan or dry turbojet engines were specified for an advanced supersonic aircraft.

It is anticipated that growth versions of many present-day aircraft will continue to be in service up to at least 1990, and advanced engines utilizing low NO_x combustor technology could be incorporated into the design of these aircraft between 1980 and 1985. Advanced subsonic and supersonic aircraft could become operational in the early 1990's. It appears quite probable that JP-type fuels will remain as the main energy source for commercial jet aircraft until at least the late 1990's.

Minor combustor modifications implemented by technological advances made within the next 4 to 7 years could reduce the NO_x emission index by approximately 30 percent. However, greater reductions will be needed in order to meet proposed clean air standards. It is anticipated that major combustor redesigns to reduce NO_x emission indices by as much as 75 percent below that of current production engines might require 7 to 10 years for development and engine certification. Minimum emission limits determined from chemical kinetics calculations for a combustor burning premixed-prevaporized fuel predict that even lower NO_x emission levels are theoretically possible. This theoretical minimum actually represents a goal to be approached in practical combustor design.

APPENDIX - AD HOC COMMITTEE MEMBERS

Mr. Jack B. Esgar, Chairman	NASA Lewis Research Center
Mr. Joseph N. Barney	Detroit Diesel Allison Division of General Motors
Dr. Alan J. Grobecker	Department of Transportation
Mr. George Kittredge	Environmental Protection Agency
Mr. Donald P. Pascal	Pratt & Whitney Aircraft
Dr. William H. Roudebush	NASA Headquarters
Prof. R. F. Sawyer	University of California, Berkeley
Mr. Morris A. Zepkin	General Electric Company

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TABLE I. - COMMERCIAL AIRCRAFT SYSTEMS

(a) Subsonic

	Production turbofans (CTOL)		Future turbofan (ATT) - NASA study
Aircraft designation	747B-200	DC-10 Series 30	------
Takeoff gross weight, kg	354 000	252 000	113 000
Passengers	374-500	250-380	200
Range, km	11 900	9550	5560
Cruise Mach number	0.85	0.85	0.85
Cruise altitude, meters	10 700	10 700	12 200
Engine make and model	P&WA JT9D-7	G.E. CF6-50	-------
Number of engines	4	3	3
Noise level, EPNdB	107	~105	96
Max power @ S.L., N (lbf)	209 000 (47 000)	227 000 (51 000)	115 000 (25 800)
SFC @ max power, $\frac{kg/hr}{N}\left(\frac{lbm/hr}{lbf}\right)$	0.037 (0.36)	0.040 (0.39)	0.056 (0.55)
Overall compression ratio @ max power	23	29.4	23.9
Max power @ cruise, N (lbf)	-----	----	18 260 (4100)
SFC @ cruise, $\frac{kg/hr}{N}\left(\frac{lbm/hr}{lbf}\right)$	-----	----	0.073 (0.718)
Overall compression ratio @ cruise	-----	----	26.4

TABLE I. - Concluded. COMMERCIAL AIRCRAFT SYSTEMS

(b) Supersonic

	Concorde AB turbojet	Future duct-burning turbofan (ASST) - NASA study
Takeoff gross weight, kg	175 000	382 000
Passengers	128	250
Range, km	5900	7400
Cruise Mach number	2.0	2.7
Cruise altitude, meters	17 700	19 800
Engine model	Olympus 593	
Number of engines	4	4
Noise level, EPNdB	115	108
Max power @ S.L., N (lbf)	170 000 (38 000)	306 000 (68 700)
SFC @ max power, $\frac{kg/hr}{N}$ $\left(\frac{lbm/hr}{lbf}\right)$	-------	0.078 (0.763)
Overall compression ratio @ max power	14.8	10
Max power @ cruise, N (lbf)	29 650 (6666)	85 600 (19 250)
SFC @ cruise, $\frac{kg/hr}{N}$ $\left(\frac{lbm/hr}{lbf}\right)$	0.121 (1.189)	0.157 (1.54)
Overall compression ratio @ cruise	-------	4

TABLE II. - CRUISE OPERATING CONDITIONS

(a) Subsonic

	Production turbofan (P&WA JT9D)	Future turbofan (ATT) - NASA study
Cruise Mach number	0.85	0.85
Cruise altitude, meters	10 700	12 200
Total airflow rate, kg/sec	304	151
Bypass ratio	4.9	7.8
Compressor discharge airflow rate, kg/sec	51.5	17.2
Combustor inlet temperature, K	710	661
Combustor inlet pressure, atm	9.7	7.2
Combustor exit temperature, K	1410	1540
Fuel-air ratio	0.018	0.026
Fuel flow rate, kg/hr (per engine)	2800	1610

TABLE II. - Concluded. CRUISE OPERATING CONDITIONS

(b) Supersonic

	Concorde: AB turbojet (Olympus 593)*	Future duct-burning turbofan (ASST) - NASA study
Cruise Mach number	2.0	2.7
Cruise altitude, meters	17 700	19 800
Total airflow rate, kg/sec	83	336
Bypass ratio	0	2.36
Compressor discharge airflow rate, kg/sec	83	100
Combustor inlet temperature, K	824	810
Combustor inlet pressure, atm	6.5	4.7
Combustor exit temperature, K	1320	1770
Combustor fuel-air ratio	0.0141	0.0295
Combustor fuel flow rate, kg/hr	4200	10 750
Augmentor airflow rate, kg/sec	------	236
Augmentor inlet temperature, K	------	635
Augmentor inlet pressure, atm	------	2.6
Augmentor inlet velocity, m/sec	------	90
Augmentor exit temperature, K	------	835
Augmentor fuel-air ratio	------	0.00495
Augmentor fuel flow rate, kg/hr	------	4200
Total fuel flow rate, kg/hr (per engine)	4200	14 950

*Afterburner is not used for steady-state cruise.

TABLE III. - CATEGORIES OF PROJECTED COMBUSTION SYSTEM DESIGN MODIFICATIONS TO REDUCE EMISSIONS DURING CRUISE

Class change	Modification	Descriptive examples
1	Minor modification Basis: Retrofit production engine Minor change or improvement to growth version of production engine	Substitute Improved Fuel Injector to improve fuel atomization
2	Major modification Basis: Advanced state-of-the-art	Utilize "Experimental Clean Combustor Program" technology

TABLE IV. - ESTIMATED EMISSION INDICES FOR H_2O, CO, SO_2, PARTICULATES (SOOT) AND TOTAL TRACE ELEMENTS AT CRUISE CONDITIONS WITH JP FUEL

Constituent	Emission index, g/kg fuel
H_2O	1.25×10^3
CO_2	3.22×10^3
Soot (as carbon)	0.1
SO_2	1-2
Total trace elements	0.01
Lubricating oil	0.1

TABLE V. - EXHAUST EMISSION ESTIMATES FOR PRODUCTION PROPULSION SYSTEMS AT CRUISE CONDITIONS (NASA STUDY)

	JT9D*	Olympus 593**
Oxides of nitrogen $\frac{g(NO_2)}{kg\ fuel}$	16-23	18-19
Carbon monoxide $\frac{g(CO)}{kg\ fuel}$	0.2-0.8	1-5
Total hydrocarbons $\frac{g(CH_2)}{kg\ fuel}$	0.1-0.3	<1
Combustion efficiency, percent	~100	99.9

*Based on ref. 33 (p.IV-311).

**Based on ref. 1 (pp. 173-179).

TABLE VI. - EXHAUST EMISSION INDICES FORECAST FOR FUTURE PROPULSION SYSTEMS AT CRUISE

CONDITIONS WITH JP FUEL (NASA STUDY)

	Turbofan - Advanced CTOL (ATT)			Duct-burning turbofan (ASST)								
				Combustor (core engine)			Augmentor (duct-burner)			Overall engine emissions		
Changes*	Class 1	Class 2	Minimum	Class 1	Class 2	Minimum	Class 1	Class 2	Minimum	Class 1	Class 2	Minimum
Oxides-of-nitrogen $g(NO_2)$ / kg fuel	9-13	4-6	** 0.2-2	13-15	5-9	** 0.7-7	3	1	0.1-0.7	10-11	3-7	** 0.7-7
Carbon monoxide g(CO) / kg fuel	0.2-0.8	0.2-0.8	0.[illegible]-0.8	0.2-0.8	0.2-0.8	0.2-0.8	60	30	0.2-0.8	17.4	8.7	0.2-0.8
Total hydrocarbons $g(CH_2)$ / kg fuel	0.1-0.3	0.1-0.3	0.1-0.3	0.1-0.3	0.1-0.3	0.1-0.3	5	2.5	0.1-0.3	1.5	0.9	0.1-0.3
Combustion efficiency, percent	~100	~100	~100	~100	~100	~100	98	99	100	----	---	-------

*Class 1: Minor combustor modification.
Class 2: Major combustor modification.
Minimum: Theoretical limit from chemical kinetics calculations.

**Upper and lower limits represent minimum primary zone equivalence ratios of 0.6 and 0.5, respectively.

TABLE VII. - CONSENSUS OF ESTIMATED JET AIRCRAFT EXHAUST EMISSIONS POSSIBLE USING PROJECTED TECHNOLOGY; CRUISE OPERATING CONDITIONS; JP FUEL (AD HOC COMMITTEE STUDY)

	Current technology			CTOL/ turbofan		Nonaugmented ASST (dry) turbojet		ASST/duct burning turbofan	
	CF6, JT9D, RB211	Olympus 593, NK-144	JT3D, JT8D	*1	*2	*1	*2	*1	*2
Oxides-of-nitrogen $g(NO_2)$/kg fuel	16	18	6-8	8	3	14	3	12	3
Carbon monoxide g(CO)/kg fuel	4	3.5	4	3	3	3	3	30	15
Total hydrocarbons $g(CH_2)$/kg fuel	0.1	0.2	0.1	0.5	0.1	0.5	0.1	10	3
Soot g(C)/kg fuel	0.1	0.1	0.1	0.02	0.02	0.02	0.02	0.02	0.02

*1 Anticipated emission reduction technology.
*2 Advanced emission reduction technology.

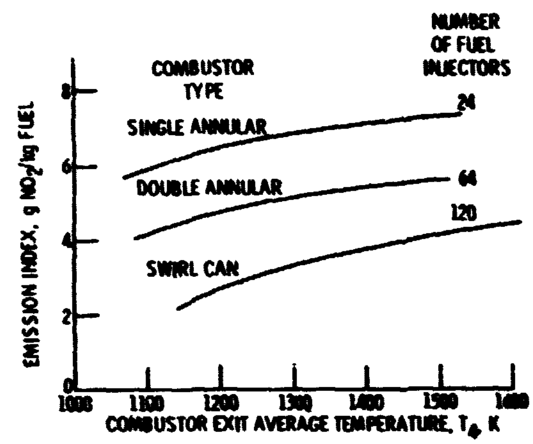

Figure 1. - Variation of oxides-of-nitrogen emission index with combustor exit average temperature for single-zone and multizone combustors. Combustor inlet total temperature, T_3, 590 K; combustor inlet total pressure, P_3, 6 atmospheres; reference velocity, V_r, 32 m/sec.

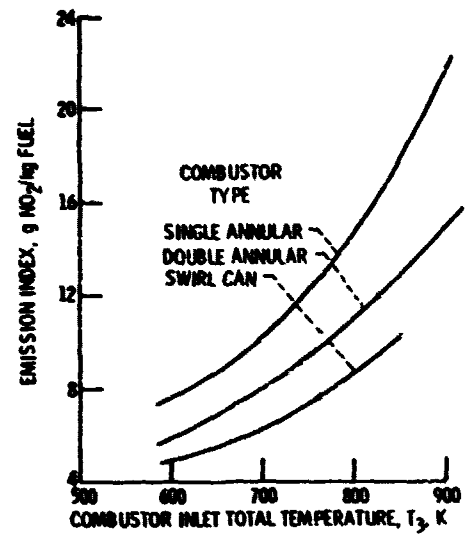

Figure 2. - Variation of oxides-of-nitrogen emission index with combustor inlet total temperature for single-zone and multizone combustors. Combustor inlet total pressure, P_3, 6 atmospheres; combustor exit average temperature, T_4, 1500 K.

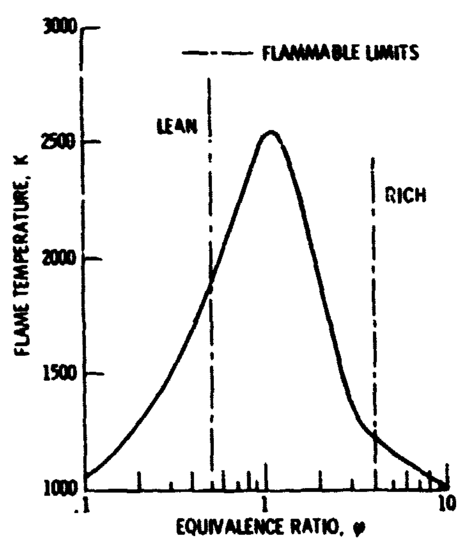

Figure 3. - Theoretical flame temperature. Combustor inlet total temperature, T_3, 800 K; combustor inlet total pressure, P_3, 5 atmospheres

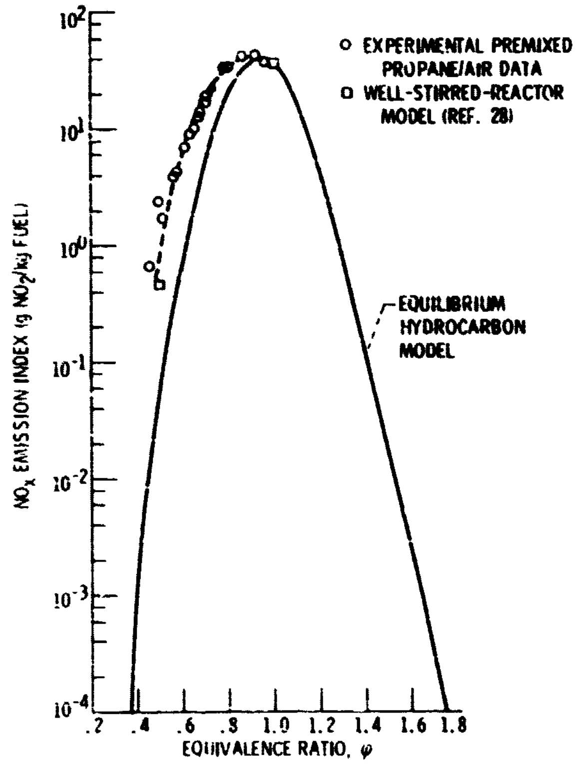

Figure 4. - Theoretical NO_x emission index for a combustor burning premixed-prevaporized hydrocarbon fuel; inlet temperature, 800 K; inlet pressure, 5 atmospheres; dwell time, 2 milliseconds.