TECHNOLOGY FOR CONTROLLING EMISSIONS OF OXIDES OF NITROGEN FROM SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

Various experiments have been and continue to be sponsored by and conducted by NASA to explore the potential of advanced combustion techniques for controlling aircraft engine emissions into the upper atmosphere. Of particular concern are the oxides of nitrogen (NO_x) emissions into the stratosphere. The experiments utilize a wide variety of approaches varying from advanced combustor concepts to fundamental flame-tube experiments. Results are presented which indicate that substantial reductions in cruise NO_x emissions should be achievable in future aircraft engines. A major NASA program is described which focuses the many fundamental experiments into a planned evolution and demonstration of the prevaporized-premixed combustion technique in a full-scale engine.

INTRODUCTION

This paper describes those activities currently under way at NASA that are specifically directed toward reducing the cruise oxides of nitrogen (NO_x) emissions of high-altitude aircraft.

Two recent studies regarding the potential adverse impact of aircraft exhaust emissions on the upper atmosphere (stratosphere) concluded that the NO_x and oxides of sulfur (SO_x) emitted by future fleets of high-altitude cruise aircraft could influence the stratospheric ozone concentration and the albedo of the Earth (refs. 1 and 2). Both studies recommended that major reductions in both NO_x and SO_x be sought in future gas turbine engines for high-altitude cruise aircraft. The recommended SO_x levels can be achieved by removing the sulfur contained in the fuel for the aircraft. However, the recommended NO_x emission reductions to levels from 1/6 to 1/20 of current levels will require major modifications to conventional engine combustion systems. NASA is promoting, conducting, and sponsoring projects that are directed toward evaluating the combustion techniques needed to achieve these reductions, and if possible, to incorporate attractive NO_x emission reduction techniques into the design of practical engine combustors. These projects encompass levels of technology ranging from minor modifications to existing conventional engine combustors to fundamental flame-tube studies. The final goal of these efforts is to reduce cruise NO_x emissions to the lowest possible level while still maintaining acceptable performance in terms of fuel consumption, durability, maintainability, and safety. In addition to these constraints, any viable combustion system must be also capable of meeting local environmental standards, such as the proposed Environmental Protection Agency (EPA) supersonic aircraft standards. Therefore, emissions at idle, climbout, and takeoff must also be controlled.

This paper presents and discusses some of the results obtained from research and development programs being sponsored, directed, and/or conducted by NASA. Although we recognize that much important work is being conducted at or sponsored by universities, private industry, and other government agencies (DOD, FAA, EPA, etc.), this paper concentrates on NASA programs only. Activities ranging from investigating variations of conventional combustion systems to evaluating advanced catalytic techniques are being pursued. Application of these techniques to future aircraft engines are being considered. The results pertinent to the NO_x emission reduction efforts are presented and discussed along with an assessment of the projected development difficulties and a forecast of potential emission level reductions. A recently implemented NASA effort called the Stratospheric Cruise Emission Reduction Program (SCERP) is also described and discussed.

OXIDES OF NITROGEN EMISSION CONTROL TECHNIQUES

The largest single factor which controls the formation of NO_x in a combustion process is the flame temperature in the reaction zone. An example of this effect is illustrated in figure 1, where NO_x concentration is plotted as a function of flame temperature. The values shown were calculated by using a well-stirred-reactor model and are representative of the levels generated in a completely homogeneous prevaporized-premixed combustion process with a 2-msec residence time (typical of contemporary engine combustors).

Because of the exponential variation of NO_x formation as a function of flame temperature, controlling flame temperature in a combustion process should provide a very powerful tool for controlling NO_x emissions. Combustion scientists and engineers are pursuing and evaluating techniques to achieve flame temperature reductions by using the so-called lean-combustion approach. Lean combustion is presently taken to be associated with an equivalence ratio (ratio of local to stoichiometric fuel-air ratio) φ between 0.4 and 1. The NASA aircraft gas turbine engine NO_x emission reduction efforts are primarily directed toward exploring the potential of this lean-combustion approach for eventual application to practical engine combustors.

Lean-Combustion Experiments

Conventional combustion. - Advanced technology approaches using conventional techniques for emission reduction are being evaluated in the NASA Experimental Clean Combustor Program (contract effort with General Electric and Pratt & Whitney) (refs. 3 and 4), and a variety of modifications have been evaluated. Examples of several of these modifications are described in the section APPLICATION OF EMISSION CONTROL TECHNIQUES. Work done up to this time indicates that NO_x reductions of up to 50 percent may be achievable in conventional type combustors by employing lean combustion in the primary zone and by controlling residence time. It also appears that these reductions can be achieved along with acceptable combustor performance, as indicated in references 3 and 4.

Forced-circulation technique. - The term "forced circulation" is used to describe the use of strong swirling flow or impinging jets to form one or more powerful recirculation cells in a combustor primary zone. The powerful recirculation cell provides a mechanism for entraining hot combustion gases into the flame region and thereby establishing a stable zone for lean combustion to occur. When these recirculation cells are coupled with a partially prevaporized-premixed fuel-air mixture, as is illustrated in figure 2, the combustion process can begin to approach the homogeneous process more closely than any modification using conventional combustion techniques. The two concepts shown in figure 2, jet induced circulation (JIC) and vortex airblast (VAB), are being evaluated under NASA contract to the SOLAR Division of International Harvestor Company. To date these concepts have been and continue to be evaluated in a tubular configuration, but use of a full annular model is planned for the future. References 5 and 6 give details of these experiments, and a representative plot of the best emission results obtained is shown in figure 3. The VAB concept achieved a NO_x emission index of approximately 1 g NO_2/kg fuel at the designated simulated supersonic cruise operating design point (although inlet pressure was not a true simulation). The JIC concept was capable of producing a NO_x emission index of 2 g NO_2/kg fuel. Both of these values represent substantial reductions (to a level of approximately 1/10 of conventional combustor emissions) at similar operating conditions. Both concepts were optimized for lean combustion at the design point (designated cruise conditions); hence, low temperature rise performance was characterized by instability and low efficiency. Design point efficiency was in excess of 99.5 percent. Currently, the ability of these concepts to satisfy off-design (idle through takeoff) operating requirements is being evaluated.

Prevaporized-premixed technique. - Perhaps the most successful method of reducing NO_x emissions to extremely low levels has been the completely prevaporized-premixed combustion technique. Studies of this technique have been conducted by a large cross section of the combustion technical community. In most instances, the studies are conducted in experimental flame tubes such as the two illustrated in figure 4. Both flame tubes employ a vaporizer-mixer section, a flameholder (a cone in the General Applied Science Laboratory (GASL) apparatus and a perforated plate in the NASA apparatus), a flame zone, and a gas sample extraction probe. The NASA apparatus has both liquid and vapor fuel capability. Application of the completely prevaporized-premixed technique to actual combustors has been suggested, but no combustorlike hardware has been investigated by NASA.

The results of some of the NASA and GASL experiments (sponsored by NASA) are summarized in figures 5 and 6. Details regarding these experiments are given in references 7 and 8. Values of NO_x emission index below 0.5 g NO_2/kg fuel were achieved in both of the experiments, and close agreement between the results of the two experiments was realized. From figure 5 one can see that, if combustion efficiency is to be maintained above 99.5 percent (a likely requirement for cruise performance), the NO_x emission index would have to be 0.4 g NO_2/kg fuel or higher. A principal factor which controls efficiency of the prevaporized-premixed combustion process is residence time, as shown in figure 6. If one allows residence time to increase (either by reducing flow velocity or making the combustor larger), high values of efficiency can be obtained at the very low equivalence ratios needed for obtaining extremely low NO_x emissions. Therefore, values below 0.5 g NO_2/kg fuel would be obtainable if residence time could be independently controlled. In evaluating the values of emission index obtained in these experiments and displayed in figures 5 and 6, one should use considerable caution. These were carefully controlled experiments, wherein all parameters such as airflow, fuel flow, pressure, and temperature were maintained very stable; this environment does not necessarily represent that which would be present within a normal gas turbine engine. Also, the experiments represent near design point operation (particularly inlet temperature), where conditions are favorable for effective fuel vaporization and lean-combustion stability. Nevertheless, the results do indicate that the prevaporized-premixed combustion technique is a strong candidate for reducing aircraft NO_x emissions to extremely low values and certainly warrants continued investigation.

Catalytic Combustion Experiments

Perhaps one of the most unique concepts for reducing aircraft gas turbine emissions is the potential application of catalyst elements to enhance the reaction process of extremely lean fuel-air mixtures. For exploring the potential of this concept, NASA is employing the apparatus shown schematically in figure 7 and described in detail in reference 9. The apparatus consists of a vaporizer-mixer section, a catalyst element section, and a probe for extracting a gas sample for analysis. The schematic illustration shows that up to four catalyst elements can be used in a typical test. All four elements can be varied in terms of the catalyst type and the substrate structure. This allows for an optimization of pressure drop and temperature rise across the entire catalyst bed. Extremely low NO_x emissions (below measurable quantities) have been obtained in experiments in which propane fuel premixed with air was used. Propane was used to ensure complete vaporization prior to contact with the catalyst elements. Several of the problems of using this concept are the inherently narrow efficient operating range (dramatic efficiency losses occur at very low off-design equivalence ratios), the temperature limitation due to catalyst and substrate melting, potential catalyst poisoning by fuel impurities, and the need to preheat the bed or fuel-air mixture to initiate reactions (cold starting is not possible). Nevertheless, the catalyst concept will continue to be explored both as a total combustion system and as a possible lean stability augmentation device for application to a hybrid catalyst - prevaporized-premixed combustion system.

Off-Design Considerations

Up to this point all the discussion has centered about results obtained at selected design points simulating supersonic cruise conditions. Optimization for low NO_x emissions at this condition requires the use of lean burning, which for a primary-zone φ of less than 0.5 uses much of the available air in the combustion process. This type of airflow distribution presents a problem when the combustor must be operated at the low overall equivalence ratios that are required for engine idle. Poor stability and poor efficiency generally are the result. The SOLAR VAB concept was reconfigured to optimize the primary-zone φ for the idle condition in order to improve stability and to minimize the formation of idle pollutants such as carbon monoxide (CO). The effect of this change on both the idle and cruise point emissions is shown in figure 8. As the fuel flow was increased to obtain the required cruise temperature rise, the primary-zone φ went through stoichiometric and into a rich burning condition. The result was unacceptably high levels of NO_x and CO emissions.

Results such as these clearly indicate the need for either some form of staged combustion or variable control that can maintain primary-zone φ at the optimum level needed to satisfy both engine demands and emission level requirements. A significant effort to evaluate the potential of the staged combustion approach, using conventional combustion techniques, has been and continues to be put forth in the NASA Experimental Clean Combustor Program (refs. 3 and 4). NASA plans to explore the potential of the variable-geometry approach in SCERP, which is described in the section STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM. Regardless of which technique proves to be the most desirable and practical, the impact of off-design performance and emission requirements must be considered in evaluating the level of potential gains that may be achieved by employing the advanced combustion techniques currently being investigated. Many compromises are certainly going to be required in order to evolve practical, operational combustors for future aircraft engines.

APPLICATION OF EMISSION CONTROL TECHNIQUES

Since future supersonic cruise aircraft may employ variable-cycle engines with possible thrust augmentation, the potential application of the NO_x emission control techniques must be evaluated in terms of both primary combustors and thrust augmentors (especially duct burners). In response to the need for evaluating the problems involved in these applications, NASA is currently conducting studies to apply conventional (staged) low NO_x combustion techniques to contemporary engine primary burners and to experimental duct burners. Two of these efforts are described in this section. No comparable effort has been undertaken to evaluate the application difficulties expected for the forced-circulation, prevaporized-premixed, or catalytic techniques up to the present time, although plans to do so in the future are being formulated and are described in the section STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM.

Main Burners

The principal effort to apply conventional lean-burning techniques to primary burners of current subsonic and possible future supersonic cruise aircraft engines has been conducted in the Experimental Clean Combustor Program. In all cases, the desired application required the use of the staged combustion approach, wherein one stage (pilot) was optimized for acceptable idle and taxi emissions and performance, and one stage (main) was optimized for high power takeoff emissions and performance. Several examples of staged concepts are illustrated in figure 9. Figures 9(a) and (b) represent cross sections of full annular adaptations of a two-row swirl-can-modular concept and a double-annular concept for a General Electric CF6-50 engine, and figure 9(c) represents a concept for a Pratt & Whitney JT9D-7 engine called a vorbix. Although these concepts were designed for specific subsonic engines, they were also modified in an attempt to optimize their NO_x emission performance at simulated supersonic cruise conditions (refs. 3 and 4). Proper scheduling of both fuel flow and airflow between the two stages reduced NO_x emissions approximately 50 percent at selected subsonic and supersonic cruise conditions, as compared with those of present in-service engines at comparable operating conditions. The principal development activities still needed to make these two-stage combustors acceptable for operational engine adaptation include (1) defining and optimizing the staging characteristics during acceleration, deceleration, and part power operation and (2) defining accurate control parameters and control functions to permit smooth staging to occur. A considerable amount of information regarding these staging characteristics as well as emission performance will be generated during the full-scale engine tests of the double annulus in the CF6-50 and the vorbix in the JT9D-7 that are scheduled during the latter part of 1976.

Duct Burners

NASA currently is sponsoring two activities with the objective of defining the expected emission levels that can be obtained by applying NO_x emission control techniques to candidate duct burners for possible supersonic cruise aircraft engines. Both efforts, an experimental study by General Electric and an analytical study by Pratt & Whitney, are being conducted under contract with NASA. The NO_x emission level goal for the duct burner application is 1 g NO_2/kg fuel at the designated supersonic cruise condition with a 99 percent or higher combustion efficiency. Further considerations include the necessity to meet proposed local emission standards currently under study by the EPA and performance requirements during transonic acceleration (most severe temperature rise condition). These multiple requirements when coupled with operational considerations, such as "soft" lightoff, led to the need for a staged combustion concept.

A schematic illustration of one configuration of a staged combustion concept currently under evaluation at General Electric is shown in figure 10. As with the main burners, one stage (pilot) is optimized to provide low CO and unburned hydrocarbon emissions at low power, and the other stage (main) low NO_x at high power. The configuration shown is a variation of a radially and axially staged primary combustor that was evaluated in the work of reference 3. Experimental testing has just recently begun.

The Pratt & Whitney analytical study is examining a number of concepts for both pilot and main stages of a staged duct burner combustion system. These concepts include premixers, prevaporizers, swirl stabilizers, flash vaporizers, variable-geometry features, and other advanced techniques. The analytical study is being expanded into an experimental study of several of the most attractive concepts.

ASSESSMENT OF RESULTS

The NO_x emission reduction potential of the various control techniques for future engines was estimated by utilizing projected engine cycle conditions and accepted extrapolation and correlation methods. Although extrapolation and correlation methods are constantly being updated as experimental results are obtained, the results of the previously described activities were extrapolated to the projected cycle conditions by using the following equation:

$$(EI)_2 = (EI)_1 \left[\frac{(P_3)_2}{(P_3)_1}\right]^{0.5} \exp\left[\frac{(T_3)_2 - (T_3)_1}{288}\right] \left[\frac{(T_4)_2}{(T_4)_1}\right] \tag{1}$$

where

EI	emission index
P_3	combustor inlet pressure
T_3	combustor inlet temperature
T_4	combustor outlet temperature
1	experimental test conditions
2	designated operating conditions

Projected Engine Cycles

The projected supersonic cruise engine cycle parameters that are needed as inputs to equation (1) are presented in table I. The operating conditions of the SNECMA/Rolls-Royce Olympus 593 (as reported in ref. 10) and two advanced study engines were used. The Olympus 593 engine represents current turbojet technology with an engine cycle pressure ratio of approximately 15:1. The cycle cruise parameters for the Olympus 593 were computed at a Mach 2.0 cruise speed and a 17.7-km altitude. The afterburner is not used for steady-state cruise. The two study engine cycles, one by Pratt & Whitney and one by General Electric, represent current values from a NASA sponsored study to evaluate potentially attractive propulsion systems for possible future supersonic cruise aircraft. These study engines encompass an engine cycle pressure ratio range of approximately 20:1 to 25:1, and a Mach 2.32 cruise speed at an average altitude of 16 km was used to compute the engine cycle parameters. Since the NASA sponsored study is not yet complete, the final values for the cycle parameters of the two study engines could vary somewhat from those shown in table I. However, for the purpose of estimating the NO_x emissions for future supersonic cruise aircraft engines, the values shown should be reasonably representative.

Emission Level Forecast

From the engine cycle cruise parameters shown in table I, emission level forecasts were made for the various NO_x control techniques previously described. In figures 11 and 12 the emission level forecasts are presented and compared with levels that could be expected from current technology combustors operating at the same cycle parameter conditions. All the values shown in these figures represent extrapolations from either rig or engine test conditions to the designated cruise conditions made by using equation (1). They also represent NO_x emission levels at combustion efficiencies in excess of 99.5 percent.

The application of the clean combustor technology to the contemporary turbojet (Olympus 593) cycle parameters shown in figure 11 would provide a potential reduction in projected cruise NO_x emissions to a level of about 1/2 of current levels. If reductions to a level of 1/6 of current levels (recommendation of ref. 1) are to be achieved, the implementation of either the forced-circulation, prevaporized-premixed, or catalytic combustion techniques will be required. Of these three techniques, the forced-circulation technology is farthest along in the process of converting fundamentals to combustor hardware but also offers the least gains. Based on the extrapolations, only the prevaporized-premixed and catalytic techniques offer the potential for reducing emissions below 1 g NO_2/kg fuel at the designated cruise conditions.

The projected emission levels of the various techniques for the advanced study engine cycles are shown in figure 12. As in the contemporary turbojet projections, the level of potential reduction is greater with the lesser developed techniques. In addition, the projected values for the advanced engines are approximately a factor of 2 higher than the projected values for the contemporary turbojet engine because the combustor inlet and outlet conditions are more severe from a NO_x formation standpoint (higher cycle pressure ratios). Because of the more severe conditions in the advanced engine cycles, employing clean combustor technology would result in reducing the NO_x emissions to levels nearly equal to those of the current supersonic aircraft turbojet engines ($\simeq$20 g NO_2/kg fuel). Achieving reductions to a level of 1/6 or less of the current 20 g NO_2/kg fuel level will definitely require the application of prevaporized-premixed or catalytic techniques.

The actual achievable levels may be somewhat different from those shown in figures 11 and 12 when the described emission control techniques are developed into operational engine hardware. Tradeoffs among emissions, performance, altitude relight, durability, maintainability, and complexity as well as the influence of the actual engine environment as opposed to the carefully controlled rig experimental conditions will have to be considered. The end result will likely be some upward adjustment to the levels shown in figures 11 and 12. Actual engine demonstration and technology development must be conducted before the levels can be quantified and considered to represent achievable levels accurately. However, the general trends displayed by employing the various techniques should be correct.

In evaluating these results, please bear in mind that the levels were extrapolated to the designated conditions by using equation (1). In some of the fundamental investigations (e. g., prevaporized-premixed concept), the effect of combustor inlet pressure and temperature resulted in some anomalies from the relations described by equation (1). These anomalies could have an impact on the final extrapolated levels and are discussed in the next section. The trends, however, are clear. The low levels of cruise NO_x emissions recommended by references 1 and 2 will most likely require the development and implementation of the less developed, higher risk technology associated with the prevaporized-premixed and catalytic techniques.

STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM

In response to the need for substantial cruise NO_x emission reductions, highlighted by the studies mentioned previously (refs. 1 and 2), NASA has initiated SCERP. The SCERP objectives are to develop and demonstrate the technology necessary to reduce cruise NO_x emissions to a level of 1/6 or less of current levels and to meet the current EPA 1979 emission standards (ref. 11) for the airport vicinity. The technology will be designed for the high-bypass-ratio, high-pressure-ratio engines currently powering the wide-body subsonic transports. Technology evolved by SCERP, although not directly applicable, should also aid in the development of low NO_x combustors for future supersonic cruise aircraft engines.

The prevaporized-premixed technique for emission reduction will be explored in the SCERP activity. The results shown in figure 5 indicate that this technique has the potential to meet or exceed the program goal. While this technique does not offer the emission reduction potential of the catalytic approach, the practical problems associated with its application are viewed as less severe. However, from the earlier discussion of off-design considerations it is apparent that a form of variable geometry will likely be necessary to maintain acceptable combustor performance as well as low emissions over the entire flight envelope. In addition, it is expected that an advanced digital control system will likely be required for the eventual engine application.

The program plan for SCERP is broken into an initial phase consisting of a number of fundamental studies to establish design criteria for prevaporizing-premixing combustors and a final phase wherein promising combustor designs will be experimentally evaluated, developed, and eventually demonstrated in an engine. The fundamental studies in the initial phase are grouped in the following four areas: lean combustion, fuel-air mixture preparation, autoignition and flashback, and engine constraints. Specific studies in each of these areas are being initiated by NASA through a combination of both in-house and contracted research as well as university grant activities.

In the first area, lean combustion, a study will be conducted to examine the effect on emissions of various fuel spray characteristics including the degree of vaporization, the mean drop size, the fuel-air distribution, and other factors. Another lean combustion study will parametrically examine the effects of engine cycle parameters on emissions in order to develop correlations. Emission measurements of a premixed-propane combustor will be made over a wide range of conditions up to 40 atm and 1000 K. The problem of extrapolating emission data over a wide range of conditions is illustrated in figure 13, which shows emission data taken from the GASL experiment described in reference 8. The expected dependency of NO_x emission index on the square root of pressure is not evident, and emission minimums occur near 8 atm. This effect is likely associated with the prevaporizing-premixing process and may result from an improvement in degree of vaporization or fuel distribution at the higher pressure conditions. Other lean-combustion studies include an investigation of the effect of flameholder geometry on emissions and performance and an examination of several schemes for improving lean stability limits.

In the second area, fuel-air mixture preparation, engine measurements are being made to characterize the compressor discharge turbulence. The nature of the turbulence in the diffuser inlet may promote fuel mixing and vaporization if fuel is introduced in this region. In addition, techniques for vaporizing fuel external to the combustor will be studied, and schemes for controlling radial fuel-air distribution will be examined.

The third area, autoignition and flashback, presents serious hazards to potential prevaporizing-premixing combustors. In many of the flame-tube studies, including those at GASL and NASA, autoignition or flashback have occurred at some conditions. Figure 14 illustrates the autoignition problem. The vaporization times shown in the figure were derived from a simplified model developed at NASA, and the ignition delay values were obtained from reference 12. It is apparent that, if the fuel is given sufficient time to vaporize completely at the higher cycle pressure ratios, it may autoignite. The SCERP studies in this area include a parametric study of the factors influencing autoignition delay up to pressures in excess of 30 atm, a study of the effect of hot surfaces on autoignition, and an examination of the effects of boundary layers and engine transients on flashback.

The fourth area, identified as engine constraints, refers to problems arising from the interfaces between the combustor and the engine. The characteristics of the compressor discharge airflow are of particular concern in a premixing combustor to assure control of the homogeneity of the fuel-air mixture. In addition to the turbulence measurements mentioned previously, an investigation of the circumferential airflow uniformity at the compressor exit will be conducted. Another study will examine the effects of nonideal turbine inlet temperature profiles on turbine life and performance. With an extremely lean primary zone, considerably less dilution air may be available for tailoring the combustor exit temperature profile. And finally, a simplified combustor model will be incorporated into an engine transient performance computer routine to investigate the interaction of the combustor with the remainder of the engine during acceleration and deceleration. With variable geometry, transient performance may be a serious concern.

As the results of the initial studies become available, the design data will be applied to combustor concepts. Variable-geometry techniques and controls will be incorporated into the designs as required. As the designs evolve, an assessment of their potential with regard to both emissions reduction and practical application will be made. The most promising concepts will then be selected for experimental screening.

CONCLUDING REMARKS

Results obtained from a variety of projects, varying in degree of technological advancement, currently being conducted and sponsored by NASA indicate that substantial reductions in cruise NO_x emissions should be achievable in future supersonic aircraft gas turbine engines. The degree of reduction achievable is, of course, dependent upon the level of advanced combustion technology that is judged to be developable into operational combustors. At designated cruise design points for current intermediate-pressure-ratio engines, advanced combustor technology of the type being evaluated in the NASA Experimental Clean Combustor Program offers the promise of reducing NO_x emissions to a level of 1/2 of current engine levels. Reductions beyond these levels will require the application of higher risk technology such as prevaporized-premixed combustion concepts. Results from controlled experiments indicate that this more advanced technology may provide reductions to levels of 1/6 of current levels. It is important to note that these reductions have only been achieved in controlled rig experiments and they must certainly be quantified in full-scale engines. Since control of emissions at all operating conditions, from idle and taxi up to cruise, will be required in future engines, some form of combustion staging or variable geometry will be needed regardless of the level of advanced technology employed. This added complexity will likely affect the final achievable levels of cruise NO_x and will also increase the development risk involved. Much additional information is still needed before the impact of off-design conditions can be quantified.

Continuing studies directed toward defining the probable engine cycle conditions for future supersonic cruise vehicles indicate that cycle pressure ratios are likely to be higher than those previously used for estimating future engine emissions. These higher cycle pressure ratios have a direct impact on the NO_x emission levels that can be forecast on the basis of the present experimental results. Values considerably higher than previous estimates are projected when conventional correlating parameters are applied. Recent parametric tests of the full and partial prevaporized-premixed techniques, however, revealed some anomalies with regard to the pressure and temperature effects on NO_x formation. Much more information on these effects must be obtained before reasonably accurate extrapolations can be made.

The message then would seem to be clear. A careful, systematic approach is needed to answer the anomalies; to fill in the gaps in fundamental knowledge, such as autoignition and flashback; to determine the tradeoffs between complexity and emission reduction potential; and finally to demonstrate the performance of the high risk, low NO_x emission technology in an actual engine environment. The goals and approach of the NASA Stratospheric Cruise Emission Reduction Program (SCERP) have been structured to satisfy most of these needs. Because of the NO_x emission reduction promise that the high risk technology has indicated in controlled experiments, programs such as SCERP are needed to provide the data bank required to assess properly the ability to convert this technology into practical engine combustors. This then will help determine the ability of future high-altitude cruise aircraft engines to meet the levels recommended by environmental studies.

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TABLE I. - ENGINE CYCLE CRUISE PARAMETERS

ENGINE	COMBUSTOR INLET PRESSURE, atm	COMBUSTOR INLET TEMPERATURE, K	COMBUSTOR EXIT TEMPERATURE, K
OLYMPUS 593[a]	6.5	824	1320
GENERAL ELECTRIC DOUBLE BYPASS[b]	9.4	887	1809
PRATT & WHITNEY VARIABLE STREAM CONTROL[b]	14.1	985	1755

[a] MACH 2.0; 17.7-km ALTITUDE (NONAFTERBURNING).
[b] MACH 2.32; 16-km ALTITUDE.

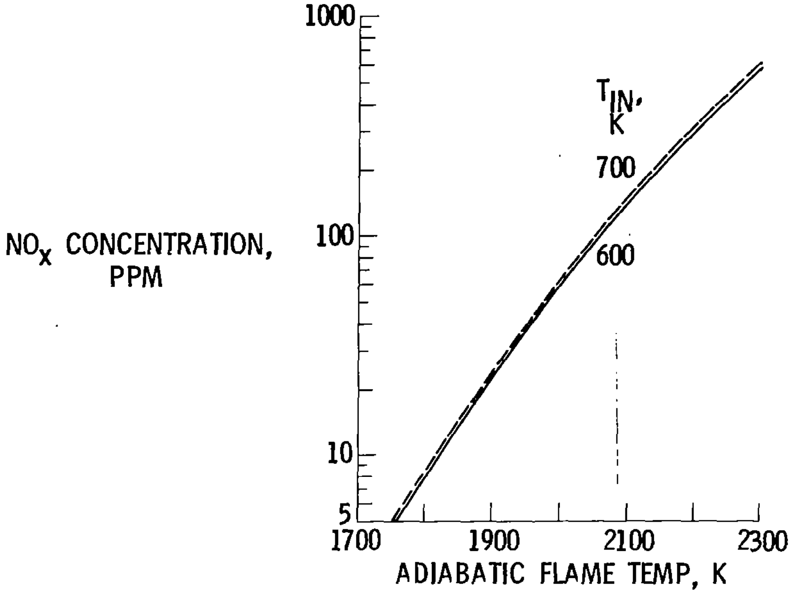
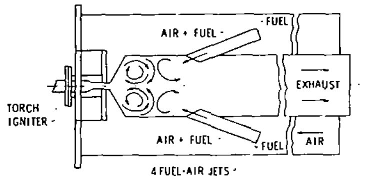
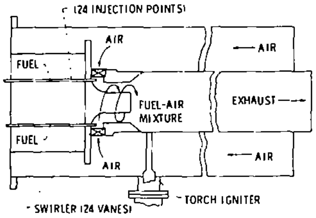


Figure 1.- Effect of flame temperature on theoretical oxides of nitrogen concentration formed in homogeneous prevaporized-premixed combustion process (from well-stirred-reactor prediction). Inlet pressure, 56 N/cm^2; residence time, 2 msec.

FORCED CIRCULATION TECHNOLOGY



JET-INDUCED CONCEPT



VORTEX AIRBLAST CONCEPT

Figure 2.- Schematic illustrations of advanced combustor concepts used in fundamental experiments at SOLAR.

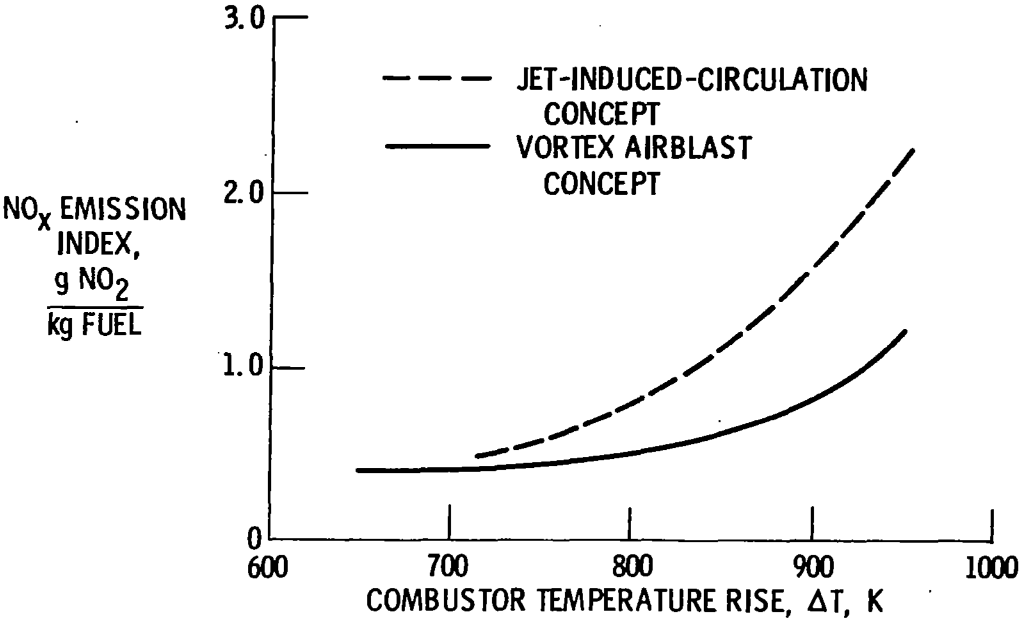
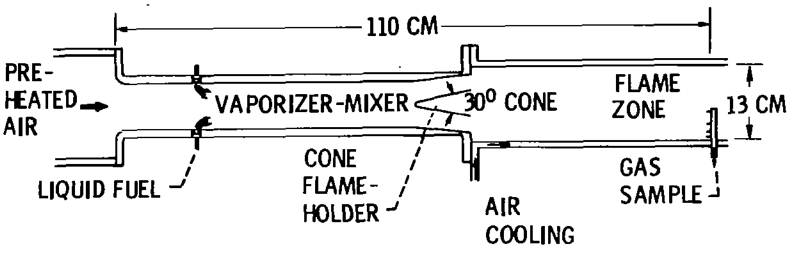
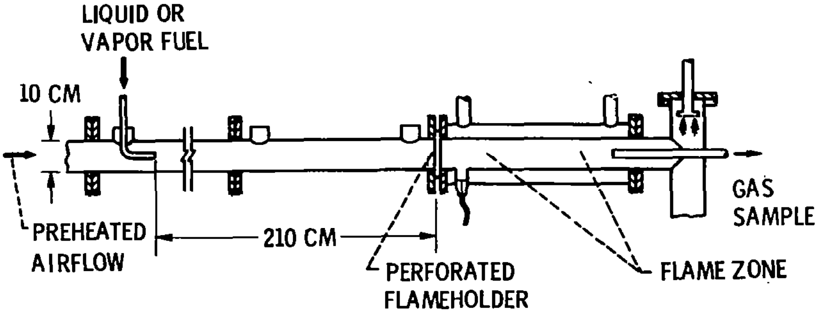


Figure 3.- Effect of combustor temperature rise on NO_x emissions of two SOLAR low NO_x combustor concepts. Jet A-1 fuel; inlet temperature, 830 K; inlet pressure, ~20 N/cm^2.



(a) GASL premixed primary zone test section.



(b) NASA premixed primary zone test section.

Figure 4.- Schematic illustrations of experimental flame-tube apparatus used in GASL and NASA prevaporized-premixed combustion studies.

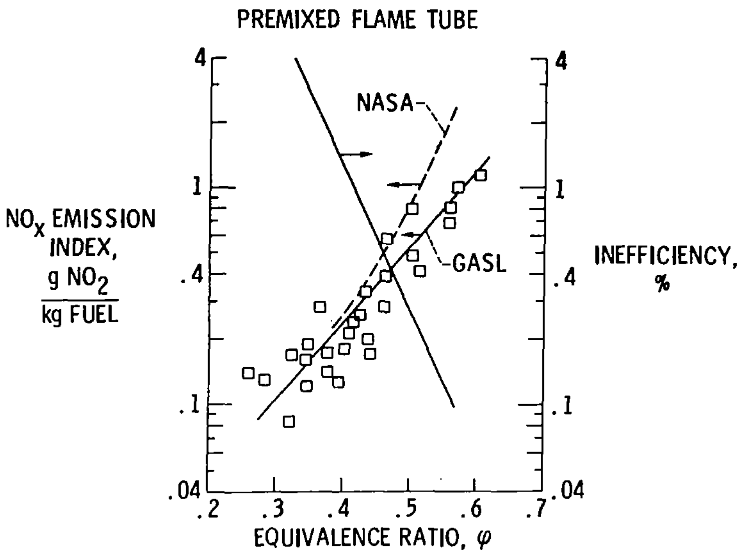


Figure 5.- Impact of combustion equivalence ratio on formation rate of oxides of nitrogen and on combustion inefficiency for GASL and NASA fundamental experiments. Inlet pressure, 40 N/cm^2; inlet temperature, 830 K; Jet-A fuel.

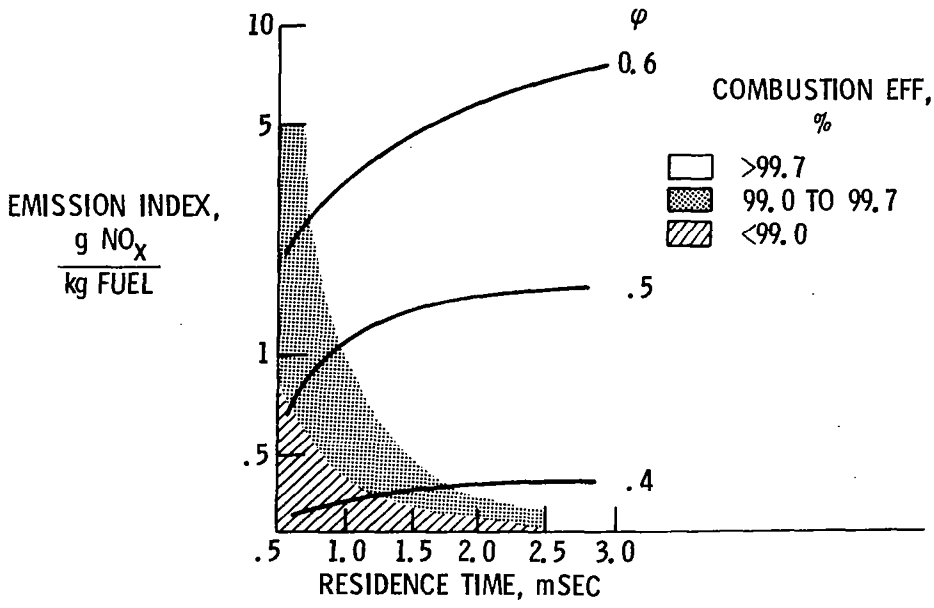
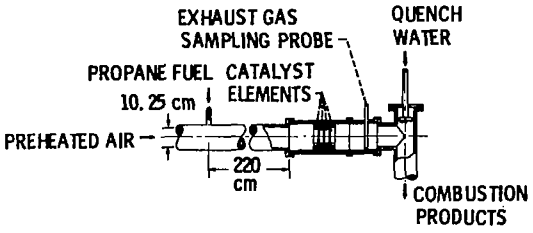


Figure 6.- Impact of combustion residence time and equivalence ratio on formation of oxides of nitrogen and combustion efficiency in prevaporized-premixed flame zone. Inlet pressure, 60 N/cm^2; inlet temperature, 700 K; gaseous propane fuel.



OVERALL SCHEMATIC OF TEST APPARATUS

CATALYTIC REACTOR

Figure 7.- NASA catalyst element experimental test apparatus.

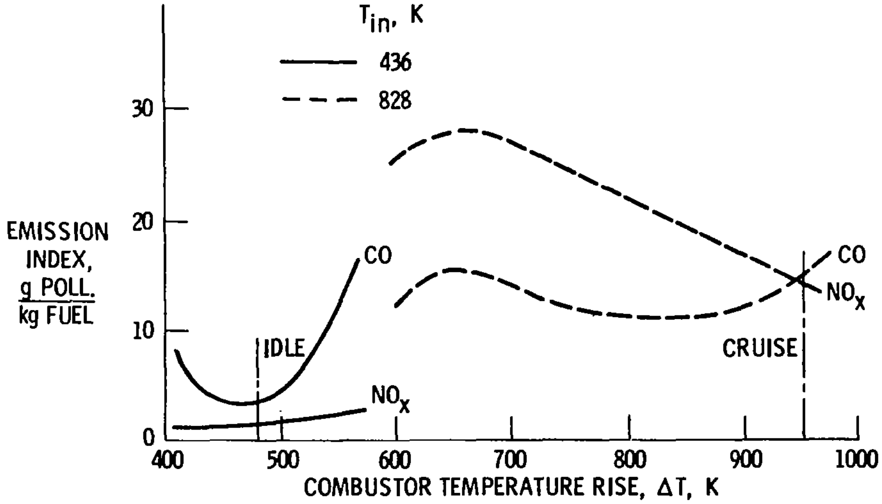
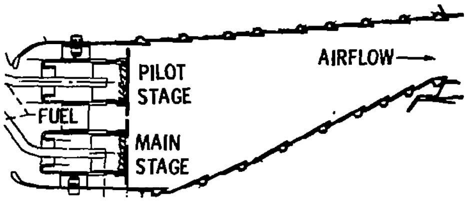
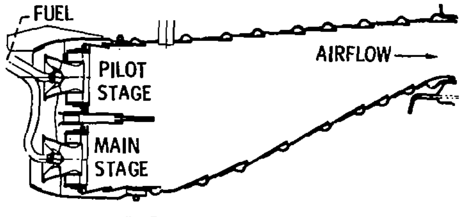


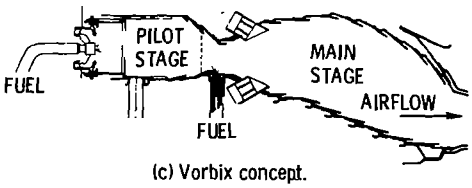
Figure 8.- Effect of optimized idle equivalence ratio on cruise emissions of fixed geometry configuration of SOLAR VAB concept. Inlet pressure, 14 N/cm^2; Jet A-1 fuel.



(a) Swirl-can modular concept.

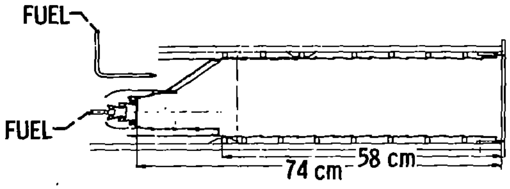


(b) Double-annular concept.

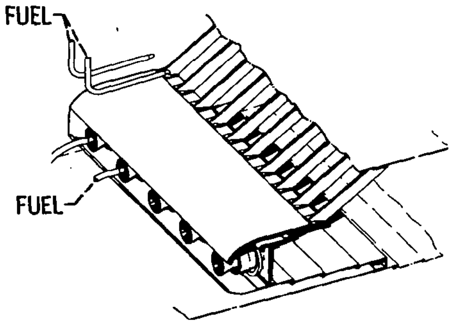


(c) Vorbix concept.

Figure 9.- Schematic illustrations of three types of advanced combustor concepts evaluated at simulated supersonic cruise conditions.



(a) Cross-sectional view.



(b) Configuration sketch.

Figure 10.- Schematic illustrations of staged-combustion advanced duct-burner concept for supersonic cruise engine.

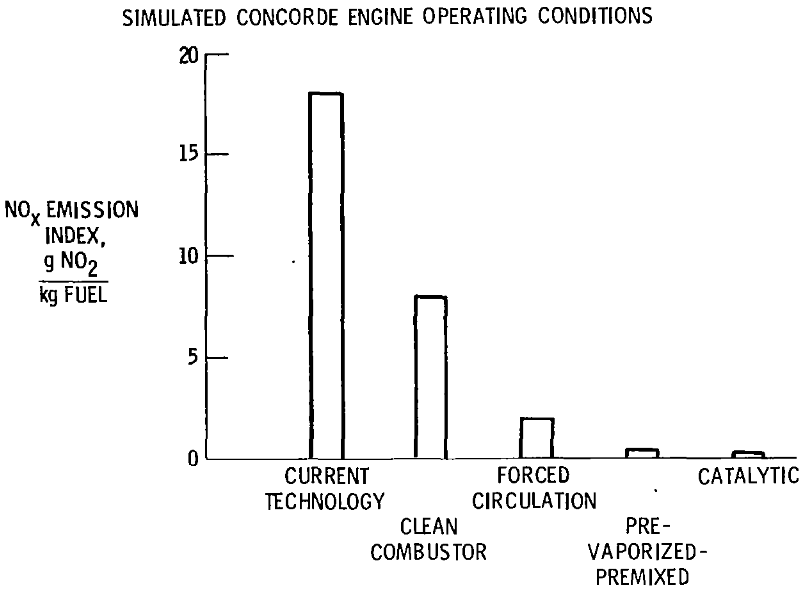


Figure 11.- NO$_x$ emission index forecast for contemporary turbojet engine cycle (Olympus 593) for nonafterburning supersonic cruise. Mach number, 2.0; altitude, 17.7 km.

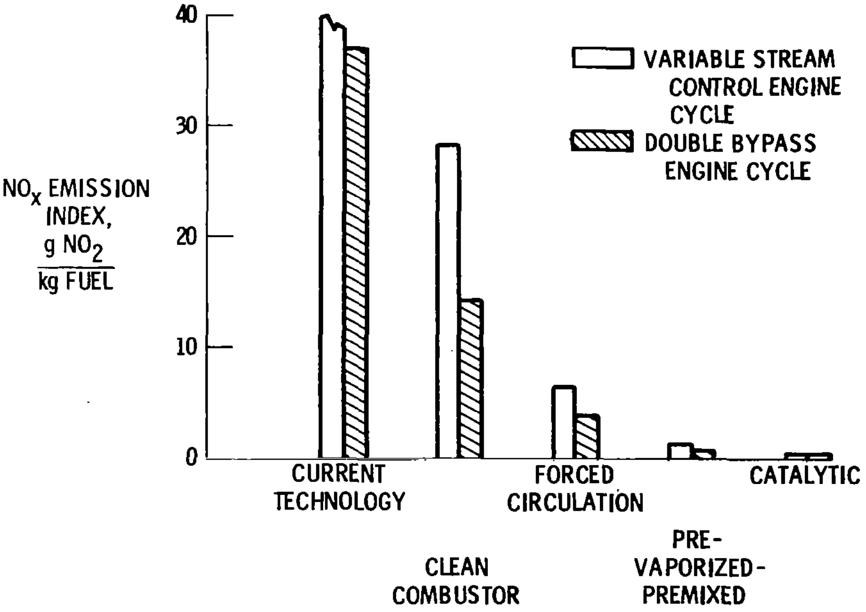


Figure 12.- NO$_x$ emission index forecast for advanced engine cycles for supersonic cruise. Mach number, 2.32; altitude, 16 km.

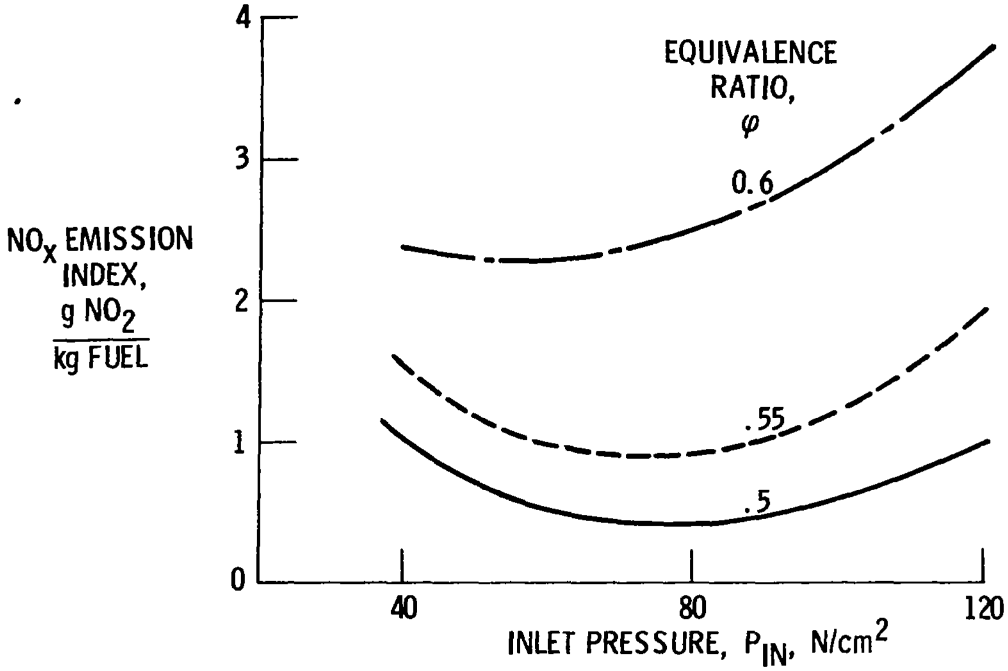


Figure 13.- Effect of inlet pressure and equivalence ratio on NO_x emissions from GASL experiment. Inlet temperature, 900 K; Jet-A fuel.

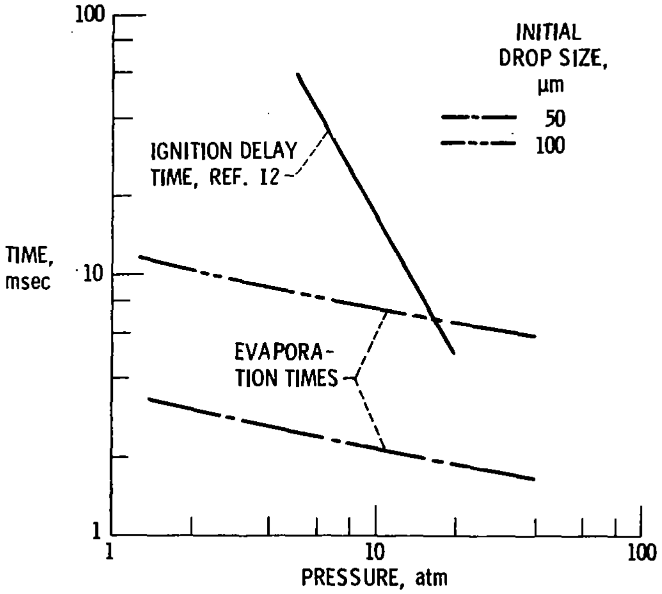


Figure 14.- Effect of pressure on ignition delay and vaporization times for JP-4. Inlet air temperature, 833 K.