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THE IMPACT OF EMISSION STANDARDS ON THE DESIGN OF AIRCRAFT GAS TURBINE ENGINE COMBUSTORS

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ABSTRACT

The advent of environmental standards for controlling aircraft gas turbine engine emissions has led to a reevaluation of combustor design techniques. Effective emission control techniques have been identified and a wide spectrum of potential applications for these techniques to existing and advanced engines are being considered. Results from advanced combustor concept evaluations and from fundamental experiments are presented and discussed and comparisons are made with existing EPA emission standards and recommended levels for high altitude cruise. The impact that the advanced low emission concepts may impose on future aircraft engine combustor designs and related engine components is discussed.

THIS PAPER DESCRIBES and discusses the results from a variety of NASA programs aimed at evaluating the emission reduction potential of advanced combustion techniques and the probable impact of translating these concepts into operational jet aircraft engine combustors.

The Clean Air Act of 1970 charged the Environmental Protection Agency (EPA) with the responsibility to establish acceptable exhaust emission levels of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke for all types of aircraft engines. In response to this charge, the EPA promulgated the standards described in reference (1).* Prior to the release of these standards, the aircraft engine industry, various independent research laboratories and universities, and the government were involved in the research and development of low emission gas turbine engine combustors. Some of this research was used as a guide to set the levels of the EPA standards. The levels established in the standards and the first compliance date, January 1, 1979, have acted as a catalyst for evolving and developing advanced technology combustors. Two major NASA sponsored low emissions technology development programs, the Experimental Clean Combustor Program (ECCP) implemented six months prior to the issuance of the standards and the Pollution Reduction Technology Program (PRTP) implemented within one year after the issuance date, have emission level goals consistent with the EPA standards. Most Independent Research and Development (IR&D) programs in industry are also using the EPA standards as goals for advanced technology developments.

Considerable success has already been achieved by industry to reduce the visible smoke of current aircraft gas turbine engines. The principal technique used was to "lean-out" the combustor primary zone thus eliminating the "fuel-rich" combustion that produces carbon particle formation, reference (2). Most of the current narrow body jet aircraft, B-727, B-737 and DC-9, engines have been retrofitted with low smoke combustors and the wide body jet aircraft, B-747, DC-10 and L-1011, engines entered service with low smoke combustors. Therefore, the principal goal in the research and development programs currently underway is to reduce the levels of the CO, THC, and NO_x emissions while still maintaining acceptable smoke emissions and without adversely effecting fuel consumption, durability, maintainability, and safety.

Two recent U.S. studies regarding the potential adverse impact of aircraft exhaust emissions in the upper atmosphere (stratosphere) have 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 earth's albedo, references (3) and (4). Both of these studies recommended that major reductions in both NO_x and SO_x be sought in future aircraft gas turbine engines. The recommended levels of SO_x can be controlled by de-sulphurizing the fuel used in the high altitude cruise aircraft. However, major modifications will be needed in engine combustion systems to achieve the recommended levels of NO_x reductions. Fundamental studies underway at NASA have been aimed toward evaluating attractive combustion techniques that can achieve these major reductions in NO_x. Based on the results of these studies and in response to the study recommendations, NASA has initiated a Stratospheric Cruise Emission Reduction Program (SCERP). The goal of this program is to evaluate the emission reduction potential of the prevaporized-premixed lean combustion technique and the development needs required to translate this technique into operational combustors for future jet aircraft engines. Again, acceptable performance in terms of fuel consumption (combustion efficiency) as well as durability, maintainability and safety considerations will be taken into account.

This paper describes the EPA emission standards and recommended high altitude cruise levels, some of the emission control techniques that have been and continue to be evaluated, and several design approaches used to translate these techniques into experimental combustors. Also included is a comparison of current results with the standards and recommended levels and a discussion of some of the engine

*Numbers in parentheses designate References at end of paper.

related factors that must be considered.

This paper will concentrate on NASA programs only. It is recognized, however, that considerable information on low emission advanced technology combustors is being generated in work supported by other government agencies (DOD, FAA and EPA) and the aircraft engine industry.

AIRCRAFT ENGINE EMISSIONS

The potential aircraft emission problem is generally divided into two separate categories: (1) in the local airport vicinity under 3000 feet altitude and (2) in the upper atmosphere (stratosphere).

THE LOCAL ENVIRONMENT - The potential problem which is encountered locally encompasses all of the principal pollutants. Both CO and NO_x are toxic gases that can adversely effect health. Partially oxidized hydrocarbons along with NO_x and sunlight combine to produce photochemical smog and are also the primary source of exhaust odors that are prevalent around airports. Even though aircraft contribute only a small part of the overall urban pollution problem, they are a principal source in the airport vicinity. Recognition of this fact led to the establishment of the EPA standards.

EPA Standards - In trying to relate all of the aircraft operating modes into a regulatory number, the EPA constructed an emission parameter (EPAP) which integrates the total emissions over a prescribed landing-takeoff (LTO) cycle for various types of engines. EPAP is defined as:

EPAP = lbs poll./1000 lbs thrust-hrs/cycle
(for jet aircraft)

or

EPAP = lbs poll./1000 SHP-hrs/cycle
(for prop aircraft)

The EPAP standards for the principal pollutant emissions associated with prescribed engine categories are given in Table I along with corresponding values for current engines included in each category. The engine categories are defined on Table I and in reference (1). The range of values shown for current engines indicates that each category covers a wide variety of engine types. In general, the range of improvement required to comply with the standards requires reductions in EPAP values of from 1/2 to 1/4 of current levels. The 1979 standards are for all engines manufactured after 1979 and, hence, includes many of the current engines whereas the 1981 levels, although stricter, are only for new engines certified after 1981.

Landing-Takeoff (LTO) Cycle - The landing-takeoff cycle as established for the EPA standards has some slight variations from one engine class to another, see reference (1). However, in a general sense it can be described by the characteristics illustrated in figure 1. Approximately 26 minutes of the prescribed cycle is associated with low power engine operation during idle/taxi. In this mode of operation, most engines emit comparatively high concentrations (g pollutant/Kg fuel burned) of CO and THC as opposed to high power operation. Therefore, control of CO and THC is most needed at these low power conditions. During the takeoff and climbout portion of the cycle, the concentrations of NO_x emissions are at their peak. Even though the cycle time is short, a large quantity of fuel is burned during takeoff and climbout, hence the control of NO_x during this part of the cycle will have the most impact on the total integrated EPAP value. The approach portion consumes about three minutes of the total cycle and control of all emissions during this phase is equally important. In general, because of the characteristics of aircraft engines and their operational relationships to the LTO cycle, effective emission control techniques must be primarily directed toward reducing CO and THC at low power and NO_x at high power.

THE UPPER ATMOSPHERE - The principal high altitude (stratosphere) problem is associated with the potential effects of the NO_x and SO_x emissions. Of these, the SO_x problem can be minimized by removing the sulfur from the fuel. The main potential culprit is NO_x and its associated reaction with ozone (O_3) principally by the mechanisms:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

The end result of these reactions can be a reduction of O_3 which could increase the ultraviolet radiation reaching the earth's surface thereby producing possible biological effects. Therefore, NO_x is the one emission of most concern for high altitude cruise aircraft (subsonic and supersonic).

In an effort to quantify the potential adverse impact of NO_x emissions on the levels of O_3 in the stratosphere, the Department of Transportation established the Climatic Impact Assessment Program (CIAP). The analysis and conclusions reached during the course of CIAP (≈1971 to 1975) were reported in a series of monographs, one of which concerned aircraft emissions, reference (3). Others included considerations such as biological effects and socio-economic effects. One of the principal recommendations offered was that efforts should be undertaken to reduce high altitude cruise NO_x emissions to levels of from 1/6 to 1/60 of current aircraft levels. During 1974, the National Academy of Sciences convened a Climatic Impact Committee (CIC) to study the possible biological and climatic effects of aircraft emissions in the stratosphere. The resultant report, reference (4), was published in 1975. One of the principal recommendations offered was to immediately undertake research and development programs to develop combustors to reduce high altitude cruise NO_x emissions to levels of from 1/10 to 1/20 of current levels. These levels of NO_x reductions are being used as a guide to establish goals for research programs that investigate combustion techniques for NO_x control in future aircraft engine combustors.

EMISSION CONTROL TECHNIQUES

The relationship between engine operating conditions and the combustion process is illustrated in figure 2. This figure relates the causes, effects, results, and corrective actions required to control the pollutant emissions at the two extreme operating conditions, i.e., low power idle and high power takeoff. During low power idle operation, combustor inlet temperature, T_{in}, and pressure, P_{in}, and fuel-air ratio, F/A, are low causing the effects which contribute to combustion inefficiency and thus the production of CO and THC. At high power takeoff, combustor inlet temperature and pressure, and fuel-air ratio are all high which results in high combustion flame temperature, plus the other effects shown, all of which contribute to the production of NO_x. Since aircraft gas turbine engines must operate effectively at both extremes (idle and takeoff) and many conditions between them, low emission combustors that are compatible to all operating conditions must be developed. If we observe the list of corrective approaches shown in figure 2, we can recognize that a dilemma exists at the two operating extremes. Those corrective approaches which can reduce CO and THC are directly the opposite of those required to reduce NO_x with one exception; improved fuel distribution. The challenge then is to develop advanced combustor technology that can take advantage of a needed correction at a particular engine operating condition without adversely effecting the pollutant production at the other operating conditions.

LOW POWER EMISSIONS - Of the many techniques explored to reduce low power emissions, the use of air-assist and airblast techniques to improve fuel atomization, reference (5), and the use of fuel and air scheduling to increase equivalence ratio (ratio of local to stoichiometric fuel-air ratio), reference (6), have proved to be very effective. In the air-assist technique, high pressure air is used in place of fuel in the secondary flow passage of the nozzle. A typical result using this technique is shown in figure 3 where CO was reduced to about 1/3 of the initial value and THC was reduced to about 1/6 of the initial value by increasing the air-assist differential pressure. Details of implementing this technique are discussed in reference (5). The ability of fuel and air flow scheduling to control idle emissions is illustrated in figure 4. Reductions in CO to about 1/2 and THC to about 1/6 of the initial values were achieved in an experimental combustor. The effectiveness of these techniques in specific applications will be described in a later section of this paper.

HIGH POWER EMISSIONS - The two techniques being most actively explored to reduce the high power NO_x emissions are: (1) to reduce flame temperature by reducing equivalence ratio to values below 0.7, normally referred to as lean combustion, and (2) to reduce residence time in the high temperature combustion region. Of these two the lean combustion approach offers the most potential to achieve the reduction levels recommended by the CIAP and CIC studies.

Lean Combustion - Experiments aimed at exploring the potential of lean combustion have covered a wide spectrum of investigations ranging from modifications to conventional combustors to fully prevaporized-premixed flame tube studies. Results from an experiment which explored the potential reductions possible by modifying a conventional combustor, reference (7), are illustrated in figure 5. NO_x emission index (gNO_2/Kg fuel) is plotted as a function of a calculated primary-zone equivalence ratio, ϕ_p, and an overall equivalence ratio, ϕ_o. At a constant overall equivalence ratio of 0.21, NO_x emissions were reduced approximately 30 percent by reducing the primary zone equivalence ratio from 0.74 to 0.34. This reduction is many times smaller than what is theoretically possible. The inability to effectively reduce NO_x emissions using this approach is most likely due to nonhomogeneities in the primary zone thus causing local "rich" combustion regions. These rich regions form higher levels of NO_x then would result from a homogeneous mixture.

The potential of premixed-prevaporized lean combustion has been evaluated by many experimenters. One such study which employs what could be termed partial prevaporized-premixed combustion is being performed under contract to NASA by the SOLAR Division of International Harvester Company, reference (8). A potential application of two attractive concepts being evaluated in this contract will be described later. Flame tube studies being conducted by, and under contract to, NASA are being used to evaluate the NO_x emission reduction potential of what is termed "full prevaporized-premixed lean combustion." An example of results obtained at NASA and the General Applied Physics Laboratory (GASL) are shown in figure 6. NO_x emission indices below 1 g NO_2/Kg fuel were achieved in both experiments. The NO_x emission levels were more than an order of magnitude lower than those achieved with the modified conventional combustion approach at a comparable equivalence ratio, figure 5, and were very close to theoretically achievable values. At combustion efficiencies that would be acceptable for cruise (>99.5 percent), NO_x emission levels as low as 0.5 g NO_2/Kg fuel were achieved. Please note that these levels were achieved under very carefully controlled conditions and should not be considered to be quantitatively representative of what may be achieved in an actual engine environment.

Residence Time - The impact of residence time (that time period corresponding to molecular exposure that would result in reactions between free nitrogen and oxygen) in a conventional combustor is illustrated in figure 7. Increasing or decreasing residence time from 2 milliseconds (typical of current conventional combustors) produces a nearly linear effect on NO_x emission index. In a homogeneous prevaporized-premixed flame, the impact of residence time can be much less pronounced, figure 8, as the equivalence ratio is reduced to very lean conditions ($\phi < 0.4$). This reduced effect indicates that the extremely low NO_x emission levels (< 0.5 g NO_2/Kg fuel) illustrated in figure 6 may be achievable with high levels of efficiency (> 99.5 percent) if residence time can be optimized. Again it must be noted that conditions were very carefully controlled and this was a "fundamental" type of study. Nevertheless, the implication is that low emissions and high efficiency may be achievable given the proper selection and allowable latitude in critical design parameters, such as residence time.

LOW EMISSION COMBUSTOR DESIGN APPROACHES

In considering how a designer might apply the previously described emission reduction techniques to actual combustors, one can consider several levels of emission control and design complexity. As would be expected, the larger the reduction required and need to control all emissions, not just a selected one, generally results in greater design complexity. The discussion in this section of the paper will illustrate this effect.

MODIFIED CONVENTIONAL COMBUSTORS - The NASA Pollution Reduction Technology Program (PRTP), is structured to investigate varying degrees of combustor design complexity on emission reduction potential. The effect of modifications, such as improving fuel atomization and changing fuel-air distribution, was evaluated using low emission combustor concepts such as those illustrated in figures 9 and 10. Figure 9 illustrates two modifications to a can-annular type combustor used in the Detroit Diesel Allison 501-D22A engine. The reverse flow combustor concept represents a rather minor modification in that only the flow distribution along the liner wall was changed and a more efficient (better atomization) fuel nozzle was installed. The prechamber combustor represents somewhat of an increase in complexity but still has only one fuel injection zone. Both of these combustors have been evaluated in rig tests and the results from the reverse flow design will be discussed later. A modification such as the reverse flow combustor probably represents the minimum type of modification that could be employed to reduce emissions. Its effect however, is rather limited as to the type of emissions that can be reduced.

Two levels of design complexity related to modifying the combustor used in the Garrett-AiResearch TFE 731-2 engine are shown in figure 10. The modified conventional configuration, figure 10(a), utilized air-assist fuel injection and increased combustor bleed to improve fuel atomization and fuel-air distribution. As with the 501-D22A reverse flow combustor, this modification is considered minimal and the emission control potential is limited. The piloted airblast injection concept, figure 10(b), was designed to have variable geometry features in the fuel injector and was more complex to implement and design than the modifications to the conventional combustor. It did, however, produce better emission reduction control but still lacked the capability to effectively control all of the undesirable emissions.

More complex concepts were or are being evaluated for both the 501-D22A and TFE731-2 engines. A description of these concepts is given in references (9) and (10).

Implementation of the technology level illustrated in figures 9 and 10 into operational engines is considered to be "short to mid term" in nature, taking approximately 3 years, and is judged to present a rather low development risk.

STAGED COMBUSTORS - The need to effectively control all the emissions over the entire engine operating range leads one to the staged combustor design approaches being evaluated in the NASA Experimental Clean Combustor Program (ECCP), references (11) and (12). Two types of staged designs are being considered. One representing a parallel type of staging, double annular, is compared to the conventional combustor in figure 11. One stage (pilot) is designed to control the CO and THC emission at idle and the other stage (main) is designed to control the NO_x emissions at high power. The concept shown in figure 11 is designed to fit within the General Electric CF6-50 turbofan engine. A somewhat different approach to staging, series as compared to parallel, is shown in figure 12. The function of the two stages is the same as in the double annular. The vorbix concept shown in figure 12(b) is designed to fit within the Pratt & Whitney JT9D-7 engine. Both of the staged concepts represent a considerable increase in design complexity as compared to the 501-D22A and TFE731-2 concepts previously discussed. Both staged combustor designs have completed evaluations in test rigs and are currently being tested in full-scale engines. Results from the rig tests and a description of the type of information being sought in the full scale engine tests will be discussed later.

Implementation of these staged combustor designs into operational engines is considered to be "mid to far term" in nature taking approximately 5 years or more, and is judged to present a rather high development risk. The implementation of the staged type of combustor design is necessary however, if all the undesirable engine emissions must be reduced to satisfy environmental requirements.

VARIABLE GEOMETRY COMBUSTORS - Perhaps the ultimate approach to control all of the undesirable emissions over the entire engine operating envelope will be found by employing variable geometry in future combustors. Theoretically, the proper implementation of completely variable and independent control of both fuel and air flow could allow one to maintain the optimum equivalence ratio and fuel-air distribution needed to effectively control emission formation at any operating condition. Practically, this approach has not been successfully demonstrated for an aircraft engine type of application.

A conceptual approach to implementing variable geometry in the two advanced concepts being evaluated by SOLAR is illustrated schematically in figure 13 and was provided by reference (13). The JIC concept, figure 13(a), would employ a coupled variable slide valve for primary and dilution area control, airblast fuel atomization, mixing tubes for fuel vaporization to be completed prior to the bend, and convective type cooling. The VAB concept, figure 13(b), would employ coupled swirlers for primary and dilution area control, airblast fuel atomization, and convective cooling. Since these are only conceptual designs, the potential for development is an unknown. But it is anticipated that these types of combustor designs would certainly fall into the category for "far term" applications and have a very high risk development potential. If they could be successfully developed, however, rig test data indicate that extremely low cruise NO_x emissions may be achievable along with LTO cycle emission levels that would also satisfy the EPA standards.

NASA is currently in the process of implementing a program to evaluate and evolve advanced combustor concepts employing the fully prevaporized-premixed techniques previously described in the EMISSION CONTROL TECHNIQUES section of this paper. The objectives, goals, and approach of this program, called the Stratospheric Cruise Emission Reduction Program (SCERP) are presented in Table II. The program will be conducted in four phases each successively building upon the knowledge gained in the previous phase. The culmination of the program is expected to be a full-scale engine demonstration of a lean burning (likely a completely prevaporized-premixed combustion technique) variable geometry experimental combustor sometime in the early to mid 1980's. Again this is basically an effort to evolve combustors for "far term" applications and has a very high development risk potential.

The successful development of variable geometry schemes would certainly have a lasting impact on the design of future aircraft engines and on the environmental acceptability of these future engines.

TEST RESULTS - The results of test programs conducted using the designs previously described along with several other combustor concepts evaluated in the NASA ECCP and PRTP are summarized in Table III. This table compares the test rig results obtained using the "best" configurations tested to date with the requirements as specified by the 1979 EPA standards and the current engine baseline (conventional) combustors. All of the EPAP values shown are corrected to actual engine operating conditions. The "best" configurations were selected based on the ability to reduce all of the undesirable emissions and to satisfy other engine performance requirements such as combustion efficiency, pressure drop and temperature pattern factor.

All of the selected "best" advanced concepts produced emission levels of THC and smoke that were below the levels needed to meet the EPA standards. The CF6-50 double annular concept and the 501-D22A reverse flow concept reduced the CO emissions to values less than the EPA standards. The 501-D22A reverse flow concept and the JT9D-7 vorbix concept were capable of achieving NO_x emission levels below the EPA standards. The prime reason for the success of the 501-D22A concept in achieving the NO_x emission level requirements is due to the low initial level for the baseline combustor as compared to the EPA standards. The JT9D-7 vorbix concept, the JT8D-17 vorbix concept, and the TFE731-2 piloted-airblast concept did not achieve CO emission levels low enough to meet the EPA standards. Further reductions in CO levels should be achievable with the vorbix concepts through continued development, but whether the standard levels can be achieved is uncertain at this time. The piloted-airblast concept will also require further development to meet the EPA CO standards. As shown in Table III, the NO_x emission levels were not low enough to satisfy the EPA standards for three of the five advanced concepts. A more detailed discussion and analysis of these results are given in reference (14). Please note that these are test rig results and that some variation in actual levels achievable in operational engines will most likely be encountered.

In addition to evaluating the emission reduction capability of the various concepts as referenced to the EPA standards, several of the concepts were evaluated for NO_x reduction capability at simulated high altitude subsonic cruise conditions. Also the the NO_x emission results from several fundamental type studies, such as the SOLAR contract and the NASA flame-tube experiment, were extrapolated to engine operating conditions simulating high altitude subsonic cruise. The results of these evaluations and extrapolations are compared with the present levels associated with conventional combustors in figure 14. Operating conditions corresponding to a 30:1 engine cycle pressure ratio at an aircraft flight speed of 0.85 Mach number and an altitude of 35,000 feet were used for this comparison. The Clean Combustor type technology can provide a potential reduction in cruise NO_x to about 1/2 of current levels. To achieve the levels recommended by the climatic impact studies, 1/6 or less than current levels, will certainly require the successful development of the prevaporized-premixed technique. This then implies that the very high risk level of technology (such as being evaluated in SCERP) must be brought to the fore if these recommended environmental constraints become regulatory requirements. In so doing, the design of future aircraft engine combustors will undergo a significant change from both today's conventional technology and the advanced technology designs currently being evolved in an attempt to satisfy EPA standards.

ENGINE RELATED FACTORS

In order to properly assess the applicability of the various low emission combustor concepts to in-service aircraft engines, one must certainly consider the impact on the overall engine operating characteristics. Other factors such as maintainability and safety must also be considered. Evaluation of these factors must be undertaken to properly assess whether or not trade-offs between emissions, performance and operational characteristics are required. Some of the factors of concern, but certainly not all, will be discussed in this section.

COMPLEXITY CONSIDERATIONS - One important factor that must be considered in assessing the applicability of converting the low emission concepts into production type engine combustors is the impact of the increased complexity that some of these concepts will bring forth compared to the baseline combustors currently in use. No significant problems would be expected in applying the reverse flow concept to the 501-D22A engine since minimal or no changes in the engine fuel system and fuel control functions should be necessary. Applying the piloted-airblast type concept to the TFE731-2 engine would require some changes to the engine/combustor structure but would not be expected to significantly effect the engine fuel system or control. The level of emission control produced by these concepts, Table III, should, therefore, be possible to achieve with a minimal impact on the design of other engine components.

The staged concepts, such as the double annular and vorbix, will certainly increase the complexity of both the engine fuel system and the required control functions. For example, the number of fuel injectors needed to adapt the staged double annular concept to the CF6-50 engine would be twice the number currently used in the baseline combustor. The same order of increase is required to adapt the vorbix concept. In addition, the staged concepts will require an additional fuel manifold and the fuel flow to the two manifolds must be controlled independently and accurately. Studies conducted by both GE and P&WA in the Experimental Clean Combustor Program (ECCP) have shown that this increase in complexity is of concern and will probably require continued development. However, at this time it does not appear to be an insurmountable problem to the successful application of the staged concepts. Hydromechanical controls have been designed and used in military engines to handle the type of dual flow functions required. The probability of electronic digital fuel control systems entering service in the future should make this required dual control mode much more positive and easier to manage.

A real unknown at the present time is the probable impact that variable geometry would impose upon the engine controls. Since one of the prime reasons for using variable geometry is to accurately control the equivalence ratio (flame temperature) some type of sensor and appropriate feedback function will be needed. This will most certainly increase the complexity of the control but to what degree is difficult to judge. The added actuators and variable mechanism needed will also increase the basic mechanical complexity. Information regarding these factors will be obtained during the conduct of the Stratospheric Cruise Emission Reduction Program (SCERP).

OPERATIONAL CONSIDERATIONS - Many operational factors that must be met to insure successful engine application must be considered. Meeting engine starting requirements, acceleration and deceleration requirements, and finally verifying emission levels with engine imposed variations in flow, temperature, and pressure profiles (the "real world" compared to the controlled environment of the combustor test rigs) have not yet been evaluated. These factors can only be explored in full-scale engine tests and until they are quantitatively evaluated, it is not possible to determine if trade-offs between engine requirements and emission levels are going to be necessary. Successful combustor light-offs and reasonably smooth transitions observed during staging (for the double annular and vorbix concepts) in the combustor rig tests would seem to indicate that significant trade-offs of emissions versus operational performance are not likely to be required. However, the inability to maintain accurate and repeatable control of the staging point during acceleration and deceleration is likely to present a difficult development problem.

MAINTENANCE AND SAFETY CONSIDERATIONS - The additional hardware required to apply the staged and variable geometry concepts to engines will certainly have an impact on maintenance requirements. The increased number of fuel injectors and fuel manifolds needed for the staged designs adds to the potential for problems and thus may increase required maintenance. The maintenance requirements of variable geometry type concepts will likely be greater than the staged concepts but to what degree is unknown at this time. This factor must be quantitatively evaluated.

The safety factors of most concern would be associated with engine acceleration, altitude relight and the potential for auto-ignition and flashback in the prevaporized premixed combustion technique. The first two factors have or are currently being evaluated for the staged combustor concepts in the ECCP. No significant problems are expected in obtaining acceptable altitude relight and combustor rig tests indicate that smooth staging should be achievable to provide acceptable acceleration. Acceleration and deceleration tests will be performed during the full-scale engine tests in the ECCP. The problems and solutions associated with auto-ignition and flashback in premix combustors will be evaluated in the SCERP.

CONCLUDING REMARKS

Results obtained from a variety of advanced technology combustion investigations, ranging from fundamental flame tube studies to experimental combustors, indicate that substantial reductions in undesirable exhaust emissions should be achievable in contemporary and future aircraft gas turbine engines. Emission reductions approaching both local EPA standards and high altitude cruise recommendations have been achieved in controlled rig tests. The degree of reduction achievable will, of course, be dependent upon the level of advanced technology that is judged to be developable into operational combustors.

Final proof-of-concept type tests in full-scale engines are needed to quantify the achievable levels as well as to evaluate the impact of increased complexity on engine operational characteristics. Further considerations with regard to other engine related factors, such as controls, maintenance and safety, must also be evaluated. Nevertheless, results obtained to date indicate that advanced concepts, such as the staged combustors, should be capable of development into operational engines.

Modifications to conventional combustors (improved fuel atomization and fuel-air flow distribution) can provide the capability to effectively reduce low power emissions (CO and THC) and smoke with a minimum impact on complexity and a low development risk. Effective control of all the emissions (CO, THC, NO_x and smoke) will require the implementation of staged or variable geometry type combustor concepts. The staged or variable geometry concepts will have a significant impact on complexity and involve a high to very high development risk but their inherent total emission control capability certainly warrants continued evaluation and eventual development. NASA programs to evolve staged concepts into experimental combustors and evaluate capabilities and problems when adapted to full-scale engines are currently underway. The extremely low levels of high altitude cruise NO_x emissions recommended by environmental impact studies implies that the successful development of prevaporized-premixed combustion technique will be needed. In addition, the use of staged or variable geometry approaches will surely be needed for satisfying both local and high altitude emission requirements. Variable geometry when coupled with the prevaporized-premixed combustion technique, will make this an extremely high risk development task. The NASA Stratospheric Cruise Emission Reduction Program (SCERP) is aimed at evaluating the potential for achieving the successful adaptation of the prevaporized-premixed variable geometry concept.

The successful translation of all of the advanced combustion concepts described in this paper into operational engines certainly presents a difficult challenge to design and development engineers. Whether or not success is achieved will depend upon the ingenuity and inventiveness of the engineers involved in aircraft engine research and development.

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TABLE I. - EPA PARAMETER EMISSION LEVELS FOR THE LTO CYCLE

1979 EPA STANDARDS

*ENG CLASS	THC		CO		NO_x		SMOKE	
	PRES	STD	PRES	STD	PRES	STD	PRES	STD
T1	4-16	1.6	15-60	9.4	2.5-4.5	3.7	-----	<32
T2, T3, T4	2-21	.8	7-20	4.3	3-10	3.0	20-65	<25
P2	6-12	4.9	20-30	26.8	6-10	12.9	-----	<50
PISTON	3-4.5	1.9	50-120	42	0.2-1.3	1.5	-----	---

1981 EPA STANDARDS

T2, T3, T4	2-21	0.4	7-20	3.0	3-10	3.0	20-65	<25

*T1 - JET AIRCRAFT GAS TURBINE ENGINES, <8000 LB THRUST.
T2 - JET AIRCRAFT GAS TURBINE ENGINES, >8000 LB THRUST.
T3 - JT3D ENGINES.
T4 - JT8D ENGINES.
P2 - TURBOPROP AIRCRAFT GAS TURBINE ENGINES.

TABLE II. - STRATOSPHERIC CRUISE EMISSION REDUCTION PROGRAM

OBJECTIVE	ESTABLISH AND DEMONSTRATE THE TECHNOLOGY TO REDUCE ENGINE EMISSIONS TO ENVIRONMENTALLY ACCEPTABLE LEVELS OVER THE ENTIRE AIRCRAFT OPERATING RANGE WITH MINIMUM ADVERSE EFFECTS ON PERFORMANCE, WEIGHT, AND COMPLEXITY
GOALS	• ACHIEVE MINIMUM OF 6- TO 10-FOLD REDUCTION IN SUBSONIC CRUISE NO_x EMISSIONS FROM CURRENT LEVELS • MEET OR EXCEED ESTABLISHED EPA STANDARDS FOR THE LTO CYCLE
APPROACH	• UTILIZE I-H, CONTRACT AND UNIV. GRANT CAPABILITIES • MULTI-PHASE ACTIVITY PHASE I - FUNDAMENTAL STUDIES PHASE II - CONCEPT SCREENING PHASE III - EXPERIMENTAL COMBUSTOR DEVELOPMENT PHASE IV - ENGINE DEMONSTRATION

TABLE III. - SUMMARY OF EMISSION LEVELS (EPAP VALUES) ACHIEVED WITH THE "BEST" ADVANCED TECHNOLOGY COMBUSTOR CONCEPTS FOR ALL ENGINES CONSIDERED IN THE ECCP AND PRTP. ALL EPAP VALUES COMPUTED FOR ACTUAL ENGINE OPERATING CONDITIONS (STANDARD DAY)

EMISSIONS / ENGINES	CO			THC			NO_x		
	CONV COMB.	ADV TECH	EPA STDS	CONV COMB.	ADV TECH	EPA STDS	CONV COMB.	ADV TECH	EPA STDS
CF6-50 ENGINE (DOUBLE ANNULAR CONCEPT)	10.8	3.0	4.3	4.3	0.3	0.8	7.7	4.2	3.0
JT9D-7 ENGINE (VORBIX CONCEPT)	8.6	6.5	4.3	3.9	0.3	0.8	4.9	2.2	3.0
JT8D-17 ENGINE (VORBIX CONCEPT)	16.1	8.9	4.3	4.4	0.2	0.8	8.2	4.4	3.0
TFE731-2 ENGINE (PILOTED-AIRBLAST CONCEPT)	17.5	10.1	9.4	5.3	0.4	1.6	5.3	3.9	3.7
501-D22A ENGINE (REVERSE FLOW CONCEPT)	31.5	4.6	26.8	15.0	0.3	4.9	6.2	7.3	12.9

SMOKE REQUIREMENTS SHOULD BE ACHIEVABLE FOR ALL CONCEPTS

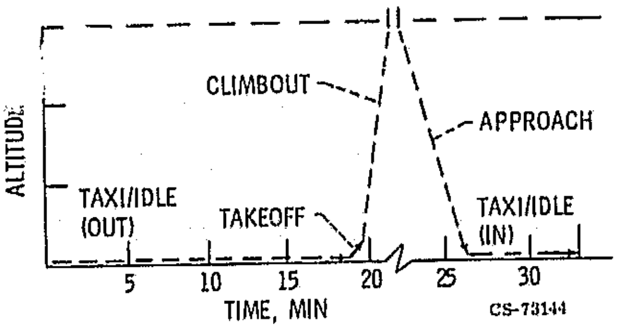


Figure 1. - EPA landing-takeoff cycle, T2 class engine.

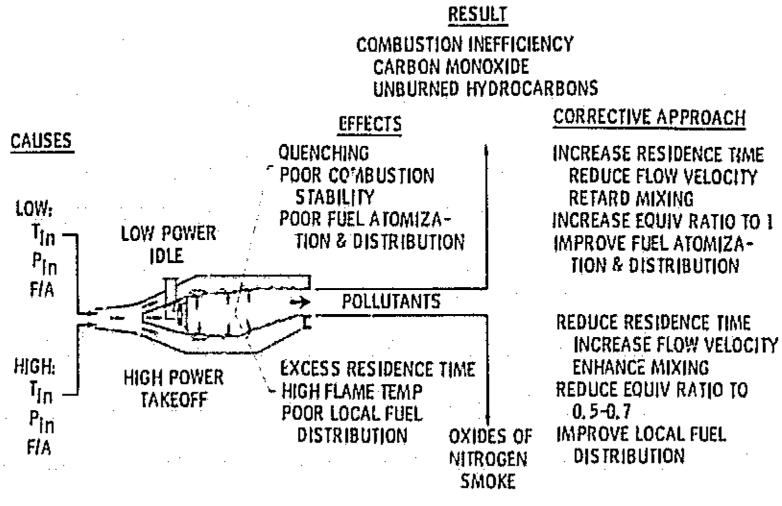
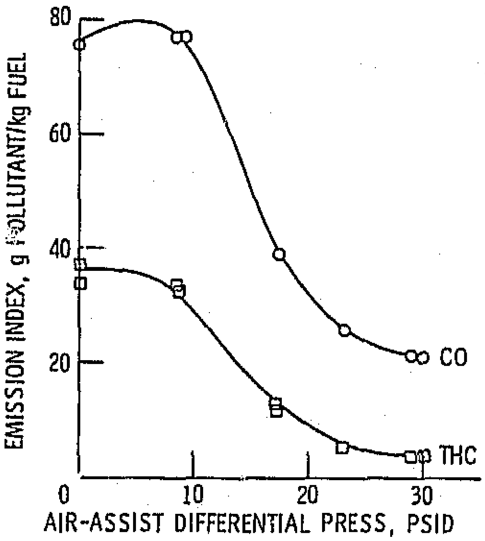


Figure 2. - Aircraft gas turbine combustor pollution considerations.

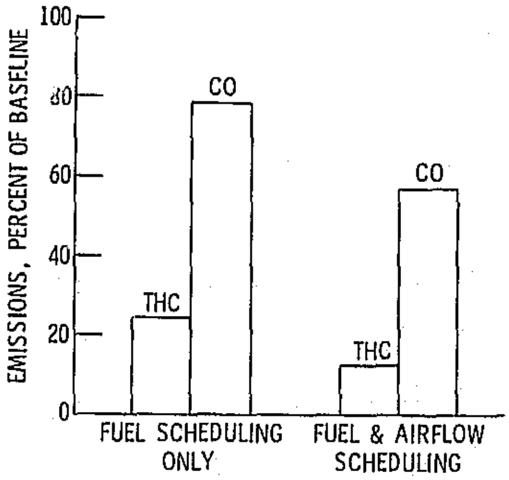
CS-69635

E-8836



CS-73153

Figure 3. - Effect of improving fuel atomization on idle emissions in conventional combustor using the air-assist technique. Inlet temperature, 580 K, Inlet pressure, 25 N/cm^2, f/a, 0.011.



CS-73155

Figure 4. - Effect of fuel flow and airflow scheduling on idle emissions of an experimental combustor. Inlet temperature, 580 K, Inlet pressure, 25 N/cm^2, f/a, 0.011.

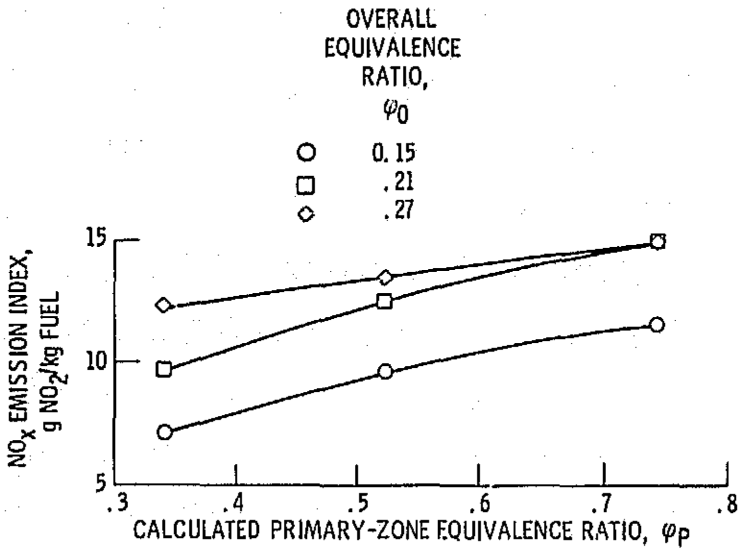


Figure 5. - Effect of primary-zone equivalence ratio on NO_x emissions for varying overall equivalence ratio in a "conventional" combustor. Jet A fuel; inlet temperature, 810 K; inlet pressure, 40 N/cm^2; reference velocity, 213 m/sec.

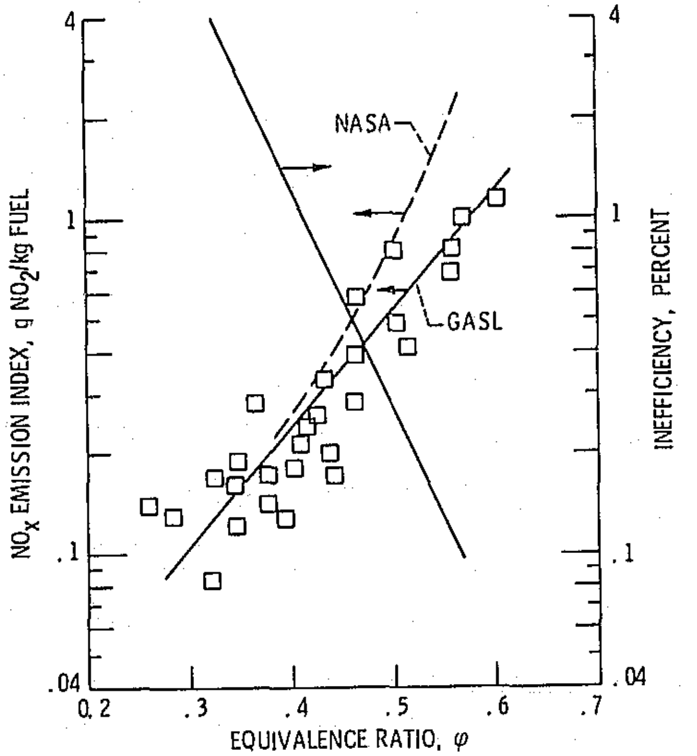


Figure 6. - Effect of equivalence ratio on NO_x in a prevaporized-premixed combustion scheme. Jet A fuel; residence time, 2 milliseconds; inlet temperature, 830 K; inlet pressure, 40 N/cm^2.

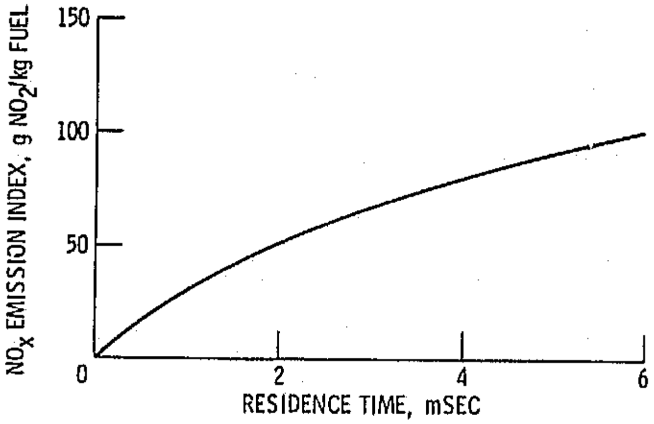
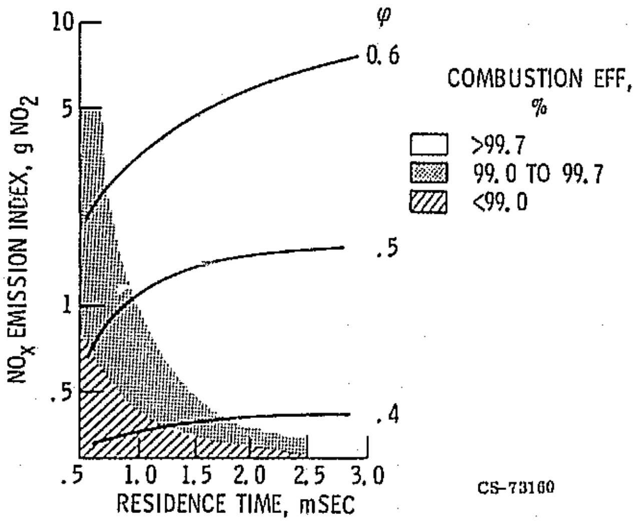


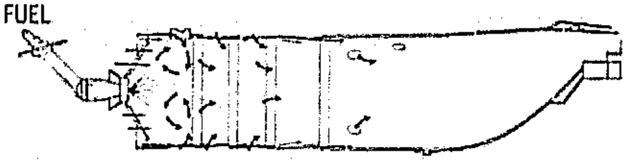
Figure 7. - Effect of residence time on NO_x emissions from a conventional type combustor operating at near takeoff conditions.

E-8884

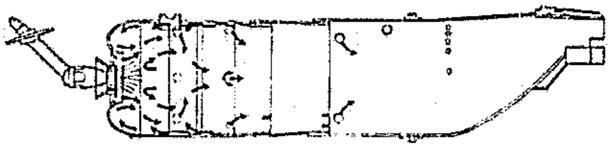


CS-73160

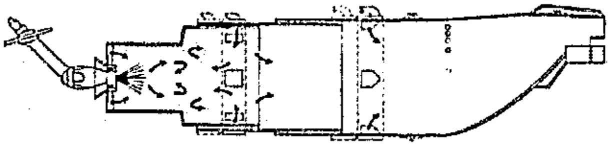
Figure 8. - Impact of combustion residence time and equivalence ratio on the formation of oxides of nitrogen and combustion efficiency in a prevaporized/premixed flame zone. Inlet pressure, 60 N/cm^2, inlet temperature, 700 K, gaseous propane fuel.



(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

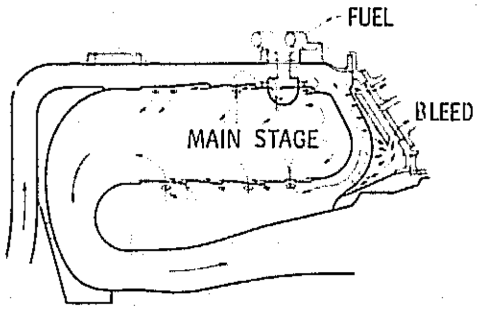


(b) REVERSE FLOW COMBUSTOR CONCEPT.

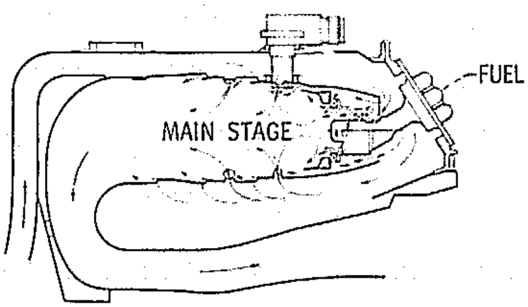


(c) PRECHAMBER COMBUSTOR CONCEPT.

Figure 9. - Cross-sectional illustration of two low emission combustor concepts for the Detroit Diesel Allison 501-D22 turboprop engine. EPA Class P2.

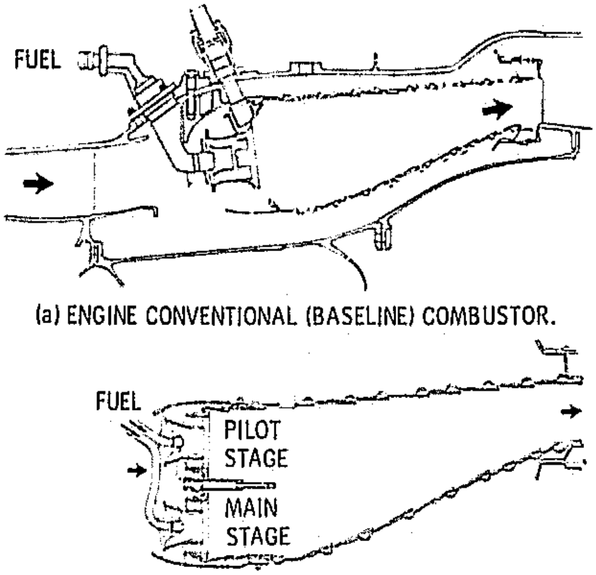


(a) MODIFICATIONS TO BASELINE COMBUSTOR.



(b) PILOTED AIRBLAST INJECTION COMBUSTOR CONCEPT.

Figure 10. - Cross-sectional illustration of emission reduction modifications for the AiResearch TFE731-2 turbofan engine combustor. EPA Class T1.

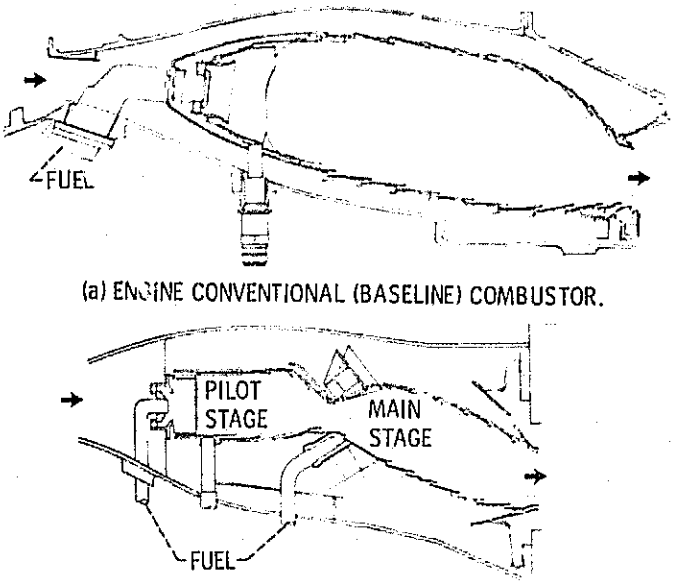


(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

(b) DOUBLE ANNULAR CONCEPT.

Figure 11. - Cross-sectional illustration of a staged combustor concept for the General Electric CF6-50 turbofan engine. EPA Class T2.

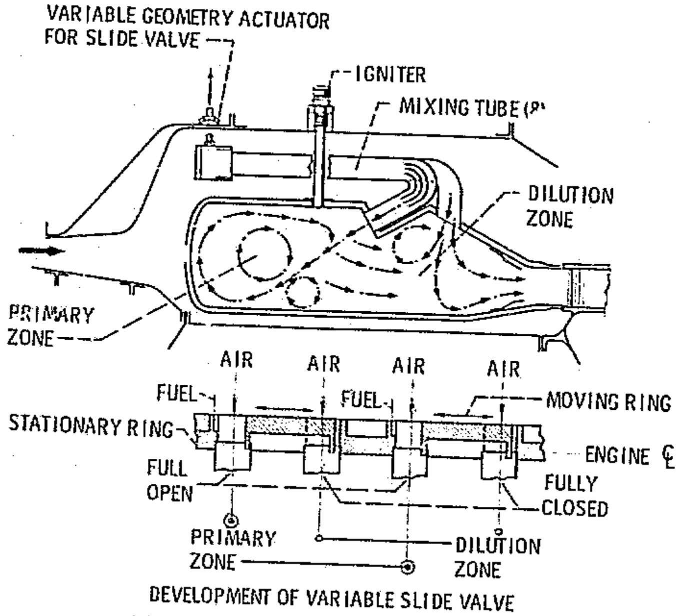
E-8886



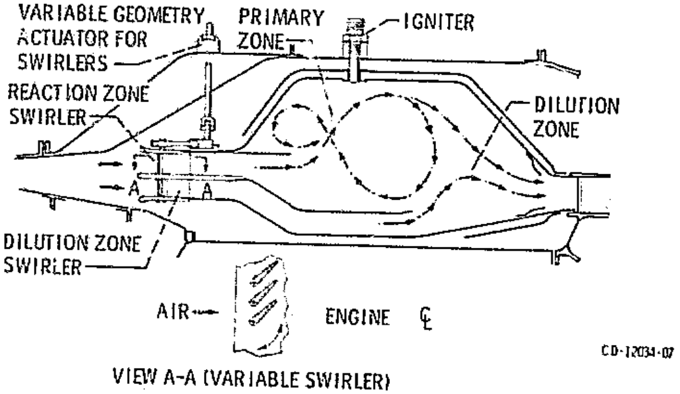
(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

(c) VORBIX CONCEPT.

Figure 12. - Cross-sectional illustration of a staged combustor concept for the Pratt and Whitney JT9D-7 turbofan engine. EPA Class T2.



(a) JET-INDUCED-CIRCULATION (JIC) CONCEPT.



(b) VORTEX-AIRBLAST (VAB) CONCEPT

Figure 13. - Cross-sectional illustration of two conceptual approaches for implementing variable geometry into full annular configurations of the SOLAR JIC and VAB combustor concepts.

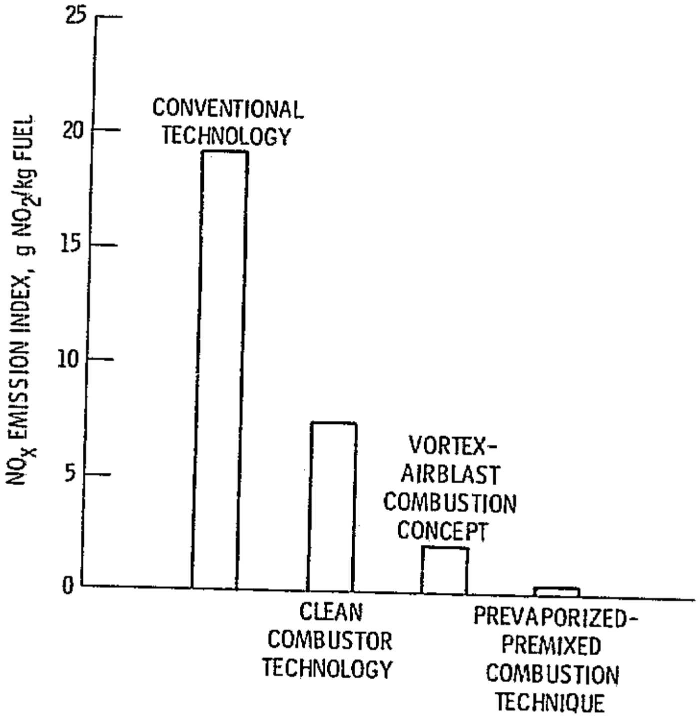


Figure 14. - Projected subsonic cruise NO_x emission levels using the results from the various emission reduction techniques. Flight Mn, 0.85, flight altitude, 10.7 km (35 000 ft). Engine cycle pressure ratio, 30:1.