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MEMORANDUM**

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**STATUS REVIEW OF NASA PROGRAMS FOR REDUCING
AIRCRAFT GAS TURBINE ENGINE EMISSIONS**

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SUMMARY

E-8620

Programs have been initiated by NASA to develop and demonstrate low emission advanced technology combustors for reducing aircraft gas turbine engine pollution. Program goals are consistent with urban emission level requirements as specified by the U.S. Environmental Protection Agency (EPA) and with upper atmosphere cruise emission levels as recommended by the U.S. Climatic Impact Assessment Program (CIAP) and National Research Council. Preliminary tests of advanced technology combustors indicate that significant reductions in all major pollutant emissions should be attainable in present generation aircraft gas turbine engines without adverse effects on fuel consumption. Preliminary test results from fundamental studies indicate that extremely low emission combustion systems may be possible for future generation jet aircraft. The emission reduction techniques currently being evaluated in these programs are described along with the results and a qualitative assessment of development difficulty.

INTRODUCTION

This paper describes some of the combustion techniques that are being evaluated for reducing the pollutant emissions of both contemporary and future aircraft gas turbine engines. Advanced technology combustion concepts being developed are adaptable to a wide variety of current in-service aircraft engines which have been identified for emission control by the U.S. Environmental Protection Agency (EPA). Related fundamental combustion studies that are being conducted are generating results which indicate that future aircraft gas turbine engines may be able to utilize combustion systems with extremely low pollutant emissions.

The U.S. Clean Air Act of 1970 charged the U.S. 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 the timely development of 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 (PRTTP) implemented within one year after the issuance date, have emission level goals consistent with the EPA standards.

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 sulphur (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. Therefore, the principal goal in fundamental combustion research programs currently underway is to investigate and evolve emission control techniques that can reduce NO_x emissions by a factor of 10 or greater at the cruise operating conditions expected in future commercial subsonic and supersonic high altitude cruise aircraft. Again, acceptable performance in terms of fuel consumption (combustion efficiency) as well as durability, maintainability, and safety considerations must be taken into account for future development of these techniques into engine combustors.

This paper describes and discusses the results from some of the research and development programs being sponsored, directed, and/or conducted by NASA. Although this paper concentrates on NASA programs only, work supported by other U.S. government agencies (DOD, FAA, & EPA) and industry has provided considerable data on low emission advanced technology for aircraft gas turbine engine combustors. The results from the two major NASA technology development programs, the ECCP and the PRTP, are presented and compared with the requirements of the 1979 U.S. EPA standards and results from fundamental combustion studies are also described. The potential for application of the advanced technology combustion systems is also discussed.

ENGINE EMISSION CHARACTERISTICS

The levels of gaseous emission pollutants vary with engine operating conditions, for most conventional combustors, in the manner illustrated in figure 1. The emission index (grams of pollutant/kilogram of fuel burned) levels of CO and THC are highest at the off-design operating conditions, such as low power idle, where combustion efficiency is at the lowest level. Conversely, the NO_x (normal practice is to express NO_x levels in terms of complete conversion to NO₂) is the highest at the takeoff condition because combustion gas temperatures and pressures are at their highest levels. Because of this dependence on engine operating conditions, any emission control techniques that would have merit on an overall engine operating curve would certainly have to be most effective at these two extreme points, e.i. CO and THC must be drastically reduced at idle and NO_x at takeoff. Intermediate power points also contribute to the overall emissions hence they too

must be considered but to a lesser degree.

The relationship between engine operating conditions and the combustion process is shown in figure 2. This figure relates the causes, effects, results, and corrective approaches needed for the various 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 the production of CO and THC and thus combustion inefficiency. 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 . 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 the needed corrective approaches at a particular engine operating condition without adversely effecting the rate of pollutant formation at the other operating conditions.

FUNDAMENTAL EXPERIMENTS

NASA is sponsoring and conducting fundamental combustion experiments which are aimed at developing an understanding of the factors which contribute to pollutant formation at both the low and high power operating conditions. The goal of these experiments is to identify techniques which are effective in controlling the principal factors which govern pollutant formation rate and to determine the magnitude of the reductions possible by employing various control techniques. As such, these experiments envelope a wide variety of control techniques that would be applicable to combustion systems in general rather than exploring a specific combustor size or type.

Low Power Emissions

Many techniques to reduce low power emissions have been evaluated by NASA including the use of air-assist fuel nozzles, airblast fuel nozzles, and fuel scheduling in the primary zone. Air-assist and airblast fuel nozzles use high pressure and high velocity air, respectively, to aid in atomizing the fuel and are very effective for reducing CO and THC at idle conditions, references 5 and 6. Fuel scheduling reduces the number of fuel nozzles that are supplied with fuel thus resulting in improved atomization for a constant fuel flow rate, reference 7. The effectiveness of improving fuel atomization by using air-assist and airblast fuel nozzles is reasonably well documented and will not be explored in detail in this report but specific application will be described in later sections.

High Power Emissions

Techniques to reduce high power emissions have concentrated on evaluating the effect of prevaporizing and premixing fuel and air prior to combustion using a "flame tube rig" at the NASA, Lewis Research Center which is shown schematically in figure 3. Gaseous or atomized fuel is injected upstream of a perforated flame holder with sufficient distance to provide a completely prevaporized/premixed fuel/air mixture to the primary zone (flame zone) test section. A composite representation of results obtained

from these "flame tube rig" tests is shown in figure 4. At the test conditions indicated, extremely low levels of NO_x emissions (E.I. < 1 g/kg) were obtained at very lean equivalence ratios, ϕ (ratio of the fuel/air ratio to stoichiometric fuel/air ratio). These low NO_x E.I. values were obtained at reasonable residence time (about 2 milliseconds) and at combustion efficiencies in excess of 99.7. This type of data is being used in an attempt to define minimum levels to which NO_x may be reduced by utilizing the lean pre-vaporized/premixed combustion technique. Therefore, the operating conditions for the experimental tests were very carefully controlled and do not necessarily duplicate conditions in an actual engine except for the levels of inlet pressure and temperature which simulate a supersonic cruise condition. At extremely lean equivalence ratios ($\phi < 0.5$) combustion stability can be a problem because operation is near the lean flammability limit, thus limiting the NO_x emission reduction potential of the lean combustion technique.

A similar experiment is being conducted under contract with the General Applied Sciences Laboratories (GASL). A schematic diagram of the test apparatus is shown in figure 5 and typical NO_x emission index levels obtained as a function of equivalence ratio are shown in figure 6. Also shown on this figure are results from the NASA "flame tube rig" showing that good agreement between the two experiments was realized. Specific details of the GASL experiment are given in reference 8 and further tests are underway to explore the effect of a wider range of test conditions on the results obtained in this experiment.

Another evaluation of the premix technique is being conducted under contract to the Solar Division of International Harvester using "quasi-combustor" type tubular test hardware, figure 7. Concepts A and B represent two different approaches to achieve very lean combustion using premixed fuel and air. Concept A uses jets of premixed fuel and air to create a large recirculation of hot gases into the flame zone which aids in maintaining combustion stability at very low equivalence ratios. Concept B uses a rotating flow field to create a similar effect. An example of the results obtained in this experiment are presented in figure 8 where various pollutant emission indices are plotted as a function of combustor temperature rise at a simulated supersonic cruise condition for the VAB (vortex airblast) concept. Specific details of this experiment along with additional results are given in reference 9. As with the GASL experiment, this experiment is also being expanded to explore the effects of a wider range of test conditions.

The use of catalytic reactors to enhance the combustion process using extremely lean fuel/air mixtures is also being evaluated in fundamental studies. Both in-house and contract work is underway and some of the preliminary results obtained have been reported in reference 10. Extremely low values for all of the pollutant emissions are possible using the catalytic technique, however, they are limited to a very narrow fuel/air ratio operating range. Special emphasis is being placed on the capability to control NO_x emissions at simulated high altitude cruise conditions.

ADVANCED TECHNOLOGY COMBUSTORS

The evaluation to determine the ability of advanced technology to reduce the pollutant emission levels of combustors is being explored using both in-house (Lewis Research Center) and contract efforts. The in-house effort is focused on testing a variety of large and small scale combustor concepts that are similar to contemporary and future engine combustion systems whereas the contract efforts are focused on applying a wide variety of emission

control techniques to develop new or improve existing combustors for specific aircraft engines currently in service. The emission level goals of all these efforts are primarily responsive to the U.S. EPA 1979 aircraft emission standards.

Experimental Combustors

For the past five years, NASA has been evaluating several experimental combustors which incorporate a variety of the emission control techniques. The majority of the effort on the evaluation of low pollutant emission combustors conducted at the Lewis Research Center has been with the swirl-can-modular combustor which is described in detail in references 11 to 13. This combustor consists of a large number (80 to 120) of swirl can modules (each acting as a small, separate fuel/air mixer) arranged into a full annular array. A fuel and air mixture passes through a swirler which, in conjunction with a flame stabilizer, forms a small stable flame zone. The combination of a small flame zone and the partially premixed fuel and air provides for short residence times and some degree of flame temperature control. Thirty to fifty percent reductions in NO_x emission index have been obtained with this concept over a range of combustor inlet temperatures typical of present day aircraft gas turbine engines. The greatest difficulty in the development of this combustor concept has been the inability to simultaneously reduce low power emissions of CO and THC and high power emissions of NO_x . Low values of CO and THC have been achieved by using specialized module designs and by employing fuel scheduling but these modifications were not successfully coupled with low NO_x designs to provide an integrated combustor for low emissions at all operating conditions.

Other types of NASA experimental combustors have also been evaluated to explore their pollutant reduction potential. A double annular combustor, reference 14, has been used to study the effects of fuel scheduling and air velocity control on CO and THC at low power. The impact of air velocity on NO_x formation was also studied with this combustor. Also, an in-house project has recently been initiated at the Lewis Research Center to evaluate many emission reduction techniques as applied to small gas turbine engine combustors that would have potential application to helicopter and small general aviation class engines.

Technology Development and Application

The development and application of various pollutant emission reduction techniques to in-service aircraft gas turbine engine combustors are being investigated in two large NASA/Industry contract programs. The emission reduction techniques that are being emphasized use the advanced technology approach (combustor design changes) rather than the use of operational (increased compressor bleed) and/or functional (water injection) approaches.

Experimental Clean Combustor Program. - The Experimental Clean Combustor Program (ECCP), was initiated in December 1972 with the objective to develop and demonstrate, in a full-scale engine, advanced technology combustors that are capable of reducing pollutant emissions in the large high bypass ratio engines (U.S. EPA Class T2, thrust over 8,000 lbs.) that power the wide body jets. The original emission level goals were established from NASA studies and were subsequently adjusted to be consistent with the EPA Standards published in mid 1973. The two contractors that were selected, and are currently under contract, are Pratt & Whitney Aircraft (JT9D-7 engine) and the

General Electric Company (CF6-50 engine). The program is a three-phased effort scheduled to culminate in engine demonstration tests in 1976. Testing in Phase I (screening of a multitude of low emission concepts) and Phase II (refinement for engine adaption) has been completed by General Electric. Pratt & Whitney has completed the Phase I tests and Phase II testing is nearly complete. Both contractors are under contract and are in the preliminary stages of Phase III. A complete description of the ECCP is given in reference 15.

The two advanced technology CF6-50 engine combustor concepts that were evaluated in Phase II are shown schematically along with the conventional CF6-50 engine combustor in figure 9. Both advanced technology designs utilize staged combustion for reducing pollutant emissions over the entire engine operating range. The pilot stages of both the radial/axial staged and the double annular are optimized for high efficiency (low CO and THC emissions) at engine low power (idle) and the main stages are optimized for lean combustion (low NO_x) at full power (takeoff). Various combinations of combustion staging can be used for off-design operation such as approach power settings. The radial/axial staged configuration utilizes a premixed fuel and air technique in the main stage whereas the double annular configuration uses airblast fuel nozzles and airflow control in the main stage. The double annular concept has been chosen for the Phase III engine demonstration tests. All of the testing in Phases I and II was performed in a full annular combustor test rig which closely duplicates the flow path of the CF6-50 engine. All engine inlet and exit operating conditions were simulated except for combustor inlet pressure which was limited to a maximum of 10 atmospheres. Further details are given in references 16 and 17.

The two advanced technology JT9D-7 engine combustor concepts that are being evaluated in Phase II are shown schematically along with the conventional JT9D-7 engine combustor in figure 9. As with the CF6-50 concepts, both designs use staged combustion as the principal approach to controlling overall pollutant emissions. The hybrid concept utilizes a parallel (radial) staging approach which includes a premix technique in the pilot stage and a variation of the swirl can concept in the main stage. This configuration is an attempt to mate the lowest CO and THC emission design (premix pilot stage) and the lowest NO_x emission design (swirl-can-module stage) that was tested in Phase I. The vorbix configuration utilizes a series-type (axial) fuel staging approach with standard pressure atomizing fuel nozzles in both the pilot and main stages. High intensity swirlers are located immediately downstream of the main stage fuel injection point to promote very intense, rapid mixing of the fuel and air in the flame zone. The combination of the intense mixing and hot gases exiting from the pilot stage allows lean combustion in the main stage and also reduces residence time due to quick quenching of the hot gases. The vorbix concept has been selected for the Phase III engine demonstration tests. All of the testing in Phases I and II was conducted in a 90 degree sector test rig which closely duplicated the JT9D-7 engine flow path. Again, all operating conditions except inlet pressure, which was limited to approximately 6 atmospheres, were simulated. Further details are given in references 16 and 18.

Pollution Reduction Technology Program. - The second major program that has been implemented to evaluate the application potential of emission control techniques is the Pollution Reduction Technology Program (P RTP). The P RTP was initiated in mid-1974 as an effort to develop advanced technology combustors to reduce pollutant emissions for three classes of engines included in the 1979 U.S. EPA standards that were not considered in the ECCP. The contractors and the respective engines selected for the P RTP are

Pratt & Whitney Aircraft, JT8D-17 (EPA Class T4), the AiResearch, TFE 731-2 (EPA Class T1), and the Detroit-Diesel Allison, 501-D22A (EPA Class P2). The advanced technology combustor evaluations are being conducted in a multiphase approach similar to the ECCP with engine demonstrations scheduled in 1977. Phase I (concept screening tests) is underway with all three contractors and preparations are being made to implement Phase II with two contractors.

The advanced technology combustor concepts selected for the Phase I screening tests are shown in figures 11, 12, 13 for the JT8D-17, TFE 731-2, and 501-D22A engines, respectively. The advanced technology combustor concepts were selected based on a trade-off between estimated degree of emission reduction potential and development risk. In all cases, the selected configuration representing the least development risk (A or B) have the least likelihood of achieving all of the pollutant emission goals. The B, C or D configurations represent a higher development risk but provide a better potential for achieving or exceeding the pollutant emission reduction goals.

The JT8D-17 Phase I concepts are being tested with air-assist fuel nozzles, airblast fuel nozzles, staged combustion, lean combustion, and premixing emission reduction techniques. The TFE 731-2 Phase I concepts use all of the above techniques and the modified baseline combustor is also being tested to document the effects of increased compressor discharge bleed and water injection. The 501-D22A Phase I concepts use similar techniques to those described for the JT8D-17. Although all the engine programs use similar types of emission reduction techniques, the applications of these techniques to the individual engines vary. For example, the TFE 731-2 concept C uses parallel or radial combustion staging whereas the 501-D22A concept D uses series or axial combustion staging as does the JT8D-17 concepts B and C. Other differences of note are that the JT8D-17 and 501-D22A are can-annular combustors whereas the TFE 731-2 is a full annular design and that the TFE 731-2 is a reverse flow design versus the axial flow types of the JT8D-17, 501-D22A and JT9D-7 and CF6-50 of the ECCP.

The essential point is that although the pollutant control techniques are similar for all of these advanced technology combustors, the methods for applying the techniques to actual engine constrained designs must be and is being varied as the individual engine configuration dictates. The degree of success of any one application will not only be dependent upon the emission reduction techniques used but to a great degree will also depend upon the ability and ingenuity of the engineer to adapt these techniques to the engines' specific characteristics.

Emissions and Performance

The emission reduction potential of the various emission reduction techniques which have been evaluated in the ECCP and PRTP are described along with applicable performance results. Results obtained at discrete operating conditions as well as the integrated Landing Takeoff (LTO) cycle values used in the U.S. EPA standards are presented and discussed.

Low Power Emissions. - The reduction in low power emissions that were obtained in combustor rig tests using "selected" advanced technology combustor concepts are shown in figures 14 and 15 for all five of the engine applications considered in the ECCP and PRTP. The "selected" advanced technology concepts were chosen from all of the configurations tested to date based on the following factors: (1) the lowest combined emission levels

obtained at all of the engine operating conditions; (2) acceptable performance in terms of pressure drop, combustion efficiency, and exit temperature pattern factor; and (3) acceptable off-design characteristics such as combustion transition for the staged designs at the approach condition. Development potential in terms of durability, operational stability, altitude relight capability, and overall engine/control integration were also considered. All of the values of emission index shown on these figures are corrected to or were obtained at operating conditions consistent with the manufacturers recommended idle power setting for the various engines.

Reductions in carbon monoxide (CO) emissions of up to a factor of 3, figure 14, were obtained by some of the advanced concepts and four out of the five concepts were capable of achieving or nearly achieving the goal values of CO emission index. The inability of the piloted-airblast concept (TFE 731-2 engine) to achieve the goal value was because the particular configuration selected for presentation was modified for NO_x emission control and hence some premature quenching was obtained which adversely effected CO oxidation. Achieving the goal values for CO with this concept is anticipated with continued development. The goal values of emission index shown on figure 14, and all subsequent figures, were computed from the Environmental Protection Agency Parameter (EPAP) values of the 1979 U.S. EPA standards by assessing the emission reductions needed to satisfy the standards at each individual operating point of the LTO cycle, see reference 1. All of the advanced technology concepts achieved or nearly achieved the goal values for total unburned hydrocarbons (THC), figure 15.

In general, the combustor test rig results indicate that low power emissions can be reduced to levels below or approaching preselected goals based on environmental local air quality standards. However, variations about the levels obtained are likely when these advanced concepts are applied to in-service aircraft engine combustors and full-scale engine tests will be needed to quantify the levels which will be achievable in actual operation.

High Power Emissions. - The reductions in high power emissions that were obtained using the "selected" advanced technology combustor concepts are shown in figure 16. The indicated concepts are the same ones used for the low power emission reduction evaluation. All values shown were either measured or extrapolated to engine operating conditions at takeoff power (see reference 16 for extrapolation techniques). Significant reductions in NO_x emission index levels, up to 50 percent, were achieved using the three staged concepts, i.e. double annular (CF6-50 engine) and the two vortex designs (JT9D-7 and JT8D-17 engines). An increase in the NO_x emission index was realized with the reverse flow concept (501-D22A engine)^x because the particular configuration selected was optimized for reducing CO and THC at low power conditions.

The principal reason for the "short fall" in NO_x emission level reduction, compared to the goals, can be attributed to the inability to make maximum use of the lean burning approach to control NO_x in the advanced concepts. In all cases, lean burning and quick quenching techniques were employed in the main stages of the staged concepts but the effectiveness of lean burning is significantly reduced unless the fuel is prevaporized and premixed with the combustor inlet air prior to the combustion process. The technology needed to design and evolve effective and practical prevaporized/premixed concepts is still several years in the future. Therefore, the reductions in NO_x emission levels presented in figure 16 are probably the "best" attainable with the level of advanced technology evaluated for the

CF6-50, JT9D-7 and JT8D-7 engines. The term "best" is used here to describe the level of the achievable reductions bearing in mind that variations about this level will likely occur with the application of these advanced technology combustor concepts to operational aircraft engines. Since the piloted-airblast and reverse flow concepts are primarily applicable for controlling low power emissions, the ability to achieve reduced levels of NO_x emissions using advanced technology in the TFE731-2 and 501-D22A engines will likely require different techniques.

In comparing the minimum levels of NO_x emissions achieved by the various advanced concepts, variations are certainly apparent. One factor that is paramount in the production of NO_x is combustion flame temperature. In a diffusion flame process (fuel droplet burning), the flame temperature is principally controlled by the inlet temperature and pressure of the air entering the combustion zone. The impact that these parameters can have on NO_x emissions is illustrated in figure 17 where NO_x E.I. is plotted as a function of combustor inlet temperature. The range of inlet temperature shown on figure 17 encompasses all of the engines considered in the ECCP and PRTP. The upper curve, designated as that which applies to current conventional combustor emission characteristics, is from reference 19.

Emission levels for all of the ECCP and PRTP engine conventional (baseline) combustors are indicated by the open symbols on this figure and although they do not precisely fit the conventional combustor curve they do follow the same trend. Also shown for reference is a curve obtained from test results of the swirl-can-modular combustor test at the Lewis Research Center and the values obtained using the "selected" advanced concepts that were tested in the ECCP and PRTP (solid symbols). The CF6-50, JT9D-7 and JT8D-17 engine advanced concept results agree quite closely with the swirl can combustor results in terms of both level of reduction and the trend of NO_x formation with inlet temperature. The 501-D22A engine reverse flow concept and the TFE731-2 piloted-airblast concept results tend to agree with the conventional combustor NO_x values which is to be expected since they were configured to primarily reduce CO and THC emissions at low power. These results clearly illustrate that the advanced concepts tested in the ECCP and PRTP produced varying levels of NO_x emissions which were dependent upon the combustor inlet temperature (function of cycle pressure ratio) of the intended engine application and the level of technology employed. This dependency between combustor inlet conditions and NO_x emissions is extremely important when evaluating the ultimate capability of advanced technology for reducing aircraft engine emissions.

LTO Cycle Emissions. - A summary of the emission levels achieved with these concepts as compared to the respective engine conventional (baseline) combustors and the 1979 U.S. EPA standards is presented in Table I. All values shown are in terms of EPAP levels corrected to actual engine operating conditions.

The computation of the listed Environmental Protection Agency Parameter (EPAP) values is consistent with the recommended procedure from reference 1, where EPAP is defined as:

$$\text{EPAP} = \text{lbs of pollutant}/1000 \text{ lbs thrust-hours}/\text{cycle}$$

or

$$\text{EPAP} = \text{lbs of pollutant}/1000 \text{ shaft horsepower-hours}/\text{cycle}$$

Details of the EPA calculations using equation 1 are given in reference 16.

All of the selected advanced concepts produced emission levels of THC and smoke that were below the levels needed to meet the standards. The

CF6-50 double annular concept and the 501-D22A reverse flow concept reduced the CO emissions to values less than the standards. The 501-D22A reverse flow concept was the only one that was capable of achieving NO_x emission levels below the 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 standards. The JT9D-7 vortex concept, the JT8D-17 vortex concept, and the TFE731-2 piloted-airblast concept did not achieve CO emission levels low enough to meet the standards. Further reductions in CO levels should be achievable with the vortex concepts through continued development, but whether the standard levels can be achieved is uncertain at this time. The piloted-airblast concept should be capable of achieving the standards for CO with further development. As shown in Table I, the NO_x emission levels were not low enough to satisfy the standards for four out of five of the advanced concepts. The TFE731-2 piloted-airblast concept data is too preliminary to make a final judgement as to the achievable levels. Some reduction is certainly possible but the magnitude of this reduction has not been quantified. Because of factors previously discussed (see High Power Emissions section), it is unlikely that any further appreciable improvement in NO_x emission reduction can be expected with the level of technology evaluated. Therefore, the advanced technology combustor concepts evaluated in the ECCP and PRTP will not be capable of meeting the NO_x emission requirements of the promulgated U.S. EPA standards for the engine applications investigated.

Performance. - Overall performance results for the "selected" advanced technology combustor concepts indicated that combustion efficiencies at all the LTO cycle operating points were in excess of 99 percent. At approach and high power conditions (climbout and takeoff), combustion efficiencies were virtually 100 percent which is comparable to baseline engine combustor performance. The increases in idle efficiencies represented substantial improvements from the baseline combustors. Both exit temperature pattern factors and altitude reflight results indicated that these important performance considerations were within developable limits for engine application.

Altitude Cruise Emissions. - The ability of the various emission reduction techniques to control cruise NO_x emissions, as determined from both the fundamental experiments and the advanced technology combustor programs, was evaluated and is presented in figure 18. The estimated supersonic cruise NO_x emission indices are compared for conventional technology combustors, the advanced technology combustor concepts evaluated in the ECCP and PRTP, the "flame tube rig" experiments, and very preliminary catalytic combustion experiments. Reductions of a factor of two from current levels can be anticipated using the advanced technology concepts at both subsonic and supersonic cruise conditions. Potential reductions of an order of magnitude or greater will require the use of prevaporized/premixed combustion schemes or catalytic combustion schemes. Because of the relative experimental nature of the premix and catalytic combustion results, extreme caution must be used in judging final achievable levels for this level of technology. A considerable amount of fundamental type data is still needed on lean combustion stability, autoignition and flashback constraints, and variable geometry concepts before these combustion schemes can be developed into usable combustors for actual engine application.

ASSESSMENT OF RESULTS

Based on the emission reduction results obtained to date in the ECCP, PRTP, and the NASA in-house studies, a qualitative assessment of the ability of the various control techniques to reduce engine emissions was made and is summarized in Table II. The relative degree of difficulty estimated to accomplish a successful application in new production engines is also shown. Most of the minor to moderate modifications would be variations of existing baseline combustor concepts, such as the 501-D22A engine reverse flow concept shown in figure 13B. As such, they are judged to have a low or low to moderate "development risk." The term "development risk" is defined as the estimated degree of difficulty required to convert a demonstrated experimental technique into a production combustor for a newly manufactured engine.

In addition to the emission control and performance factors involved in assessing the potential of the emission reduction techniques that were evaluated, many other factors must also be considered before final engine emission reduction levels can be quantified. Some of the principal factors would include: increases in complexity of the staged designs; engine acceleration and deceleration characteristics, and the effect of engine imposed variations in flow, temperature and pressure. These factors will be evaluated during the planned full-scale engine tests along with the verification of emission reductions achievable in the actual engine environment.

CONCLUDING REMARKS

Although the NASA Experimental Clean Combustor Program (ECCP) and Pollution Reduction Technology Program (PRTP) are in various stages of program completion, the results indicate that significant reductions in the levels of all pollutant emissions (CO, THC, NO_x and smoke) can be achieved by employing advanced technology combustor concepts in selected engines designated in four of the six aircraft gas turbine engine classes specified in the U.S. EPA standards. Simultaneous reduction of all the emissions, over the entire range of engine operation, required the use of staged combustion techniques. The actual level of NO_x emissions achieved with the staged double annular and vortex concepts, as listed in Table I, are judged to be representative of the "best" values that can be achieved with the level of technology currently being developed. Implementation of advanced technology combustors in aircraft engines can result in cruise NO_x reductions as well as reductions for the LTO cycle and, as such, represents an attractive approach for improving air quality in both the low and high altitude aircraft operating regimes.

Proof-of-concept type tests in full-scale engines are still needed to quantify the success of the advanced concepts in terms of the absolute levels of emissions that are achievable and to demonstrate the capability to successfully satisfy all of the engine operational requirements. Selective reductions in certain emission levels, e.g. CO and THC, can be achieved by employing relatively minor to moderate modifications to current engine baseline combustors at an estimated low development risk. The range of emission level reductions obtained in the ECCP and PRTP, as compared to the complexity and the estimated development risk factors, provides a large data bank for the evaluation of emission reduction potential. Because of the inherent total emission control capability of the staged combustor concepts, the continued development of these concepts for application to future newly manufactured engines seems highly desirable. The added complexity involved

in the staged concepts will likely require continued development beyond the scope of the current programs.

In the evaluation of emissions levels that can be achieved by employing advanced technology, considerable care must be taken to account for all of the factors which influence the rate of formation of the pollutants during the combustion process. Paramount among these factors are the combustor inlet pressure and temperature which are direct functions of the engine cycle pressure ratio. Since most modern day engines employ high pressure ratio, particularly the high bypass ratio engines, the emission index (E.I.) levels for NO_x have been steadily increasing for conventional type combustors. Even though the staged combustor concepts investigated in the ECCP and PRTP employ lean combustion techniques which decrease the level of NO_x formed at a given operating point, the characteristic trait of increasing NO_x E.I. with increasing pressure ratio still persists.

Results of fundamental combustion studies indicate that a new generation of jet aircraft engine combustor technology may be possible that would provide emission levels far below those currently possible with the advanced technology concepts developed in the ECCP and PRTP. Considerable fundamental knowledge is still needed, however, before the techniques being studied can be translated into useful combustors. Successful development of these techniques into operational engine combustors would provide the level of NO_x emission reductions desired for both local air quality and high altitude cruise considerations.

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

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)	14.3	*6.3	4.3	5.3	0.6	0.8	4.9	3.5	3.0
JT8D-17 ENGINE (VORBIX CONCEPT)	16.1	*9.0	4.3	4.4	0.2	0.8	8.2	4.3	3.0
TFE731-2 ENGINE (PILOTED-AIRBLAST CONCEPT)	17.5	**10.7	9.4	5.3	0.6	1.6	5.3	**4.5	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

*LOWER VALUES EXPECTED WITH FURTHER DEVELOPMENT, I.

**PRELIMINARY VALUE.

TABLE II. - QUALITATIVE COMPARISON OF THE ESTIMATED EMISSION REDUCTION POTENTIAL AND APPLICATION DIFFICULTY FOR SELECTED CONTROL TECHNIQUES EVALUATED IN NASA PROGRAMS

EMISSION CONTROL TECHNIQUE	EMISSION REDUCTION POTENTIAL	ENGINE APPLICATION DIFFICULTY
AIR-ASSIST FUEL INJECTION (MOD BASELINE COMBS.) (REVERSE FLOW CONCEPT)	GOOD FOR CO & THC N/A FOR NO _x	MINOR MODIFICATION * (LOW DEVEL RISK)
AIR BLAST FUEL ATOMIZATION (MOD BASELINE COMBS.) (PILOTED-AIRBLAST CONCEPT) (PILOT STAGES)	GOOD FOR CO & THC SMALL FOR NO _x	MODERATE MODIFICATION (LOW DEVEL RISK)
QUICK QUENCHING (MAIN STAGES)	N/A FOR CO & THC MODERATE FOR NO _x	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)
LEAN COMBUSTION (MAIN STAGES)	N/A FOR CO & THC GOOD FOR NO _x	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)
WATER INJECTION (MOD BASELINE COMB.)	N/A FOR CO & THC VERY GOOD FOR NO _x	MODERATE MODIFICATION (LOW TO MODERATE DEVEL RISK)
STAGED COMBUSTION (DOUBLE ANNULAR CONCEPT) (VORBIX CONCEPT)	GOOD FOR CO & THC GOOD FOR NO _x	MAJOR MODIFICATION (MODERATE TO HIGH DEVEL RISK)
PREVAP/PREMIX COMBUSTION (FUNDAMENTAL EXPERIMENTS)	EXCELLENT FOR CO & THC EXCELLENT FOR NO _x	VERY MAJOR MODIFICATION (VERY HIGH DEVEL RISK)

*DEVELOPMENT RISK IS DEFINED AS THE ABILITY TO CONVERT A DEMONSTRATED EXPERIMENTAL TECHNIQUE INTO A SATISFACTORY ENGINE COMBUSTOR.

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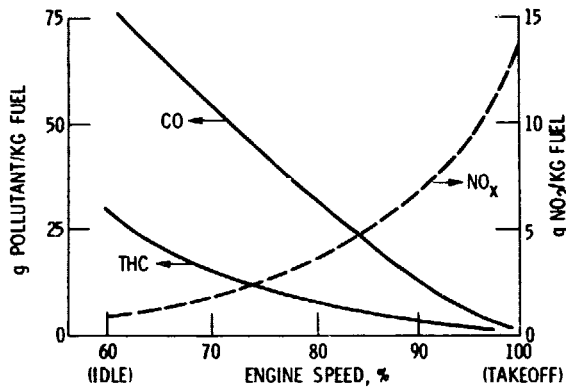


Figure 1. - Typical jet aircraft gas turbine engine exhaust emission characteristics.

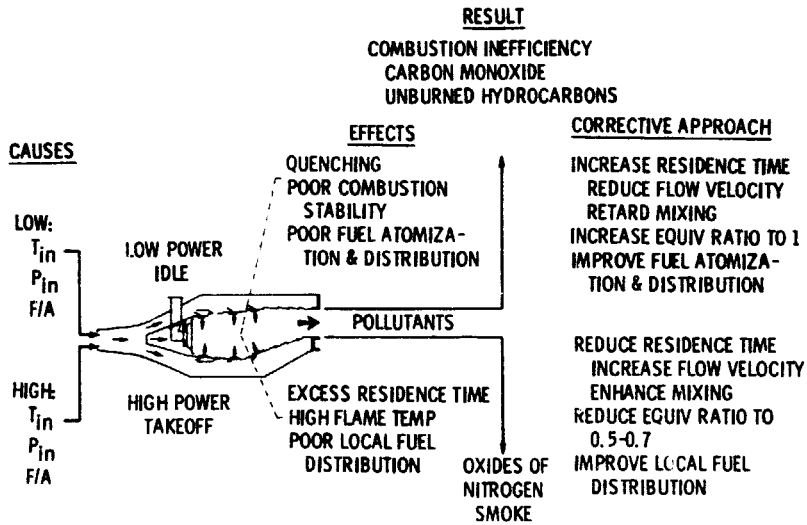


Figure 2. - Aircraft gas turbine combustor pollution considerations.

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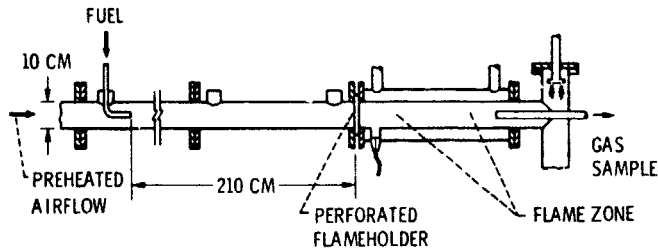


Figure 3. - Schematic illustration of the prevaporized/premixed flame tube test rig at the NASA Lewis Research Center.

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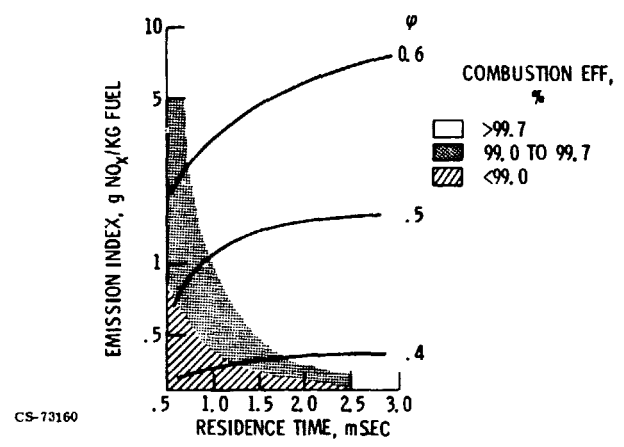


Figure 4. - Impact of combustion residence time and equivalence ratio on the formation of oxides of nitrogen and combustion efficiency in a prevaporized/premixed flame zone. Inlet pressure, 60 N/cm², inlet temperature, 700 K, gaseous propane fuel.

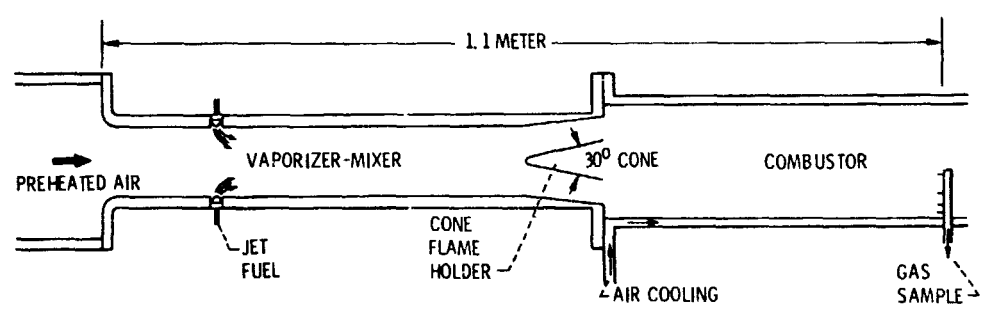


Figure 5. - Schematic illustration of the experimental apparatus used in the prevaporized/premixed lean combustion studies at GASL.

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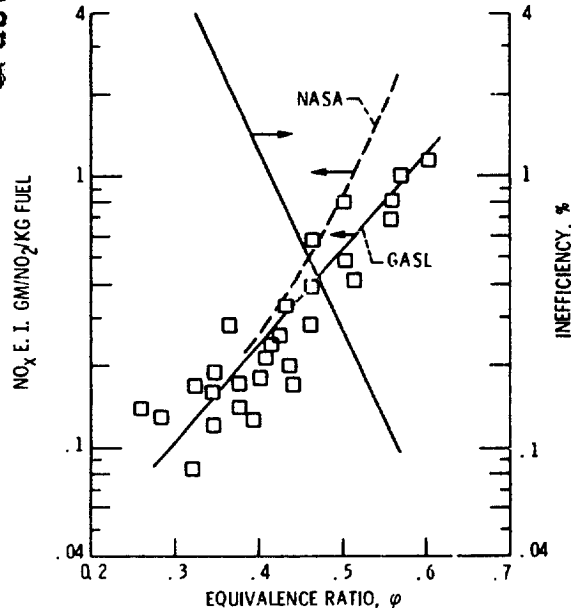


Figure 6. - Impact of combustion equivalence ratio on the formation rate of oxides of nitrogen and on combustion inefficiency for the GASL and NASA fundamental experiments. Inlet pressure, 40 N/cm^2 , inlet temperature, 830 K . Jet A fuel.

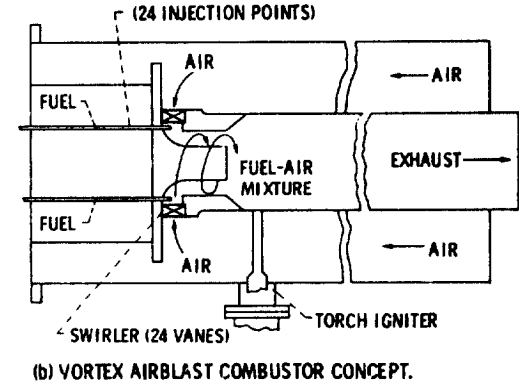
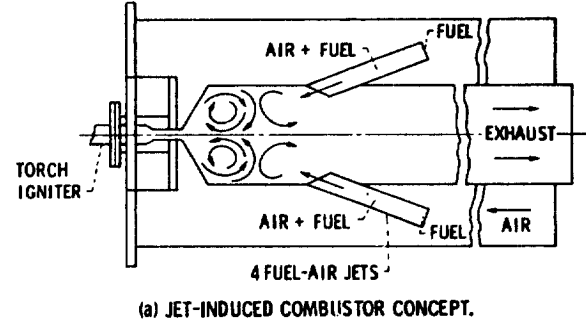


Figure 7. - Schematic illustration of the low oxides of nitrogen emission combustor concepts used in fundamental experiments at SOLAR.

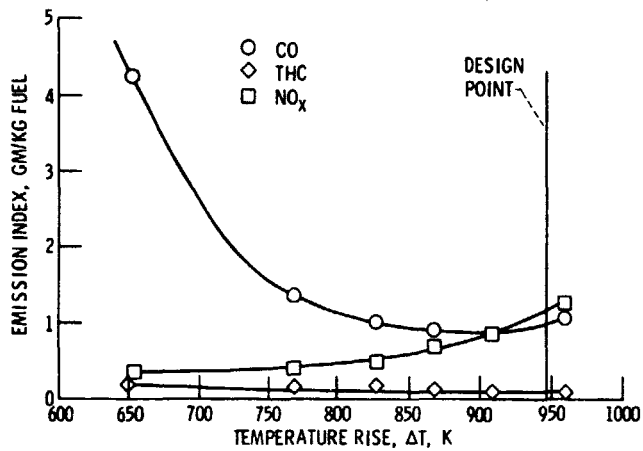
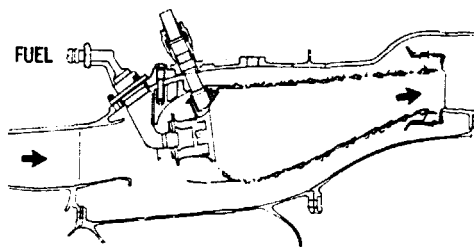
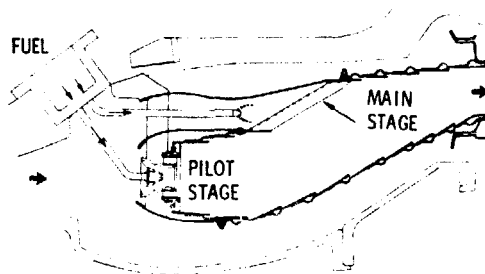


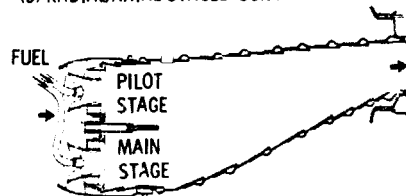
Figure 8. - Emission characteristics of the SOLAR vortex airblast (VAB) combustor concept as affected by combustor temperature rise. Inlet temperature, 820 K, inlet pressure, 49 N/cm². Jet A-1 fuel.



(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.



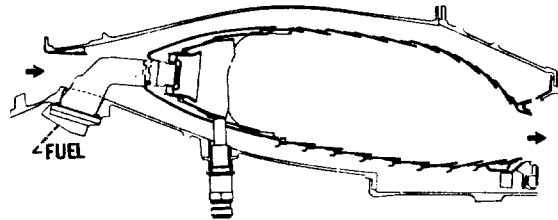
(b) RADIAL/AXIAL STAGED CONCEPT.



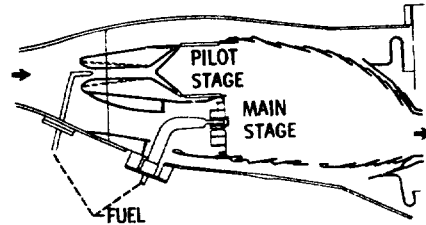
(c) DOUBLE ANNULAR CONCEPT.

Figure 9. - Experimental clean combustor program (ECCP), phase II advanced technology concepts for the CF6-50 engine (EPA class T2).

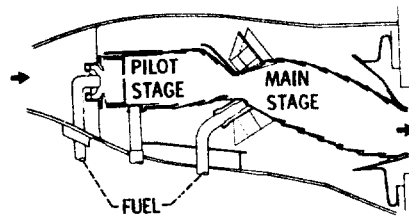
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(a) ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.

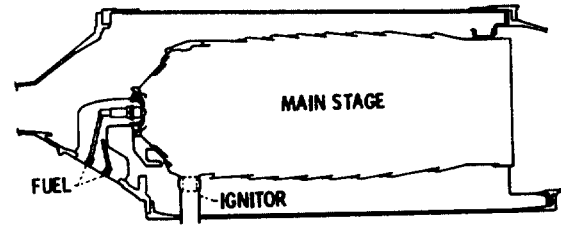


(b) HYBRID CONCEPT.

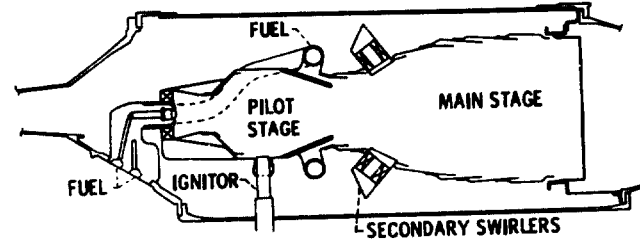


(c) VORBITX CONCEPT.

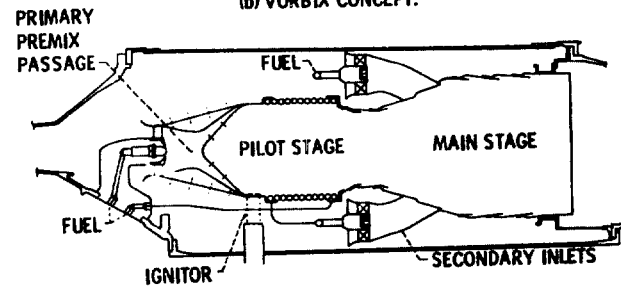
Figure 10. - Experimental clean combustor program (ECCP), phase II advanced technology concepts for JT9D-7 engine (EPA class T2).



(a) MODIFICATIONS TO ENGINE CONVENTIONAL (BASELINE) COMBUSTOR.



(b) VORBITX CONCEPT.



(c) STAGED PREMIX CONCEPT.

Figure 11. - Pollution reduction technology program (PRTTP), phase I advanced technology concepts for the JT8D-17 engine (EPA class T4).

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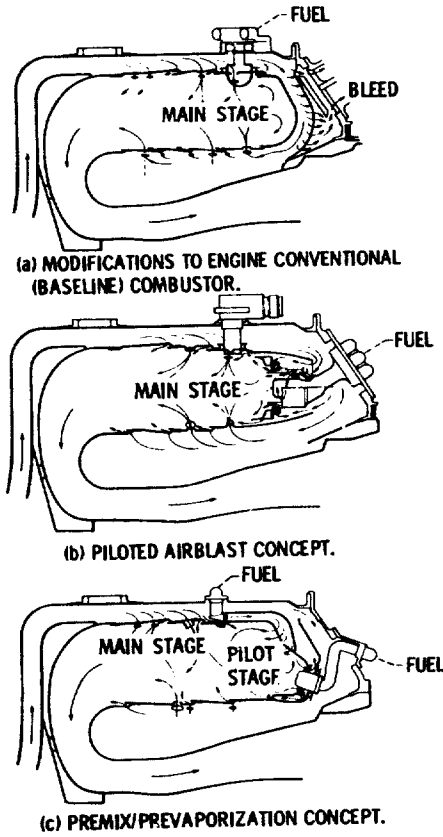


Figure 12 - Pollution reduction technology program (PRTP), phase I advanced technology concepts for the TFE 731-2 engine (EPA class T1).

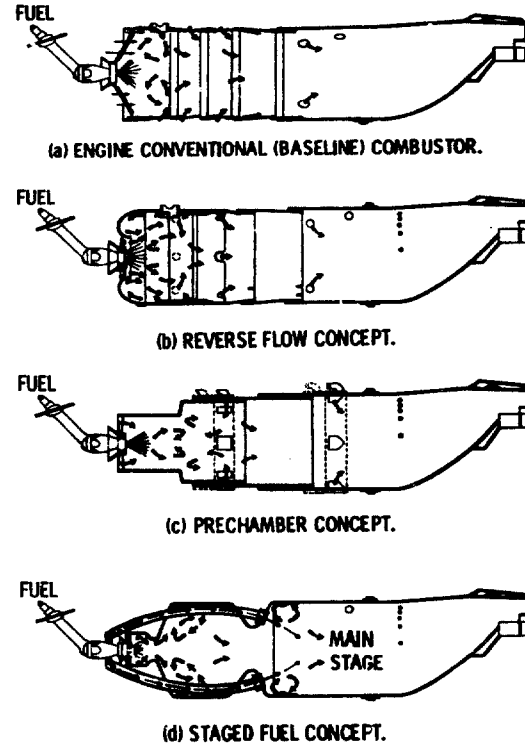


Figure 13 - Pollution reduction technology program (PRTP), phase I advanced technology concepts for the 501-D22A engine (EPA class P2).

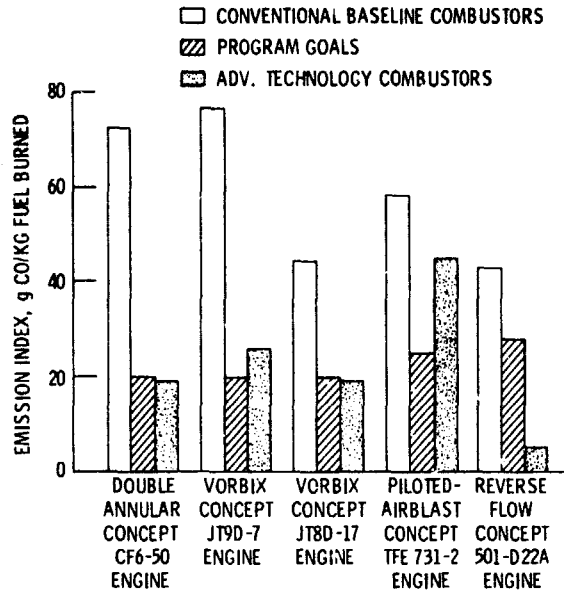


Figure 14. - Summary of carbon monoxide emission index levels achieved with selected advanced technology combustor concepts. All values are corrected to standard day engine idle operating conditions.

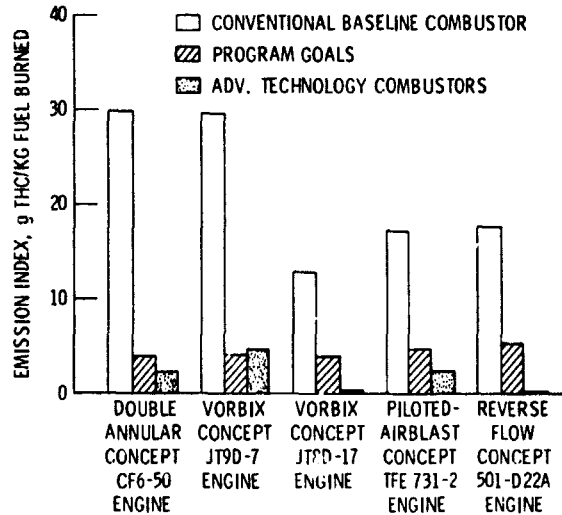


Figure 15. - Summary of total unburned hydrocarbon emission index levels achieved with selected advanced technology combustor concepts. All values are corrected to standard day engine idle operating conditions.

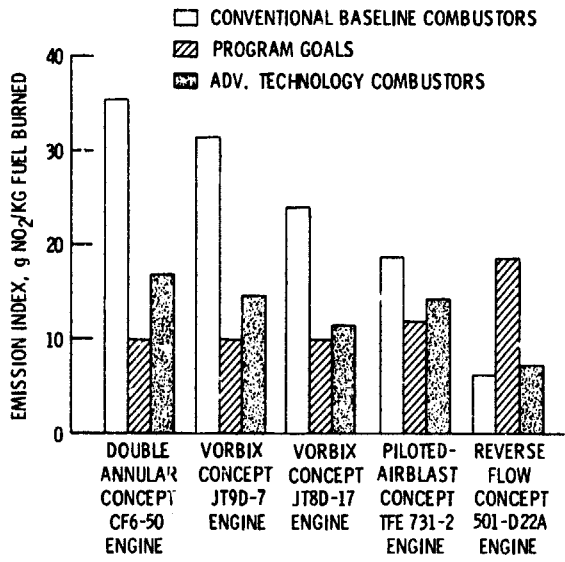


Figure 16. - Summary of oxides of nitrogen emission index levels achieved with selected advanced technology combustor concepts. All values are corrected to standard day engine seal level takeoff operating conditions.

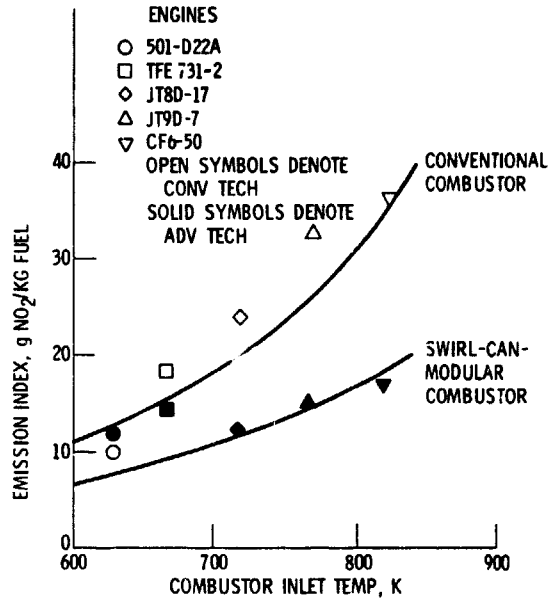


Figure 17. - Comparison of oxides of nitrogen emission levels for conventional and advanced combustors at high power (takeoff) conditions.

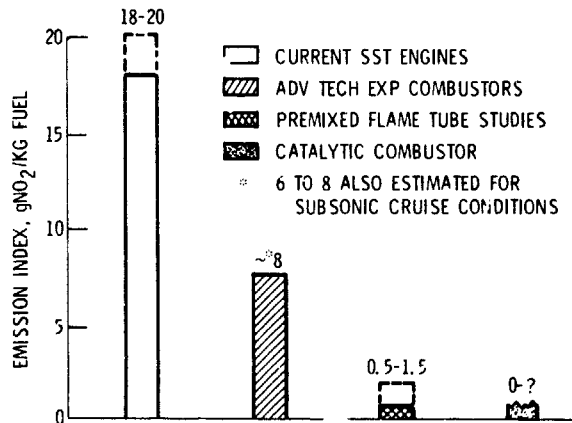


Figure 18. - High altitude cruise oxides of nitrogen reduction status, simulated supersonic cruise conditions.