NASA Technical Memorandum 79009

RESULTS AND STATUS OF THE NASA AIRCRAFT ENGINE EMISSION REDUCTION TECHNOLOGY PROGRAMS

(NASA-TM-79009) RESULTS AND STATUS OF THE NASA AIRCRAFT ENGINE EMISSION REDUCTION TECHNOLOGY PROGRAMS (NASA) 53 p HC A04/MF A01 CSCL 21E
N78-33102
Unclas
G3/07 33634

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October 1978

SUMMARY

This report reviews the results and status of various combustion research and technology efforts conducted at the NASA Lewis Research Center for the past 5 years. The purpose of these efforts was to evolve and evaluate new combustor concepts that have the potential for significantly reduced exhaust emissions. The emission goal levels corresponded to the 1979 EPA emission standards. In addition to a variety of in-house programs, two major efforts were contracted with aircraft engine manufacturers. These contracted efforts were the Experimental Clean Combustor Program (ECCP) and the Pollution Reduction Technology Program (PRTP). Several of these multiphase efforts culminated in engine tests of the advanced technology combustors. Test results show that advanced two-stage combustor concepts could produce significantly lower levels of all gaseous pollutants. A Vorbix combustor concept tested in an experimental JT9D-7 engine was able to achieve all of the 1979 EPA standards except smoke. A Double/Annular combustor concept tested in an experimental CF6-50 engine was only able to achieve the unburned hydrocarbon standard, although significant reductions in other gaseous emissions were obtained. A Vorbix combustor concept designed for the JT8D-17 engine was evaluated in a combustion test facility at actual engine pressures and temperatures. This particular combustor had emission index values as low as any combustor concept tested during these programs. However, the use of this combustor in a JT8D-17 engine would result in values of the CO and NO_x emissions parameter greater than the 1979 EPA standards due to the level of the specific fuel consumption that is typical of these low bypass ratio, older technology engines. Emissions obtained with the reverse-flow-dome combustor designed for the 501-D22A engine were all below the required 1979 EPA standard levels. These emissions were measured in a combustion test facility at actual engine operating conditions. The ability of these advanced combustor concepts to achieve the newly proposed 1981 and 1984 Newly Manufactured Engine EPA standards is also assessed and discussed. Other factors such as combustor concept complexity and durability and the effect of engine-to-engine variation on emissions are also discussed. An estimate of the ability of the advanced combustor technology evolved in these programs to meet the 1984 Newly Certified Engine Standard was made and is discussed. This report also briefly reviews efforts being conducted in-house and on contract related to advanced CTOL engine combustors, the Prevaporized/Premixed Combustor Technology Program and fuels technology.

E-9793

INTRODUCTION

This report describes emission reduction research and technology programs conducted and managed by NASA Lewis Research Center. The various programs will be described, the emission results presented in detail and assessments made of the potential of advanced combustor technology to achieve the present as well as the proposed Environmental Protection Agency (EPA) Aircraft Emission Standards. This report will be an update of previous reports (refs. 1 and 2) written in 1976 to document the status of these programs at that time.

The Clean Air Act of 1970 charged the 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. The EPA promulgated the standards described in reference 3 in 1973. 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 on low emission gas turbine engine combustors. Some of this research was used as a guide to set the levels of the 1979 EPA standards (ref. 3).

The aircraft emission standards have acted as a catalyst for the timely evolution of advanced technology combustors. Two major NASA sponsored programs, the Experimental Clean Combustor Program (ECCP) implemented 6 months prior to the issuance of the standards and the Pollution Reduction Technology Program (PRTP) implemented within 1 year after the issuance date, have emission level goals consistent with the 1979 EPA standards. Most Independent Research and Development programs in the industry are also using the 1979 EPA standards as goals for advanced technology developments.

The Experimental Clean Combustor Program had the objective to evolve and evaluate the potential of advanced technology combustors to achieve the 1979 EPA standards for aircraft engines of the EPA T2 class. A further goal was to verify the emission reduction achieved by engine test. The program consisted of three phases. In the first phase, a variety of combustor concepts were screened to evaluate their potential for low emissions. In Phase II, the best concepts from Phase I were further tested and refined. Phase III, consisted of full-scale engine tests of the "best" combustor. The contractors and aircraft engines selected for this program were: General Electric with the CF6-50 engine and Pratt and Whitney Aircraft with the JT9D-7 engine. The Experimental Clean Combustor Program was completed in the Fall of 1977.

The Pollution Reduction Technology Program was begun to evolve and evaluate the potential of advanced technology combustors to reduce the emissions from aircraft engines in the EPA classes T1, T4, and P2. The contractors and engines selected were: Garrett AiResearch, TFE-731-2 engine (T1 class), Pratt and Whitney Aircraft, JT8D-17 engine (T4 class) and Detroit-Diesel-Allison, 501-D22A engine (P2 class). Program goals were the achievement of the 1979 EPA emission standards. The PRTP is complete except for the experimental engine tests to be conducted in the TFE-731-2 engine at AiResearch in early 1979.

The results of these programs to date will be presented in subsequent sections. The results will be presented and discussed on a comparative basis with the 1979 EPA standards for these engines. Subsequently, these results will also be discussed and assessed on a comparative basis with the newly proposed EPA standards for 1981 and 1984.

Research programs conducted by the Lewis Research Center will also be described and results presented. Two major new programs that are underway are the Premixed/Prevaporized Combustor Technology Program and the Fuels Technology Program. The first program arose from the need to develop new technology for future aircraft engines that would reduce stratospheric cruise NO_x levels to the levels recommended by the Climatic Impact Assessment Program study (ref. 4). The fuels program is the direct result of the shortening supply of domestic crude oil and the increasing price of imported crude oil. These two factors have led to extensive research into alternative fuels and fuels with broadened specifications. The fuels technology program is attempting to identify and characterize these fuels and assess their impact on existing combustors. In addition new combustor concepts are being studied that may be less sensitive to changes in fuel type or quality. In addition to these programs, work still continues to investigate new combustor concepts that have the potential for significantly reduced emission levels.

This report will confine itself to discussion of the results of the programs conducted and managed by NASA Lewis Research Center. The various engine manufacturers have their own Independent Research and Development (IR&D) programs that have been devoted to the achievement of the 1979 EPA standards. Their efforts complement the work conducted under ECCP and PRTP, but will not be discussed nor assessed in this report.

STATUS

The status of the major contracted programs as well as the research activity conducted at the Lewis Research Center will be discussed in this section.

Experimental Clean Combustor Program

A schedule showing the present status of the various contract programs is given in figure 1. The first two items in the schedule comprise the Experimental Clean Combustor Program, and as the figure indicates this program is now complete. The program ended with experimental engine tests using the advanced technology combustors that were evolved during Phase II of the program. In the Phase III experimental engine tests, the Vorbix combustor of P&W was installed and tested in a JT9D-7 engine. The Double/Annular combustor developed at General Electric was installed and tested in CF6-50 engine. Final contractor reports covering all phases of the work have been published (refs. 5 to 10). References 9 and 10 cover the Phase III engine test results at P&W and G. E., respectively.

Pollution Reduction Technology Program

The last three items shown in the schedule of figure 1 comprise the Pollution Reduction Technology Program. The experimental programs conducted on the JT8D-7 engine combustor and the 501-D22A engine combustor are complete. The programs conducted with these combustors were taken only through the rig test phase.

The test program on the Garrett AiResearch TFE-731-2 engine combustor is proceeding. The combustor refinement phase was completed early in 1978. The experimental engine test phase is scheduled for completion in 1979. Contractor reports have been published on all Phase I efforts and are listed as references 11 to 14.

Premixed/Prevaporized Combustor Technology Program

Figure 2 is a milestone chart for the Premixed/Prevaporized Combustor Technology Program. This program has as its goal the evolution of new combustor technology that will significantly reduce the levels of NO_x emissions during stratospheric cruise and also meet the requirements of EPA local emission standards. As shown in figure 2, the program consists of four phases. Phase I, concept assessment, is devoted to fundamental studies on techniques to achieve lean premixed, prevaporized combustion. Subsequent phases consist of combustor concept screening to select the most promising concepts, Phase II; these concepts would be further tested and refined during Phase III; and the best concept would be installed and tested in an engine during Phase IV. More detailed description of this program is contained in reference 15.

Fuels Technology

NASA is studying the characteristics of future aircraft fuels produced from either petroleum or nonpetroleum sources such as oil-shale or coal (ref. 14). These future hydrocarbon based fuels may have chemical and physical properties that are different from present aviation turbine fuels. This research is aimed at determining what those characteristics may be and how present aircraft, engine components and engine emissions would be affected by fuel specification changes. The results of work conducted as part of the Experimental Clean Combustor Program and at Lewis Research Center have shown that changes in fuel composition may alter combustor performance, exhaust emissions, and durability. The fuels technology program seeks to determine how engine emission performance may degrade and to identify new combustors that are less sensitive to varying fuel characteristics. This fuels technology program has been organized to include both in-house and contract research on the synthesis and characterization of fuels, component evaluations of combustors, turbines, and fuel systems, and, eventually, full-scale experimental engine tests. The entire effort has been integrated with a similar program being conducted by the Air Force Aero Propulsion Laboratory and is being coordinated with other concerned agencies within government and industry.

Emission Reduction Research and Technology

In addition to the programs described above, there are current and planned programs relevant to combustor emissions at the NASA Lewis Research Center. Current program activities include research studies of a variety of new combustor concepts to evaluate their potential for reduced emissions.

Particular attention is being given to staged combustion concepts. Several variable geometry concepts are also being studied to determine effective means of emission control by this technique. Combustor concepts that are shown to have excellent potential will be pursued and eventually tested in the new High Pressure Facility presently nearing completion at Lewis. To assist in this research several unique supporting facilities are being utilized. A fuel spray test facility uses a laser to determine the mean drop sizes of fuel sprays in combustor primary zones. The test facility can operate up to pressures of 30 atmospheres and evaluate pressure effects on fuel sprays. A combustor flow visualization facility uses a variety of techniques to map flow patterns in two-dimensional segments of the new combustor being studied.

The preliminary results from a contracted program to develop low idle pollutant combustor technology are very encouraging. Idle CO emission levels an order-of-magnitude lower than production combustor levels have been demonstrated with concepts consisting of hot walls (no liner film cooling), regenerative heating of the inlet-air, and by the use of catalysts. This technology is such that it has potential application as the pilot zone of a multistage combustor. Testing to date has been at simulated idle conditions only.

Contracted programs are also underway investigating the potential for using catalytic combustion in aircraft gas turbines in order to reduce NO_x emissions. Each of two contractors has defined six combustor concepts for this study program and are evaluating these designs in terms of potential for low pollutant emissions, for combustor performance as good as or better than current combustion systems, and for feasibility for integration into an advanced aircraft gas turbine engine. Final reports will be available in early 1979.

RESULTS

Experimental Clean Combustor Program

The results obtained with the advanced technology combustors installed in experimental engines are presented and discussed in this section. As described previously the Experimental Clean Combustor Program was conducted in three phases. The first two phases were devoted to evolving, testing, and refining new concepts having the potential for significantly reduced pollutant levels. In phase III, the most "engine-ready" combustor was installed in an engine and tested to measure the actual emission reduction achieved with the advanced technology combustor. This report will present only those results obtained during the Phase III engine tests.

CF6-50 engine. - Figure 3 is a cross-sectional sketch of the Double/Annular combustor developed by General Electric. The combustor consists of two annular burning zones. The outer zone is the low power zone, designed for operation at engine idle conditions. This zone also serves as a pilot for the inner or main zone which is used at all other engine power settings. This combustor was selected for the experimental engine tests as it demonstrated the lowest combined emissions performance, and the best performance in terms of pressure loss, combustion efficiency, exit temperature pattern factor, ground starting characteristics and acceptable fuel staging characteristics. Other factors such as ground starting, soot deposition, and altitude relight capability were also superior to other combustors evaluated during the first two phases of the program.

The emission results of the engine test are presented in table I and are compared to production engine combustor values. As indicated, only the 1979 EPA standard for hydrocarbons was achieved in engine test. Levels of NO_x and CO emissions were substantially below that of the production engine combustor, but exceeded the 1979 EPA standards. In addition, the smoke level was increased over the production engine combustor and also exceeded the 1979 EPA standard. These results had not been anticipated. Estimates of engine emissions had been made based on tests of the Double/Annular combustor in the combustor test facility. Tests at simulated engine idle, with exact duplication of engine pressure, temperature and air flow rate, indicated that CO and THC EPAP values would be below the 1979 EPA standard (ref. 7). The level of NO_x emissions was estimated to be above the 1979 EPA value of 3.0 and a value of the EPA Parameter (EPAP) of 4.5 was extrapolated from rig test results. The combustor tested in the engine was substantially altered from the final experimental version tested in Phase II. These alterations were necessary to insure that the experimental engine combustor incorporated realistic design features typical of combustors operated in a high pressure environment for an extended period of time. Typical features that were incorporated in the experimental engine combustor were a revised liner cooling design, greater allowances for thermal expansion, modified attachment of combustor parts and a reconfigured inner liner. These changes compounded in a manner to seriously deteriorate the fuel injection pattern and mixing occurring in the pilot stage. The result was a large increase in CO and THC emission levels over the values obtained during Phase II (ref. 10).

Smoke emissions were also above the standard value. Tests during Phases I and II at rig pressure levels of 6 to 8 atmospheres had not indicated that smoke levels would be any higher than the CF6 production value of about 15. Engine smoke numbers could be reduced to a value of 19 by increasing the amount of fuel supplied to the lean main zone of the combustor. However, there was a slight increase in the level of NO_x emissions (ref. 10). The listed smoke numbers were not actually obtained during the engine test. The smoke number values presented were estimated by extrapolation of the data obtained at high engine fuel-air ratios to those fuel-air ratio values normally required of the CF6-50 engine at takeoff and climb conditions. Operation at higher than normal fuel-air ratios was required in order to obtain the EPA landing-takeoff cycle points due to the high SFC of this experimental engine.

Table II is an assessment of the development status of the Double/Annular combustor. The areas requiring further development are the engine emission levels and the exit temperature profile. There is good reason to believe that CO emissions can be reduced to levels below the 1979 EPA standard values as such performance was achieved during Phase II. Smoke emission levels must be reduced and should require only a normal development effort. NO_x emissions are quite high, exceeding the 1979 EPA value to such an extent that a major development effort is required. Exit temperature profiles also require a major development effort. While the measured temperature profiles are not radically different from the required profile, the small amount of air available to adjust the profile and the sensitivity of emission levels to small air flow schedule changes, means that achieving the desired temperature profile will be considerably more challenging than in previous combustor development efforts. Fuel nozzle coking will also require additional work to assure that there will be minimum fuel degradation in the main stage fuel lines and nozzles. With the exception of the above items all other combustor performance factors were as good as the production CF6-50 combustor (ref. 10).

JT9D-7 engine. - Figure 4 is a cross-sectional sketch of the Vorbix combustor for use in the JT9D-7 engine by Pratt and Whitney. The combustor consists of two burning zones arranged in series. The upstream zone or pilot zone is designed as a conventional swirl-stabilized combustion zone. Hot gases exiting from this zone pass through the narrow throat and ignite the fuel-air mixture in the main or high power zone. In the main zone, additional fuel is added and mixed with a large quantity or air admitted through rows of swirlers. The swirling action of this air serves to quickly mix and distribute the main zone fuel so that mixture ratio can be uniformly fuel lean. The version of the Vorbix combustor shown in figure 4, was selected after extensive testing during Phase II to optimize its emissions and combustion performance (ref. 8). The version selected exhibited the best overall performance in terms of emissions, combustion efficiency, exit temperature pattern factor, and total pressure loss.

Table III compares the emission results obtained with the Vorbix combustor, the production engine combustor values and the 1979 EPA standards (ref. 9). The Vorbix combustor as tested in an experimental JT9D-7 engine was able to meet all of the 1979 gaseous emissions standards. The smoke standard was exceeded by a large margin. The engine CO EPA parameter (EPAP) value is about half the value anticipated from Phase II testing and reflects some changes to the pilot zone in the engine combustor. Smoke emissions were not routinely measured during rig tests as the values were quite low and were comparable to the level of the JT9D-7 production combustor in rig test (ref. 8). Thus, the high smoke level obtained in the engine test was not expected.

To identify the reason for the high smoke levels, several engine tests were conducted where the number of fuel injectors used in the main zone was decreased by one-half. This caused a large increase in the measured smoke level and identified the main zone fuel injection technique as the principal source of the high smoke levels.

Other engine and combustor performance parameters are listed in table IV from reference 9. Items requiring further improvement by way of a normal development effort include exit temperature profiles, engine acceleration, coking, and liner durability. Temperature profiles were close to production engine values but some further work is needed to achieve the desired profile. Exit temperature pattern factors were the same or slightly better than those of the production combustor. Engine acceleration was marginal, meeting the required FAA standards only under certain conditions. Acceleration times from idle to full power were substantially slower than present JT9D-7 engines. This effect is due primarily to the fill time of the main zone fuel injector manifold tubes during the staging process. Further work on fuel manifold design should decrease engine acceleration time. There were areas on the liner where soot was deposited and local overheating occurred. Normal development should correct those deficiencies (ref. 9). Two areas requiring extensive development are sea-level starting and fuel passage coking. Ground starts were obtained slowly with the Vorbix combustor. This was primarily due to the choice of fuel injector in the pilot zone. A fuel injector with the proper flow characteristics should give improved ground start performance. However, this injector must also provide adequate altitude relight performance. Extensive relight testing was not conducted during Phase II, though results were obtained with one configuration that duplicated rig relight results obtained with the production combustor (ref. 8). Additional development would be required to simultaneously achieve the desired ground start and altitude relight characteristics without adversely effecting the CO and THC emissions. Fuel passage coking was detected in the main stage fuel lines. Staged combustors employing two or more zones of fuel injection can be expected to encounter increased frequency of fuel line coking. This is because the fuel lines are exposed to hot air during periods when fuel is not flowing in the line. The combination of high temperature and exposure to hot air can result in increased tendency of the fuel in the line to breakdown, eventually forming coke. Extensive development will be required to design staged fuel injection systems that minimize the tendency of the fuel to coke.

ECCP summary. - In general, the Experimental Clean Combustor Program was very successful. Advanced technology combustors were designed and tested in experimental engines and low emission levels were achieved. The Vorbix combustor in the JT9D-7 engine at a pressure ratio of 22:1 achieved all of the 1979 EPA gaseous emission standards. While smoke levels were above the standard, a development effort should reduce smoke levels to below required levels. Emissions from the Double/Annular combustor in the CF6-50 engine (pressure ratio 29.8:1) were not as low as had been measured and extrapolated from Phase II rig results. Smoke levels are only slightly over the goal and should be reduced with future effort.

The performance characteristics for both combustors in the engine were quite acceptable considering their limited state of development. Improvements in fuel staging and fuel manifold design will be needed to reduce the problems encountered with the Vorbix combustor on the JT9D-7 engine, and additional efforts will be required to achieve the desired ground start and altitude relight requirements. The tests conducted with the Double/Annular combustor encountered no such problems. The main problem was that the exit temperature profile was hub peaked and caused some damage to turbine vanes. Both the JT9D-7 and the CF6-50 engines were run to full power conditions with these combustors. The two experimental engines are routinely used by the engine manufacturers for the conduct of a wide variety of test purposes. Thus these engines did exhibit more performance degradation due to wear. This degradation was manifested by the requirement of higher than normal fuel-air ratios to achieve full thrust levels. In the case of the CF6-50 engine, the fuel-air ratio at full power averaged 17 percent higher at takeoff than normal. For the Double/Annular combustor most of the fuel at full power passes through the inner annulus main stage, thus a hub hot profile might be expected. Further refinement of the design and appropriate operating conditions should correct this problem. In spite of the high fuel-air ratios, no liner hot spots or soot buildups were observed. In all other operational characteristics, the Double/Annular combustor performed as well as, or better than the production combustor.

Pollution Reduction Technology Program

The emissions and combustion performance results obtained from the "best" configurations of each of the advanced technology combustors are given in tables V, VI, and VII. The judgment as to "best" configuration was based on emissions as well as other combustor performance features including exit temperature profile, pattern factor, pressure loss, and combustion efficiency. All of the values listed in the tables have been computed by extrapolating, when necessary, rig values to engine design table values. No extrapolations of data were required for the JT8D-17 and 501-D22A engine combustors. Tests on these combustors were conducted at actual engine conditions. The tables compare the emissions of the advanced technology combustors to those of the production combustor. The relevant 1979 EPA standards are also listed.

JT8D-17 engine. - Table V gives the emission levels obtained with the best advanced technology combustor concepts for the JT8D-17 engine (ref. 11). Figure 5 has cross-sectional sketches of the three combustors studied. The combustor concepts shown in figure 5 include a minor variation of the production combustor, a Vorbix combustor, and a staged-premixed combustor. These combustor concepts are listed in order of increasing combustor complexity and in increasing potential to achieve all of the program goals. The modified production combustor whose emissions are listed in table V consisted of the use of an air-blast fuel nozzle and a modification to increase the primary zone fuel-air ratio over that of the production combustor. This approach was successful in reducing CO and THC emissions but had only a minor effect on NO_x emissions and no effect on smoke levels. The Vorbix combustor shown in figure 5(b) is similar in concept to the Vorbix combustor used in the JT9D-7 engine. However, in this design, the main stage fuel is injected into two premixing tubes arranged on either side of the combustor. The resulting fuel-air mixture is injected into the main zone at the throat separating the pilot and main stage burning zones. The emissions of the best version are listed in table V and show that only the THC and smoke standards were achieved though the CO and NO_x levels were reduced to nearly one-half of the production combustor values. The staged-premixed combustor shown in figure 5(c) incorporates two burning zones. The pilot stage was designed with a premixing fuel passage upstream of a punched cone flameholder. The walls of the pilot stage are wrapped with fuel tubes so that the main stage fuel can be preheated to a level where it will flash vaporize upon injection. Main stage injection took place in six fuel-air premixing tubes that exhaust into the main combustion zone. The emissions listed in table V indicate that preheating the fuel had little benefit in reducing gaseous emissions below the levels already achieved with the Vorbix combustor. The very lean operation of this design accounts for the very low smoke level value of 2 and the generally poorer performance in reducing CO emissions.

All three combustor concepts had total pressure losses equal to or slightly less than that of the production combustor. Measured pattern factors generally exceeded the program goal value of 0.25 but were amenable to substantial reduction by alteration of dilution airflow rates. The levels of pattern factor that were obtained were consistent with the level of development of these concepts. But test results indicated that a normal combustor development effort could probably bring these values down to or even below production combustor values (ref. 11). Altitude relight testing was conducted on the modified production combustor and on the Vorbix combustor. Lean dome versions of the production combustor were deficient in this area, but the more promising rich dome versions, though not tested, should closely duplicate present engine levels. Altitude relight limits of the Vorbix pilot stage were not acceptable and an additional development effort would be required to improve relight limits. Some specific problems encountered with these combustors were: (1) local liner hot spots were common with modified versions of the production combustor; (2) the throat of the Vorbix combustor was subject to local overheating requiring additional cooling airflow; and (3) the premixed pilot of the staged premix combustor consistently failed and, therefore, the pilot stage of the Vorbix combustor was substituted in its place.

TFE-731-2 engine. - Table VI lists the emission results obtained during the Phase I combustor rig tests using the combustor concepts illustrated in figure 6 (ref. 12). This program effort was similar to the combustor effort for the JT8D-17 engine. The combustor configurations evaluated typically increased in complexity from the production engine version with increased potential for achieving the 1979 EPA standards.

The results listed in table VI for the modified production combustor were obtained by the use of an air-assist fuel nozzle and diffuser bleed during engine idle and the use of water injection at takeoff. Emissions of the THC are below program goals while emissions of CO and NO_x slightly exceed program goals. The EPA parameter values shown are estimates based on extrapolated emission levels at the approach and climb power setting. The second combustor concept shown in figure 6(b) is a modest but significant departure from the production engine combustor. The combustor uses 20 airblast, air-assisted fuel nozzles. The airblast injector operates at all conditions while the air-assist is used during engine idle. In addition, the swirler around the nozzle is intended to have a variable geometry feature to modulate the airflow through the swirler during idle and high power operation. The emissions results shown in table VI show that only the THC standard was achieved though the CO and NO_x standards are closely approached and may be achieved with further development. The staged-premixed combustor shown in figure 6(c) is the most complex design, but has the greatest potential to achieve all the program goals. This is a staged combustion concept similar to those employed in the ECCP where a pilot zone serves to ignite a fuel-air mixture supplied to the main combustion zone. The pilot zone of this combustor is a conventional swirl stabilized zone designed to operate near an equivalence ratio of 1.0 during engine idle. The main zone employs fuel-air premixing and is designed to operate fuel lean. An array of 40 premixing passages, each with its own fuel injector, is fastened to the outer combustor liner wall. The fuel-air mixture exits from these tubes, mixes with the hot gases from the pilot, ignites and burns. Emission results obtained with this concept (table VI) are all below program goals except for CO which is close and should be achieved with further development. Smoke emissions have been low on all concepts tested but test data were obtained at only 4 atmospheres pressure and smoke extrapolations with pressure are unreliable. However, all concepts should have smoke levels equal to or substantially lower than the production combustor values. Recent engine tests of the piloted airblast combustor yielded a smoke number at simulated sea level takeoff of 16.5 (ref. 13). Other combustor performance features such as total pressure loss and exit temperature pattern factor have been at or below levels obtained with the production combustor and have not been difficult to obtain. Altitude relight characteristics have not yet been measured and await a further definition of the final combustor design. Combustor concept B, piloted-airblast combustor, has been selected for the engine test program (ref. 13).

501-D22A engine. - The combustor concepts tested during the program on the 501-D22A engine are shown in figure 7. As before, these concepts are arranged in order of increasing combustor complexity and potential for achieving emission goals. Table VIII lists the EPA parameter values obtained for each concept and the levels of the production combustor (ref. 14). A reverse flow concept (fig. 7(b)), represents a minor change to the production combustor consisting of a primary zone reconfiguration to increase the recirculation around the airblast fuel injector. The emissions performance of the concept listed in table VII, show that all emission goals were obtained. Substantial reductions in CO and THC were noted. Although the level of NO_x emissions rose slightly over that of the production combustor, the EPA standard was not exceeded. The prechamber combustor shown in figure 7(c), employs fuel injection from an air-blast fuel injector and fuel introduced on the wall of the prechamber. A radial swirler at the end of the prechamber serves to atomize and mix the fuel injected on the wall. A variable-geometry band was used to modulate the airflow through dilution jet holes along the combustor. The emissions performance of this concept also met all program goals and smoke levels were essentially nil. Emissions of NO_x were the highest of all the concepts tested for this engine, but were still well below the EPA standard value. The staged fuel combustor (fig. 7(d)), employs two-stage combustion with a pilot and a main combustion stage. A small fuel-air preparation prechamber is employed on the pilot stage to provide good initial fuel-air mixing and good flame stabilization and mixing in the subsequent combustion zone. The main zone was designed to burn fuel lean mixtures which were supplied by six premixing tubes arranged alongside the pilot zone. The mixture exiting from these tubes was mixed with additional air supplied by swirlers surrounding each tube. Those gases were then ignited by the products from the pilot stage and combustion is completed within the main zone of the combustor. The emissions of this concept also all met the EPA standards and smoke levels were very low. Emission levels of CO were higher for this concept than any of the other designs. This was due to the difficulty of completing CO combustion reactions at the low temperatures that occur during fuel-lean operation.

Combustor total pressure losses and exit temperature pattern factors were equal to or below production combustor values. Other factors, such as durability and maximum liner temperature appeared to offer no problem. Altitude relight performance was not investigated, but production engine levels should be achieved with minor development effort.

PRTP summary. - The Pollution Reduction Technology Program is nearly complete. The efforts on the combustor concepts designed for the JT8D-17 and 501-D22A engines were terminated at the end of Phase I. Only the Phase III engine test of the TFE-731-2 engine remains to be completed. In the case of the 501-D22A engine, all of the combustor concepts tested were capable of achieving the 1979 EPA standards based on rig test results. This was possible because the NO_x emission levels of the production combustor are significantly below the 1979 EPA standards and therefore the required CO and THC reductions could be accomplished by allowing a slight increase in NO_x emissions. Emission levels of the advanced technology combustors for the TFE-731-2 engine either meet or are very close to meeting the 1979 EPA standards. Further refinement tests during Phase II prior to engine test may bring the remaining high emission levels within the EPA standards. The rig test results of advanced technology Vorbix combustor for the JT8D-17 engine showed that all emissions were substantially reduced though only the THC standard was achieved. It is unlikely that modifications to this combustor concept would produce any further substantial reduction in either CO or NO_x levels. Substantial reductions in CO and NO_x are required to meet the 1979 standards. The emission index values that have been obtained for CO and NO_x (refs. 8 and 11) are at the same level as the best attained with the Vorbix combustor used in the JT9D-7 engine tests. Further large reductions in these emission indices with the Vorbix combustor is not likely and the failure to meet the EPA standard values for CO and NO_x is due to the high specific fuel consumption of this engine.

Other combustor performance factors (pressure loss, exit temperature profile and pattern factor) for the advanced combustor concepts were equal to or better than the production combustors for the 501-D22A and TFE-731-2 engines. Temperature pattern factor and profile of the Vorbix combustor concept designed for the JT8D-17 engine would have to be improved. Test rig evaluated fuel staging characteristics of the two-zone combustors seemed adequate. Altitude relight capability was not extensively investigated and if deficient would require a development effort. Additional cooling air appears to be needed at the throat of the Vorbix combustor for the JT8D-17 engine as some metal burning was often noted during high pressure tests. Rig tests of the 501-D22A engine combustors, conducted at actual engine conditions, revealed no serious problems. Tests of the TFE-731-2 combustors have been conducted at only 4 atmospheres pressure and while minor liner overheating has been encountered, a high pressure engine test is required to pinpoint durability problem areas.

PREMIXED/PREVAPORIZED COMBUSTOR TECHNOLOGY PROGRAM

Although the Phase I activity for this program is not yet completed, some early results are worth mentioning. The fundamental studies comprising the first phase have been divided into four elements as follows: lean combustion, fuel-air preparation, autoignition and flashback, and engine interfaces (ref. 15). Each element represents a problem area related to lean premixed-prevaporized combustion where more information is needed before realistic combustor designs can be developed or assessed.

In the lean combustion element, an effort has been completed to determine the pressure effect on premixed combustor emissions. The tests that were conducted used propane as the fuel over a range of equivalence ratios, inlet-air temperatures and pressures up to 30 atmospheres. A final report on this effort has been published (ref. 16). Another effort is using a similar propane-fueled flametube to examine a number of flameholder designs. Data is being acquired with a variety of cones, gutters, and swirlers to assess the effect of flameholder geometry on lean emissions and stability. In another study, several concepts for improving the lean stability of bluff-body flame stabilizers are being investigated. An analytic evaluation of piloted, catalytic, and heat recirculation concepts has identified the most promising designs which will next be experimentally evaluated. Another study has provided data on the effect of the degree of fuel prevaporization on lean combustion emissions.

In the second element, fuel-air preparation, a facility is being assembled to obtain detailed measurements of fuel spray characteristics in a flowing system. A laser doppler system will be used to spatially resolve droplet size distribution and velocity components at pressures up to 15 atmospheres. The spray data will then be used to calibrate and verify a spray mixing model which is under development.

In the third element, a multiyear study into the autoignition characteristics of various fuels as a function of pressure, temperature, and equivalence ratio has been started. The test facility has been built and checked-out and some preliminary data obtained. Fuels that will be extensively investigated are JP-4, ASTM Jet-A, and Diesel No. 2. Accurate autoignition data and relationships are required to successfully design and safely operate premixed-prevaporized combustors. Flashback phenomena will be investigated in a flame-tube rig. The rig includes a windowed test section for optical measurements and has a test capability of up to 25 atmospheres and 800 K.

The last element, engine interfaces, pertains to problems and considerations associated with incorporating a lean premixed-prevaporized combustor in an aircraft engine system. For example, the combustor must tolerate nonideal compressor discharge conditions and flow transients typical of aircraft engines. As an addendum to the Experimental Clean Combustor Program an effort was conducted to measure the turbulence level of air leaving the compressor of the JT9D and CF6 engines. These tests have been completed; the final reports with the JT9D and CF6 engine results have been published (refs. 17 and 18, respectively).

FUELS TECHNOLOGY PROGRAM

Results illustrating the effect of varying jet fuel properties on exhaust emissions are summarized in reference 19. Decreases in volatility can reduce altitude relight capability and increase idle emissions, although, based on the limited amount of data available to date, the effect is not large for the boiling range investigated. Increases in aromatic content, or conversely decreases in hydrogen content of the fuel, on the other hand, have a pronounced effect on exhaust smoke levels. Current Jet-A fuel has an average aromatic concentration of about 17 percent (vol.). Jet fuel produced from certain heavy crudes may have aromatic concentrations as high as 25 percent (vol.). Exhaust smoke levels have been correlated with fuel hydrogen content (refs. 20 to 22). The variation of hydrogen content with the concentration of aromatic compounds follows the approximate trends illustrated in figure 8. Although the fuel aromatic content does not uniquely specify the fuel hydrogen content, increases in aromatic content generally reduce the hydrogen content of the fuel.

Combustor test evaluations of the effect of fuel blends with varying aromatic concentrations have been performed using a single JT8D combustor can. The effect of hydrogen content of the fuel on smoke number is shown in figure 9. The results which were obtained at both simulated cruise and takeoff conditions for the JT8D engine (Compressor Pressure Ratio, 16) show a significant increase in exhaust smoke as the hydrogen content of the fuel is decreased. Limited unpublished results have been obtained in Phase III for the NASA Experimental Clean Combustor Program that compare the smoke number for the Double/Annular Combustor using Jet-A and No. 2 Diesel Fuel at the takeoff conditions for the G.E. CF6-50 engine (PR = 30). These results indicate that this particular combustor's smoke number is relatively insensitive to the hydrogen content. Aircraft engines that have a marginally acceptable smoke number using current Jet-A fuel may be unable to meet the established standards for smoke number using fuels with increased aromatic content.

ASSESSMENT OF RESULTS

In assessing the impact of the advanced technology combustors on both current and future aircraft gas turbine engines, prime emphasis was placed on the ability to control the emission levels of CO, THC, NO_x, and smoke while maintaining acceptable performance characteristics. The assessment will emphasize the potential for application of advanced technology combustors to newly manufactured (Proposed 1981 and 1984 standards) and newly certified (proposed 1984 standards) engines (ref. 23).

The results obtained from the ECCP and PRTP provided comprehensive definitive data regarding emissions and performance. Operational factors such as altitude relight, durability, coking, staging characteristics, etc., were not evaluated to the same detail. The ECCP experimental engine tests did however provide considerable input concerning these factors. For example, based on the engine tests, it was possible to determine if any serious engine operating difficulties would be encountered that could not be solved during development activities that are normally undertaken to satisfy operational characteristics. Also, the assessment will address, at least in a qualitative sense, other factors such as the impact of engine variability, combustor complexity, and the influence of variations in fuel composition on emission levels.

Emissions

The advanced technology combustors for each engine considered in the ECCP and PRTP were previously described in the STATUS AND RESULTS section. In this section, the emission levels achieved with these concepts are compared to the respective engine baseline combustors and the revised EPA standards as proposed for amendment (ref. 23). All values shown are in terms of EPA parameter levels corrected to actual engine operating conditions.

The results of these programs are shown in figures 10 and 11. These figures show the proposed level of the newly manufactured and newly certified engine standards. The results of each combustor program will be compared and discussed relative to the ability of this advanced technology to achieve the 1981 and 1984 EPA standards for newly manufactured and newly certified engines.

<u>T1 engine class</u>. - Since the newly proposed EPA regulations do not call for regulation of engines in this class, the performance of the advanced technology combustors for the TFE-731 engine will not be discussed here. The reader is referred to published reports and the discussion in the preceding RESULTS section.

T2 engine class. - The emission results obtained from tests of the advanced technology combustors in the experimental CF6-50 and JT9-7 engines have been recomputed according to the new procedure and are presented in table VIII. The conversion factor has been computed by assuming the engine idle power setting recommended by the manufacturer. Figures 10(a) to (d) present the new standards for T2 class engines. The experimental engine test results are shown on each figure.

Figure 10(a) compares advanced technology combustor performance with the proposed standards for 1981 and 1984. The Vorbix combustor installed in an experimental JT9D-7 engine easily met the 1981 standard for CO emissions and very closely approached the 1984 standard. The CO emissions of the Double/Annular Combustor installed in an experimental CF6-50 engine were significantly higher than the 1981 standard level. It should be noted that, as discussed previously, the CO emissions of the Double/Annular Combustor as measured during rig testing were lower than those achieved in the engine tests and were low enough to meet the 1981 NME standard. This result indicates that the Double/Annular combustor concept does have the potential to achieve the NME 1981 standards. Unburned hydrocarbon levels (fig. 10(b)), for both combustor concepts were well below the levels required by the 1981 and 1984 NME and NCE standards.

The proposed NO_x emission standard (fig. 10(c)) is significantly changed from the 1979 standard. The base level of the standard has been increased by 33 percent and an engine pressure ratio correction is allowed for engines of pressure ratio greater than 25:1. The pressure ratio correction, however, applies only to the 1984 NME standard. The JT9D-7 engine at a pressure ratio of 21.2 has no correction applied. The short line shown on figure 10(c) is for the CF6-50 engine at a pressure ratio of 29.8 and the measured NO_x emissions of the Double/Annular Combustor must be judged against that corrected standard value. As indicated in the figure the NO_x emissions of the Vorbix combustor are substantially below the 1984 NME standard level while the emissions from the Double/Annular Combustor exceed the corrected 1984 NME standard level. The 1984 NCE standard is also achieved by the vorbix combustor as tested in the experimental JT9D-7 engine at a pressure ratio of 22:1. Since the pressure ratio correction is not applied to the 1984 NCE standard, the emissions of the Double/Annular combustor substantially exceed the allowable level. Unless a pressure ratio correction is applied to this standard, these combustor concepts will likely fail to meet the 1984 NCE standards in any engine having a pressure ratio greater than 25.

Figure 10(d) is a graphical representation of the EPA smoke standard. The advanced technology combustors in the JT9D-7 and CF6-50 engines failed to achieve the standard. Additional development effort would be required to get the smoke levels of these combustors down to the levels presently achieved by JT9D-7 and

CF6-50 production combustors.

On the basis of the results obtained from the Experimental Clean Combustor Program, the advanced technology combustors should be able to meet both the 1981 and 1984 standards for unburned hydrocarbons. Since the smoke levels of these combustors are close to achieving the standard, minor combustor airflow rescheduling should be successful in reducing the smoke level. However, the effect of airflow adjustments on exhaust pollutant levels must be carefully monitored to prevent large increases in gaseous emission levels.

The 1981 NME standard for CO should be achievable with the Vorbix combustor in the JT9D-7 engine as indicated in figure 10(a). Additional effort will be required with the Double/Annular combustor to achieve the levels below the standard that were obtained during the earlier combustor rig tests. It should be noted, however, that the results shown in figure 10(a) with the Double/Annular combustor were obtained by operation with the pilot burner only during the approach phase of the landing-takeoff cycle. Test results show large increases in CO levels when both pilot and main stages are burning during approach. On the basis of the information available at this time, it does not appear possible to achieve the 1981 NME CO emission standard with both combustion zones fueled during approach.

Based on the data obtained from the JT9D-7 experimental engine test, the Vorbix combustor has the potential to meet the 1984 NME standards for NO_x emissions. The Double/Annular combustor in the CF6-50 engine will require extensive development to meet the 1984 NME standard. Achievement of the 1984 NCE standard, which does not allow for an engine pressure ratio correction, does not appear possible with existing Double/Annular combustor technology as applied to high pressure ratio engines such as the CF6-50. Achievement of the 1984 NCE NO_x standard does not appear possible with any combustor technology evaluated in this program without the inclusion of a pressure ratio correction for those engines having pressure ratios substantially greater than 25.

T4 engine class. - The results obtained with advanced technology combustors designed for the JT8D-17 engine are presented in table IX in the proposed new units. These data and the EPA standards are also shown in figures 10(a) to (d), for CO, THC, NO_x, and smoke, respectively. As shown in figure 10(a), changes to the production combustor resulted in significant reductions in CO achieving the 1981 NME standards. Similarly, the hydrocarbons were reduced (fig. 10(b)), achieving this standard with considerable margin. As expected there was virtually no change in the emissions of NO_x (fig. 10(c)), or smoke (fig. 10(d)). It was not anticipated that minor changes to the production combustor would have much beneficial effect on NO_x. A larger change in the combustor design is required to make a significant change in the NO_x level. The other emissions, CO, THC, and smoke should be significantly altered by variations in the primary zone equivalence ratio. The Vorbix combustor was designed to reduce the NO_x level as well as the other emissions. The CO level of the Vorbix combustor (fig. 10(a)), was reduced below that of the production combustor but did not achieve the level of 1981 standard. Hydrocarbons were quite low achieving both the 1981 and 1984 standards (fig. 10(b)). NO_x emissions (fig. 10(c)) from this two-stage combustor were nearly one-half the level of the production combustor, but did not achieve the required standard. Similarly, smoke emissions (fig. 10(d)) were slightly above the standard.

On the basis of these results one can conclude that minor modifications of the production combustor will not produce a simultaneous reduction in the level of all pollutants. Such changes can reduce the CO and THC to below the required levels of the 1981 NME standards but will have only a small effect on NO_x emissions.

The emission index values obtained with the advanced technology two-stage Vorbix combustor were nearly the lowest obtained with any combustor studied. Yet the EPA standards for CO and NO_x were not met. Furthermore, it is very doubtful that the 1981 CO and the 1984 NME NO_x standard could ever be achieved with this combustor technology when applied to engines such as the JT8D-17. While the emission indices are very low, the high specific fuel consumption of such low by-pass ratio engines virtually makes the attainment of the CO and NO_x standards impossible.

P2 engine class. - The emissions of the 501-D22A production engine combustor are listed in table X, along with the revised standards and the levels of the modified reverse-flow-dome combustor. These data are shown in figures 11(a) to (d). The minor combustor modification, the reverse-flow-dome version, was capable of achieving all of the required standards with considerable margin. This was due in part to the fact that the NO_x standard (fig. 11(c)) was already met by the production combustor. Thus a slight increase in NO_x could be accepted for a large decrease in CO, THC, and smoke levels. Further emissions development of this combustor would not seem required.

Summary of emission and development status with respect to the proposed NME standards. - Table XI gives a brief qualitative summary of the emission reduction potential of the combustors, based on the engine test results, for achievement of the EPA standards for 1981 and 1984 newly manufactured engines, NME. The Double/Annular combustor, installed in the CF6-50 engine can, with additional development, achieve the 1981 NME standards. This determination is based upon the results from the experimental engine tests as well as the combustor rig test results. However, it seems unlikely that, with the combustor technology generated in this program, the 1984 NME NO_x standard can be achieved without further extensive development. New technology will be required if such a development effort is unsuccessful.

Additional development of the Vorbix combustor installed in the JT9D-7 engine should enable this technology to achieve the 1981 and 1984 NME standards.

The Vorbix combustor installed in the JT8D-17 engine can meet THC and smoke standards but is not able to meet the CO and NO_x standards. New combustor technology, as yet undefined, would be required to achieve CO and NO_x emission index values low enough for the JT8D-17 to simultaneously meet all standards. As reported in reference 14, the Vorbix combustor has achieved CO and NO_x emission index values as low as any other combustor studied. The high SFC of the JT8D engine is the reason why the calculated EPA Parameter value is larger than the standards. Although engine SFC may improve with future versions of the JT8D, the resultant EPAP values are still not likely to meet the EPA standards. Based on the EPAP values presented in table V, the JT8D-17 SFC would have to be reduced to about one-half the present value before compliance with the standards would be achieved.

Modified versions of the production combustor for the JT8D-17 engine should be capable of meeting the 1981 EPA standards for CO, THC, and smoke with additional development. These standards were not achieved in the NASA program as the goal of simultaneous reduction in all pollutants including NO_x precluded optimixing the combustor concept for control of CO, THC, and smoke only. The results of the NASA program do indicate that minor modifications to the production combustor will not result in attainment of all the EPA standards. New technology will be required to achieve the 1984 NME NO_x standard.

<u>Summary of emission and development status with respect to proposed NCE standards</u>. - In any discussion of the application of advanced combustor technology to newly certified engines, NCE, there has to be some idea as to what those engines will be and what their performance might be. The most obvious performance changes may appear in engines such as those proposed in the NASA Energy Efficient Engine Program (ref. 24). Such engines may have pressure ratios of 30 or more at takeoff, turbine inlet temperatures up to 1650 K and exhibit substantially lower values of specific fuel consumption. Higher pressure ratios at takeoff and climb will increase the level of NO_x emissions as will the high turbine inlet temperatures. The improved specific fuel consumption will act to reduce the computed value of the EPA Parameter.

The following discussion is based upon the application of the advanced technology combustors to a future "energy efficient engine." The ability to attain the proposed 1984 NCE standards is based upon information presented in references 9, 10, and 24. The emission goals selected for the NASA Energy Efficient Program are the 1981 NCE standards (ref. 3), rather than the proposed 1984 NCE standards. Aside from the compliance date the major difference in the two standards is that the proposed 1984 NCE standard has increased the allowable NO_x emission level by 33 percent. The following discussion is confined to a projection of the ability of advanced technology combustor concepts to achieve the proposed 1984 NCE standards.

An assumed engine cycle has been derived based upon the engine cycles proposed for Energy Efficient Engines (ref. 24). This assumed cycle, listed in table XII, has values of engine pressures and temperatures, takeoff thrust, and specific fuel consumption representative of future engine cycles. The cycle points tabulated in table XII are those needed for the extrapolation of the emission levels obtained in the JT9D-7 and CF6-50 experimental engine tests. Using this cycle and the information in references 9 and 10, emissions and operating conditions of the JT9-7 and CF6-50 engines, respectively, an estimate was made of the emissions levels that would represent the operation of the Vorbix and Double/Annular combustors in this assumed future engine cycle. From these estimates the EPA Parameter was then calculated and compared to the proposed standards. This estimation process simply assumes that the Vorbix and Double/Annular combustors would be essentially identical in the future engine to those tested in the experimental JT9-7 and CF6-50 engines. In reality such future versions of these advanced technology combustors would probably be different, in size or length for instance, from those tested in the NASA program. Such changes do affect emission levels and in known manner as is discussed later. The purpose of these extrapolations is to show the general level of emissions reduction technology afforded by these advanced combustor concepts and indicate in a general way those areas where standards are likely to be met and those areas requiring additional development.

Table XIII lists the extrapolated values of emissions for the Vorbix and Double/Annular combustors in the assumed future engine cycle. The equations used in extrapolating the emissions are listed in reference 9. It is not possible to reliably extrapolate smoke data from one operating condition to another, so it has been assumed that both combustors would exhibit takeoff smoke levels below a smoke number of 20, the required EPA Standard level. Two values of idle CO emissions are shown for the Double/Annular combustor. The larger value is obtained by extrapolation of the experimental engine test results and the lower value extrapolated from combustor rig test results.

The emission values of table XIII were used to calculate values of the EPA Parameter for each of the advanced technology combustor concepts. These EPA Parameter values are listed in table XIV along with the EPA 1984 NCE standards for comparison.

The Double/Annular combustor fails to meet the CO standard based on the results obtained in experimental engine test (ref. 10), but does achieve the standard based upon the results of the combustor rig tests (ref. 7). As mentioned previously, the CO emissions performance of the Double/Annular combustor as tested in the experimental CF6-50 engine does need additional development to achieve the standard. That such achievement is possible is indicated by the results of the combustor rig test (ref. 7). The Double/Annular combustor concept should achieve the 1984 NCE THC standard as indicated by the estimated value of 2.8. The estimated value of the NO_x EPAP exceeds the standard level and indicates an area requiring additional development.

The Vorbix combustor also seems to need additional development to achieve the CO standard. The estimated value is close to the standard level, however, as is discussed later, lower values of emissions will likely be required in order to compensate for possible engine-to-engine variability. The Vorbix concept appears to achieve the THC standard easily and meet the NO_x standard with some margin. As was indicated previously smoke data cannot be reliably extrapolated and therefore both combustor concepts have been assumed to meet the standard.

It is difficult to say with absolute certainty whether the new combustor technology as typified by the Vorbix and Double/Annular concepts will meet the 1984 NCE NO_x and CO standards. The ability of engines employing these combustor concepts to meet the standards will depend upon the relative interplay of competing factors and trends. These competing factors are depicted in figure 12. This figure serves to illustrate the relationship between CO and NO_x emissions. Similar CO-NO_x plots have been used in the past to illustrate the trade-off in values of these two emissions. Lines qualitatively representing the 1984 NCE CO and NO_x standards are shown and are the bounds of a compliance area. For discussion purposes a point outside of the compliance area is shown as typical of CO-NO_x performance. The arrows represent the trends for greater or lesser emissions as imposed by future engine design characteristics. The trend to higher pressure ratios and high combustor exit temperatures is to produce more NO_x, conversely, shorter combustor lengths, reduced residence times and lean main zone burning tend to decrease NO_x emissions. Short combustor lengths and low residence times tend to increase CO levels. However, the higher pressure and temperatures of advanced engines at idle tend to decrease CO emissions. Both CO and NO_x EPA parameter values are lowered by the lower SFC values of more efficient engines.

The use of staged combustor concepts tends to reduce the impact of these trends. Each burning zone can be optimized to produce minimum emissions; pilot zones control idle emissions CO, and THC, and main zones NO_x and smoke. The successful implementation of a two-stage combustor concept can utilize the full benefit of improved engine SFC values in lowering the calculated EPA Parameter value. If the full benefit of two-stage combustion cannot be realized, due for instance by the requirement for a very short combustor, then a trade-off may exist between CO and NO_x emissions as illustrated in figure 12.

The area enclosed by the dashed lines in figure 12 is intended to represent an increase in the NO_x standard by application of a pressure ratio correction. The present 1984 NCE NO_x standard does not allow a pressure ratio correction, although the 1984 NME standard does. As indicated by the estimated emission performance of advanced technology combustors in future engines (table XIV), there may be a need for a pressure ratio correction to the 1984 NCE NO_x standard. The Double/Annular combustor does not meet the standard. Significant NO_x reductions can be obtained by the techniques indicated in figure 12, that is, lean burning, short length, short residence time, and improved SFC. Lean burning is already incorporated into the concept of the Double/Annular combustor and improved SFC has been included in the estimation of the future engine emissions values. Short length and low residence time can be employed to reduce NO_x, but these approaches tend to increase CO levels as indicated in figure 12. In this case, the use of a pressure ratio correction would permit an increase in the allowable level of NO_x emissions which would in turn, permit the use of combustion approaches that trade the increased NO_x emissions for decreased CO emissions. In addition, the future engine cycle assumed in these calculations had a takeoff compressor pressure ratio of 30.5 to 1. Future engine cycles may have pressure ratios approaching 40 to 1 at takeoff. A NO_x pressure ratio correction would certainly be needed to account for the significantly higher NO_x emission levels associated with these pressure levels. Improved engine SFC could not overcome the combination of factors (high pressure ratio and high compressor exit temperature) that increase NO_x levels exponentially. A NO_x correction to the 1984 NCE standard similar to that presently promulgated for the 1984 NME standard would seem to be warranted.

ENGINE VARIABILITY

The EPA aircraft engine standards specify that all engines must have emission levels below the standard value for the entire engine lifetime. Aircraft engines exhibit a considerable degree of variability in measured emissions performance. This is due in part to variations in emissions due to variations in ambient conditions for which correction factors have been determined (ref. 25). There is also a source of variability in the emission measurement technique and the instrumentation, though these have been carefully specified by the EPA (ref. 23). The most unconstrained source of variability is the engine itself. In spite of the precision with which aircraft engines are manufactured, there is still a wide variability in their emissions performance that can only be traced to engine-to-engine variability (refs. 26 and 27). The effect of this variation in emissions performance means that emissions measured from the "average" engine must be lower than the EPA standards by a sufficient amount to insure that all engines in the family would comply.

No such information on engine-to-engine variability was generated in the emission reduction technology effort described in this report. The "best" that might be assumed is that the emissions of these advanced technology combustors are representative of average engine performance. Thus, compliance can only be assured if these values of emissions are well below the standard. Further development of these combustor concepts to improve performance as indicated in tables II and IV may impact emissions in yet undetermined ways. As shown in figures 10(a) to (d) and indicated in tables XI and XIV further emissions development of these advanced technology combustors is required. For example, in figure 10(a), the modified production combustor for the JT8D-17 engine barely meets the CO standard. Further improvement of the CO emissions performance is clearly indicated but how low the value should be depends upon typical engine-to-engine variability for the JT8D-17 engine. It was assumed in table XI that the modifications to the production combustor were relatively minor and engine-to-engine variations with the new combustor would be no worse than existing JT8D-17 engine variability. Such may not be the case for the JT9D-7 engine employing the Vorbix combustor. As shown in figure 10(a), the 1981 NME CO standard is met with some margin. However, it is not possible to determine if the margin is sufficient to account for future JT9D-7 engines with the Vorbix combustor.

Similar arguments can be made for the measured NO_x and smoke emissions performance as shown in figures 10(c) and (d). Measured values of unburned hydrocarbons (fig. 10(b)), appear to be well enough below the 1981 NME standard to insure compliance and may be low enough for the 1984 NCE standard. While these unburned hydrocarbon values are very low, they were obtained with experimental combustors in brief engine tests. Further combustor development to remedy performance deficiencies is required and may adversely effect all of the emissions. Further, the engine-to-engine variability with these advanced technology combustors may be greater (or less) than that of present production engines such that there is a need to reduce emissions to the lowest possible level in order to assure compliance with the regulations.

COMBUSTOR COMPLEXITY

The advance technology combustors such as the Vorbix and Double/Annular combustor concepts are much more mechanically complex than present production combustors. This combustor complexity was needed to achieve the required combustor performance and emission level goals of the NASA programs. Less complex combustor designs have been attempted but failed to achieve the simultaneous reduction in all pollutant levels required by the EPA standard. Only where one or more emission standards have already been met by the production combustor, as in the case of the NO_x emissions of the 501-D22A engine, have minor combustor changes been successful in achieving the standards (ref. 14).

The engine complexity typified by the advanced technology combustors consists of multiple fuel manifolds, additional fuel nozzles, and a new fuel control system that can control the staging of fuel to two burning zones. These increases in complexity will likely require increased inspection and maintenance of the combustor and its associated fuel injection and control system. In addition to the increased base cost of these more complex combustors, any resultant additional maintenance and inspection efforts would add to the life cycle cost of the engine.

The use of staged combustors may prove to have benefits not yet realized in the limited testing conducted to date. Since each zone performs a special task the combustor can be designed specifically for known operating conditions. Generally, these burning zones operate fuel lean and have the tendency to operate at lower flame temperatures than production combustors. These two factors; design optimized for a specific task over a narrow operating range and fuel lean operation could possibly lead to beneficial results as far as combustor life and durability are concerned. If proven in practice, such a result could ameliorate possible maintenance and cost penalties that may occur due to the greater mechanical complexity of the staged combustor designs as described above.

FUELS SPECIFICATION

The latest version of Aircraft Engine Emission Standards (ref. 19) specifies that a fuel "meeting the specifications, ASTM D1655- latest version - Jet A, shall be used." Figure 13 shows the trend upward in aromatics content of Jet A fuel from 1960 to the present. Also identified are the aromatics level of Jet A obtained from certain heavy Arabian and Alaskan crude oils. To allow for the use of these higher aromatic crude oils, the ASTM waived the aromatics specification to permit limited use of fuel with greater than 20 but less than 25 percent aromatics.

The effect of increased aromatic content in the fuel has been documented in several reports (refs. 28 and 29). These reports show that all of the combustor performance characteristics of advanced technology two-stage combustors were virtually unaffected by the use of fuel with higher aromatic content. It is worth noting, however, that these results were obtained in test rigs at low pressure, not in engines. Both combustors in ECCP engine tests exhibited very high smoke numbers that were not anticipated from rig test results. Test results from a conventional JT8D combustor, at actual engine pressure levels, show that an increase in aromatics level will cause an increase in smoke level (ref. 22).

If the aromatic content of the fuel is to continue to rise, and there is reason to believe that it will, then engines certified with today's Jet A fuel will in the future emit higher levels of smoke and may fail to meet the smoke standard even though low smoke combustor technology is being used.

CONCLUDING REMARKS

With the exception of the engine verification tests of the TFE-731, the NASA Experimental Clean Combustor Program (ECCP) and Pollution Reduction Technology Program (PRTP) have been completed. The data generated in these programs provides a reasonable indication of the potential of advanced technology combustors for reducing current jet engine emissions while maintaining satisfactory engine performance and operation. Fundamental and applied research studies are now underway to evaluate the potential for additional emission reduction capability in future generation aircraft gas turbine engines.

The results obtained with combustors designed for and tested in T2 Class engines have indicated 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. Simultaneous reductions in all emissions over the total engine operating regime will require the use of staged combustors. As part of the ECCP, staged combustor designs were evaluated in JT9D-7 and CF6-50 experimental engines. In terms of the proposed amended EPA standards, technology to reduce THC to the required levels appears well in hand. Success in the control of NO_x tended to depend on the advanced concept utilized and the cycle to which it was adapted. Application to cycles with high pressure ratios or high specific fuel consumption were not successful in achieving the required levels. A NO_x pressure ratio correction term may be required if high pressure ratio engines are going to comply with the 1984 NCE standard. In a like manner, success in achieving CO levels in compliance with the standards depended on the concept utilized and the cycle to which it was adapted. Smoke characteristics of most of the staged combustors were above the required levels. Additional combustor development should rectify this problem area.

Reduction of CO and THC emissions were achieved with combustors in EPA Classes T1, T4, and P2 with designs consisting of minor modification to the baseline combustor. These combustor designs are representative of the level of emission reduction technology that may be achievable in a retrofit program. Based on the results of these studies, 1981 NME CO and THC standards are judged to be achievable. Additional development effort would be required for some of the advanced concepts to achieve the 1984 NCE CO and THC standards.

Verification tests conducted in experimental engines played an integral role in the ECCP efforts by substantiating combustor rig test emission levels and demonstrating the ability of advanced combustors to operate successfully in an engine. While additional development work would be required to make these concepts acceptable for production engines, no operational difficulties were encountered which would preclude their eventual fitness for use.

The measured engine emissions are subject to wide possible variations caused by engine-to-engine variability. To ensure that all engines will meet the EPA standard it is necessary that measured emissions be sufficiently below the standard level to account for this variability.

The advanced technology combustors studied in the NASA programs are considerably more complex mechanically than production combustors. Several specific problem areas that will require further work are those related to the operation and durability of the staged fuel injectors. Increases in costs associated with the increases in complexity may be offset by improvements in performance that can be achieved by using the lean combustion technique.

The levels of combustion pollutants in an engine are related to the fuel properties and composition. Present levels of aromatics in Jet-A fuel are increasing resulting in a trend toward increased exhaust smoke levels. It is probable that future fuel specifications will be broadened in the interest of economy and fuel availability. Fuels derived from alternative sources may exhibit different properties, particularly the inclusion of fuel bound nitrogen compounds. These changes in fuel specifications and properties will most likely have an adverse effect on pollutant emissions. NASA currently has additional technology programs underway to evaluate the effect of broadened fuel specifications and to develop new low emission combustor technology as required. It will be several years before this technology is in hand. In addition to these efforts, programs are underway to provide a new generation of low emission combustor concepts that would provide emission levels far below those currently possible with the concepts generated in the ECCP and PRTP.

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TABLE I. - SUMMARY OF EMISSIONS OF THE DOUBLE/ANNULAR COMBUSTOR IN AN EXPERIMENTAL CF6-50 ENGINE[a]

	CO^b	THC	NO_x	Smoke
1979 Standards	4.3	0.8	3.0	19
Production combustor	10.8	4.3	7.7	13
Double/Annular combustor	6.3	0.3	5.6	25

[a]From ref. 10.
[b]Dimension of the EPAP are pounds pollutant per 1000-lb thrust-hr per cycle.

TABLE II. - ASSESSMENT OF DOUBLE/ANNULAR COMBUSTOR DEVELOPMENT STATUS[a]

	No further development required	Additional development required	Extensive additional development required
Emission levels			
CO		X	
HC	X		
NO_x			X
Smoke		X	
Ground starting	X		
Altitude relight	X		
Main stage crossfiring	X		
Pressure loss	X		
Combustion efficiency	X		
Exit temperature profile/ pattern factor		X	
Metal temperature	X		
Acoustic resonance	X		
Carboning	X		
Fuel nozzle coking		X	

[a]From ref. 10.

TABLE III. - SUMMARY OF EMISSIONS OF THE VORBIX COMBUSTOR IN AN EXPERIMENTAL JT9D-7 ENGINE[a]

	CO	THC	NO_x	Smoke
1979 EPA Standards	4.3	0.8	3.0	19
Production combustor	10.4	4.8	6.5	4
Vorbix combustor	3.2	0.2	2.7	30

[a]From ref. 9.

TABLE IV. - ASSESSMENT OF VORBIX COMBUSTOR DEVELOPMENT STATUS[a]

	No further development required	Additional development required	Extensive additional development required
Pressure loss	X		
Exit temperature pattern factor		X	
Exit temperature radial profile		X	
Idle stability (lean blowout)	X		
Sea-level starting			X
Main-stage ignition	X		
Altitude relight	--	(Not evaluated)	--
Transient acceleration		X	
Combustion instability	X		
Carbon:			
Liner deposits		X	
Fuel passage coking			X
Liner durability (overheating)		X	

[a]From ref. 9.

TABLE V. - SUMMARY OF EMISSIONS OF THE ADVANCED TECHNOLOGY COMBUSTORS FOR THE JT8D-17 ENGINE[a]

	CO	THC	NO_x	Smoke
1979 EPA standards	4.3	0.8	3.0	30
JT8D-17 Production combustor	16.1	4.4	8.2	28
(a) Modified production combustor[b]	5.1	0.1	7.4	28
(b) Vorbix combustor[b]	8.9	0.2	4.4	27
(c) Prevaporized/Premixed combustor[b]	14.3	0.4	4.6	2

[a]From ref. 11.
[b]Data from combustion rig tests.

TABLE VI. - SUMMARY OF EMISSIONS OF ADVANCED TECHNOLOGY COMBUSTORS FOR THE TFE-731-2 ENGINE[a]

	CO	THC	[b]NO_x	Smoke
1979 EPA standards	9.4	1.6	3.7	36
TFE-731-2 Production combustor	17.5	6.6	5.0	40
(a) Modified production combustor[c]	10.6	0.4	4.1	--
(b) Pilot-airblast combustor[c]	10.0	0.4	3.9	--
(c) Premixed staged combustor[c]	10.9	1.0	2.6	--

[a]From ref. 12.
[b]Extrapolated to engine pressures.
[c]Data from combustion rig test.

TABLE VII. - SUMMARY OF EMISSIONS OF THE ADVANCED TECHNOLOGY COMBUSTORS FOR THE 501-D22A ENGINE[a]

	CO	THC	NO_x	Smoke
1979 EPA standards	26.8	4.9	12.9	22
501-D22A Production combustor	31.5	15.0	6.2	59
(a) Reverse flow-dome combustor[b]	4.6	0.3	7.3	17
(b) Prechamber combustor[b]	2.1	0.4	8.5	1
(c) Staged premixed-combustor[b]	8.4	0.4	8.1	4

[a]From ref. 14.
[b]Data from combustion rig tests.

TABLE VIII. - ADVANCED COMBUSTOR RESULTS FROM EXPERIMENTAL ENGINE TESTS

COMPARED TO THE PROPOSED EPA STANDARDS

	CO		THC		NO_x		Smoke	
	EPA[a] standard	Advanced combustor	EPA[a] standard	Advanced combustor	EPA[a] standard	Advanced combustor	EPA standard	Advanced combustor
JT9D-7 engine Vorbix combustor	[b]36.1	[b]30.3	6.7	1.9	33	25.5	19	30
CF6-50 engine Double/Annular combustor	36.1	48.7	6.7	2.4	38.7	43.9	19	25

[a]1981 and 1984 NME standards.

[b]EPAP units of grams of pollutant per kilonewton of thrust as per proposed EPA standards.

TABLE IX. - EMISSIONS OF VORBIX AND PRODUCTION

COMBUSTOR FOR JT8D ENGINE (EPA T4 CLASS)[a]

	[b]CO	[b]THC	[b]NO_x	Smoke[c]
1981 Standard	49.8	9.8	----	25.5
1984 Standard	49.8	9.8	33.0	25.5
Production combustor	149	40.4	76.1	28
Modified production combustor	46.9	0.5	68.9	28
Vorbix combustor	82.9	1.7	40.6	27

[a]Data from combustor rig test.
[b]EPAP units of gms pollutant per kilonewton of thrust as per proposed EPA standards.
[c]SAE smoke number.

TABLE X. - EMISSIONS OF PRODUCTION AND REVERSE-FLOW

DOME COMBUSTORS FOR 501-D22A ENGINE[a]

	CO	THC	NO_x	Smoke
1984 NCE standards	0.34	0.045	0.45	28.2
Production combustor	1.608	0.768	0.319	55
Reverse-flow-dome combustor	0.234	0.0148	0.373	17

[a]Data from combustion rig test.

TABLE XI. - POTENTIAL FOR ATTAINMENT OF EPA 1981 AND 1984

NME EMISSION STANDARDS

Engine/Combustor	1981	1984
CF6-50 engine, Double/Annular combustor	CO - Additional development THC - Meets standard Smoke - Additional development	NO_x - Extensive additional development/New technology required
JT9D-7 engine, Vorbix combustor	CO - Meets standard THC - Meets standard Smoke - Additional development	NO_x - Meets standard
JT8D-17 engine, Vorbix combustor	CO - New technology required THC - Meets standard Smoke - Additional development	NO_x - New technology required
JT8D-17 engine, Modified production combustor	CO - Additional development THC - Meets standard Smoke - Additional development	NO_x - New technology required

TABLE XII. - ASSUMED FUTURE ENGINE CYCLE

OPERATING CONDITIONS

Operating condition	% F_N	F_N, kN	P_3, atm	T_3, K	f/a	W_{fuel}, kg/sec	SFC, g/sec/kN
Idle	5.5	9.71	3.76	475.5	0.0124	0.118	12.15
Approach	30	52.98	11.67	626.5	0.0138	0.392	7.4
Climb	85	150.19	26.45	779.3	0.0222	1.237	8.23
Takeoff	100	176.61	30.47	812.0	0.0241	1.510	8.55

TABLE XIII. - ESTIMATED EMISSIONS OF ADVANCED TECHNOLOGY COMBUSTORS IN A FUTURE ENGINE

Condition	Emission	Combustor concept	
		Double/Annular	Vorbix
Idle	CO	[a]23.3/13.3	[a]18.0
	THC	1.5	1.1
	NO_x	5.0	2.8
Approach	CO	12.8	9.6
	THC	2.2	0.3
	NO_x	10.2	5.6
Climb	CO	1.8	1.1
	THC	0	0
	NO_x	19.0	15.1
Takeoff	CO	2.0	1.1
	THC	0	0
	NO_x	22.4	17.3
	Smoke	[b]<20	[b]<20

[a]Units are g/kg.
[b]SAE smoke number.

TABLE XIV. - ESTIMATED EMISSIONS PERFORMANCE

OF ADVANCED TECHNOLOGY COMBUSTORS

IN A FUTURE ENGINE

	CO	THC	NO_x	Smoke
EPA 1984 NCE standards	[a]25.0	[a]3.3	[a]33.0	[b]20
Double/Annular concept	[c]33.5/[d]15.5	2.8	36.3	<20
Vorbix concept	25.3	1.3	26.0	<20

[a]Units are g/kN.
[b]SAE smoke number.
[c]Data extrapolated from ref. 10.
[d]Data extrapolated from ref. 7.

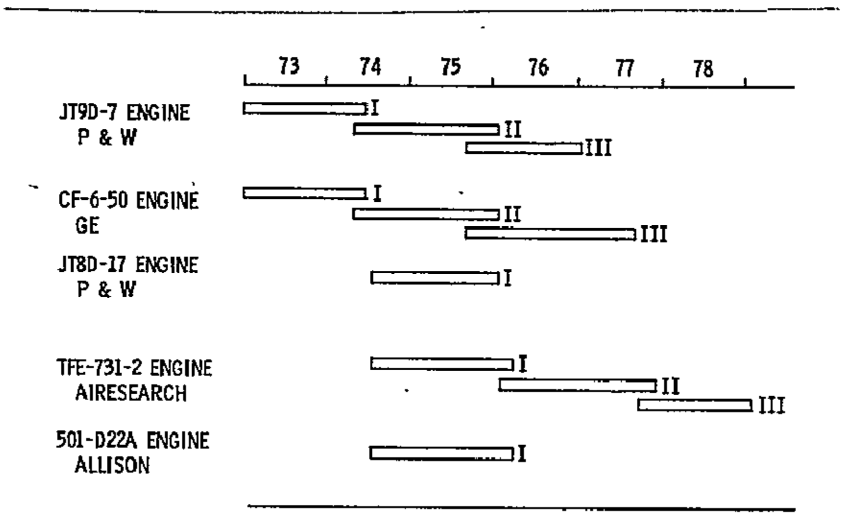

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Figure 1. - Emissions reduction technology program schedule.

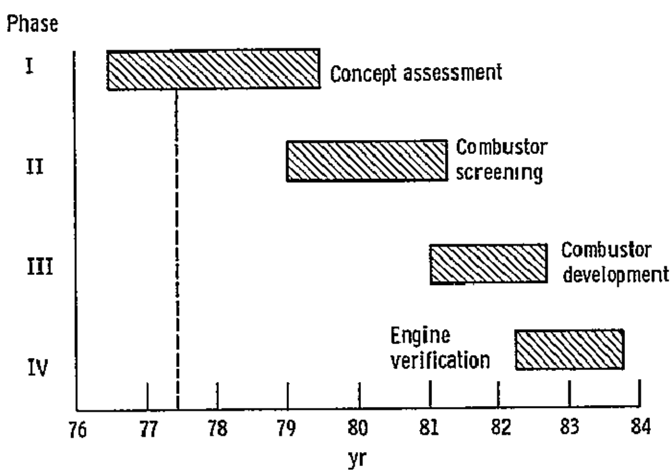


Figure 2. - Premixed/Prevaporized Combustor Technology Program plan.

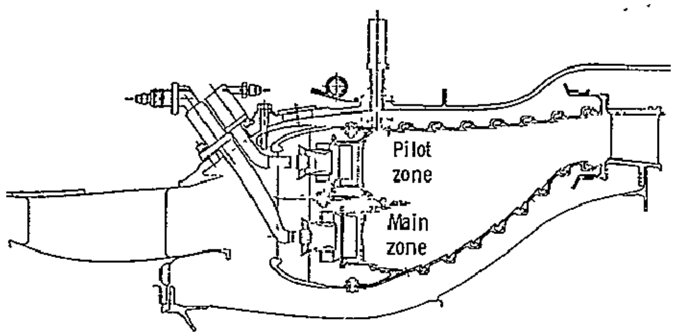


Figure 3. - General Electric Double Annular combustor for the CF6 engine.

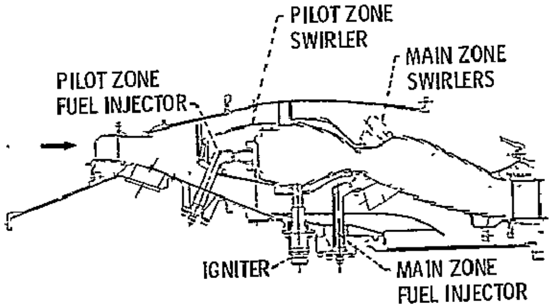
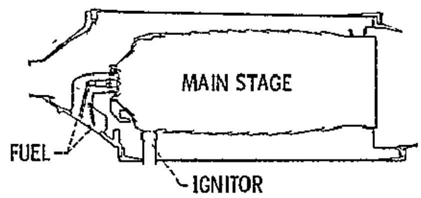
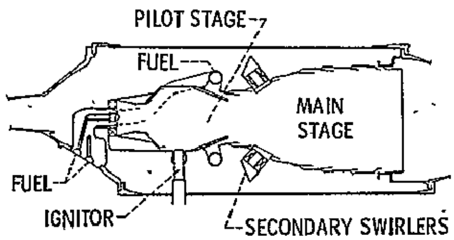


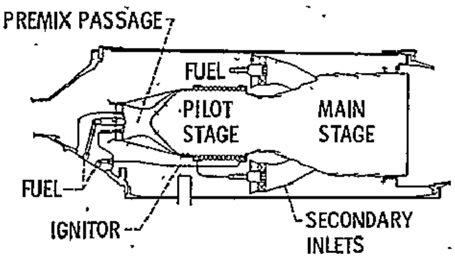
Figure 4. - Pratt and Whitney Vorbix combustor for the JT9D-7 engine.



(a) Baseline combustor.

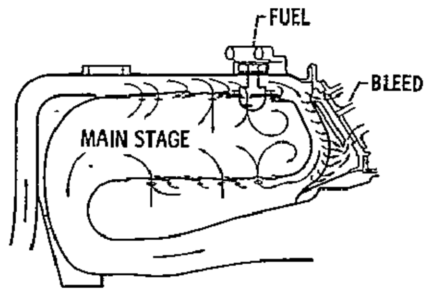


(b) Vorbix combustor.

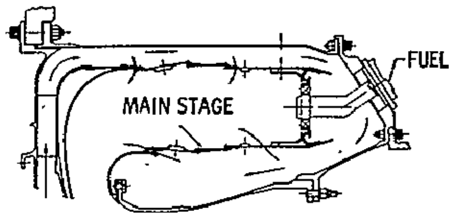


(c) Staged premix combustor.

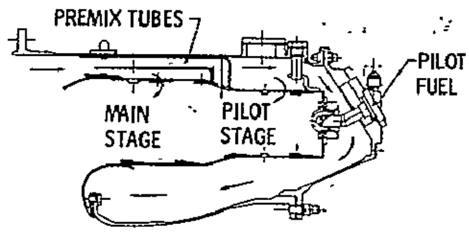
Figure 5. - Pratt and Whitney combustor concepts for the JT8D-17 engine.



(a) Modified production combustor.

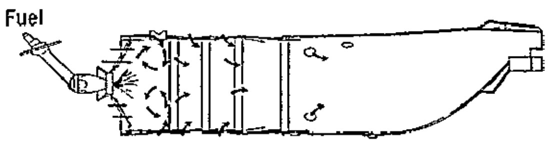


(b) Piloted airblast combustor.

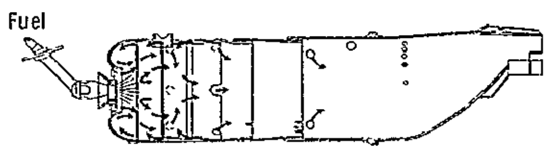


(c) Premix/prevaporization combustor.

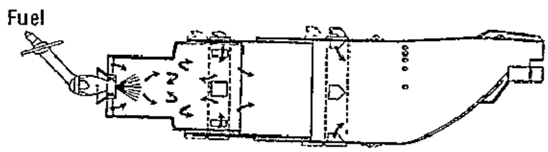
Figure 6. - Garrett AiResearch combustor concepts for the TFE-731-2 engine.



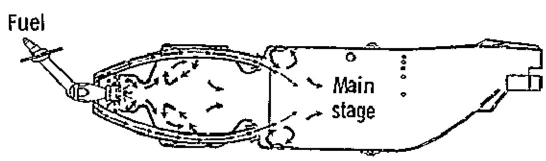
(a) Production combustor.



(b) Reverse-flow dome combustor.



(c) Prechamber combustor.



(d) Staged-premixed combustor.

Figure 7. - Detroit-Diesel-Allison combustor concepts for the 501-D22A engine.

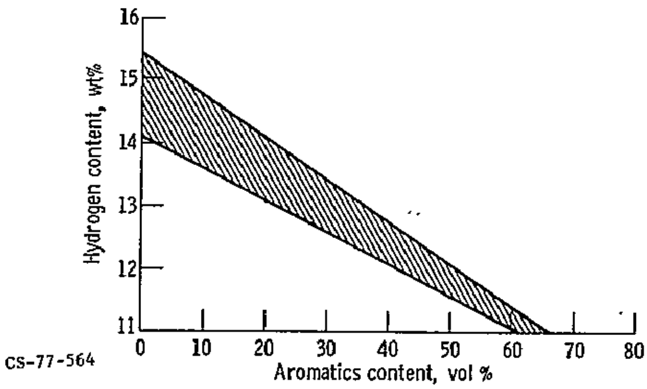


Figure 8. - Variation of hydrogen content with aromatics content.

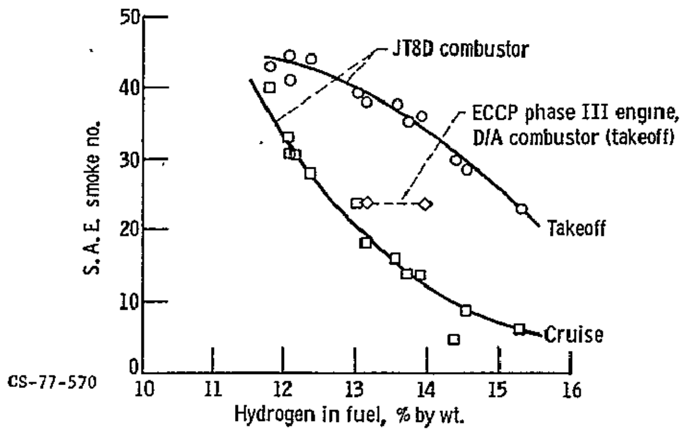


Figure 9. - Effect of hydrogen content of fuel on SAE smoke number.

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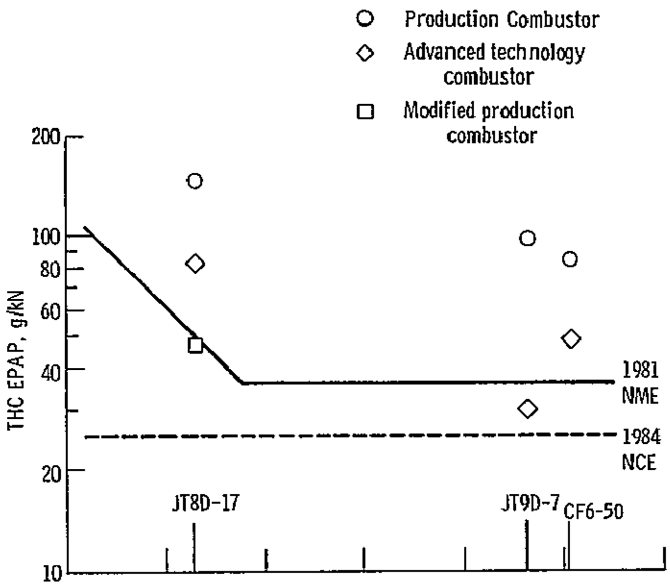
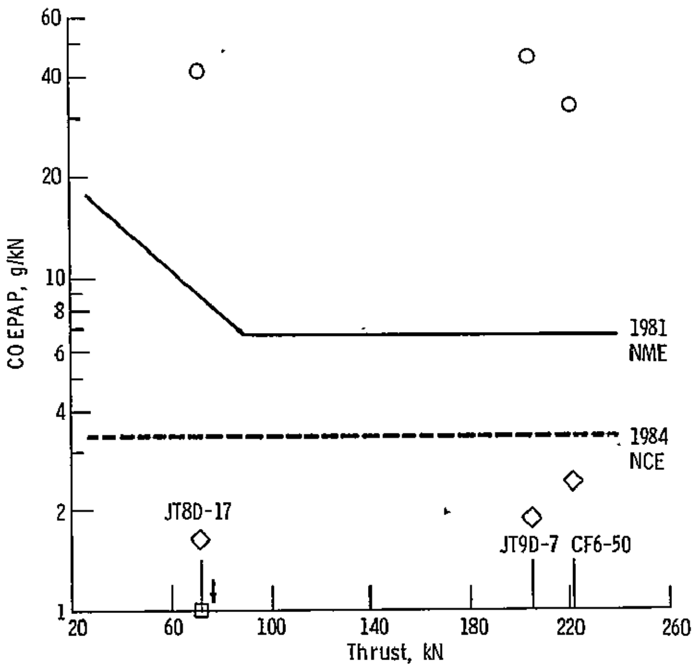
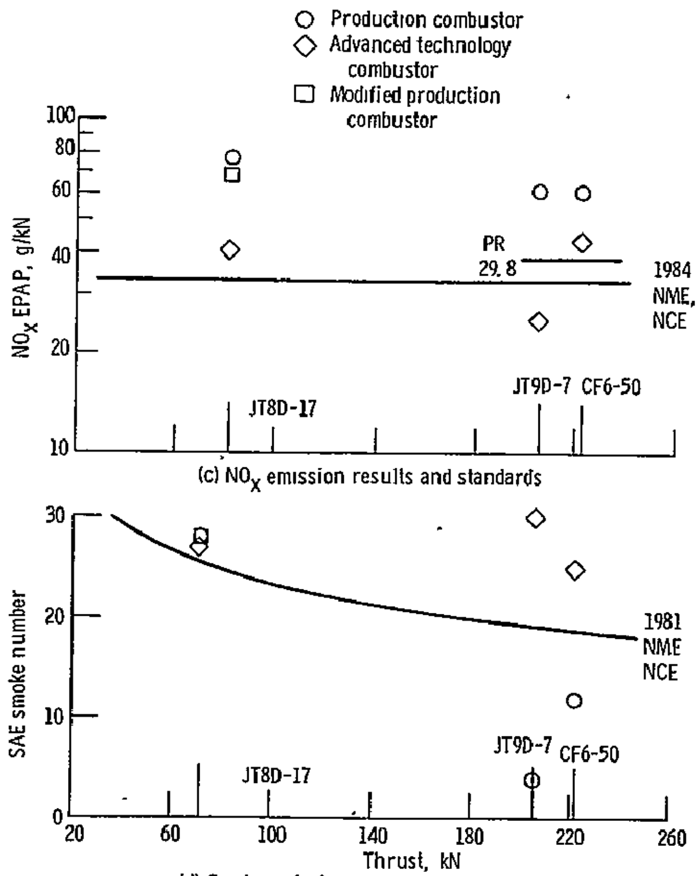


(a) CO emission results and standards.



(b) THC emission results and standards.

Figure 10. - Revised EPA standards for EPA engine classes T1, 2, 3, and 4 and results of emissions tests.



(c) NO_X emission results and standards

(d) Smoke emission results and standards.

Figure 10. - Concluded.

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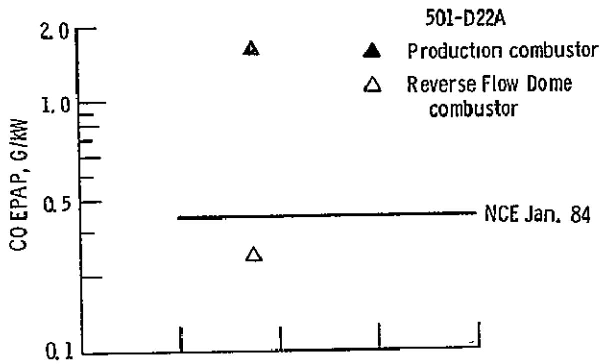
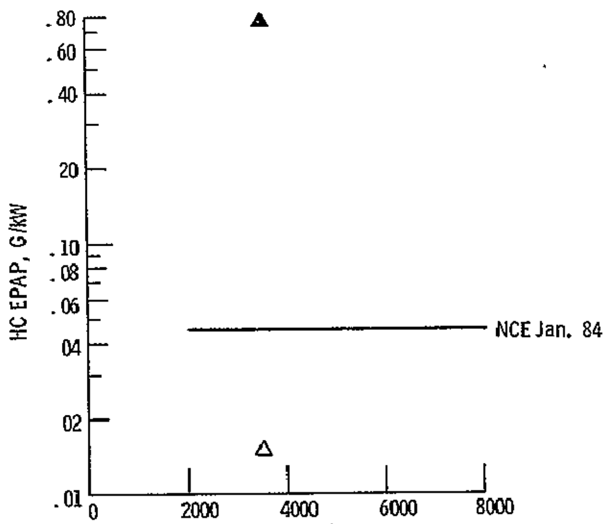
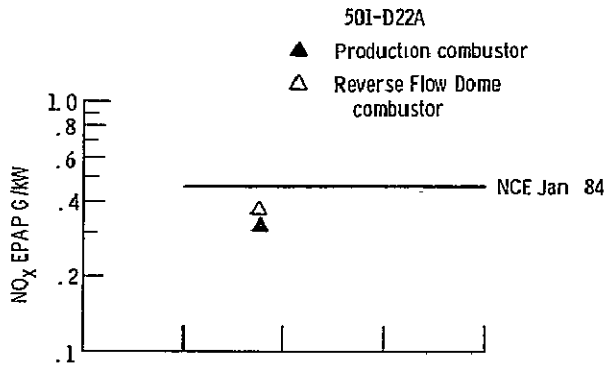


(a) CO emission standards.

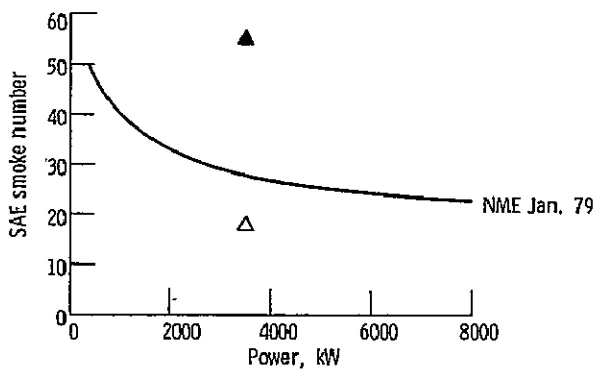


(b) THC emission standards.

Figure 11. - Revised EPA standards for P2 class engines.



(c) NO_x emission standards



(d) Smoke emission standards.

Figure 11. - Concluded.

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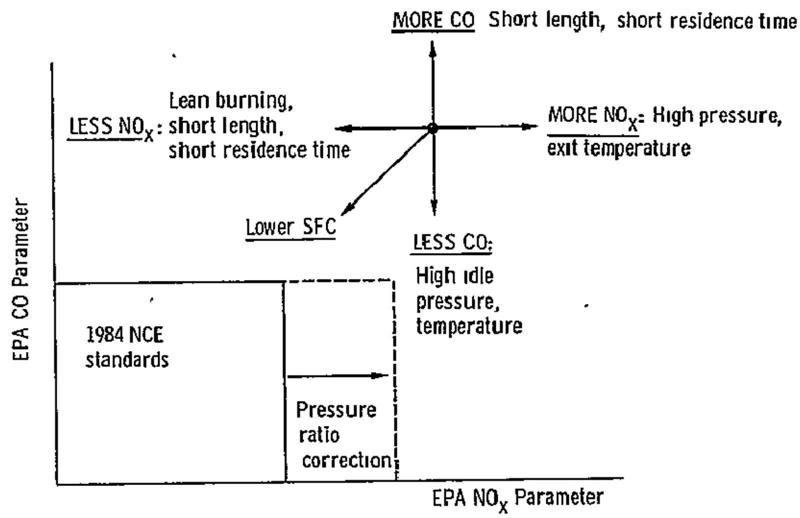

Figure 12. - Emission trends of future aircraft engines

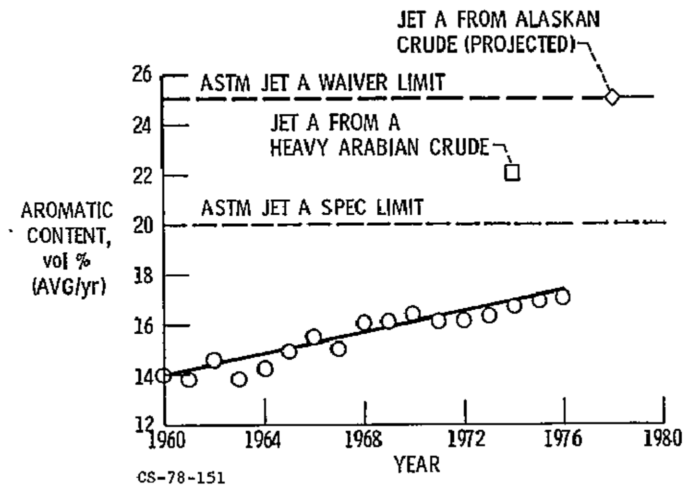

Figure 13. - Trends in aromatic content of commercial jet A fuel.

1. Report No. NASA TM-79009	2. Government Accession No.	3. Recipient's Catalog No
4. Title and Subtitle RESULTS AND STATUS OF THE NASA AIRCRAFT ENGINE EMISSION REDUCTION TECHNOLOGY PROGRAMS		5. Report Date
		6. Performing Organization Code
7. Author(s) R. E. Jones, L. A. Diehl, D. A. Petrash, and J. Grobman		8 Performing Organization Report No E-9793
		10. Work Unit No
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13 Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14 Sponsoring Agency Code

15 Supplementary Notes

16. Abstract

The results and status of the NASA effort in aircraft engine emission reduction research and technology are reviewed in detail. As part of this effort two major NASA sponsored industry programs were conducted, the Experimental Clean Combustor Program and the Pollution Reduction Technology Program. The objective of these programs was to evaluate the capability of new combustor concepts to produce significantly lower levels of exhaust emissions than present production combustors. The results of the technology programs are reviewed as to the ability of these new combustor concepts to achieve the 1979 EPA standards. The development status of each combustor concept is discussed relative to its potential for future implementation in aircraft engines. Also the ability of these combustor concepts to achieve newly proposed NME and NCE EPA standards is discussed. In addition to these NASA sponsored industry programs, other related NASA Lewis activities are also reviewed. These activities include the Premixed/ Prevaporized Combustor Technology Program, advanced CTOL combustor technology and a Fuels Technology Program.

17. Key Words (Suggested by Author(s)) Emissions Combustion Gas turbine engines		18 Distribution Statement Unclassified - unlimited STAR Category 07	
19 Security Classif. (of this report) Unclassified	20 Security Classif. (of this page) Unclassified	21. No. of Pages	22 Price*

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