VII. POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR SMALL JET AIRCRAFT ENGINES - CLASS T1

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For the past decade, public concern over the deterioration in environmental quality has been steadily increasing. As a result of this concern, the United States Congress specifically addressed the mounting dangers to the atmosphere through the Clean Air Act Amendments of 1970. In compliance with this legislation, the Environmental Protection Agency (EPA), on July 17, 1973, issued standards for aircraft engines (ref. 1) that required major reductions in emissions of total unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and smoke. Furthermore, the EPA established a landing/takeoff (LTO) cycle, representative of adverse airport traffic conditions, over which pollutant emissions were to be integrated for various engine categories. It was recognized by the aviation industry and the National Aeronautics and Space Administration (NASA) that successful attainment of the standards would require significant advances in combustion technology. As a result, NASA implemented various Experimental Clean Combustor Programs and Pollution Reduction Technology Programs for the various engine categories. This paper presents the results, to date, for one of these programs, the Pollution Reduction Technology Program for small jet aircraft engines, which includes all jet engines of class T1 (35.6-kN thrust and less).

PROGRAM OBJECTIVES

The Pollution Reduction Technology Program for small jet aircraft engines (EPA class T1, turbojet and turbofan engines of less than 35.6-kN thrust) is a multiyear effort begun in 1974 and scheduled for completion by late 1978. The overall program objectives are

(1) To identify technology capable of attaining the emissions reduction goals consistent with performance constraints

(2) To screen and develop configurations employing these technological advances through full-scale rig testing

(3) To demonstrate the most promising approaches in full-scale engine testing

The AiResearch model TFE731-2 turbofan engine combustion system was selected for the T1 class development effort. It is expected that the technological advances derived from this program will be applicable to other engines within the T1 class and possibly to engines in other classes as well. The results of this program may also suggest additional designs or techniques that might merit further evaluation for other specific engine applications or under other research programs.

PROGRAM EMISSIONS GOALS

The emissions goals for this program are consistent with the EPA class T1 gas turbine engine requirements currently specified by the EPA for new aircraft gas turbine engines manufactured after January 1, 1979. The goals for the individual emission constituents and average levels measured on production engines are listed in table VII-1 in terms of the EPA parameter (EPAP). The goals listed in table VII-1 are based on the simulated LTO cycle shown in table VII-2. These goals are to be sought at no sacrifice to existing TFE731-2 engine combustion system performance. The operating conditions of the TFE731-2 combustion system are listed in table VII-3.

Emission indices, expressed as grams of pollutant per kilogram of fuel burned, that approximately correspond to the EPA gaseous emissions standards at specific operating conditions are listed in table VII-4. These are calculated levels that, at specific operating conditions, will allow the EPAP values for given pollutants to meet the individual pollutant LTO cycle goals if the emission indices of the pollutants at other operating points do not increase.

To compare test rig data for NO_x with the EPAP NO_x goal for the engine, the test rig goal must be adjusted to account for the fact that the maximum pressure capability of the rig is 414 kPa (60 psia), compared with an engine value of 1424 kPa (207 psia) at takeoff. Therefore, the NO_x goal for the test rig is adjusted according to the following expression:

$$EI_{NO_x,\,engine} = EI_{NO_x,\,rig}\left(\frac{P_{T3,\,engine}}{P_{T3,\,rig}}\right)^n$$

where

P_{T3} combustor inlet pressure

EI emission index

n pressure correction exponent

Limited engine-to-rig correlation data obtained on the production TFE731-2 combustion system, which operates with a near-stoichiometric primary zone, indicate that the value of n is 0.35. However, for systems that operate with leaner primary zones, such as the systems evaluated in this program, data derived from other programs indicate that the value of n may be as high as 0.5. To derive a rig NO_x goal that, when extrapolated, accurately represents what would be obtained in an engine, the value of n in this paper has been chosen to be a range between 0.35 and 0.5. Using this range of pressure correction exponents yields a test rig NO_x goal of 5.5 to 6.6 g/kg fuel, which would correspond to an engine goal of 10.0 g/kg fuel.

PROGRAM PLAN

The Pollution Reduction Technology Program for small jet aircraft engines is a three-phase effort with each phase independently funded. The three phases are

(1) Phase I - Combustion rig screening tests of low-emission concepts
(2) Phase II - Combustion rig refinement and optimization tests
(3) Phase III - Engine testing of selected combustor concept or concepts

Phase I

The 19-month phase I effort involved the design, rig testing, and data analysis of a number of candidate approaches for reducing HC, CO, NO_x, and smoke emissions. The objective of this phase was to identify and develop emissions control technology concepts.

Phase II

During phase II the two most promising combustor configurations identified in phase I are undergoing extensive refinement testing on the test rig to develop systems that optimize emissions reductions consistent with acceptable combustion system performance required in an engine application. Therefore, the testing involved in phase II entails development in the areas of off-design-point operation, lean stability and altitude relight capability, exit temperature profile, and pattern factor. In addition to the rig tests, a provision has been made in phase II to conduct limited engine tests using test rig adaptive hardware in order to correlate the emissions levels measured on the engine and on the test rig. These tests will be confined to brief correlation checks, and no refinement or development work scheduled for phase III will be conducted in phase II.

Phase III

The most promising combustion system developed and refined during phase II will be assembled on a TFE731-2 engine and will undergo a series of tests to verify the actual performance and emissions characteristics in an engine at essentially sea-level-static test conditions.

PROGRAM SCHEDULE

The schedule for the Pollution Reduction Technology Program for small jet aircraft engines is shown in figure VII-1. Phase I was a 19-month technical effort that has been completed. Phase II, which was awarded in June 1976, is a 14-month program. Phase III is anticipated to be a 15-month effort with a completion date prior to 1979.

Phase I

The rig testing was divided into two segments. The first segment, designated as combustor screening tests, was of 9 months duration and involved the testing of six configurations each of the three concepts. The majority of these tests were run only at the takeoff and taxi-idle power points, with parametric evaluation limited to determining the optimum emissions reduction potential of a configuration. The second segment of testing, refinement tests, was of 2 months duration and involved a more-detailed evaluation of two configurations each of the two most promising concepts. Most of these configurations were tested over the four LTO-cycle power settings, and limited ignition and stability tests were run.

The testing was conducted in a full-scale annular test rig designed to simulate the aerodynamic envelope and operation of the TFE731-2 combustion system. The combustor pressure, temperature, and velocity conditions were identical with those of the engine with the exception of combustor inlet pressure at the climbout and takeoff conditions. At the takeoff condition the actual engine combustor inlet pressure is 1424 kPa (207 psia); the corresponding rig pressure is limited by the laboratory facility to 414 kPa (60 psia).

Three combustor concepts underwent screening tests and represent increased potential for emissions reduction commensurate with increased developmental risk and complexity:

(1) Concept 1 - Advanced modifications to the existing TFE731-2 combustion system
(2) Concept 2 - Airblast fuel injection system
(3) Concept 3 - Premixing-prevaporizing combustion system

Concept 1. - This conceptual approach to the reduction of emissions, shown in figure VII-2, was based on advanced modifications to the production TFE731-2 combustion system. The production system consisted of a reverse-flow annular combustor with a manifold of 12 dual-orifice pressure atomizers inserted radially through the combustor liner outer wall. A basic combustion system and five modifications were evaluated. Table VII-5 lists the techniques used in each build, and figure VII-3 summarizes the emissions results for each test configuration.

In concept 1, it was demonstrated that HC and CO values could be reduced to below the program goals with the use of air assist and compressor bleed. With water-methanol injection (70/30 mixture by volume) at the takeoff condition, NO_x levels were also reduced below the program goals. Smoke levels were reduced from the production baseline but remained above the program goals.

Air assist and compressor bleed were evaluated at the taxi-idle condition (separately and in combination) as a means of controlling HC and CO. In the air-assist mode, air at pressures above compressor discharge pressure was injected through the secondary fuel circuit of the dual-orifice fuel injectors, while all of the fuel was introduced through the primary circuit. The purpose of the air assist was to improve fuel atomization, thereby increasing combustion efficiency. A range of air-assist pressures was evaluated, and the effect of this technique on HC and CO formation is shown in figures VII-4 and VII-5. In the bleed mode, a portion of the combustor inlet air was bled from the system through a baffle located at the dome of the combustor. In order to maintain the required taxi-idle power, it was necessary to increase the fuel flow, which in turn resulted in improved atomization and a richer reaction zone. A series of bleed-flow rates up to 23 percent of the combustor inlet airflow were evaluated. The results are shown in figures VII-6 and VII-7. Combinations of air assist and bleed were also evaluated, and these results are also shown in figures VII-6 and VII-7.

The configuration that was most compatible with the production combustion system utilized a compressor bleed of 11.5 percent and an air-assist flow rate of 0.36 kg/min at 544-kPa nozzle differential air pressure. This resulted in HC and CO levels of 0.6 and 30.0 g/kg, respectively. However, the air-assist levels needed for these reductions would require an external pressure augmentation device, which would add to the hardware complexity of the engine.

Tubes were used to inject a water-methanol solution in the combustor primary zone at the simulated takeoff thrust setting as a means of reducing NO_x. A series of increasing water-methanol flow rates were evaluated with the results shown in figure VII-8. From figure VII-8, it can be calculated that a water-methanol flow rate of 663 kg/hr is required to meet the 1979 EPA emissions standards. While this approach did produce low NO_x levels, the logistic and aircraft weight penalties associated with this technique make it an impractical solution from an applications standpoint.

Concept 2. - Concept 2 represents the application of technology that is a moderate departure from the production TFE731-2 combustion system. The developmental risk and the potential for emissions reductions are considered to be between those for concept 1 and concept 3. The concept 2 combustion system, shown in figure VII-9, is based on the use of 20 air-assisted, airblast fuel nozzles inserted axially through the combustor dome. The airblast feature of the fuel nozzle operates during all conditions, while the air-assist feature is intended for use only at low-power conditions (although in phase I it was needed at higher power conditions to prevent nozzle passage plugging). As shown in figure VII-10, the fuel nozzle swirlers are replaced at low-power conditions by grommets, thus simulating two-position variable-geometry airflow swirlers. The purpose of this design is to minimize HC and CO formation at the taxi-idle condition by maintaining a stoichiometric primary-zone fuel-air ratio and then allowing full airflow through the swirlers at takeoff to produce the lean primary zone necessary for low NO_x formation. However, to assess the ultimate need for a variable-geometry airflow system, both the taxi-idle and takeoff conditions were evaluated with full-flow swirlers and grommets.

During phase I, eight configurations (six screening tests and two refinement tests) of concept 2 were evaluated. Table VII-6 lists the details of each modification, and figure VII-11 presents a summary of the emissions results for each test.

The second refinement test configuration of concept 2 produced the best overall emissions performance for that concept. At taxi-idle with reduced airflow swirlers, emission index values of 1.6 and 32.1 g/kg fuel were measured for HC and CO, respectively. At takeoff, with full-flow swirler airflow, NO_x was measured to be 6.5 g/kg fuel.

The LTO-cycle EPAP values were calculated for refinement test 2 by the following method. The HC and CO emission indices were corrected for pressure at the climbout and takeoff power settings. NO_x values were corrected to standard-day humidity conditions, and the climbout and takeoff NO_x

levels used a 0.5 pressure exponent to correct measured rig values to engine conditions. The 0.5 pressure correction exponent would yield the upper limit of expected NO_x EI values used in the EPAP calculation. If the pressure correction exponent is less than 0.5, as AiResearch production TFE731-2 engine combustion system data have indicated, the NO_x EPAP value is slightly lower. Therefore, the use of the 0.5 pressure correction exponent for NO_x provides a conservative computation of the EPAP value.

EPAP values for concept 2, refinement test 2, are compared with the program goals in the following table:

Pollutant	EPAP, lb/1000 lb thrust-hr/cycle	
	Program goal	Concept 2, refinement test 2
HC	0.4	1.6
CO	10.0	9.4
NO_x	3.9	3.7

These LTO values were based on the use of changes in swirler geometry. Test data from all the configurations in phase I of this concept have demonstrated the need to vary the swirler airflow so as to maintain the reaction-zone equivalence ratio for minimum emissions levels of both taxi-idle HC and CO and climbout and takeoff NO_x.

Engine-rig correlation tests performed on production combustion systems consistently produced taxi-idle rig values of CO approximately 1.25 times the measured engine data. In view of the fact that the rig and engine airflow conditions at the taxi-idle condition were identical, and the same combustor system hardware was used for both tests, no plausible explanation could be given for the difference and, therefore, the correction term was not applied. However, the difference was consistent for three engine-to-rig correlation tests. If the correction term had been applied to the taxi-idle CO term in the LTO calculation, the CO EPAP value would be below the required goal at 8.3 g/kg fuel.

The test results from concept 2, with simulated variable-geometry airflow swirlers, indicate that significant reductions were achieved in all pollutants over the baseline production combustion system emissions. However, it appears from data contained in figure VII-12 that meeting the program goals for taxi-idle CO and takeoff NO_x simultaneously with a given combustor configuration, even with variable-geometry airflow swirlers may require further advances in technology. Figure VII-11 presents a curve of taxi-idle CO versus takeoff NO_x for each concept 2 test configuration. Although there is some data scatter, a curve can be drawn that represents a trade-off line between CO and NO_x. Concept 2 has made improvements in lowering these emissions levels from the production combustor data point listed. However, to meet the goals, the trade-off line must fall within the dashed-line box representing the CO taxi-idle goal and NO_x takeoff goal. It is encouraging that the final concept 2 test in phase I, refinement test 2, produced a data point that was very close to meeting the goals.

Concept 3. - Concept 3, a staged premixing-prevaporizing combustion system, offers the greatest potential for overall emissions reduction of the three concepts tested. The technology involved in this concept represents a considerable advance from present-day combustion state of the art and likewise involves the greatest developmental risk of the three concepts. The predominant difficulties of a staged premixing-prevaporizing combustion system center around two areas: (1) the danger of spontaneous ignition and/or flashback, and (2) the developmental complexity involved in fuel and air scheduling for a staged system.

All premixing-prevaporizing combustion systems have an inherent danger because of the presence of a combustible mixture of fuel and air ahead of the intended combustion location. Certain combinations of pressure, temperature, and residence time in the premixing-prevaporizing section can result in spontaneous ignition of the fuel and air mixture. In addition, if the velocity of the fuel and air mixture is less than the flame speed in the mixture, flashback can occur.

In the concept 3 staged-combustion-system design at the taxi-idle condition, the system operates only on the pilot zone with a nearly stoichiometric fuel-air ratio to minimize HC and CO emissions. The main combustion zone is phased in at operation above taxi-idle and is designed to operate at a low equivalence ratio at high-power conditions in order to minimize NO_x emissions. A staged system, because of the presence of rich and lean zones, has the tendency at certain conditions to produce pollutants that are not characteristic of that condition, that is, high CO at takeoff and high NO_x at approach. To offset these emissions in the LTO cycle requires further reductions at the other LTO-cycle points. There is a high degree of developmental complexity involved in obtaining a system that optimizes fuel and air metering to the two stages with regard to performance, emissions, reliability, and safety. This translates into added hardware complexity and cost.

The concept 3 design shown in figure VII-13 employed axially staged fuel injection with a pilot zone located at the dome end of the combustor and a main combustion region immediately downstream of the pilot zone. The pilot zone had 20 fuel nozzles inserted through the combustor dome. For most of the configurations tested, these fuel nozzles were of the simplex pressure-atomizing type. However, air-assisted airblast injectors were evaluated in the second refinement test. The pilot zone was continuously operated at all power settings, and the development of this region centered around producing minimum HC and CO at taxi-idle, as well as acting as an efficient ignition source for the main combustion zone at the higher power settings without producing excessive NO_x.

The main combustion zone was adjacent to and downstream of the pilot. Fuel was staged into this zone only at operating modes above the simulated taxi-idle power setting. In the staging operation, fuel was injected into a mixing region upstream of the combustor by simplex atomizing nozzles. This fuel was premixed with air and the mixture was injected into the main burning zone. This mixture was then ignited by the hot gases exiting the pilot zone. An extensive portion of the development testing of this configuration was used in optimizing the fuel-air ratios of the main combustion zone mixture and the fuel flow split between this region and the pilot zone. Ideally, in a premixing configuration, most of the fuel is introduced into the main combustion zone. This fuel is premixed with a sufficient amount of air to produce a very lean reaction zone, thereby minimizing the NO_x formation. The fuel flow to the pilot region is maintained as low as possible to minimize the NO_x formation in the pilot, but high enough to produce a hot gas ignition source for the main combustion zone that will result in acceptable HC and CO levels. Several parameters were evaluated to ensure thorough mixing of the fuel and air and to prevent flashback or autoignition of the mixture. These parameters include fuel injection length; premixing residence time; premixing fuel-air ratio; and velocity in the premixing tubes.

The first four combustion system configurations tested, as shown in figure VII-14, utilized 40 tubes external to the combustor plenum as premixing chambers. The tubes, connected to an air supply separate from but providing air at the same temperature as the main combustor inlet air, allowed the examination of the effects of fuel-air ratio and premixing velocity on emission formation. Premixing velocity was evaluated with the use of premixing tube sets that had a different inside diameter, making it possible to vary pilot-to-main zone splits and tube velocity independently. Each tube had five fuel injection points spaced at 7.6-cm intervals along its length to determine the optimum premixing length for minimum emissions levels. Initially, gaseous propane was used as the premixing fuel to eliminate vaporization of the fuel as a variable. Later tests used liquid Jet A fuel.

Based on test results attained with the external premixing system, an internal system was designed that was compatible with the existing engine envelope. An annular passage next to the plenum wall was utilized as the premixing region. This annulus was connected to 40 combustor chutes that injected the fuel-air mixture into the main combustion zone. Two fuel injection points (premixing lengths) were evaluated.

In phase I, eight configurations of concept 3, outlined in table VII-7, were evaluated in the test rig. Figure VII-15 presents the results of each individual test.

The first four test configurations of concept 3, with external premixing-prevaporizing tubes, were intended to establish the emissions reduction potential of the premixing-prevaporizing system. The initial tests utilized gaseous propane as the fuel for the premixing-prevaporizing stage. The flame temperature of propane is similar to that of vaporized Jet A fuel, and NO_x data obtained with gaseous propane were expected to indicate the maximum NO_x reduction potential of fully vaporized Jet A fuel. The external configurations were evaluated over an extensive matrix of test points using both propane and Jet A fuel in the premixing-prevaporizing system. Data was taken at taxi-idle, simulated approach, and simulated takeoff power settings that evaluated the effects of the following variables on emission formation and combustion characteristics:

(1) Premixing to pilot-zone air and fuel flow splits
(2) Premixing length
(3) Pilot nozzle flow number
(4) Comparison of NO_x levels with liquid fuel and propane as premixing fuels

The best overall emissions reductions for concept 3 in an external premixing-prevaporizing configuration were obtained in modification 3, using 0.90-flow-number pilot pressure atomizers, Jet A fuel, and a 20.3-cm premixing injection length. At taxi-idle, the configuration had HC and CO levels of 2.1 and 0.7 g/kg fuel, respectively, with a premixing airflow rate of 24 percent of the total. The HC value was well below the program goal, and the CO level was only slightly above the goal of 30.0 g/kg fuel. At the simulated takeoff point with the pilot fuel flow equal to 30 percent of the total and the premixing-prevaporizing airflow equal to 24 percent of the total, the measured NO_x level was 3.4 g/kg fuel. The measured smoke number was zero, and the combustion efficiency at this point was calculated from emissions to be 99.94 percent. Other takeoff combustor performance parameters such as pattern factor (0.15) and pressure loss (4.4 percent) were within engine requirements.

LTO cycle points calculated from the test data are shown in the following table:

Pollutant	EPAP, lb/1000 lb thrust-hr/cycle	
	Program goal	Concept 3, modification 3
HC	1.6	0.6
CO	9.4	8.8
NO_x	3.7	2.7

These factors were calculated from rig data with all NO_x emission indices corrected to standard humidity and the climbout and takeoff NO_x indices corrected for pressure differences between rig and engine test points. A pressure exponent of 0.5 was used. The HC and CO indices were corrected as an inverse of the engine to rig pressure levels at climbout and takeoff.

Following the test of the modification 3 external premixing configuration, which demonstrated the potential of the premixing-prevaporizing concept to provide substantial reductions in emissions, the remainder of the phase I testing for concept 3 centered around implementing an internal premixing system. As can be seen in figure VII-13, the internal premixing-prevaporizing system consisted of an annulus surrounding the outer wall of the combustor and extending from the diffuser deswirl vanes to the axial midpoint of the burner. At this point, the premixing-prevaporizing annulus was divided into 40 chutes that ducted the fuel-air mixture into the combustor. The combustor remained unchanged from the modification 3 configuration. To maximize the premixing length, the premixing-prevaporizing annulus was extended to the diffuser discharge, thereby necessitating the removal of the outer portion of the deswirl vanes. The swirl angle in the premixing-prevaporizing annulus remained at essentially the compressor exit swirl angle of 55°, as compared with 35° downstream of the deswirl vanes in the inner airflow passage. The inner and outer walls of the premixing-prevaporizing annulus were connected by five equally spaced ribs, each in the form of a 55° helix alined in the direction of the swirl angle. Premixing fuel was introduced through 40 equally spaced pressure-atomizing fuel nozzles. Two axial premixing lengths were investigated - 7.6 and 20.3 cm. Both 0.68- and 0.90-flow-number pressure-atomizing nozzles were evaluated as pilot nozzles.

The system was tested at all four LTO-cycle points. At the taxi-idle condition, tests were made both with and without simulated compressor bleed. At the higher power settings, parametric tests were run to evaluate the effect of fuel-flow splits on emissions. Prior to combustion testing, tests were performed on the internal premixing-prevaporizing system to determine the airflow distribution, as compared with the external premixing-prevaporizing system of the previous configuration. The test data indicated that the premixing-prevaporizing airflow rate had been reduced 21 percent (from 24 to 19 percent of the total airflow) from modification 3. Additionally, the premixing-prevaporizing system exhibited nonuniform air distribution within the annulus. The hardware was reworked to reduce the nonuniformity through improved control of the tolerances; but the flow variations were still significant, and the airflow rate through the premixing-prevaporizing tubes was unaffected.

Because of the low airflow and circumferential nonuniformities in the premixing annulus, the emissions reduction potential established with the modification 3 external tube configuration could not be attained with any of the internal annulus configurations tested. The refinement test 2 configuration produced the best overall emissions reductions of any of the internal premixing configurations tested. The HC and CO indices for this configuration were 3.2 and 25.7 g/kg fuel, respectively, which were obtained with 5-percent compressor bleed and 195.6-kPa differential air-assist pressure. The simulated-takeoff NO_x emission index measured was 3.5 g/kg fuel. The LTO EPAP values from this test are shown in the following table. The data for the climbout point were approximated, since test data were not obtained for this point in this configuration.

Pollutant	EPAP, lb/1000 lb thrust-hr/cycle	
	Program goal	Concept 3, refinement test 2
HC	1.6	1.0
CO	9.4	10.9
NO_x	3.7	2.6

These data show that, while this configuration meets the HC and NO_x program goals, the CO value is high. This was caused by abnormally high levels of CO being produced at the takeoff condition as a result of an improper airflow split between the pilot and main combustion region.

Summary of Phase I Program Results

Concept 1, incorporating advanced modifications to the production TFE731-2 combustion system, demonstrated approaches that produced significant reductions in taxi-idle emissions levels below the TFE731-2 production baseline values. The most promising of the concept 1 configurations tested employed compressor bleed and air-assisted fuel atomization. A combination of these techniques produced emission indices of 0.6 and 30.0 g/kg fuel for HC and CO, respectively. The air-assist feature requires an external source of high-pressure air, which could be supplied in an engine application only through added hardware. At takeoff, the only concept 1 configuration that met the NO_x goal utilized water-methanol injection into the combustor primary zone. An NO_x value of 5.5 g/kg fuel was attained with a ratio of water-methanol to fuel injection rate of 0.88.

Concept 2, which incorporated 20 air-assisted airblast fuel injectors inserted axially through the combustor dome, also significantly reduced gaseous emissions below the baseline levels as well as reducing the smoke number. The conept 2 configurations that simultaneously produced the greatest reduction in emissions employed techniques that simulated variable-geometry air swirlers for the purpose of controlling the primary-zone equivalence ratio over the combustor operating envelope. At the taxi-idle conditions, emission index values of 1.6 and 32.1 g/kg fuel were measured for HC and CO, respectively, utilizing 5-percent bleed and 387-kPa differential air-assist pressure at takeoff. NO_x was measured to be 6.5 g/kg fuel and the smoke number was zero.

The concept 3 staged premixing-prevaporizing combustion system demonstrated the greatest overall emissions reductions of the three concepts evaluated in phase I. The potential for emissions reduction of this concept was established with an external premixing-prevaporizing system, which provided the capability to parametrically control critical factors such as premixing fuel-air ratio, premixing velocity, premixing residence time, and premixing fuel injection length. The best overall external premixing configuration had HC and CO levels of 2.1 and 30.7 g/kg fuel, respectively, at taxi-idle. At simulated takoeff, NO_x was 3.4 g/kg fuel with a combustion efficiency of 99.94 percent and a smoke number of zero, as measured on the rig. Configurations of concept 3 with an internal premixing-prevaporizing system did not achieve the emissions reductions established in the best external configuration because of nonuniformities in the premixing annulus and lower-than-design-point airflow in the premixing section. The best overall results obtained for a concept 3 internal premixing configuration had taxi-idle HC and CO values of 3.2 and 25.7 g/kg fuel, respectively, which were obtained with 5-percent compressor bleed and 195.6-kPa differential air-assist pressure. The simulated takeoff NO_x value was 3.5 g/kg fuel.

Concepts 2 and 3 were selected at the conclusion of the phase I screening testing to proceed into refinement testing, and ultimately into phase II. These concepts were judged to embody technology that would offer the best potential of meeting the program goals with practical combustion systems.

The following conclusions can be drawn from the phase I testing:

(1) All three concepts met the taxi-idle HC goal with margin.

(2) All three concepts either met or were very close to the taxi-idle CO goal through the use of air assist and/or compressor bleed.

(3) With regard to the takeoff NO_x goal, (a) water injection provided the only means of concept 1 meeting the goal, (b) concept 2 is marginally close to the goal, and (c) concept 3 met the goal with considerably margin.

(4) From the test data in phase I, it appears unlikely that concept 2 can meet the emissions goals without the use of at least two-position variable-geometry fuel nozzle air swirlers. Even with variable geometry, concept 2 will at best only marginally meet the emissions goals.

(5) Concept 3 offers the greatest demonstrated potential for emissions reductions below the program goals but will require extensive development for a safe and practical system.

Phase II

Based on the test results obtained in phase I, concepts 2 and 3 were selected to undergo further design and refinement testing in phase II. The objective of phase II is to optimize emissions reductions over the complete operating range of the engine, consistent with acceptable performance for ultimate incorporation within an engine. The phase II test program is divided into two rig testing segments. The first segment, designated as combustor refinement testing, is scheduled to be conducted over a 5-month period for both selected concepts. Following this segment, the most promising concept will be chosen to undergo the second segment of testing, designated combustor optimization testing, to be conducted over a 2-month period. Performance parameters, which will be of particular interest during both segments of testing, include combustor exit temperature profiles (pattern factor, radial, and circumferential), durability (wall temperatures), carbon deposition, fuel staging at cut-on and cut-off points between power settings, combustor pressure loss, altitude relight performance, ignition characteristics, and lean stability limits over the operating envelope of the engine. During the rig testing, combustion system operation, which will ultimately interface with engine control systems, will be closely monitored. As the needed control functions become defined in the latter stages of rig testing, final design of a control system for phase III engine testing will begin. This design activity will be completed in phase III.

In addition to the phase II rig testing, provision has been made to conduct a maximum of two engine tests with test rig hardware and adaptive pieces where necessary. The purpose of this is solely to obtain accurate engine-to-rig correlation factors for concepts 2 and 3. Any development work necessary for proper engine operation, and intended for phase III, will not be conducted during these tests. The data obtained will be valuable in determining if engine-to-rig correlation factors vary from concept to concept.

The phase II effort began in June 1976. The design effort on concept 2 centered around incorporating a variable-airflow swirler capability, improving the design of the airblast fuel nozzle, and improving the durability of the combustor in the dome area. The concept 3 design effort focused on improving the design of the premixing passage annulus by specifying closer tolerances and improved fabrication techniques to eliminate the airflow distribution problems encountered in phase I. As of this writing, the initial test segment is underway, but no conclusive data are available at this time.

Phase III

The culmination of this program is expected to begin in the latter half of 1977 with phase III. During this phase, hardware designs that incorporate the technology evolved through phase I screening and phase II refinement will be completed for inclusion of the technology within the TFE731-2 engine. In addition, design activity on the engine control system will be completed. Hardware will be fabricated and assembled in a TFE731-2 engine for a series of engine tests. The purpose of the tests is basically to determine if the emissions reductions obtained through rig testing are actually realized in the engine system. Additionally, the tests will determine if engine operation is affected by the combustion system and establish, on a limited basis, combustor durability in an engine environment.

REFERENCE

1. Environmental Protection Agency. Control of Air Pollution for Aircraft Engines - Emission Standards and Test Procedures for Aircraft. Fed. Regist., vol. 38, no. 136, pt. II, July 17, 1973, pp. 19088-19103.

EMISSION COMPARISON - PROGRAM GOALS VERSUS TFE731-2 ENGINE CHARACTERISTICS

POLLUTANT	PROGRAM GOALS		TFE731-2 ENGINE CHARACTERISTICS*		AVERAGE PERCENT REDUCTION NEEDED TO MEET GOALS
	GASEOUS EMISSIONS, LB/1000 LB THRUST–HR/LTO CYCLE	SMOKE NUMBER	GASEOUS EMISSIONS, LB/1000 LB THRUST–HR/LTO CYCLE	SMOKE NUMBER	
TOTAL UNBURNED HYDROCARBONS (HC)	1.6		6.6		76
CARBON MONOXIDE (CO)	9.4		17.5		46
OXIDES OF NITROGEN (NO_x)	3.7		5.0		26
SMOKE		40		36	

*AVERAGE OF SIX ENGINES MEASURED PRIOR TO START OF PROGRAM (1973).

Table VII-1.

EPA SPECIFIED LANDING TAKEOFF CYCLE FOR CLASS T1 ENGINES

MODE	DURATION OF MODE (MINUTES)	ENGINE POWER SETTING, (PERCENT OF RATED POWER)
TAXI-IDLE (OUT)	19.0	5.7[a]
TAKEOFF	0.5	100
CLIMBOUT	2.5	90
APPROACH	4.5	30
TAXI-IDLE (IN.)	7.0	5.7[a]

[a] RECOMMENDED POWER SETTING OF 0.89 kN THRUST FOR TAXI-IDLE OPERATION OF THE AIRESEARCH TFE731-2 TURBOFAN IN ACCORDANCE WITH APPLICABLE FEDERAL AVIATION ADMINISTRATION REGULATIONS.

Table VII-2.

TFE731-2 COMBUSTION SYSTEM OPERATING PARAMETERS

CONDITION	P_{T_3}, kPa	T_{T_3}, °K	W_a Kg/SEC	W_f Kg/HR
TAXI-IDLE	202	370	2.3	87.4
APPROACH (30% RATED THRUST)	532	505	5.9	241.6
CLIMBOUT (90% RATED THRUST)	1301	666	12.6	668.2
TAKEOFF (100% RATED THRUST)	1424	685	13.6	754.9

P_{T_3} = COMBUSTOR INLET PRESSURE

T_{T_3} = COMBUSTOR INLET TEMPERATURE

W_a = COMBUSTOR INLET AIRFLOW

W_f = FUEL FLOW

Table VII-3.

OPERATING CONDITION EMISSION INDICES GOALS

POLLUTANT	OPERATING CONDITION	EMISSION INDEX, g/kg FUEL
HC	TAXI-IDLE	6
CO	TAXI-IDLE	30
NO_x	TAKEOFF	10

Table VII-4.

CONCEPT 1 TEST CONFIGURATIONS

CONFIGURATION	MODIFICATION
BASIC CONFIGURATION	(a) WATER INJECTION AT TAKEOFF (b) AIR-ASSIST AT TAXI-IDLE (c) COMPRESSOR BLEED AT TAXI-IDLE
MODIFICATION 1	(a) QUADRANT FUEL STAGING
MODIFICATION 2	(a) INCREASED AIRFLOW PASSAGE OF FUEL NOZZLE AIR SWIRLER
MODIFICATION 3	(a) AIRBLAST NOZZLES
MODIFICATION 4	(a) COMBUSTOR ORIFICE CHANGE TO PRODUCE A LEANER PRIMARY ZONE WITH CONTINUED USE OF AIRBLAST NOZZLES
MODIFICATION 5	(a) COMBUSTOR DOME MODIFICATION

Table VII-5.

CONCEPT 2 TEST CONFIGURATIONS

CONFIGURATION	MODIFICATION
BASIC CONFIGURATION	(A) AIR-ASSIST AIRBLAST FUEL NOZZLES.
MODIFICATION 1	(A) PRIMARY ORIFICE CHANGE TO REDUCE PRIMARY FUEL/AIR RATIO AND PRODUCE EARLY QUENCH. (B) INCREASED SWIRLER AREA BY 1.5 FACTOR.
MODIFICATION 2	(A) ADDED PRIMARY ORIFICE ROW FOR NO_x CONTROL.
MODIFICATION 3	(A) RELOCATED PRIMARY ORIFICES DOWNSTREAM FOR CONTROL OF TAXI-IDLE EMISSIONS. (B) REDUCED JET PENETRATION OF OUTER PRIMARY ORIFICES FOR NO_x CONTROL.
MODIFICATION 4	(A) RELOCATED AND INCREASED DIAMETER OF OUTER PRIMARY ORIFICES TO INCREASE JET PENETRATION. (B) LOW AIRFLOW SWIRLERS.
MODIFICATION 5	(A) RELOCATED AND MODIFIED OUTER PRIMARY ORIFICES TO PRODUCE LEANER PRIMARY ZONE.
REFINEMENT 1	(A) RELOCATED INNER AND OUTER PRIMARY ORIFICES TO PRODUCE SAME AIRFLOW AS BASIC CONFIGURATION AND ADDED ROW OF OUTER PRIMARY ORIFICES FOR NO_x CONTROL. (B) LOW AND HIGH AIRFLOW SWIRLERS EVALUATED.
REFINEMENT 2	(A) MODIFIED PRIMARY ORIFICES TO INCREASE AIRFLOW AND OBTAIN A PRIMARY ZONE EQUIVALENCE RATIO OF 0.5 AT TAKEOFF. (B) MODIFIED HIGH AIRFLOW SWIRLERS.

Table VII-6.

CONCEPT 3 TEST CONFIGURATIONS

CONFIGURATION	MODIFICATION
BASIC CONFIGURATION	(A) EXTERNAL PREMIX TUBES.
MODIFICATION 1	(A) PILOT OD PRIMARY ORIFICES INCREASED TO ISOLATE PILOT FROM MAIN COMBUSTION ZONE.
	(B) MAIN COMBUSTION ZONE COOLING AIR DECREASED.
MODIFICATION 2	(A) ADDED COARSE PORE COOLING TO ID INCLINED WALL.
	(B) USED BOTH JET A AND PROPANE PREMIX FUEL.
MODIFICATION 3	(A) ADDED PREMIX CHUTES TO IMPART 45° SWIRL TO FLOW.
	(B) DILUTION ORIFICE LOCATION AND ANGLE CHANGE TO INCREASE MAIN COMBUSTOR RESIDENCE TIME.
	(C) ADDED IMPINGEMENT FILM COOLING BAND TO ID INCLINED WALL.
	(D) ADDED FILM COOLING BAND TO PILOT OD WALL.
MODIFICATION 4	(A) CONVERTED PREMIX TUBES TO INTERNAL ANNULUS.
MODIFICATION 5	(A) PILOT SWIRLER AIRFLOW REDUCED 50 PERCENT.
REFINEMENT 1	(A) PILOT PRIMARY AIR ORIFICES REMOVED.
	(B) PILOT COOLING AIR DECREASED 50 PERCENT.
	(C) USED HALF AREA AND FULL AREA PILOT SWIRLERS.
REFINEMENT 2	(A) AIRBLAST PILOT NOZZLES.

Table VII-7.

PROGRAM SCHEDULE

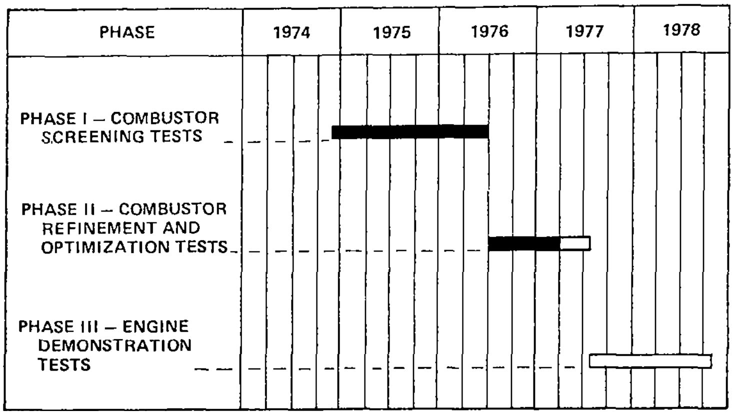


Figure VII-1.

CONCEPT 1 COMBUSTION SYSTEM

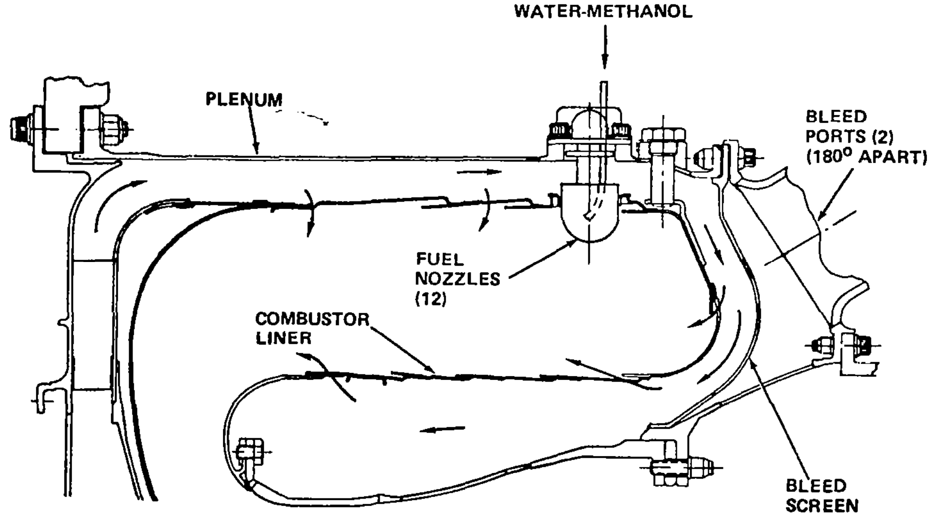


Figure VII-2.

CONCEPT 1 SUMMARY OF EMISSIONS TEST

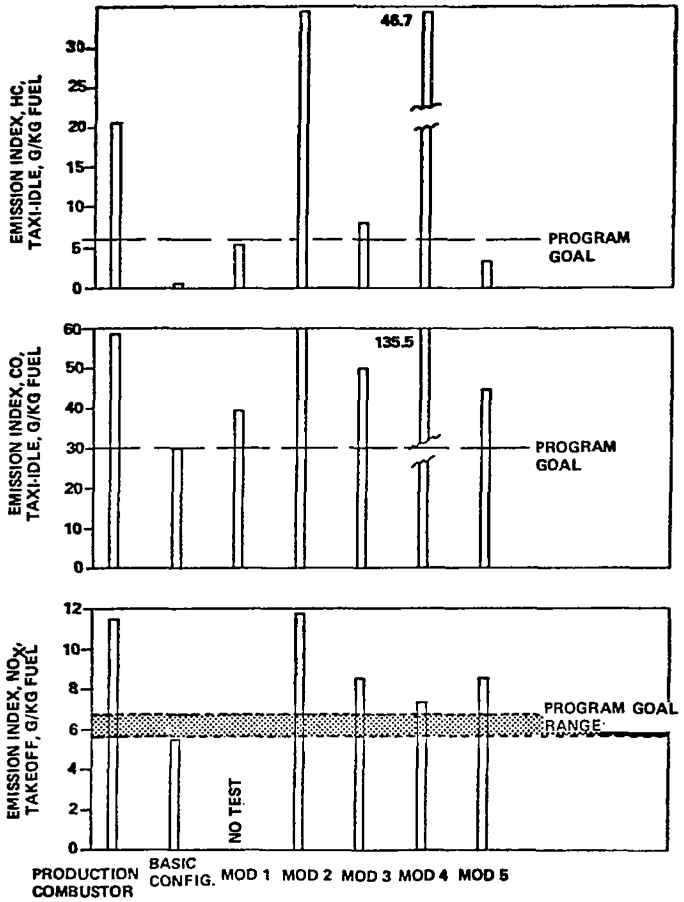


Figure VII-3.

EFFECT OF AIR ASSIST ON HC EMISSIONS, CONCEPT 1

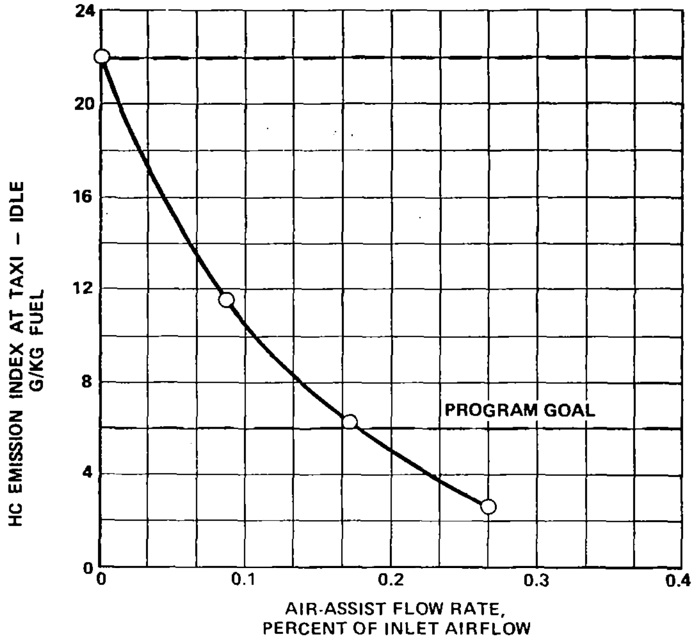


Figure VII-4.

EFFECT OF AIR ASSIST ON CO EMISSIONS, CONCEPT 1

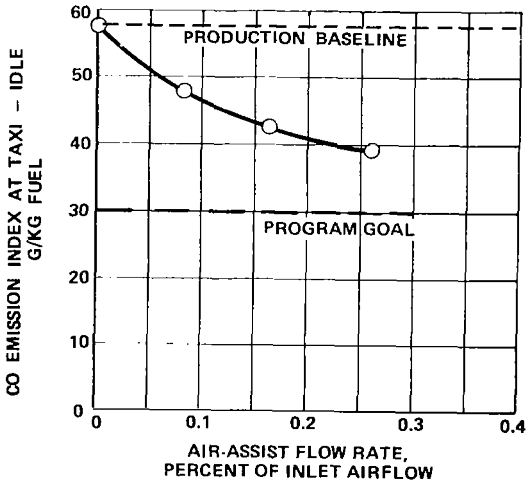
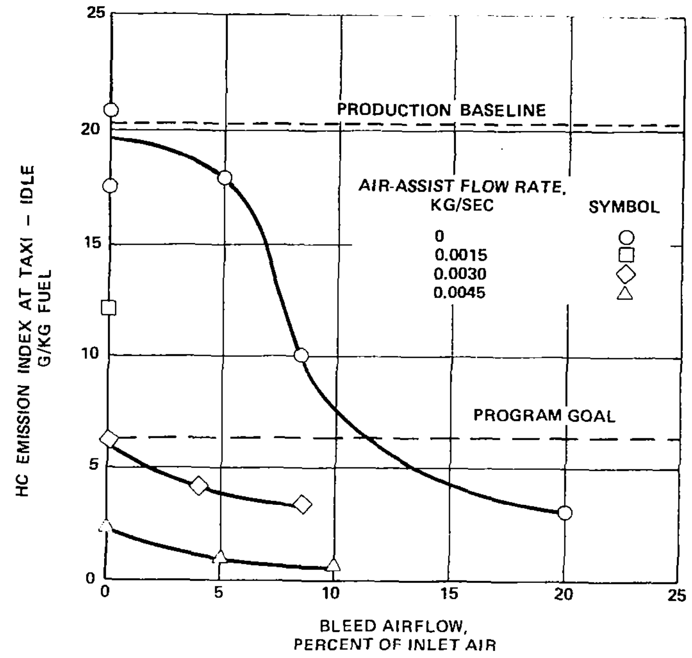
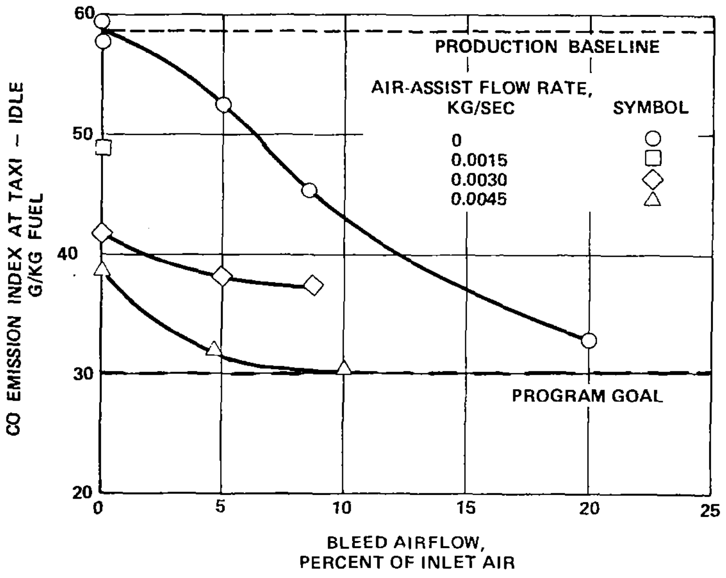


Figure VII-5.



EFFECT OF BLEED AND AIR ASSIST ON HC EMISSIONS, CONCEPT 1

Figure VII-6.



EFFECT OF BLEED AND AIR ASSIST ON CO EMISSIONS, CONCEPT 1

Figure VII-7.

EFFECT OF WATER-METHANOL INJECTION ON NO_X EMISSIONS, CONCEPT 1

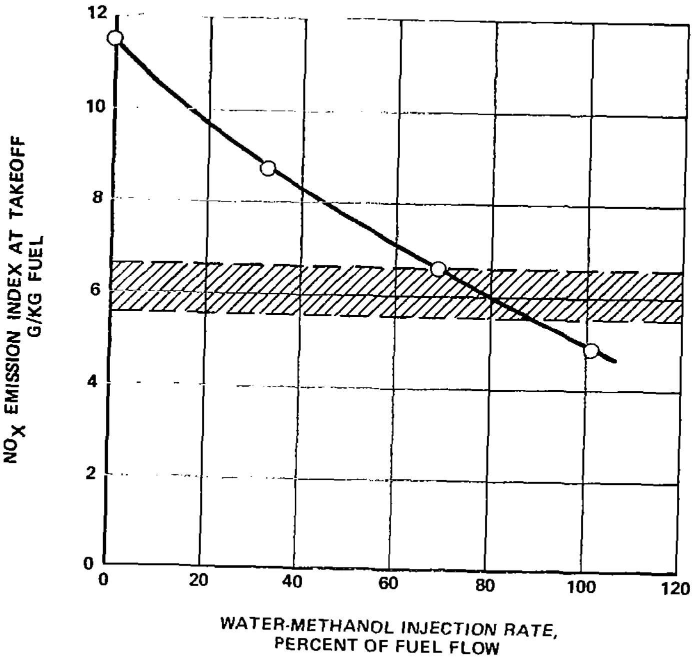


Figure VII-8.

CONCEPT 2 COMBUSTION SYSTEM

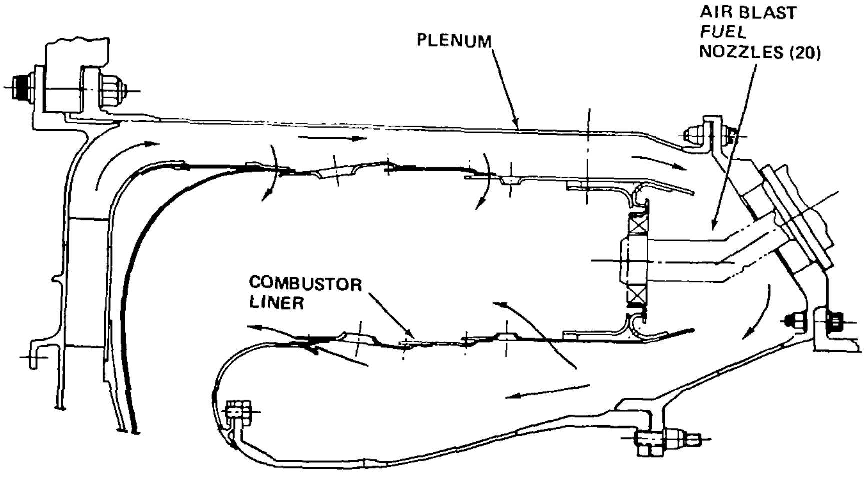


Figure VII-9.

CONCEPT 2 SIMULATED VARIABLE-GEOMETRY COMBUSTION SYSTEM

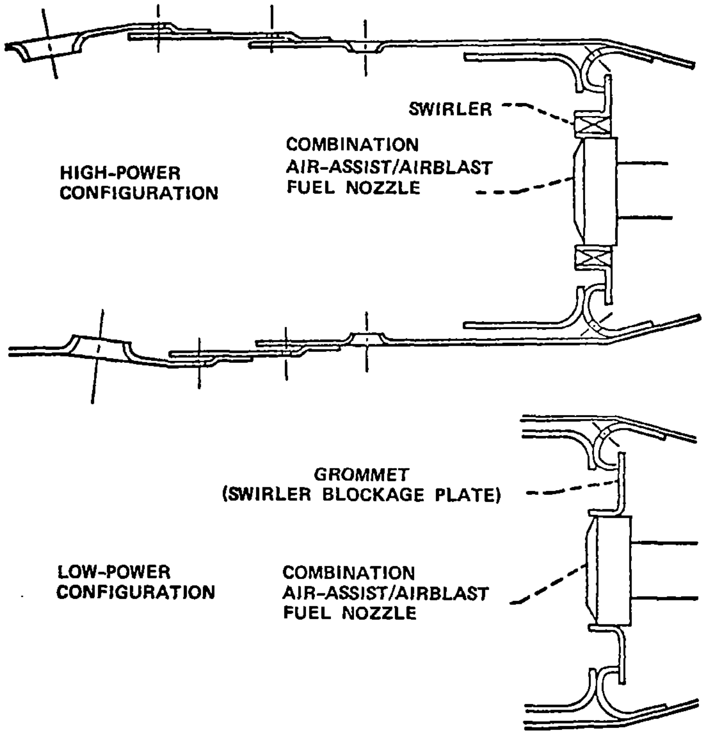


Figure VII-10.

CONCEPT 2 SUMMARY OF EMISSIONS TEST

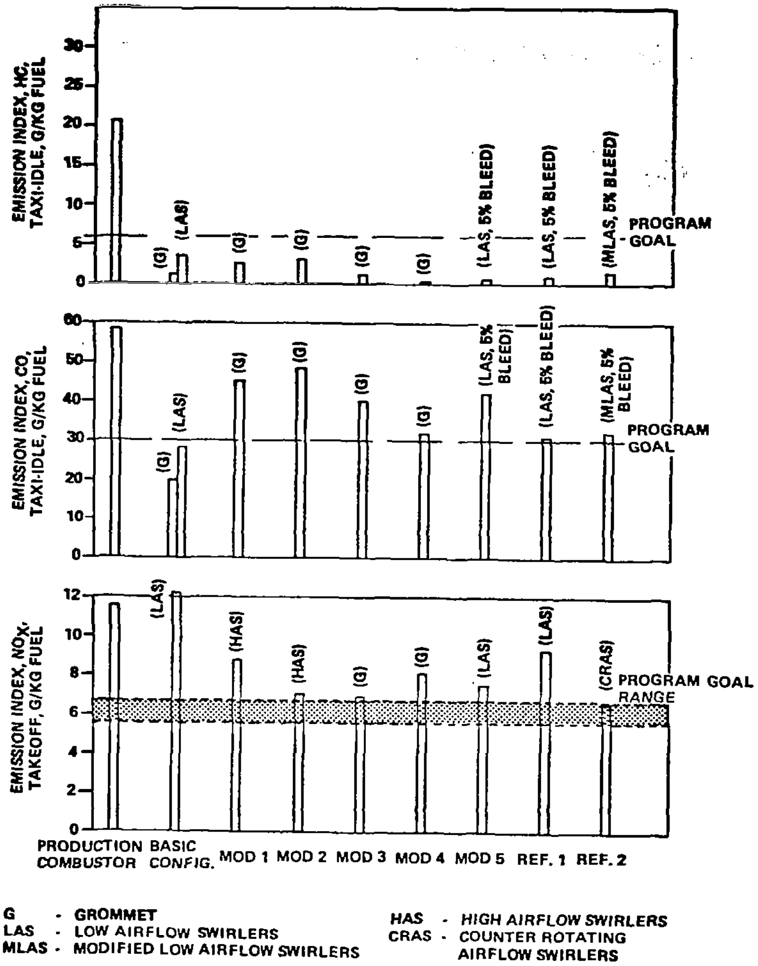


Figure VII-11.

CONCEPT 2 TAXI-IDLE CO AND TAKEOFF NO_X RELATIONSHIP

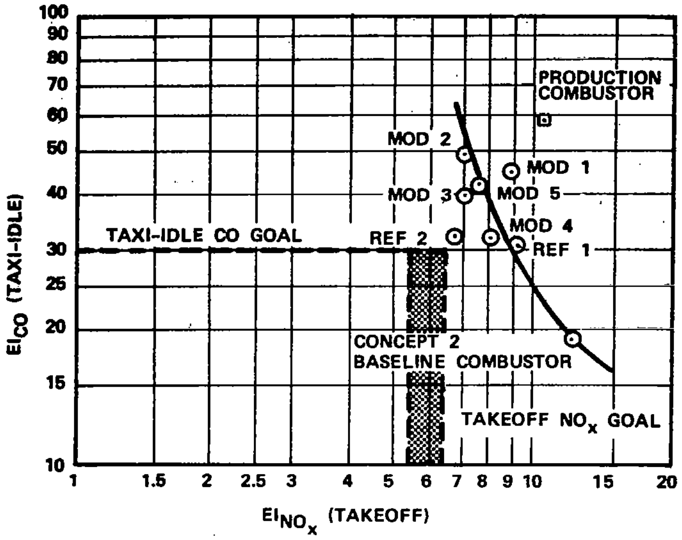


Figure VII-12.

CONCEPT 3 EXTERNAL PREMIXING COMBUSTION SYSTEM

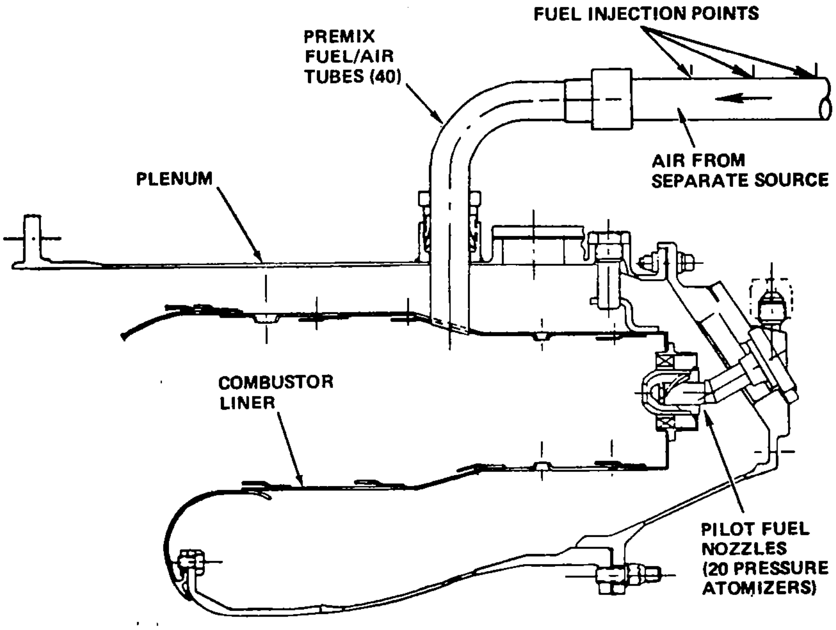


Figure VII-13.

CONCEPT 3 COMBUSTION SYSTEM

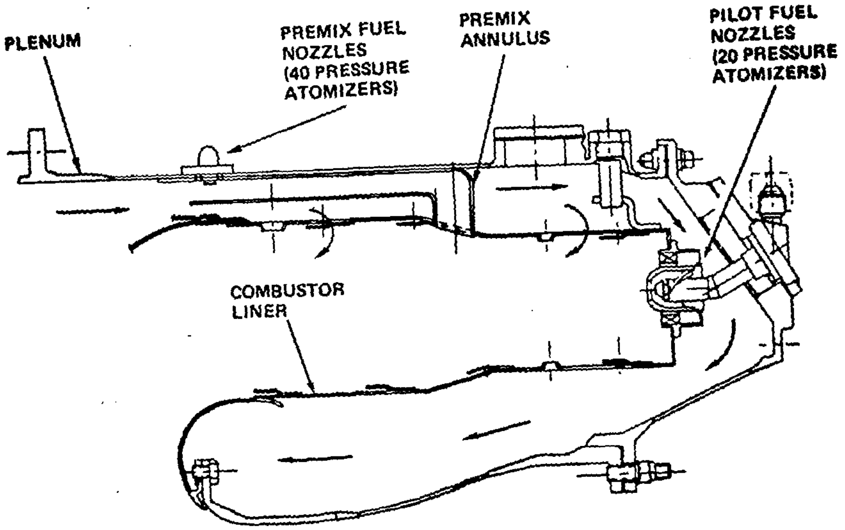


Figure VII-14.

CONCEPT 3 SUMMARY OF EMISSIONS TEST

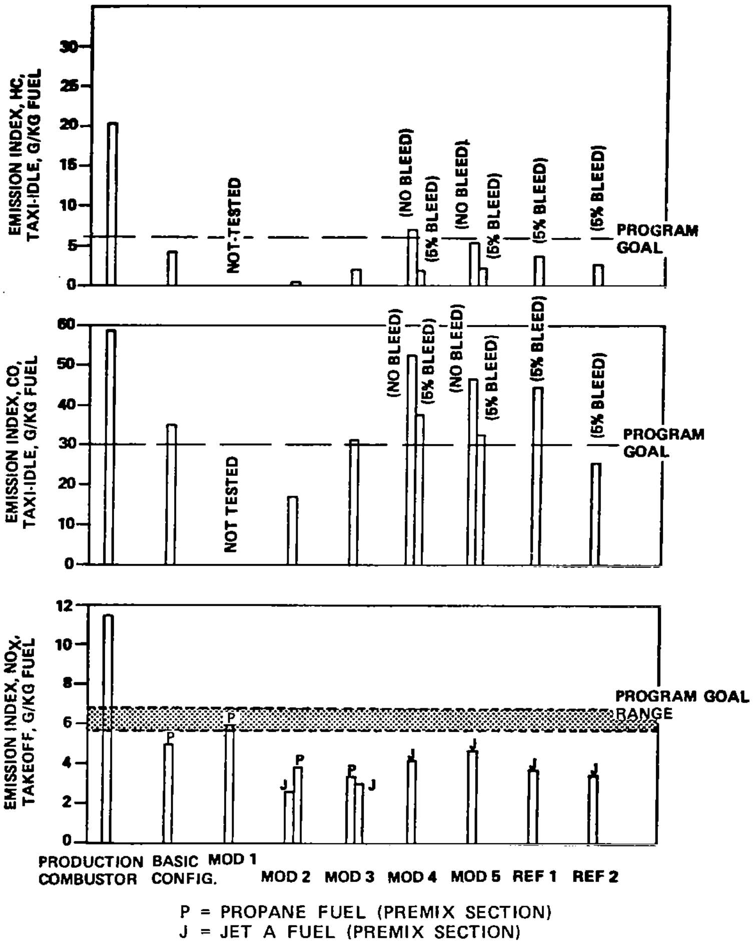


Figure VII-15.