IV. POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR CLASS T4(JT8D) ENGINES

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The Pollution Reduction Technology Program for can-annular combustors was conducted to generate and demonstrate the technology required to develop commercial gas turbine engines with reduced exhaust emissions. This program was directed to can-annular combustor systems for the JT8D engine family (EPA class T4). The Pratt & Whitney JT8D-17 was selected as the reference engine, although the technology developed will be applicable to other engines with can-annular combustor systems. This engine is the current production version of the JT8D engine, which is in widespread use throughout the commercial transport fleet. The JT8D turbofan engine is an axial-flow, dual-spool, moderate-bypass-ratio design. It has a two-stage fan, a four-stage low-pressure compressor driven by a three-stage low-pressure turbine, and a seven-stage high-pressure compressor driven by a single-stage high-pressure turbine. Figure IV-1 is a cross section of the JT8D-17 showing the mechanical configuration. Key specifications for this engine are listed in table IV-1.

The JT8-17 combustor section consists of nine combustion chambers in a can-annular arrangement. Each chamber contains one centrally located duplex fuel nozzle. Two of the chambers are equipped with spark igniters. The nine combustion chambers are interconnected by tubes for flame propagation during starting. Each combustion chamber is of welded construction comprised of a series of formed sheet-metal cylindrical liners. Each chamber is supported at the front by the fuel nozzle strut and a mount lug and at the rear by a sliding joint at the face of the turbine inlet transition duct. A cross-sectional schematic of the JT8D-17 combustor is shown in figure IV-2 and its key operating parameters are listed in table IV-2.

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Standards issued by the Environmental Protection Agency (EPA) (ref. 1) establish maximum emission levels in a gas turbine engine exhaust for carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke at altitudes below 915 meters. The 1979 EPA standards for class T4 were adopted as program goals. The gaseous pollution goals, summarized in table IV-3, are expressed as integrated EPA parameters (EPAP's) that represent a weighted average of emission index (g/kg fuel) at the operating points of idle, approach, climb, and sea-level takeoff (SLTO) over a specified landing/takeoff (LTO) cycle.

The emission indices (EI) listed in table IV-4 are one set of hypothetical values that would meet the program EPAP goals. These values are consistent with the program combustion efficiency goal of 99 percent and exhibit a trend with engine power level that might be expected from a successful low-emission combustor concept. Due to the summation procedure involved in the determination of the EPAP, numerous other hypothetical EI values would also satisfy the EPAP goals. Comparison with the baseline rig emission levels measured from the JT8D-17 production combustor shown in table IV-4 indicates the magnitude of reduction required. Except for the total unburned hydrocarbons at high-power settings (SLTO and climb) and the smoke number, substantial reductions in pollutant levels are required to meet the goals.

Inasmuch as smoke emissions have been reduced to below the visible threshold on current commercial engines, this work focused primarily on reductions of oxides of nitrogen, carbon monoxide, and total hydrocarbons. These reductions in pollutant emissions were to be accomplished while meeting requirements for altitude relight, durability, and other performance and operational parameters.

The overall program was accomplished by means of the design, fabrication, experimental combustor rig testing, and assessment of results for a series of three successively more advanced combustor concepts. The three concepts evaluated under this program represent increasing potential for achieving the program emissions goals but with attendant increases in complexity, difficulty of development, and adaption to an operational engine. Program element I consisted of minor modifications to the existing single-stage JT8D combustor and fuel system. These modifications included evaluation of airblast fuel nozzles, changes in the basic airflow distribution of the JT8D combustor, and a carburetor tube premixing scheme. In all, six configurations were evaluated. Program element II evaluated nine advanced versions of the Vorbix (vortex burning and mixing) combustor concept. Vorbix combustors previously evaluated under the NASA/P&W Experimental Clean Combustor Program and other P&W programs have exhibited potential for significant emissions reductions. Relative to program element I, element II hardware was more complex and more difficult to adapt to an operational engine. Program element III evaluated a two-stage combustor concept that employs prevaporized fuel as a means of controlling flame stoichiometry for attaining minimum emissions levels. Emphasis was placed on NO_x reduction at high-power operating conditions. This program element, while having the highest potential for meeting the program goals, represented great difficulty in development and adaptation to the JT8D engine.

Values are given in SI or U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

TEST RIG AND INSTRUMENTATION

A schematic of the JT8D combustor rig is presented in figure IV-3. This rig simulates a 40° sector of the JT8D engine including compressor discharge, diffuser struts, and air-cooled turbine entrance transition duct. In addition, provisions were made for extracting outside-diameter (OD) and inside-diameter (ID) bleeds in amounts representative of the turbine cooling air requirements of the JT8D-17 engine. This allowed a more precise simulation of the JT8D-17 engine operating conditions. Combustor exit gas samples were withdrawn through a fixed sample port array mounted in an air-cooled vane pack. The vane pack, shown in figure IV-4, comprises seven JT8D first-stage turbine vanes. The five center vanes were each instrumented with five sampling ports. The 25 sampling ports were connected to a common plenum in order to provide a representative gas sample. The sampling ports were additionally used to measure average combustor exit total pressure. The five center vanes were also instrumented with two thermocouples each, located near the center of each vane, to concentrate measurements in the expected areas of highest temperature.

Gas samples were analyzed by using equipment and techniques that, with minor exceptions, conformed to the EPA requirements described in reference 1. Smoke concentrations in the combustor exhaust were measured with a smoke meter that conformed to the specifications of the SAE ARP 1179 (ref. 2). Details of the test facility and gas analysis instrumentation are presented in references 3 and 4.

TEST CONDITIONS

The combustor rig test conditions selected for this program match the actual JT8D-17 engine operating conditions specified by the EPA for the calculation of EPAP's. These test conditions, listed in table IV-5, correspond to idle, approach, climb, and SLTO. All testing was conducted with fuel that conformed to the American Society for Testing and Materials (ASTM) Jet-A specifications. Parametric variations of combustor fuel-air ratio were investigated for most of the combustor concepts at both the idle and SLTO operating conditions. At intermediate- and high-power conditions, the pilot-to-main fuel flow split was varied for most of the two-stage configurations, while the total fuel was maintained constant. The resulting data permitted identification of the optimum fuel distribution between the pilot and main burning zones on the basis of competing NO_x, combustion efficiency, and smoke levels.

COMBUSTOR CONFIGURATIONS TESTED

Element I Combustor Configurations

The objective of the element I program was to determine the magnitude of emission reduction obtainable with minimal changes to existing combustion section hardware. The fuel-air mixture in a conventional, direct-injection combustor may be characterized as nonhomogeneous, with a wide spectrum of local equivalence ratios. The key ingredients for emissions improvement in such a combustor are improved control of the burning fuel-air mixture equivalence ratio, through improved fuel-air mixture preparation, and manipulation of the combustor primary- and secondary-zone air schedules. Since element I was confined to single-stage concepts, a compromise between the competing requirements for control of idle and high-power emissions was necessary. The modifications investigated include airblast fuel nozzles, fuel-air carburetion, and changes to the primary-zone airflow distribution. Table IV-6 lists the six configurations tested in element I.

Two airblast nozzles were chosen for investigation. Nozzle I is a scaled version of a nozzle that had demonstrated some effectiveness in reducing high-power smoke and low-power CO and THC emissions in an earlier engine development program. The nozzle is a dual-orifice type comprising a conventional pressure-atomizing primary surrounded by an annular airblast secondary. The second airblast nozzle configuration was selected during the test phase of this contract because of very favorable low-power emissions produced during another engine development program. This nozzle, shown in figure IV-5 with the lean front-end configuration (I-4), incorporates a pressure-atomizing primary and an airblast secondary and is similar in concept to airblast nozzle I. A significant design difference is that this nozzle tip features a dynamic air feed, whereas nozzle I relies on a static air feed. The airflow distribution shown in figure IV-5 and later figures is based on percentage of total combustor airflow. Liner cooling airflow is not indicated in the figures.

The carburetor tube concept, shown in figure IV-6, was intended to provide additional improvement in fuel-air mixture preparation. The carburetor tube design features three annular air streams for control of radial fuel distribution and primary-zone stoichiometry. The original configuration was developed through testing at a high-pressure fuel spray facility. An air gap and radial inflow swirler at the head of the carburetor tube were incorporated to eliminate wall wetting of the premixing tube. Primary-zone mixing is enhanced by a counterrotating secondary air swirler located at the carburetor tube exit. Air from the diffuser exit is channeled directly to this flame stabilizing swirler through an annulus concentric with the carburetor tube. A suitable low-blockage pressure-atomizing nozzle was selected for this combustor.

The element I configurations may be classified in terms of the primary-zone airflow distribution as either "lean" or "rich" when compared with the baseline JT8D-17 production combustor. These terms imply deviation from the baseline rather than an absolute value of average primary-zone equivalence ratio. These concepts proceeded from prior experience where high-power NO_x was reduced by approximately 30 to 50 percent (ref. 5). However, since the fuel and air typically were not well mixed, excessively lean or rich mixtures, on a bulk basis, were required before the NO_x reduction was achieved. This approach compromises other aspects of burner operation. Lean front-end burners tend to have problems with lighting, lean blowout, altitude relight, and low-power emissions. Rich front-end burners tend to produce excessive smoke and carbon, while improving CO and THC at idle. The approach taken in this program was to combine improved fuel preparation, either by means of an airblast nozzle or carburetor tube, with a less-extreme lean or rich air schedule change. A general emissions prediction model (ref. 6) was utilized to analytically select specific air distribution arrangements for fabrication and testing.

Element II - Advanced Vorbix Combustor Concept

The second program element consisted of testing nine configurations of the two-stage advanced Vorbix combustor concept. The configurations are summarized in table IV-7. A schematic and photograph representative of combustor configurations II-2 to II-9 are shown in figure IV-7. Features of the Vorbix concept are an appropriately sized swirl-stabilized pilot zone, a reduced-height throat section axially separating the pilot and main burning zones, and an array of swirlers for the introduction of main-zone combustion air. Main-combustion-zone fuel is introduced at the throat location. In the present can-annular form, six cold-to-hot gas interfaces created by the hot pilot gas and the air inflow from the six air injection swirlers are arranged circumferentially about the burner centerline. The relatively large amount of air introduced through the main swirlers, coupled with an increased mixing rate at the hot-to-cold gas interface, acts to minimize residence time in the high-temperature reaction zone.

The element II Vorbix combustor concept differs significantly from previous Vorbix designs in the manner in which the main fuel is supplied and injected into the burning zone. In the present design, main fuel is mixed with air at the front of the combustor, swirled about the exterior of the pilot through two carburetor tubes, and then injected into the hot pilot gas at the throat section through a circumferential array of holes. The objective of the element II test program was to optimize the Vorbix concept by experimentally evaluating those design parameters thought to be of importance. With reference to table IV-7, major design parameters investigated were throat velocity, location and flow rate of main-zone swirlers, and amount and distribution of dilution air.

Element III - Prevaporizing-Premixing Combustor Concept

The objective of element III was to design and test a concept that had the highest probability of meeting the program goals, with particular emphasis on NO_x. It was considered permissible to require high complexity and difficulty of application to an operational engine. Previous research work (ref. 7, e.g.) has indicated that the requisite approach for ultimate NO_x reduction at high power is to burn a highly homogeneous fuel-air mixture at a lean equivalence ratio. However, previous attempts to provide premixed lean combustion in practical hardware by direct injection of liquid fuel into a premixing passage directly upstream of the burning zone have not successfully achieved a homogeneous vapor-phase mixture condition. This is due to physical limitations on vaporization and mixing rates, constrained by an upper limit on premixing passage residence time imposed by autoignition considerations.

The two-stage concept selected for element III is shown in figure IV-8. This concept represents an attempt to improve fuel-air homogeneity in the main burning zone by vaporizing the fuel prior to its injection into the premixing passages, thereby eliminating fuel vaporization as a rate-limiting step. The approach taken was to regeneratively heat the fuel while it is maintained above the critical pressure of approximately 22 atm. The hot liquid fuel is allowed to flash vaporize upon injection into the premixing passages. The premixing tubes were sized to allow maximum residence time for mixing within the constraints of autoignition (ref. 8).

Regenerative heating of the fuel eliminated the need for an auxiliary energy source and presented the possibility of further NO_x reduction by pilot heat extraction. The regenerative heat exchanger was sized to provide fuel temperatures from 590 to 700 K at SLTO operation with the pilot burning at an equivalence ratio of 0.75.

The five configurations tested in element III are presented in table IV-8. Testing of configurations III-1 and III-2 was limited to idle operation due to durability problems encountered with a premixing type of pilot-zone design. To expedite the program, a pilot design derived from the element II Vorbix concept was adopted for configurations III-3 to III-5. For the fixed-geometry element III concept, a low main-zone equivalence ratio at approach and other low-power operating points will tend to produce unstable operation and poor combustion efficiency. Configurations III-4 and III-5, therefore, evaluated the effect of staging only three of the six main fuel injectors. An alternative approach to improving part-power operation in a fully premixed combustor system would be to incorporate a variable-geometry premixing tube air-metering area. However, variable geometry was not investigated in this program.

DATA CALCULATION PROCEDURE

The raw emissions data generated at each test condition were transmitted directly to an on-line computer for processing. The voltage response of the gaseous constituent analyzers was first converted to an emission concentration based on the calibration curves of each instrument and then used to calculate emission indices, carbon balance fuel-air ratios, and combustion efficiency. The equations used for these calculations were equivalent to these specified in SAE ARP 1256 (ref. 9).

Adjustment Procedure

While every effort was made to set exact design conditions for the test runs, it was rarely possible to set test conditions to precisely match the design point fuel-air ratio. Therefore, the data have been corrected to design condition by interpolation, using plots of emission concentration as a function of metered fuel-air ratio. The data for NO_x have been corrected for humidity at all operating conditions by means of the exponential humidity term in the following equation. Where correction of the NO_x data to design point conditions was not possible by interpolation, extrapolation was accomplished by using the additional terms in the following equation (ref. 10). These corrections were small, generally not exceeding 5 percent.

$$NO_x EI_{corr} = (NO_x EI_{meas}) \left[e^{18.8(H_{meas} - H_{corr})}\right] \left(\frac{P_{t4,corr}}{P_{t4,meas}}\right)^{0.5} \times \left(\frac{V_{ref,meas}}{V_{ref,corr}}\right) \left(\frac{T_{t5,corr}}{T_{t5,meas}}\right) \left[e^{(T_{t4,corr} - T_{t4,meas})/288}\right] \quad (1)$$

where

$NO_x EI$	emission index of oxides of nitrogen
P_{t4}	inlet total pressure, atm
T_{t4}	inlet total temperature, K
V_{ref}	reference velocity, m/sec
H	inlet specific humidity, g H_2O/g air
T_{t5}	combustor exit temperature, K
corr	relates to value at corrected condition
meas	relates to value at measured condition

EPA Parameter Calculation

The EPA emissions standards for aircraft engines are expressed in terms of an integrated EPA parameter (EPAP). This parameter combines emissions rates at specified engine idle, approach, climb, and takeoff operating modes, integrated over a specified landing/takeoff cycle (ref. 1). The equation for this calculation is

$$EPAP_i = \frac{\sum_{1}^{j} \frac{t_j}{60} W_{F,j} EI_{i,j}}{\sum_{1}^{j} \frac{t_j}{60} F_{N,j}} \text{ (lbm pollutant/1000 lbf thrust-hr/LTO cycle)} \qquad (2)$$

where

EI emission index, lbm pollutant/1000-lbm fuel

t time at engine mode, min

F_N net thrust, lb

W_F fuel flow rate, lbm/hr

i emission category (CO, THC, NO_x)

j engine mode (idle, approach, climb, SLTO)

Substituting JT8D-17 engine performance parameters into equation (2) yields

$$EPAP_i = 0.3366\ EI_{i,\text{idle}} + 0.1256\ EI_{i,\text{approach}} + 0.1969\ EI_{i,\text{climb}} + 0.0777\ EI_{i,\text{SLTO}}$$

RESULTS AND DISCUSSION

Element I Results

The emission test results for the element I configurations are presented in table IV-9, with goal and baseline values included for comparison. The EPAP values indicate that the air-blast nozzle configurations are capable of significantly reducing CO and THC, with slight reductions in NO_x. Only the THC value met the program goal, with the best CO level slightly above the goal. The NO_x level remained well above the goal for the airblast nozzle configurations. The exhaust smoke level was slightly over the goal for the best configurations. The carburetor tube configurations, designed to reduce high-power NO_x levels by achieving lean fuel-air burning through improved fuel preparation, reduced the NO_x EPAP 30 percent below the baseline. The CO and THC EPAP's are quite high for the carburetor tube scheme due to high CO and THC levels at low-power operation. Very low values of smoke number were measured, as is consistent with lean, well-mixed operation at high power.

The graphical presentation of the element I results, shown in figure IV-9, indicates that the better element I configurations bear a common relationship to the peak primary-zone equivalence ratio calculated from the analytical model (ref. 6). This peak equivalence ratio occurs in the immediate vicinity of the fuel nozzle and is affected by the inflow of air around the nozzle and subsequent fuel droplet evaporation. The air-blast nozzle configurations were optimized for good low-power emission characteristics, while the carburetor tube was optimized for good high-power emissions and smoke characteristics. Figure IV-9 illustrates a basic shortcoming of single-stage combustor designs. The inlet condition or combustor design changes that minimize NO_x formation tend to increase the CO and THC levels, and conversely, CO and THC at idle decline sharply as primary-zone equivalence ratio is increased. The NO_x and smoke at high power exhibit inverse characteristics. These data suggest that there is limited potential for overall emissions control with a single-stage combustor and that a two-stage combustor or other advanced concept is necessary for simultaneous control of low- and high-power emissions. The lower slope of the NO_x trend and the leveling off at lean equivalence ratio are indicative of the difficulty in creating a uniform fuel-air mixture with direct liquid fuel injection.

Element II Results

The emission test results for the nine element II configurations are presented in table IV-10. These results indicate that the advanced Vorbix combustor concept is capable of substantial reductions in all three gaseous emissions. The CO and NO_x levels were reduced to approximately 50 percent of the baseline values but were still above the EPAP goals. The THC level was reduced to below the EPA standard. A review of the smoke numbers presented in table IV-9 reveals that only one configuration achieved the goal of 25. However, the final configurations should meet the goal with modest additional development.

Since the Vorbix combustor concept employs two burning zones, the results presented in table IV-10 correspond to specific values of pilot-to-main fuel split at each of the simulated engine power settings. The pilot-to-main fuel distribution was a primary test variable, and data were selected for inclusion in the EPAP calculation on the basis of best simultaneous control of all three gaseous emissions. Both burning zones were fueled at the climb and SLTO operating conditions, while only the pilot zone was fueled at the idle and approach power settings. Figure IV-10 summarized the effects of varying pilot-to-main fuel split at the approach, climb, and SLTO conditions for configuration II-9. At approach, all three emission indices decreased when all of the fuel was introduced through the pilot nozzle. At climb and SLTO, increasing the percentage of pilot fuel sharply reduced THC and CO emissions while increasing NO_x at a lower rate.

Figure IV-11 illustrates the strong effect of throat velocity on emissions levels for three configurations (II-4, 5, and 6), where this parameter was varied by throat diameter change only. An examination of the figure reveals that THC and CO emission indices are reduced significantly at both idle and SLTO as throat velocity is decreased. The NO_x emission index at SLTO increased at a much lower rate with reduction in throat velocity. This was one of the most significant results of the element II testing, in that this geometric change was able to provide a substantial reduction in CO and THC emission levels with minimal NO_x penalty.

Element III Results

The emission test results for the element III configurations are presented in table IV-11. As in the case of the element II combustors, data are presented at specific values of pilot-to-main fuel split on the basis of the best simultaneous reduction of CO, THC, and NO_x. Table IV-11 indicates that reductions of approximately 50 percent in NO_x and 10 percent in CO were obtained relative to the baseline, while the THC goal was met. Smoke was virtually eliminated in all configurations.

The values of EPAP quoted for configuration III-3 correspond to operation of only the pilot zone at approach. Attempts to ignite the main zone at the approach power point with fuel supplied to all six premixing tubes were unsuccessful. The number of active main-zone fuel injectors was reduced from six to three for configurations III-4 and III-5. The purpose of this modification was to increase premixing-tube equivalence ratio to a level where efficient operation of the main zone at the approach condition was possible. Data from configurations III-4 and III-5 have been combined to calculate EPAP's for operation of the combustor with three main-zone premixing tubes fueled at the approach, climb, and takeoff power points. The increase in the EPAP above the goal level is attributable to the increase in the THC emission index at the approach power point. Data from configurations III-3 and III-4 were combined to calculate a third set of EPAP's for the element III combustor corresponding to operation of the main zone with three injectors at approach and six at climb and SLTO. As shown in table IV-11, this mode of operation resulted in the best NO_x EPAP, at some sacrifice in both CO and THC.

To maintain heat exchanger fuel temperatures at desired levels, it was necessary to bypass some of the heat exchanger fuel flow at most operating conditions. A portion of the heat generated in the pilot zone was therefore removed. To evaluate this effect on combustor performance, test points were taken at various heat exchanger fuel flows while combustor inlet conditions and fuel-air ratio were held constant. Heat removal had negligible effect on emissions at both the idle and SLTO power points. On this basis, no attempt was made to correct emissions data for heat removal by the bypassed fuel flow. Attempts to evaluate the main-zone performance at various degrees of fuel preheating were unsuccessful due to the inability to reduce fuel temperature low enough to overcome the heat supplied by the inlet air within the premixing tubes. No significant effect on high-power emissions was observed for the range of main-zone fuel temperature investigated.

SUMMARY OF EMISSIONS RESULTS

The emission indices for NO_x, CO, and THC are shown in figures IV-12 to IV-14, respectively. These emission indices correspond to simulated sea-level static engine operation. Comparison is also made to the baseline and the set of hypothetical emission index goals. A summary of the EPAP's and maximum smoke numbers for the best configurations within each program element is presented in table IV-12.

An examination of the NO_x EPAP values reveals that each concept reduced NO_x relative to the JT8D baseline, but that none achieved the goal. As shown in figure IV-12, both two-stage burners, representing elements II and III, produced significant high-power NO_x reductions but fell short of the desired goal. The element III concept demonstrated slightly greater NO_x reduction at high power, attributable to the prevaporizing feature of the main zone. The element II concept, however, had the lower NO_x EPAP due to the emphasis placed on the idle and approach emission indices in the EPAP calculations. The element I configuration produced slightly better high-power NO_x levels than the baseline due to improved fuel preparation. However, the single-stage designs have limited potential for further significant NO_x reduction.

The lowest CO and THC emissions were attained by the element I configuration with airblast nozzle II. In particular, configuration I-2 produced EPAP's lower than the THC goal and very close to the CO goal. However, the single-stage carburetor tube concept (I-6), which incorporates a lean front end for NO_x control at high power, illustrates how readily idle CO and THC can be compromised for relatively modest additional NO_x reduction. The representative configurations from elements II and III also produced THC EPAP's below goal level and reduced CO EPAP's relative to the baseline. Both of these reductions are the results of improved pilot performance attributable to the improved fuel preparation and distribution techniques developed during the single-stage combustor tests of element I. As illustrated in figures IV-13 and IV-14, the two-stage concepts for NO_x control resulted in higher CO and THC levels at climb and SLTO when compared with the baseline and element I configurations. Because of this characteristic, the CO and THC EPAP's for the two-stage concepts do not achieve the levels of the best single-stage concepts.

The ultimate emissions reduction potential of the two-stage combustor concepts is affected by operational problems encountered at intermediate-power operation. For example, the element II configurations exhibited lower combustion efficiency (and hence higher levels of CO and THC) when the main burning zone was fueled at the approach power point. Since pilot-only operation at approach is accompanied by an increase in NO_x emission index, a decision which favors either the NO_x or the CO and THC EPAP values must be made. A similar NO_x - CO, THC trade-off versus pilot-to-main fuel split was encountered at the higher power operating points. Thus, depending on the particular regulation format being addressed, the absolute CO, THC, and NO_x emission levels for a given level of technology are open to manipulation.

CONCLUDING REMARKS

The results of the Pollution Reduction Technology Program for can-annular combustors would suggest that the emissions reduction potential of a combustor concept is inversely proportional to the deviation from current engine design practice and difficulty of development. Minor modifications to the existing JT8D-17 combustor design were capable of significant reduction in low-power emissions of CO and THC, approaching the 1979 EPA standards for these emissions. The element I single-stage concepts that achieved these low-power emission reductions are also attractive when considering development time and cost. Attaining simultaneous control of CO and THC as well as NO_x emissions will require more advanced two-stage concepts with an attendant increase in complexity. The advanced Vorbix concept evaluated in program element II achieved both high- and low-power emissions reductions. NO_x emission reductions of approximately 50 percent were demonstrated at SLTO power. The CO and THC emissions at idle exceeded the levels obtained with the element I concept; however, they were still well below the baseline JT8D-17 values. The prevaporizing-premixing concept, evaluated in program element III, fell short of the NO_x reduction potential of a fully premixing system. This result may demonstrate that simply injecting vaporized fuel into a swirling air stream and allowing it to mix for a predetermined time does not ensure a completely homogeneous mixture. Since even localized regions burning at higher equivalence ratio can produce significant increases in NO_x level, it is evident that future development must concentrate on achieving absolutely uniform fuel-air mixture preparation if the full potential of the concept is to be realized.

Emissions reduction potential has been emphasized in this combustor rig assessment program, and relative ranking of the concepts has been done on this basis. Combustor performance and durability characteristics were measured in conjunction with the emissions tests in order to better estimate the practicality of the individual configurations. A number of deficient areas, such as altitude relight capability, were observed, but no performance development was attempted. Particular performance deficiencies and an assessment of the engine applicability of each combustor concept are treated at some length in reference 4. The pollutant emission reduction reported in this paper should be considered as a technology base only and should not be considered representative of fully developed, engine-worthy hardware. Development of satisfactory performance characteristics and durability will tend to degrade the demonstrated emissions reductions. In addition to a margin for development, it is likely that engine-to-engine variations and component degradation will also increase the emission levels continuously produced by a large fleet of in-service engines.

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KEY SPECIFICATIONS OF JT8D-17 ENGINE

Weight (kg)	1510.5
Length (m)	3.045
Maximum Diameter, cold (m)	1.080
Pressure Ratio	16.9
Airflow Rate (kg/s)	148.3
Maximum Sea-Level Static Thrust (kN)	71.2
Cruise Performance	
Mach Number	0.8
Altitude (m)	9140
Thrust (kN)	18.9
Specific Fuel Consumption (kg/Ns)	2.273×10^{-5}

Table IV-1.

KEY OPERATING PARAMETERS OF JT8D COMBUSTOR

Compressor Exit Axial Mach Number	0.42
Compressor Discharge Temperature (K)	714
Combustor Temperature Rise (K)	633
Average Combustor Exit Temperature (K)	1348
Combustor Section Pressure Loss (%)	8.2
Combustor Exit Temperature Pattern Factor	0.39
Burner Length (cm)	45.4

Table IV-2.

PROGRAM EMISSIONS GOALS

Pollutant	EPAP (lbm pollutant/1000 lbf thrust-hr/LTO cycle)
Carbon Monoxide	4.3
Total Hydrocarbons	0.8
Oxides of Nitrogen*	3.0
Smoke	Maximum SAE Smoke Number of 25

*Nitrogen Dioxide equivalent of all the Oxides of Nitrogen.

Table IV-3.

EMISSION INDEX GOALS AT JT8D-17 POWER LEVELS COMPARED TO BASELINE

Mode	CO ($\frac{g}{kg\ fuel}$)		THC ($\frac{g}{kg\ fuel}$)		NO_X ($\frac{g}{kg\ fuel}$)		SAE Smoke No.	
	Goal	Rig Baseline	Goal	Rig Baseline	Goal	Rig* Baseline	Goal	Rig Baseline
Idle	12.2	44.5	2.1	12.8	3.2	3.7		
Approach (30% SLTO)	1.1	7.5	0.40	0.67	4.2	8.5		
Climb (85% SLTO)	0.20	0.89	0.13	0.04	5.1	20.0		
SLTO	0.16	0.55	0.11	0.03	5.2	24.4		
EPAP	4.3	16.1	0.8	4.4	3.0	8.2	$<$25	25–30

*Specific humidity = 6.3 grams of water per kilogram of dry air.

Table IV-4.

SINGLE-SEGMENT-RIG OPERATING CONDITIONS FOR EMISSIONS TESTING

JT8D-17 Mode	Total Inlet Pressure (atm)	Total Inlet Temperature (K)	Combustor Total Airflow (kg/sec)	Combustor Fuel Flow (kg/sec)	Fuel-Air Ratio
Idle (w/o Customer Bleed)	2.87	412	1.58	0.0158	0.0100
Approach 30% Power	6.83	535	3.43	0.0384	0.0112
Climb 85% Power	15.08	678	6.67	0.1094	0.0164
SLTO 100% Power	17.40	714	7.46	0.1357	0.0182

Table IV-5.

ELEMENT I CONFIGURATION

Configuration	Fuel Injector	Primary Bulk* Air Schedule Classification
I-1	Airblast Nozzle I	Baseline
I-2	Airblast Nozzle II	Rich
I-3	Airblast Nozzle II	Rich
I-4	Airblast Nozzle II	Lean
I-5	Carburetor I with Pressure Atomizing Nozzle	Lean
I-6	Carburetor II with Pressure Atomizing Nozzle	Lean

*Primary zone combustion airflow relative to baseline.

Table IV-6.

ELEMENT II CONFIGURATIONS

Configuration	Pilot Hood	Main Fuel Injector Type	Main Fuel Deflector	Throat Dia. (cm)	Main Swirler Location	Number of Main Fuel Injector Feed Holes	Pilot Airflow % W_{ab}	Main Swirler Airflow % W_{ab}	Main Zone Dilution Airflow % W_{ab}	
									Row 1	Row 2
II-1	No	a	Yes	6.6	Louver 5	24	23.1	38	10.5	–
II-2	Yes	b	Yes	6.6	Louver 5	24	26.4	27	21.5	–
II-3	Yes	b	No	5.8	Louver 5	6	24.3	25	21.5	–
II-4	Yes	b	No	5.8	Louver 5	6	24.3	15	28	4
II-5	Yes	b	No	7.1	Louver 5	6	24.3	15	28	4
II-6	Yes	b	No	7.1	Louver 7	6	24.3	15	28	4
II-7	Yes	b	No	8.1	Louver 7	6	24.3	15	28	4
II-8	Yes	b	No	8.1	Louver 7	6	27.1	15	28	–
II-9	Yes	b	No	8.1	Louver 7	6[c]	24.9	15	30	–

Main Fuel Injector Type: a = Pressure/Atomizing Nozzles
b = Low Pressure Drop, Low Blockage Air/Atomizing Injection
c = Main fuel injector airflow increased 26%

Table IV-7.

ELEMENT III CONFIGURATIONS

Configuration	Pilot Airflow % W_{ab}	Main Premix Tube Airflow % W_{ab}	Main Dilution Airflow % W_{ab}	Main Premix Tube Equivalence Ratio*	Number of Main Zone Fuel Injectors
III-1	11	38	20	0.56	6
III-2	17	38	10	0.56	6
III-3	16	33	10	0.64	6
III-4	16	33	10	1.28	3
III-5**	16	33	10	1.28	3

*Based on a 20% Pilot/80% Main Zone Fuel Split
**Heated Pilot Fuel

Table IV-8.

ELEMENT I EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP (lbm/lbf thrust-hr/LTO cycle) NO_x	CO	THC	Maximum SAE Smoke Number
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25–30
Airblast Nozzle				
I-1	–	–	–	25
I-2	7.42	5.05	0.05	28
I-3	7.86	4.77	0.77	49
I-4	7.54	6.91	1.46	12
Carburetor Tube				
I-5	–	–	–	1
I-6	5.78	51.98	22.55	2

Table IV-9.

ELEMENT II EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP (lbm/lbf thrust-hr/LTO cycle) NO_x	CO	THC	Maximum SAE Smoke Number
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25-30
II-1	–	–	–	–
II-2	–	–	–	–
II-3	4.52	22.75	0.76	38
II-4	4.65	20.60	0.60	31
II-5	4.61	12.30	0.29	31
II-6	4.59	10.45	0.14	18
II-7	4.75	8.71	0.17	30
II-8	4.49	10.84	0.28	26
II-9	4.39	8.93	0.18	27

Table IV-10.

ELEMENT III EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP (lbm/lbf thrust-hr/LTO cycle)			Maximum SAE Smoke Number	Comments
	NO_x	CO	THC		
Goal	3.0	4.3	0.8	25	
JT8D-17 baseline	8.2	16.1	4.4	25-30	
III-3	4.6	14.32	0.42	2	6 main zone injectors fuels at climb & SLTO. All pilot approach.
III-4 & 5*	5.1	14.5	1.5	2	3 main zone injectors fueled at approach, climb and SLTO.
III-3 & 4	4.2	17.0	1.7	2	3 main zone injectors fueled at approach and 6 at climb and SLTO.

*Climb and SLTO emission indices from configuration III-5.

Table IV-11.

EPAP COMPARISON

Configuration	EPAP (lbm/lbf thrust-hr/LTO cycle)			Maximum SAE Smoke Number
	NO_x	CO	THC	
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25-30
Airblast Nozzle I-2	7.42	5.05	0.05	28
Carburetor Tube I-6	5.78	51.98	22.55	2
Advanced Vorbix II-9	4.38	8.93	0.18	27
Prevaporized, Premixed III-3	4.56	14.30	0.43	2

Table IV-12.

CROSS-SECTIONAL SCHEMATIC OF JT8D-17 ENGINE

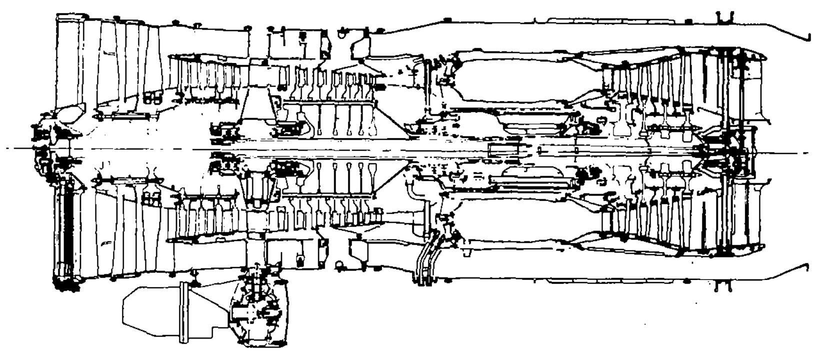


Figure IV-1.

CROSS-SECTIONAL SCHEMATIC OF BASELINE JT8D-17 COMBUSTOR

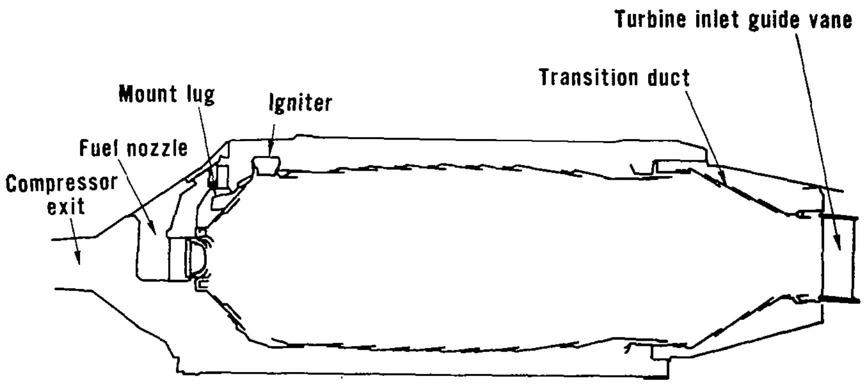


Figure IV-2.

CROSS-SECTIONAL SCHEMATIC OF JT8D COMBUSTOR RIG

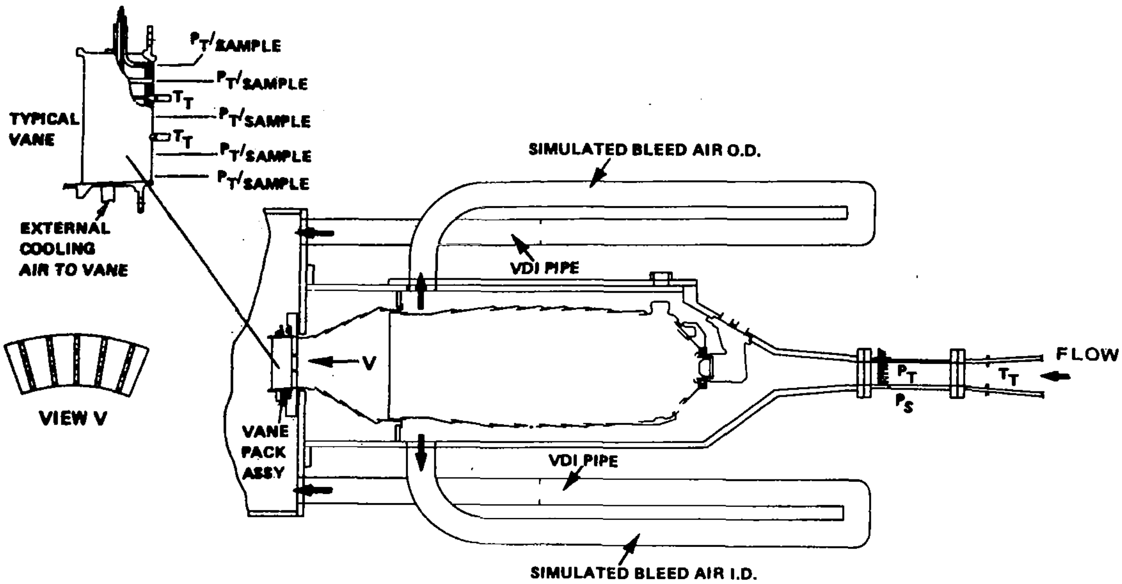


Figure IV-3.

COMBUSTOR EXIT INSTRUMENTATION VANE PACK

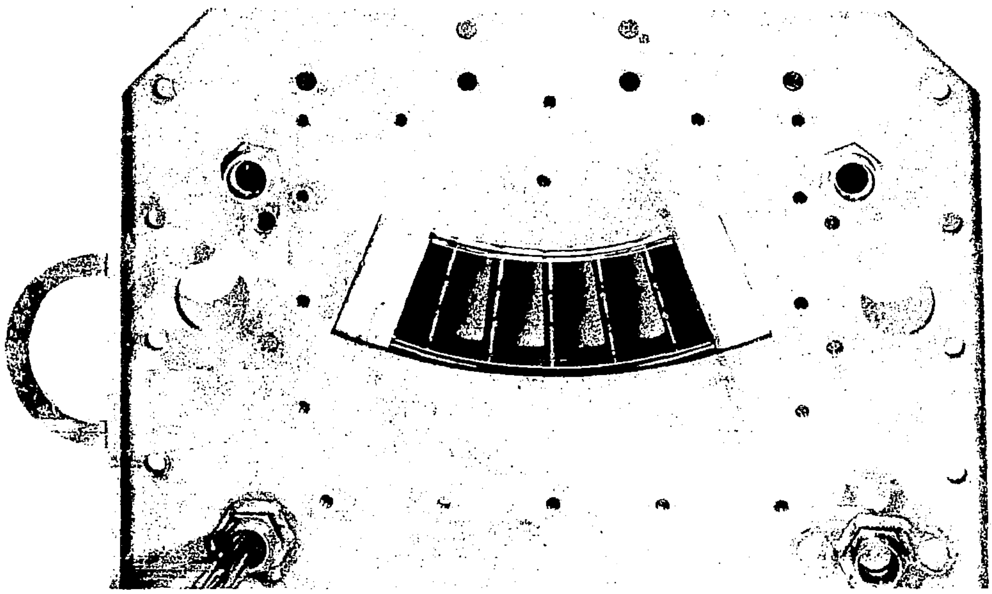
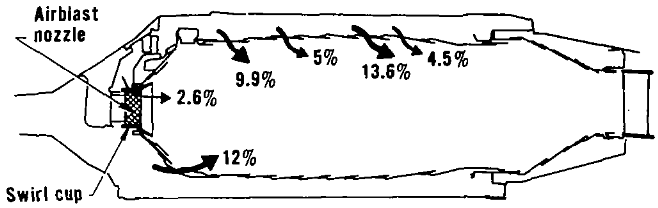
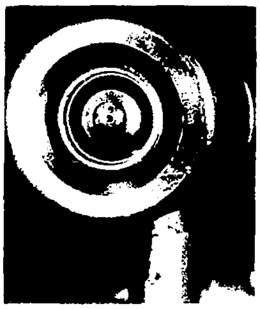


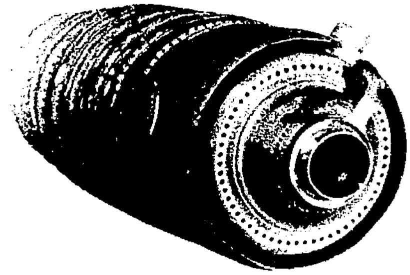
Figure IV-4.

ELEMENT I AIRBLAST NOZZLE CONFIGURATION I-4



Lean primary zone with airblast nozzle II

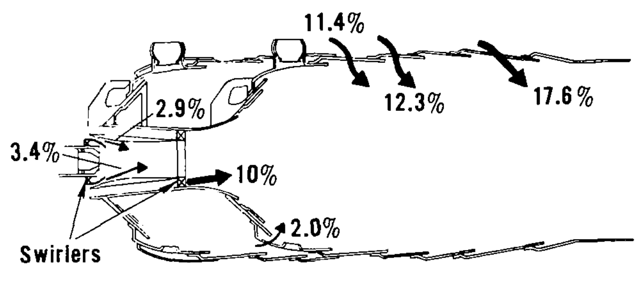


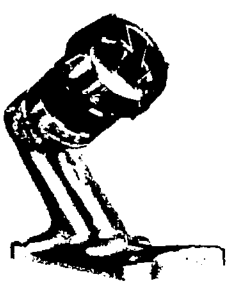


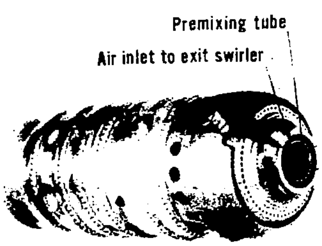
Nozzle II

Figure IV-5.

ELEMENT I CARBURETOR TUBE CONFIGURATION I-5



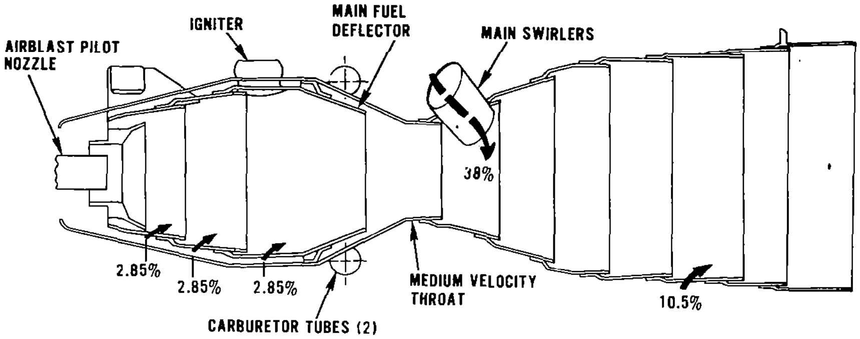




Nozzle and inlet swirler

Figure IV-6.

ELEMENT II VORBIX COMBUSTOR



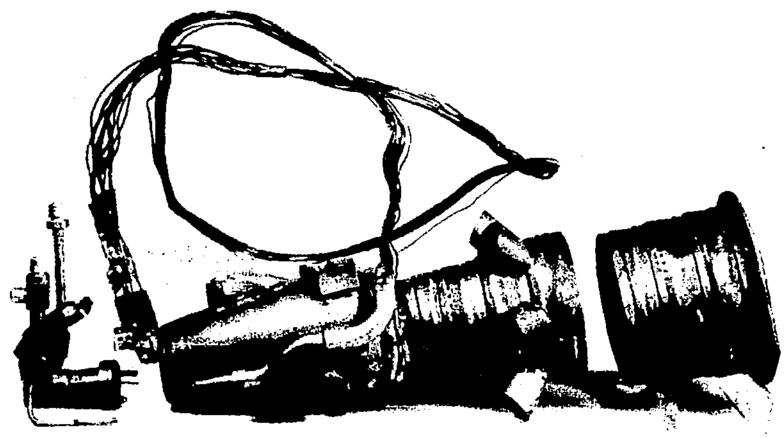
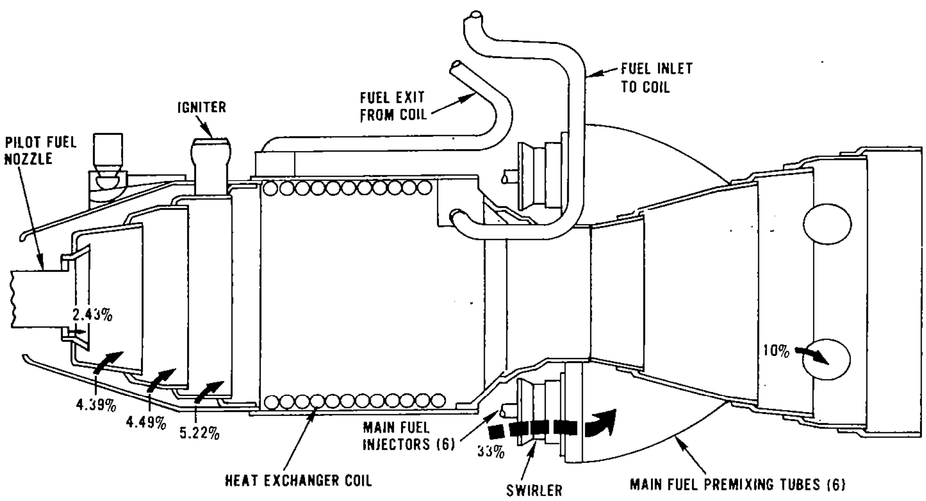


Figure IV-7.

ELEMENT III PREVAPORIZING - PREMIXING COMBUSTOR



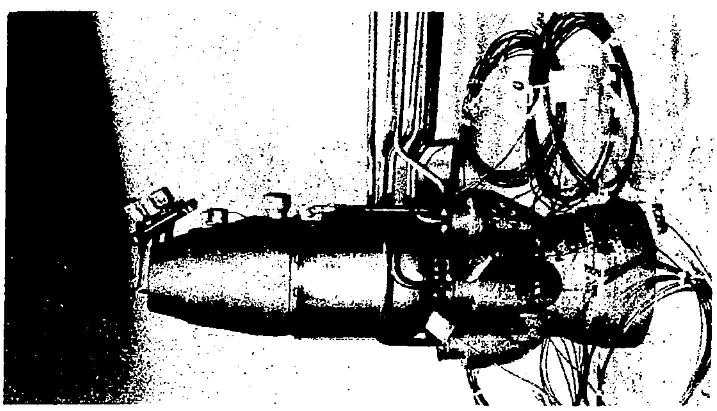


Figure IV-8.

ELEMENT I EMISSIONS AND SMOKE NUMBER AS FUNCTION OF PEAK EQUIVALENCE RATIO AT IDLE

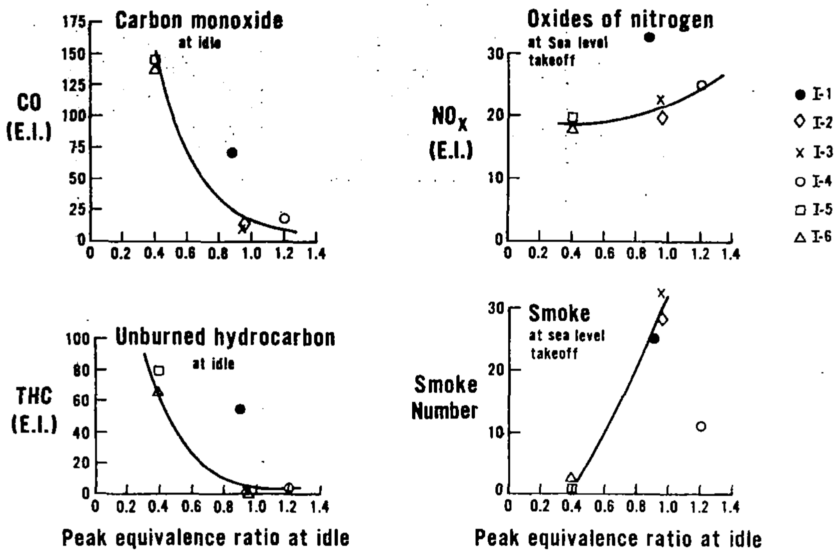


Figure IV-9.

EMISSIONS AT APPROACH, CLIMB, AND SLTO CONDITIONS AS FUNCTION OF PILOT-TO-MAIN FUEL FLOW SPLIT

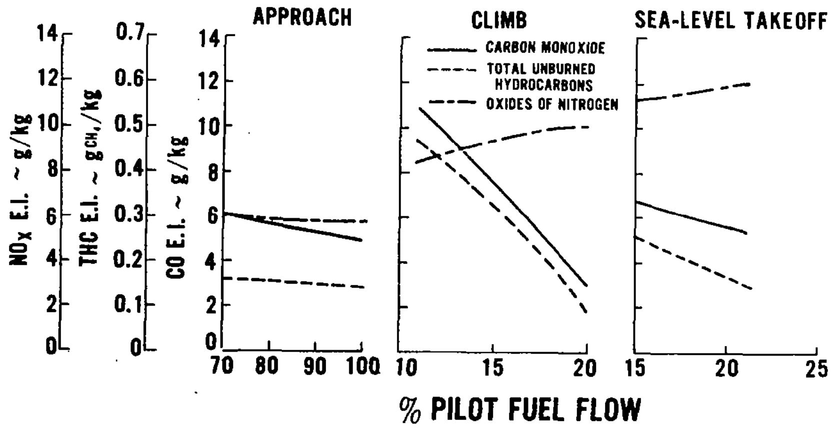


Figure IV-10.

ELEMENT II EMISSIONS LEVELS AS FUNCTION OF VARIATION IN THROAT VELOCITY

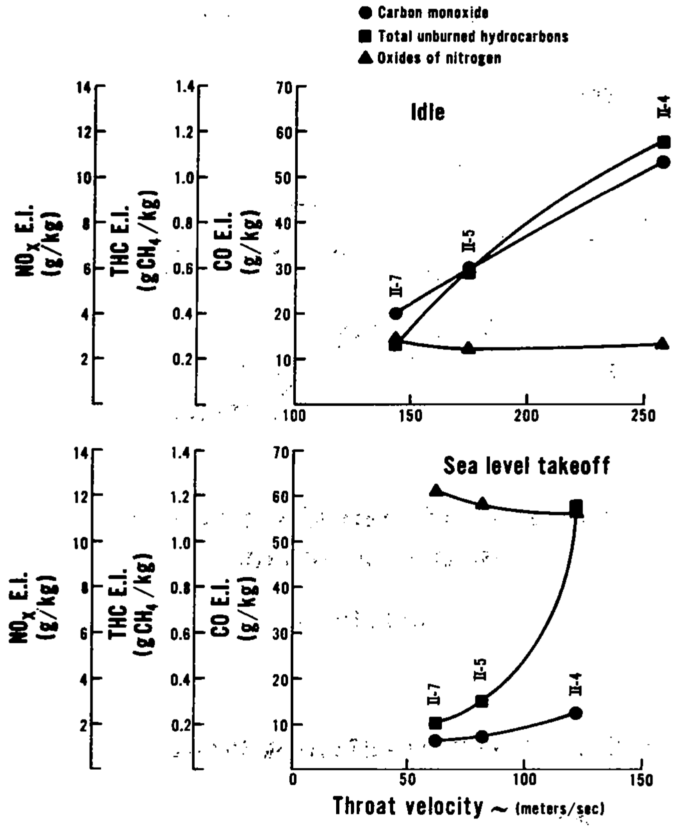


Figure IV-11.

SUMMARY OF NO_X EMISSION RESULTS AT SIMULATED ENGINE OPERATION

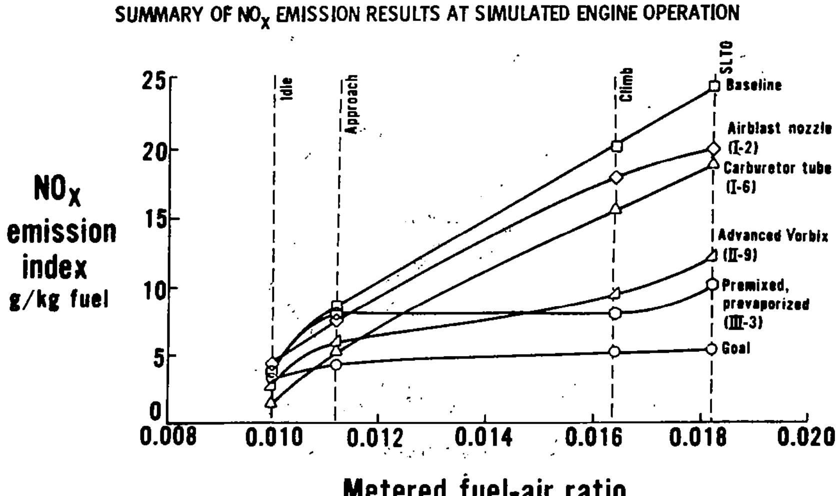


Figure IV-12.

SUMMARY OF CO EMISSION RESULTS AT SIMULATED ENGINE OPERATION

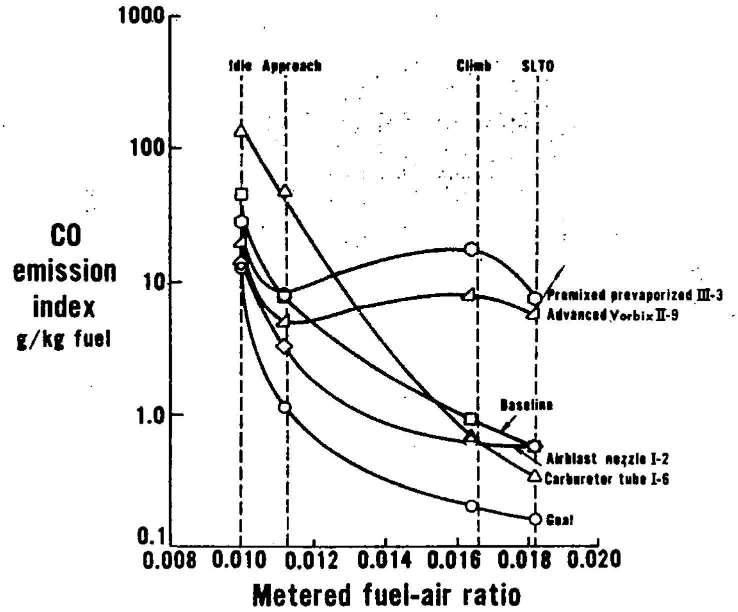


Figure IV-13.

SUMMARY OF THC EMISSION RESULTS AT SIMULATED ENGINE OPERATION

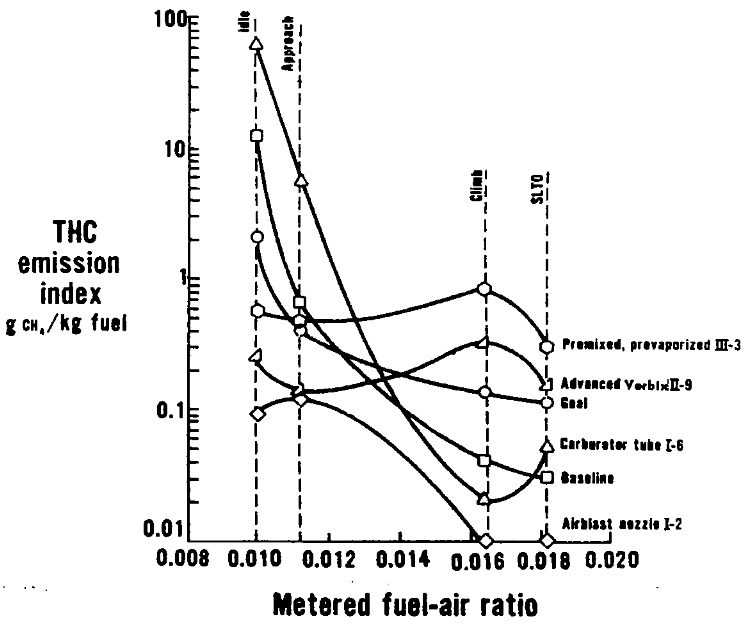


Figure IV-14.