

V. NASA/PRATT & WHITNEY EXPERIMENTAL CLEAN COMBUSTOR PROGRAM - ENGINE TEST RESULTS

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A two-stage Vorbix (vortex burning and mixing) combustor and associated fuel system components were successfully tested in an experimental JT9D engine at steady-state and transient operating conditions, using ASTM Jet-A fuel. Full-scale JT9D experimental engine tests were conducted in phase III of the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program (ECCP). The low-pollution combustor, fuel system, and fuel control concepts were derived from earlier phase I and phase II programs in which several combustor concepts were evaluated, refined, and optimized in a component test rig.

Concern with air quality in the vicinity of airports has led to the issuance of emission standards by the Environmental Protection Agency (EPA) for aircraft engines manufactured after January 1979 (ref. 1). These standards establish limits for the emission of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke at altitudes under 914 meters (3000 ft). Recently introduced gas turbine engines, such as the JT9D family, already meet the requirement for producing no visible smoke. However, compliance with the standards for the gaseous pollutants will require substantial improvements relative to current engine emission levels.

The rudiments of pollution control are understood; however, when incorporating pollution reduction features, aircraft combustors must also accommodate a diversified range of factors that greatly add to the development complexity of a practical low-emissions combustor system. Physical constraints on fuel vaporization, turbulent mixing rate, dilution air addition, and residence time impose absolute limits on the combustion process. Per-

formance requirements for uniform exit temperature distribution, combustion stability, relight capability, durability, and operational safety must also be considered. Furthermore, it is desirable to maintain component weight, costs, and mechanical complexity at a minimum.

Specific combustor-engine designs had not demonstrated the required pollutant reductions without compromising other performance parameters, indicating the need for additional technology. In response to this need, the National Aeronautics and Space Administration (NASA) initiated the Experimental Clean Combustor Program in December 1972, to be conducted in three phases culminating in testing of the single most promising combustor concept in a full-scale JT9D engine.

The Experimental Clean Combustor Program was begun in December 1972 and completed in November 1976. This major program was directed toward two primary objectives:

- (1) The generation of combustor system technology required to develop advanced commercial aircraft engines with lower exhaust pollutant emissions than those of current technology engines
- (2) The achievement of significant pollutant emission reductions and acceptable performance in a full-scale engine in 1976

The program was aimed at generating technology primarily applicable to conventional takeoff and landing (CTOL) type aircraft engines with high cycle pressure ratios in the range of 20 to 35. While the technology generated should be applicable to all advanced engines in the large-thrust category, design and development efforts were directed toward the Pratt & Whitney JT9D-7 engine model. The technology will also provide the foundation for developing further refinements and for identifying other avenues for continued exploration and experimental research. The program was divided into three phases as shown in the program schedule (fig. V-1).

Phase I consisted of screening combustor design approaches to identify the most promising concepts for refinement during phase II. Three advanced combustor concepts (swirl can, staged premix, and swirl vorbix) were tested in a 90⁰-sector component rig at simulated engine idle and sea-level-takeoff conditions. The results of phase I are discussed in detail in references 2 and 3.

The phase II program involved refinement and optimization of the most promising concepts identified in phase I. The concepts selected for phase II

were the Vorbix combustor and a hybrid combustor created by merging the pilot zone of the staged premix combustor with a main burning zone derived from the swirl-can combustor. After initial testing, the program was reduced to the Vorbix combustor concept and the remaining test effort was devoted to developing performance characteristics in preparation for the phase III engine tests. A fuel control design study was also conducted to establish fuel management requirements for two-stage combustors. Results of the phase II program are presented in references 4 to 6.

The phase III program, just completed, consisted of a detailed evaluation of the most promising phase II combustor concept in a JT9D engine. The objective was to achieve significant pollution reductions with an advanced combustor that meets the performance, operating, and installation requirements of the engine. The test program included steady-state pollution and performance evaluations, as well as transient acceleration and deceleration engine operation. The results of the phase III work are summarized in this paper and will be discussed in detail in reports to be published in the near future.

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

PROGRAM GOALS

Program goals were defined for both pollutant emissions and combustor aero-thermodynamic performance. The goals for gaseous pollutants and smoke represent the primary program focus. The performance goals were set to ensure that the reductions in pollutant emissions are not achieved at the expense of performance. All goals are predicated on the use of commercial-grade Jet A aviation turbine fuel.

Pollution Goals

The gaseous pollutant emission goals are summarized in table V-1. The goals are expressed as integrated EPA parameter (EPAP) values. The EPA parameter (ref. 1) is a thrust-normalized measure of the total mass of

pollutant emitted in a prescribed landing/takeoff (LTO) cycle. In general, because of the characteristics of aircraft engines and their operational relationships to the LTO cycle, effective emissions control must be primarily directed toward reducing CO and THC at low power and NO_x at high power. As shown by comparing the goals with the current production JT9D-7A engine emissions, attaining these goals involves significant pollutant reductions, by factors of 2.2 to 6 on the EPAP basis. The exhaust smoke goal is expressed as a maximum SAE smoke number that approximates the threshold of visibility for engines in the JT9D thrust class. The maximum value typically occurs at the sea-level-takeoff power setting. The current JT9D engine family meets this requirement with margin.

Performance Goals

The key combustor performance goals are presented in table V-2. The goals do not represent an appreciable departure from current JT9D-7 operating levels, with the exception of the pattern factor and the combustion efficiency at idle engine conditions. Implicit in the goal for exit temperature pattern factor is the achievement of an average radial temperature profile at the combustor exit that is substantially equivalent to that produced by the current production JT9D-7 combustor. The goal for combustion efficiency of 99 percent or better at all operating conditions ensures that the reduction in NO_x emissions is not achieved at the cost of engine efficiency.

An additional performance goal is the requirement that the combustor mechanical durability be consistent with long-term engine operation, equivalent to the current JT9D-7 combustor. This goal encompasses structural integrity, liner coolant air level, liner pressure drop, fuel-system metal temperature, etc.

REFERENCE ENGINE AND COMBUSTOR

The JT9D-7A engine was selected as a reference for the Experimental Clean Combustor Program. This model is one of the current versions of the JT9D engine, which has acquired widespread acceptance as the powerplant

for Boeing 747 and Douglas DC-10 wide-bodied aircraft. The JT9D-7A engine is an advanced high-bypass-ratio, dual-spool, axial-flow turbofan engine. The mechanical configuration is shown in figure V-2. The low-pressure spool consists of a single-stage fan and a three-stage low-pressure compressor driven by a four-stage low-pressure turbine. The high-pressure spool consists of an 11-stage high-pressure compressor driven by a two-stage high-pressure turbine.

The mechanical design of the JT9D-7A reference diffuser-combustor is shown in figure V-3. The combustor is of an annular configuration and incorporates a number of advanced features. The combustor consists of two assemblies: the outer liner and head plate, and the inner liner. The outer liner is positioned by 10-radial pins extending inward from the diffuser case to mount lugs integral with the combustor head. The inner liner is supported at the rear as part of the assembly containing the turbine inlet guide vanes. Slip joints are provided at the junction of the inner liner and head plate and at the aft end of the outer liner to allow for thermal expansion.

The primary diffuser incorporates an inner ramp and an outer trip followed by a dump section. A burner hood is used to provide a positive pressure feed to the combustor front end. The hood is indented locally in 10 places downstream of each diffuser case strut. A film-cooled louver construction is used for the combustor liners. Fuel is introduced through 20 duplex pressure-atomizing nozzles equally spaced around the engine circumference at the diffuser exit. The nozzle portions of the fuel injectors are enclosed in 20 conical swirler modules, which provide primary-zone flame stabilization.

The overall length of the diffuser combustor section (between the trailing edge of the compressor exit guide vanes and the leading edge of the first turbine inlet guide vane) is 0.58 m (23.0 in.). The burning length between the fuel nozzle face and turbine inlet guide vane leading edge is 0.45 m (17.6 in.). Minimum and maximum diameters are 0.62 m (24.3 in.) and 1.07 m (42.2 in.), respectively.

PHASE III TEST HARDWARE

Vorbix Combustor

A cross-sectional drawing of the phase III Vorbix (vortex burning and mixing) combustor is shown in figure V-4. A front view of the pilot fuel system arrangement and the circumferential location of the pilot and main fuel injectors is shown in figure V-5. Figure V-6 shows the outer combustor liner and head assembly after installation of the hood. The inner combustor liner is shown in figure V-7 mounted on the instrumented first-stage turbine vane assembly.

The Vorbix concept incorporates two burning zones separated axially by a high-velocity throat section. The pilot zone is a conventional swirl-stabilized, direct-injection combustor employing 30 fuel injectors. It is sized to provide the required heat release rate for idle operation at high efficiency. Emissions of carbon monoxide and unburned hydrocarbons are minimized at idle operating conditions primarily by maintaining a sufficiently high pilot-zone equivalence ratio to allow complete burning of the fuel.

At high-power conditions, the pilot exhaust equivalence ratio is reduced as low as 0.3 (including pilot dilution air) to minimize NO_x formation. The minimum equivalence ratio for the pilot zone is determined by the overall lean blowout limits, the combustion efficiency, and the need to maintain sufficient pilot-zone temperature to vaporize and ignite the main-zone fuel. Main-zone fuel is introduced through fuel injectors located at the outer wall of the liner downstream of the pilot-zone discharge location. Sixty fuel injectors are used. Main-zone combustion and dilution air is introduced through 60 swirlers positioned on each side of the combustor (120 total).

The phase III combustor design was based on the final phase II rig configuration. Minor adjustments were made to the liner cooling airflow distribution based on temperature measurements made during the final phase II rig tests. Additionally, total liner metering area was reduced slightly to increase liner pressure loss. A close correspondence between the engine and rig hardware was felt to be necessary in order to provide maximum assurance that the extrapolated rig results could be achieved in the engine.

The combustor cooling louver construction, cooling air levels, and liner material are representative of current production engine technology. This

cooling technology is projected to provide adequate durability for the JT9D-7A cycle pressure ratio and combustor temperature rise.

Minor geometric changes were required in areas such as pilot swirler radial travel and to incorporate the JT9D-7 production mounting and slip joint arrangement. Combustor liners, hood panels, thrust cooling scoops, and fuel injector supports were designed to avoid low-order, engine-excited resonance. Where the uniqueness of the Vorbix design (requiring experimental structural development work) or constraints of cost and time prevented designing to the program life goals, minimum criteria of 100 hours and 1000 cycles were chosen for satisfying the requirements of the phase III test program.

Fuel Control

A fuel control design study was conducted as part of phase II (ref. 4) to identify control system requirements added by the staged combustor concepts developed in the Experimental Clean Combustor Program. A number of conceptual designs that satisfy the functional requirements were specified, and the most promising concepts were selected on the basis of available technology and estimated life cycle cost. A breadboard control system design, involving modification of the current JT9D fuel control, was specified for the phase III engine test program.

The two-stage Vorbix combustor is characterized by two separate combustion zones and two physically separate sets of fuel injectors and manifolding. Since each combustor zone must be operated within generally narrow limits for optimum emission formation and combustion efficiency, fuel distribution to each zone must be based on engine fuel-air ratio rather than on total fuel flow. In addition, a number of mechanical constraints such as maximum fuel pump pressure, minimum controllable flow rate, fuel nozzle turn-down ratio, and manifold head effect act to further limit the fuel control designer's freedom in varying pilot-to-main fuel distribution. Specification of the pilot-to-main fuel split for the Vorbix combustor operating at sea level is shown in figure V-8. Minimum and maximum limits are imposed on the pilot-zone fuel-air ratio to prevent lean blowout and excessive thermal stresses in the pilot zone. These limits were developed from the phase II

combustor rig testing and define the practical operating envelope that can be used for pilot-to-main zone fuel schedule optimization in the engine.

An additional requirement imposed by the staged Vorbix combustor is that passage through the staging point (transition from pilot-only to pilot-plus-main-zone operation) must be accomplished in a rapid and continuous manner. This is required for reasons of flight safety and is specified by the FAA airworthiness standards (ref. 7) in terms of a 5-second maximum allowable elapsed time for engine acceleration from flight idle to 95-percent thrust. The current production JT9D-7 fuel system is fully staged at ground idle, thereby eliminating "fill time" delays associated with the volume of the secondary fuel manifold, distributions tubes, and fuel nozzle supports. However, the Vorbix combustor must stage between the idle and approach operating conditions. Uncompensated manifold fill time delays will seriously impact engine transient response. For this reason, the breadboard control design provides continuous fuel recirculation through the main fuel manifold when the engine is operating on pilot only.

TEST CONDITIONS AND PROCEDURES

Steady-State Testing

The phase III engine tests were conducted in a manner similar to other JT9D experimental engine tests at Pratt & Whitney Aircraft. Test-stand inlet conditions are not artificially controlled so that the engines are run during various ambient temperature and barometric conditions and rarely on a "standard" day. Engine performance parameters are normally corrected to standard-day conditions. Since the nature of this program was oriented to measurement of emissions at specific power levels, the steady-state emissions data were taken for most points by establishing the combustor inlet temperature level, regardless of ambient conditions. The standard-day JT9D-7A gas generator reference conditions are tabulated in table V-3 for the four EPA-specified sea-level-static power settings. The emissions data were corrected from the observed combustor inlet conditions to the corresponding standard-day reference conditions for presentation in this paper. Additional test points were added as required during the engine test run depending on emis-

sions data obtained or combustion efficiency or to set a specific value of another engine parameter, such as corrected thrust. Variation of the pilot-to-main fuel split is primary test variable at the higher engine power settings. Following an approximately 5-minute stabilization period at each test point, a set of engine performance data, combustor section pressure and temperature data, combustor exit temperature data, and exhaust gas emissions data was simultaneously recorded. For steady-state testing with the exit thermocouple instrumentation in place, the engine power level was limited so as not to exceed 1839 K (2850° F) gas temperature on the turbine inlet guide vanes or the redline limit for the engine exhaust gas temperature (EGT).

Exhaust gas sampling instrumentation. - Most of the exhaust gas sampling was done with an eight-arm rake mounted in the core engine exhaust stream 0.36 m (14 in.) downstream of the exhaust nozzle exit plane. The unmounted rake, shown in figure V-9, was designed for use with a JT9D experimental tailpipe (cylindrical section). Twenty-four sampling ports are located on eight radial arms at the centers of equal areas. The sampling ports are manifolded such that by sampling at different connections, gas samples can be taken from either four or eight equally spaced arms (12 or 24 sample ports). The sampling rake was also mounted on a traverse gear that permitted rotation over a 45° arc in 5-degree increments. Data were recorded using these alternative rake configurations for comparison with the stationary eight-arm baseline configuration.

An additional exhaust gas sampling system used for comparison purposes in the phase III ECCP test program consisted of the standard production engine exhaust total pressure probes (PT₇). These were manifolded to deliver a single gas sample to the analysis equipment. The circumferential and radial positions of the sampling ports are shown in figure V-10.

Data reduction procedure. - The raw emissions data 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 ratio, and combustion efficiency. The emission index and carbon balance fuel-air ratio calculations were performed in accordance with the procedures established in SAE ARP 1256 (ref. 8).

To compare combustor engine emissions data between runs and with the JT9D-7A production baseline, it was necessary to correct emissions data to the standard conditions listed in table V-3. The basis for setting most test points was combustor inlet temperature T_{t4} . All adjustment of observed emissions data was made relative to the observed value of combustor inlet temperature, thereby obviating the need to make an inlet temperature correction. Curves of combustor inlet pressure and fuel-air ratio versus inlet temperature were generated for the reference JT9D-7A engine operating at standard-day ambient conditions. The magnitude of corrections required was determined by comparing the observed and reference parameter values at the observed value of inlet temperature.

Comparison of observed and reference combustor operating conditions for the steady-state tests revealed that only inlet pressure deviated significantly (up to 15 percent) from the reference engine characteristics. Fuel-air ratios were within 3 percent of standard engine values. In view of the relative imprecision of currently available fuel-air ratio correction factors and the demonstrated dependence on combustor configuration, it was decided to correct the gaseous emissions data only for deviation in combustor inlet pressure. In addition, the NO_x data were corrected to a standard inlet air humidity of 6.3 g $\text{H}_2\text{O}/\text{kg}$ dry air. The data adjustment equations for the gaseous emission species are as follows:

$$\text{NO}_{x, \text{corr}} = \text{NO}_{x, \text{meas}} \frac{(P_{t4, \text{std}})^{0.5}}{P_{t4, \text{meas}}} e^{0.0188(H_{\text{meas}} - 6.3)} \quad (1)$$

$$\text{CO}_{\text{corr}} = \text{CO}_{\text{meas}} \frac{P_{t4, \text{meas}}}{P_{t4, \text{std}}} \quad (2)$$

$$\text{THC}_{\text{corr}} = \text{THC}_{\text{meas}} \frac{P_{t4, \text{meas}}}{P_{t4, \text{std}}} \quad (3)$$

where

NO_x emission index of oxides of nitrogen, g/kg fuel
CO emission index of carbon monoxide, g/kg fuel
THC emission index of total hydrocarbons, g/kg fuel
 P_{t4} combustor inlet total pressure
H inlet specific humidity, g H_2O /kg air
corr relates to corrected value
meas relates to value at measured condition
std relates to value at standard condition

Exhaust smoke data are presented on an as-recorded basis. Smoke numbers were not corrected for either pressure or fuel-air ratio since sufficiently accurate techniques are not currently available.

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

$$\text{EPAP}_i = \frac{\sum_1^j \frac{t_j}{60} W_{F,j} \text{EI}_{i,j}}{\sum_1^j \frac{t_j}{60} F_{N,j}} \quad (\text{lbm pollutant}/1000 \text{ lbf thrust-hr}/\text{LTO cycle}) \quad (4)$$

where

EI emission index, lbm pollutant/1000-lbm fuel
t time at engine mode, min
 F_N net thrust, lbf
 W_F fuel flow rate, lbm/hr
i emission category (CO, THC, NO_x)
j engine mode (idle, approach, climb, SLTO)

Substituting JT9D-7A performance data into equation (4) yields

$$EPAP_i = 0.158 EI_{idle} + 0.072 EI_{approach} + 0.114 EI_{climb} + 0.0441 EI_{SLTO} \quad (5)$$

The emission indices used in equation (5) were obtained from plots at the four JT9D-7A combustor inlet temperatures corresponding to the EPA power points (table V-3).

Transient Testing

Engine acceleration and deceleration tests were conducted following completion of the steady-state emissions and performance testing to determine transient characteristics of the two-stage Vorbix combustor and fuel system. The testing consisted of a series of progressively more rapid engine accelerations from an idle setting to 95-percent rated thrust and deceleration back to idle. Testing was conducted from both ground idle (fuel-air ratio, 0.0105) and a simulated flight idle (fuel-air ratio, 0.0115) power settings. The "snap" acceleration test requires that the power lever be advanced from the selected idle position to the full-power position in 1 second or less.

RESULTS AND DISCUSSION

The phase III program accumulated approximately 82 hours of engine testing, consisting of 8 hours of shakedown testing, 56 hours of steady-state performance and emissions data acquisition, and 18 hours of acceleration and deceleration testing. Testing of the first configuration, S25E, was limited to intermediate- and low-power levels by local liner overheating. The two subsequent configurations, however, were successfully tested at power levels through full sea-level-takeoff combustor inlet temperatures and fuel-air ratios. The data presented in this paper have been confined to those which substantiate the major accomplishments of the program and therefore consist primarily of reduced and analyzed data for the final (S27E) combustor configuration.

Emissions Results

The primary emphasis of the emissions data analysis was the determination of the engine emissions characteristics. Also determined were the effects of ambient operating conditions, emission sampling technique, and pilot-to-main zone fuel split on both the levels of each emissions species and the possible trades among the species. These results were then analyzed to calculate the optimum EPAP's and smoke numbers to relate the emissions performance to the program goals.

The EPAP's and smoke numbers obtained for the final Vorbix combustor configuration (S27E) using the optimum fuel flow split between the pilot and main zones are shown in table V-4 together with the corresponding program goals and the values for the current JT9D-7A. As shown, the Vorbix combustor met the goals for all three gaseous emission species. Oxides of nitrogen emissions were 10 percent below the goal, carbon monoxide emissions were 26 percent below the goal, and total unburned hydrocarbon emissions were 75 percent below the goal. Relative to the JT9D-7 combustor, NO_x emissions were reduced by 58 percent, CO emissions were reduced by 69 percent, and THC emissions were reduced by 96 percent. The smoke emissions goal was not achieved. Smoke levels were substantially above those for the current JT9D-7A combustor. Smoke numbers were not corrected for either pressure or fuel-air ratio since sufficiently accurate techniques are not currently available. However, the corrections required are believed to be very small (of the order of 3 percent) for each parameter.

The emissions data were analyzed to develop parametric curves relating the pilot-zone fuel-air ratio to the emissions of each species as a function of power setting, with the power setting defined in terms of the observed combustor inlet temperature. Results, shown in figure V-11, consist of parametric, emissions curves plotted against combustor inlet air temperature for various pilot-zone fuel-air ratios.

The curves show that smoke number reached a maximum value at the sea-level-takeoff power setting and was insensitive to pilot-zone fuel-air ratio at that condition. At lower power settings, smoke number decreased with increasing pilot-zone fuel-air ratio. The NO_x emissions showed a reverse trend, with the emissions increasing with increasing pilot-zone fuel-air ratio, but the sensitivity was relatively small. Oxides of nitrogen

levels at all pilot-zone fuel-air ratios were sufficiently low to permit achievement of the program EPAP goals. Carbon monoxide emissions were lower at the higher power settings, with the lowest values being obtained at the higher pilot-zone fuel-air ratios. On the basis of the smoke data, described in figure V-11, and analysis of exit temperature distribution effects, the highest pilot-zone fuel-air ratio (0.0070) was selected for the EPAP calculation for the high-power portion of the power spectrum from approach through sea-level takeoff. A pilot-zone fuel-air ratio of 0.0095 was selected below approach down through the flight idle power setting. This upward shift in pilot-zone fuel-air ratio reduced carbon monoxide and total hydrocarbon emissions. Exhaust smoke is not a concern below approach power. Below the flight idle power setting only the pilot zone is fueled.

These selections result in two discontinuities in the pilot-to-main zone fuel split. The first discontinuity, occurring immediately below the flight idle power setting, represents staging of the main zone. This is unavoidable since a minimum step increase in fuel flow is required to ignite the main zone because of physical fuel system constraints such as minimum metered fuel and manifold gravity head. It is significant, however, that the Vorbix combustor can be operated fully staged down to the flight idle power setting while maintaining a combustion efficiency level (in terms of CO and THC emissions) comparable to or better than that of the current production JT9D-7A combustor. This capability eliminates the need for combustor staging and the associated system lag within the flight regime, which is important from both an engine operational and a flight safety standpoint. The second discontinuity, occurring immediately below the approach power setting, reflects the manner in which the parametric curves were prepared for the analysis rather than a real engine requirement. The control system for the engine could provide a constantly varying pilot-zone fuel-air ratio to eliminate the discontinuity. The effect on emissions would be relatively small.

The selected fuel splits provide large reductions in the gaseous emissions of the Vorbix combustor relative to the emissions of the JT9D-7A. As shown in figure V-12, large reductions were achieved in NO_x emissions at high-power settings and in CO and THC emissions at low power settings.

Gas Sampling Techniques

Five gas sampling techniques were used to obtain the engine exhaust emissions data. The techniques and their symbol designations are defined in table V-5. With the exception of the station 7 engine pressure probes, all are variations of the basic eight-arm rake.

In comparing the results obtained with the various techniques, the 24-point, stationary 8-arm rake (24F) was used as the baseline since the majority of the experimental data were acquired in this manner. The comparisons were made by plotting the corrected emissions data obtained with each technique against the corrected emission value obtained with 24F at the same engine operating conditions. The resulting plots are shown in figures V-13, -14, and -15. As shown, the data obtained from the various rakes for NO_x emissions are in excellent agreement. For CO emissions, 24E generally provided lower indications than the other rakes by approximately 10 percent. The station 7 probe (rake ST7) produced the largest difference, averaging indications that were approximately 11.5 percent above those of the baseline rake. The total unburned hydrocarbon emissions data appear to indicate a large amount of data scatter. However, this scatter results in large part from inaccuracies associated with measurement of the very small concentrations of unburned hydrocarbons produced by the Vorbix combustor.

Smoke measurements were made with both the 12- and the 24-point fixed rakes (rakes 24F and 12E); the results were nearly identical.

The conventional measure of gas sample validity is comparison of the metered fuel-air ratio based on direct measurement of the engine fuel flow and core mass flow with the calculated fuel-air ratio based on the carbon balance of the exhaust gas species concentrations detected by the sampling probe. Data for this comparison are presented in figure V-16 and show that gas sampling provided carbon balance fuel-air ratios that were within 5 percent of those obtained by direct measurement. The probes generally provided values that were slightly above those determined by direct fuel flow and airflow measurement. Rake ST7 provided the greatest deviation.

The effects of rake blockage were determined by analyzing the engine performance data obtained with and without the rake installed. This analysis detected no measureable effect on performance attributable to the rake installation used in the program.

Performance Status

Combustion efficiency met the program goal of 99 percent at all power levels. Additionally, pressure loss, idle stability, main-stage ignition and combustion instability currently satisfy performance requirements. As indicated in table V-6, five categories have been identified as requiring normal development. This is taken to mean that acceptable performance is judged to be within reach after suitable development. These categories are discussed here.

Pattern factor and radial profile. - Although pattern factors equal to or lower than the current JT9D-7 production values were obtained, the program goal of 0.25 was not achieved. At a pilot-zone fuel-air ratio of 0.007, the pattern factor was approximately 0.4. The average radial temperature profile was slightly too high on the outside diameter at the 0.007 pilot-zone fuel-air ratio setting.

Transient acceleration. - Acceleration times achieved are shown in figure V-17. Although it equaled the ECCP goal, and thereby satisfied the FAA requirement, when it was accelerated from a fully staged flight idle condition, the Vorbix combustor/experimental engine X-686 was deficient when compared with current production JT9D-7A engines. When it was accelerated from an unstaged (pilot zone only) flight idle condition, acceleration time was increased by over 1 second. Since the main-zone manifold carried recirculating flow, this additional time is the time required to fill the fuel injector supports and jumper tubes downstream of the staging valves. Additional development and possible fuel system redesign will be required to reduce the acceleration time to the production engine levels.

Liner carbon deposits and liner durability. - The Vorbix combustor exhibited localized carbon deposition near the pilot- and main-zone fuel injectors, attributable to fuel entrainment in "dead" flow regions, and on the downstream portion of the pilot-zone liners, attributable to fuel spray impingement. In addition, local liner overheating was observed at the inside-diameter throat louver and on the outside-diameter downstream of the main-zone swirlers. With the exception of fuel impingement, problems of this type are treated by localized redistribution of liner cooling and purge airflow.

Two categories have been identified where extensive additional development work is required. In this context, extensive development may be synonymous with design changes.

Sea-level starting. - The starting problem is a consequence of meeting pilot-zone maximum fuel flow requirements with a simplex (single passage) pressure-atomizing nozzle. Fuel pressure drop at the nominal starting fuel flow is very low providing poor atomization quality. When 20 of the 30 pilot injectors were turned off to raise nozzle pressure drop, a propagation problem took the place of the lighting problem. Correction of this deficiency will require fuel system design changes, such as higher-pressure-drop and/or increased-spray-style fuel nozzles.

Fuel passage coking. - Main-zone fuel injector support and nozzle tip coking occurred from overheating of residual fuel following shutdown of the main zone. Since the pilot- and main-zone injectors are axially separated, the main injectors do not benefit from the coolant effects of the continuous pilot flow. While the problem will be ameliorated somewhat by running fully staged at all low-altitude flight conditions, it will still exist at high-altitude flight idle descent, where low fuel flow will require that the main zone be shut down. The solution will probably require external cooling of the main-zone fuel support and/or incorporation of an effective purge system.

Two additional performance categories were not investigated in the phase III ECCP testing. These are altitude engine operation, including altitude relight, and long-term hardware durability cyclic endurance testing. However, the difficulties encountered in sea-level starting and the phase II altitude relight rig results (ref. 4) suggest that there are problems to solve in this area.

CONCLUDING REMARKS

The results presented in this paper along with addendum reports, complete the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program. This major program has proceeded in three phases from concept screening through rig development to successful full-scale engine testing of an advanced, low-emissions combustor concept in the Pratt & Whitney Aircraft JT9D-7 engine. While exhaust smoke level and several performance items did not completely achieve the program goals, the carbon monoxide, total hydrocarbons, and oxides of nitrogen emission goals were met and combustor performance was adequate for full-power engine testing. Altitude re-

light performance of the final Vorbix combustor configuration tested in the engine was not evaluated.

Additional Vorbix combustor improvements in the areas of exit temperature distribution, transient acceleration, liner coke deposits, and liner overheating will be needed to satisfy production engine requirements. These can probably be obtained through the normal development effort conducted for production incorporation of any new combustor.

Problems with smoke emissions, sea-level starting, and secondary fuel system coking will probably require extensive efforts for their solutions. Because solutions may require significant modifications to the Vorbix combustor design, they should be developed prior to the initiation of the normal development effort for production incorporation.

The impact on gaseous emissions of modifications to the Vorbix combustor that may be required to resolve problems or to enhance its "practicality" cannot be predicted. Although future effort would strive to maintain the excellent gaseous emissions demonstrated in this phase III Experimental Clean Combustor Program, it may be necessary to define trade-offs between emissions and other requirements such as performance, durability, cost, and weight. The primary focus of the Experimental Clean Combustor Program was pollutant reduction within the JT9D-7A envelope and operating conditions, with a concept that would be acceptable for eventual production use. Weight and complexity, with associated hardware cost and aircraft payload penalties, were allowed to increase as necessary to achieve the primary goals. A breadboard fuel control system was used. If the Vorbix concept is selected for further development for a production application, an attempt should be made to simplify the design, to minimize weight and cost impact, and to improve maintainability while simultaneously addressing the deficient performance, emission, and life-limiting areas.

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3. Sofrin, T. S.; and Ross, D. A.: Noise Addendum, Experimental Clean Combustor Program, Phase I, Final Report. (PWA-5252, Pratt & Whitney Aircraft; NAS3-16829.) NASA CR-134820, Oct. 1975.
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7. Federal Aviation Regulations, Part 33, Airworthiness Standards, Aircraft Engines, Subpart E, Paragraph 33.73, Power or Thrust Response, January 1, 1974.
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POLLUTION GOALS AND CURRENT JT9D-7A LEVELS

Pollutant	EPA parameter, lbm pollutant/1000 lbf thrust/hr LTO cycle	
	Goal	Current JT9D-7A engine status
Oxides of nitrogen (as NO ₂)	3.0	6.5
Carbon monoxide	4.3	10.4
Total unburned hydrocarbons	.8	4.8
Maximum SAE smoke number	19	4

Table V-1.

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM PERFORMANCE GOALS

Maximum total pressure loss, percent	5.4
Exit temperature pattern factor at takeoff	0.25
Combustor efficiency, percent	99 or better at all operating conditions
Lean blowout fuel-air ratio	0.004 ± 0.001
Altitude relight capability altitude at flight Mach number 0.5 to 0.8, meters	9144

Table V-2.

STANDARD DAY JT9D-7A GENERATOR REFERENCE CONDITIONS

EPA power level	Thrust		Inlet fuel flow		Combustor inlet temperature		Combustor inlet pressure		Combustor fuel-air ratio
	N	lbf	kg/hr	lbm/hr	K	°F	N/m ²	psia	
Idle	14 234	3 200	780	1 720	447	345	3.69×10 ⁵	53	0.0105
Approach	61 585	13 845	2109	4 650	588	598	8.91	129	.0134
Climb	174 494	39 228	6010	13 250	736	864	19.38	281	.0206
Take off	205 284	46 150	7303	16 100	764	916	21.68	323	.0229

Table V-3.

EPAP AND SMOKE RESULTS

	EPA parameter ^a			
	Oxides nitrogen	Carbon monoxide	Total unburned hydrocarbons	Smoke number
ECCP phase III goal	3.0	4.3	0.8	19
Current JT9D-7A	6.5	10.4	4.8	4
Phase III combustor S27E	2.7	3.2	.2	30

^aEPAP values based on pilot fuel-air ratio of 0.0070 at approach, climb, and sea-level takeoff. All emissions data are corrected to standard JT9D-7A engine conditions and inlet humidity of 6.3 g H₂O/kg dry air. JT9D-7A data based on current production test results for engine with combustor EC 289386.

Table V-4.

GAS SAMPLING TECHNIQUE IDENTIFICATION

Symbol	Description
24F	24-Port, eight-arm, radial array, fixed
24T	24-Port, eight-arm, radial array, traversed over 45° in 5-degree increments
12S	12-Port, four-arm, cruciform oriented vertical and horizontal, fixed
12E	12-Port, four-arm, cruciform oriented 45° from vertical and horizontal, fixed
ST7	Six Station 7 pressure probes with eight radial pressure taps each

Table V-5.

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM VORBIX

CONFIGURATION S27E PERFORMANCE STATUS

	Currently satisfies requirements	Normal development required	Extensive 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	

Table V-6.

ECCP PROGRAM SCHEDULE

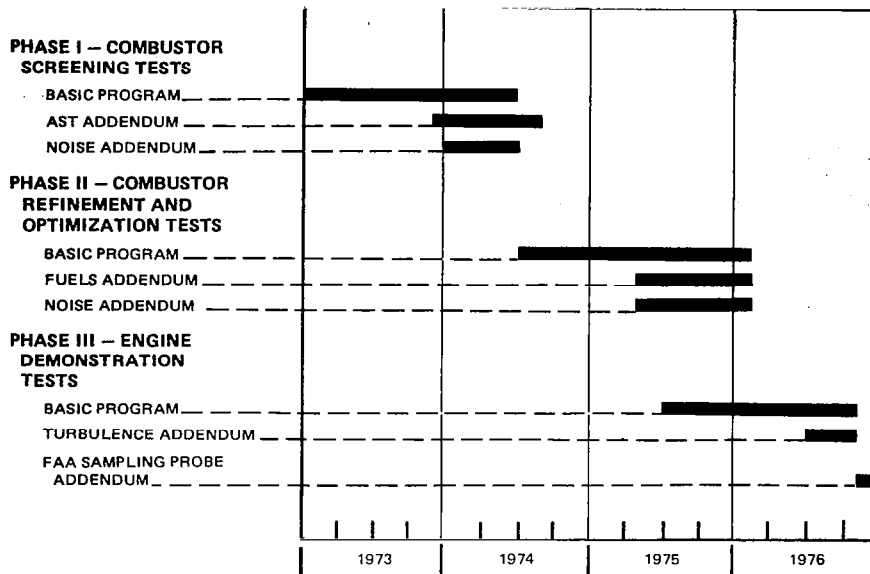


Figure V-1.

CROSS-SECTIONAL SCHEMATIC OF JT9D-7A REFERENCE ENGINE

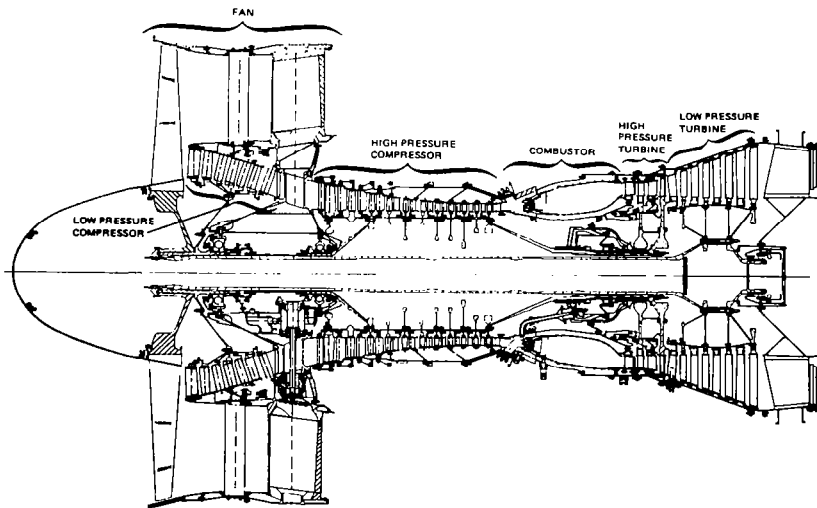


Figure V-2.

CROSS-SECTIONAL SCHEMATIC OF JT9D-7A COMBUSTOR

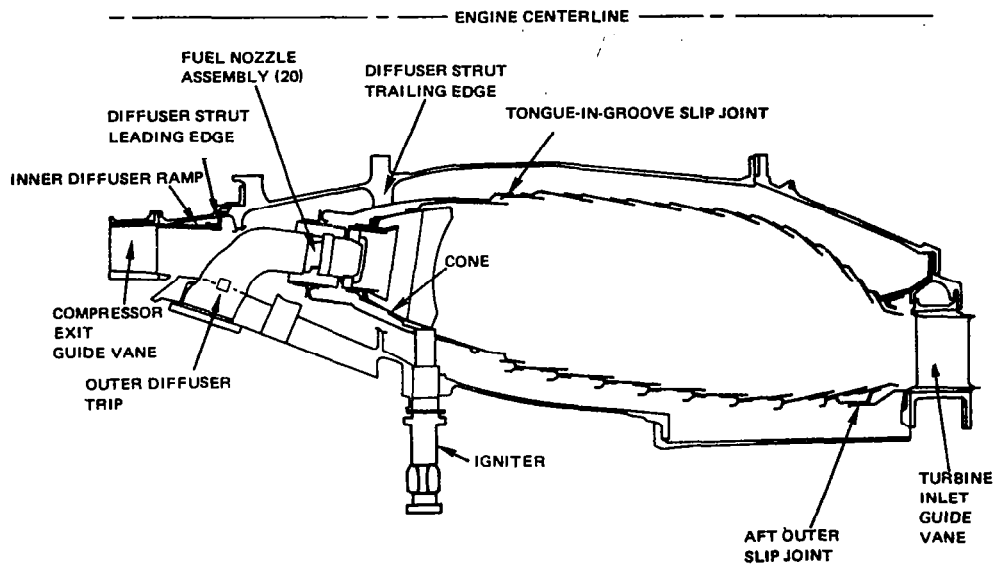


Figure V-3.

CROSS-SECTIONAL SCHEMATIC OF ECCP PHASE III VORBIX COMBUSTOR

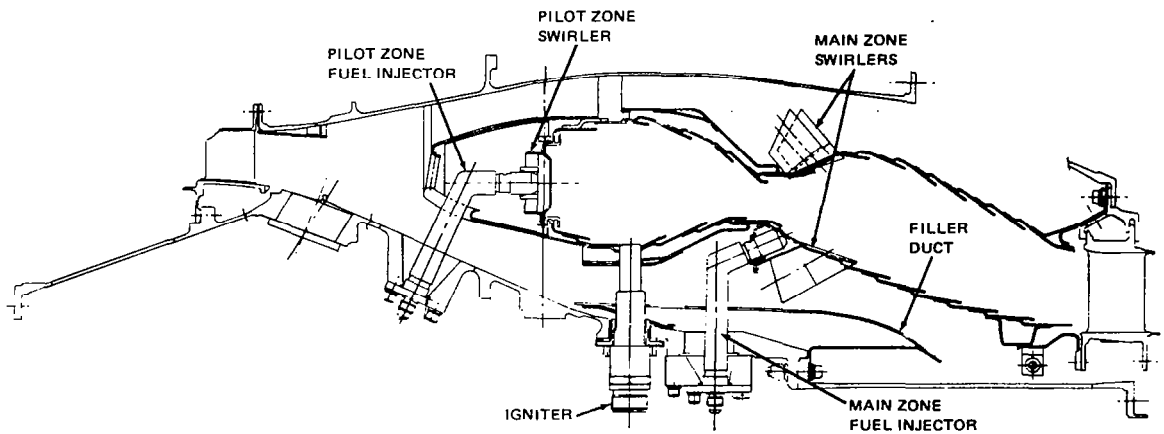


Figure V-4.

VORBIX COMBUSTOR FUEL INJECTOR ARRANGEMENT

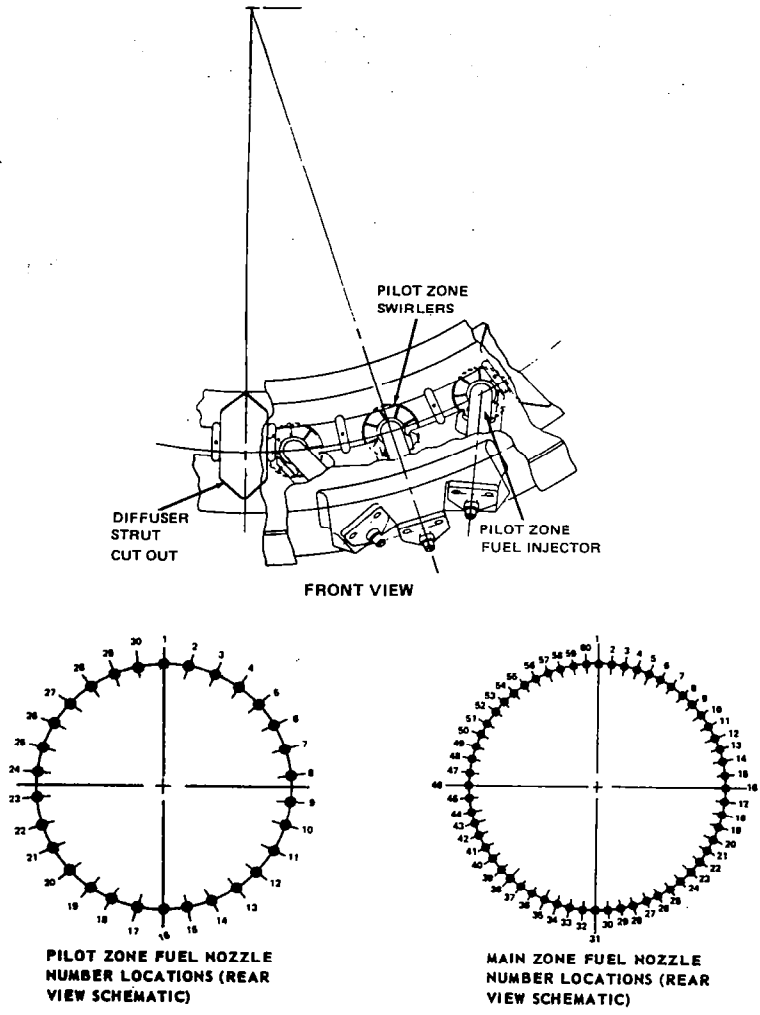


Figure V-5.

PHASE III VORBIX OUTER COMBUSTOR LINER

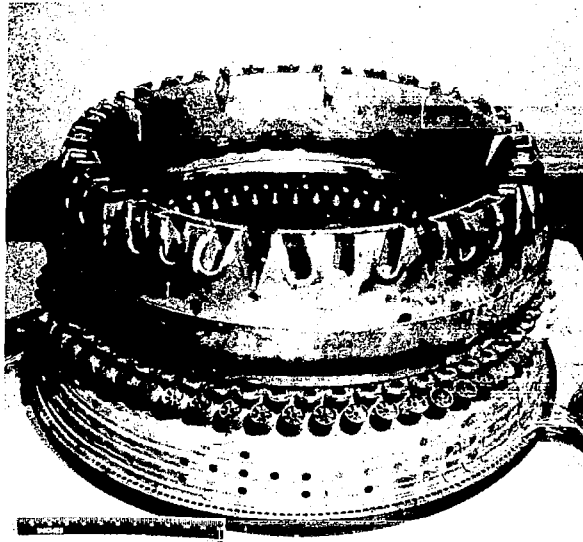


Figure V-6.

PHASE III VORBIX INNER COMBUSTOR LINER MOUNTED ON FIRST-STAGE
TURBINE VANE ASSEMBLY

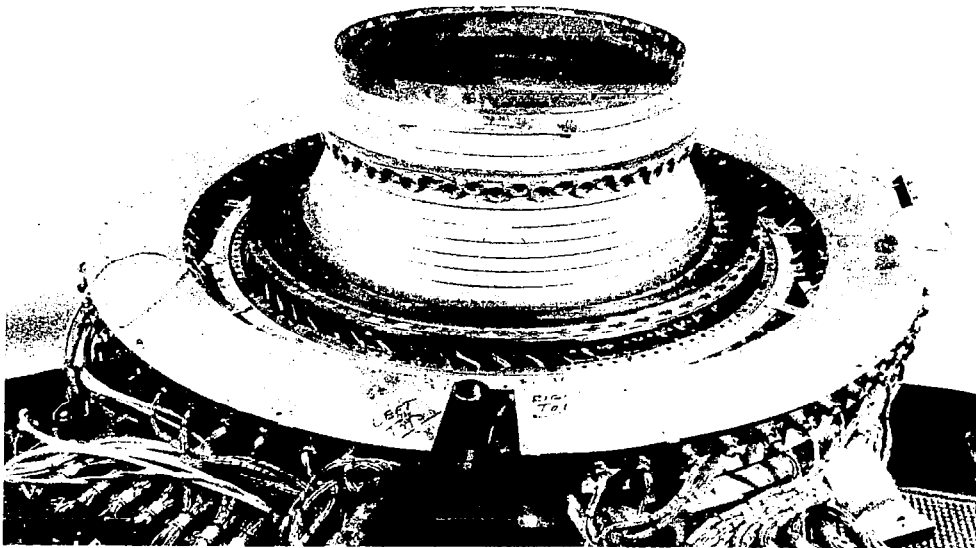


Figure V-7.

FUEL SCHEDULING REQUIREMENTS FOR TWO-STAGE
VORBIX COMBUSTOR BASED ON PHASE II
RIG TEST RESULTS

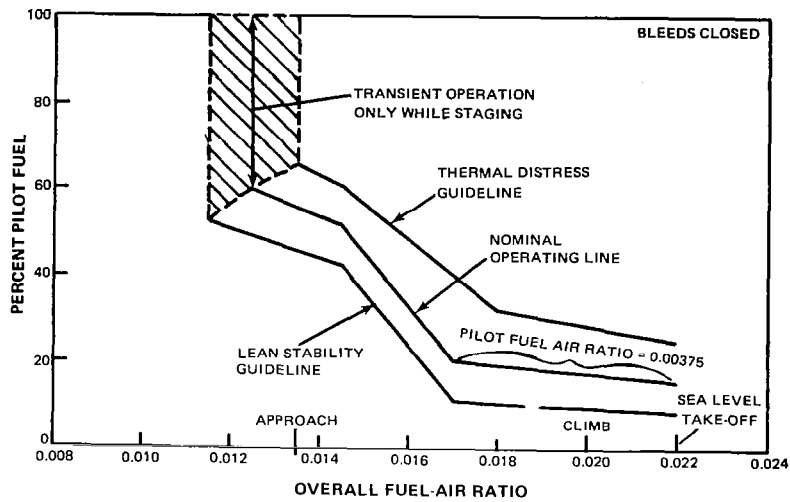


Figure V-8.

EXHAUST EMISSIONS RAKE FOR ECCP
PHASE III TESTS

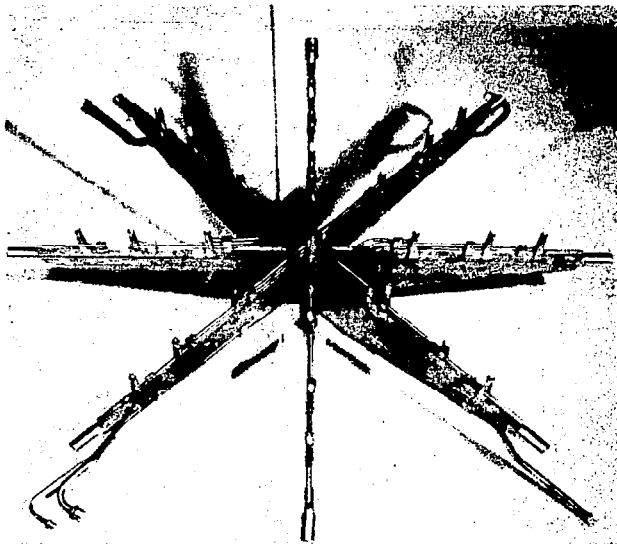


Figure V-9.

STATION 7 GAS SAMPLE PROBE ARRAY USED IN ECCP
PHASE III TESTS

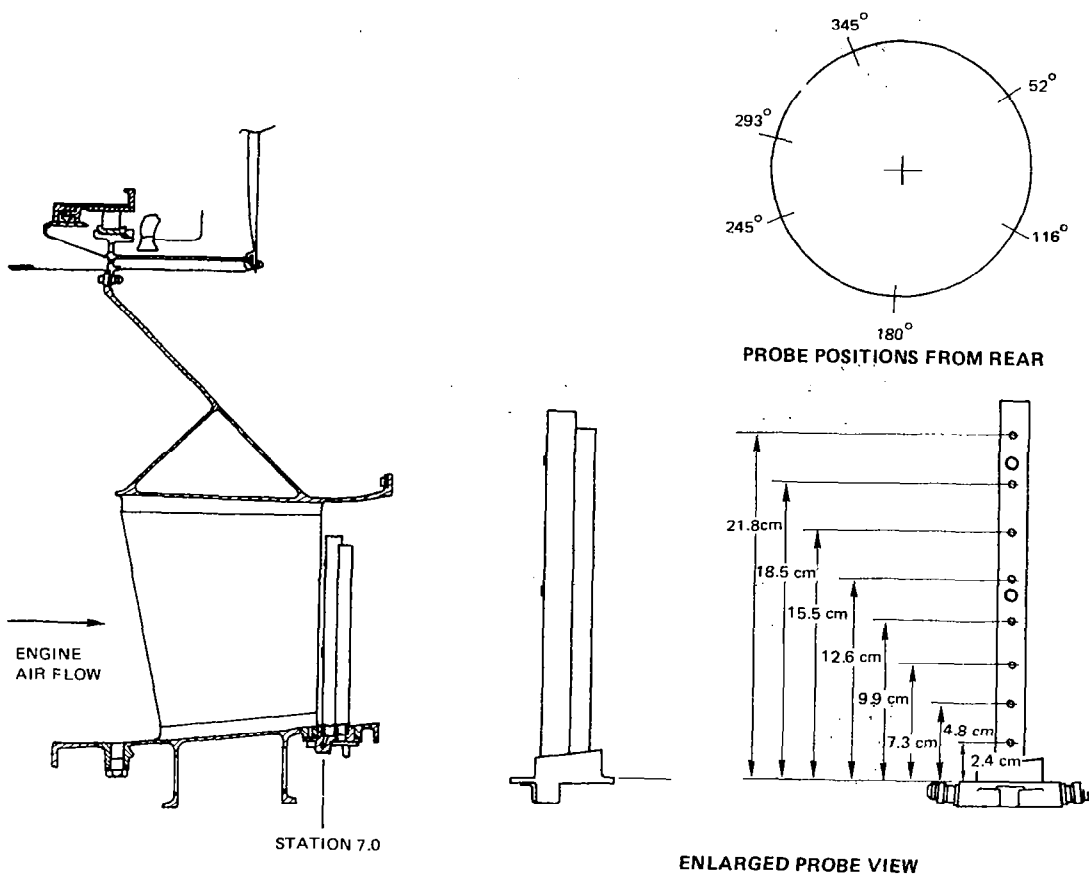


Figure V-10.

EFFECT OF PILOT-ZONE FUEL-AIR RATIO ON EMISSIONS

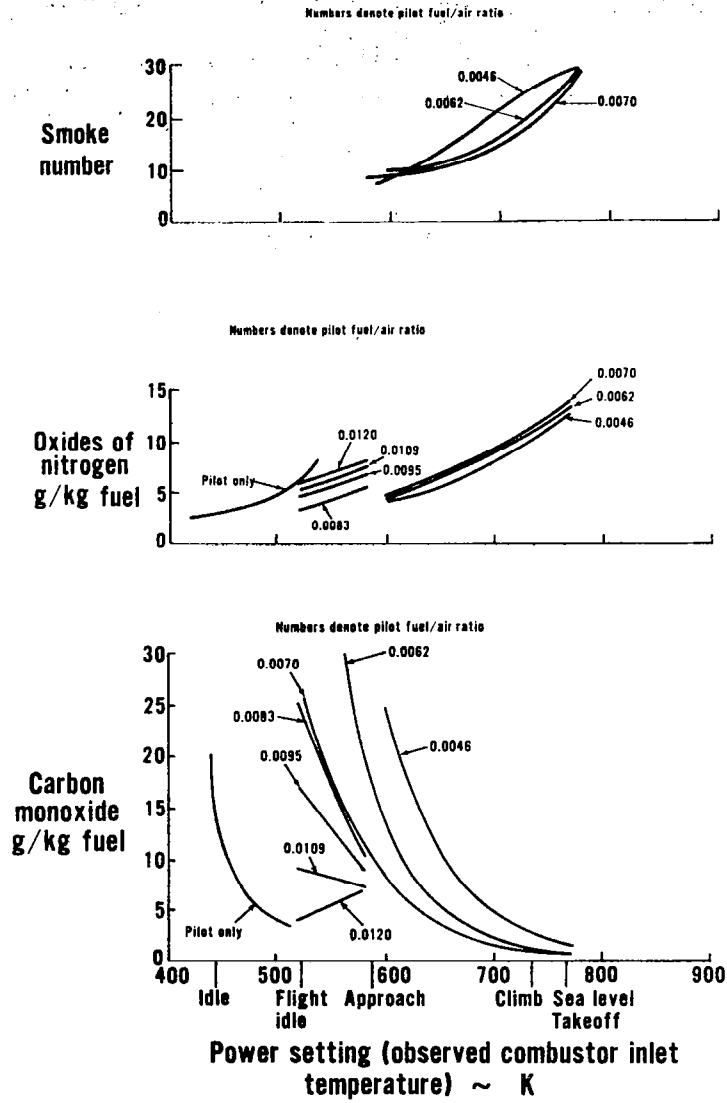


Figure V-11.

VORBIX COMBUSTOR EMISSIONS RELATIVE TO JT9D-7A COMBUSTOR

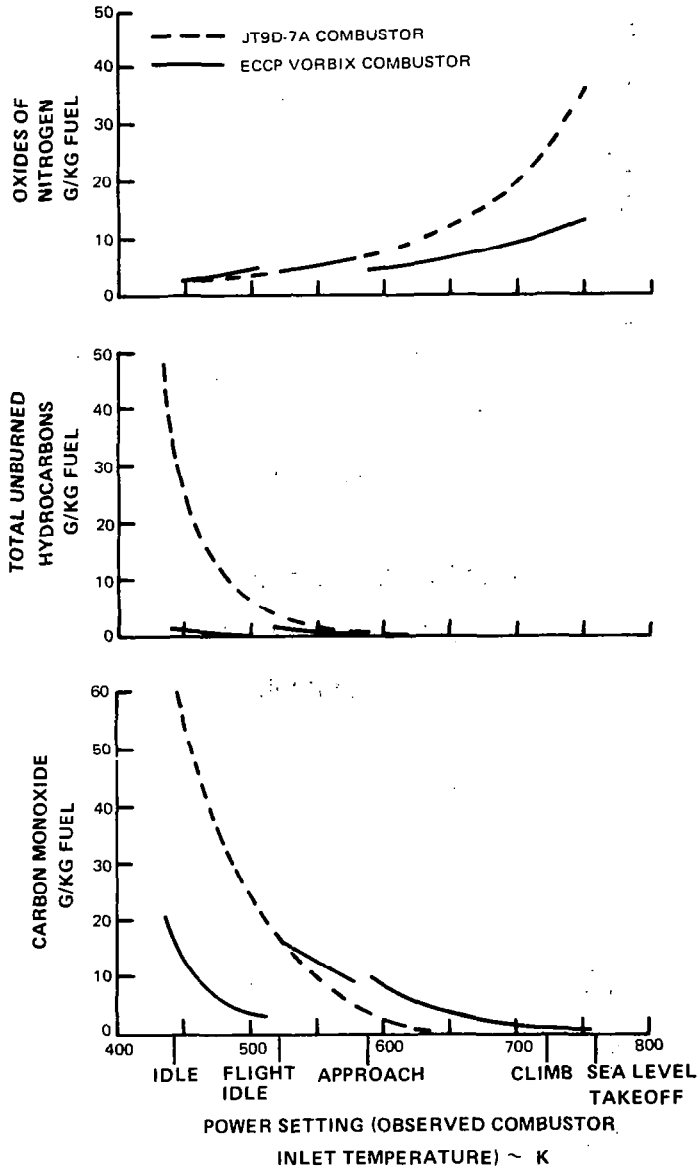


Figure V-12.

RELATIVE INDICATIONS OF GAS
SAMPLING RAKES FOR
NO_x EMISSIONS

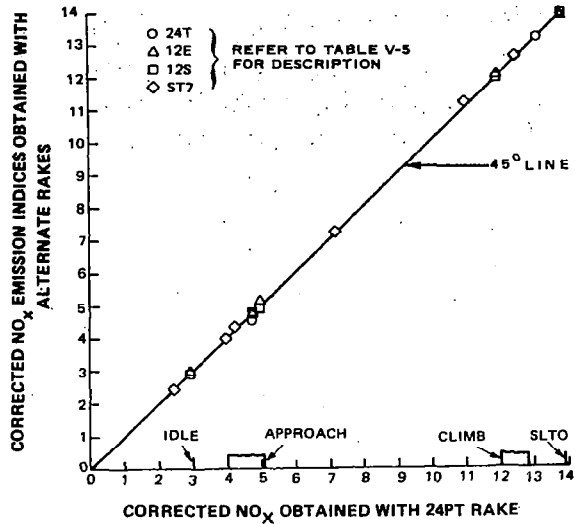


Figure V-13.

RELATIVE INDICATIONS OF GAS
SAMPLING RAKES FOR
CO EMISSIONS

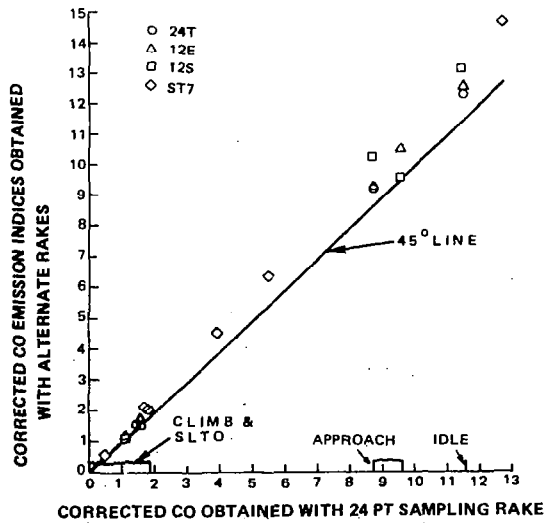


Figure V-14.

RELATIVE INDICATIONS OF GAS SAMPLING RAKES FOR UNBURNED THC EMISSIONS

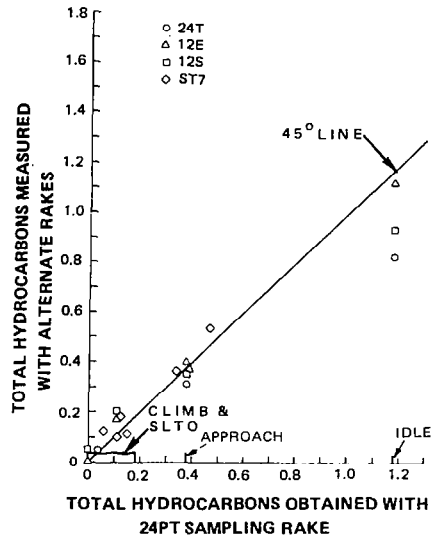


Figure V-15.

COMPARISON OF FUEL-AIR RATIOS DETERMINED BY CARBON BALANCE AND DIRECT MEASUREMENT

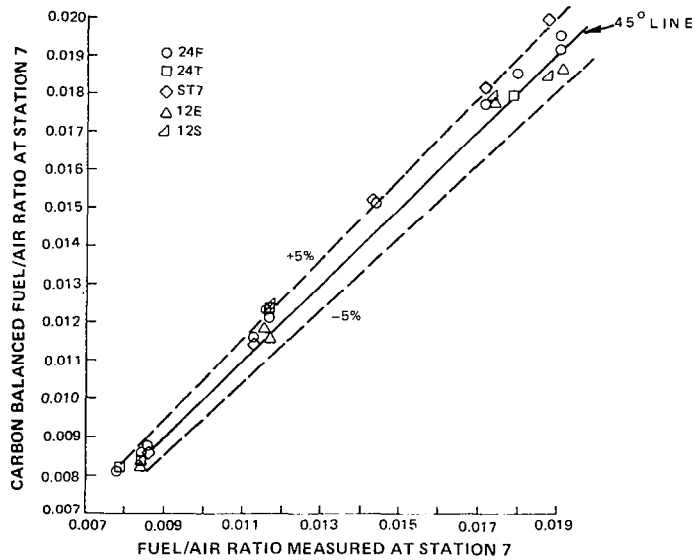


Figure V-16.

ACCELERATION TIMES

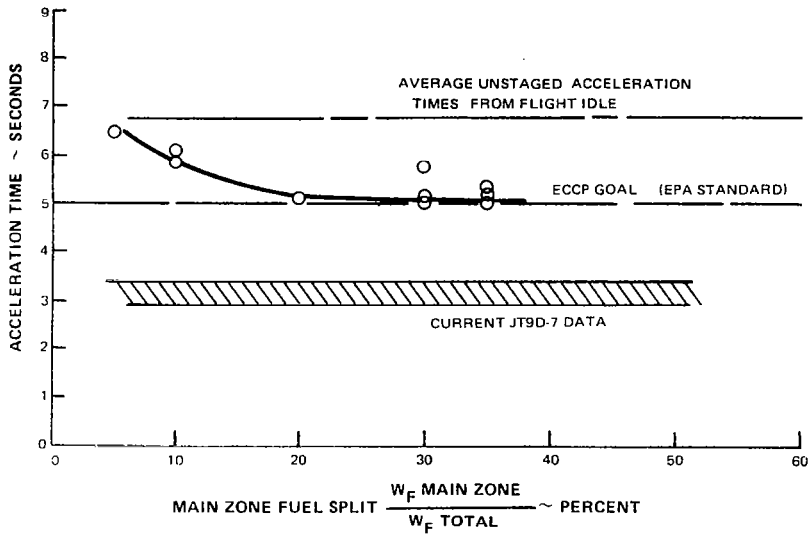


Figure V-17.