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EXPERIMENTAL CLEAN COMBUSTOR PROGRAM
PHASE III
FINAL REPORT

by

R. Roberts, A. Fiorentino, and W. Greene

UNITED TECHNOLOGIES CORPORATION
PRATT & WHITNEY AIRCRAFT GROUP
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16. Abstract

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. The combustor exceeded the program goals for all three emissions species, with oxides of nitrogen 10 percent below the goal, carbon monoxide 26 percent below the goal, and total unburned hydrocarbons 75 percent below the goal. Relative to the JT9D-7 combustor, the oxides of nitrogen were reduced by 58 percent, carbon monoxide emissions were reduced by 69 percent, and total unburned hydrocarbons were reduced by 96 percent. Smoke emissions, however, did not meet the goals and were in the visible range. The combustor efficiency and exit temperature profiles were comparable to those of the production combustor. Acceleration and starting characteristics were deficient relative to the production engine. In addition, durability and coking problems require additional development.

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FOREWORD

This document describes the work conducted and completed by the Commercial Products, Division, Pratt & Whitney Aircraft Group of United Technologies Corporation during Phase III of the Experimental Clean Combustor Program. This final report was prepared for the National Aeronautics and Space Administration Lewis Research Center in compliance with the requirements of Contract NAS3-19447.

The authors of this report wish to acknowledge the guidance and assistance of Mr. Richard Niedzwiecki, NASA Project Manager of the Experimental Clean Combustor Program. Appreciation is also expressed for the contributions made by Mr. G. U. Parks and his Engine Test Group, Mr. J. R. Baker and Mr. D. A. Mickey of the Advanced Controls Group, and Mr. S. J. Markowski who originally conceived the Vorbix concept at Pratt & Whitney Aircraft.

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SUMMARY

The Experimental Clean Combustor Program was directed toward the development and experimental engine evaluation of the technology required to reduce pollutant emissions for both current and future gas turbine engine combustors. The program was conducted in three phases. Phase I involved experimental rig screening of combustor concepts to identify the best approaches for reducing emission levels. Phase II consisted of evaluation and refinement of the best two combustor concepts identified in Phase I. Emphasis was placed on documentation of emission characteristics over the full range of operating conditions and development of satisfactory combustor performance. A fuel control design study was conducted to establish fuel management requirements for two-stage combustors. Phase III, which is the subject of this report, consisted of full-scale engine tests of the Vorbix combustor.

The Phase III program gaseous emission goals are the integrated EPA parameter 1979 standards. Compared with the current production JT9D-7A engine, attainment of the program goals represented a significant reduction in pollutants, ranging from 53 to 93 percent.

The engine with the Vorbix combustor installed demonstrated emissions of oxides of nitrogen that were 10 percent below the goal, emissions of carbon monoxide that were 26 percent below the goal, and emissions of total unburned hydrocarbons that were 75 percent below the goal. Relative to the current production JT9D-7A combustor, these emissions levels represent a reduction of 58 percent for oxides of nitrogen, a reduction of 69 percent for carbon monoxide, and a reduction of 96 percent for total unburned hydrocarbons. However, these reductions were accompanied by a considerable increase in smoke level which was approximately 50 percent over the standard level.

The engine, with the vorbix combustor installed, performed satisfactorily over the entire operating range, including 100 percent takeoff thrust levels. Performance in several aspects, was not as good as the production engine. The acceleration rate from flight idle met the applicable FAA standard of five seconds, but exceeded the acceleration time for the production engine of approximately three seconds. In addition, the starting characteristics with the Vorbix combustor were poorer, requiring approximately twice the fuel-air ratio of the production combustor.

Combustor pressure loss was essentially the same as that for the production combustor. The exit temperature pattern factor for the Vorbix combustor was also essentially the same as that for the production combustor, but did not meet the program goal which was set approximately 40 percent lower. The Vorbix combustor efficiency was better than the goal of 99 percent at all operating conditions, providing improved efficiency at idle conditions and essentially matching the efficiency of the production combustor at approach and high power conditions.

The Vorbix combustor experienced some durability problems, particularly on the main zone outer liner downstream of the swirlers and on the pilot zone liner louver lips in the vicinity of the throat. In addition, coking occurred on the main zone nozzle tips and fuel nozzle support internal passages. Further development of the deficient areas and additional fuel system design work will be required before the Vorbix concept can be considered for production engine applications.

In conjunction with the Phase III program, work was performed on two addendums: Turbulence Characteristics of Compressor Discharge Flows and Evaluation of a Federal Aviation Administration (FAA) Exhaust Sampling Probe. Results of these programs are discussed in NASA Report NASA CR-135277 and NASA CR-152213/FAA-RD-77-115, respectively.

INTRODUCTION

This report describes the results of full-scale JT9D experimental engine tests conducted in Phase III of the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program (ECCP). The low pollution vorbix 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.

The concern with air quality in the vicinity of airports has led to the issuance of emission standards by the U.S. Environmental Protection Agency for aircraft engines manufactured after January, 1979 [Reference 1]. These standards limit the emission of carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_x), and smoke at altitudes under 914 meters (2998 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-emission combustor system. Physical constraints on fuel vaporization, turbulent mixing rate, dilution air addition, and residence time impose absolute limits on the combustion process. Performance 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 and culminating in demonstration testing of the single most promising combustor concept in a full-scale JT9D engine.

A summary of the program plan and goals of the Experimental Clean Combustor Program is provided in Chapter I. Chapter II contains a description of the reference engine (JT9D-7A) and combustor used as a basis for the program work; a description of the Vorbix Combustor design, fuel system, and control tested in Phase III; a description of the experimental JT9D engine and test installation; and a description of the test and analysis procedures. The Phase III program results are presented in Chapter III along with a summary of the development status. Concluding remarks are presented in Chapter IV. Additional information concerning equipment and experimental procedures is contained in Appendix A. Experimental data are tabulated in Appendix B. References are provided in Appendix C.

CHAPTER I

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM DESCRIPTION

A. GENERAL DESCRIPTION OF OVERALL PROGRAM

The Experimental Clean Combustor Program was a multi-year effort that was initiated in December, 1972 and completed in November, 1976. This major program was directed towards 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, and

2. The demonstration of the 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 Aircraft 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.

B. PROGRAM PLAN

The program was divided into three individually funded phases which provided a step-by-step approach for developing the technology required for reducing emissions.

1. PHASE I PROGRAM

Phase I was directed toward identifying promising concepts, screening them, and establishing the design trends in sufficient detail to provide a firm basis for refinement of the more promising concepts in Phase II. Three concepts were tested in a 90-degree sector component rig at simulated engine idle and sea level takeoff operating conditions. These were a Swirl-Can combustor concept, a Staged Premix combustor concept, and a Swirl Vorbix combustor concept. Thirty-two configurations were evaluated.

Concurrent with Phase I, additional efforts were carried out in two addendums, an Advanced Supersonic Technology (AST) Addendum and a Combustion Noise Addendum. The objective of the AST Addendum was to evolve combustor design technology for reducing the NO_x emission levels of AST engines at supersonic cruise operating conditions. The purpose of the Combustion Noise Addendum was to obtain experimental data on the acoustic characteristics of low pollution combustors.

Detailed descriptions and results of Phase I and the AST Addendum are contained in Reference 2. Combustion Noise Addendum results are presented in Reference 3.

2. PHASE II PROGRAM

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. More comprehensive sector rig testing simulating the full range of engine operating conditions was conducted to fully document pollutant emission characteristics, to identify previously undetected problem areas, and to assess combustor performance, After initial testing, the program was reduced to the Vorbix combustor concept and the remaining test effort was devoted to development of performance characteristics in preparation for the Phase III engine demonstration tests. A fuel control design study was also conducted to establish fuel management requirements for two-stage combustors.

Concurrent with Phase II, additional efforts are also carried out in two addendums, a Combustion Noise Addendum and an Alternate Fuels Addendum. The purpose of the Noise Addendum was to obtain additional acoustic data, and to relate the acquired noise data to combustor design and operating parameters. The objective of the Alternate Fuels Addendum was to investigate the effect of degraded aviation fuel properties on the pollutant emission and performance characteristics of low-emission combustors.

A description and results of the Phase II program are presented in Reference 4. Results of the Alternate Fuels and Combustor Noise Addendum are contained in References 5 and 6.

3. PHASE III PROGRAM

The Phase III program, just completed, consisted of a detailed evaluation of the Vorbix combustor concept in a JT9D engine. The objective was to demonstrate significant pollution reductions with an advanced combustor which meets the performance, operational, 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. Details of the Phase III work are contained in the following chapters of this report.

In conjunction with the Phase III program, additional efforts were also carried out in two addendums: Turbulence Characteristics of Compressor Discharge Flows; and Evaluation of a Federal Aviation Agency (FAA) Exhaust Sampling Probe. The purpose of the Turbulence Measurement Addendum was to determine turbulence intensity and scale in the compressor discharge of the JT9D engine by means of hot wire/hot film measurements. The objective of the second addendum was the evaluation of a FAA-supplied emission sampling rake installed in the tail pipe of the demonstrator JT9D engine. Descriptions and results of the two addendums are presented in References 7 and 8, respectively.

C. PROGRAM SCHEDULE

The overall program schedule for the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program is presented in Figure 1.

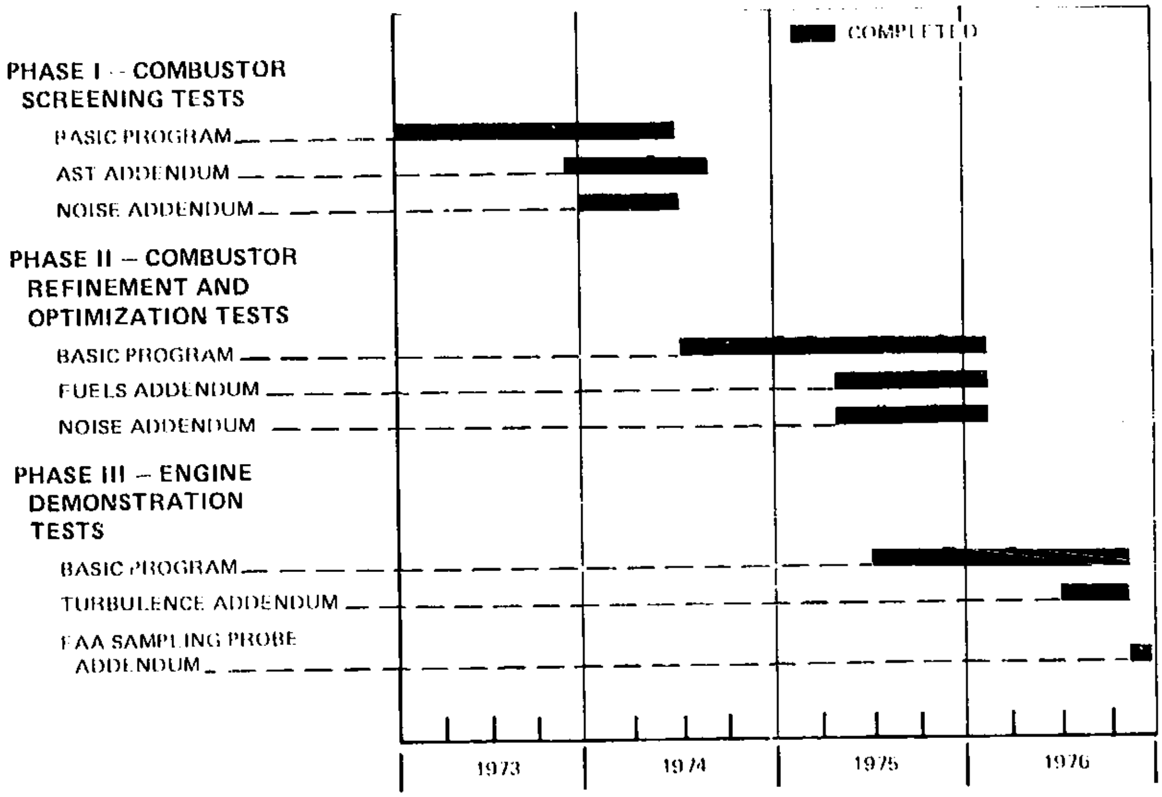

Figure 1 NASA/Pratt & Whitney Aircraft Experimental Clean Combustor Program Schedule

D. 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.

1. POLLUTION GOALS

The pollutant emission goals are summarized in Table I. The gaseous pollutant emission goals are expressed as integrated EPA parameter (EPAP) values. The EPA parameter [Reference 1] is a thrust-normalized measure of the total mass of pollutant emitted in a prescribed landing and takeoff cycle. In general, because of the characteristics of aircraft engines and their operational relationships to the landing and takeoff cycle effective emission control must be primarily directed toward reducing CO and THC at low power and NO_x at high power. As shown by a comparison of the goals with the current production JT9D-7A engine, the attainment of these goals involves significant pollutant reductions by factors of 2.2 to 6 on an EPAP basis.

TABLE I

POLLUTION GOALS AND CURRENT JT9D-7A LEVELS [1]

Pollutant	Goal	Current JT9D-7A Engine Status
EPA Parameter (lbm. pollutant/1000 lbf. thrust-hr/landing takeoff cycle)		
Oxides of Nitrogen [2] (As NO_2)	3.0	6.5
Carbon Monoxide	4.3	10.4
Total Unburned Hydrocarbons	0.8	4.8
Maximum SAE Smoke Number	19	4

Notes: 1 Data represent average emission levels for a JT9D-7A production engine incorporating combustor configuration EC 289386. Ground idle data is without compressor air bleed.

2 Oxides of nitrogen data presented as nitrogen dioxide equivalent, corrected to 6.3 g H_2O/kg dry air.

The exhaust smoke goal is expressed as a maximum SAE smoke number which 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.

2. PERFORMANCE GOALS

The key combustor performance goals are presented in Table II. 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 the emission of oxides of nitrogen is not achieved at the cost of engine efficiency.

TABLE II

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM PERFORMANCE GOALS

Maximum Total Pressure Loss (%)	5.4
Exit Temperature Pattern Factor	0.25 at takeoff
Combustor Efficiency (%)	99 or better at all operating conditions
Lean Blowout Fuel/Air Ratio	0.004 ± 0.001
Altitude Relight Capability Altitude at Flight Mach Number of 0.5 to 0.8 (m)	9144

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.

CHAPTER II

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A. REFERENCE ENGINE AND COMBUSTOR

1. REFERENCE ENGINE DESCRIPTION

The JT9D-7A engine was selected as a reference for the NASA/Pratt & Whitney Aircraft Experimental Clean Combustor program. This model is one of the current versions of the JT9D engine which was designed and developed by Pratt & Whitney Aircraft. Since its introduction into commercial service, this engine has acquired widespread acceptance as the powerplant for models of the Boeing 747 and Douglas DC-10 wide bodied aircraft.

The JT9D-7A engine is an advanced high bypass dual spool axial flow turbofan engine. The mechanical configuration is shown in Figure 2. All JT9D engines employ a modular assembly concept to facilitate maintenance and service. The five major modules are: (1) fan and low pressure compressor, (2) high-pressure compressor, (3) diffuser and combustor, (4) high-pressure turbine, and (5) low-pressure turbine.

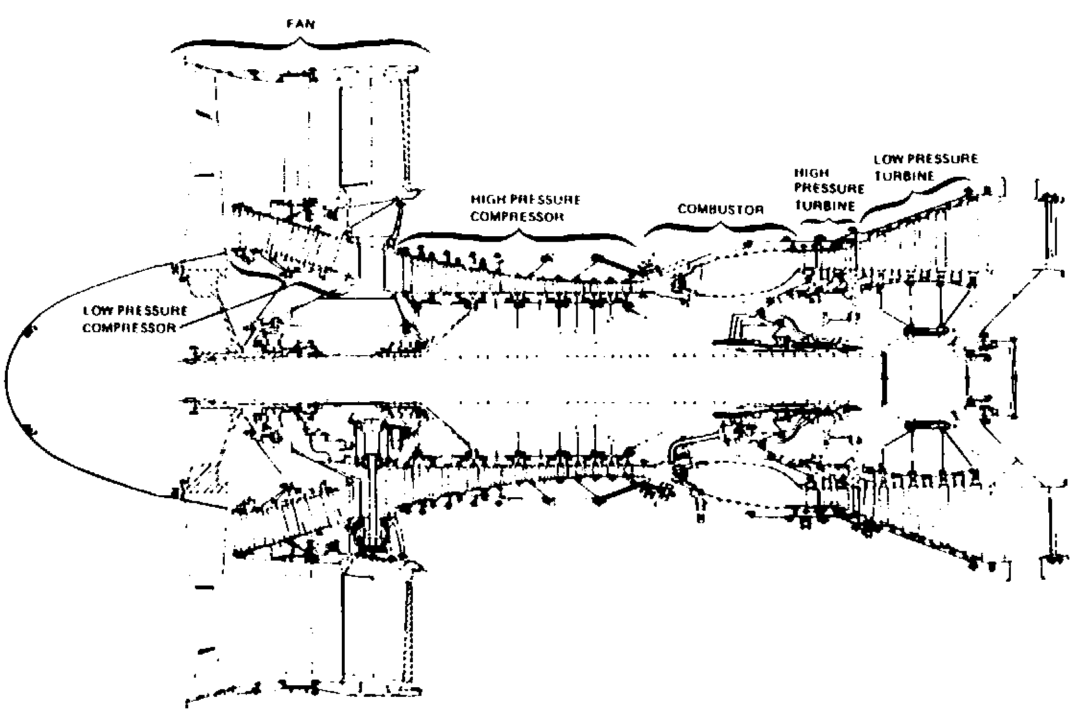

Figure 2 Cross-Sectional Schematic of the JT9D-7A Reference Engine

The components making up the modules differ slightly for the several JT9D engine models. The JT9D-7A arrangement is as follows: 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 eleven-stage high-pressure compressor driven by a two-stage high-pressure turbine. The accessory gearbox is driven by the high-pressure compressor through a tower shaft and right angle gearbox located between the high and low-pressure compressor. The gearbox is mounted at the bottom of the engine beneath the forward portion of the diffuser/combustor module. In addition to providing power for various airframe requirements, the gearbox contains the engine starter, fuel pump, fuel control, and main oil supply pumps.

Selected key specifications for the JT9D-7A engine are listed in Table III.

TABLE III

JT9D-7A SPECIFICATION

Maximum Sea Level Thrust (Dry) – 2.05×10^5 N (46.150 lbf)

Cruise Performance (Standard Day)	
Mach No.	0.85
Altitude	10,668m (35,000 ft)
Thrust	4.63×10^4 N (10,400 lbf)
Specific Fuel Consumption	0.065 kg/hr/N (0.641 lbm/hr/lbf)
Weight	3,972 kg (8,750 lbm)
Length	3.92m (154.16 in)
Maximum Diameter (Cold, Room Temperature)	2.43m (95.56 in)
Pressure Ratio	
$\frac{\text{Compressor Discharge}}{\text{Engine Inlet}}$	23
Total Engine Airflow (Dry)	686.3 kg/sec (1513 lbm/sec)

2. REFERENCE COMBUSTOR DESCRIPTION

The mechanical design of the JT9D-7A reference diffuser/combustor is shown in Figure 3. The combustor is of an annular configuration consisting of two assemblies, the outer liner and head plate and the inner liner. The outer liner is positioned by ten 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 and at the aft end of the outer liner to allow for thermal expansion.

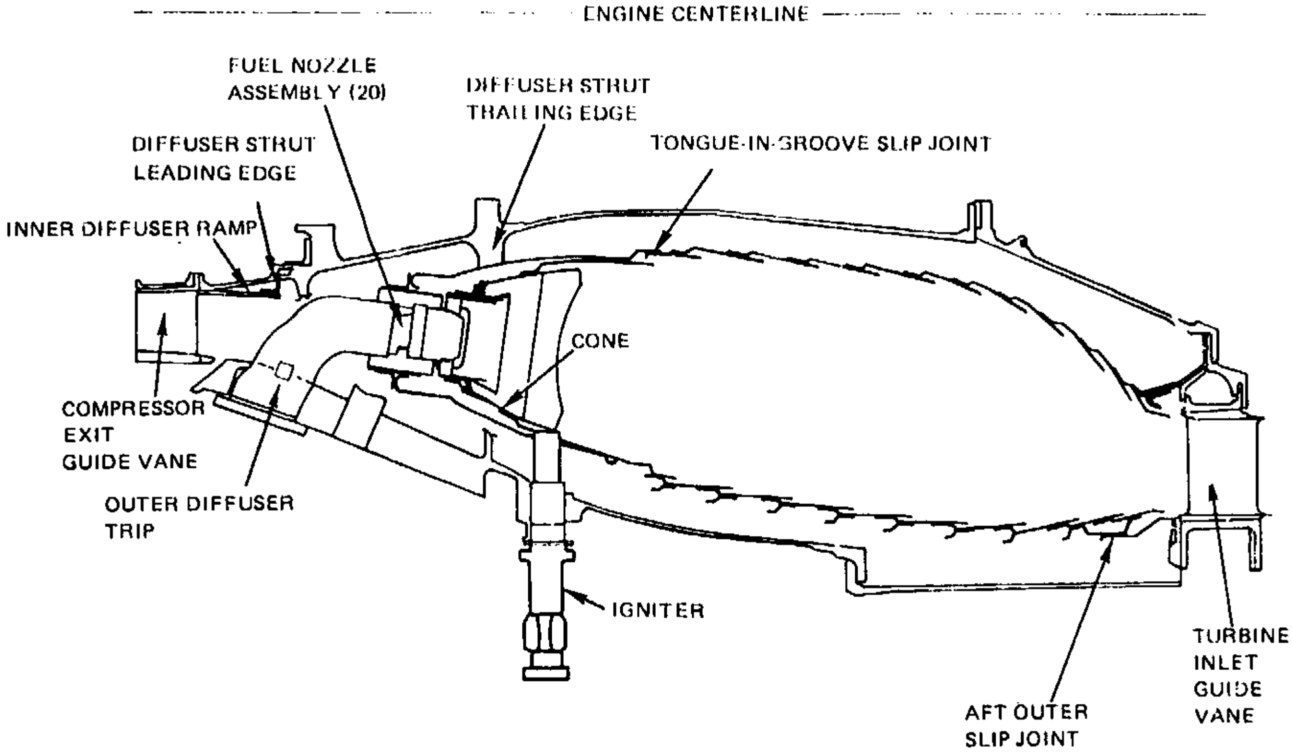

Figure 3 Cross-Sectional Schematic of the JT9D-7A Combustor

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

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 0.58m (23.0 in.). The burning length between the fuel nozzle face and turbine inlet guide vane leading edge is 0.45m (17.6 in.). Minimum and maximum diameters are 0.62m (24.3 in.) and 1.07m (42.2 in.) respectively.

Key performance parameters of the JT9D-7 reference combustor are summarized in Table IV.

TABLE IV

KEY OPERATING PARAMETERS OF THE
JT9D-7A REFERENCE COMBUSTOR

Compressor Exit Axial Mach Number	0.26
Compressor Discharge Temperature (K)	764
Combustor Temperature Rise (K)	783
Combustor Section Pressure Loss (%)	5.40
Outer Liner Pressure Drop (%)	1.71
Inner Liner Pressure Drop (%)	1.78
Combustor Exit Temperature Pattern Factor	0.45
Average Combustor Exit Temperature (K)	1547

Note: All data for standard sea-level static takeoff conditions.

The values of combustor section pressure loss listed in Table IV are specified as percentages of the high-pressure compressor discharge total pressure at sea level takeoff power. The overall section loss includes 0.8 percent attributed to the compressor exit guide vanes. The exit average radial temperature profile is shown in Figure 4. The JT9D-7 airstart requirement is shown in Figure 5.

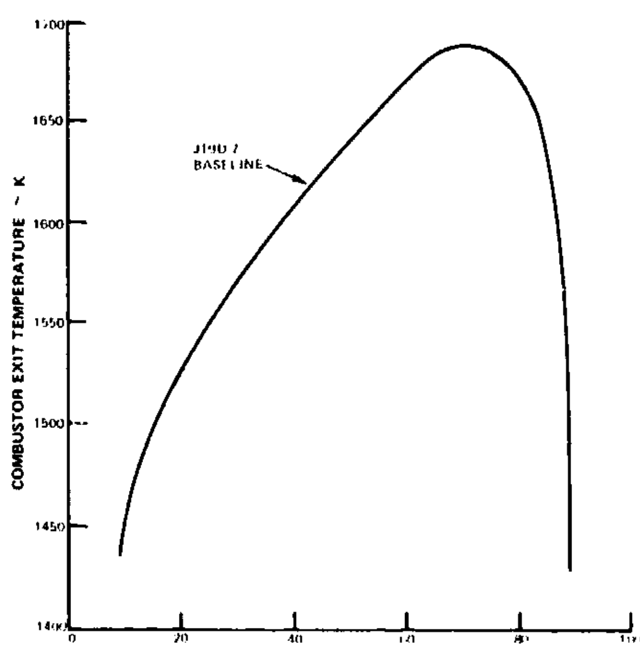

Figure 4 Combustor Exit Average Radial Temperature Profile

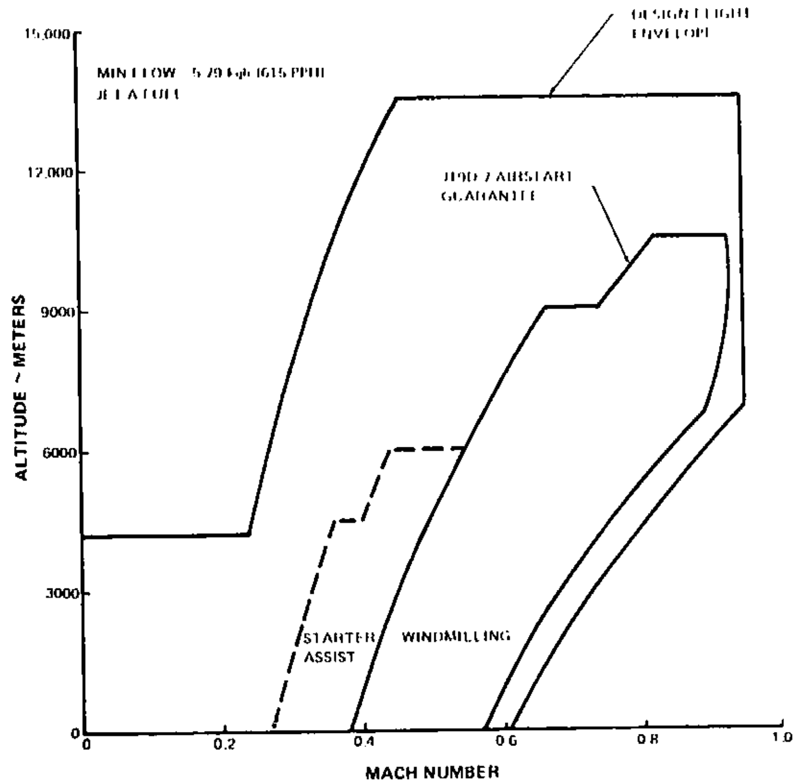

Figure 5 JT9D-7 Airstart Envelope

3. REFERENCE ENGINE COMBUSTOR POLLUTION LEVELS

Since the JT9D engine and combustion system were designed prior to current concerns regarding gaseous pollutants, the combustor was not specifically intended to provide low emissions. However, the combustor does incorporate smoke reduction features and produces no visible smoke at any operating condition.

Exhaust emissions are periodically monitored during JT9D production acceptance tests, and typical results for the idle, 30 percent, 85 percent, and 100 percent sea level static thrust engine power settings are shown in Table V. These power settings correspond to the Environmental Protection Agency (EPA) specified simulated ground idle, approach, climbout, and takeoff conditions which are used in the establishment of aircraft engine emission standards. The data presented in Table V represent average emission levels for JT9D-7A production engines incorporating the combustor configuration defined by engineering change number 289386. This combustor configuration has been installed in JT9D-7A production engines shipped since November 1975. The data have been corrected to standard day temperature and pressure and to an ambient humidity level of 6.3 g H_2O/kg dry air. Jet A fuel was used for the tests. The corresponding values of the EPA Parameter (EPAP) are also presented in Table V. This parameter combines emission rates at the engine idle, approach, climb, and takeoff operating modes, integrated over a specified landing/takeoff cycle. (Reference 1).

TABLE V

REPRESENTATIVE JT9D-7A PRODUCTION ENGINE EMISSION LEVELS [1] AND EXPERIMENTAL CLEAN COMBUSTOR PROGRAM GOALS

A. Emission Indices

Operating Condition	Carbon Monoxide Emissions (g/kg fuel)	Total Unburned Hydrocarbons Emissions (g/kg fuel)	Oxides of Nitrogen Emissions [2] (g/kg fuel)	SAE Smoke Number
Ground Idle [3]	58.0	27.0	3.1	
Approach (30% Power)	3.3	0.6	7.4	
Climb (85% Power)	0.4	0.3	31.6	4
Sea Level Takeoff (100% Power)	0.4	0.3	42.4	4
B. EPA Parameter (lbm Pollutant/1000 lbf Thrust-hr/Landing-Takeoff Cycle)				
JT9D-7	10.4	4.8	6.5	4
ECCP Goals	4.3	0.8	3.0	≤19

1979 EPA Standards

Notes: 1 Data represent average emission levels for a JT9D-7A production engine incorporating combustor configuration EC 289386.

2 Oxides of nitrogen data presented as nitrogen dioxide equivalent, corrected to 6.3 g H_2O/kg dry air.

3 Ground idle data is without compressor air bleed.

B. TEST COMBUSTOR

1. VORBIX COMBUSTOR DESCRIPTION

A cross section drawing of the Phase III Vorbix (vortex burning and mixing) combustor is shown in Figure 6. A front view of the pilot fuel system arrangement and the circumferential location of the pilot and main fuel injectors is shown in Figure 7. Figures 8 and 9 present photographs of the outer combustor liner and head assembly, before and after installation of the hood. The inner combustor liner is shown in Figure 10 mounted on the instrumented first-stage turbine vane assembly. Figure 11 is an upstream view of the outer liner illustrating the installed positions of the pilot and main fuel injectors.

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 thirty 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 formation of oxides of nitrogen. The minimum equivalence ratio for the pilot zone is determined by the overall lean blowout limits, 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 sixty swirlers positioned on each side of the combustor, (120 total).

A common fuel injector support assembly was designed for both the pilot and main stages to reduce fabrication cost. An exploded view of the injector assembly is shown in Figure 12.

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.

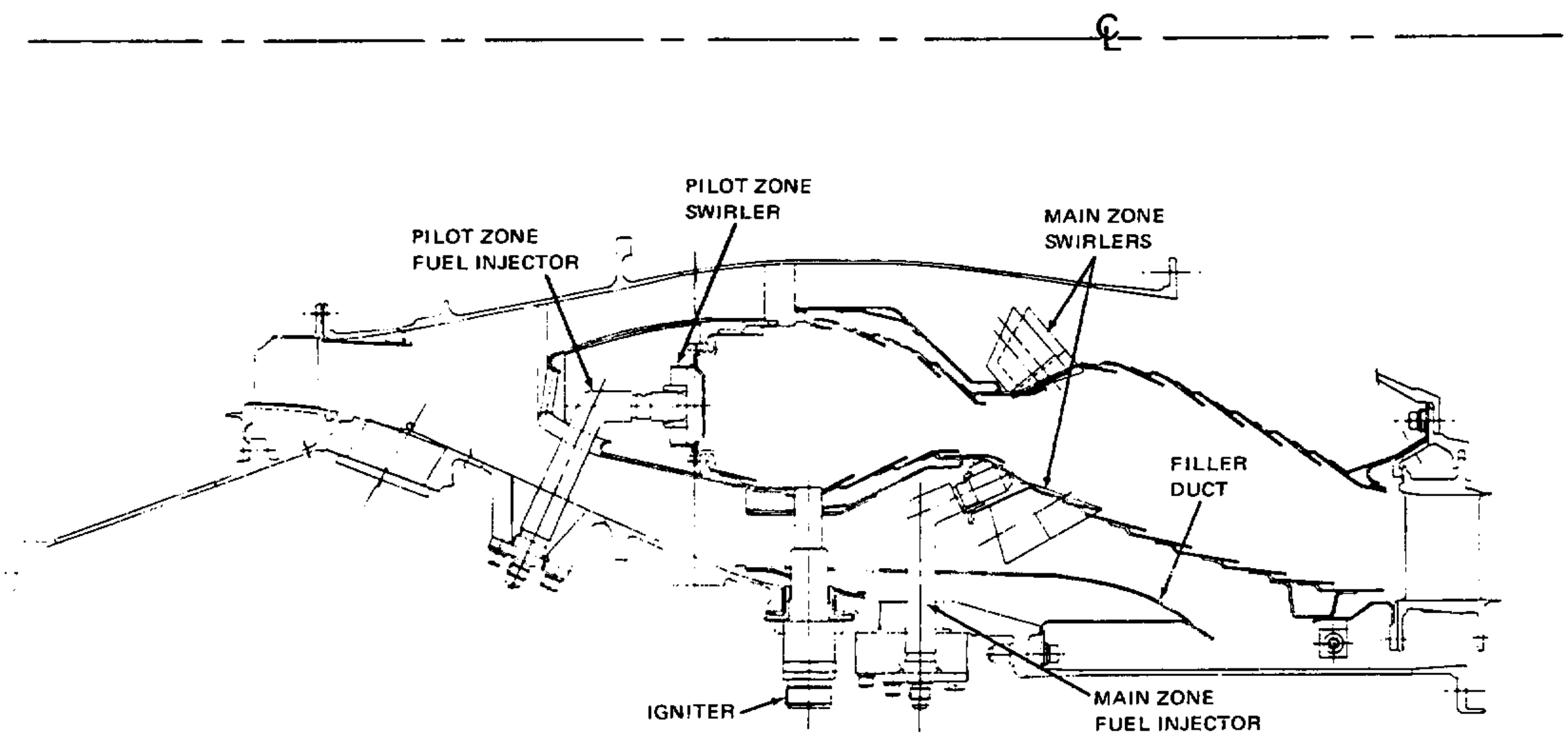

Figure 6 *Cross Section of Experimental Clean Combustor Program Phase III Vorbix Combustor*

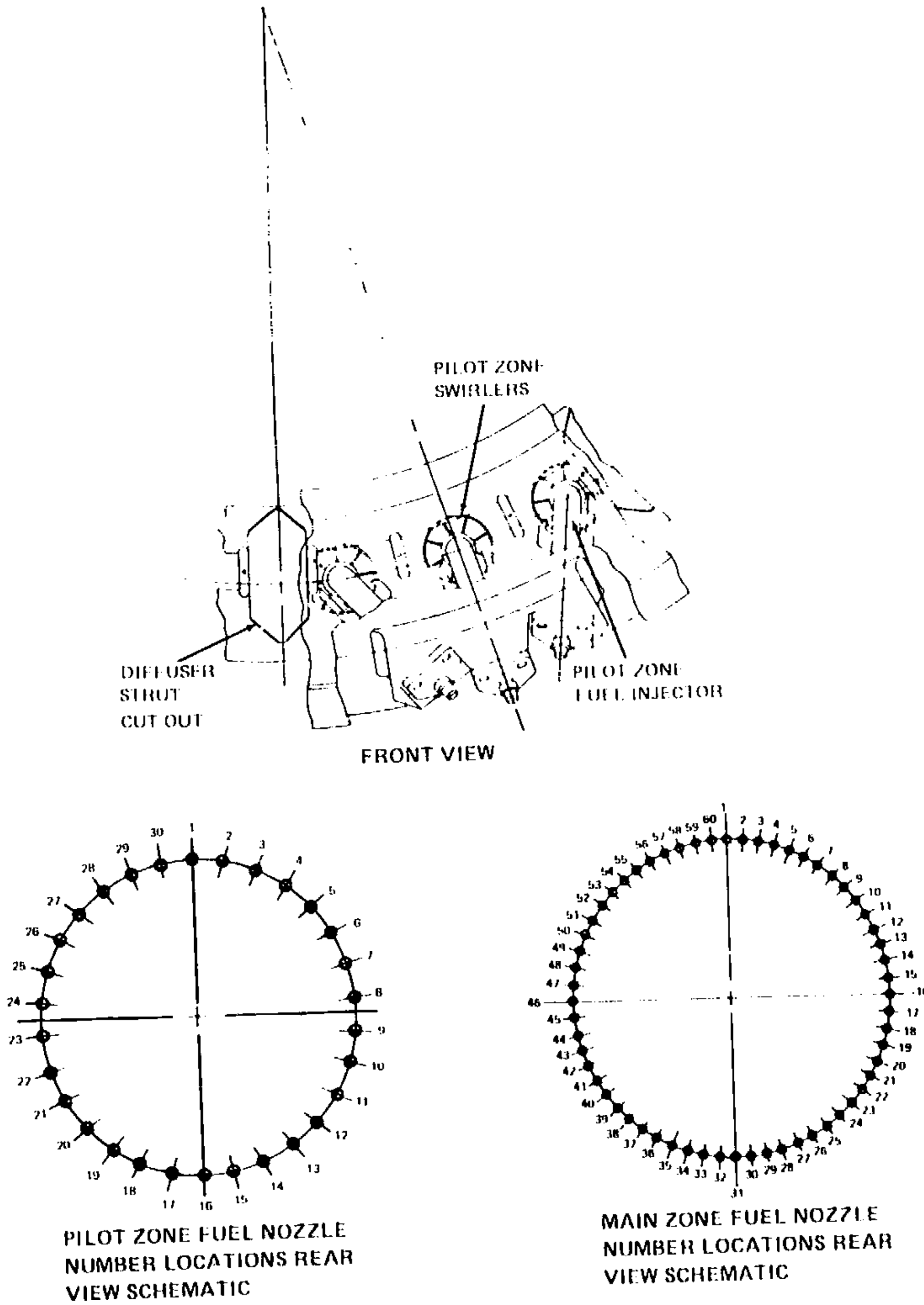

Figure 7 Vorbix Combustor Fuel Injector Arrangement

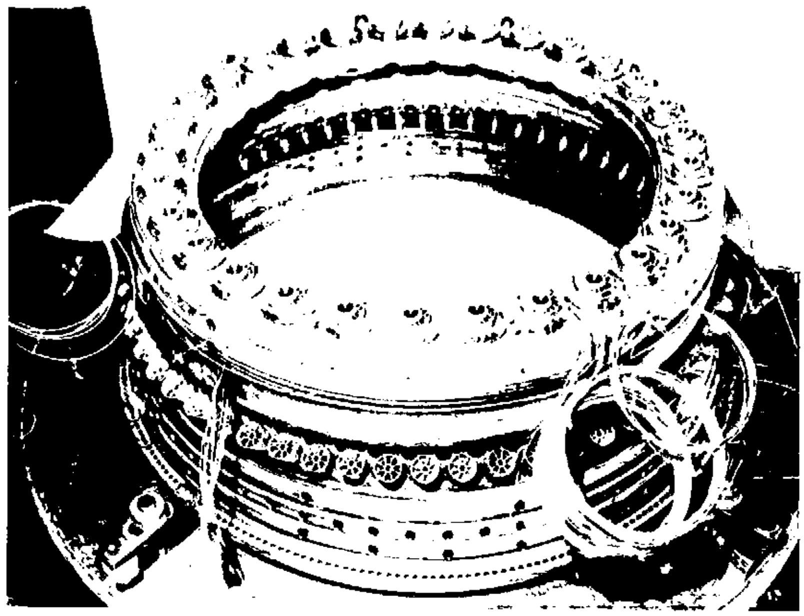

Figure 8 Phase III ~~Vorbix Outer Combustor~~ Liner Prior to Hood Installation (X-45564)

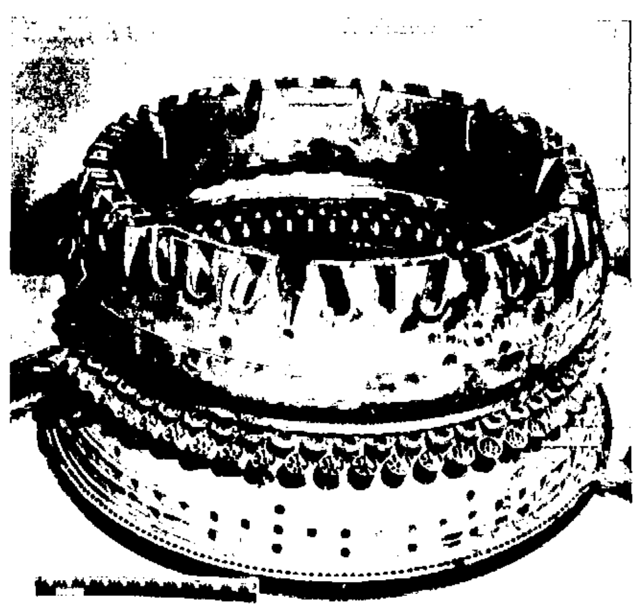

Figure 9 Phase III Vorbix Outer Combustor After Hood Installation (XPN-59997)

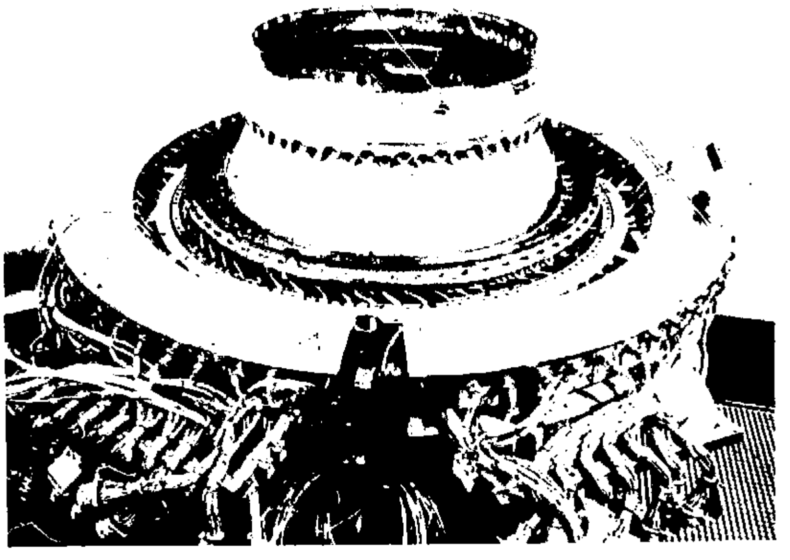

Figure 10 Phase III Vorbix Inner Combustor Liner Mounted on First-Stage Turbine Vane Assembly (XPN-59678)

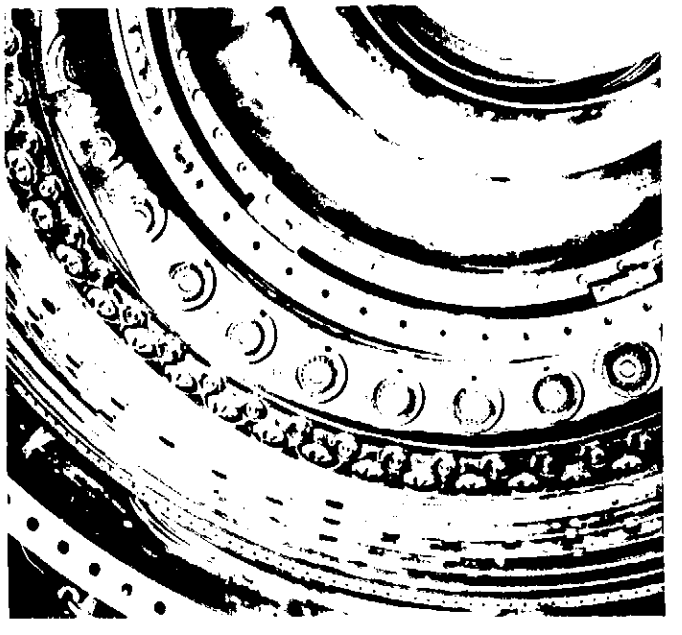

Figure 11 View Looking Upstream of Phase III Vorbix Combustor With Fuel Nozzles Installed (XPN-60089)

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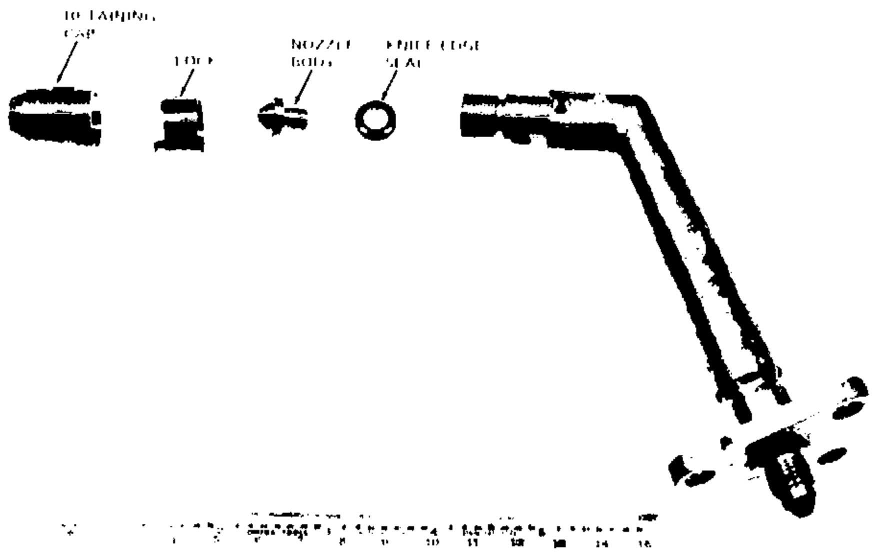

Figure 12 Fuel Injector Assembly (K-21448)

2. TEST CONFIGURATIONS

The initial Phase III configuration (designated S25E) was intended to duplicate the final Phase II sector rig configuration (S25) as closely as possible. The engine configuration is compared to the rig configuration in Table VI.

TABLE VI

COMPARISON OF RIG AND ENGINE AIRFLOW METERING

	Comparison of Engine Design (S25E) With Rig Design (S25)
Pilot Swirler	Same
Pilot ID and OD Dilution	Same
Main Zone Swirler ID and OD	Same
Main Zone Dilution	Decreased 3 percent
Liner Cooling	Increased 5 percent
Total A_{CD}	Decreased 2 percent

$$\text{*Percent Change} = \frac{A_{CD}\text{ engine} \quad A_{CD}\text{ rig}}{\text{total } A_{CD}\text{ engine}}$$

A_{CD} = Measured area x flow coefficient

Three vorbix combustor configurations were tested in Phase III. The three configurations were geometrically identical, with minor differances in airflow distribution. The configurations tested are summarized in Table VII.

The baseline engine configuration was S25E. The first modification (S26E) incorporated a small reduction in ID swirler airflow to provide additional cooling airflow for the outer combustor liner at locations downstream of the main swirlers. The second modification (S27E) involved airflow redistribution in both the pilot and main zones. Pilot dilution airflow was reduced slightly to shift the minimum CO level at idle to the design idle fuel/air ratio. In the main zone, additional ID swirler airflow and a small amount of OD dilution airflow were transferred to the aft cooling louvers on the outer liner in order to reduce the OD radial exit temperature profile.

TABLE VII

AIRFLOW DISTRIBUTION FOR VORBIX COMBUSTOR CONFIGURATIONS

	A_{CD}*			Percent Total Combustor Flow		
Description	S25E	S26E	S27E	S25E	S26E	S27E
Pilot Swirler	14.59	14.59	14.59	12.0	12.0	12.0
Pilot ID Dilution	7.96	7.96	7.18	4.6	4.6	4.1
Pilot OD Dilution	11.82	11.82	10.76	7.7	7.7	7.0
Bulkhead	3.28	3.28	3.28	3.0	3.0	3.0
Main Swirler ID	13.55	11.33	8.53	10.8	9.0	6.8
Main Swirler OD	33.60	33.60	33.60	27.2	27.2	27.2
Main Dilution OD	1.50	1.50	1.11	1.1	1.1	0.8
Main Dilution OD	4.50	4.50	4.50	3.4	3.4	3.4
Main Dilution OD	9.00	9.00	9.00	6.7	6.7	6.7
Main Nozzle	1.13	1.13	1.13	0.8	0.8	0.8
ID Liner Cooling	10.84	10.84	10.84	7.9	7.9	7.9
OD Liner Cooling	15.06	17.28	22.15	11.9	13.6	17.4
Turbine Vane Platform	3.49	3.49	3.49	2.8	2.8	2.8

*A_{CD} = Measured area x flow coefficient

3. DIFFUSER CASE MODIFICATION

In order to adapt the two-stage Vorbix combustor to the JT9D engine, several internal design changes to the JT9D diffuser case were required. These changes include providing additional mounting bosses for the pilot and main fuel injectors and the relocation of the igniter bosses. Diffuser case mount flanges, combustor mount flanges and pins, diffuser case inner and outer wall contours, and strut arrangements remain unchanged.

An exploded view of the modifications made to the standard production JT9D-7 diffuser case is shown in Figure 13. The boss locations for the pilot and main fuel injectors were defined by requirements for servicing of fuel system components, minimization of structural compromises, and relative ease of reoperation of an existing part for use in the Phase III test program. A used experimental JT9D-7 case was the base for the modifications.

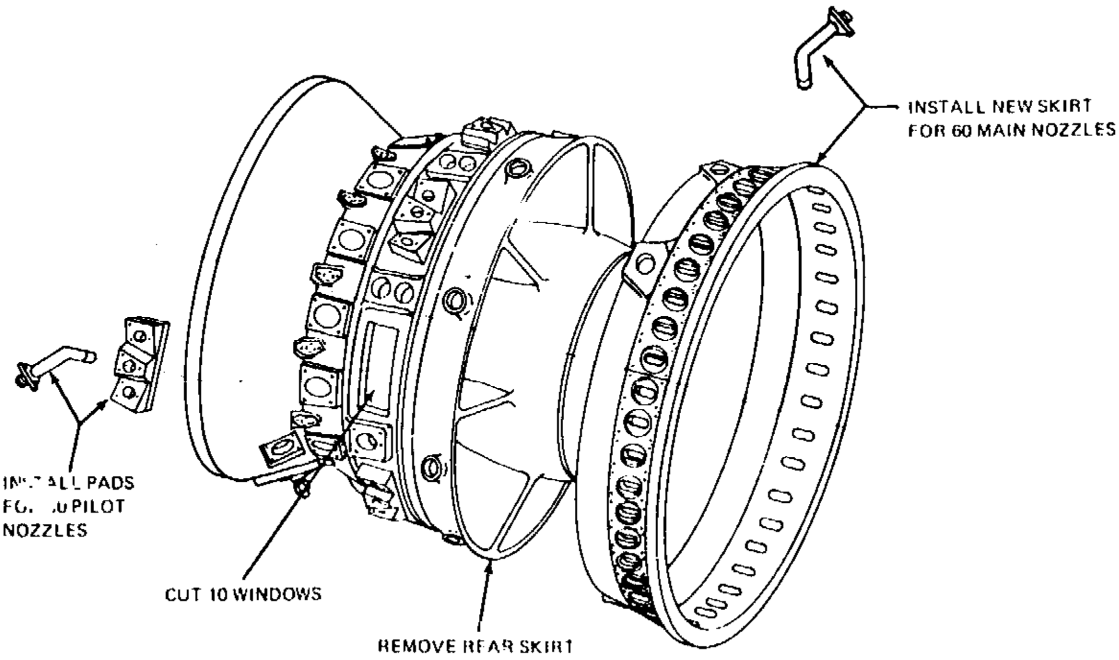

Figure 13 Vorbix Diffuser Case Modification

The rear outer skirt was removed and a new forged ring welded in its place Ten rectangular windows were cut between diffuser struts downstream of the production fuel injector bosses, and forged pads were welded in place. The pilot fuel injector mount pads were clustered in groups of three to reduce the amount of welding required and to eliminate interference with the diffuser case bleed bosses. Plasma arc welding was used to minimize local shrinkage.

The diffuser case was supported with rigid fixtures during welding and machining operations to reduce distortion to previously machined surfaces. An abbreviated stress relief cycle was performed prior to final machining. A photograph of the reoperated case is shown in Figure 14.

Twenty probe bosses were installed at the compressor discharge station for experimental instrumentation. An OD filler duct was installed to reduce OD shroud passage height in the vicinity of the combustor throat and swirlers. Flush plugs were used to fill the twenty existing JT9D-7 fuel injector parts.

Although the extensive welding and design compromises required to permit use of an existing part drastically reduced the cyclic life of the diffuser case, it was acceptable for the experimental use intended. Achievement of the cyclic life necessary production engine applications would require fabrication of a complete new part and proper heat treatment.

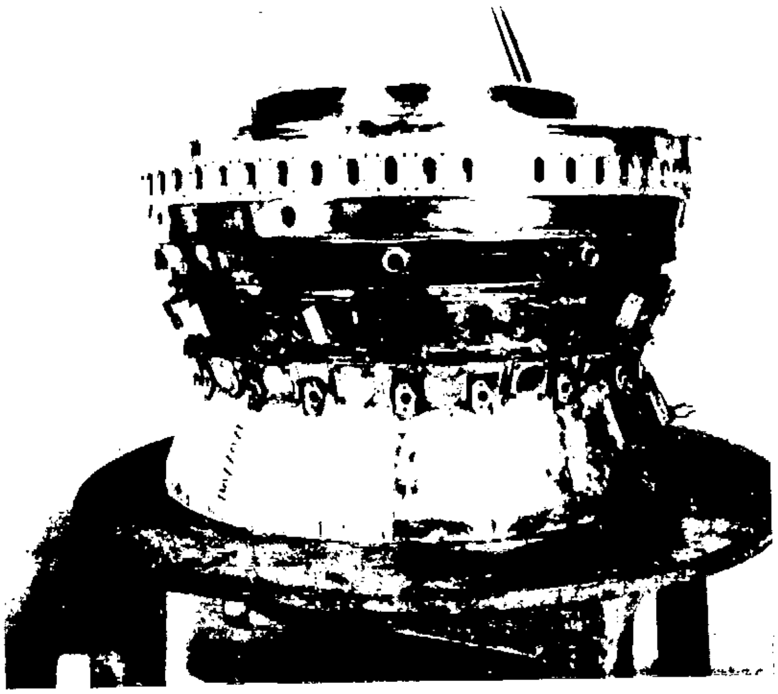

Figure 14 Reoperated Diffuser Case for Phase III Engine Tests (XPN-59774)

C. FUEL SYSTEM

1. FUEL MANIFOLDS

The external fuel system design was unique to the Phase III Vorbix combustor installation. It included pilot and main zone manifolds, staging valves, jumper tubes, and mounting hardware. The pilot and main zone manifolds with valve arrangements are shown schematically in Figures 15 and 16. Representative photographs of the pilot and main zone fuel systems and associated hardware are presented in Figures 17 and 18.

Thirty pilot fuel injectors are equally spaced in clusters of three around the engine circumference. Ten of these are connected directly to the pilot fuel manifold. Control of the fuel flow to the remaining twenty fuel injectors is provided by the pilot solenoid valves. Each valve controls the outer pair of injectors in each cluster of three. The objective of this valving arrangement was to provide flexibility in partial pilot unstaging, if necessary, to improve starting or pilot-to-main staging.

The sixty main zone fuel injectors are controlled by sixteen solenoid valves arranged to permit circumferential zoning or sequencing in staggered groups of four injectors. The main zone solenoid valves perform the staging function and are arranged to permit symmetric operation on either thirty or sixty injectors. In order to minimize the impact of manifold fill time on engine acceleration, the fuel jumper tube volume downstream of the staging valves was kept to a minimum consistent with mounting and serviceability requirements. Staging logic was programmed into the fuel control computer, and each solenoid valve could be operated individually if desired.

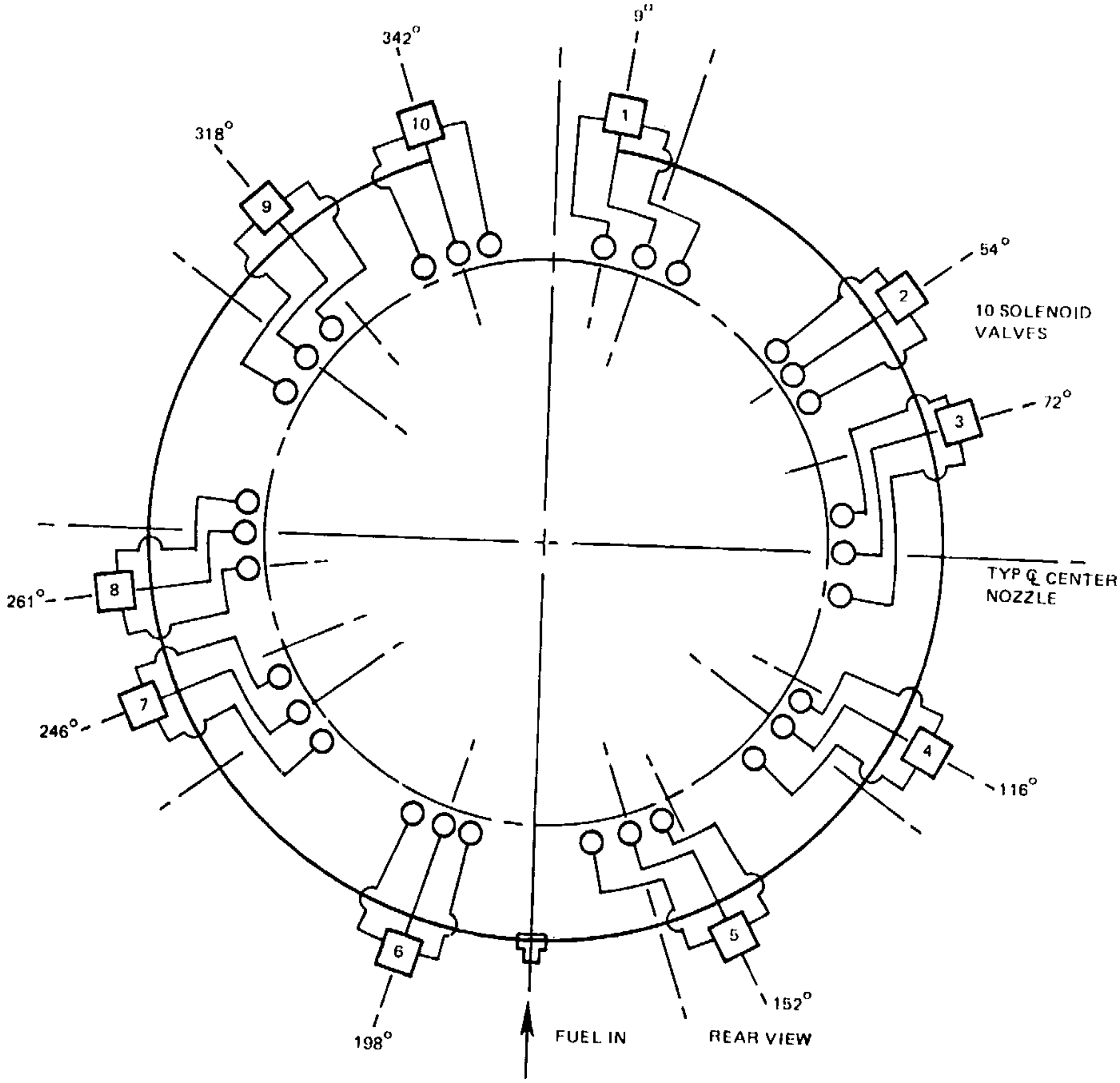

Figure 15   External Fuel System Schematic, Pilot Zone

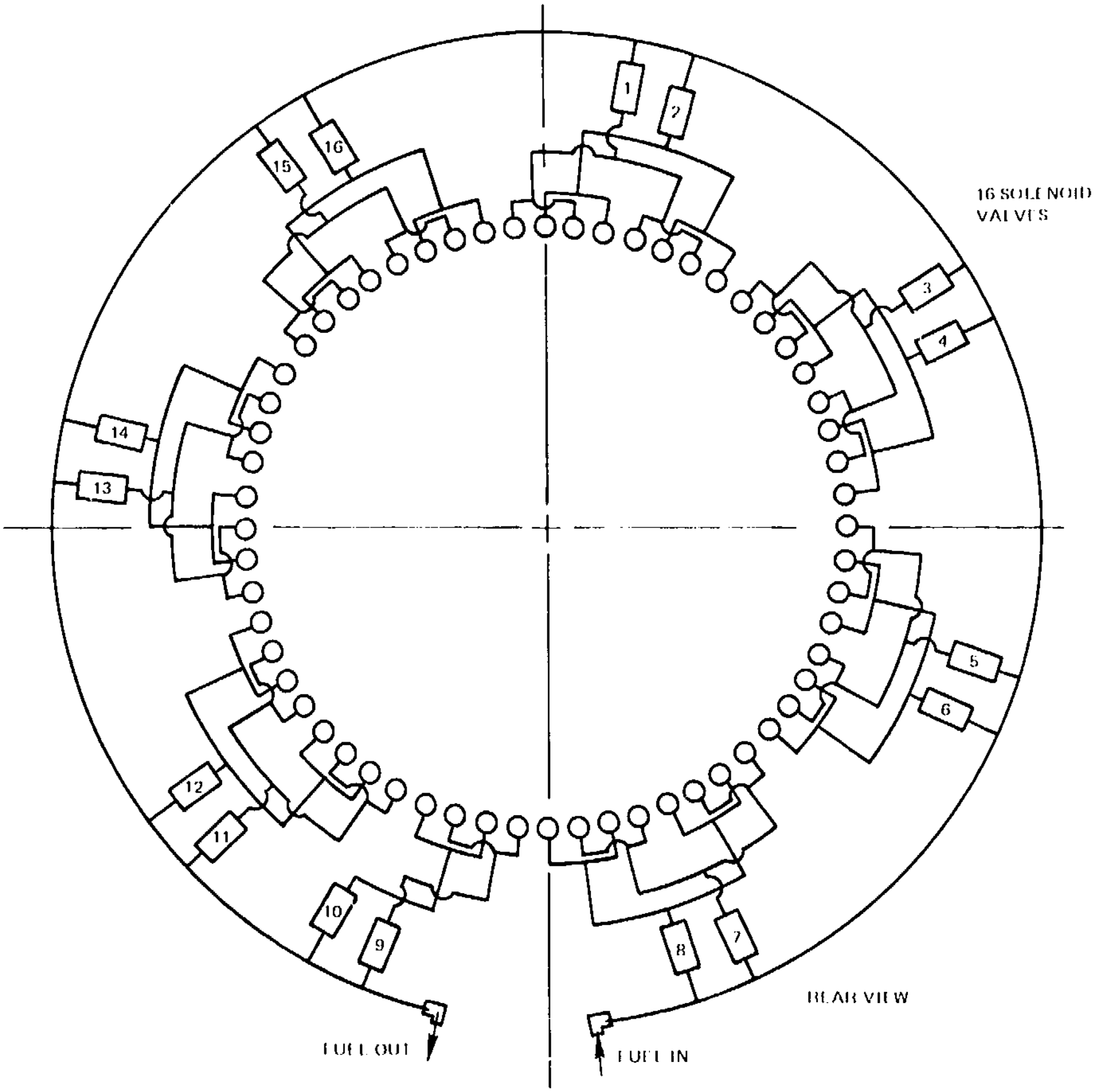

Figure 16   External Fuel System Schematic, Main Zone

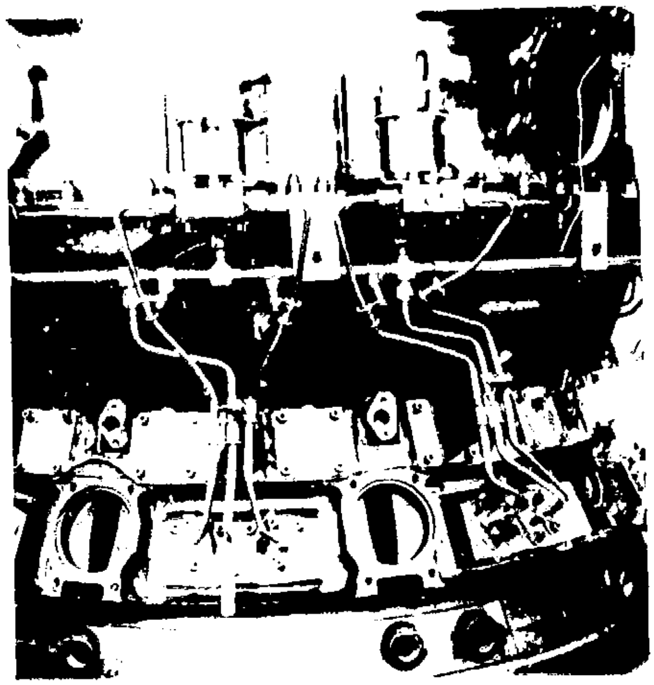

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Figure 17 Typical View of Pilot Zone Fuel Manifold, Solenoid Valves, and Jumper Tubes (X-45713)

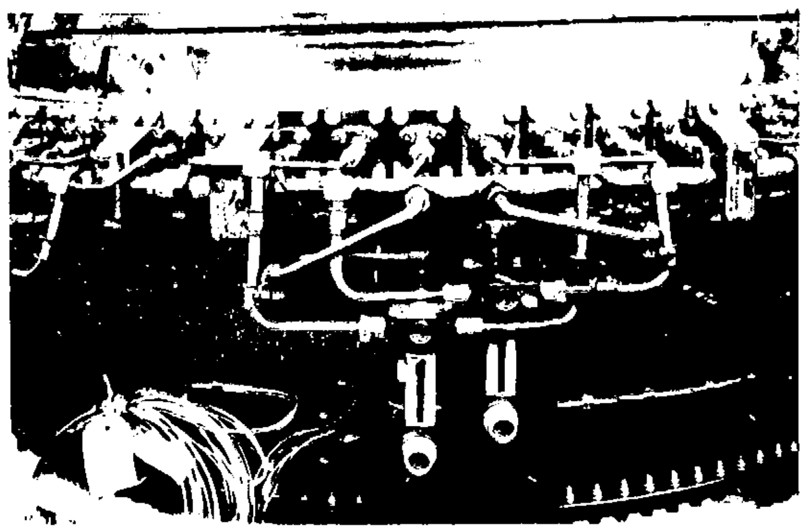

Figure 18 Typical View of Main Zone Fuel Manifold, Solenoid Valves, and Jumper Tubes (X-45703)

The external fuel system was intended strictly as experimental hardware for the Phase III engine test program. Primary reasons for this approach were the additional flexibility desired and the requirement that all components be readily accessible for repair or replacement. Manifold and jumper tube volumes, valve operation, etc., were designed to be flightworthy in function but structurally adequate only for the extent of the engine test program. Since the experimental engine was to be used without a flight-type nacelle and airframe plumbing, the fuel system components were designed with minimum consideration given to external hardware interferences. To ensure integrity of the engine mounted fuel system, the fuel manifolds and valves were assembled on the diffuser case and evaluated for component resonance in the engine operating range. Apparent high stress areas were strain-gaged and the assembled hardware was subjected to a range of frequencies and amplitudes expected during engine tests. The vibration test installation is shown in Figure 19. As a result of this testing, a number of modifications were made to the mounting brackets and tube clips.

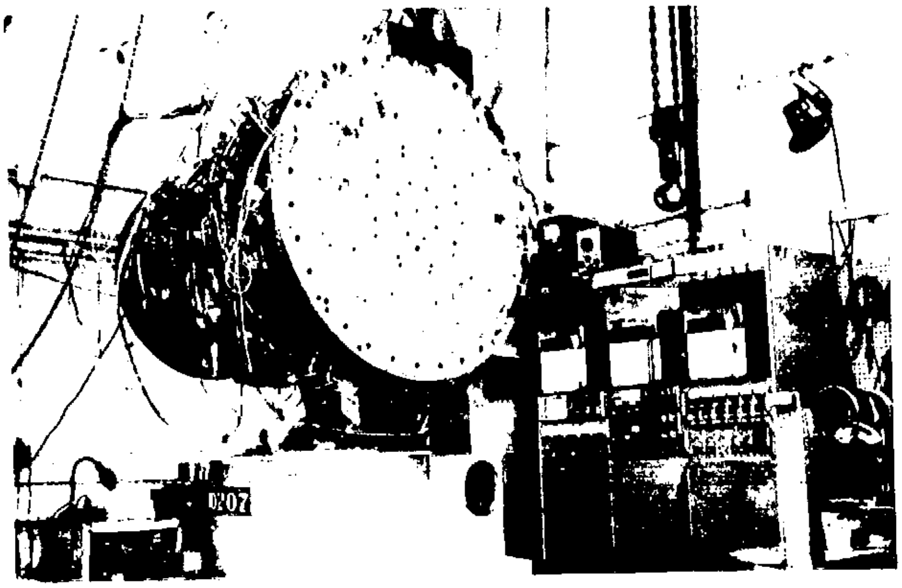

Figure *Figure 19 Diffuser Case and External Fuel System Hardware Durcing Resonance Evaluation Prior to Engine Test* *(X-45651)*

2. FUEL CONTROL

A fuel control design study was conducted as part of Phase II [Reference 4] to identify control system requirements added by the staged combustor concepts developed in the Experimental Clean Combustor Program. A number of conceptual designs which 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 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, manifold head effect, etc., act to further limit the fuel control designer's freedom in varying pilot to main fuel distribution. Specification of the pilot/main fuel split for the Vorbix combustor operating at sea level is shown in Figure 20. 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 which can be used for pilot/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 [Reference 9] in terms of a five-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 operating the engine on pilot only.

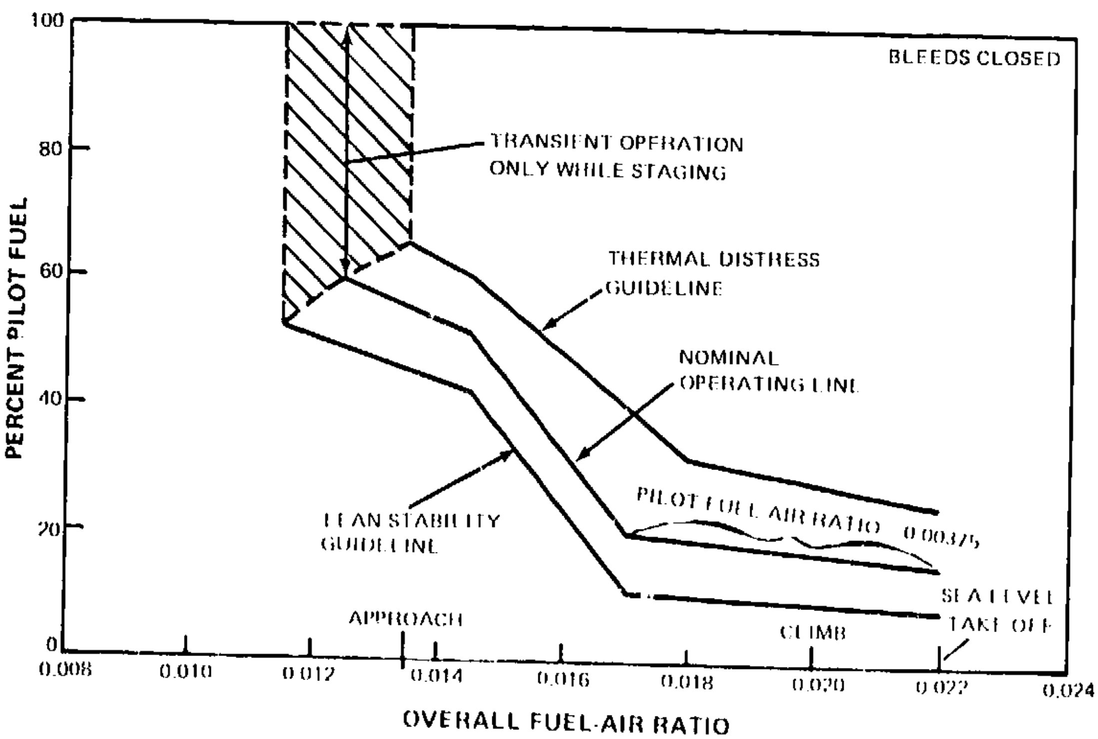

Figure 20 Fuel Scheduling Requirements for Two-Stage Vorbix Combustor Based on Phase II Rig Results

The breadboard fuel control and distribution system for the Phase III engine testing is shown schematically in Figure 21. The main fuel pump, main fuel control, and the fuel-oil cooler are JT9D production components used without alteration. By leaving the engine control intact, the engine fuel flow versus thrust characteristic, and the assorted trims and biases, remain unchanged. All other engine control functions, such as bleed operation and high-pressure compressor vane angle scheduling, continue to be accomplished by the production control. The flow distribution valve (percent split valve) is a Hamilton Standard Division component with appropriate modifications to meet the flow requirements of the Vorbix combustor. The percent split valve is controlled by a reprogrammable PDP 11/40 digital computer. Overall combustor fuel/air ratio, required as a principle control parameter, is sensed by its proportionality to total fuel flow divided by combustor inlet pressure. All breadboard fuel system components not mounted on the engine were mounted on a portable skid, shown in Figure 22. A view of the electronic fuel control computer console installed in the engine test cell control room is shown in Figure 23.

The breadboard control system was divided into five functional subdivisions:

a. A start return bypass to the main fuel pump to provide for fuel flow metering and adjustment during starting;

b. A circulation system to keep the main manifold full when operating on pilot only;

c. A percent split valve to provide metered flow to the pilot and main nozzles;

d. A nitrogen gas purge system for purging the main fuel nozzles when unstaging to minimize coking;

e. A pressurizing and dump valve used to provide a dump for the pilot nozzles when shutting down.

In addition, an emergency fuel shutoff valve was included to ensure fail-safe engine shutdown in the event of a component or logic failure.

The computer was programmed to provide pilot-to-main burner fuel split as a function of overall fuel/air ratio. This function was manually overriden during steady state operation to permit variation of fuel flow split so as to permit determination of the effect of fuel split on emissions and exit temperature profile.

During initial testing, staging was done manually to allow investigation of the transient characteristics of the staging process. Staging was then automated to occur at a selected value of fuel/air ratio, which, in turn, was determined from a correlation curve of steady state values of fuel/air ratio versus combustor pressure. After staging, the percent split valve was modulated to satisfy a function of percent split versus fuel/air ratio which could be trimmed as required. Unstaging was done by a manual push button which sequentially turned on the nitrogen purge for a period of time and then turned on the circulation flow.

During engine testing, the reprogrammable computer proved to be valuable in that it was possible to rapidly alter the percent split versus overall fuel/air ratio schedule, the selection of scheduling parameters, and programmed constants to optimize transient performance.

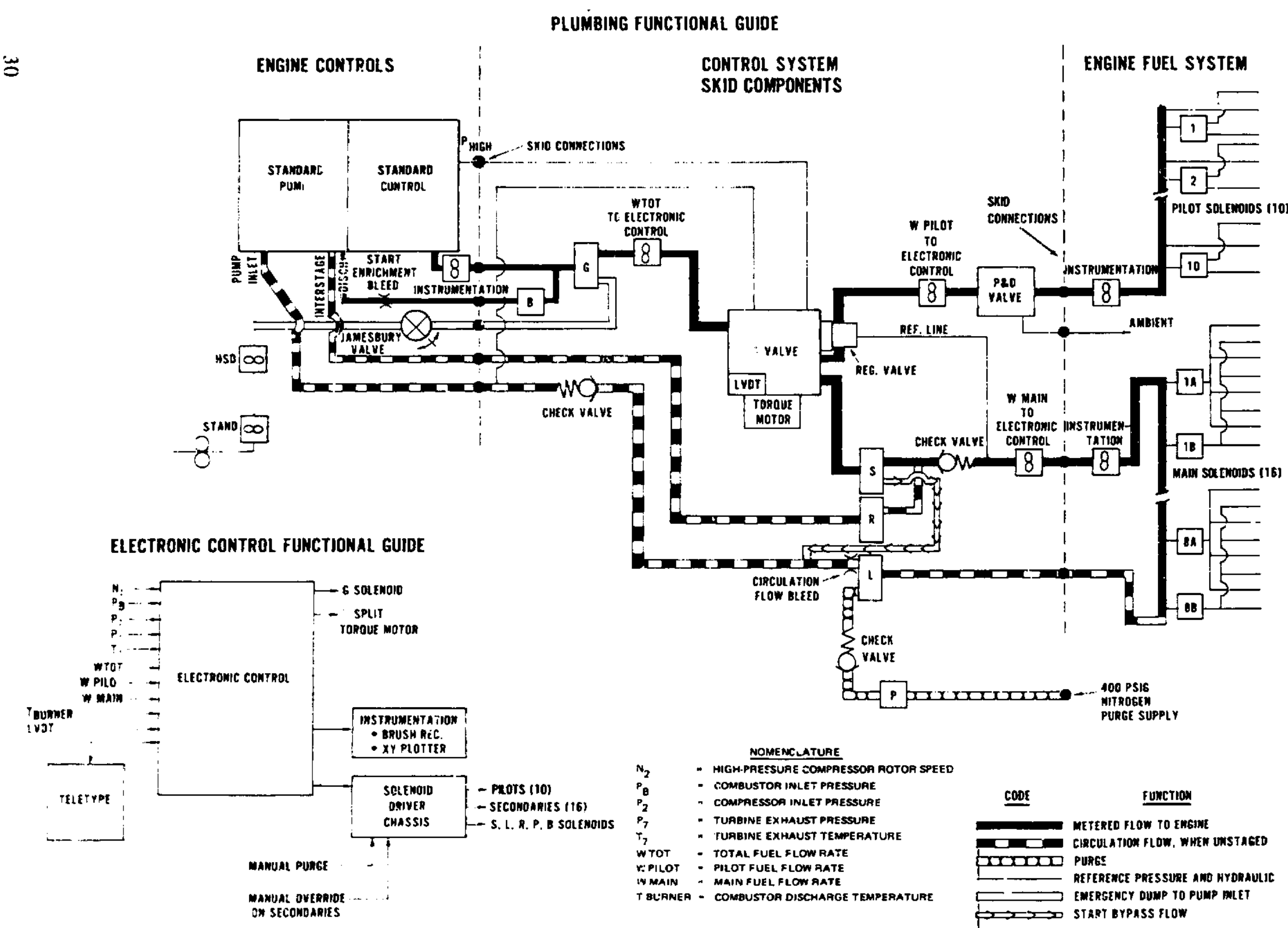

Figure 21   Experimental Clean Combustor Program Phase III Control System Schematic

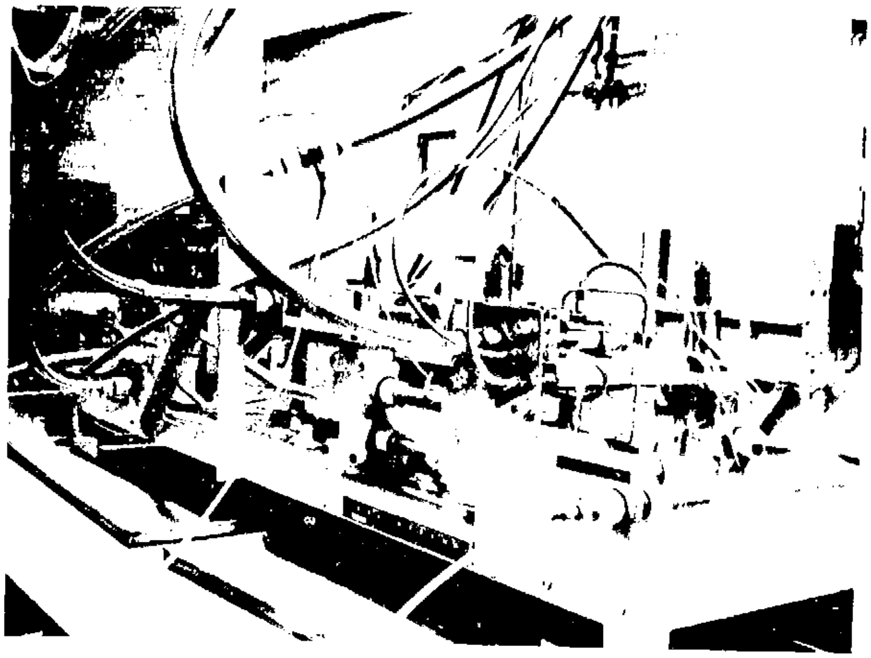

Figure 22   Phase III Breadboard Fuel Control Skid   *(X-45832)*

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Figure 23   Experimental Clean Combustor Program Phase III Electronic Fuel Control Computer Console

(X-45833)

D. EXPERIMENTAL ENGINE X-686 DESCRIPTION

1. ENGINE CONFIGURATION

Experimental JT9D-20 engine X-686 was the test vehicle for the Phase III Experimental Clean Combustor Program. The JT9D-20 engine model is equivalent to the JT9D-7A reference engine in gas generator configuration and performance. The major differences between the two models are the locations of the mounting attachment points, accessory gearbox and other external components. Figures 24 and 25 compares the two configurations. The JT9D-20 model is preferred for combustor development work because the gearbox is located forward and away from the combustor case. The design of experimental fuel manifolds and instrumentation is considerably simplified by removal of the JT9D-7 envelope constraints, and the external components are easily accessible for service. The engine was operated at JT9D-7A combustor inlet parameters and thrust levels for the Phase III test program.

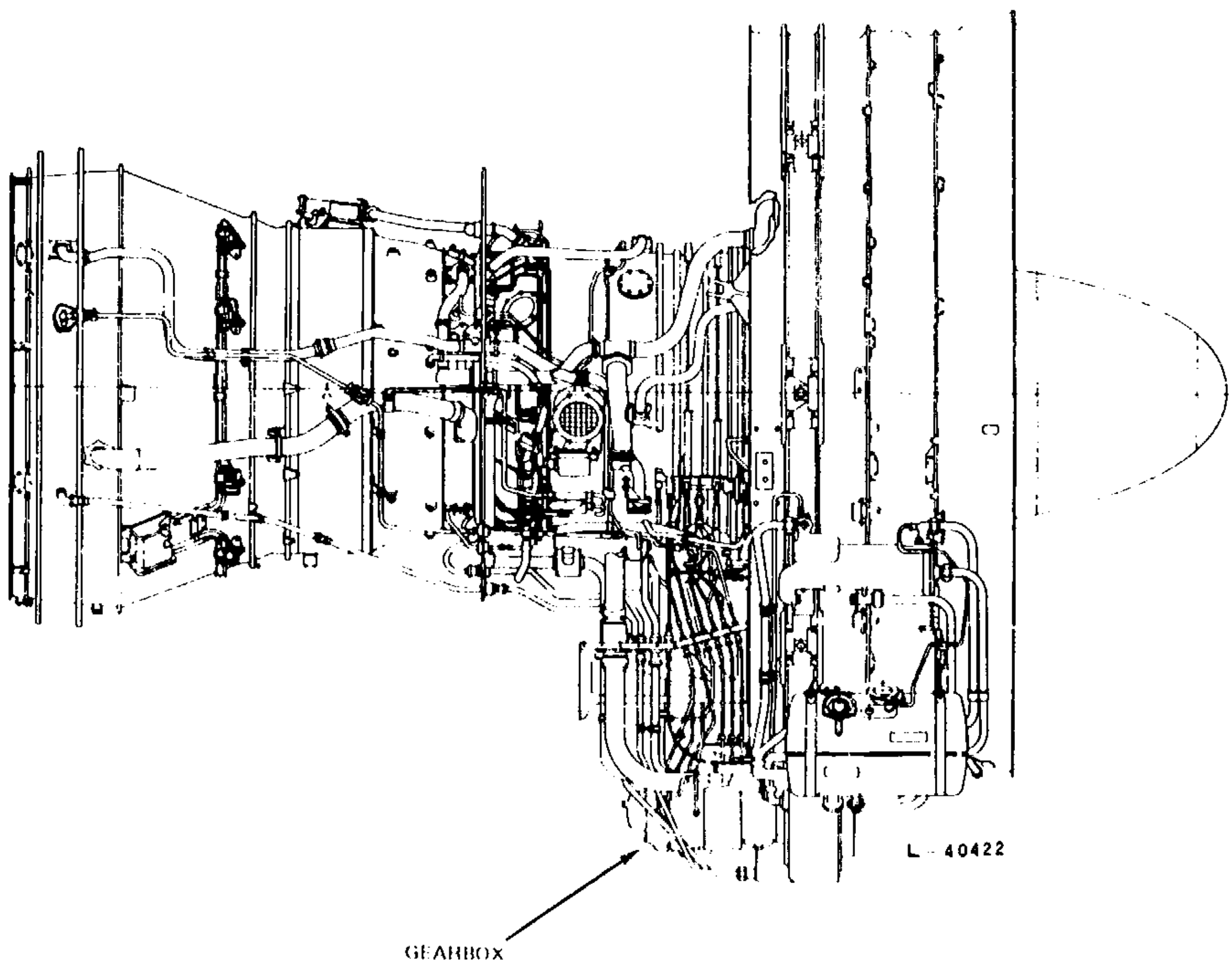

Figure 24 JT9D-20 Engine External Configuration (Right Side)

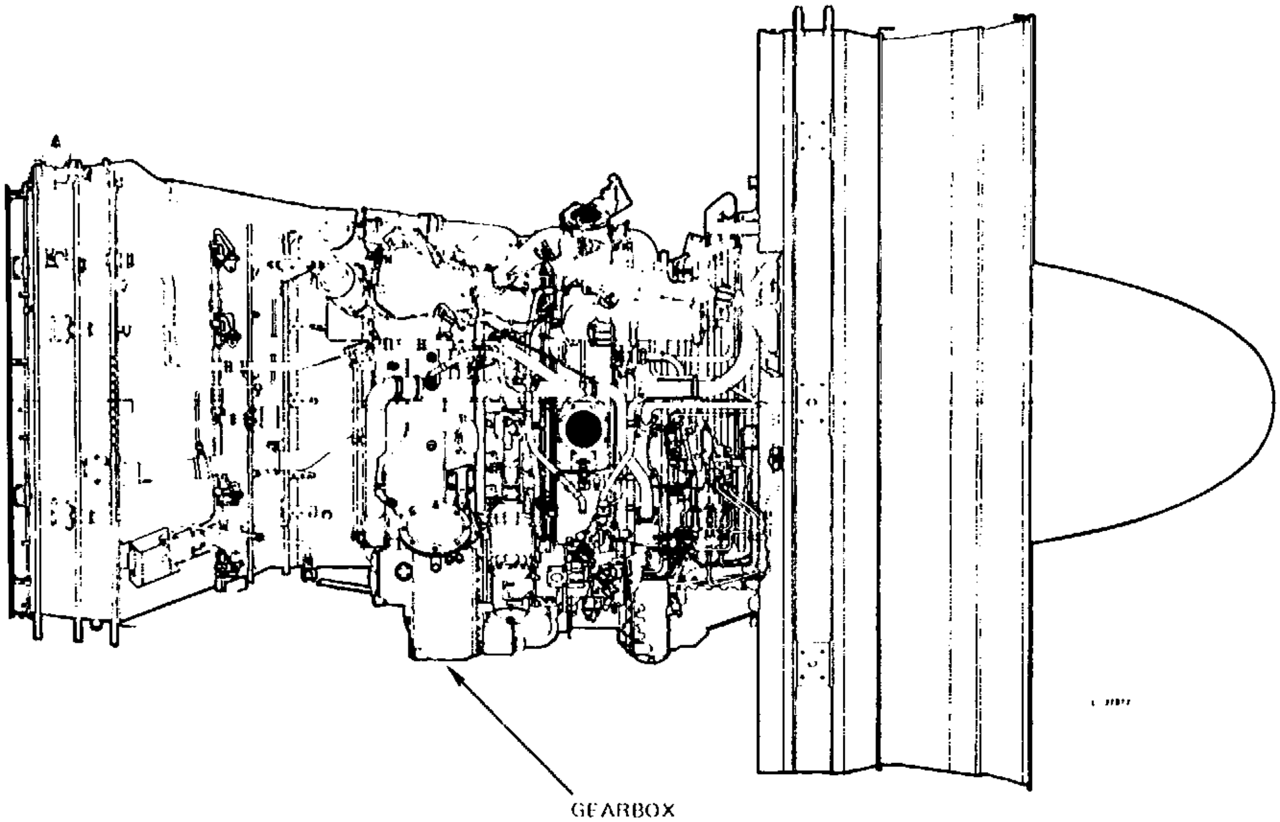

Figure 25   JT9D-7 Engine External Configuration (Right Side)

Figures 26 and 27 show external views of engine X-686 prior to the start of Phase III testing. The two-stage Vorbix external fuel system is visible, as is the first-stage turbine inlet guide vane ARTS (Automatic Recording Temperature System) instrumentation package.

2. PERFORMANCE INSTRUMENTATION

In order to compute overall performance characteristics, experimental engine X-686 was instrumented to measure the following engine operating parameters.

- Engine inlet temperature T_{t2}
- Low rotor speed N_1
- High rotor speed N_2
- Gearbox breather pressure   P
- Gearbox breather temperature   T
- Engine thrust F_N
- Engine inlet total pressure P_{T2}
- Fan discharge total pressure $P_{t2.5}$
- Engine exit total pressure P_{t7}
- High turbine discharge temperature T_{t6}
- Engine exit total temperature T_{t7}
- Burner pressure P_{s4}
- Total engine fuel flow W_f

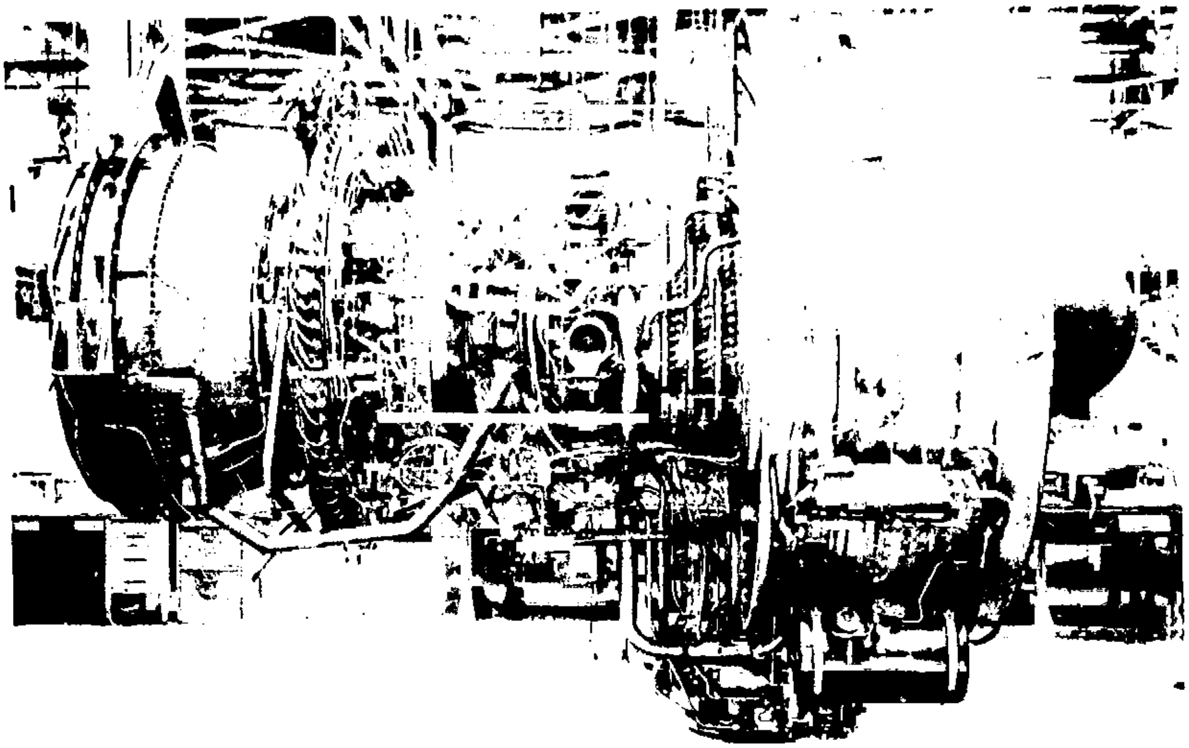

Figure 26 *Experimental JT9D-20 Engine X-686 With Vorbix Combustor and ARTS Instrumentation Ready for Initial Test (Right Side)* *(CN-57360)*

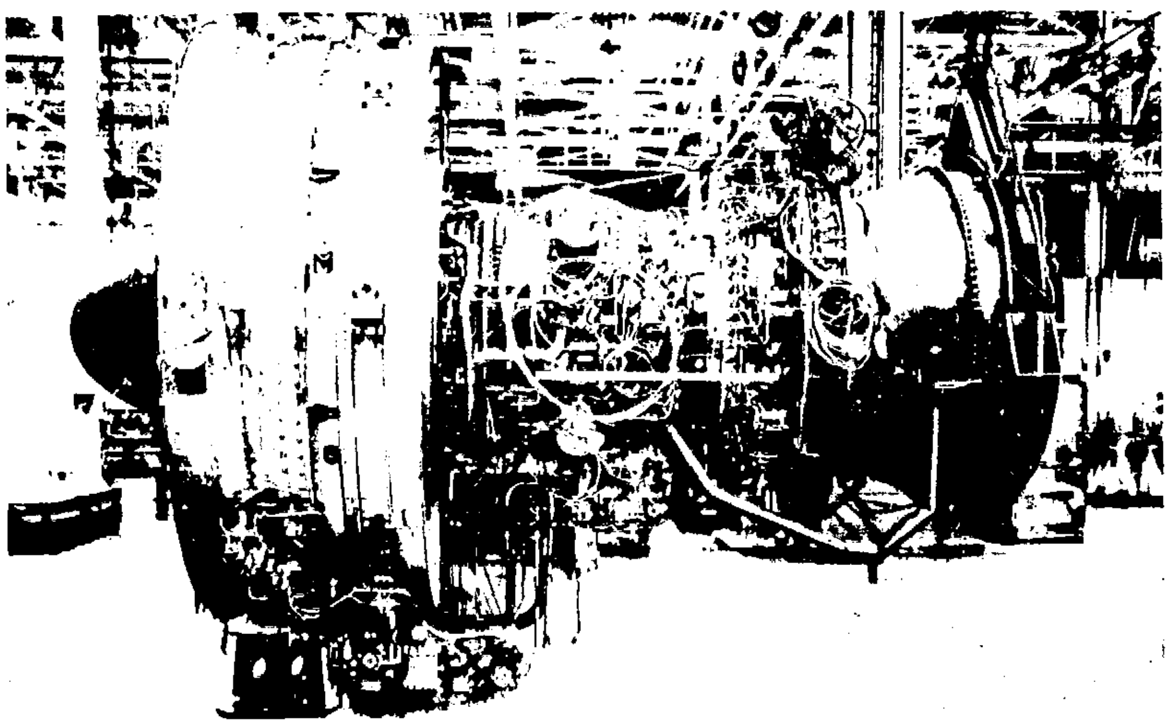

Figure 27 *Experimental JT9D-20 Engine X-686 With Vorbix Combustor and ARTS Instrumentation Ready for Initial Test (Left Side)* *(CN-57360)*

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In addition, pressure and temperature probes were added to the compressor discharge station to measure combustion inlet conditions; extensive instrumentation (total and static pressure taps) was added to the diffuser/combustor section to establish airflow distribution into the combustor liners; thermocouples were installed at critical locations on the combustor liner skin, and gas samples were withdrawn through taps at the downstream end of the ID and OD diffuser shroud passages and passed through a hydrocarbon analyzer to detect internal fuel leakage, fuel aspiration, or combustor damage should it occur. The engine and combustor section instrumentation is described in more detail in Appendix A.

Experimental engine X-686 was also fitted with first-stage turbine inlet guide vane thermocouple ARTS (Automatic Recording Temperature System) instrumentation for the initial testing sequences. This instrumentation permits determination of combustor exit temperature pattern under actual engine operating conditions. Figure 10 presents an overall view of the assembled ARTS pack, connecting leads, etc., with the inner combustor liner in place. A close-up view of a portion of the ARTS instrumentation is shown in Figure 28. The ARTS pack is comprised of 290 platinum/rhodium thermocouple elements welded to the leading edges of 58 first-turbine vanes. Four vanes are instrumented with total pressure sensors and are located at approximately 90 degree intervals around the circumference. An additional four blank vanes serve as inner combustor liner instrumentation lead pass-throughs. Radiation and conduction errors are minimized by the use of a radiation shield around each thermocouple sensor and by ducting exhaust gas flow around the junction. Sequencing of the thermocouple data acquisition is controlled by the Pratt & Whitney Aircraft 2104 Data Acquisition System installed at the engine test stand. The inclusion of ARTS instrumentation imposes a maximum limit of 1839K (2850°F) on local turbine inlet temperature. The ARTS pack was replaced by a standard first-turbine vane assembly for the final test sequence.

3. EXHAUST GAS SAMPLING INSTRUMENTATION

Most of the exhaust gas sampling was conducted with an eight-arm rake mounted in the core engine exhaust stream 0.36 m (14 inches) downstream of the exhaust nozzle exit plane. The unmounted rake shown in Figure 29 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 mounted on a traverse gear which permitted rotation over a 45 degree arc in five degree increments. Data were recorded using these alternate rake configurations for comparison with the stationary eight-arm baseline configuration.

An additional exhaust gas sampling system utilized for comparison purposes in the Phase III test program was comprised of the standard production engine exhaust total pressure probes. (P_{t7}). 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 30.

A description of the exhaust rake installation and the gas analysis and conditioning equipment is presented in Appendix A.

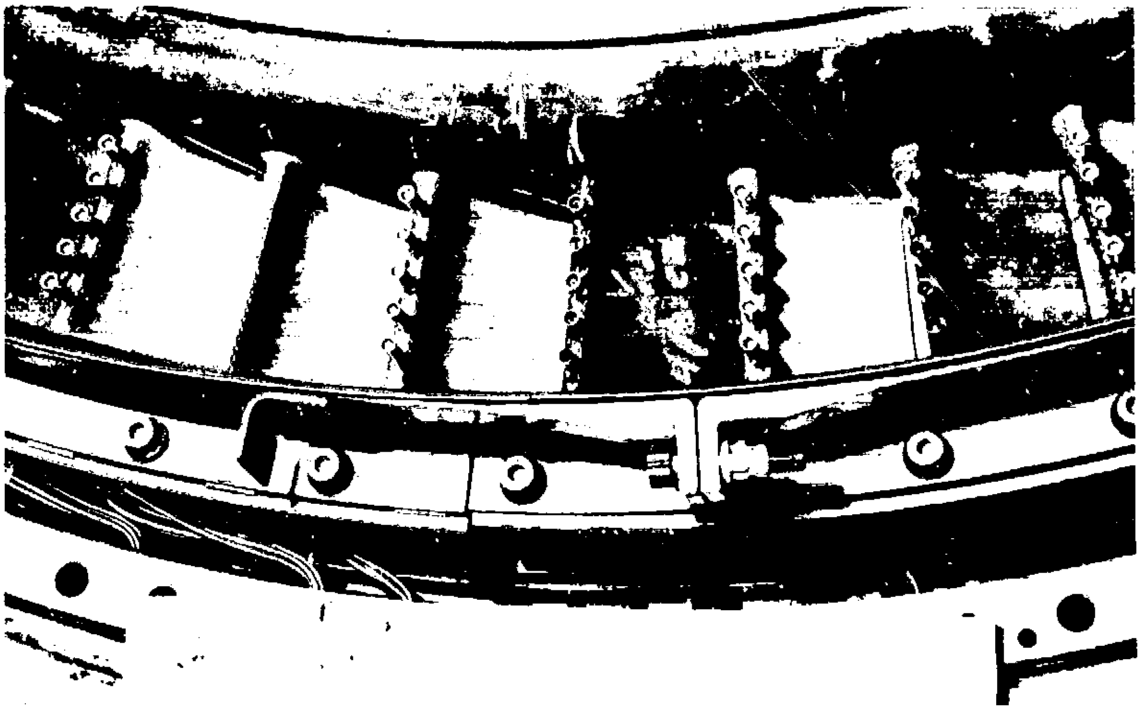

Figure 28 *Instrumented First-Stage Turbine Vane Assembly* (XPN-60093)

Figure 29 *Exhaust Emissions Rake for Experimental Clean Combustor Program* (XPN-59484)

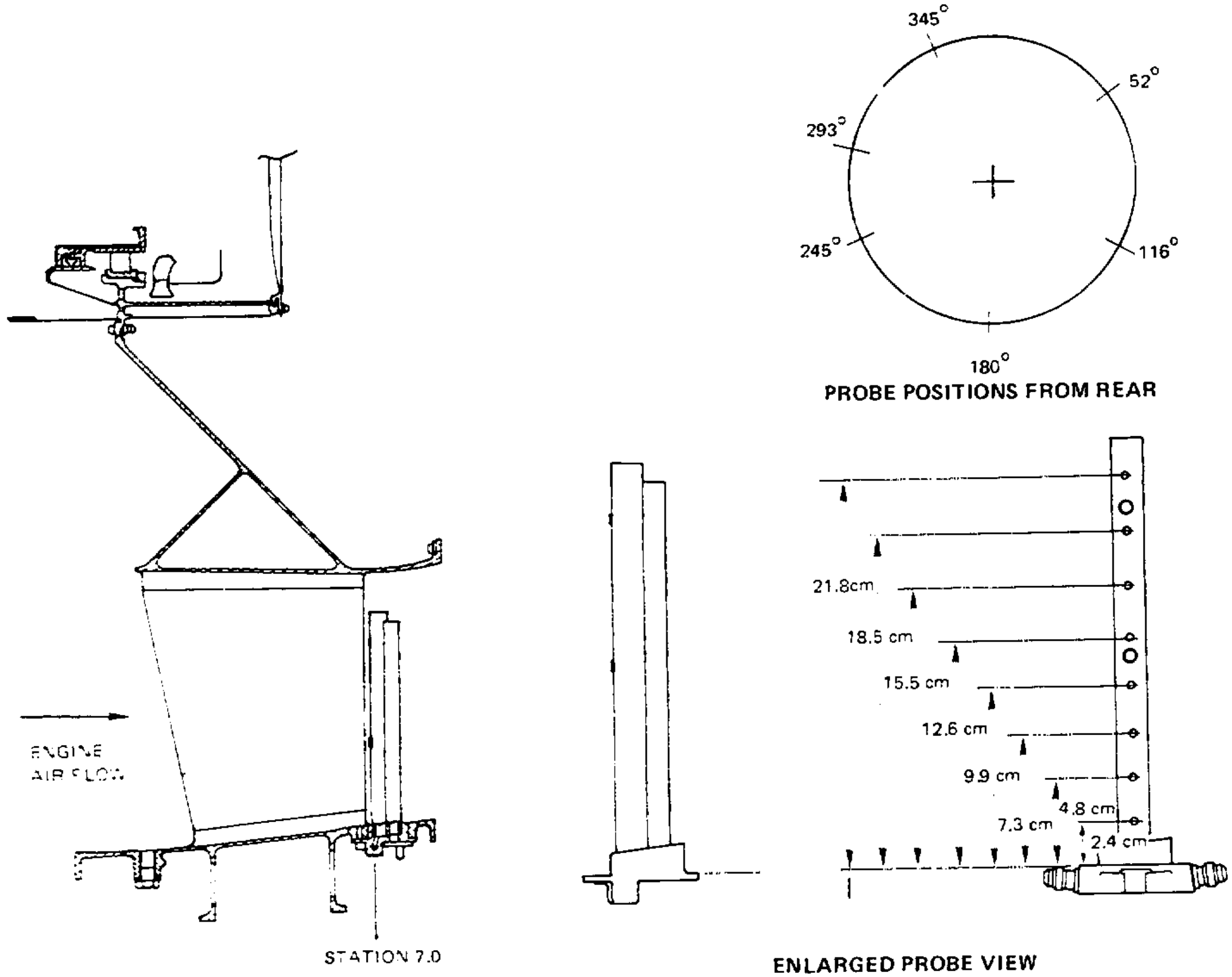

Figure 30 Station 7 Gas Sample Probe Array Used in the Phase III Test Program

4. P-6 TEST STAND

All engine testing in the Phase III Experimental Clean Combustor Program was conducted at the Pratt & Whitney Aircraft production test facility in Middletown, Connecticut. This facility includes a series of ambient inlet, indoor test cells with sufficient cell volume and flow capacity to test high airflow engines in the JT9D thrust class. The P-6 test stand has been equipped with the additional instrumentation and data handling capability required for ARTS and low-emission combustor development programs. A description of the test stand and data acquisition system is given in Appendix A.

E. TEST CONDITIONS AND PROCEDURES

1. STEADY–STATE TESTING

The Phase III engine tests were conducted in a manner similar to that of other JT9D experimental engines 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 (Appendix A). Since the program was oriented to measurement of emissions at specific power levels, the steady state emissions data were taken for most points by establishing combustor inlet temperature level, regardless of ambient conditions. The Standard Day JT9D-7A Gas Generator Reference Conditions are tabulated in Table VIII for the four EPA-specified sea level static power settings. The emission data were corrected as described in Section F1 from the observed combustor inlet conditions to the corresponding standard day reference conditions for presentation in this report.

TABLE VIII

STANDARD DAY JT9D-7A GAS GENERATOR REFERENCE CONDITIONS

Engine Model	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	
JT9D-7A	Idle	14,234	3,200	780	1,720	447	345	3.69×10^5	53	0.0105
	Approach	61,585	13,845	2,109	4,650	588	598	8.91×10^5	129	0.0134
	Climb	174,494	39,228	6,010	13,250	736	864	19.38×10^5	281	0.0206
	Takeoff	205,284	46,150	7,303	16,100	764	916	21.68×10^5	323	0.0229

The ground idle operating conditions defined in Table VIII correspond to engine operation without compressor service air bleed and auxiliary gearbox-mounted components required to drive aircraft systems (power extraction). This is consistent with current Pratt & Whitney Aircraft experimental engine and production acceptance test procedures, and conforms to the requirements of the EPA aircraft engine emission standards (Reference 1).

A typical steady-state engine test program is shown in Table IX. Additional test points were added as required during the engine test run depending on emission data obtained, combustion efficiency, or to set a specific value of another engine parameter, such as corrected thrust. Variation of the pilot/main fuel split is a primary test variable at the higher engine power settings. Following an approximately five minute stabilization period at each test point, a set of engine performance data, combustor section pressure and temperature data, exit temperature (ARTS) data, and exhaust gas emission data were simultaneously recorded. Idle emissions data were obtained at the start and completion of each engine run to determine if the cold or hot engine condition had any significant effect on emission levels. For steady-state testing with the ARTS instrumentation in place, operation was limited so as not to exceed 1839K (2850°F) gas temperature on the turbine inlet guide vanes or the redline limit for the engine Exit Gas Temperature (EGT).

2. TRANSIENT TESTING

a. Acceleration/Deceleration

Engine acceleration/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 ARTS instrumentation was not used in these tests. 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 (F/A = 0.0105) and a simulated flight idle (F/A = 0.0115) power settings. The elapsed time to 95 percent thrust is automatically recorded by the test stand APTDAC system (See Appendix A). The "snap" acceleration test requires that the power lever be advanced from the selected idle position to the full power position in one second or less. Snap acceleration data are presented in the format shown in Figure 31. Figure 31 also shows the contract goal [Reference 9] and representative JT9D-7A production engine performance.

Particular attention was paid to passage through the pilot-to-main staging point, and various combinations of pilot/main fuel schedule and fuel control response parameters were investigated. Tests were conducted for both unstaged and staged (main zone fueled) idle operation, as indicated in Figure 32. The breadboard fuel control was designed to permit considerable adjustment in fuel management around the staging point. Main zone unstaging under deceleration was adjusted to prevent combustor blowout.

TABLE IX

PHASE III STEADY-STATE TEST PROGRAM

Engine Run Point	Emission Sample Type 24 Pt. Fixed	12 Pt. Fixed	24 Pt. Traverse	Sta. 7	Engine Condition	T_4(1) (K)	(^oF)	Percent Pilot Fuel	Smoke(2)
1,2	X	X	X	X	Idle	447	345	100	
3	X				Sub Idle	439	330	100	
4	X				Rich Idle	514	465	100	
5	X				Lean Approach	550	530	50	
6	X				Approach Split	587	598	30	X
7	X				Approach Split	587	598	40	X
8,9	X	X	X	X	Approach Split	587	598	50	X
10	X				Approach Split	587	598	60	X
11	X				Rich Approach	614	645	40	
12	X				50% Power Split	680	765	30	
13	X				50% Power Split	680	765	40	
14	X				50% Power Split	680	765	25	
15	X				50% Power Split	680	765	20	
16	X				50% Power Split	680	765	15	
17	X				Sub Climb Split	708	815	30	
18	X				Sub Climb Split	708	815	20	
19	X				Sub Climb Split	708	815	10	
20	X				Climb Split	735	864	25	X
21,22	X	X	X	X	Climb Split	735	864	20	X
23	X				Climb Split	735	864	15	X
24	X				Climb Split	735	864	10	X
25	X				Sub SLTO	750	890	20	
26	X				SLTO Split	764	916	25	X
27,28	X	X	X	X	SLTO Split	764	916	20	X
29	X				SLTO Split	764	916	15	X
30	X				SLTO Split	764	916	10	X
31	X				Idle	447	345	100	
32	X				Idle	455	360	100	
33	X				Idle	511	460	100	

(1) Average Combustor Inlet Temperature

(2) Smoke Data obtained with 24 Pt rake only

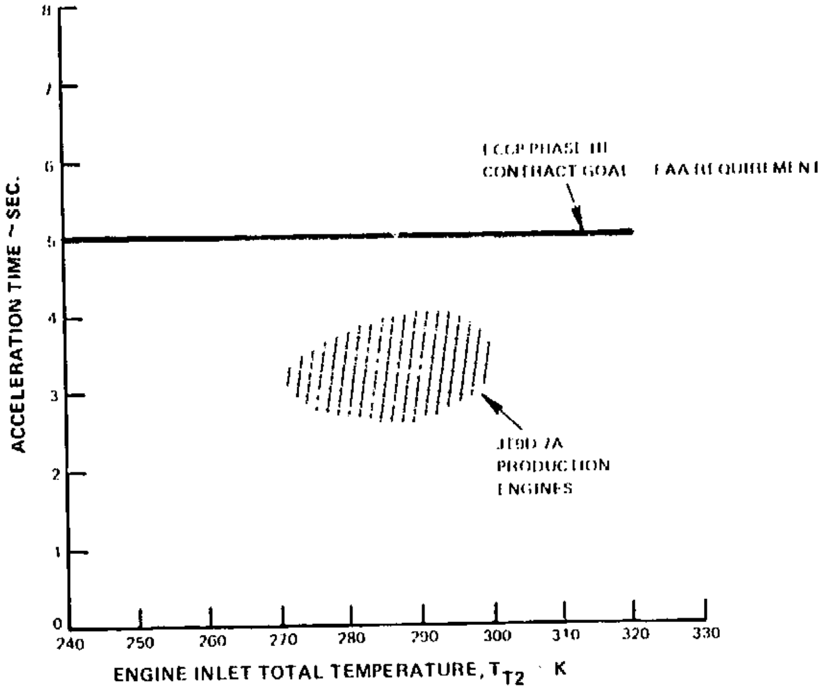

Figure 31 Comparison of JT9D-7A Snap Acceleration Capability and Experimental Clean Combustor Program Phase III Goal (FAA Requirement)

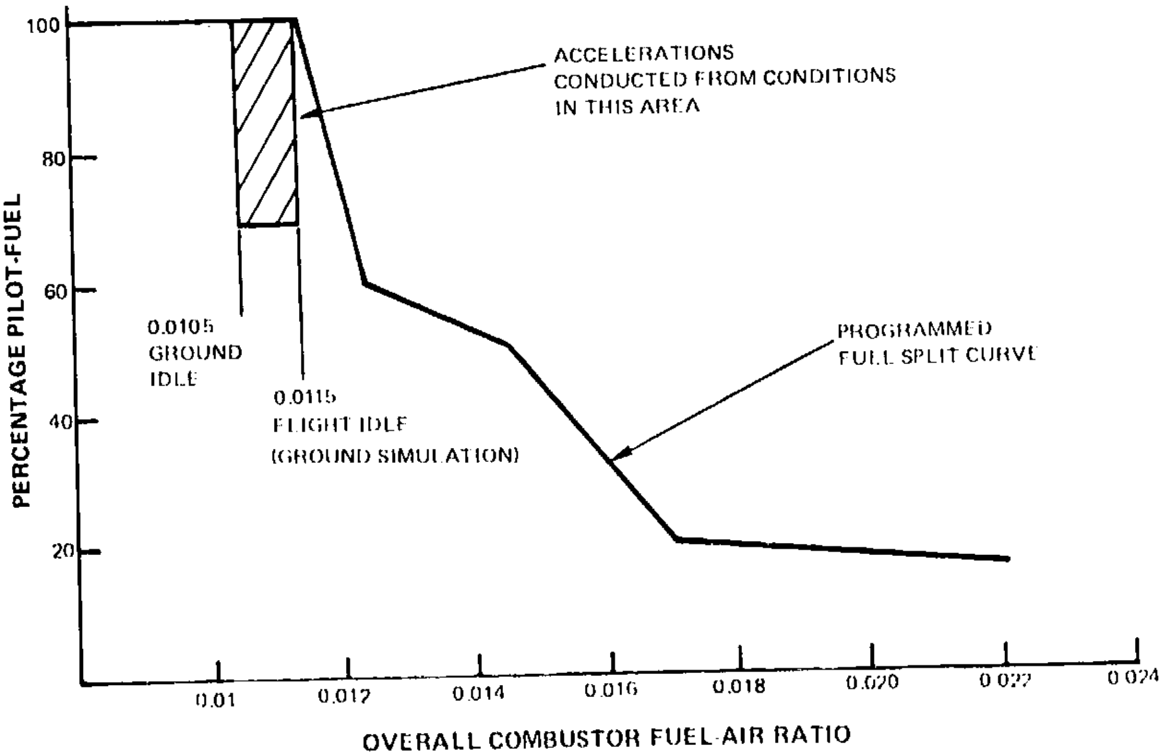

Figure 32 Phase III Engine Acceleration Program

Emissions data were not taken during the engine acceleration tests due to the stabilization requirement for gas samples. Visual observations were made of the exhaust during each acceleration for the presence of unburned fuel.

b. Sea Level Starting

A program was conducted to define the starting characteristics of the test engine with the Vorbix combustor. Engine starts were attempted at high rotor speeds of 1400 and 1800 rpm and various fuel flow/combustor pressure ratios as shown in Figure 33. An engine start is considered satisfactory if the engine successfully accelerates to the ground idle condition. dition.

F. DATA ANALYSIS PROCEDURES

1. EMISSION DATA REDUCTION PROCEDURE

The raw emission data were transmitted directly to an online 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 [Reference 10].

In order to compare combustor development engine emission data between runs and to the JT9D-7A production baseline, it is necessary to correct emission data to the standard conditions listed in Table VIII. As discussed earlier, the basis for setting most test points was combustor inlet temperature (T_{t4}). All adjustment of observed emission 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 and are contained in Appendix A. The magnitude of inlet pressure, etc., correction 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 in experimental engine X-686 revealed that only inlet pressure deviated significantly from the reference engine characteristics. Deviations up to 15 percent were recorded at high power engine conditions. Deviations were less than 10 percent at low power engine conditions. The fuel/air ratio was only slightly (0-3 percent) higher than the standard engine. 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 emission 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 H_2O/kg dry air. The data adjustment equations for the gaseous emission species are as follows:

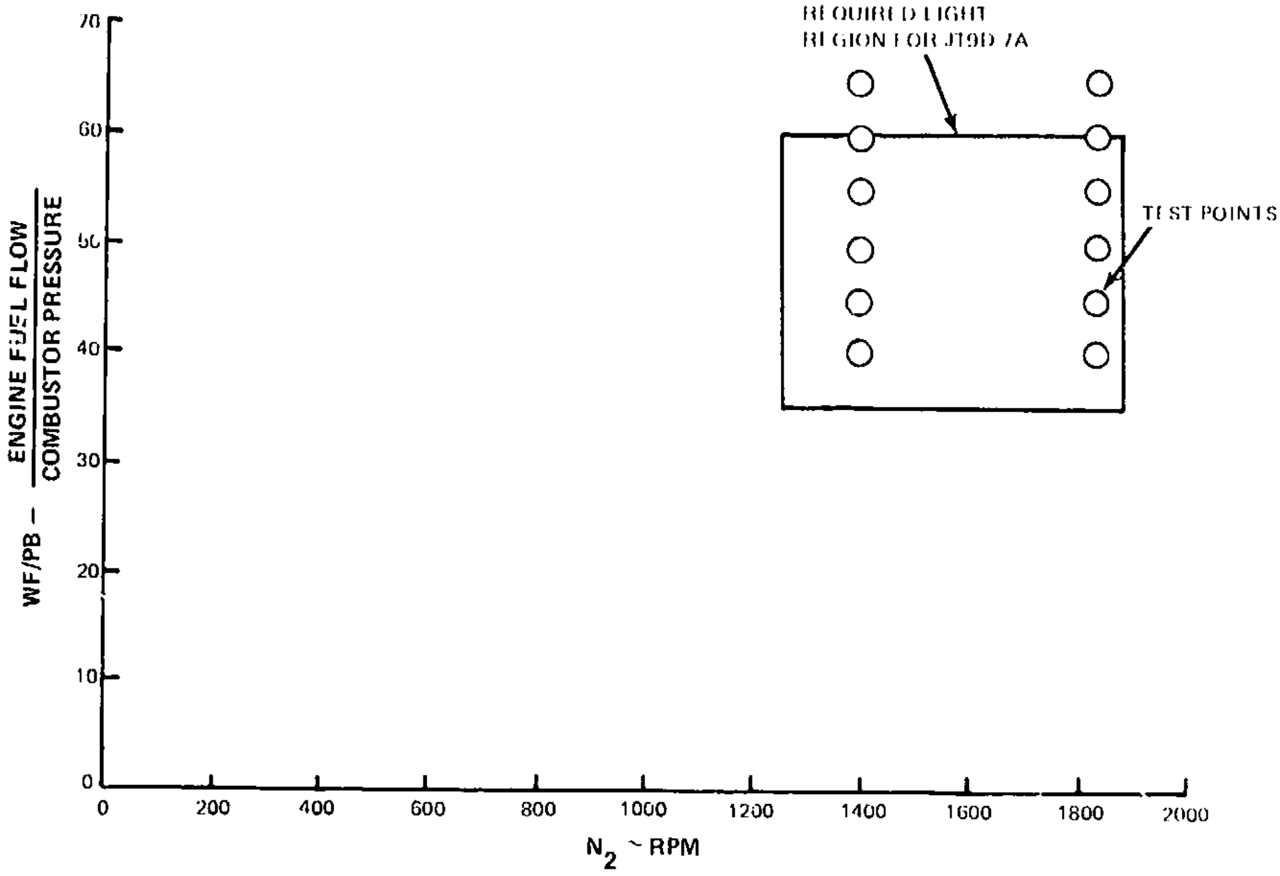

Figure 33 Phase III Vorbix Combustor Starting Program

(1) $$NO_x \text{ corr.} = NO_x \text{ meas.} \left(\frac{(P_{t4} \text{ std.})}{(P_{t4} \text{ meas.})}\right)^{0.5} e^{0.018\,(H \text{ meas.} - 6.3)}$$

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

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

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)

and subscripts:

std	=	Relates to value at standard condition
corr.	=	Relates to value at corrected or standard condition
meas.	=	Relates to value at measured condition.

Exhaust smoke data are presented on an as-recorded basis. Smoke corrections are believed to be very small, on the order of 3 percent for each parameter. Since the data were obtained at slightly lower pressures and slightly higher fuel/air ratios than reference values, the corrections tend to compensate each other.

2. EPA PARAMETER CALCULATION

The U. S. Environmental Protection Agency emission standards for aircraft engines are expressed in terms of an integrated EPA parameter (EPAP). This parameter combines emission rates at the engine idle, approach, climb, and takeoff operating modes, integrated over a specified landing. takeoff cycle [Reference 1]. The equation for this calculation is as follows:

$$(4)\quad EPAP_i = \frac{\Sigma j \, \frac{t_j}{60} \, W_{Fj} \, EI_{ij}}{\Sigma j \, \frac{t_j}{60} \, F_{Nj}} \quad \text{(lbm pollutant/1000 lbf thrust-hr/LTO cycle)}$$

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)

and subscripts:

i	=	emission category (CO, THC, NO_x)
j	=	engine mode (idle, approach, climb, SLTO)

The net thrust and fuel flow engine data used to calculate the EPAP are presented in Table X, and were obtained from the latest JT9D-7A performance table.

TABLE X

JT9D-7A ENGINE DATA FOR EPAP CALCULATION

Engine Mode	Time (t) min.	Net Thrust (F_n) lbf	Fuel Flow (W_f) lbm/hr
Idle (unbled)	26.0	3200	1720
Approach	4.0	13845	4650
Climb	2.2	39228	13250
SLTO	0.7	46150	16100

Substituting the engine data from Table XI equation (4) becomes:

(5) $EPAP_i = 0.174 EI_{Idle} + 0.072\ EI_{approach} + 0.114\ EI_{climb} + 0.0441\ EI_{SLTO}$

The emission indices used in equation (5) are obtained from plots at the JT9D-7A four values of combustor inlet temperature corresponding to the EPA power points (Table VIII).

3. COMBUSTOR PERFORMANCE CALCULATION PROCEDURE

Measured and calculated combustor performance parameters are listed in Table XI.

TABLE XI

SUMMARY OF REPORTED COMBUSTOR PERFORMANCE PARAMETERS

Parameter	Symbol	Units	Measured	Calculated
Total Airflow	W_{a4}	kg/s	X	
Total Combustor Airflow	W_{ab}	kg/s		X
Pilot Fuel Flow	W_f pilot	kg/s	X	
Main Fuel Flow	W_f main	kg/s	X	
Inlet Total Temperature	T_{t4}	K	X	
Inlet Total Pressure	P_{t4}	atm	X	
Reference Velocity	V_{ref}	m/s		X
Pattern Factor	PF			X
Inlet Air Humidity	H	gH_2O/kg air	X	
Fuel/Air Ratio	f/a			X
Pressure Loss	$\Delta P_t/P_t$			X
Combustion Efficiency	η_c			X

Definitions of those calculated parameters which require further clarification are presented below.

a. **Total Combustor Airflow**

The total combustor airflow is determined by subtracting the turbine cooling air and other fixed bleed flows from the Station 7 measured flow.

b. **Reference Velocity** —

The reference velocity (V_{ref}) is defined as that flow velocity that would result if the total combustor airflow, at the compressor discharge temperature and static pressure, were passed through the combustor liner at the maximum cross sectional area. This area is $0.218 m^2$ for the Vorbix combustor tested in this program.

c. **Pattern Factor** —

The pattern factor (PF) at the combustor exit is defined by the expression below.

$$(6) \quad PF = \frac{T_{t5\ max} - T_{t5\ avg}}{T_{t5\ avg} - T_{t4}}$$

where:

$T_{t5\ max.}$	=	Highest local temperature measured at the combustor exit plane (K)
T_{t4}	=	Measured combustor inlet temperature (K)
$T_{t5\ avg.}$	=	Calculated from the measured combustor fuel/air ratio and inlet conditions.

d. **Fuel/Air Ratio**

Both measured and carbon derived fuel/air ratios (f/a) have been calculated and recorded for all test points run in this program. The measured, or performance fuel/air ratio, is the ratio of total fuel flow to total combustor airflow. The pilot and main fuel/air ratios are defined by multiplying the overall fuel/air ratio by the fractional pilot and main fuel split, respectively. The carbon balance derived fuel/air ratio is determined by using gas sample data to determine the carbon balance of the exhaust gases.

e. Total Pressure Loss

The total pressure loss ($\Delta P_t/P_t$) is calculated from the following equation:

$$(7) \qquad \frac{\Delta P_t}{P_t} = \frac{P_{t5} - P_{t4}}{P_{t4}}$$

where:

P_{t5} = Average combustor exit total pressure
P_{t4} = Average compressor discharge total pressure

f. Combustion Efficiency

The combustion efficiency (η_c) is calculated on a deficit basis using the measured concentrations of carbon monoxide and total unburned hydrocarbons from the gas sample data. The calculation is based on the assumption that the total concentration of unburned hydrocarbons could be assigned the heating value of methane (CH_4). The equation is:

$$(8) \qquad \eta_c = 100 - 100\left(\frac{4343\ X + 21500Y}{18.4\,(10)^6}\right)$$

where:

X = measured carbon monoxide concentration in g/kg fuel

Y = measured total unburned hydrocarbon concentration in gCH_4/kg fuel.

CHAPTER III

PHASE III RESULTS AND DISCUSSION

A. INTRODUCTION

This chapter contains the engine emissions and performance test results for the two-stage Vorbix combustor and fuel system evaluated in the Phase III program. The data have been confined to that which substantiates the major accomplishments of the program, and consist primarily of reduced and analyzed data for the final (S27E) combustor configuration. A compilation of all data obtained during the program is presented in the appendices.

B. TEST PROGRAM SUMMARY

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. A breakdown of the test program running hours is shown in Table XII.

Testing of the first configuration, S25E, was limited to intermediate and lower power levels by local liner overheating. The two subsequent configurations, however, were successfully tested at power levels up through full sea level takeoff combustor inlet temperatures and fuel/air ratios.

C. EMISSION 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 primary-to-main zone fuel split on both the levels of each emissions specie, and the possible trades among the species. These results were then analyzed to calculate the optimum EPAPs and smoke number to relate the emissions performance to the program goals. The EPAP results and smoke number results are presented in Section IIIC1; the detailed emissions results are presented in Section IIIC2; and the procedure used for optimizing the pilot zone fuel/air ratio is discussed in Section IIIC3.

The program included evaluation of the effects of changing the number of main zone fuel injectors while maintaining the same total fuel flow. The results of this parametric study are presented in Section IIIC4.

Results obtained with five different gas sampling techniques are discussed in Section IIIC5.

1. EPAP AND SMOKE RESULTS

The EPA parameters (EPAPs) 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 XIII together with the corresponding program goals and the values for the current JT9D-7A.

TABLE XII

TEST PROGRAM SUMMARY

Run Number	Combustor Configuration	Test Hours	Test Activity
1A	S25E	8	Shakedown Testing
1B	S25E	9	Steady State Performance and Emissions Data Acquisition
2	S26E	11	Steady State Performance and Emissions Data Acquisition
3	S27E	36	Steady State Performance and Emissions Data Acquisition
4	S27E		Steady State Performance and Emissions Data Acquisition With First-Stage Turbine Vane ARTS Instrumentation Removed
5	S27E	18	Transient Testing and Sea Level Starting With First-Stage Turbine Vane ARTS Instrumentation Removed
Total		82	

TABLE XIII

EPAP AND SMOKE RESULTS

	EPAP			
	Oxides Nitrogen	Carbon Monoxide	Total Unburned Hydrocarbons	Maximum 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	0.2	30

Notes: EPAP 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 H_2O/kg dry air.

JT9D-7A data based on current production test results for engine with combustor EC 289386.

As shown, the Vorbix combustor met the goals for gaseous emissions for all three species. Oxides of nitrogen 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, oxides of nitrogen were reduced by 58 percent, carbon monoxide emissions were reduced by 69 percent, and total unburned hydrocarbons were reduced by 96 percent.

The smoke emission goal was not achieved. Smoke levels were substantially above those for the current JT9D-7A combustor.

2. EMISSION INDEX RESULTS

The emissions data were analyzed to develop parametric curves relating the pilot zone fuel/air ratio to the emissions of each specie as a function of power setting, with the power setting defined in terms of the observed combustor inlet temperature.

An interpolation procedure was devised which resulted in parametric curves of emissions versus combustor inlet temperature for various pilot zone fuel/air ratios. The curves are shown in Figure 34. The initial step inthe procedure consisted of segregating the emissions data (corrected for pressure and humidity) by observed inlet temperature, and then plotting the data against the observed pilot zone fuel/air ratio. The emissions values corresponding to specific pilot zone fuel/air ratios could then be determined from the curves, thereby removing variations in the observed pilot zone fuel/air resulting from variations in setting the test conditions or from the effects of ambient conditions.

The curves show that smoke number reaches a maximum value at the sea-level takeoff power setting and is insensitive to pilot zone fuel/air ratio at that condition. At lower power settings, smoke number exhibited a decrease with increasing pilot fuel/air ratio.

The emissions of oxides of nitrogen 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.

Total unburned hydrocarbon emissions were extremely low at the higher power settings, with the lowest values being obtained at the higher pilot zone fuel/air ratios. Similar trends, at a somewhat higher level, were obtained for carbon monoxide emissions.

At approach and lower power settings, similar trends were observed with pilot zone fuel/air ratio. However, higher values of pilot fuel/air ratio were required to achieve acceptable levels of carbon monoxide and total unburned hydrocarbon emissions and the sensitivity of the emissions to pilot fuel/air ratio was somewhat greater.

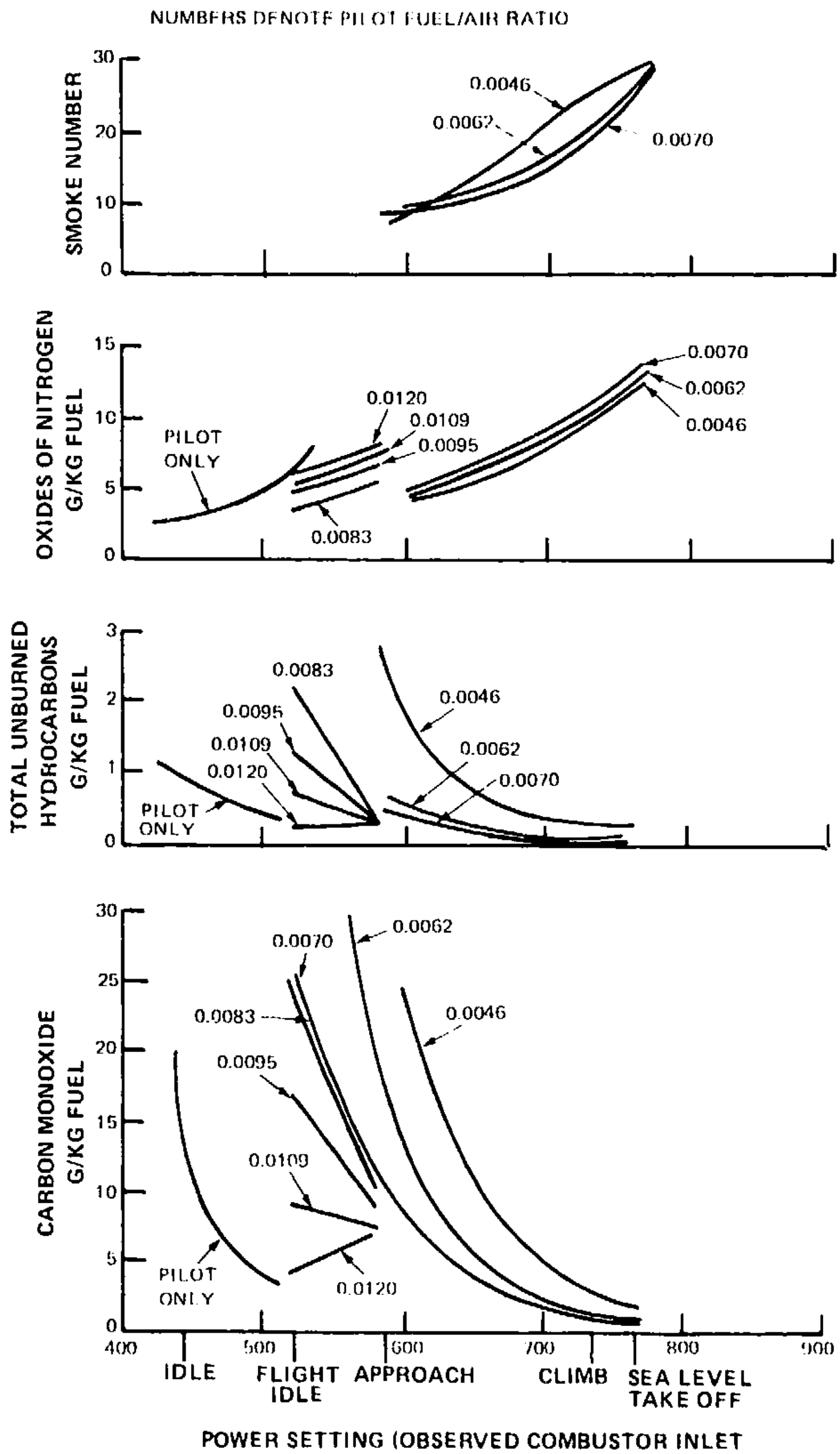

Figure 34 Parametric Emissions Data Showing Effect of Pilot Zone Fuel/Air Ratio on Emissions of Each Specie

3. SELECTION OF OPTIMUM FUEL FLOW SPLIT

On the basis of the smoke data contained in Figure 34, and analysis of the exit temperature distribution data, a pilot zone fuel/air ratio of 0.007 was selected for the EPAP calculation for the high power portion of the power spectrum from approach through sea level takeoff. Smoke levels at climbout are lowest at 0.007.

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 fuel/air ratio produced a reduction in carbon monoxide and total unburned hydrocarbons 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 of these, occurring immediately below the flight idle power setting, represents staging of the main zone. This discontinuity 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 flow 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 carbon monoxide and total unburned hydrocarbon 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 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 selected fuel splits provide large reductions in the gaseous emissions of the Vorbix combustor relative to the emissions of the JT9D-7A production combustor. As shown in Figure 35, large reductions were achieved for emissions of oxides of nitrogen at the high power settings and emissions of total unburned hydrocarbons and carbon monoxide at low power settings.

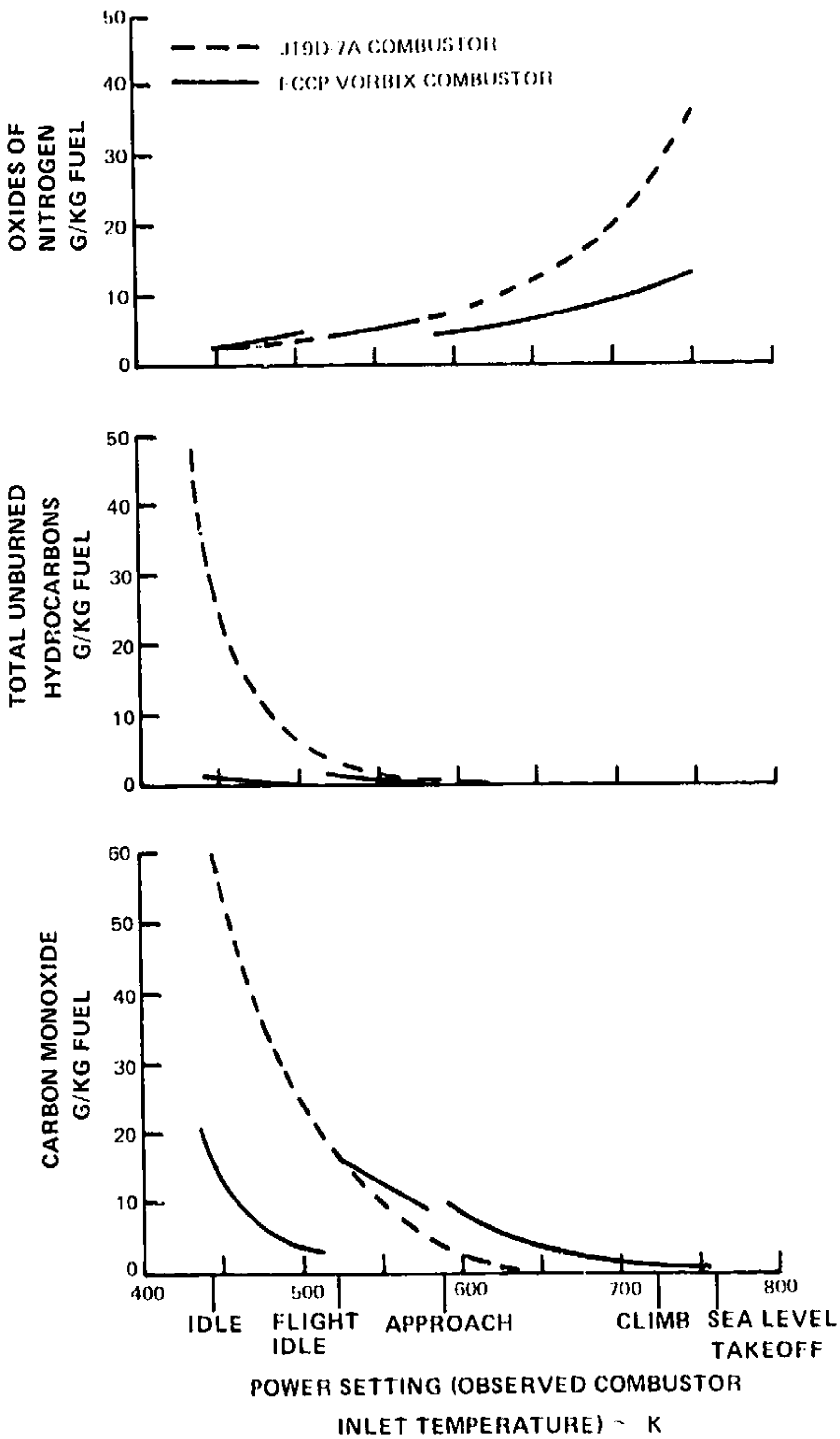

Figure 35 Emissions for Vorbix Combustor at Selected Pilot Zone Fuel/Air Ratios Levels for the JT9D-7A Combustor

4. PARAMETRIC VARIATION OF FUEL INJECTOR DENSITY

The effect of reducing the number of main zone fuel injectors from 60 to 30 was investigated in Configuration S27E by delivering fuel to only every other fuel injector. The effect of this change is shown in Table XIV.

The most significant effect of the reduction was a more than doubling of the smoke at climb conditions. This increase is believed to result from the locally fuel-rich mixture conditions produced. This conclusion is supported by the observation that smoke increased when the main zone fuel was increased (reduced pilot zone fuel/air ratio) at a fixed setting using 60 injectors.

Thirty main zone injectors also increased the emissions of carbon monoxide and total unburned hydrocarbons, particularly at climb conditions, but the resulting levels still remained very low. The effect on the emissions of oxides of nitrogen was negligible.

5. GAS SAMPLING TECHNIQUES

Five gas sampling techniques were used to obtain the engine exhaust emissions data. An additional technique using a rake of the "diamond" design was also investigated in an addendum effort. The diamond rake and results obtained with it are described in reference 8. The techniques and their symbol designations are defined in Table XV. Detailed descriptions of the rakes and the associated techniques are included in Chapter II and Appendix A. 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-port, 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 36, 37 and 38. As shown, the data obtained from the various rakes for emissions of oxides of nitrogen are in excellent agreement. For carbon monoxide emissions, 24F generally provided lower indications than the other rakes by approximately 10 percent. The traverse samples showed best agreement with those obtained with 24F. The Station 7 probe (Rake ST7) produced the largest consistent deviation, averaging indications that were approximately 11.5 percent above those of the baseline rake. The total unburned hydrocarbon emission data comparison appear to indicate a large amount of data scatter. However, this scatter results in part from inaccuracies associated with measurement of the very small concentrations of unburned hydrocarbons produced by the Vorbix combustor.

Smoke measurements made with the 12- and 24-point fixed rakes (Rakes 24F and 12F) were nearly identical.

The conventional measure of gas sample validity is a comparison of the metered fuel/air ratio based on direct measurement of the engine fuel flow and core airflow with the calculated fuel/air ratio based on the carbon balance of the exhaust gas specie concentrations detected by the sampling probe. Data for this comparison is presented in Figure 39 and shows that the 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 and air flow measurement. Rake ST7 provided the greatest deviation.

TABLE XIV

EFFECT OF MAIN ZONE FUEL INJECTOR DENSITY
ON EMISSIONS

Power Setting	Test Conditions: Pilot Fuel/Air Ratio	Test Conditions: Combustor Inlet Temperature (K)	Number of Injectors	Emissions Index (g/kg fuel): Oxides of Nitrogen	Emissions Index (g/kg fuel): Carbon Monoxide	Emissions Index (g/kg fuel): Total Unburned Hydrocarbons	Smoke Number
Approach	0.0083	602	60	5.4	8.20	0.50	---
Approach	0.0083	607	30	5.5	8.27	1.10	---
Climb	0.0074	735	60	11.75	1.35	0.15	20
Climb	0.0074	741	30	11.50	2.90	0.66	47
Climb	0.0062	735	60	11.10	1.50	0.15	21
Climb	0.0062	741	30	10.60	3.50	0.48	46

Notes: Data presented for 60 injectors was interpolated from emissions plots produced from Run 3 data; data presented for 30 injectors represents actual test conditions.

Oxides of nitrogen data reported as equivalent NO_2, corrected for pressure and for humidity of 6.3 g H_2O/kg dry air.

Total unburned hydrocarbons data reported as equivalent CH_4.

Total unburned hydrocarbons data and carbon monoxide data corrected for pressure.

TABLE XV

GAS SAMPLING TECHNIQUE IDENTIFICATION

Symbol	Description
24F	24-Port, 8 Arm, Radial Array, Fixed
24T	24-Port, 8-Arm, Radial Array, Traversed over 45 Degrees in 5-Degree Increments
12S	12-Port, 4-Arm, Cruciform Oriented Vertical and Horizontal, Fixed
12E	12-Port, 4-Arm, Cruciform Oriented 45 Degrees from Vertical and Horizontal, Fixed
ST7	6-Station 7 Pressure Probes With 8 Radial Pressure Taps

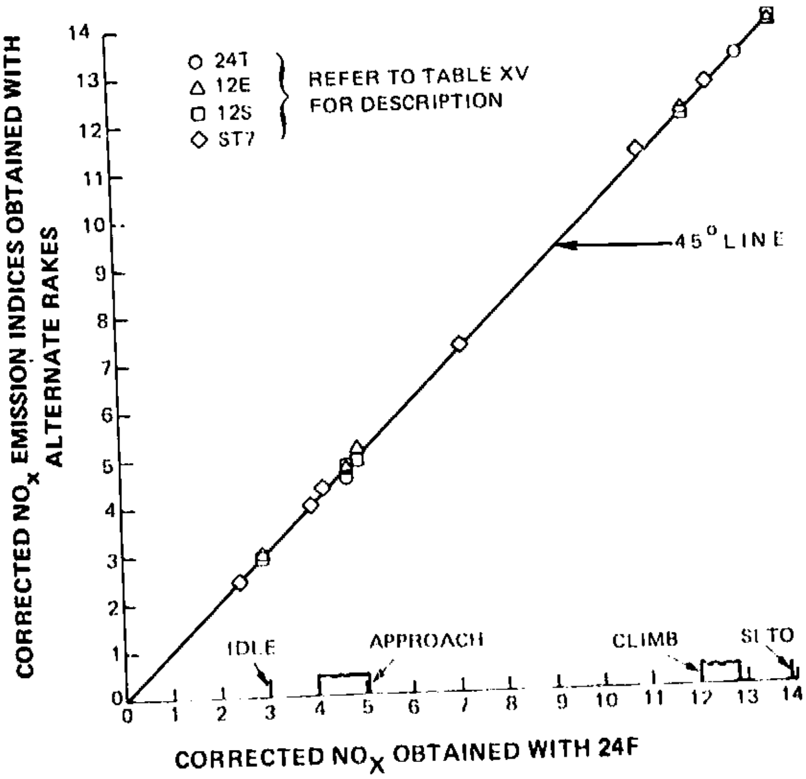

Figure 36 Relative Indications of Gas Sampling Rakes for Oxides of Nitrogen Emissions

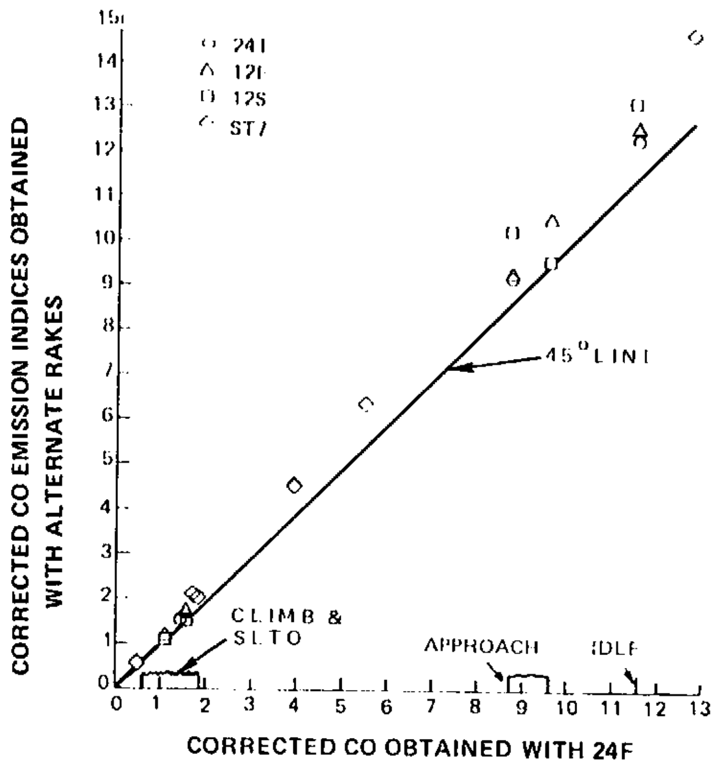

Figure 37 Relative Indications of Gas Sampling Rakes for Carbon Monoxide Emissions

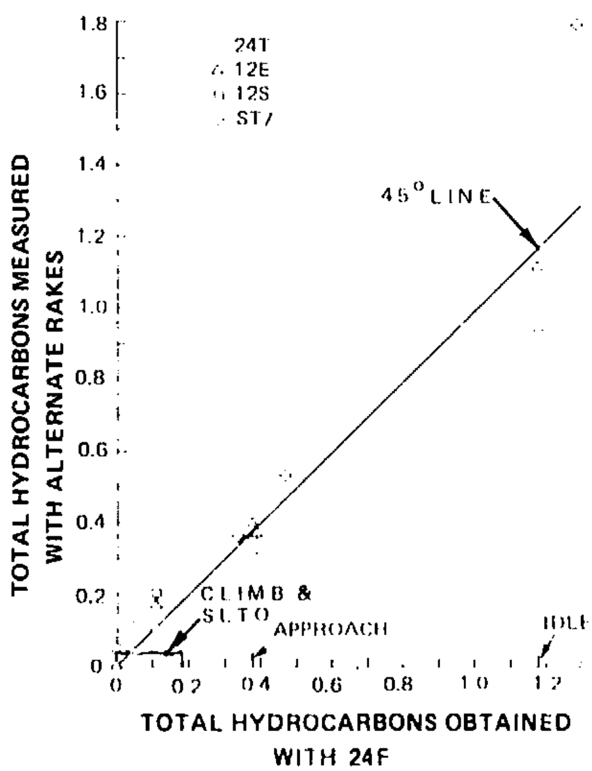

Figure 38 Relative Indications of Gas Sampling Rakes for Unburned Hydrocarbon Emissions

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

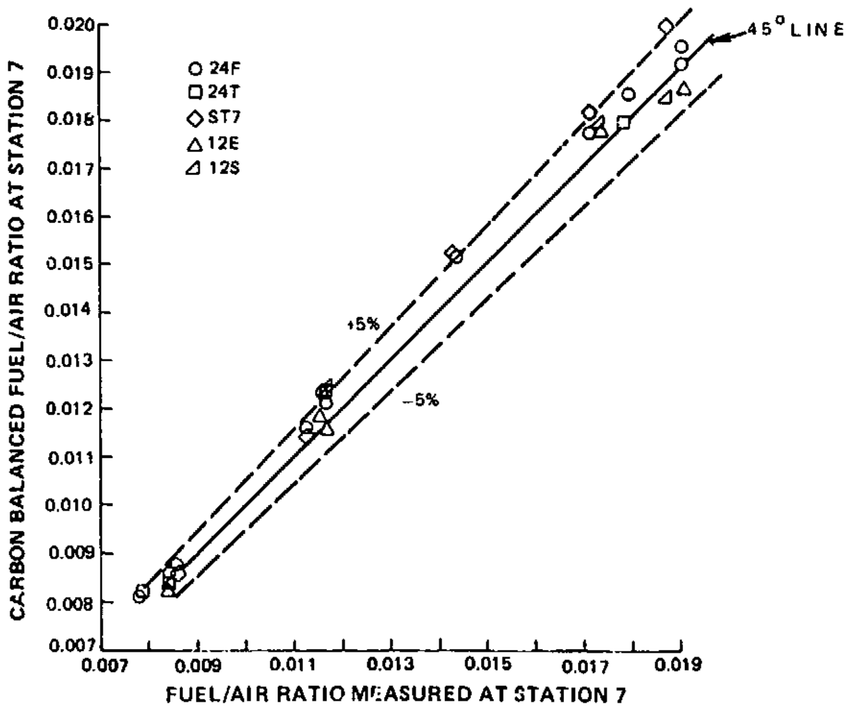

Figure 39 *Comparison of Fuel/Air Ratios Determined by Carbon Balance Method From Various Gas Sampling Probes and by Direct Measurement of Fuel Flow and Air Flow*

D. PERFORMANCE RESULTS

1. ENGINE PERFORMANCE

The overall operational specifications of the X-686 experimental engine was slightly deteriorated from the current production JT9D-7A engine. The deterioration is due to the experimental nature of the engine as well as its usage in prior experimental and development programs, rather than any lack of performance demonstrated by the vorbix combustor. The corrected thrust values for the test engine with a production first turbine vane assembly (Run No. 4) were approximately 1 to 2 percent lower than the current production engine levels at high power conditions. The key combustor operating conditions for both the test and production engines, presented in Figure 40, indicate that the Vorbix combustor operated very close to design at all engine operating conditions.

A review of the effects of the Experimental Clean Combustor Program 8-arm emissions rake on engine performance indicates that the blockage caused by this rake had no measurable effect on engine match (effective primary nozzle area).

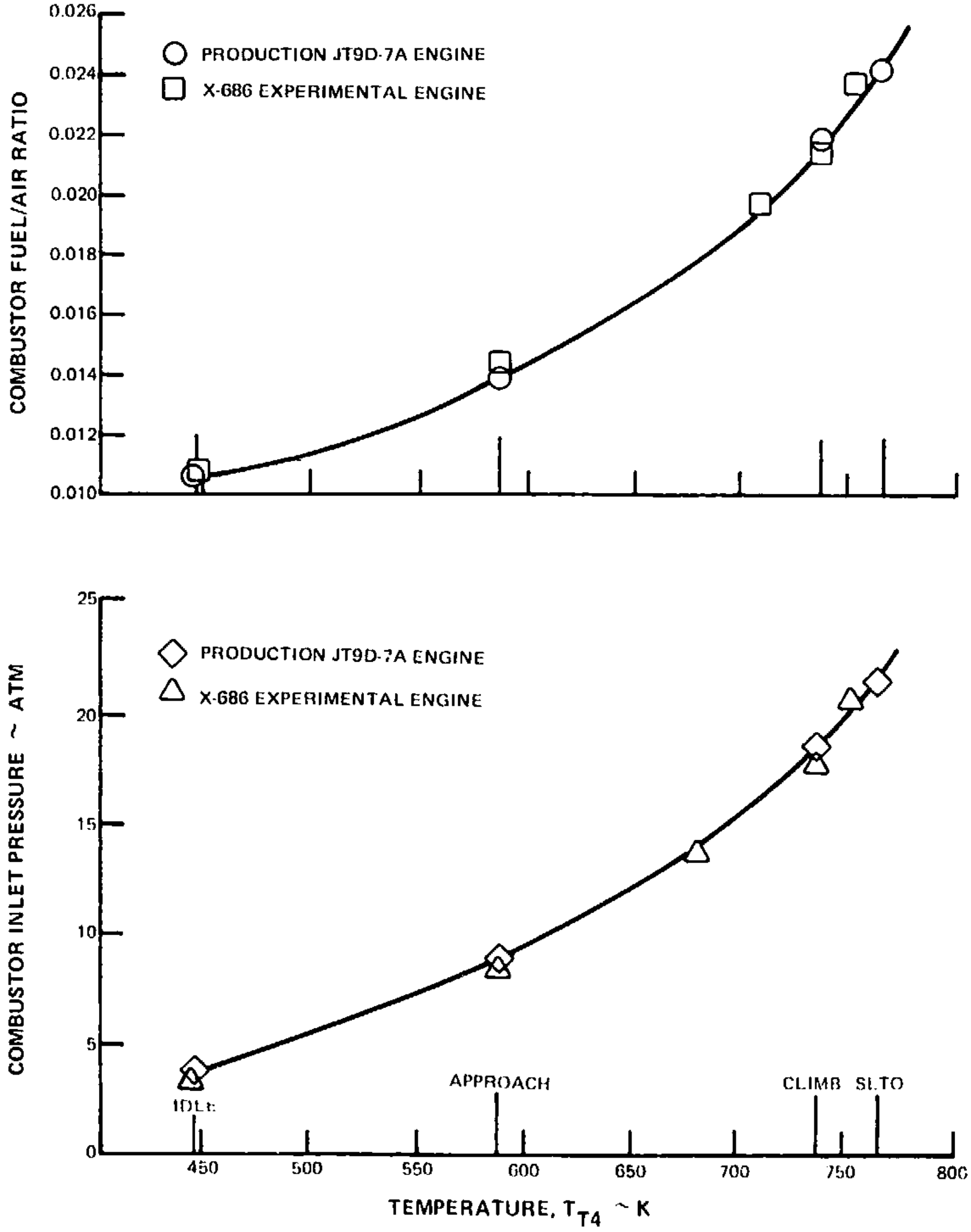

Figure 40   Comparison of Key Combustor Operating Conditions

2. STEADY STATE COMBUSTOR PERFORMANCE

In addition to the combustor emission measurements already discussed, performance parameters were recorded or calculated to determine system pressure loss, pattern factor, radial exit temperature profile, and combustor efficiency. The key performance parameters recorded for all the configurations tested are tabulated in the data Tables in Appendix B. Two other areas of performance concern were documented: combustor liner durability, and coking of both the combustor and fuel nozzles.

a. Pressure Drop

The measured values of overall and combustor pressure losses are presented in Table XVI. As shown in the table, the current production values of overall and individual OD and ID liner losses were nearly duplicated for the S27E configuration tested at high power.

b. Combustion Efficiency

The program goal of 99 percent was met by the Vorbix combustor at all levels. Combustion efficiencies (η_c) tabulated in Table XVII were calculated from the measured concentrations of carbon monoxide and total hydrocarbons described in Chapter II. Compared to the production JT9D-7, idle efficiency was improved while approach and high power efficiencies were approximately equal.

TABLE XVI

SUMMARY OF PRESSURE LOSS FOR THE VORBIX COMBUSTOR AT SLTO

Configuration	Pressure Loss (%) Overall[1]	ID Liner	OD Liner
Goal	5.4		
Production JT9D-7	5.4	1.8	1.7
S27E Pilot Zone Fuel/Air Ratio 0.0051	5.6	2.0	1.9
0.0064	5.6	2.0	1.9
0.0080	5.4	1.8	1.7

(1) Includes 0.8% compressor exit guide vane loss

TABLE XVII

SUMMARY OF COMBUSTION EFFICIENCY

Configuration	Combustion Efficiency (%) Idle	Approach	Climb	SLTO
Goal	99+	99+	99+	99+
Production JT9D-7	95.91	99.79	99.99	99.99
Vorbix Combustion[1]	99.58	99.69	99.96	99.96

(1) Configuration S27E, Pilot zone fuel/air ratio = 0.0070 at approach, climb, and SLTO power

c. **Exit Temperature Data**

Circumferential exit temperature patterns for the Vorbix combustor configuration S273E at sea level takeoff are presented in Figure 41 for several pilot fuel/air ratios. The patterns are similar and do not appear to be influenced by symmetrical disturbances such as strut wakes or nozzle locations. The high temperature zone that appears in all three patterns near the 20 degree location could not be traced to any abnormalities in combustor operation.

Pattern factors obtained at sea level takeoff for Configuration S27E are shown in Table XVIII. Although pattern factors equal to or lower than current JT9D-7 production values were obtained, the program goal of 0.25 was not achieved. At the pilot zone fuel/air ratio of 0.0070, selected as optimum for emissions and temperature distributions, the pattern factor was approximately 0.4. A tendency toward lower pattern factors was observed as pilot fuel air ratio was increased from 0.0051 to 0.0064.

Combustor exit radial average temperature profiles at sea level takeoff are presented in Figure 42 for vorbix configuration S27E at several pilot zone fuel/air ratios, vorbix configuration S26E and for the JT9D-7A production combustor.

As shown in the figure, the average radial temperatures for S27E were lower at mid-span and higher near the OD wall than those for the production engine. Increasing the pilot fuel/air ratio lowered the temperatures near the OD wall while increasing temperatures along the ID wall.

A comparison of radial profiles for Configurations S26E and S27E indicates the benefit of redistributing approximately four percent of the combustor airflow to the last three rows of the outer liner cooling holes. This modification was incorporated in S27E to lower temperatures near the outer wall. As shown, it resulted in an approximate 60 K reduction in temperature at the high pilot fuel/air ratio.

Reducing the number of main zone fuel injectors from 60 to 30 had a profound effect on the radial profile. As shown in Figure 43, the peak in the radial profile at the climb out shifted from the outer wall to the inner wall when the number of injectors was reduced, showing the effect of a quadrupling in nozzle pressure drop without any modification to the combustor airflow distribution.

d. **Combustor Durability**

The Vorbix engine combustor was a derivative of the Phase II rig program, where it experienced only minor durability problems consisting of localized hot spots on the combustor liner. The cooling airflow level and the distribution were further refined for the engine design. Skin thermocouples were used to monitor those areas of the pilot and inner and outer burner liners found in the Phase II program to be potentially troublesome.

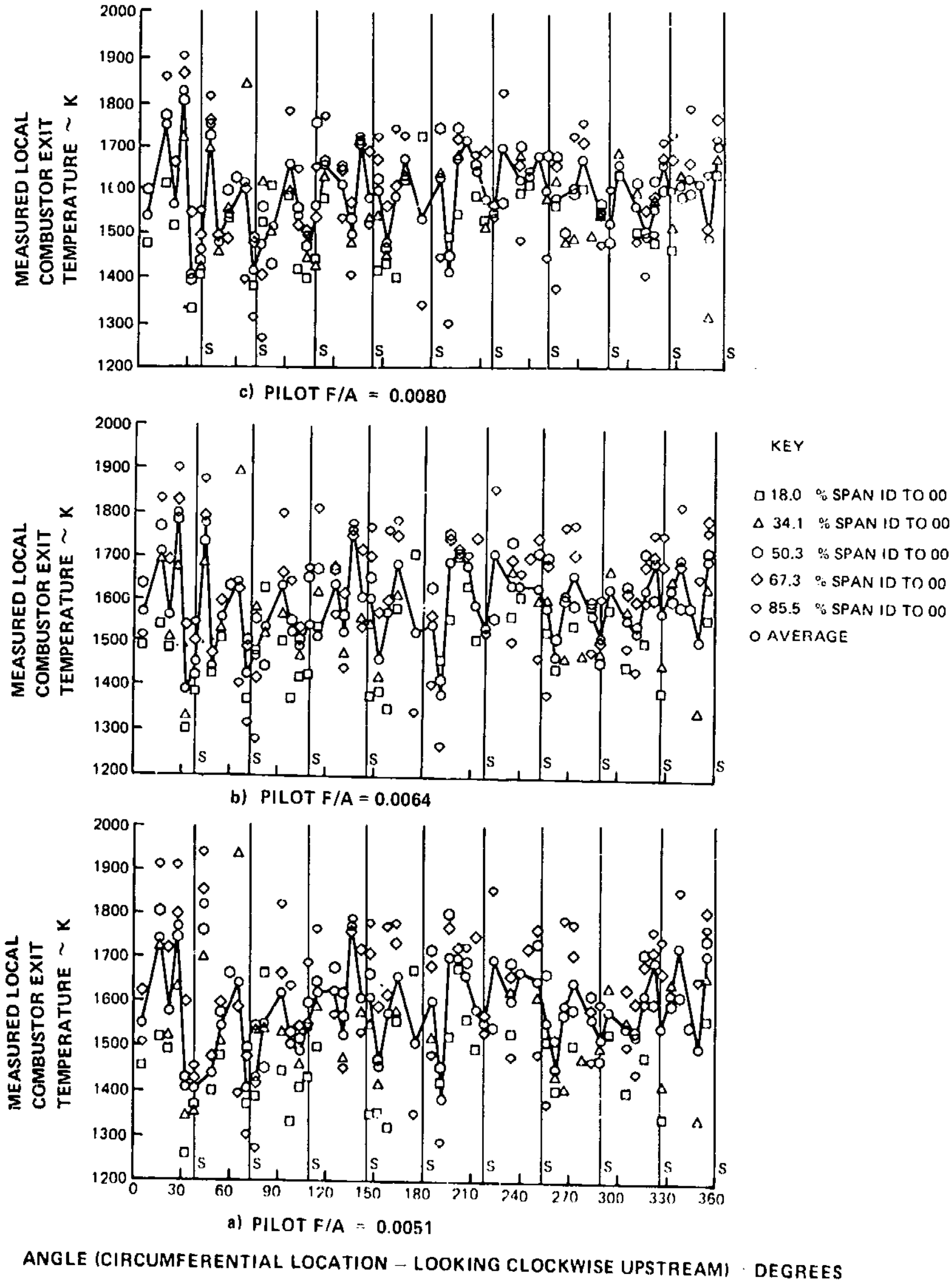

Figure 41 Circumferential Exit Temperature Pattern for the Vorbix Combustor Configuration S27E at Sea Level Takeoff

TABLE XVIII

SUMMARY OF PATTERN FACTOR FOR VORBIX COMBUSTOR AT SLTO

Configuration		Pattern Factor at SLTO
Goal		0.25
Production JT9D-7		0.45
S27E Pilot Fuel/Air		
Ratio	0.0051	0.47
	0.0064	0.41
	0.0080	0.42

Based on ideal T_{T5} average temperature calculated from the measured fuel/air ratio and maximum measured local temperature.

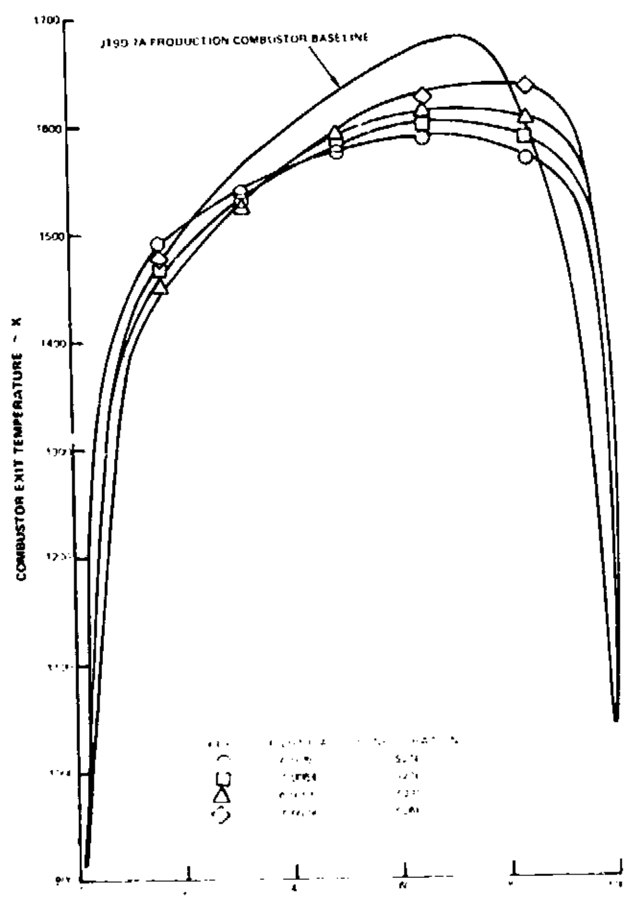

Figure 42 Exit Radial Temperature Profiles for Vorbix Combustor at SLTO Conditions Combustor Exit Average Temperature, K

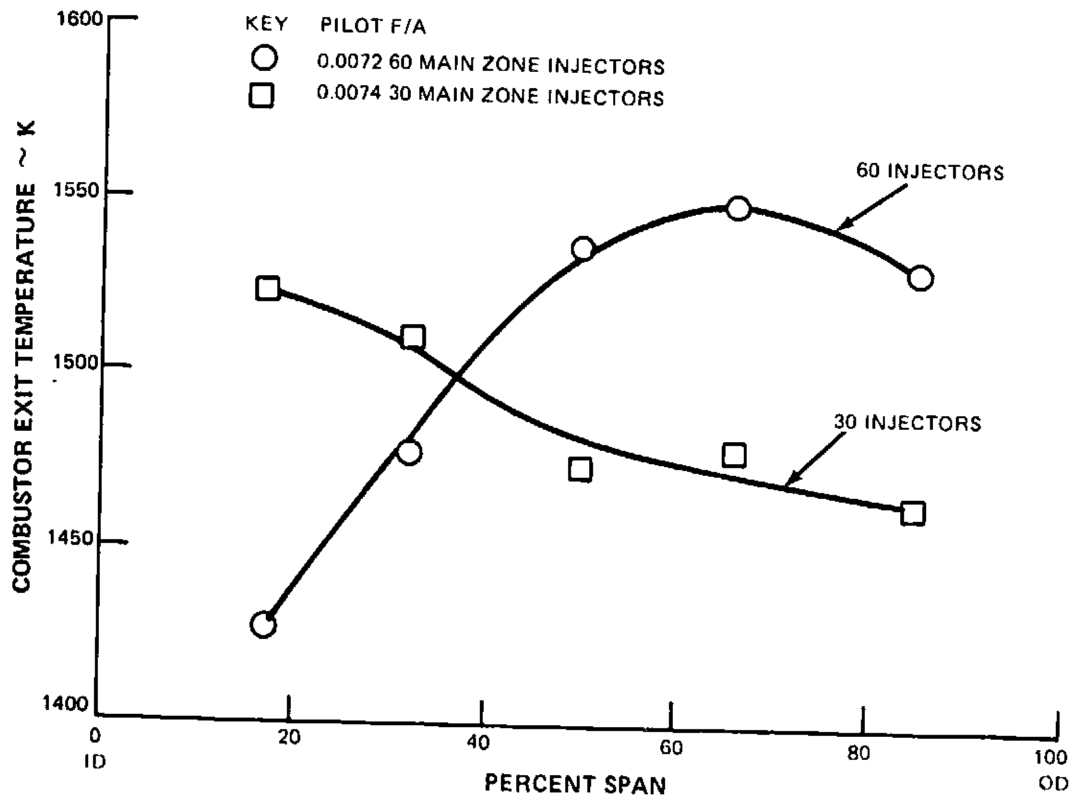

Figure 43 Exit Radial Temperature Profiles for the Vorbix Combustor at Climb Conditions Combustor Exit Average Temperature, K

The first engine test was limited to approximately 50 percent power (680 K) T_{t4} by excessive outer burner liner temperatures downstream of the main airflow swirlers. Post test inspection revealed inner burner swirler skirt distress and overheated outer burner liners downstream of main airflow swirlers, with evidence of burning in several areas. The skirt section of the inner swirlers was cut back flush with the liner to prevent flameholding and cooling air was increased in the hot areas of the inner and outer burner liners. Following the incorporation of these durability fixes, several engine runs were made to the SLTO power level without exceeding limits set with burner skin thermocouples. Combustor inspections following each run revealed continued OD liner distress downstream of the swirlers as shown in Figure 44 and ID liner louver lip distortion in the pilot zone shown in Figure 45. The outer liner distress was most severe in the areas in line with the diffuser struts where localized burning occurred in the first louver downstream of the swirlers. Moderate pilot zone inner liner louver lip distortions were common and at some locations had nearly closed the louvers.

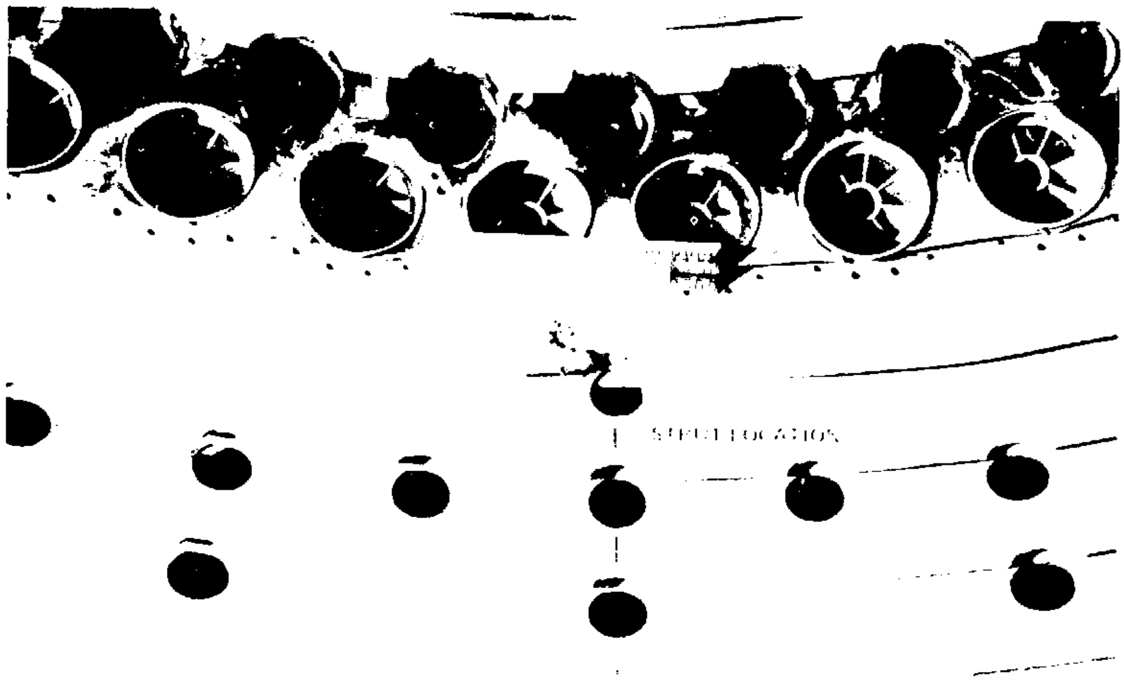

Figure 44 *Final Configuration Showing OD Liner Distress* *(76-444-4048-A)*

e. **Carboning**

Although a nitrogen purge system was provided to prevent coke formation in the main zone fuel system under hot shutdown conditions, carbon deposits proved to be a reoccurring problem on both main nozzle tips and fuel nozzle supports. The most serious main nozzle coke build-up occurred during the first engine run when the automatic purge failed to operate during several hot shutdowns due to control problems. Flow tests made following this run revealed that several main fuel nozzles and one nozzle support were completely plugged while numerous other fuel nozzles were partially restricted. On subsequent engine runs where the purge was applied manually following every shutdown, coking was reduced but still considered serious on the main nozzle tips and in fuel nozzle supports. Coke deposits on main nozzle tips and in some cases on the liner areas in the vicinity of the nozzles are shown in Figure 46.

Less serious carbon build-ups were observed on the pilot nozzle faces and on the inner liner in line with the pilot fuel nozzle location, probably due to over penetration of fuel spray. Typical carboning of this area is visible in Figure 45.

Figure 45 Final Configuration Showing Pilot Zone Inner Liner Lower Lip Distortions (76-444-9112-D)

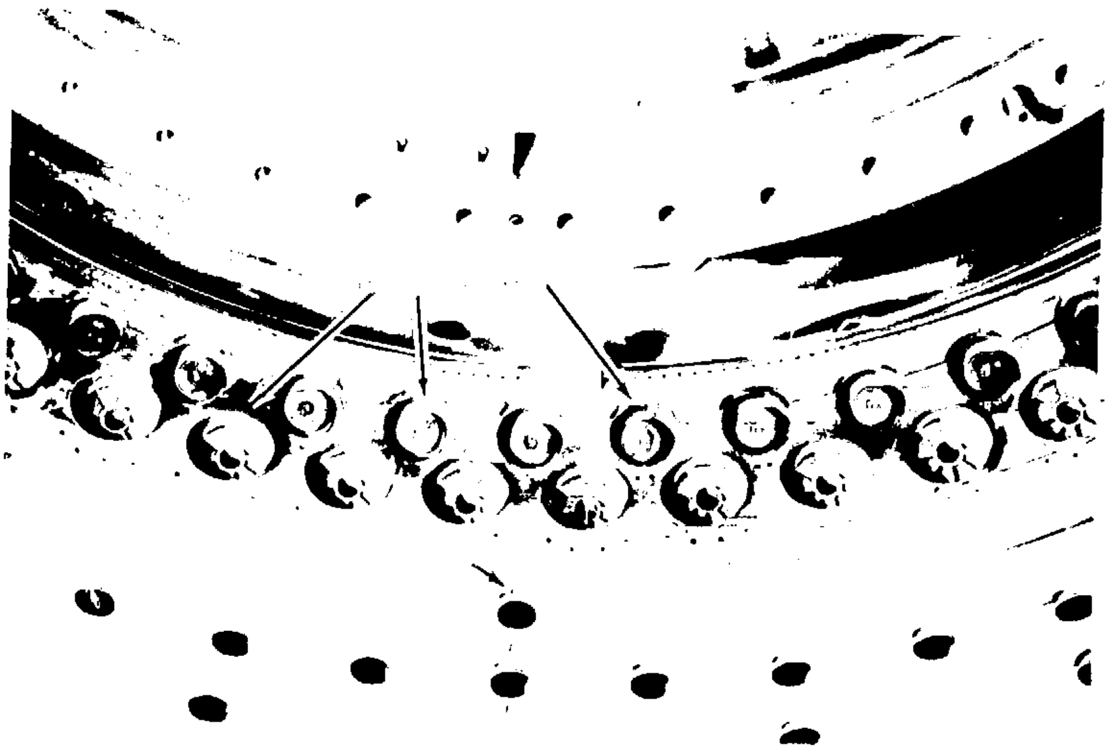

Figure 46 Final Configuration Showing Main Nozzle Coke Deposits (76-444-9022-A)

3. TRANSIENT PERFORMANCE

Acceleration/deceleration engine tests were conducted from ground idle and flight idle power settings to 95 percent rated takeoff thrust. Approximately 40 successful snap accelerations were made over a range of pilot-to-main zone fuel splits and staging points. Engine and combustor operation was monitored during all transients to prevent turbine/combustor overtemperature or compressor surge or stall. Acceleration and deceleration times from ground and flight idle are listed in Appendix B and are discussed in this section.

a. Ground Idle Accelerations

A series of ground idle acceleration tests were performed to isolate the effects of fuel staging point and fuel schedule between the pilot and main zones. The accelerations were initiated with the main zone fuel nozzles unstaged and purged. Fuel was recirculated prior to initiating the acceleration to ensure a full main zone manifold.

The fuel staging point was varied from a fuel/air ratio just above ground idle (0.0105) to 0.0126 without any significant effect on acceleration times. This is not surprising since, as shown in Figure 47, fuel/air ratio more than doubles and staging occurs instantaneously when the snap acceleration is initiated. This sudden increase in fuel flow is a typical production fuel control response to a snap acceleration.

The fuel split between the pilot and main zones was also found to have no significant effect on acceleration times. As shown in Table XIX, varying the fuel split over the range of fuel splits that appear feasible from an emissions view point, produced only small random changes in acceleration times.

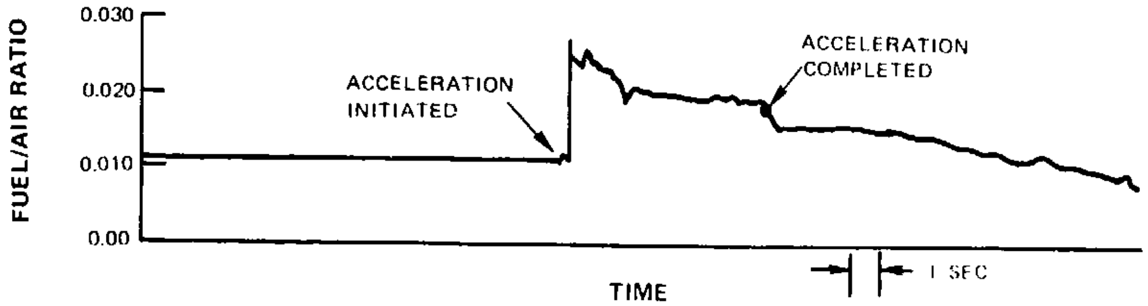

Figure 47 Typical Fuel/Air Ratio Response During Snap Acceleration

TABLE XIX

COMPARISON OF ACCELERATION TIMES FROM GROUND IDLE UNSTAGED TO 95 PERCENT THRUST FOR VARYING PILOT/MAIN ZONE FUEL SCHEDULES

Fuel Split $\frac{W_F\ Pilot}{W_F\ Total}$ (%) At Idle	SLTO	Station 2 Temperature (K)	Acceleration Time (Sec.)
100	32	285	7.6
100	32	285	6.3
100	22	285	6.4
100	22	285	6.3
100	27	285	7.0
100	27	285	6.2
100	27	285	6.2

b Flight Idle Acceleration Testing

Acceleration tests from flight idle with the main zone fuel nozzles both staged and unstaged were investigated. As shown in Figure 48, the FAA requirements of accelerating from flight idle to 95 percent of rated takeoff thrust within 5.0 seconds was achieved with the main zone fuel nozzles staged at the higher main zone fuel flows tested. At main zone fuel splits less than 10 percent as well as for the unstaged conditions, acceleration times increased above the 5.0 second level. This increase in acceleration time is attributed to the time required to fill the manifold jumper tubes and nozzle passages. The lag caused by the fill time is best seen by comparing the Station 6 (high-pressure turbine discharge) thermocouple responses during a snap acceleration for the unstaged and 35 percent staged main zone fuel conditions presented in Figure 49. As shown in the figure, over one second is lost in filling the jumper tubes and nozzles.

Typical acceleration times for the JT9D-7 production engine are also included in Figure 48. As shown, the best times for the Vorbix combustor were slower than the production engine values by approximately 2.1 seconds. An investigation was conducted to determine the reason for the slower Vorbix acceleration times.

The acceleration of the JT9D is controlled by an acceleration schedule in the hydromechanical control. A portion of the acceleration schedule is a function of the high power trim of the control. Post test checkout indicated the control was trimmed to a setting lower than that of production engines. The effect of the lower trim was analytically estimated to increase acceleration time by approximately 0.8 seconds leaving 1.3 seconds unexplained. Further testing of the engine using the same control setting as production engines would be required to establish whether or not the slower acceleration times were totally due to the control trim. It was concluded, however, that with the production trim setting the engine would have demonstrated acceleration times which achieved the FAA five second level when operating with main zone fuel splits above 20 percent.

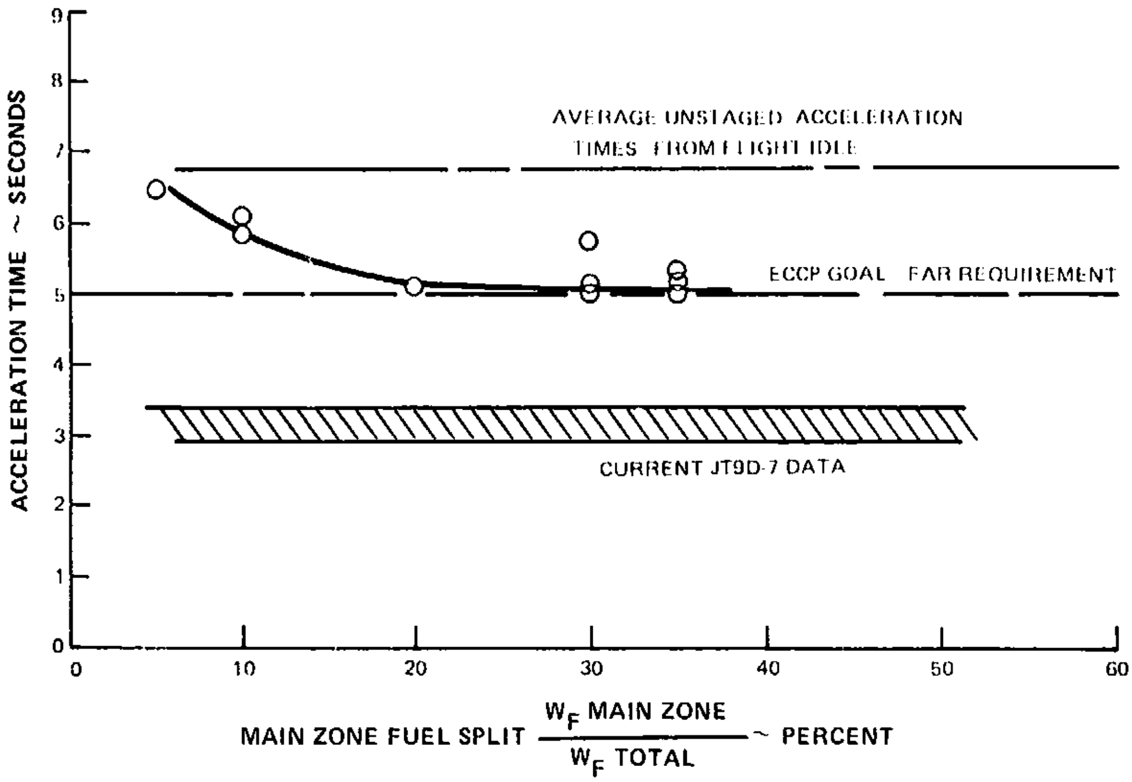

Figure 48 Acceleration Times From Flight Idle to 95 Percent Rated Thrust for Various Initial Main Zone Fuel Splits

c. Sea Level Start Testing

Sea level starting characteristics of the JT9D engine with the Experimental Clean Combustor Program Vorbix combustor were determined in an abbreviated start program. The electronic control start schedule was varied to provide different starting fuel/air ratios for the investigation. Pressurization or initiation of fuel flow to the manifold system was initiated at high rotor speeds (N_2) of 1400 and 1800 rpm.

The occurrence of a light and the extent of flame propagation was determined from temperature data recorded from five thermocouples which were located circumferentially at the discharge of the high-pressure turbine. The thermocouples were located as follows: one near the top, one near the bottom, and the remaining three equally spaced between these extremes to cover one half of the engine. The data from the five thermocouples were recorded on a brush recorder.

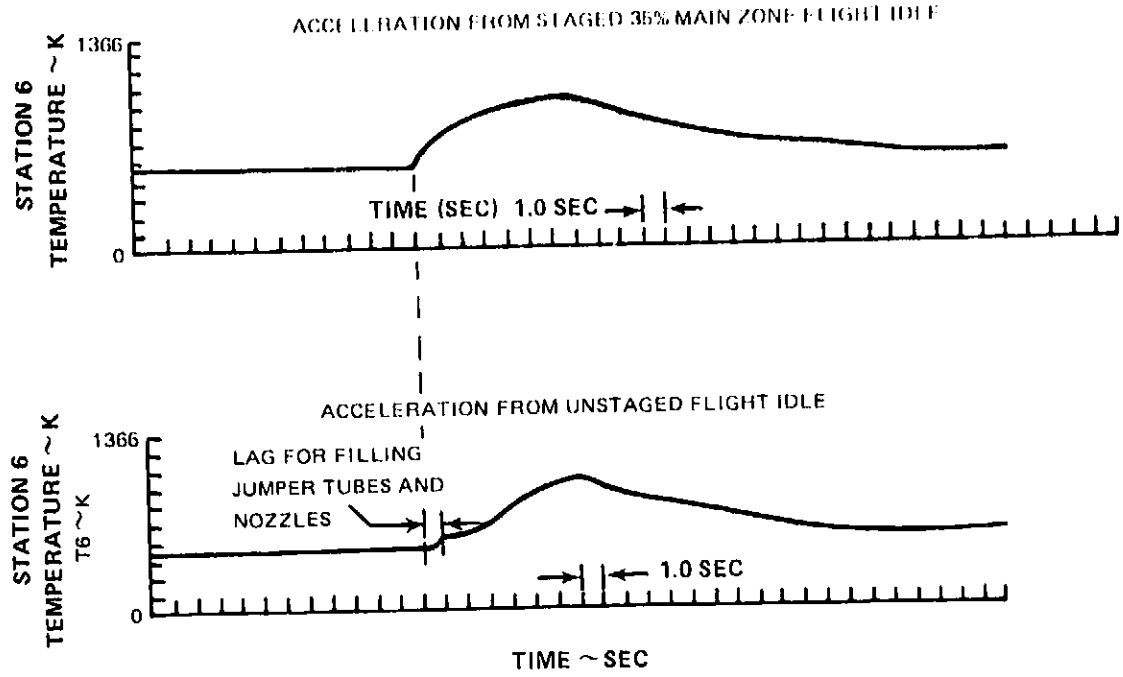

Figure 49 Typical Station 6 (High Pressure Turbine Discharge) Thermocouple Responses for Snap Accelerations From Flight Idle Unstaged and Staged

The fuel-flow to burner-pressure ratios required for ignition of the Vorbix combustor and the current JT9D-7A combustor are shown in Figure 50 and indicate that the Vorbix combustor required approximately 60 percent higher fuel flows for successful lighting and flame propagation. An analysis of a successful start was conducted to determine why high fuel/air ratios are required for starting the engine and why the engine does not stall at the high ratios. Figure 51 shows the five temperature traces from a successful start. It can be seen that a light occurs approximately eight seconds after pressurization, compared to less than four seconds for the Bill of Materials JT9D combustor. The slow propagation is probably the reason for a stall-free start at the high fuel/air ratios. In the Bill of Materials JT9D engine, the sudden light at the high fuel/air ratios causes the engine to stall.

The B/M JT9D duplex nozzle operates at a much higher fuel ΔP than the Vorbix simplex pilot nozzle at starting fuel flows. Attempts were made to improve the starting characteristics by closing the pilot nozzle solenoids to restrict the fuel flow to only 10 of the 30 pilot nozzles. This approach resulted in increased nozzle pressure drop resulting in an improvement in fuel atomization and lighting, but the flame propagation rate remained slow because of the increased spacing between the nozzles supplied with fuel. Correction of this deficiency will require a higher pressure drop pilot fuel nozzle.

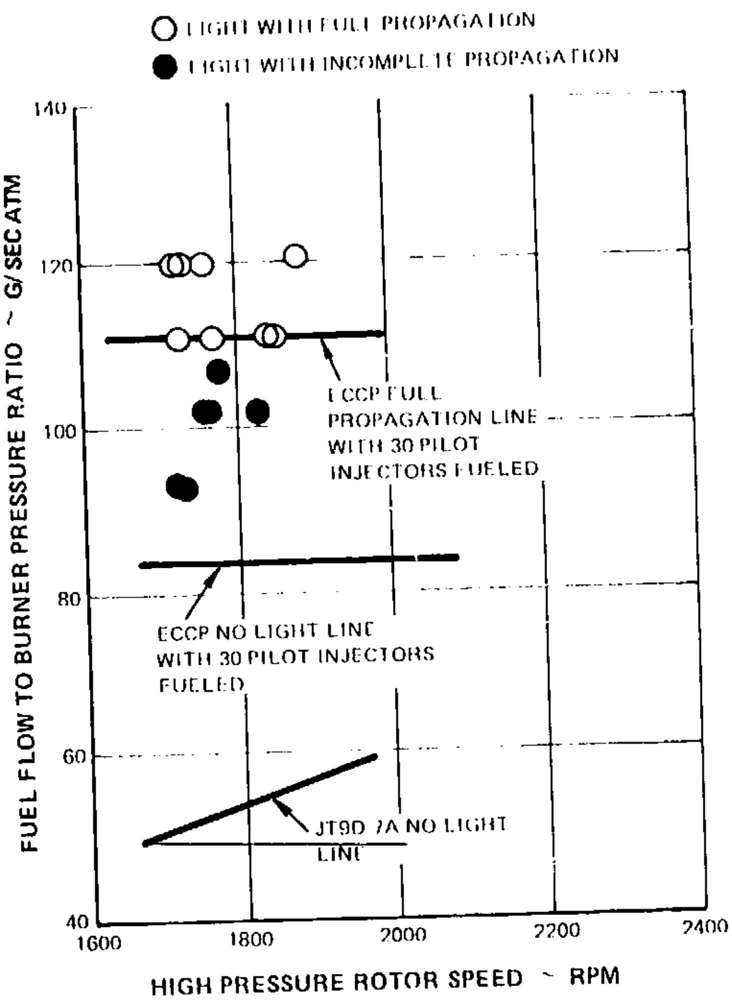

Figure 50 Vorbix Combustor Starting Program Evaluation Results

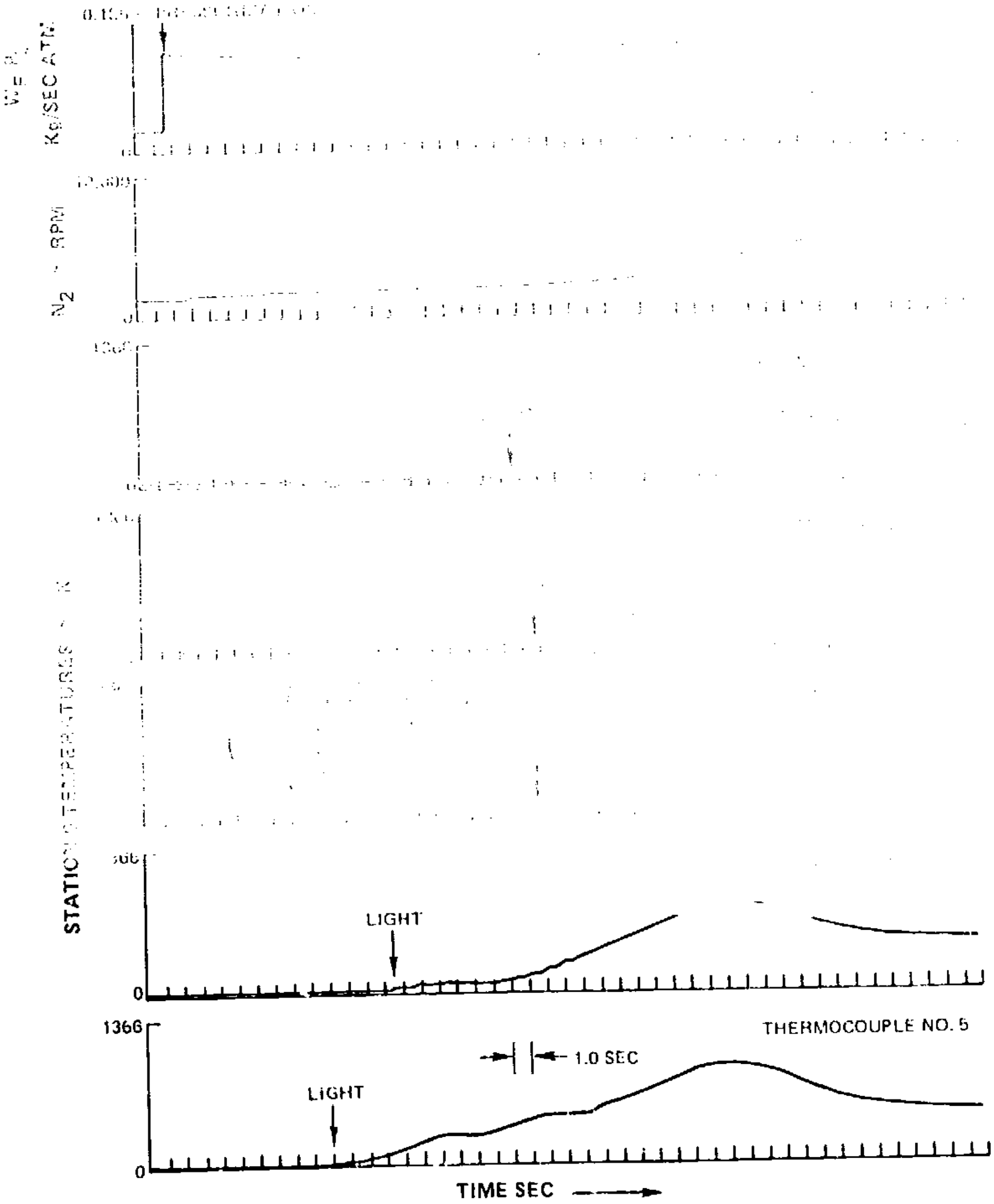

Figure 51 W_f/P_b, N_2, *and Station 6 Thermocouple Response During a Successful Start*

E. DEVELOPMENT STATUS

1. COMBUSTOR EMISSIONS STATUS

The Experimental Clean Combustor Program (ECCP) Vorbix combustor met the program goals for CO, THC, and NO_x but exceeded the smoke goal by approximately 50 percent. These emissions were obtained for an "optimum" value of pilot fuel/air ratio, selected to minimize smoke at climbout and to provide the best exit temperature pattern factor/radial profile.

Since the emissions at a given engine power level are dependent on pilot-main zone fuel split, some variations of the computed EPAP values are possible by changing the selected values of pilot fuel/air ratio. Table XX presents other possible fuel/air ratio splits. Reducing pilot fuel/air ratio at engine power levels above approach from 0.007 to 0.0046 results in negligible changes to gaseous pollutant or smoke levels. Reducing pilot fuel/air ratio at approach from 0.007 to 0.0046, causes carbon monoxide to exceed the standard, increases total unburned hydrocarbons to the standard value and reduces NO_x slightly. It thus appears that further reductions in gaseous pollutants and smoke are not achievable merely by varying fuel/air ratio split, but await more extensive vorbix combustor modification.

TABLE XX

EFFECT OF PILOT FUEL AIR RATIO ON EMISSIONS OF COMBUSTION CONFIGURATION S27I

	Pilot Fuel Air Ratio			EPA Parameter			Maximum
	Approach	Climb	Sea Level Takeoff	Carbon Monoxide	Total Unburned Hydrocarbons	Oxides of Nitrogen	Smoke Number
ECCP Goals				4.3	0.8	3.0	19
JT9D-7 Production Engine				10.4	4.8	6.5	4
Vorbix Combustor Configuration S27I							
	0.0070	0.0070	0.0070	3.2	0.2	[illegible]	30
	0.0070	0.0046	0.0046	3.4	0.25	2.6	30
	0.0046	0.0046	0.0046	4.9	0.4	2.5	30

Notes: Oxides of nitrogen data reported as equivalent NO_2, corrected for pressure and humidity of 6.3 g H_2O/kg dry air

Total unburned hydrocarbons data reported as equivalent CH_4

2. COMBUSTOR PERFORMANCE STATUS

The performance status of the ECCP Vorbix combustor is summarized in Table XXI. Five categories have been identified as requiring normal development. This is taken to mean that acceptable performance is judged to be within reach following suitable development. These are discussed below:

- **Pattern Factor and Radial Profile**

  Exit temperature pattern factor did not achieve the goal of 0.25. However, pattern factors equal to or better than the current production combustor were achieved. The average radial temperature profile is slightly too hot on the OD at the "optimum" pilot fuel/air ratio of 0.0070.

TABLE XXI

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	

- **Transient Acceleration**

While equalling the ECCP goal and satisfying the FAA Requirement when accelerated from a fully staged flight idle condition, the Vorbix combustor/experimental engine X-686 was deficient compared to current production JT9D-7A engines. When accelerated from an unstaged (pilot only) flight idle condition, acceleration time was increased by over one 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 values. Additional development and possible fuel system redesign will be required to reduce the acceleration time to the production engine levels.

- **Liner Carbon Deposits/Liner Durability**

The Vorbix combustor exhibited localized carbon deposition in the vicinity of the pilot and main 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 ID throat louver and on the OD downstream of the main zone swirlers. With the exception of the fuel impingement, problems of this type are treated by localized re-distribution of liner cooling/purge airflow.

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

- **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 replacing the simplex nozzles with a duplex design or increasing nozzle pressure drop at low flow conditions.

- **Fuel Passage Coking**

Main zone fuel injector support and nozzle tip coking was observed due to 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.

Neither altitude engine operation nor altitude relight characteristics were investigated during the Phase III program. However, the difficulties encountered in sea-level starting and the Phase II altitude relight rig test results (Reference 4) would suggest that there are problems to solve in this area. Altitude relight and stability test results from the Phase II rig program suggest that modifications of the fuel nozzle toroidal deflectors could result in significant improvement in stability.

In addition, no cyclic endurance testing has been conducted on the Phase III combustor to assess the hardware long term durability.

3. PRODUCTION ENGINE CONSIDERATIONS

In addition to the development work required to achieve acceptable smoke and combustor performance, further design work will be required before the Vorbix combustor concept can be used in a production engine application. While the combustor liner, fuel injectors and diffuser/combustor case were designed to be of a flightworthy configuration, the external fuel system was of a strictly experimental design. The external fuel manifolds, electric solenoid valves and computer-controlled breadboard fuel management system were intended to provide maximum flexibility, and ease of modification and servicing (timely procurement was also a factor). While the Phase III test program has shown that simplification is possible, the fuel system represents a very significant design and development requirement.

Translation of the external fuel system to a flightworthy design would require use of double-walled manifold construction for reasons of fire safety. Meeting this requirement is made more difficult by the axial displacement of the two fuel manifolds and the relatively large number of fuel sources. The electric solenoid valves would probably be replaced by hydromechanical staging valves in a flightworthy design, and would be reduced to the minimum number required to perform the staging function.

CHAPTER IV

CONCLUDING REMARKS

The results presented in this report, 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 experimental engine tests of an advanced, low-emission 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 CO, THC and NO_x emission goals were met and combustor performance was adequate for full-power engine demonstration testing. Altitude performance and relight of the final Vorbix combustor configuration tested in the engine were not evaluated.

Additional Vorbix combustor improvements in the areas of exit temperature distribution, transient acceleration, liner coke deposits, and liner overheating will be need 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 more extensive development. 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 which 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, weight, etc.

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 producltion use. Weight, complexity, 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, attempts should be made to simplify the design, minimize weight and cost impact, and improve maintainability while simultaneously addressing the deficient performance, smoke, and life limiting areas.

APPENDIX A

EQUIPMENT AND EXPERIMENTAL PROCEDURES

1. EXPERIMENTAL ENGINE PERFORMANCE INSTRUMENTATION

A. PARAMETERS MEASURED

Table A-1 list the engine parameters measured and indicated measurement accuracy using fixed engine and test stand instrumentation.

TABLE A-1

PARAMETERS MEASURED

Parameter	Measurement Accuracy
T_{T2} - Engine Inlet Temperature	± 0.56K (1°F)
Gearbox Breather Pressure	± 34.47 N/m^2 (0.005 psi)
Gearbox Breather Temperature	± 1.1K (2°F)
N_1 - Low Rotor Speed	± 0.1%
N_2 - High Rotor Speed	± 0.1%
F_N - Engine Thrust	± 0.5% above 111,200 N (25,000 lb)
	± 1.5% below 111,200 N (25,000 lb)
P_{T2} - Engine Inlet Total Pressure	± 137.90 N/m^2 (0.02 psi)
$P_{T2.5}$ - Fan Discharge Total Pressure	± 344.74 N/m^2 (0.05 psi)
P_{T7} - Engine Exit Total Pressure	± 137.90 N/m^2 (0.02 psi)
T_{T6} - High Turbine Discharge Temperature	± 3.89K (7°F)
T_{T7} - Engine Exit Total Temperature	± 2.78K (5°F)
P_{S4} - Burner Pressure	± 10342.13 N/m^2 (1.5 psi)
W_f - Total Engine Fuel Flow	± 0.75%

These data are used to compute overall engine performance characteristics. The pilot and main fuel flows and a redundant measurement of total fuel flow are obtained from the breadboard electronic fuel control instrumentation. Redundant measurement of other selected engine parameters was also possible using the fuel control instrumentation. The key combustor operating conditions for the JT9D-7A production engine are shown in Figure A-1.

B. ENGINE PERFORMANCE DATA CORRECTION

The observed engine performance data are corrected as follows:

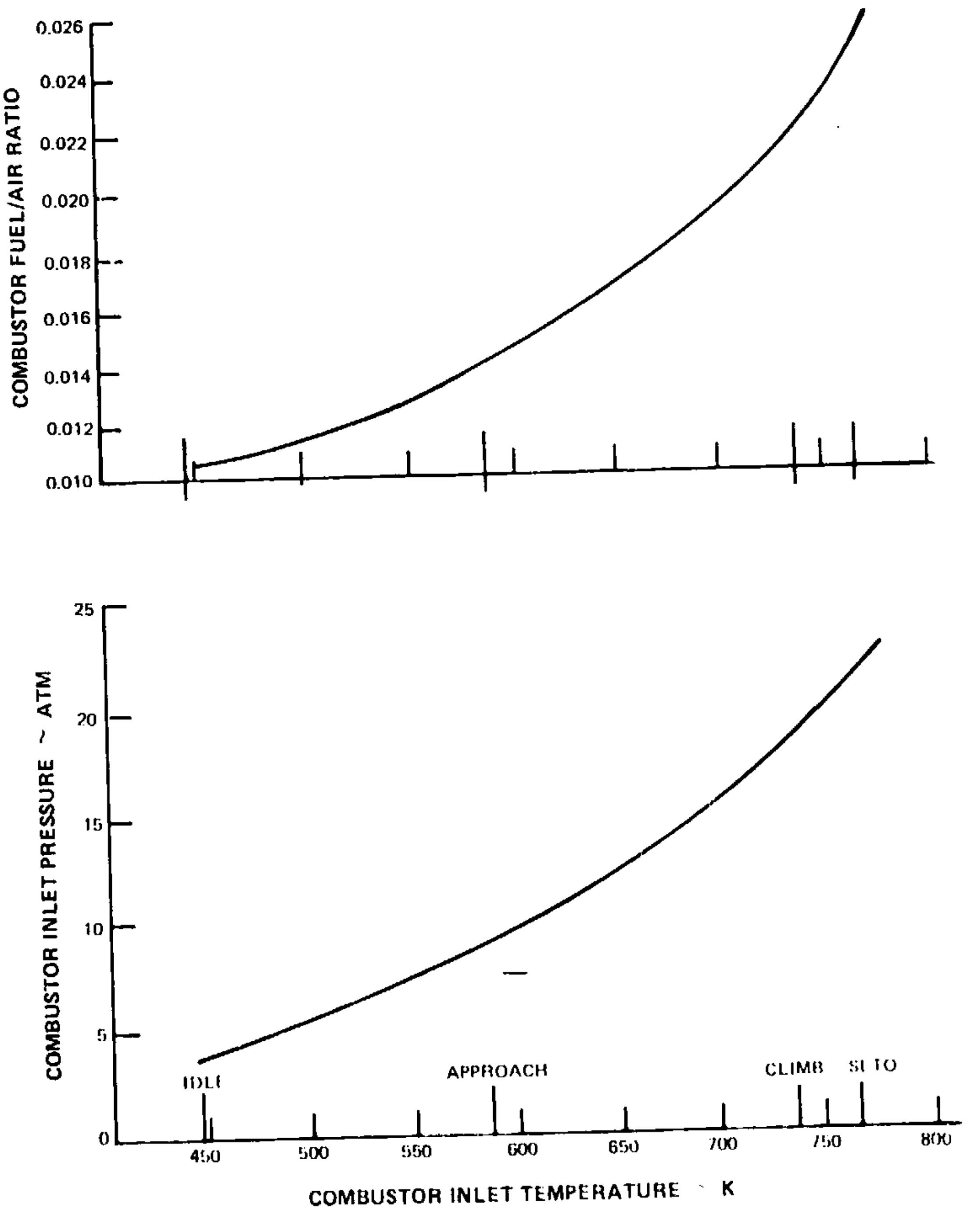

Figure 4-1 Key Combustor Operating Conditions for JT9D-7 Production Engine

- Corrected Observed Thrust

$$\frac{F_{N\,OBS}}{\delta_{t2}} = \frac{\text{Observed Thrust}}{\delta_{t2}}$$

- Corrected Net Thrust

$$\frac{F_N}{\delta_{t2}} = \frac{F_{N\,OBS}}{\delta_{t2}} + \frac{\Delta F_N}{\delta_{t2}}\ \text{corr}$$

$$\text{: where} \quad \delta_{t2} = \frac{\text{Observed inlet pressure}}{\text{Standard day inlet pressure}}$$

$$\frac{\Delta F_N}{\delta_{t2}} = \text{Correction from Figure A-2}$$

- Corrected Fuel Flow

$$W_{f\,corr} = \frac{W_f\ \text{observed}}{\delta_{t2} + K_C\ \text{(temperature correction)} \times K_n\ \text{(humity correction)}}$$

- Corrected Thrust Specific Fuel Consumption

$$TSFC_{corrected} = \frac{\text{Corrected Fuel Flow}}{\text{Corrected Net Thrust}}$$

- Corrected Rotor Speed

$$N_{corrected} = \frac{\text{Observed Rotor Speed}}{\sqrt{\theta_{t2}}}$$

$$\text{where } \theta_{t2} = \frac{\text{Observed inlet temperature}}{\text{Standard day temperature}}$$

C. DIFFUSER/COMBUSTOR INSTRUMENTATION

Pressure and temperature instrumentation installed on the Vorbix combustor liners and diffuser case passages is summarized in Figure A-3. Typical total pressure and temperature probes installed at the compressor discharge plane (Station 4.0) are shown in Figure A-4.

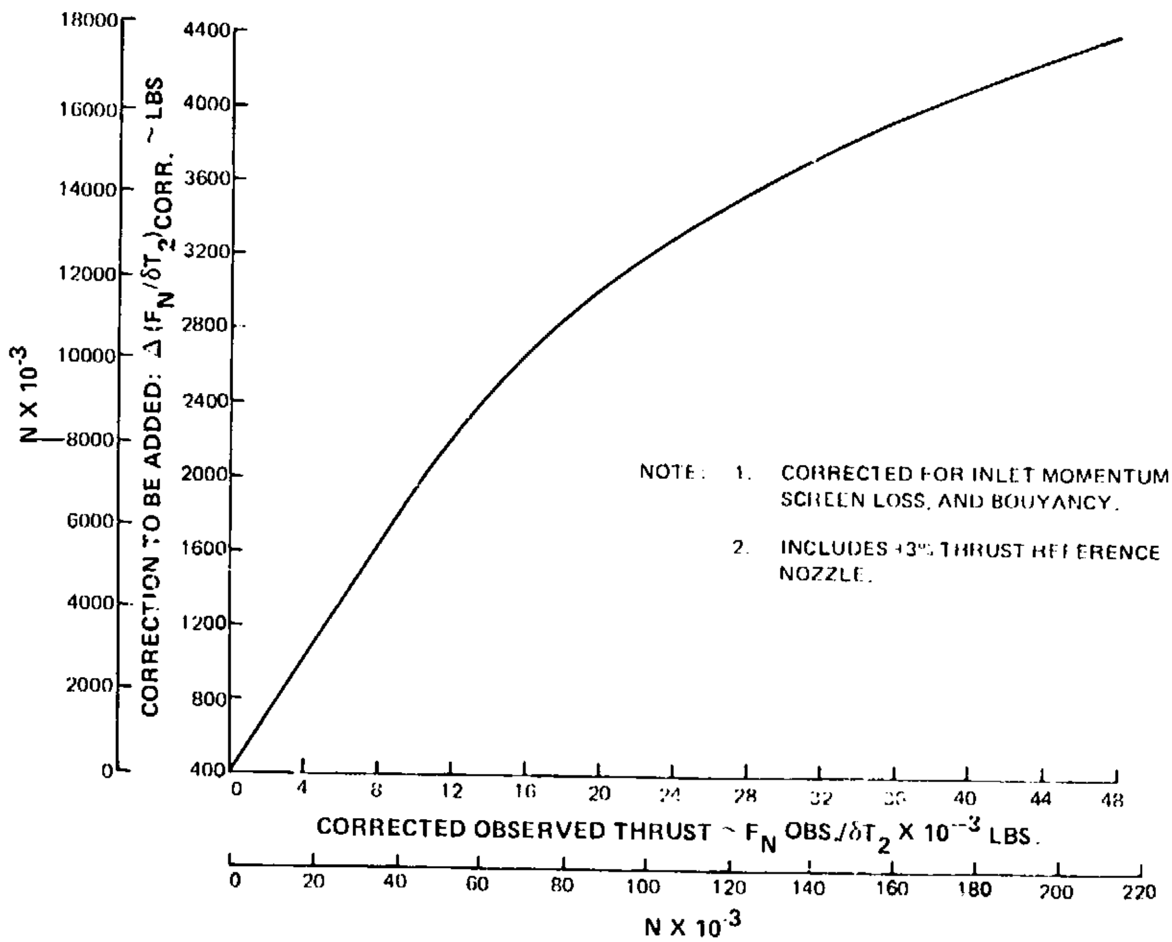

Figure A-2 JT9D Turbofan Engine Test Cell Thrust Correction for Middletown Test Cells

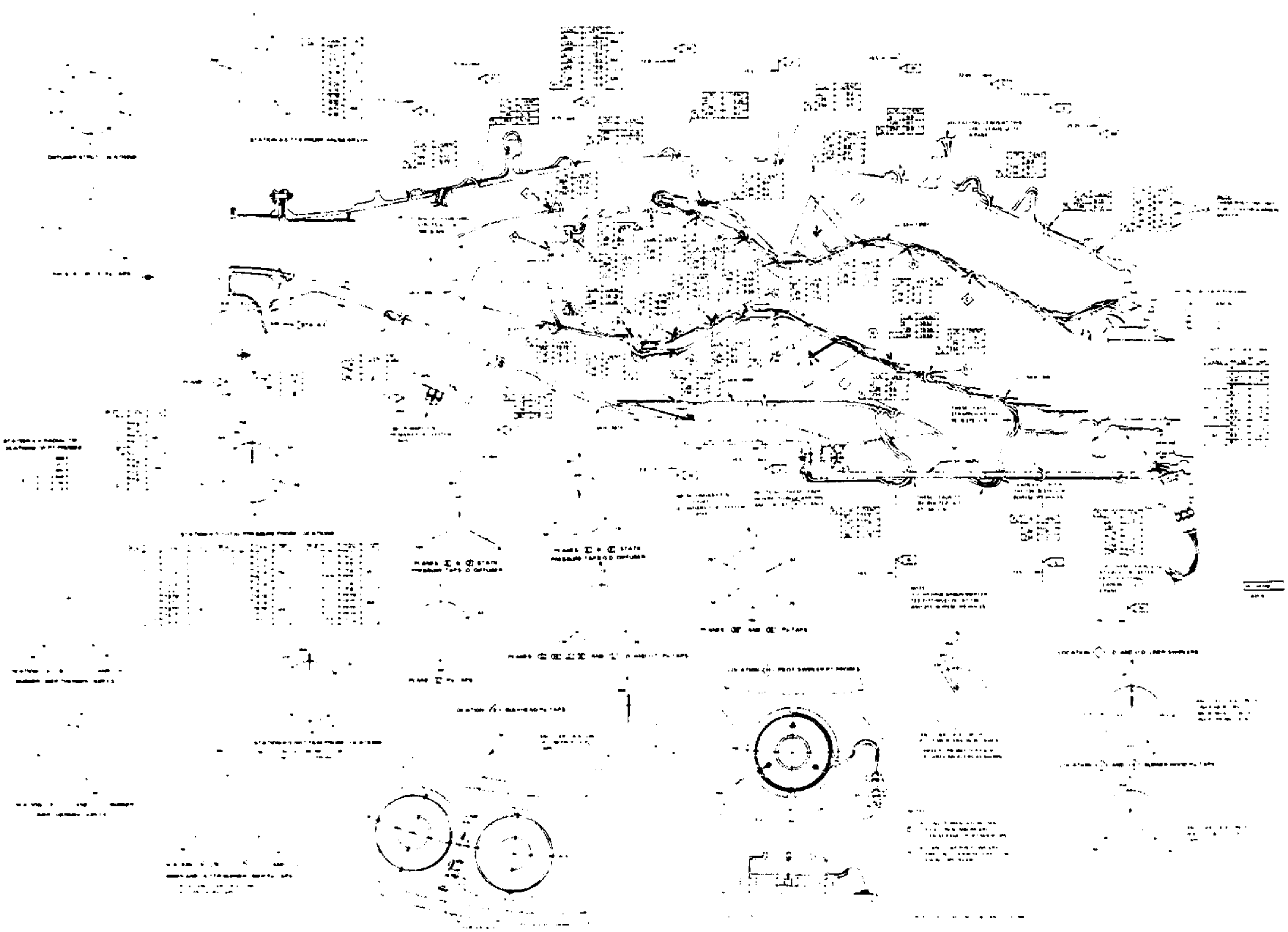

Figure A-3 *Vorbix Combustor and Diffuser Case Instrumentation, X-686*

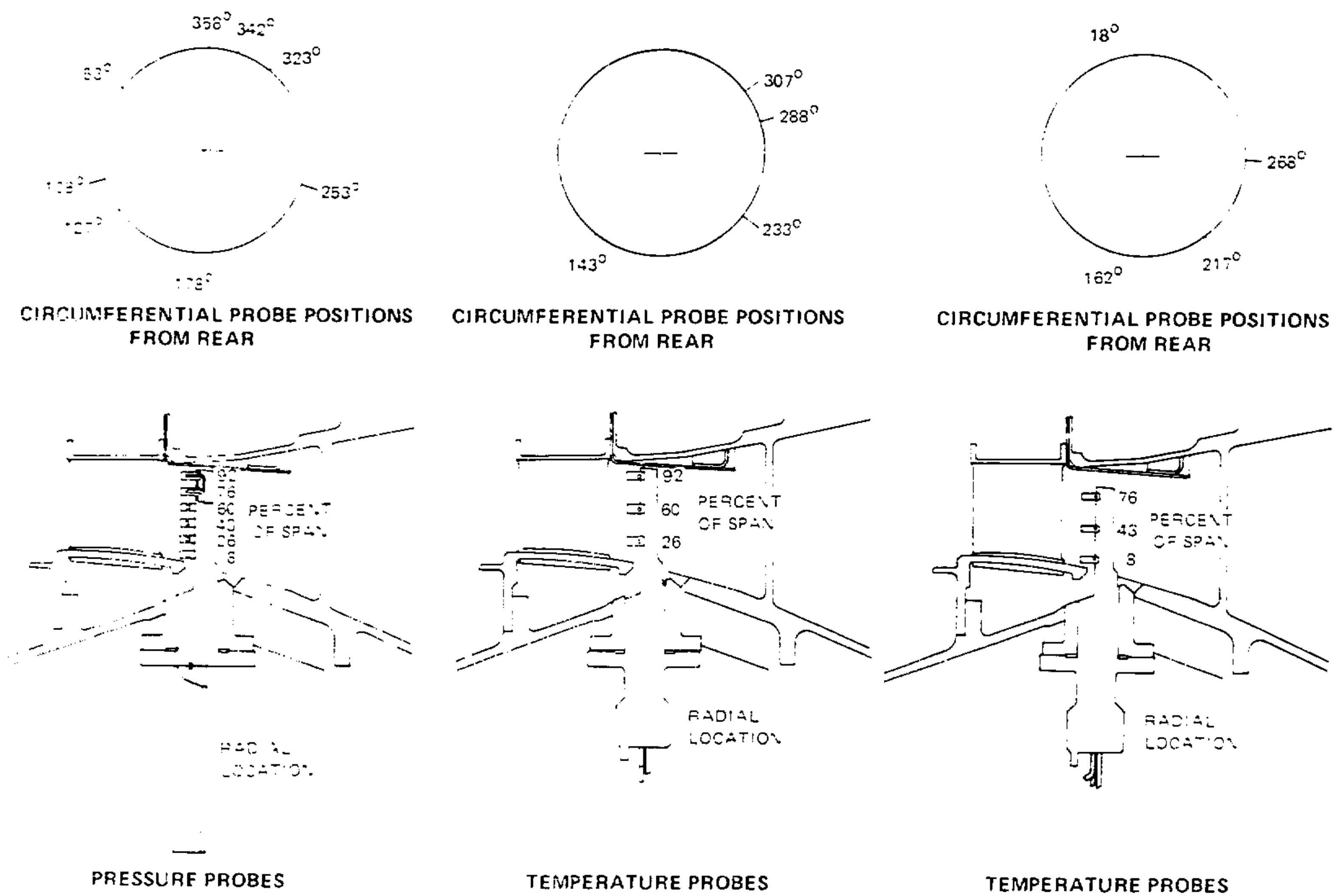

Figure A-4 Station 4 Radial and Circumferential Total Pressure and Total Temperature Probe Locations

2. GAS SAMPLING AND ANALYSIS EQUIPMENT

A. EXHAUST RAKE SYSTEM

The primary means of exhaust gas sample acquisition was a rake assembly having eight radial arms spaced at 45 degree intervals. This rake was designed for installation behind the cylindrical experimental (boiler plate) tailpipe to be used in the engine tests. Three sampling ports, located at the centers of equal areas, were provided on each radial arm. The rake construction followed that of earlier rakes designed at Pratt & Whitney Aircraft. Construction details of the eight-arm rake are shown in Figure A-5. The sample ports were connected in such a way that all 24 ports could be manifolded together or in two sets of 12 each. This latter arrangement simulated two 90 degree cruciform rakes positioned 45 degrees apart.

The eight-arm rake was mounted in a traverse stand which allowed rotation about the rake axis in increments of five degrees for a total rotation of 45 degrees. Figure A-6 shows the rake and traverse stand mounted in the P-6 engine test cell. The rake sample ports lie in a plane 0.36 m (14 inches) downstream of the engine exhaust nozzle exit plane.

Commercially available, electrically-heated Teflon gas sample lines were used to connect the discharge of the sampling rake to the inlet of the mobile gas analysis laboratory. Sample gas temperature was maintained at 450 ± 28K (350 ± 50°F).

B. MOBILE GAS ANALYSIS LABORATORY

The Pratt & Whitney Aircraft gas temperature and combustion efficiency (GT&CE) mobile laboratory (Figure A-7) is a specially designed vehicle capable of measuring gaseous combustion exhaust products. Through the use of a telephone link to the centralized Sigma 8 data reduction computer system, measured constituent concentrations can be converted to real time, on-line computations of emission index, combustion efficiency, and combustion exit temperature. The results of these computer calculations, together with the raw data, the measurement uncertainties, and data validity checks are displayed on an interactive scope in the GT&CE mobile laboratory. The GT&CE mobile laboratory is completely self-contained with the exception of the data reduction computer, and incorporates the latest on-line gas analysis instrument for the measurement of carbon dioxide, carbon monoxide, nitrogen, oxygen, hydrogen, oxides of nitrogen, total unburned hydrocarbon, and water vapor. An interior view of the mobile van is shown in Figure A-8. Individual analyzer specifications are summarized in Table A-II.

Figure A-5 Detail of Probes on Emissions Rake Used on Experimental Clean Combustor Program (XPN-59485)

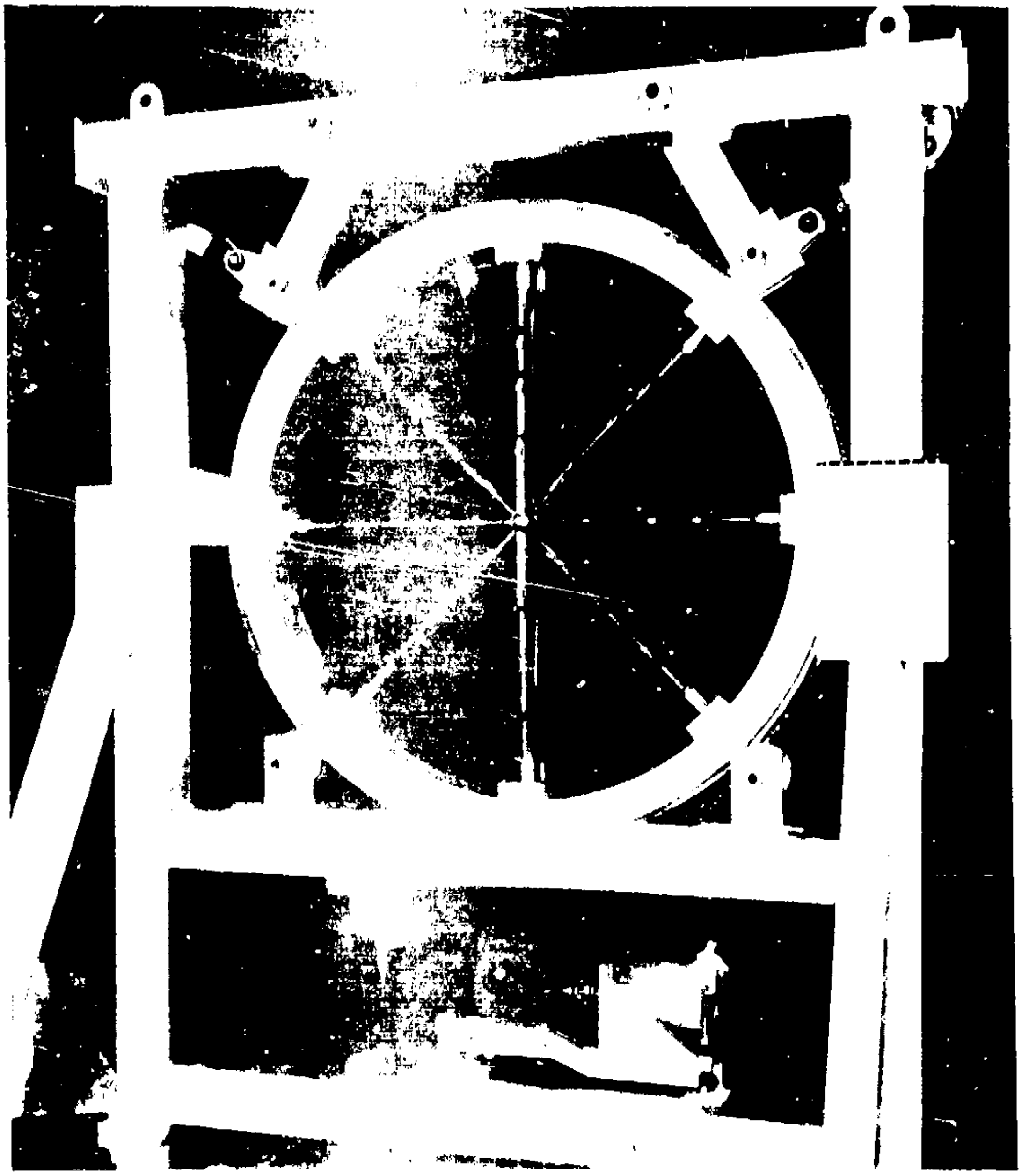

Figure A-6 Emissions [illegible] for Experimental Clean Combustor Program
([illegible])

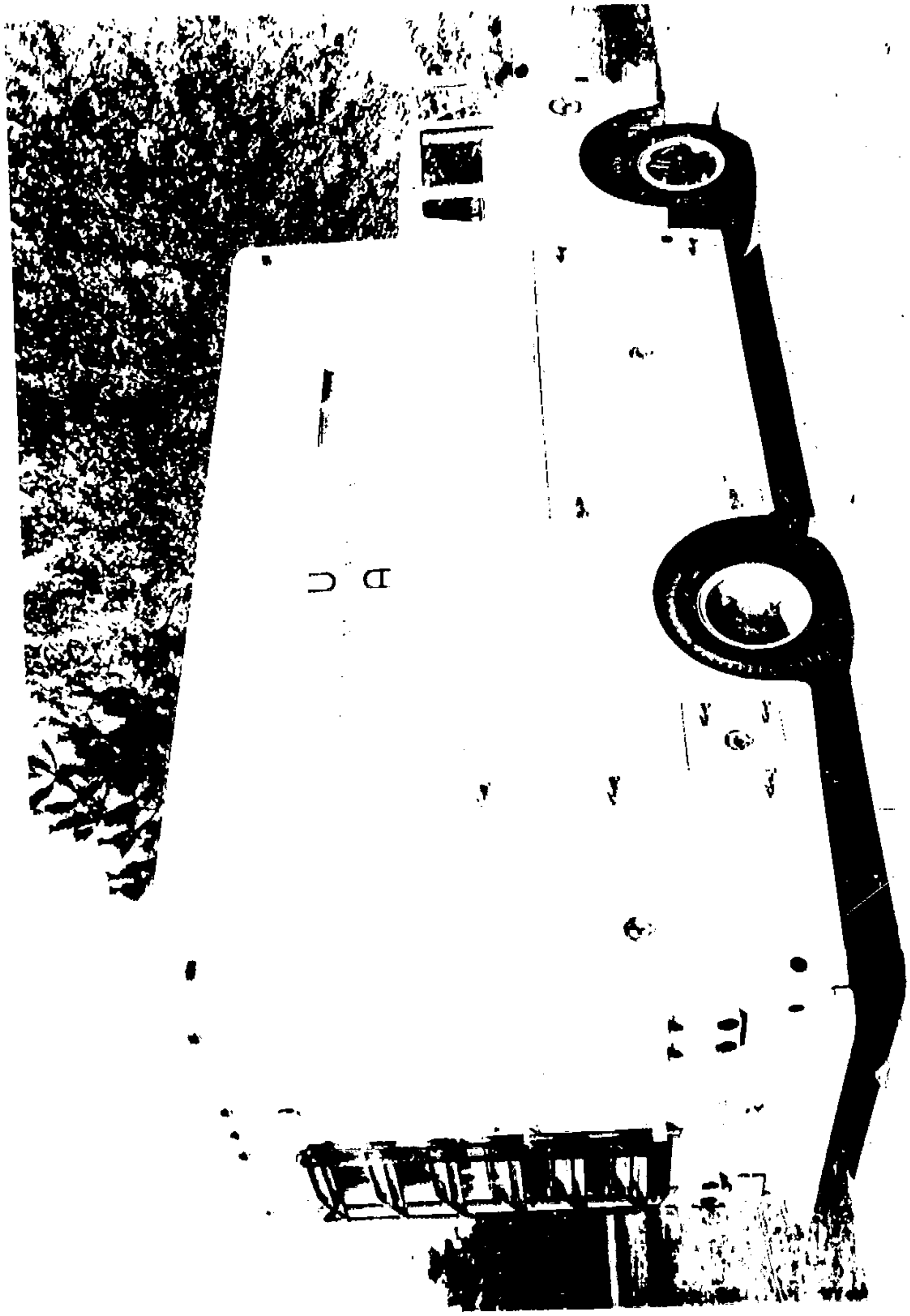

Figure A-7   Mobile Laboratory for Measurement of Gaseous Combustion Exhaust Products   (CN-40146)

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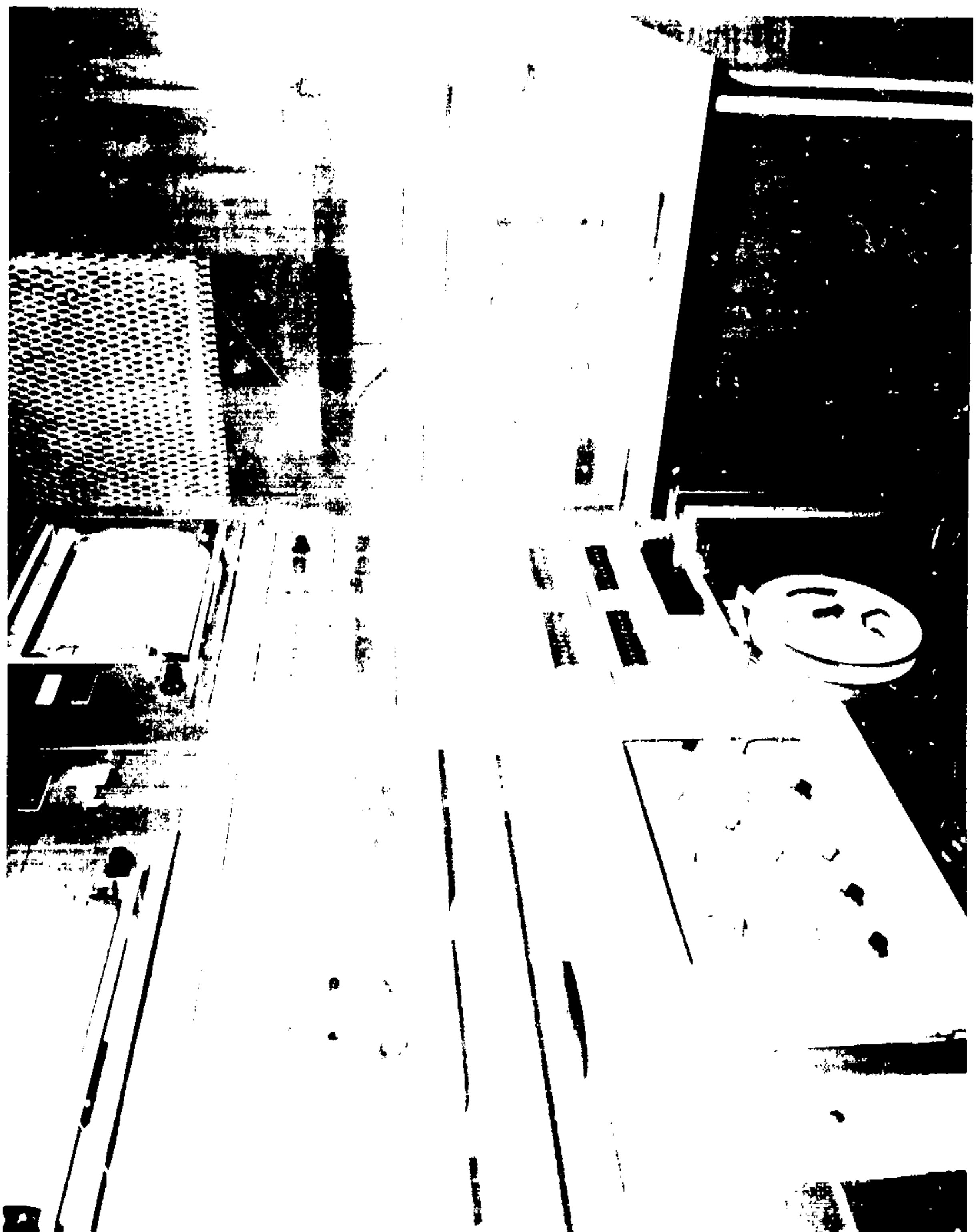

Figure A-8   On-Line Gas Analysis Equipment   (CN-40168)

TABLE A-II

ANALYZER SPECIFICATIONS

Component	Range	Direction Method	Minimum Detectability	Error % Full Scale
O_2	0-10% V 0-25% V	Amperometric	0.25% V	± 1.0%
N_2	0-90%	Gas Chromatograph	0.1% V	-
H_2	0-1% 0-5%	Gas Chromatograph	0.1% V	-
O_2	0-25%	Gas Chromatograph	0.1% V	--
CO	0-100 ppmv 0-500 ppmv 0-2500 ppmv 0-2500 ppmv	NDIR	2 ppmv	± 2.0% ± 1.0% ± 1.0% ± 1.0%
CO_2	0-2% V 0-5% V	NDIR	0.04% V 0.25% V	± 1.0% ± 1.0%
THC (As Methane)	0-1 ppmv Through 0-50K ppmv	FID	0.1 ppmv	± 5.0% ± 1.0%
NO_x	0-2.5, 0-10-6.25, 0-100 0-250 - 0 - 1000 0-2500 0-10000	CL	0.1 ppmv	± 0.5%
H_2O	-45°C - +60°C	CMHY	0.06°C	± 0.4°C

CL - Chemiluminescence
FID - Flame Ionization Detector
NDIR - Non-Dispersive Infrared
CMHY - Chilled Mirror Hygrometer
NDUV - Non-Dispersive Ultraviolet

The GT&CE mobile laboratory utilizes a heated stainless steel metal bellows sample pump to draw a sample of the jet engine combustion products into the sample measurement train. Another larger vacuum-type bypass pump is also incorporated into the sampling system to minimize the residence time of the sample in the sample line. The engine exhaust gas sample is distributed to the various instruments, with each instrument having its own flow metering system. The sample handling system is shown schematically in Figure A-9. The outputs from these instruments are recorded and monitored continuously on strip chart recorders. The analyzer outputs are also digitized and, on command, are sent via a telephone line to a Sigma 8 computer and/or recorded on a cassette-type magnetic tape recording system. The magnetic tape is compatible with the IBM-360 computer which is used for off-line special data reduction and validation programs.

Each instrument is provided with "sample" and "calibration" operating modes. The GT&CE mobile laboratory carries its own calibration, zero and span gases. In support of this mobile laboratory, an in-house analytical laboratory develops calibration gases and maintains standard reference gases which, in most cases, are traceable to the National Bureau of Standards (NBS).

C. SMOKE MEASUREMENT CONSOLE

Engine exhaust smoke measurements were obtained using a smoke measuring system that conforms to specifications of the Society of Automotive Engineers Aerospace Recommended Practice 1179 and the Environmental Protection Agency [Reference 1].

The smoke measuring console, shown in Fgure A-10, is a semiautomatic electromechanical device which incorporates a number of features to permit the recording of smoke data with precision and relative ease of operation. The smoke console was installed in the engine test cell control room for the duration of the test program. Dimensions of the filter holder and a schematic of the sampling system are shown in Figure A-10. The filter holder has been constructed with a 2.54 cm (1.0 inch) diameter spot size, a diffusion angle θ of 7.25 degrees and a converging angle α of 27.5 degrees.

The unit is designed to minimize variability resulting from operator to operator differences. One of these features is a time controlled, solenoid activated main sampling valve (Valve A, See Figure A-11) having "closed", "sample", and "bypass" positions This configuration permits close control of the sample size over relatively short sample times. In addition, this timing system operates a bypass system around a positive displacement volume measurement meter to ensure that the meter is in the circuit only when a sample is being collected or during the leak check mode. Other design features include automatic temperature control for the sample line and filter holder, and silicon rubber filter holders with support screens for ease of filter handling.

A Photovolt Model 670 reflection meter with a type-Y search unit conforming to ASA Ph 2.17-1958 "Standard for Diffuser Reflection Density" is used to determine the reflectance of clean and stained filters. A set of Hunter Laboratory reflectance plaques, traceable to the National Bureau of Standards, is used to calibrate the reflectance meter. A computer program is used to calculate the gas sample weight per unit filter area and smoke number.

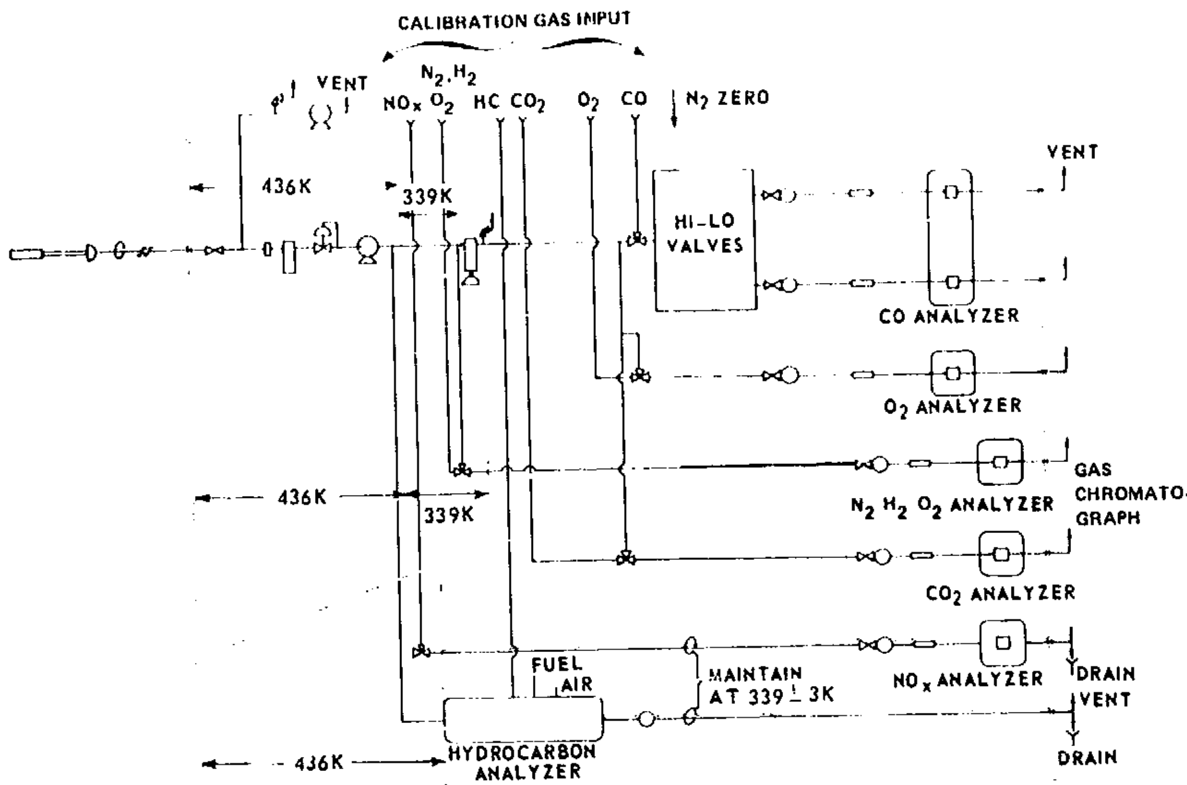

Figure A-9 Exhaust Gas Sample Handling System

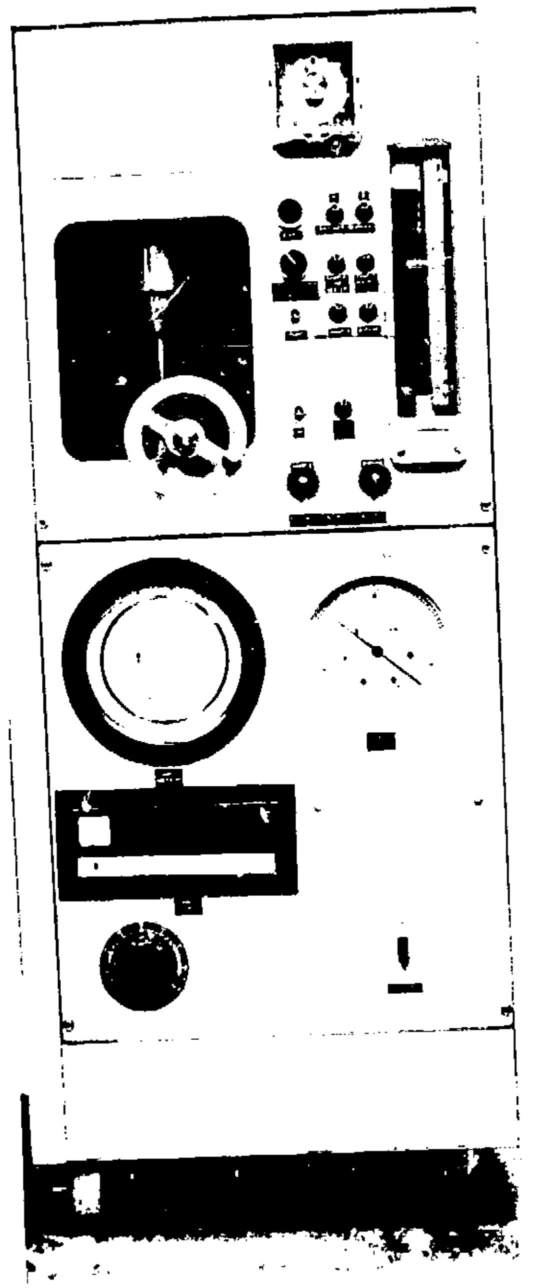

Figure A-10 SAE/EPA Smoke Meter (CN-47639)

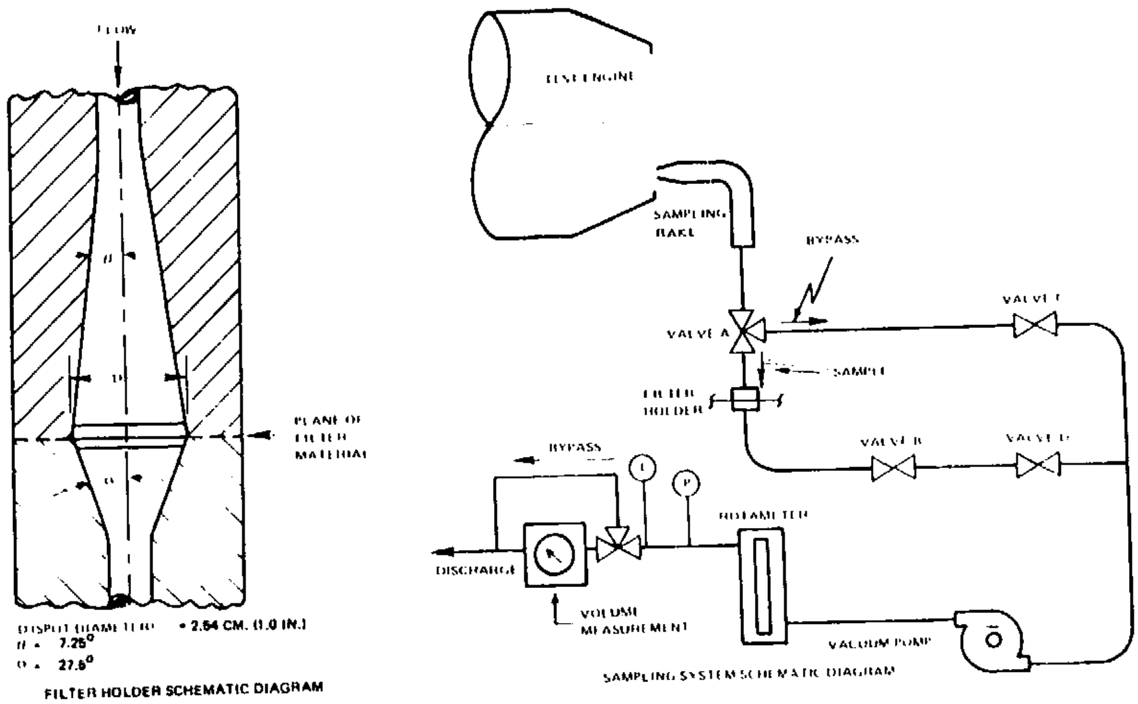

Figure A-11 Details of SAE/EPA Smoke Meter Construction

3. P-6 TEST FACILITY

A. FACILITY DESCRIPTION

The P-6 test stand, one of eight ambient-inlet indoor test cells located at the Pratt & Whitney Aircraft production facility in Middletown, Connecticut, has been fitted with the additional instrumentation and data handling capability required for automatic temperature recording system (ARTS) and low-emission combustor development programs. The facility is equipped with a monorail engine handling system to facilitate movement of the engine into and out of the test cell. A schematic view of the test cell layout is shown in Figure A-12. Figure A-13 shows a front view of a JT9D engine with inlet bellmouth and screen mounted in the test cell. All engine controls, data logging, and computer face equipment are located in the test cell control room. A view of the control console is shown in Figure A-14. The breadboard fuel control computer and peripheral equipment were also installed in the test stand control room. The mobile emissions laboratory was parked outside and to the rear of the test cell while testing was in progress.

A multiple quick disconnect Instrumentation Connection Assembly (ICA) has been incorporated into the facility to reduce the connection time when installing an engine into the test cell. Half of the ICA unit stays in the cell and remains connected to the test stand data acquisition and readout system. The other half is installed on the engine mount frame and instrument lines are connected to the engine during the preparation operation in the marshalling area outside the cell.

A flight-type nacelle is not normally employed for either experimental or production JT9D engine testing. A cylindrical core engine exhaust nozzle is used in place of the plug-type flight design. A pair of bifurcated fan ducts are used in place of the annular fan duct. The fan and core nozzle areas are sized to provide aerodynamic characteristics equivalent to the flight nacelles. The bifurcated fan ducts facilitate installation of special instrumentation and test hardware, and are readily removed for access to the core engine.

Figure A-15 shows the X-686 engine being moved into the test cell on the monorail carrier for a fuel system leak check prior to starting the Phase III Vorbix combustor test program. The leak check is conducted at engine idle power with the fan ducts off. Details of the engine mounting frame, quick-disconnect instrumentation couplings, and cylindrical core engine tailpipe are visible. The engine is shown with the bifurcated fan ducts installed in Figure A-16.

B. DATA ACQUISITION SYSTEMS

The P-6 engine test stand is equipped with two separate and complete data systems. All basic engine performance parameters are determined using the Automatic Production Test Data Acquisition and Control System (APTDAC) which is available to all production test cells. The 2104 Data Acquisition System (ADAPTS) was designed to support ARTS combustor development programs, and is available only in the P-6 test stand at the Middletown Test Facility.

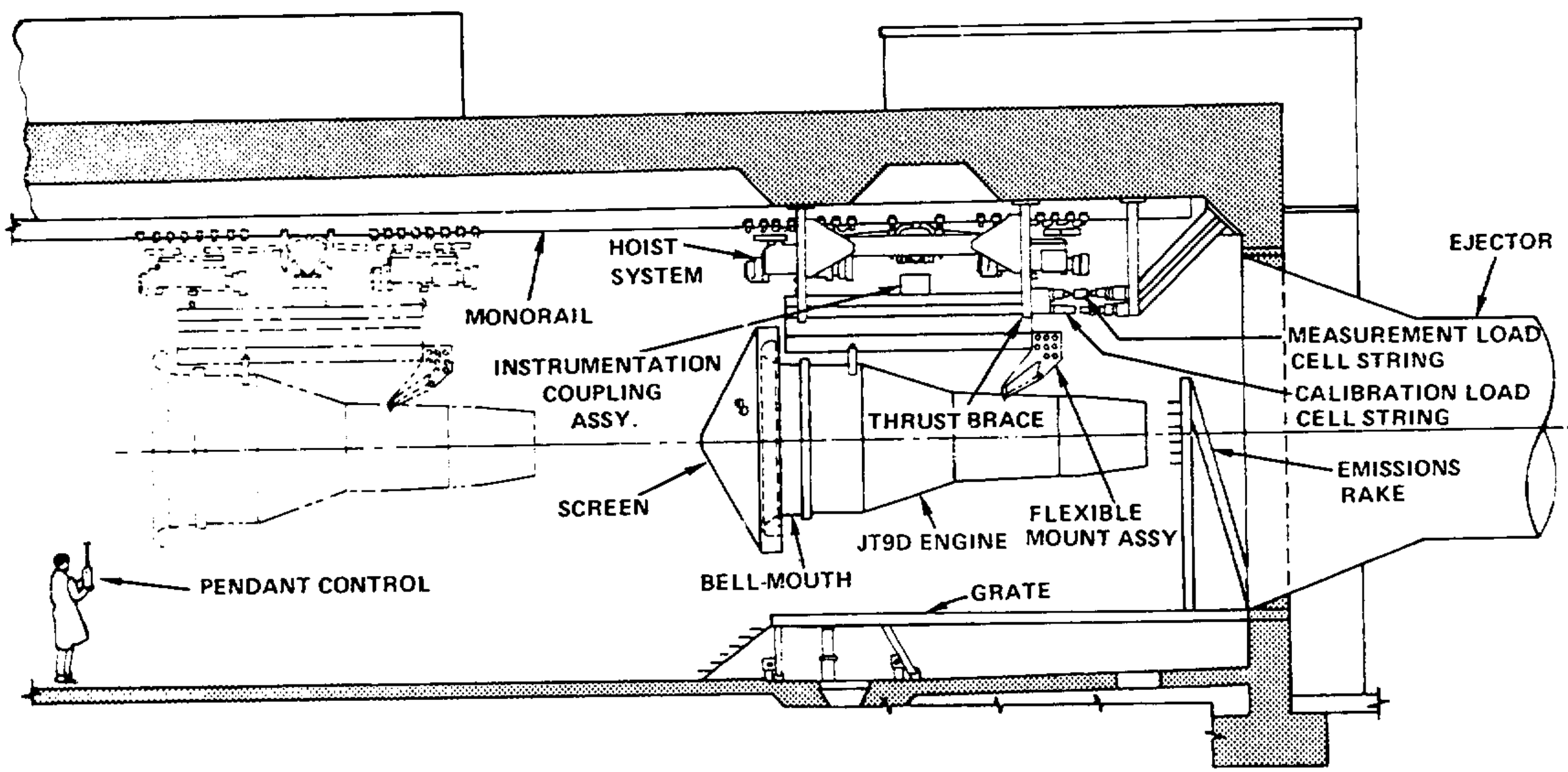

Figure A-12 P-6 Test Cell Layout

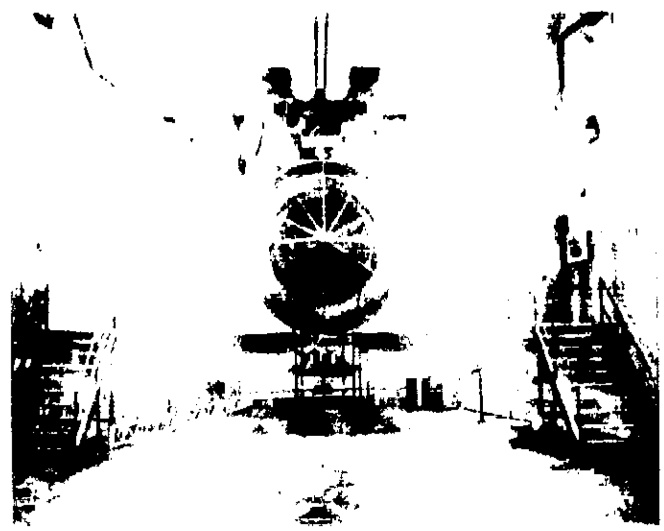

Figure A-13 JT9D Engine Mounted in Production Test Cell Showing Inlet Bellmouth and Screen

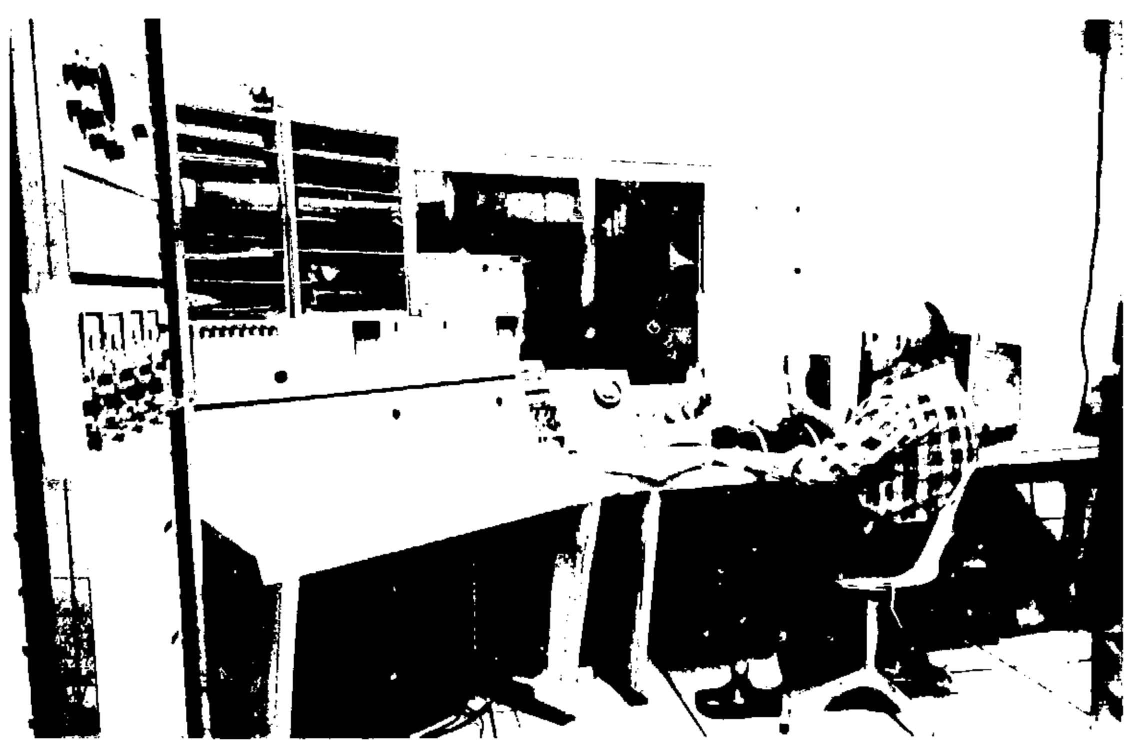

Figure A-14 Control Console in P-6 Test Stand Used in Phase III X-686 Engine Tests (76-441-4022-H)

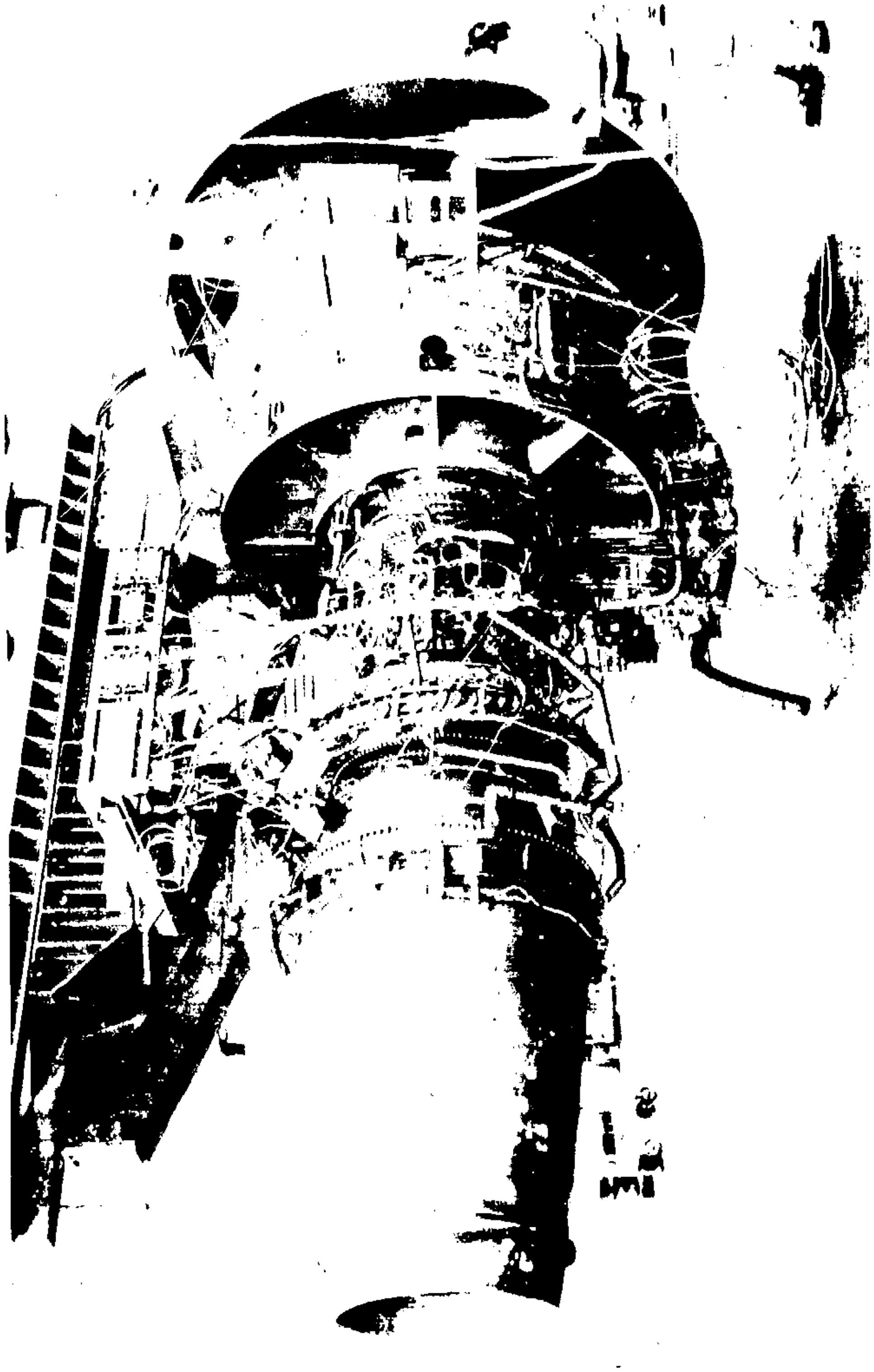

Figure A-15 Right Side View of X-686 Being Moved Into the Test Cell for the Initial Ducts Off Leak Check
CN-57344

Figure A-16 Experimental Engine, X-686, With Bifurcated Ducts Installed (X-43208)

All aspects of performance evaluation - instrumentation hookup, calibration, data logging, performance analysis, data display, and control have been streamlined by the APTDAC System. APTDAC is an integrated system of sensors, signal conditioning equipment, engine control consoles, digital computers, and cathode-ray tube display devices designed to perform all operating functions automatically. Figure A-17 presents an overview of the system functions.

The APTDAC system is capable of testing eight engines simultaneously the facility has four computers and each computer can handle two test cells. Each computer is linked to sensing devices in the engine by way of automatic data equipment. Pneumatic and electric transducers measure some 80 different engine operating parameters and relay quantitative data to the computer.

Whether measuring the operating conditions of one or two engines, the assigned APTDAC system computer performs the following acquisition, analysis, and recording tasks:

- Converts the transducer output signals to engineering units
- Corrects the data to standard conditions
- Computes the performance data needed to determine compliance with engine specifications
- Compares selected parameters against established limits and activates an alarm if limits are exceeded
- Displays the data to the operator on a cathode-ray tube
- Provides print-out of the acquired and computed data, on command.

Figure A-18 depicts the flow of data in the system. The APTDAC system is able to scan each variable 10 times, average readings, compute complete engine performance, and print out the results within 15 seconds.

Major features built into the computerized engine test system include the capability to conduct tests in either automatic or operator mode, a dynamic update system which allows program changes while running, a debug package, capability for aborting an engine run while in automatic mode when harmful conditions are sensed, and an error message which indicates possibly invalid data.

The 2104 ADAPTS system has the capacity to record up to 1000 millivolt inputs and 384 pressure inputs on five 200 channel scanners and eight 48 port scanning valves. Up to 400 Type B, 500 Type S, and 60 Type K thermocouples, plus two engine speeds, two fuel flows, and 360 pressure parameters can be recorded for any given engine. The remainder of the inputs are used as confidence and reference channels to monitor system accuracy.

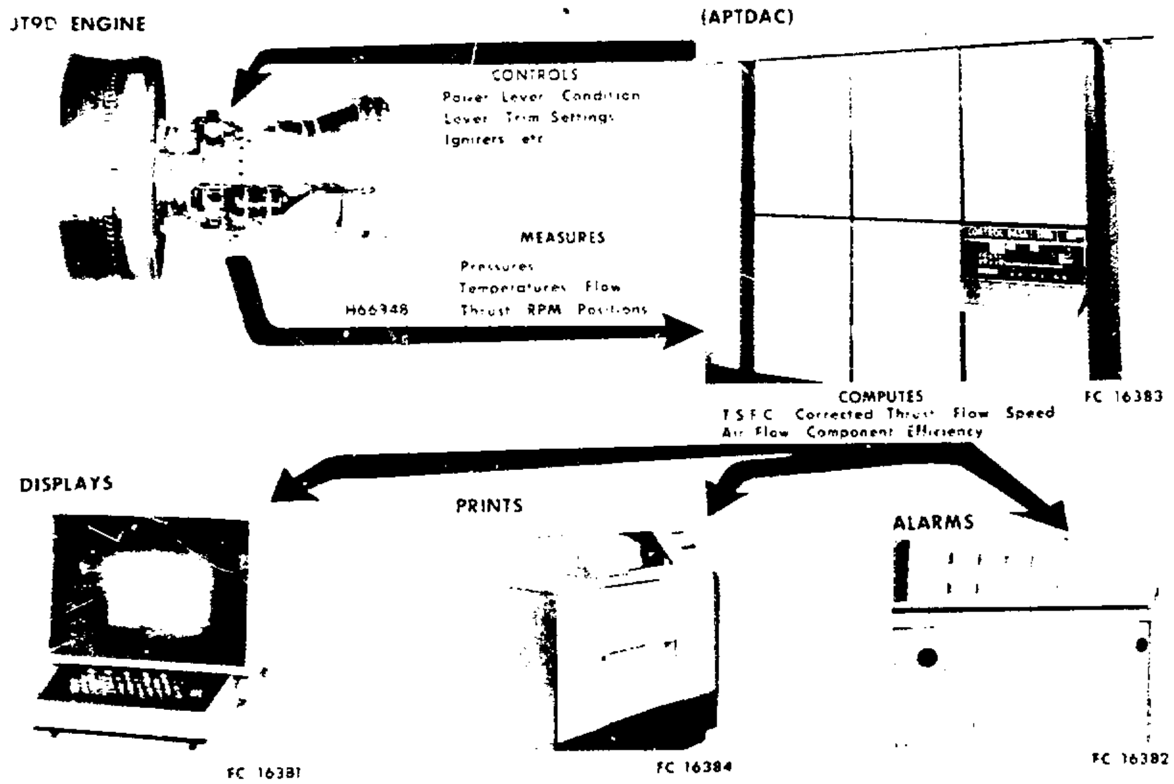

Figure A-17 Automatic Production Test Data Acquisition and Control System Functions

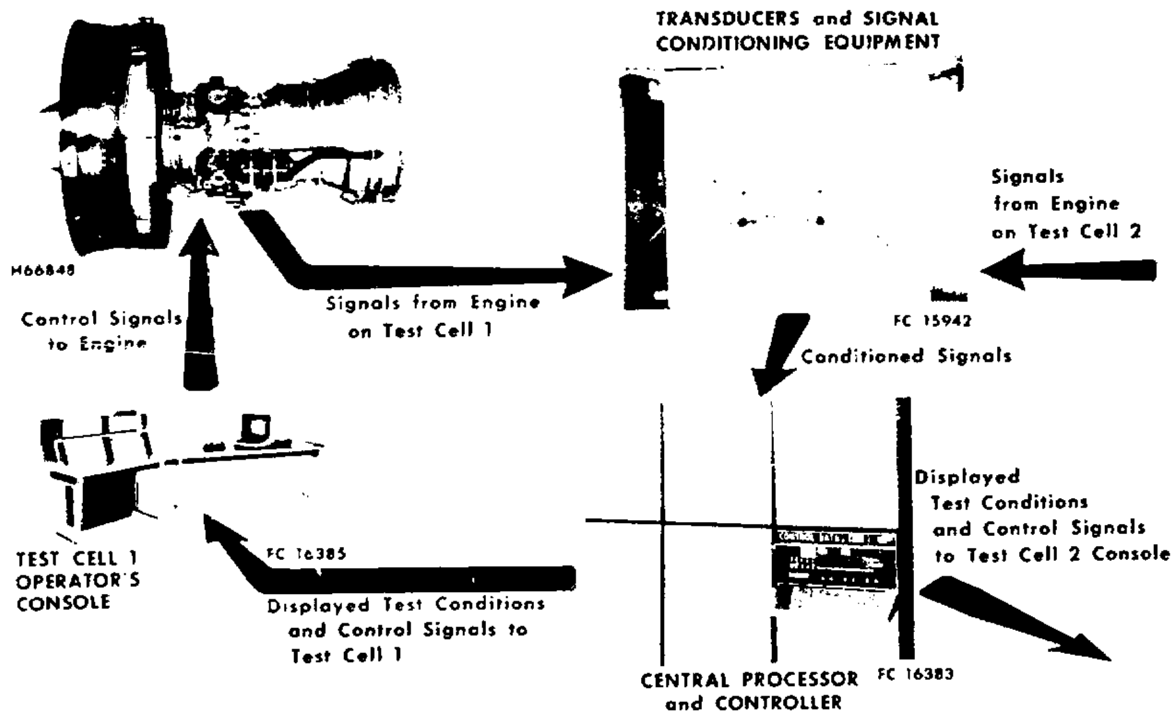

Figure A-18 Automatic Production Test Data Acquisition and Control System Data Flow

The data system has been designed with quick disconnect pressure fittings and electrical connectors to enhance the quick mount capability of the test stand. This provision allows the engine to be installed and connected to the data system in less than two hours. Special features of the data recording system include:

- Channel delete capability
- Three wire guarded system
- OHMS checking capability for thermocouple continuity
- Variable start and end point scan selection
- Manual channel monitoring

C. DATA REDUCTION AND LOGGING SYSTEM

The data reduction and logging fuction for the basic engine performance information is performed by the APTDAC system. All other data, including ARTS thermocouple readings, combustor/diffuser pressure and temperature measurements, and engine emissions data are processed by an on-line Sigma 8 computer located in East Hartford, Connecticut. The data acquisition units tramsmit the data by telephone line to the Sigma 8 computer. Approximately 45 seconds after acquisition, processed information is displayed on an alphanumeric character scope in the test stand control room. The user can select any one of several scope picture (pages) displaying data in engineering units. In addition, the user can view calculated performance parameters based on input data including air flow, Mach numbers, and ideal combustor exit temperature. This real time display of results allows precise matching of test conditions to test program parameters and immediate assessment of the quality of the data.

Editing of the data can be performed via a delete system. Hard copies of all raw data and performance parameters are available at the Sigma 8 computer room in East Hartford as the test is conducted. In addition to hard copies and scope output, the data is recorded and available in other formats.

Raw data is recorded on magnetic tape at the test stand and is available for input to an off-line data reduction computer program for additional processing. Data can be acquired on this magnetic tape unit with or without the Sigman 8 computer being on-line. At the option of the user, raw data can be printed in tabular form on a paper tape printer in the test stand control room. The user can also produce punch cards at East Hartford. All raw data received by the Sigma 8 computer is redundantly recorded on magnetic tape at East Hartford.

In order to minimize the number of entry ports to the Sigma 8 computer occupied by P-6 test stand, special equipment has been installed at the P-6 test stand to permit the 2104 ADAPTS in the test stand control room and the data logging system in the Gas Temperature and Combustion Efficiency (GT & CE) mobile laboratory to time-share the telephone link to the Sigma 8. Priority for transmission of data remains with the 2104 ADAPTS. Upon command from an operator in the P-6 control room, a special electronic switch enables the mobile laboratory to transmit data upon completion of an 2104 ADAPTS transmission. When the Sigma 8 receives the coded signal from the mobile laboratory, it reduces the data and performs the calculations in accordance with instructions in the Mobile Laboratory for Emission Analysis (MOLE) program. The results of the calculations are transmitted back to an interactive scope in the mobile laboratory.

The mobile laboratory operator selects one of three calculation pages to be displayed: an emission data reduction page, a data validation page, and an instrument calibration page. The information displayed when the emission data reduction page is selected includes: fixed identification data, emission concentration, emission index (EI) for each constituent, measured 2 sigma variation of the emission data, carbon basis fuel/air ratio, measured fuel flow, calculated air flow, and calculated combustor exit temperature.

APPENDIX B

EMISSIONS AND PERFORMANCE DATA

The following tables present the detailed emissions and performance data obtained during the program. Emissions data were obtained using five different gas sampling techniques as described in Chapter II and Appendix A. The gas sampling rakes used and their symbol designations used on the data tables are presented below:

Symbol	Description
24F	24-Port, 8-Arm, Radial Array, Fixed
24T	24-Port, 8-Arm, Radial Array, Traversed over 45 Degrees in 5-Degree Increments
12S	12-Port, 4-Arm, Cruciform Oriented Vertical and Horizontal, Fixed
12E	12-Port, 4-Arm, Cruciform 45 Degrees from Vertical and Horizontal, Fixed
ST7	Station 7 Pressure Probe With 8 Radial Pressure Taps

TEST RESULTS FOR CONFIGURATION S25E RUN 1

POINT	THRUST N	ENGINE INLET PRESSURE ATM	ENGINE INLET TEMP K	HUMIDITY GH2O/G AIR	FUEL TEMPERATURE K	AIRFLOW STATION 4 KG/S	AIRFLOW COMBUSTOR KG/S	TOTAL PRESSURE STATION 4 ATM	TOTAL TEMPERATURE STATION 4 K
129	14007.	0.984	295.	0.01063	[illegible]	25.9	20.9	3.7[illegible]	466.
130	14118.	0.984	294.	0.01064	[illegible]	25.9	20.9	3.73	468.
131	13704.	0.984	294.	0.01069	[illegible]	24.9	20.1	3.66	466.
133	11547.	0.984	296.	0.01010	[illegible]	23.6	19.0	3.34	454.
134	23881.	0.953	295.	0.01077	302.	33.6	27.1	5.09	514.
135	61067.	0.981	294.	0.00999	[illegible]	54.9	44.5	9.11	614.
136	58558.	0.981	296.	0.01054	302.	53.5	43.2	8.95	613.
138	61102.	0.981	295.	[illegible]	[illegible]	54.9	[illegible]	9.14	614.
140	60101.	0.981	295.	0.00960	[illegible]	[illegible]	[illegible]	9.0[illegible]	614.
141	47087.	0.981	296.	0.01036	[illegible]	47.6	38.5	7.60	567.
142	46998.	0.981	296.	0.00995	349.	47.6	35.5	7.60	527.
143	44077.	0.982	297.	0.00971	[illegible]	47.6	38.5	7.62	516.
144	47812.	0.982	297.	[illegible]	347.	44.1	38.0	7.70	588.
145	47058.	0.982	297.	0.00915	347.	44.1	38.0	7.16	588.
146	48007.	0.982	296.	[illegible]	347.	44.1	38.0	7.70	588.
148	33814.	0.983	296.	[illegible]	348.	[illegible]	[illegible]	[illegible]	550.
149	47598.	0.979	295.	[illegible]	[illegible]	70.9	57.1	[illegible]	674.
151	47600.	0.979	296.	0.00942	[illegible]	70.6	56.1	12.40	680.
152	47444.	0.979	296.	[illegible]	341.	70.6	57.1	12.46	680.
164	[illegible]	0.980	29[illegible].	[illegible]	305.	25.9	20.9	3.75	466.

POINT	FUEL FLOW PILOT KG/S	FUEL FLOW MAIN KG/S	IDEAL COMBUSTOR EXIT TEMPERATURE K	PATTERN FACTOR	PRESSURE LOSS TOTAL %	REFERENCE VEL M/S	FUEL AIR RATIO COMBUSTOR METERED STATION 5	FUEL AIR RATIO PILOT	FUEL AIR RATIO CARBON BALANCE STATION 7
129	0.222	0.0	676.	0.40	0.0	42.	0.0106	0.0106	0.0086
130	0.22[illegible]	0.0	883.	0.43	0.0	42.	0.0107	0.0107	0.0089
131	0.225	0.0	897.	1.35	0.0	41.	0.0112	0.0112	0.0087
133	0.199	0.0	861.	0.48	0.0	[illegible]	0.0105	0.0105	0.0086
134	0.314	0.0	855.	0.46	0.0	[illegible]	0.0116	0.0116	0.0091
135	0.301	0.334	1159.	0.36	0.0	[illegible]	0.0150	0.0075	0.0120
136	0.175	0.465	1160.	0.63	0.0	46.	0.0155	0.0045	0.0133
138	0.297	0.475	1165.	0.32	0.0	45.	0.0152	0.0040	0.0125
140	0.241	0.262	1162.	0.36	0.0	46.	0.0151	0.0046	0.0122
141	0.267	0.267	1044.	0.34	0.0	47.	0.0134	0.0064	0.0117
142	0.302	0.164	1040.	0.38	0.0	47.	0.0138	0.0046	0.0113
143	0.211	0.323	1092.	0.48	0.0	46.	0.0134	0.0055	0.0120
144	0.29[illegible]	0.248	1100.	0.29	0.0	47.	0.0134	0.0075	0.0126
145	0.297	0.246	1092.	0.28	0.0	47.	0.0134	0.0075	0.0116
146	[illegible]	0.249	1101.	0.20	0.0	47.	0.0134	0.0075	0.0116
148	0.214	0.194	1020.	0.21	0.0	46.	0.0125	0.0046	0.0105
149	0.371	0.647	1334.	0.46	0.0	50.	0.0167	0.0065	0.0163
151	0.426	0.641	1335.	0.35	0.0	50.	0.0187	0.0075	0.0156
152	0.333	0.734	1334.	0.42	0.0	50.	0.0167	0.0058	0.0161
164	0.22[illegible]	0.0	[illegible]	0.44	0.0	[illegible]	0.0107	0.0107	0.0088

POINT	F/A CB / F/A MET @ STATION 7	CO_2 %	CO (EI) AS MEASURED	THC (EI) AS MEASURED	NO_x (EI) AS MEASURED	GAS SAMPLE COMBUSTION EFFICIENCY	SAE SMOKE NO	NO_x (EI) CORRECTED FOR HUMIDITY & PRESSURE	CO (EI) CORRECTED FOR PRESSURE	THC (EI) CORRECTED FOR PRESSURE	COMMENTS (1)	RAKE
129	1.04	0.0	11.30	0.60	2.60	99.67	0.0	3.25	9.66	0.5[illegible]	IDLE	[illegible]
130	1.05	1.81	11.20	0.59	2.62	99.67	0.0	3.30	9.62	0.51	IDLE	[illegible]
131	0.99	1.79	18.80	1.20	2.51	99.42	0.0	4.11	16.69	[illegible]	IDLE	
133	1.04	1.72	18.20	1.03	2.68	99.40	0.0	3.11	15.61	0.60	IDLE	
134	0.99	1.86	4.27	0.34	4.00	99.88	0.0	3.37	3.71	0.30	IDLE	
135	1.07	2.60	9.40	0.31	4.72	99.74	0.0	[illegible]	8.51	0.27	[illegible]	
136	1.11	2.66	31.60	2.33	4.17	98.99	6.00	[illegible]	27.54	[illegible]	[illegible]	
138	1.04	2.55	7.50	0.29	5.66	99.74	12.00	6.60	[illegible]	[illegible]	[illegible]	
140	1.02	2.51	7.50	0.25	6.17	99.80	0.0	7.06	6.54	0.22	[illegible]	
141	1.06	2.36	21.30	0.44	5.02	[illegible]	7.00	[illegible]	[illegible]	[illegible]	[illegible]	
142	1.03	2.30	11.70	0.49	5.34	99.67	10.00	[illegible]	10.16	0.43	[illegible]	
143	1.09	2.40	36.00	2.62	3.75	98.00	6.00	[illegible]	[illegible]	[illegible]	[illegible]	
144	1.05	2.36	15.50	0.56	4.09	99.57	0.0	4.61	13.50	[illegible]	[illegible]	[illegible]
145	1.05	2.36	15.20	0.54	4.14	99.50	0.0	4.60	[illegible]	0.47	[illegible]	
146	1.05	2.35	15.40	0.52	4.10	99.55	0.0	[illegible]	[illegible]	0.45	[illegible]	
148	1.06	2.09	41.00	2.66	3.07	98.71	0.0	[illegible]	[illegible]	[illegible]	[illegible]	
149	1.09	3.26	3.10	0.11	7.42	99.91	0.0	6.45	[illegible]	[illegible]	[illegible]	
151	1.07	3.22	2.60	0.06	7.67	99.93	9.00	9.06	[illegible]	0.07	[illegible]	
152	1.09	3.27	4.00	0.10	7.60	99.90	9.00	[illegible]	[illegible]	[illegible]	[illegible]	
164	1.04	1.79	0.70	0.43	2.69	99.93	0.0	[illegible]	0.60	0.37	IDLE	

(1) ALL SAMPLES WERE OBTAINED WITH THE 24[illegible] RAKE SYSTEM UNLESS OTHERWISE INDICATED

TEST RESULTS FOR CONFIGURATION S26E RUN 2

POINT	THRUST - N	ENGINE INLET PRESSURE - ATM	ENGINE INLET TEMP - K	HUMIDITY - $gH_2O/gAIR$	FUEL TEMPERATURE - K	AIRFLOW STATION 4 kg/s	AIRFLOW COMBUSTOR kg/s	TOTAL PRESSURE, STATION 4 - ATM	TOTAL TEMPERATURE STATION 4 - K	FUEL FLOW PILOT - kg/s	FUEL FLOW MAIN - kg/s	IDEAL COMBUSTOR EXIT TEMPERATURE - K	PATTERN FACTOR	PRESSURE LOSS TOTAL - %	REFERENCE VEL - m/s	FUEL AIR RATIO COMBUSTOR METERED STATION 5	FUEL AIR RATIO PILOT	FUEL AIR RATIO CARBON BALANCE STATION 7	F/A CB / F/A NET @ STATION 7	CO_2 - %	CO (EI) AS MEASURED	THC (EI) AS MEASURED	NO_x (EI) AS MEASURED	GAS SAMPLE COMBUSTION EFFICIENCY	SAE SMOKE NO	NO_x (EI) CORRECTED FOR HUMIDITY & PRESSURE	CO (EI) CORRECTED FOR PRESSURE	THC (EI) CORRECTED FOR PRESSURE	COMMENTS (1)	RAKE
190	12161.	0.996	296.	0.01425	333.	23.1	18.6	3.49	455.	0.201	0.0	874.	0.45	5.39	39.	0.0106	0.0106	0.0086	1.00	1.74	15.80	1.17	2.53	99.50	0.0	3.32	14.63	1.04	IDLE	*
191	23957.	0.996	296.	0.01323	338.	32.4	26.1	5.13	514.	0.312	0.0	967.	0.52	5.40	42.	0.0119	0.0119	0.0089	0.94	1.83	4.38	0.44	4.40	99.85	0.0	5.35	5.64	0.38	IDLE	*
193	48488.	0.994	296.	0.01321	336.	47.6	38.6	7.45	584.	0.276	0.267	1103.	0.51	5.40	46.	0.0141	0.0072	0.0115	1.02	2.32	21.69	1.83	3.85	99.28	4.50	4.57	19.66	1.67	APP T4	*
194	49035.	0.993	296.	0.01327	338.	47.7	38.6	8.02	585.	0.397	0.153	1109.	0.36	5.40	45.	0.0145	0.0105	0.0117	1.04	2.39	10.12	0.42	5.32	99.71	8.10	6.32	9.30	0.39	APP T4	*
200	12081.	0.997	296.	0.01137	331.	22.6	18.4	3.34	457.	0.201	0.0	879.	0.50	6.00	36.	0.0109	0.0109	0.0091	1.06	1.85	13.92	0.62	2.59	99.60	0.0	3.02	12.34	0.55	IDLE	*
209	49182.	0.996	296.	0.01149	338.	47.3	38.2	8.06	589.	0.311	0.243	1121.	0.31	5.90	45.	0.0145	0.0082	0.0118	1.03	2.40	14.59	0.04	4.23	99.58	7.20	4.91	13.15	0.56	APP T4	*
212	61551.	0.996	296.	0.01144	337.	53.6	42.8	9.29	614.	0.254	0.429	1190.	0.32	5.90	46.	0.0159	0.0059	0.0133	1.06	2.70	17.11	0.84	4.12	99.50	0.0	4.80	15.37	0.76	APP	*
213	95142.	0.995	296.	0.01144	333.	66.7	53.9	12.43	673.	0.221	0.646	1364.	0.69	5.60	47.	0.0198	0.0041	0.0166	1.06	3.36	24.04	0.83	5.96	99.58	0.0	7.02	[illegible]	0.72	50 %	*
214	96855.	0.993	295.	0.01106	335.	67.5	54.5	12.59	677.	0.327	0.746	1365.	0.54	5.60	47.	0.0197	0.0060	0.0164	1.05	3.32	4.58	0.12	6.46	99.88	0.0	7.57	[illegible]	0.11	50 %	*
215	95745.	0.994	295.	0.01096	336.	67.2	54.7	12.50	675.	0.275	0.790	1360.	0.62	5.60	47.	0.0196	0.0051	0.0162	1.04	3.39	8.76	0.27	6.15	99.76	0.0	7.20	7.60	0.25	50 %	*
216	97892.	0.994	295.	0.01087	337.	66.2	55.0	12.76	678.	0.437	0.643	1363.	0.46	5.50	47.	0.0196	0.0079	0.0160	1.02	3.25	2.42	0.04	7.38	99.94	0.0	8.62	2.20	0.05	50 %	*
218	132275.	0.991	294.	0.01097	334.	82.5	66.6	15.74	716.	0.555	0.818	1426.	0.47	5.60	49.	0.0206	0.0083	0.0171	1.04	3.48	1.47	0.02	9.87	99.96	0.0	11.42	1.31	0.02	CLIMB F/A	*
219	132248.	0.992	294.	0.01098	334.	82.3	66.4	15.72	710.	0.424	0.956	1430.	0.65	5.66	49.	0.0207	0.0084	0.0173	1.05	3.52	2.16	0.04	8.73	99.95	0.0	10.11	1.92	0.03	CLIMB F/A	*
220	132595.	0.992	294.	0.01093	335.	82.7	66.8	15.74	718.	0.488	0.869	1427.	0.56	5.60	49.	0.0206	0.0073	0.0169	1.03	3.43	1.73	0.01	9.29	99.96	14.90	10.74	1.54	0.01	CLIMB F/A	*
222	145507.	0.991	294.	0.01107	335.	87.1	70.3	16.86	732.	0.614	0.910	1471.	0.46	5.50	49.	0.0217	0.0087	0.0181	1.05	3.68	1.25	0.07	10.80	99.96	14.40	12.52	1.11	0.06	CLIMB T4	*
225	145521.	0.992	294.	0.01120	336.	87.0	70.3	16.84	732.	0.546	0.978	1471.	0.54	5.50	49.	0.0217	0.0078	0.0185	1.08	3.76	1.39	0.06	10.45	99.96	17.23	11.92	1.25	0.05	CLIMB T4	*
226	167352.	0.990	294.	0.01116	335.	94.1	76.0	18.63	755.	0.646	1.132	1541.	0.49	5.50	50.	0.0234	0.0085	0.0196	1.05	3.98	1.17	0.04	12.39	99.97	0.0	14.39	1.04	0.04	SLTO F/A	*
237	10382.	0.998	302.	0.01153	333.	20.7	16.8	3.21	454.	0.192	0.0	898.	0.66	5.64	38.	0.0115	0.0115	0.0094	1.04	1.92	11.17	0.75	2.79	99.65	0.0	3.38	9.16	0.62	IDLE	*
241	33498.	0.996	302.	0.01233	342.	37.4	30.6	6.33	559.	0.175	0.251	1075.	0.75	5.90	44.	0.0139	0.0057	0.0117	1.06	2.32	45.67	7.53	2.95	98.06	0.0	3.61	36.24	6.31	LOW APP	*
242	34601.	0.996	302.	0.01219	344.	38.6	31.1	6.44	562.	0.240	0.164	1067.	0.48	6.10	44.	0.0136	0.0077	0.0113	1.05	2.30	16.04	1.88	3.53	99.41	0.0	4.32	13.40	1.57	LOW APP	*
243	38770.	0.996	302.	0.01234	344.	39.3	31.7	6.48	563.	0.307	0.116	1056.	0.42	6.10	44.	0.0133	0.0097	0.0110	1.04	2.23	10.19	1.23	4.05	99.62	0.0	5.09	8.54	1.03	LOW APP	*
244	43684.	0.996	302.	0.01202	342.	43.8	35.3	7.47	566.	0.292	0.122	1122.	0.42	6.00	45.	0.0146	0.0083	0.0121	1.05	2.46	9.77	1.08	4.32	99.65	0.0	5.25	8.19	0.90	LOW APP	*
245	43501.	0.995	303.	0.01182	343.	44.0	35.5	7.55	590.	0.300	0.228	1133.	0.97	6.00	45.	0.0148	0.0064	0.0124	1.05	2.51	9.51	1.46	4.46	99.61	0.0	5.40	7.97	1.24	APP SOLND**	*
246	42570.	0.995	302.	0.01152	344.	44.5	35.9	7.62	592.	0.382	0.145	1129.	0.56	5.80	45.	0.0147	0.0107	0.0122	1.05	2.48	6.64	1.15	5.98	99.71	0.0	7.20	5.56	0.97	APP SOLND**	*
247	44600.	0.995	302.	0.01186	342.	43.4	35.0	7.45	588.	0.217	0.311	1140.	1.19	6.10	44.	0.0151	0.0062	0.0125	1.04	2.52	22.94	3.00	3.74	99.12	0.0	4.51	19.24	2.57	APP SOLND**	*
257	9581.	0.997	301.	0.01169	342.	20.3	16.4	3.06	446.	0.185	0.0	879.	0.45	5.80	38.	0.0117	0.0117	0.0093	1.06	1.87	18.69	3.49	2.37	99.16	0.0	2.66	15.79	2.95	IDLE	*
258	12112.	0.996	301.	0.01197	340.	22.9	18.5	3.50	464.	0.206	0.0	844.	0.53	5.90	39.	0.0111	0.0111	0.0095	1.06	1.88	12.11	3.11	2.67	99.36	0.0	3.25	10.07	2.59	IDLE	*
259	123539.	0.989	300.	0.01177	332.	80.2	64.9	14.86	719.	0.403	0.690	1467.	0.70	5.40	50.	0.0210	0.0082	0.0175	1.10	3.55	2.83	1.19	8.10	99.60	0.0	9.62	2.36	0.99	CLIMB	*
267	129588.	0.984	304.	0.01494	336.	82.1	66.3	15.54	735.	0.562	0.823	1450.	0.44	5.60	51.	0.0209	0.0085	0.0176	1.06	3.57	1.63	1.25	9.89	99.82	0.0	12.95	1.51	1.02	CLIMB	*
268	129686.	0.984	304.	0.01487	336.	82.7	66.8	15.50	735.	0.418	0.973	1447.	0.59	5.60	51.	0.0208	0.0063	0.0176	1.08	3.62	2.15	1.07	8.52	99.83	0.0	11.14	1.74	0.86	CLIMB	*
269	129254.	0.984	303.	0.01454	336.	82.6	66.7	15.44	734.	0.356	1.039	1451.	0.60	5.70	51.	0.0209	0.0054	0.0178	1.07	3.62	3.42	1.06	8.11	99.80	0.0	10.54	2.75	0.85	CLIMB	
270	129210.	0.984	303.	0.01422	337.	82.3	66.5	15.35	734.	0.280	1.099	1444.	0.65	5.60	51.	0.0206	0.0045	0.0161	1.10	3.67	4.94	1.14	7.69	99.75	0.0	10.1	3.47	0.91	CLIMB	
271	154283.	0.983	303.	0.01454	336.	90.5	73.1	17.43	764.	0.493	1.163	1527.	0.52	5.50	52.	0.0227	0.0067	0.0193	1.07	3.92	1.56	0.94	10.60	99.85	0.0	13.62	1.26	0.75	SLTO	
272	153465.	0.982	304.	0.01456	336.	90.4	73.0	17.38	763.	0.403	1.256	1526.	0.55	5.50	57.	0.0276	0.0055	0.0192	1.07	3.90	2.03	0.95	10.09	99.84	0.0	13.17	1.63	0.76	SLTO	
273	155440.	0.982	303.	0.01415	338.	90.5	73.1	17.54	765.	0.569	1.092	1530.	0.47	5.40	51.	0.0227	0.0078	0.0192	1.06	3.89	1.45	0.97	11.40	99.85	0.0	14.75	1.16	0.77	SLTO	
274	10319.	0.991	303.	0.01407	352.	20.6	16.6	3.16	454.	0.186	0.0	884.	1.20	5.90	34.	0.0111	0.0111	0.0087	0.99	1.77	14.48	1.98	2.70	99.43	0.0	3.40	11.69	1.60	IDLE	
275	9616.	0.991	303.	0.01374	346.	17.9	16.1	3.01	446.	0.170	0.0	870.	0.54	5.80	38.	0.0111	0.0111	0.0090	1.02	1.84	17.18	2.22	2.59	99.34	0.0	3.30	13.97	1.80	IDLE	

(1) * ALL SAMPLES WERE OBTAINED WITH THE 24P RAKE SYSTEM UNLESS OTHERWISE INDICATED

** MAIN ZONE SOLENOID MALFUNCTION

TEST RESULTS FOR CONFIGURATION S27E RUN 3

Reading	Time	Combustor inlet pressure, atm	Combustor inlet temp, K	Humidity, g/g air	Fuel temperature, K	Airflow station, kg/s	Airflow combustor, kg/s	Total pressure station 4, atm	Total temperature station 4, K	Fuel flow pilot, kg/s	Fuel flow main, kg/s	Ideal combustor exit temperature, K	Pattern factor	Pressure loss total, %	Reference vel, m/s	Fuel air ratio combustor metered station 5	Fuel air ratio pilot	Fuel air ratio carbon balance station 7	F/A CB / F/A MET station 7	CO_2, %	CO EI as measured	UHC EI as measured	NO_x EI as measured	Gas sample combustion efficiency	SAE smoke no.	NO_x EI corrected for humidity & pressure	CO EI corrected for pressure	UHC EI corrected for pressure	Comments
315	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	1.87	10.51	[illegible]	2.65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
316	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	1.82	16.52	1.05	2.47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
317	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.05	1.88	13.20	[illegible]	2.65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
319	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.02	5.37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
326	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.79	15.09	0.75	2.57	[illegible]	[illegible]	[illegible]	13.66	[illegible]	[illegible]
333	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.07	2.33	34.83	2.91	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
334	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	2.63	34.79	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
335	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.05	2.63	19.59	1.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
336	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.05	2.59	12.55	0.60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
337	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	2.61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
338	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.04	2.58	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
339	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	2.78	11.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
340	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	3.39	3.72	0.76	6.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
341	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.04	3.36	2.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
342	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.05	3.59	5.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
344	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	3.41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
345	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.08	3.46	12.46	[illegible]	6.50	99.62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
348	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.08	3.44	2.64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
349	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.10	3.49	6.61	[illegible]	7.27	[illegible]	17.70	[illegible]	[illegible]	[illegible]	[illegible]
350	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.09	3.49	[illegible]	[illegible]	7.19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
351	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.07	3.71	2.69	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
354	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
355	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.04	3.63	1.70	[illegible]	9.53	[illegible]	21.20	[illegible]	[illegible]	[illegible]	[illegible]
361	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.67	1.66	0.19	10.01	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
367	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.02	3.82	11.57	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
369	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.06	3.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
370	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.02	3.69	1.50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
371	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.02	3.96	1.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
372	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.04	4.03	[illegible]	0.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
373	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.04	2.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
374	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.35	1.35	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
375	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.07	2.52	11.70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
376	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.05	2.67	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
377	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.00	3.72	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
378	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.00	3.75	[illegible]	[illegible]	9.03	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
380	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.76	9.12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
381	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.78	11.29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
382	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.80	13.76	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
383	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.06	[illegible]	[illegible]	5.78	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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OF POOR QUALITY

TEST RESULTS FOR CONFIGURATION S27E RUN 4

Point	Thrust, N	Engine inlet pressure, atm	Engine inlet temp, °K	Humidity, g H_2O/g air	Fuel temperature, K	Airflow station 4, kg/s	Airflow combustor, kg/s	Total pressure station 4, atm	Total temperature station 4, K	Fuel flow pilot, kg/s	Fuel flow main, kg/s	Ideal combustor exit temperature, K	Pattern factor	Pressure loss total, %
	[illegible]	[illegible]	292.	[illegible]	[illegible]	[illegible]	15.1	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
519	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
521	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.9	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
522	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22.5	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
523	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	28.1	[illegible]	515.	[illegible]	0.0	[illegible]	0.0	0.0
524	[illegible]	0.983	[illegible]	[illegible]	331.	[illegible]	33.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
525	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
526	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
527	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1120.	0.0	0.0
528	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1117.	0.0	0.0
529	[illegible]	0.982	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1129.	0.0	0.0
530	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1131.	0.0	0.0
531	[illegible]	0.982	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1125.	0.0	0.0
532	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
533	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
534	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
535	[illegible]	0.979	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
536	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
537	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	67.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
538	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
539	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
540	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
541	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
543	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
544	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
549	[illegible]	1.001	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
551	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	[illegible]	0.0	0.0
553	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
554	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
556	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
557	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
558	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
559	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
560	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
561	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
562	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
564	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
565	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
566	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
567	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
568	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
569	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
575	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
576	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
577	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
578	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
579	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
580	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
581	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
582	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
583	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
584	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
585	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0
586	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0

Point	Reference vel, m/s	Fuel air ratio combustor metered station 5	Fuel air ratio pilot	Fuel air ratio carbon balance station 7	F/A CB / F/A MET @ station 7	CO_2, %	CO (EI) as measured	THC (EI) as measured	NO_x (EI) as measured	Gas sample combustion efficiency	SAE smoke no	NO_x (EI) corrected for humidity & pressure	CO (EI) corrected for pressure	THC (EI) corrected for pressure	Comments (1)	Rake
	[illegible]	0.0107	0.0107	0.0065	1.01	1.73	12.62	1.29	2.67	99.56	0.0	2.98	11.57	1.18	[illegible]	[illegible]
519	39.	0.0106	0.0106	0.0064	1.06	1.71	13.36	0.90	2.65	99.56	0.0	2.97	12.26	0.82	[illegible]	[illegible]
521	[illegible]	0.0104	0.0104	0.0064	[illegible]	1.71	14.88	1.13	2.77	99.52	0.0	2.67	13.63	1.35	[illegible]	[illegible]
522	41.	0.0111	0.0112	0.0069	1.01	1.81	6.35	0.44	3.71	99.80	0.0	3.92	5.70	0.34	RI	[illegible]
523	45.	0.0116	0.0116	[illegible]	1.04	1.91	3.65	0.32	5.46	99.80	0.0	5.70	3.57	[illegible]	RI	[illegible]
524	[illegible]	0.0131	0.0064	0.0109	1.05	2.22	24.17	2.07	3.21	99.20	0.0	3.34	22.50	1.93	SAPP	[illegible]
525	[illegible]	0.0150	0.0044	0.0116	1.06	2.53	31.06	3.57	3.96	98.86	0.0	4.10	29.24	3.27	APP	[illegible]
526	[illegible]	0.0148	0.0059	0.0125	1.05	2.49	15.64	1.12	4.07	99.51	8.50	4.21	14.73	1.06	APP	[illegible]
527	[illegible]	0.0147	0.0072	0.0125	1.06	2.50	9.24	0.40	4.59	99.74	9.60	4.73	8.76	0.38	APP	[illegible]
528	[illegible]	0.0147	0.0075	0.0116	1.02	2.41	9.82	0.42	4.51	99.72	8.10	4.64	9.26	0.40	APP	[illegible]
529	[illegible]	0.0147	0.0073	0.0124	1.06	2.51	10.86	0.37	4.63	99.71	0.0	4.76	10.22	0.35	APP	[illegible]
530	[illegible]	0.0148	0.0073	0.0123	1.05	2.50	9.73	0.33	4.36	99.73	0.0	4.50	9.21	0.31	APP	[illegible]
531	[illegible]	0.0149	0.0089	0.0121	1.04	2.47	7.79	0.17	5.52	99.80	12.50	5.71	7.36	0.16	APP	[illegible]
532	[illegible]	0.0161	0.0065	[illegible]	1.05	2.77	6.42	0.21	5.18	99.78	10.50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
533	[illegible]	0.0167	0.0076	0.0156	1.07	3.21	2.31	0.04	6.36	99.94	17.50	6.75	[illegible]	[illegible]	[illegible]	[illegible]
534	[illegible]	[illegible]	0.0057	0.0161	1.08	3.27	4.50	0.09	7.41	99.88	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
535	[illegible]	0.0169	0.0035	0.0161	1.07	3.27	11.90	0.58	7.04	99.66	0.0	7.36	11.27	0.54	[illegible]	[illegible]
536	[illegible]	[illegible]	0.0067	0.0169	1.06	3.44	1.80	0.04	9.57	99.95	16.50	9.80	1.67	0.04	CLIMB	[illegible]
537	[illegible]	[illegible]	0.0057	0.0170	1.07	3.45	2.58	0.03	8.38	99.94	0.0	8.78	2.38	0.03	CLIMB	[illegible]
538	[illegible]	[illegible]	0.0061	0.0170	1.07	3.45	2.59	0.03	8.38	99.94	0.0	8.75	2.34	0.03	CLIMB	[illegible]
539	[illegible]	[illegible]	0.0073	0.0181	1.05	3.68	1.20	0.00	11.43	99.97	21.00	11.96	1.10	[illegible]	CLIMB	[illegible]
540	[illegible]	[illegible]	0.0075	0.0177	1.02	3.60	1.29	0.00	11.47	99.97	22.50	12.02	1.20	[illegible]	CLIMB	[illegible]
541	[illegible]	[illegible]	0.0074	0.0179	1.03	3.65	1.14	0.06	11.39	99.97	0.0	11.93	1.05	[illegible]	CLIMB	[illegible]
543	[illegible]	[illegible]	[illegible]	0.0184	1.06	3.75	1.17	0.02	10.92	[illegible]	[illegible]	11.40	[illegible]	[illegible]	CLIMB	[illegible]
544	[illegible]	[illegible]	0.0044	0.0187	1.08	3.60	3.26	0.0	10.07	[illegible]	27.70	10.56	[illegible]	0.0	CLIMB	[illegible]
549	[illegible]	[illegible]	[illegible]	[illegible]	1.06	1.77	12.90	0.32	3.01	99.66	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
551	[illegible]	[illegible]	[illegible]	0.0067	1.07	1.77	17.27	2.63	2.93	99.29	0.0	[illegible]	17.65	[illegible]	[illegible]	[illegible]
553	[illegible]	[illegible]	[illegible]	[illegible]	1.05	1.75	35.14	5.03	4.54	98.60	0.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
554	[illegible]	[illegible]	[illegible]	[illegible]	1.04	1.73	50.65	10.95	2.52	97.55	0.0	2.12	[illegible]	[illegible]	[illegible]	[illegible]
556	[illegible]	[illegible]	0.0075	0.0121	1.03	2.44	9.22	0.37	5.51	99.74	12.00	5.60	9.01	[illegible]	APP	[illegible]
557	[illegible]	[illegible]	[illegible]	0.0115	0.98	2.34	4.13	0.35	5.64	99.73	0.0	[illegible]	4.53	[illegible]	APP	[illegible]
558	[illegible]	[illegible]	[illegible]	[illegible]	1.05	2.50	10.04	0.35	5.36	99.73	11.90	[illegible]	10.44	[illegible]	APP	[illegible]
559	[illegible]	[illegible]	[illegible]	[illegible]	1.06	2.51	14.70	0.62	4.91	99.50	0.0	[illegible]	[illegible]	[illegible]	APP	[illegible]
560	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.41	27.03	2.26	4.66	99.11	0.0	[illegible]	[illegible]	[illegible]	APP	[illegible]
561	[illegible]	[illegible]	0.0077	0.0185	1.03	3.75	1.39	0.04	14.50	[illegible]	0.0	[illegible]	1.42	[illegible]	CLIMB	[illegible]
562	[illegible]	[illegible]	[illegible]	0.0174	1.00	3.65	1.44	0.05	14.45	[illegible]	0.0	13.15	1.44	[illegible]	CLIMB	[illegible]
564	[illegible]	[illegible]	[illegible]	0.0184	[illegible]	3.81	2.93	0.06	[illegible]	[illegible]	0.0	[illegible]	[illegible]	[illegible]	CLIMB	[illegible]
565	[illegible]	[illegible]	[illegible]	0.0191	1.00	3.87	1.56	0.11	15.20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
566	[illegible]	[illegible]	[illegible]	[illegible]	0.97	3.79	1.61	0.17	15.70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
567	[illegible]	[illegible]	[illegible]	[illegible]	0.96	3.74	1.50	0.19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
568	[illegible]	[illegible]	[illegible]	[illegible]	1.01	3.92	2.53	0.29	15.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
569	[illegible]	[illegible]	[illegible]	[illegible]	1.02	3.90	1.64	[illegible]	14.34	[illegible]	[illegible]	[illegible]	1.70	[illegible]	[illegible]	[illegible]
575	[illegible]	[illegible]	[illegible]	[illegible]	1.02	3.96	1.70	0.06	13.82	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
576	[illegible]	[illegible]	[illegible]	[illegible]	1.06	4.03	1.91	[illegible]	13.92	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
577	[illegible]	[illegible]	[illegible]	[illegible]	1.06	3.70	1.69	0.09	12.55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
578	[illegible]	[illegible]	[illegible]	0.0177	1.03	3.60	1.66	0.11	12.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
579	[illegible]	[illegible]	[illegible]	0.0151	1.05	3.07	3.69	0.14	8.09	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
580	[illegible]	[illegible]	[illegible]	[illegible]	1.06	3.09	4.06	0.15	8.12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
581	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.37	11.60	[illegible]	4.60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
582	[illegible]	[illegible]	[illegible]	0.0114	1.01	2.32	13.25	0.46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
583	[illegible]	[illegible]	[illegible]	[illegible]	1.02	1.80	5.19	0.32	4.51	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
584	[illegible]	[illegible]	[illegible]	[illegible]	1.00	1.76	5.92	0.34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
585	[illegible]	[illegible]	[illegible]	[illegible]	1.04	1.64	15.67	1.17	2.61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
586	[illegible]	[illegible]	0.0100	[illegible]	[illegible]	1.66	20.71	1.62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

TRANSIENT TEST DATA SUMMARY
RUN 1

Time	Engine Inlet Temperature (K)	Initial Fuel Air Ratio	Fuel Air Ratio at Staging Point	Initial Pilot Fuel Flow (Percent)	Staging Pilot Fuel Flow (Percent)	Acceleration Time (Sec)	Deceleration Time (Sec)	Initial Operating Condition
1545	283	0.0105	0.0120	100	90	6.1	–	Ground Idle
1552	283	0.0105	0.0120	100	90	6.8	–	Ground Idle
1636	283	0.0105	0.0120	100	100	7.6	–	Ground Idle
1641	283	0.0105	0.0120	100	100	6.3	–	Ground Idle
1650	283	0.0105	0.0120	100	90	6.4	–	Ground Idle
1655	283	0.0105	0.0120	100	90	6.3	–	Ground Idle
1700	283	0.0105	0.0120	100	95	7.0	–	Ground Idle
1706	283	0.0105	0.0120	100	95	6.2		Ground Idle
1711	283	0.0105	0.0120	100	95	6.2	–	Ground Idle
1721	284	0.0118	0.0130	100	85	Stall	–	Flight Idle
1738	286	0.0118	0.0140	100	85	Stall	–	Flight Idle
1748	286	0.0118	0.0126	100	80	Stall	–	Flight Idle
2154	287	0.0105	0.0126	100	95	6.7	–	Ground Idle
2318	287	0.0118	0.0130	Staged	80	7.2	–	Flight Idle
2324	287	0.0118	0.0130	Staged	80	5.3	–	Flight Idle
2326	287	0.0118	0.0130	Staged	80	5.3	3.8	Flight Idle
2333	287	0.0118	0.0130	Staged	90	5.9	4.1	Flight Idle
2340	287	0.0118	0.0130	Staged	70	5.3	3.0	Flight Idle
2342	287	0.0118	0.0130	Staged	95	6.5	4.3	Flight Idle
1658	284	0.0106	0.0130	Staged	90	7.6	2.6	Ground Idle
1653	284	0.0106	0.0130	Staged	90	7.5	2.6	Ground Idle
1704	284	0.0106	0.0130	Staged	95	7.8	7.6	Ground Idle
1711	284	0.0106	0.0130	Staged	95	7.8	2.8	Ground Idle
1718	284	0.0106	0.0130	Staged	85	6.3	3.3	Ground Idle
1725	284	0.0106	0.0130	Staged	85	7.0	2.4	Ground Idle
1822	282	0.0118	0.0130	Staged	80	4.8	3.9	Flight Idle

TRANSIENT TEST DATA SUMMARY
RUN 2

Time	Engine Inlet Temperature (K)	Initial Fuel/Air Ratio	Fuel/Air Ratio at Staging Point	Initial Pilot Fuel Flow (Percent)	Staging Pilot Fuel Flow (Percent)	Acceleration Time (Sec)	Initial Operating Condition
1442	287	0.0110	Staged	80	80	6.4	Low Flight Idle
1445	287	0.0110	Staged	80	80	6.3	Low Flight Idle
1448	287	0.0110	Staged	80	80	6.4	Low Flight Idle
1450	287	0.0110	Staged	90	90	6.7	Low Flight Idle
1453	287	0.0110	Staged	90	90	6.9	Low Flight Idle
1458	287	0.0108	Staged	90	90	6.9	Low Flight Idle
1500	287	0.0105	Staged	90	90	6.9	Low Flight Idle
1504	287	0.0110	Staged	70	70	5.8	Low Flight Idle
1506	287	0.0110	Staged	70	70	5.3	Flight Idle
1508	286	0.0116	Staged	70	70	5.1	Flight Idle
1510	286	0.0118	Staged	65	65	4.9	Flight Idle
1512	286	0.0115	Staged	65	65	5.3	Flight Idle
1514	286	0.0115	Staged	65	65	5.1	Flight Idle
1517	286	0.0117	Staged	80	80	5.1	Flight Idle
1520	286	0.0117	Staged	80	80	5.1	Flight Idle
1525	286	0.0116	0.0126	100	80	7.7	Flight Idle
1528	286	0.0114	0.0126	100	85	–	Flight Idle
1532	286	0.0116	0.0126	100	80	6.5	Flight Idle
1536	286	0.0114	0.0126	100	80	6.5	Flight Idle
1540	286	0.0114	0.0126	100	80	6.5	Flight Idle
1543	286	0.0114	0.0126	100	80	6.5	Flight Idle
1547	286	0.0117	0.0126	100	80	6.5	Flight Idle
1552	286	0.0104	0.0120	100	80	6.6	Ground Idle
1555	[illegible]	0.0104	0.0120	100	80	7.2	Ground Idle

APPENDIX C

REFERENCES

1. Environmental Protection Agency, "Control of Air Pollution From Aircraft and Aircraft Engines; Emission Standards and Test Procedures for Aircraft," Federal Register 38 (136) Part II: 19076, July 13, 1973.

2. Roberts, R., Peduzzi, A., and Vitti, G., "Experimental Clean Combustor Program," Phase I Final Report, NASA CR-134736, October 1975.

3. Sofrin, T., and Ross, D. A., "Noise Addendum Experimental Clean Combustor Program," Phase I Final Report, NASA CR-134820, October 1975.

4. Roberts, R., Peduzzi, A., and Vitti, G., " Experimental Clean Combustor Program," Phase II Final Report, NASA CR-134969, November 1976.

5. Roberts, R., Peduzzi, A. and Vitti, G. E., "Experimental Clean Combustor Program Phase II Alternate Fuels Addendum," NASA CR-134970, July 1976.

6. Sofrin, T. G., and Riloff, Jr., N., "Experimental Clean Combustor Program -- Noise Study," NASA CR-135106, September 1976.

7. Follansbee, P. S., and Dills, R. R. "Experimental Clean Combustor Program, Turbulence Characteristics of Compressor Discharge Flows," NASA CR-135277, 1973.

8. Fiorentino, A. J., Greene, W., and Roberts, R., "Evaluation of Federal Aviation Administration Engine Exhaust Sampling Rake," NASA CR-135213/FAA-RD-77-115, 1977.

9. Code of Federal Aviation Regulations, Part 33, "Airworthiness Standards: Aircraft Engines," Subpart E, Paragraph 33.73, Power or Thrust Response, January 1, 1974.

10. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines," SAE Aerospace Recommended Practice 1256, October 1971.