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EXPFRIMENTAL CLEAN COMBUSTOR PROGRAM

Phase III Final Report

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

The primary objectives of this three-phase program were to develop and demonstrate advanced technology combustors with significantly lower pollutant emission levels than those of current combustors. In Phase III, the Double Annular Combustor evolved in Phases I and II was evaluated in a series of CF6-50 engine tests.

Overall, this advanced, staged combustor and modified fuel control and supply components were found to operate satisfactorily at all test conditions. Engine lightoff was readily obtained and no difficulties were encountered with combustor staging. Engine acceleration and deceleration were smooth, responsive and essentially the same as those obtainable with the current production CF6-50 combustor. Significant gaseous emission level reductions, compared to the levels of the current production engine, were demonstrated. The emission reductions obtained in carbon monoxide, hydrocarbons, and nitrogen oxides levels were 55, 95, and 30 percent, respectively, at an idle power setting of 3.3 percent of takeoff power on an EPA parameter basis. Acceptable smoke levels were also obtained. The exit temperature distribution of the combustor was found to be its major performance deficiency. In all other important combustion system performance aspects, the combustor was found to be generally satisfactory.

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SUMMARY

This report describes the efforts performed and the results obtained in Phase III of the Experimental Clean Combustor Program. The primary objectives of this program were:

- To develop advanced technology combustors for current and future CTOL commercial aircraft turbine engines, with significantly lower pollutant emissions levels than those of current technology combustors;

- To demonstrate the pollutant emission reductions in an advanced commercial aircraft turbofan engine.

In Phase III, a Double Annular Combustor and new engine fuel control and supply components were first evaluated in component tests. Following these tests, the combustor and fuel control and supply components were evaluated in an extensive series of CF6-50 engine tests. In parallel with these efforts, work was also conducted on four program addenda. These addenda were the Turbulence Measurement Addendum, the Diesel No. 2 Fuel Addendum, the Noise Measurement Addendum, and the FAA Probe Validation Addendum. The results of these program addenda are presented in four separate reports.

In the Phase III component tests, the performance and operating characteristics of the Double Annular Combustor were found to be nearly the same as those of the Phase II prototype combustor configuration, and it met all development engine installation and assembly requirements. However, the carbon monoxide and hydrocarbons emission levels at engine idle operating conditions were found to be substantially higher than those of the Phase II prototype combustor. Following this finding, a series of diagnostic and development tests of the combustor was conducted in an effort to eliminate the cause of these higher emission levels. Some emission level reductions were realized, but levels equivalent to those of the Phase II prototype combustor were not obtained. It was determined that the differences in emission levels were due to small differences in the pilot stage and centerbody design details of the two combustor configurations and that disassembly of the demonstrator engine combustor and significant rework of some of its parts would be needed to eliminate these differences. Accordingly, it was decided to forego this rework and to proceed with the engine tests. However, it is fully expected that, with additional development effort, the carbon monoxide and hydrocarbons emission level deficiencies of the demonstrator engine combustor can be largely eliminated.

In the extensive series of CF6-50 engine tests, the Double Annular Combustor and the fuel control and supply components were found to operate very satisfactorily at all test conditions ranging from ground idle to takeoff

steady-state operating conditions. Engine lightoff was readily obtained and no difficulties were encountered with combustion staging between the pilot and main stages of the combustor. Overall, engine acceleration and deceleration were smooth and responsive at all operating conditions and were essentially the same as those of the current production CF6-50 engine. The demonstrator engine met the FAA requirement for acceleration from flight idle to full power within 5 seconds.

In the engine tests, significant emission level reductions, compared to those of the current production engine, were demonstrated. At the nominal CF6-50 engine idle power setting of 3.30 percent of takeoff power, EPA parameter values of 6.2, 0.3 and 5.7 lb/1000 lb thrust-hr were obtained for carbon monoxide, hydrocarbons, and nitrogen oxides, respectively. These levels represent, respectively, approximate reductions of 55, 90 and 30 percent, relative to the current production engine levels. At higher idle power settings, substantially greater reductions were demonstrated.

With these reductions, attainment of the program goal for carbon monoxide was demonstrated with an idle power setting of about 7.0 percent. However, based on the rig tests of the Phase II prototype combustor, it is fully expected that the carbon monoxide goal can also be met with an idle power setting of 3.3 percent, with some modifications to the Phase III combustor configuration. The hydrocarbon goal of the program was met with a margin, at an idle power setting of 3.3 percent. As expected from the rig test results, the nitrogen oxides goal was not met because of the high cycle pressure ratio of the CF6-50 engine. However, the nitrogen oxides level measured in the engine tests was only about 10 percent above the proposed new nitrogen oxides standard, applicable to the CF6-50 engine, as specified in the revisions to the existing standards proposed during 1978 by the Environmental Protection Agency. The measured smoke levels were higher than those obtained with the current production engine. However, the measured levels were in compliance with the applicable EPA smoke standard.

The major performance shortcoming of the Double Annular Combustor in the engine tests was its exit temperature distribution. Because the exit temperature pattern factor was higher and the peak of the radial exit temperature profile was more inboard than in the current production combustor, turbine stator and rotor distress occurred. Accordingly, improvement of the exit temperature distribution of this combustor represents an important development need. In essentially all other performance aspects, the Double Annular Combustor was found to be quite satisfactory. The measured combustor metal temperatures were well within the acceptable limits. Also, no carbon deposition or fuel nozzle coking problems were encountered.

The overall performance and emission results obtained in the demonstrator engine evaluations of the Double Annular Combustor were encouraging. However, considerable further development effort, especially in exit temperature distribution and fuel flow control to the combustor stages at other than sea-level-static operating conditions, will be needed before the Double Annular Combustor design concept can be utilized in operational engine applications.

INTRODUCTION

This report describes results of full-scale CF6-50 experimental engine tests conducted in Phase III of the NASA/General Electric Experimental Clean Combustor Program (ECCP). Installed in the experimental engine was a low pollutant Double Annular Combustor with associated fuel system and fuel control components which were derived in the prior ECCP Phases I and II.

In response to provisions of the Clean Air Act Amendments of 1970, the U.S. Environmental Protection Agency (EPA) conducted studies to assess the impact of aircraft engine pollutant emissions on air quality. Based on the results of those studies, the EPA concluded that standards regulating the quantities of carbon monoxide (CO), unburned or partially oxidized hydrocarbons (HC), oxides of nitrogen (NO_x), and smoke emissions discharged by aircraft, when operating within or near airports, are needed. Based on this finding, standards were defined for several different categories and types of fixed-wing commercial aircraft engines, and were issued in July 1973 (Reference 1). In the case of existing large subsonic commercial aircraft engines, such as the General Electric CF6 engines, smoke standards became effective in January 1976. Gaseous emission standards were to become effective in January 1979. In 1978 the EPA issued a Notice of Proposed Rulemaking which revises some of the levels or effective dates of the standards promulgated in 1973 (Reference 2).

As a result of government and industry efforts initiated more than 13 years ago, significant advances have been made in the development of smoke abatement technology for use in aircraft turbine engines. The modern aircraft turbine engines which have been introduced into service during this decade generally operate with low smoke levels. The General Electric CF6 engines, for example, operate with virtually invisible smoke levels at all power settings. These new engines are already in compliance with the smoke standards. However, compliance with the gaseous emission standards requires large reductions in the emission levels of all current technology engines. Major combustor design technology advances are needed to obtain significant reductions in gaseous pollutant emission levels.

To provide these needed combustor design technology advances, the ECCP was initiated by NASA in 1972 (Reference 3). The overall objectives of this major program were to define, develop, and demonstrate the technology of low pollutant emission combustors for use in advanced commercial CTOL aircraft engines with high cycle pressure ratios in the range of 20 to 35. However, it is also intended that this technology be applicable to advanced military aircraft engines. Because the smoke emission levels of advanced commercial and military aircraft engines have already been reduced to low values, the primary ECCP focus was on reducing the CO, HC, and NO_x emission levels of these engines.

The NASA/GE ECCP was one of the programs that comprised the overall program. The work effort was initiated in January 1973 and was conducted in three phases. The design and development efforts of this NASA/GE program were specifically directed toward providing advanced combustors for use in the General Electric CF6-50 engine. While the CF6-50 engine is the specific intended application of the advanced combustor technology development efforts of this program, this technology is also intended to be generally applicable to all advanced engines in the large thrust size category. Phase III of this overall program is the subject of this report. The results of Phases I and II are presented in References 4 through 9. The key objective of Phase III was to evaluate in CF6-50 demonstrator engine tests the Double Annular Combustor (the combustor concept evolved in this program). This report presents the detailed results of the CF6-50 engine tests of the Double Annular Combustor. Also included are the results of the combustor component tests that were conducted prior to the engine tests.

The detailed results of four Phase III addenda - the Turbulence Measurement Addendum, the Diesel No. 2 Fuel Addendum, the Noise Measurement Addendum, and the FAA probe Validation Addendum - are presented in References 10 through 13 respectively.

CHAPTER I

EXPERIMENTAL CLEAN COMBUSTOR PROGRAM DESCRIPTION

A. OVERALL PROGRAM DESCRIPTION

The Experimental Clean Combustor Program was a multiyear effort conducted by the NASA-Lewis Research Center. The primary program objectives were:

- To generate the technology required to develop advanced commercial CTOL aircraft engines with significantly lower pollutant exhaust emission levels than those of current technology engines.

- To demonstrate the low pollutant emission levels in tests of advanced commercial aircraft turbofan engines.

The intent of this major program was to reduce pollutant emission levels by development of advanced combustor designs, rather than by the use of special operational techniques and/or water injection methods. The program was aimed at generating technology which is primarily applicable to advanced commercial CTOL aircraft engines with high cycle pressure ratios in the range of 20 to 35. However, it was also intended that this technology be applicable to advanced military aircraft engines. Because the smoke emission levels of advanced commercial and military aircraft engines had already been reduced to low values, the primary focus of the program was on reducing the levels of the gaseous emissions.

The NASA/General Electric Experimental Clean Combustor Program was one of the programs that comprised the overall effort. It was conducted by the General Electric Aircraft Engine Group under contract to the NASA-Lewis Research Center. The design and development efforts were directed toward providing advanced combustors for use in the General Electric CF6-50 engine. While the CF6-50 engine is the specific intended application of the advanced combustor technology development efforts of this program, this technology should also be applicable to all advanced engines in the large thrust size category.

B. PROGRAM PLAN

The Experimental Clean Combustor Program was conducted in three sequential, individually funded phases:

Phase I: Combustor Screening

Phase II: Combustor Refinement and Optimization

Phase III: Combustor-Engine Testing

1. Phase I Program

The Phase I Program was an 18-month effort specifically directed toward screening a variety of combustor design approaches. The objective was to identify and develop the most promising combustor design approaches for obtaining pollutant exhaust emission level reductions. Phase I Program efforts involved the definition of four advanced combustor design approaches, the detailed aeromechanical design of CF6-50 engine-size versions of these approaches, the fabrication of full annular combustors, and pollution/performance evaluation tests. Configurations were evaluated in a test rig that exactly duplicates the aerodynamic flowpath and envelope dimensions of the combustor housing of the CF6-50 engine, at operating conditions identical to those of the CF6-50 engine except for pressure level. That parameter was restricted to 0.965 MPa or less due to test facility limitations. In these tests detailed measurements of the emission and performance characteristics of each combustor configurations were obtained.

In conjunction with Phase I, additional efforts were also carried out in two program addenda: the Advanced Supersonic Transport (AST) Addendum and the Combustion Noise Measurement Addendum. The purpose of the AST Addendum was to develop combustor design technology for reducing the NO_x emission levels of AST engines at supersonic cruise operating conditions by applying and extending the results of the basic program investigations. The purpose of the Combustion Noise Measurement Addendum was to obtain experimental data on the acoustic characteristics of these advanced low emission combustors, thereby enabling comparisons of their noise characteristics with those of current technology combustors.

Detailed descriptions and results of the Phase I Program and the AST Addendum are presented in Reference 4. Combustor Noise Measurement Addendum results are presented in Reference 5.

2. Phase II Program

The Phase II Program was a 15-month effort to further develop the most promising advanced combustor designs evolved in the Phase I Program. The Double Annular Combustor and the Radial/Axial Staged Combustor design approaches were selected for development in the Phase II Program. Phase II efforts included both full annular and sector combustor component tests, detailed aeromechanical design of versions of these combustors for possible use in Phase III CF6-50 engine tests, and the design of a breadboard engine fuel control system. The primary objectives of these design and development efforts were to provide advanced combustor designs which would meet the performance and installation requirements of the CF6-50 engine and that would approach the low pollution emission levels goals of the program.

In conjunction with the Phase II Program, additional efforts were also carried out in two program addenda: the Noise Measurement Addendum and the Alternate Fuels Addendum. The purpose of the Noise Measurement Addendum was to obtain additional experimental data on the acoustic characteristics of these low emission combustors and make direct comparisons of their noise characteristics with those of the current production CF6-50 combustor. The purpose of the Alternate Fuels Addendum was to obtain experimental data on the effect of relaxed fuel specifications, such as final boiling point and hydrogen content, on the pollutant emission levels and performance characteristics of low emissions combustors and the current production CF6-50 combustor.

Detailed descriptions and results of the Phase II Program are presented in Reference 6, and a summary of the Phase I and Phase II Programs is presented in Reference 7. Descriptions and results of the two addenda presented in References 8 and 9 respectively.

3. Phase III Program

The Phase III Program was a 27-month effort consisting of detailed evaluations of the most promising Phase II Program combustor design in a demonstrator CF6-50 engine. The objective was to demonstrate significant pollutant reductions with an advanced combustor which meets the performance, operational, and installation requirements of the engine. The combustor incorporated all of the aero-thermal design features that evolved in the Phase II Program, together with advanced mechanical and installation features derived from other General Electric combustor programs. General Electric furnished the required combustor parts, engine components, and fuel supply/control components from another program.

The primary intent of the engine tests was to evaluate those performance and operating characteristics of this advanced two-stage combustion system which could not be evaluated in component tests. In the engine tests steady-state performance, pollutant emission data, and acceleration and deceleration characteristics of the engine were determined.

In conjunction with the Phase III Program, additional efforts were carried out in four program addenda: the Turbulence Measurement Addendum, the Diesel No. 2 Fuel Addendum, the Noise Measurement Addendum, and the FAA Probe Validation Addendum. The purpose of the Turbulence Measurement Addendum was to characterize the turbulence scale and intensity in the compressor dis charge airflow of the CF6-50 engine. The purpose of the Diesel No. 2 Fuel Addendum was to obtain additional data on the effects of relaxed fuel specifications in engine tests with the Double Annular Combustor. The purpose of the Noise Measurement Addendum was to obtain additional data on the acoustic characteristics of low emission combustors in engine tests. The purpose of FAA Probe Validation Addendum was to validate the design of an engine emissions sampling probe developed by the FAA.

Detailed descriptions and results of the Phase III Program are presented in Chapters II through IV of this report. Descriptions and results of the four addenda are presented in References 10 through 13, respectively.

C. PROGRAM SCHEDULE

The overall schedule plans of the NASA/General Electric Experimental Clean Combustor Program are presented in Figure 1.

D. PROGRAM GOALS

1. Pollutant Emission Level Goals

The pollutant emissions goals with the status levels of the current production CF6-50 engine are presented in Table 1. As shown by this comparison, attainment of these goals involves significant pollutant emission level reductions. The goals were intended to be optimistic projections of the attainable pollutant emission level reductions. The intent of the program was to generate advanced combustor design technology rather than to verify already available combustor design technology. Further, the use of water injection into the combustor to obtain lower NO_x emissions levels was specifically excluded as an approach to be considered in the program.

2. Combustor Performance Goals

The key combustor performance goals are presented in Table 2. Except for combustion efficiency levels at low engine power operating modes, the current production CF6-50 engine combustor already provides performance levels equal to or better than the goals. Thus, the major challenge of this program was to develop advanced combustor designs which significantly reduce pollution levels without compromising performance characteristics. The current CF6-50 engine does not achieve the 99 percent combustion efficiency goal at the idle operating mode. This goal is specified as 99.0 percent to be consistent with the CO and HC emission level goals.

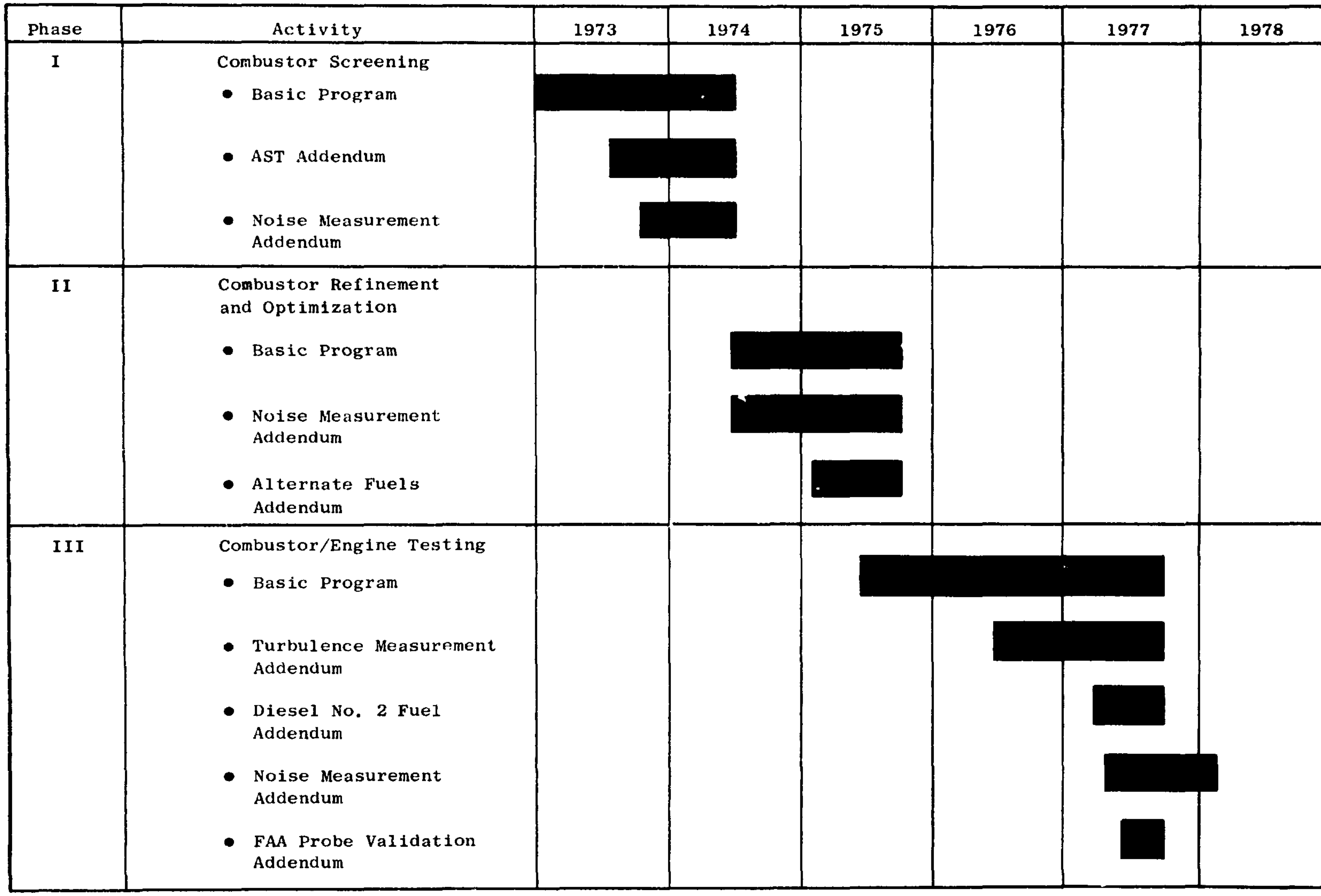


Figure 1. NASA/General Electric Clean Combustor Program Schedule.

Table 1. Pollutant Emissions: Goals and Current CF6-50C Engine Status.

- Prescribed Class T2 Engine Takeoff/Landing Cycle

Pollutant Emission		Program Goal*	Current CF6-50C Engine Status**
NO_x (as NO_2)	lb/1000 lb Thrust-Hour	3.0	7.7
CO	lb/1000 lb Thrust-Hour	4.3	14.9
HC (as CH_4)	lb/1000 lb Thrust-Hour	0.8	8.0
Smoke Maximum SAE Number		19	12

* Same as EPA 1979 Class T2 engine standards in Reference 1.

** Idle Thrust 3.31 percent of takeoff thrust.

Table 2. Combustor Performance Goals of the NASA/General Electric Experimental Clean Combustor Program.

Performance Parameter	Engine Operating Mode	Program Goal
Minimum Combustor Efficiency	All	99.0%
Maximum Pressure Drop	Cruise	6.0%
Maximum Exit Temperature Pattern Factor	Takeoff and Cruise	0.25%
Altitude Relight	Windmilling	Meet CF6-50 Engine Relight Envelope
Mechanical Durability	All	Equivalent to Current CF6-50 Combustor

CHAPTER II

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A. REFERENCE ENGINE/COMBUSTOR DESCRIPTION

1. Reference Engine Description

The NASA/General Electric Experimental Clean Combustor Program has been specifically directed toward developing an advanced low-emission combustor for use in the General Electric CF6-50 engine family. The CF6-50 engine family is the higher-power series of the two CF6 high bypass turbofan engine families which have been developed by General Electric. The other one is the CF6-6 engine family. Models of the CF6-50 engine family are in commercial service as the powerplants for the McDonnell Douglas DC-10 Series 30 aircraft, the Airbus Industrie A300B aircraft, and the Boeing 747-200 aircraft.

The CF6-50 engine is a dual-rotor, high bypass ratio turbofan engine incorporating a variable-stator, high pressure ratio compressor, an annular combustor, an air-cooled core engine turbine, and a coaxial front fan with a low pressure compressor driven by a low pressure turbine. The engine is designed to be disassembled into major components and modules for ease of maintenance. Basically, the engine consists of a fan section, compressor section, combustion section, turbine section, and accessory drive sections. The major features of the engine are shown in Figure 2.

The CF6-50C engine model operating parameters were selected for use as the combustor design and test conditions of this program. Key overall specifications of this engine are presented in Table 3.

2. Reference Combustor Description

The combustor configuration used in production CF6-50 engines is a high-performance design with demonstrated low exit-temperature pattern factors, low pressure loss, high combustion efficiency, and low smoke emission at all operating conditions. A cross-sectional drawing of this combustor, as installed in the engine is shown in Figure 3. The key features of this combustor are its low-pressure-loss step diffuser, its carbureting swirl-cup dome design, and its short burning length. The short burning length reduces the amount of liner cooling air required. More air is thus available to control exit temperature pattern and profile factors. The step diffuser design provides very uniform, steady airflow distributions into the combustor.

This combustor contains 30 vortex-inducing axial swirl cups, one for each fuel nozzle. The combustor consists of four major sections that are

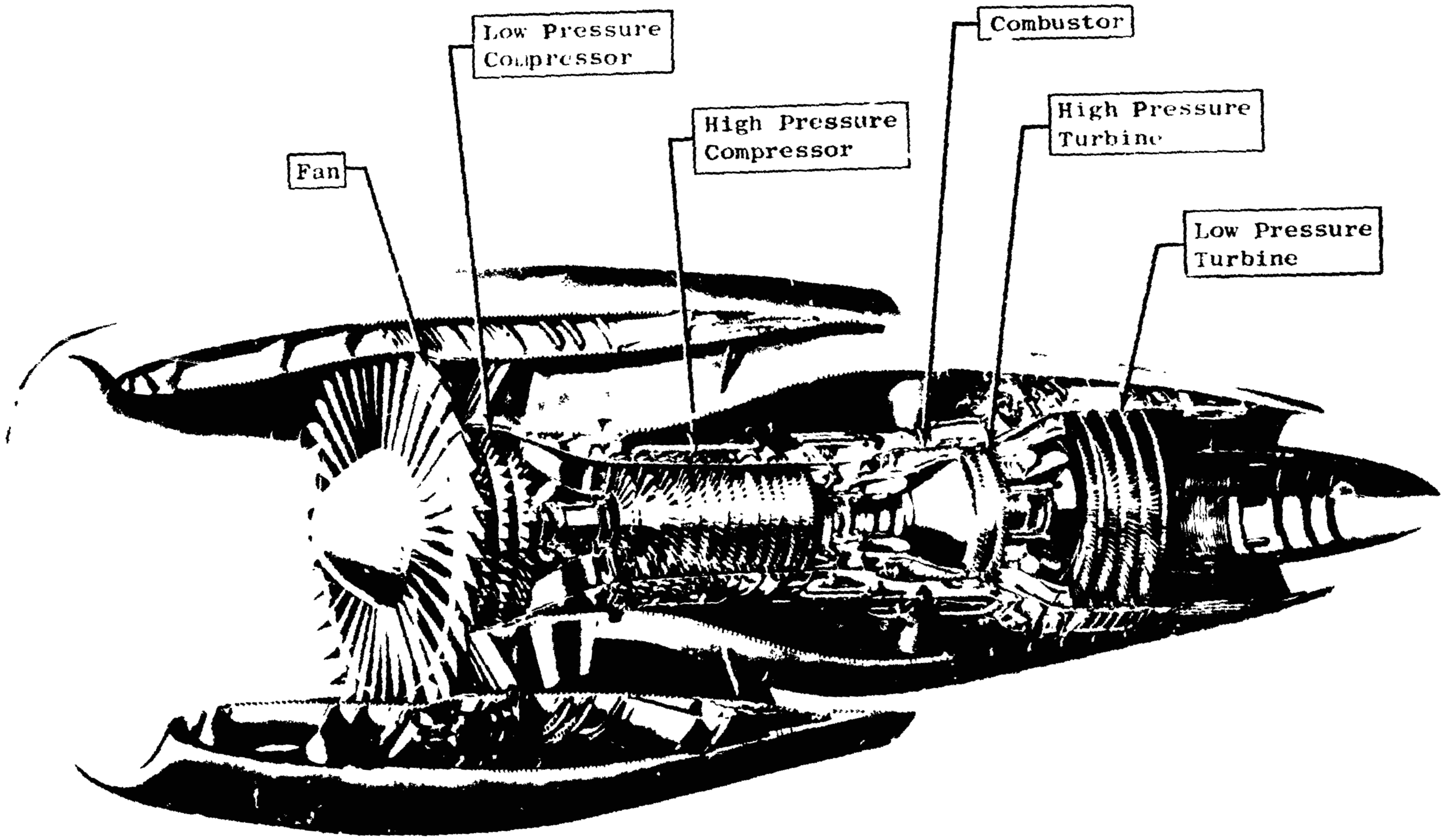


Figure 2. General Electric CF6-50 High Bypass Turbofan Engine.

Table 3. CF6-50C Engine Specifications.

Takeoff Rating (SLS)	
Thrust	224.2 kN (50,400 lbf)
Specific Fuel Consumption	10.7 g/kN-s (0.0377 lbm/lbf-hr)
Maximum Cruise (Mach 0.85/10.7 km)	
Thrust	48 kN (10,8000 lbf)
Specific Fuel Consumption	18.6 g/kN-s (0.656 lbm/lbf-hr)
Weight	3780 kg (8330 lb)
Length	482 cm (190 in)
Maximum Diameter	272 cm (107 in)
Pressure Ratio	
Takeoff	29.4
Maximum	31.4
Bypass Ratio (Takeoff)	4.4
Total Airflow (Takeoff)	659 kg/s (1452 lbm/s)

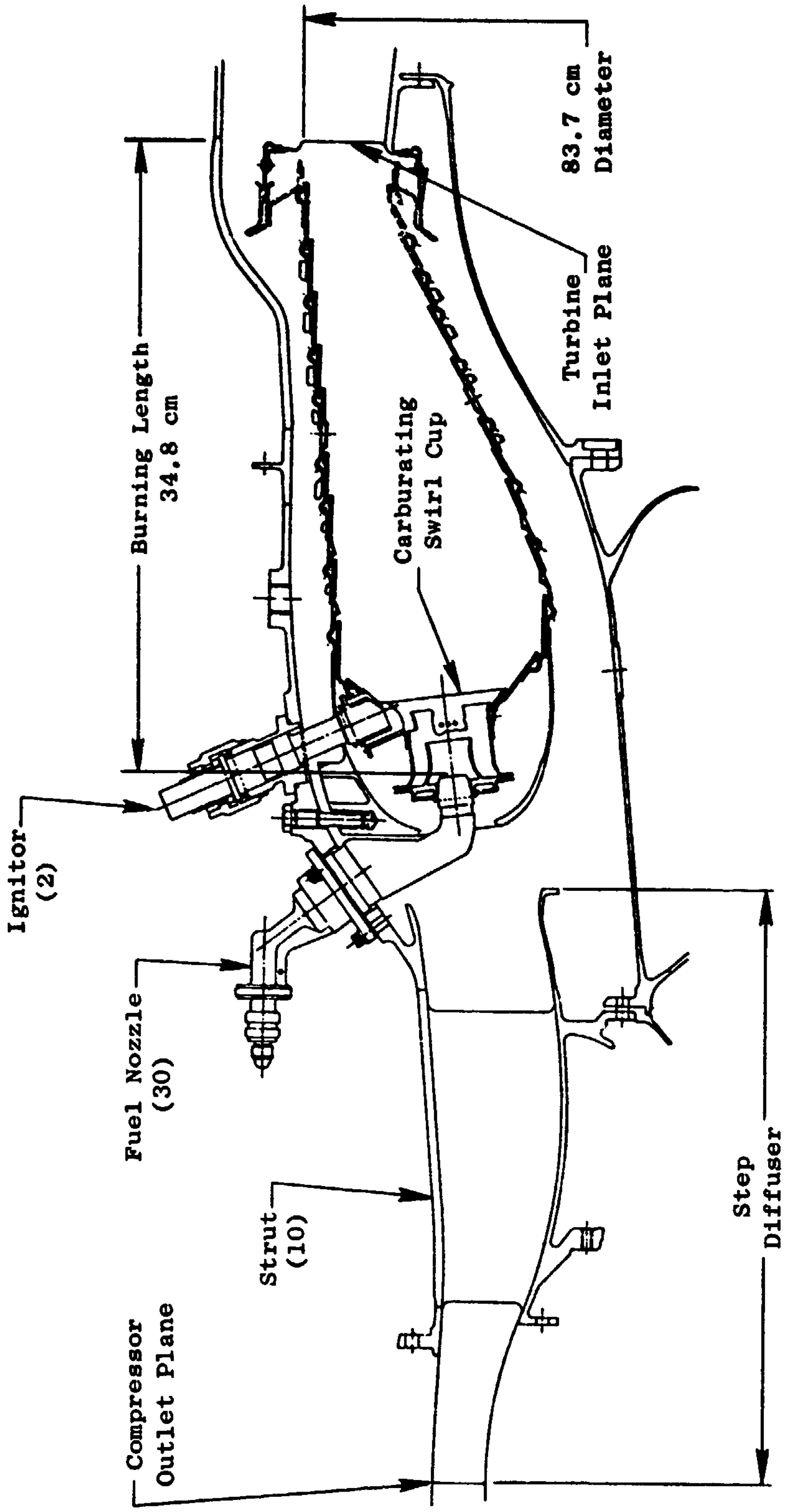


Figure 3. Production CF6-50 Engine Combustor.

riveted together into a single unit and spot welded to prevent rivet loss: the cowl assembly, the dome, and the inner and outer liners. The liners each consist of a series of circumferentially stacked rings that are joined by resistance-welded and brazed joints. The liners are film cooled by air that enters each ring through closely spaced circumferential holes. Three axial planes of dilution holes on the outer liner and five planes on the inner liner are employed to promote additional mixing and lower the combustor exist temperatures. Key design and performance parameters of this CF6-50 combustor are presented in Table 4. Combustor exit profile characteristics are shown in Figure 4.

3. Reference Engine Combustor Pollutant Emission Levels

Representative pollutant emission levels of the production CF6-50C engine equipped with the standard production combustor are presented in Table 5. These data were taken from a series of engine tests and have been corrected to production CF6-50C engine standard-day operating conditions.

The CF6-50 production combustor was originally designed and developed to meet low smoke emission requirements, and to provide virtually invisible plumes. As shown in Table 5-A, the levels are well below the allowable limits at all operating conditions. However, the combustor was designed and developed before gaseous pollutant emission standards were established. As shown in Table 5-B, significant reductions are required to meet the EPA standards. The gaseous emission levels, however, compare very favorably with other current technology production combustor designs, particularly when engine cycle conditions such as idle thrust and overall pressure ratio are considered.

B. TEST COMBUSTORS

1. Double Annular Low Emission Combustor Concept

In the Phase I and II Programs, four advanced combustor design concepts were evaluated in CF6-50 engine-size full annular combustor rig tests (References 1 and 3). The best results were obtained with the Double Annular combustor configuration D12, shown in Figure 5, which was the prototype for the Phase III demonstrator Double Annular combustor. The Double Annular combustor comprises two annular concentric burning zones, separated by a short centerbody. Thirty fuel nozzles are used in each annulus. The outer annulus is the pilot stage as is fueled at all engine operating conditions. The inner annulus is the main stage and is fueled only at high-engine-power operating conditions. The airflow distribution is highly biased to the main stage in order to reduce both idle and high-power emissions. The pilot-stage airflow is specifically sized to provide nearly stoichiometric fuel-air ratios and long residence times at idle power settings, thereby minimizing CO and HC emissions levels. At high-power operating conditions, most of the fuel is supplied to the main stage. In this stage, the residence times are very short. Also, at high-power operating conditions, lean fuel-air ratios are maintained in both stages to minimize NO_x and smoke emission levels.

Table 4. Production CF6-50 Combustor Parameters.

Key Dimensional Parameters	
Overall System Length (OGV to TND)	76.0 cm
Burning Length (Fuel Nozzle tip to TND)	34.8 cm
Dome Height/Area	11.4 cm/2440 cm^2
Reference Passage Height/Area	18.0 cm/3730 cm^2
Key Standard-Day Takeoff Parameters	
Compressor Exit Mach Number	0.27
Reference Velocity	25.5 m/s
Total Pressure Drop (Including Diffuser)	4.3%
Temperature Rise ($T_{4\ avg} - T_3$)	790 K
Exit Temperature Factor ($T_{4\ max} - T_3$)/($T_{4\ avg} - T_3$)	
Profile Factor (Circ. Avg Max)	0.09
Pattern Factor (Local Max)	0.25
Combustion Efficiency	>99.9%

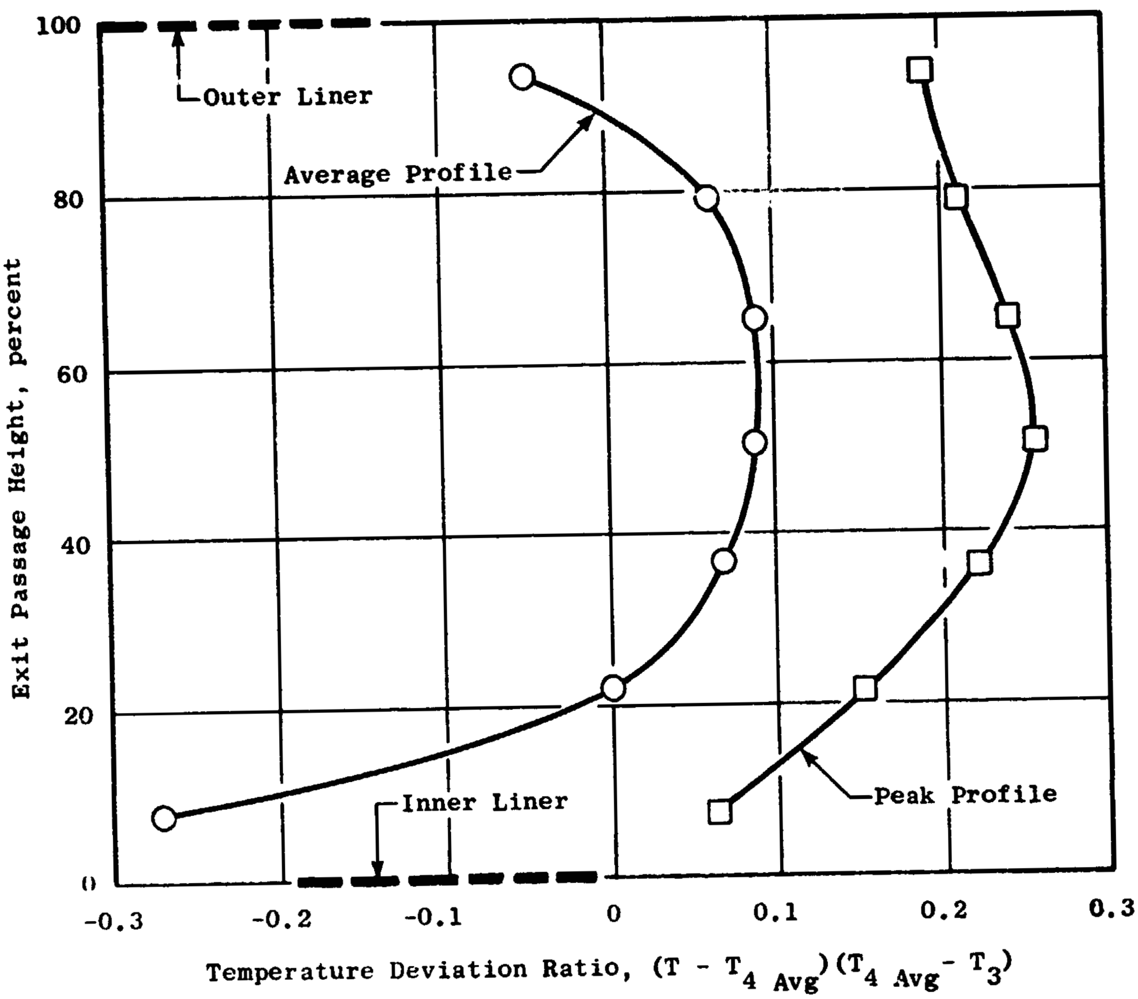


Figure 4. Typical Exit Temperature Profile Characteristics of the CF6-50 Production Combustor.

Table 5. Reference CF6-50C Production Engine Pollutant Emission Levels.

- Kerosene Fuel
- Standard-Day Operating Conditions (Ambient Humidity = 6.3 g/kg)

A. Emission Indices

Engine Operating Mode	NO_x (as NO_2) g/kg Fuel	CO g/kg Fuel	HC (as CH_4) g/kg Fuel	SAE Smoke No.
Std Idle (3.3% F_N, Full Burning) (No Bleed)	3.1	107.0	58.9	$\leq$12
Approach 30.0% F_N)	12.0	3.9	0.7	$\leq$ 5
Climbout (85.0% F_N)	29.1	0.8	0.1	$\leq$ 6
Takeoff (100.0% F_N)	33.9	0.7	0.1	$\leq$ 7

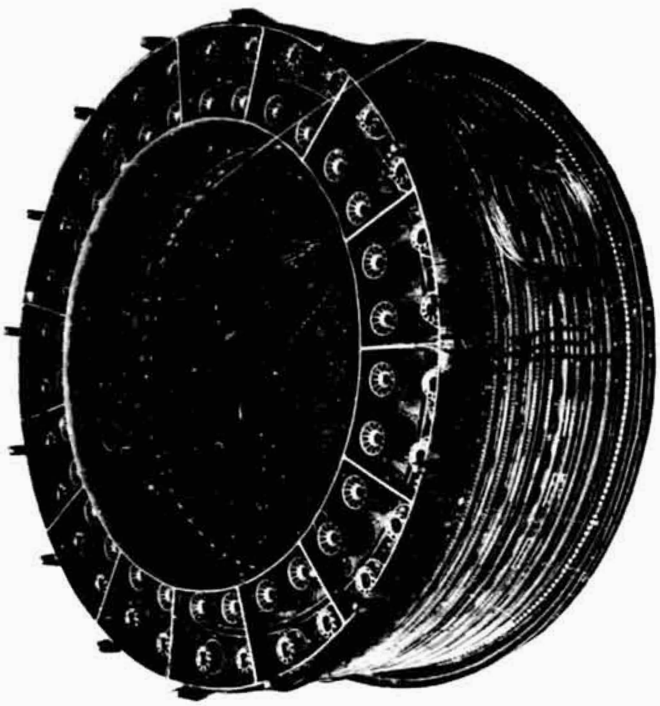
B. EPA Emission Parameters

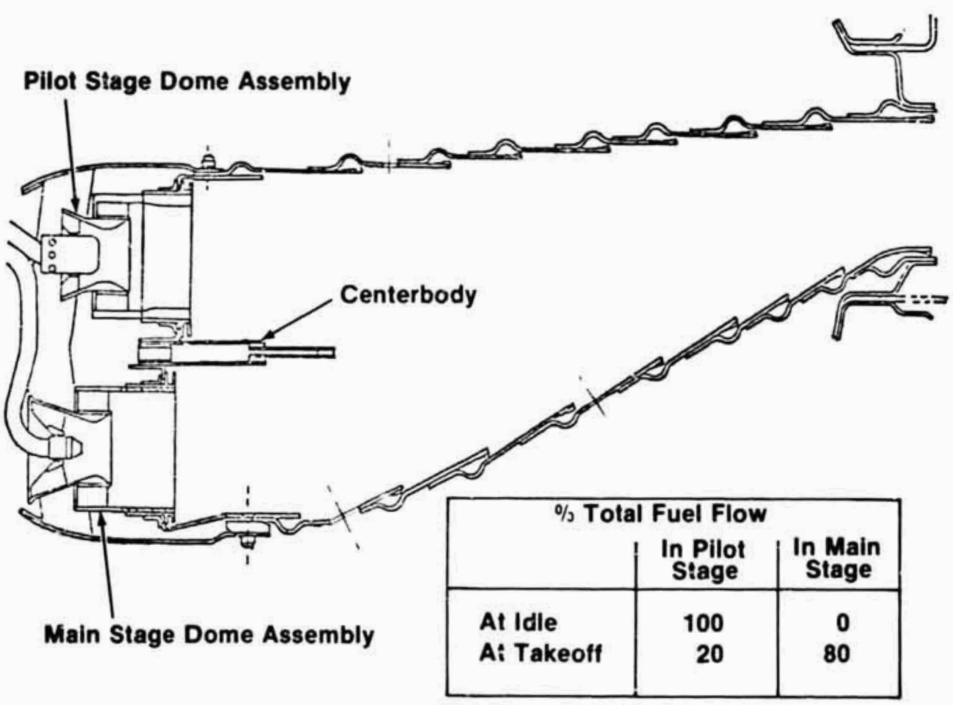
1. Current 1979 Standards Calculation Method (cycle thrust-hour weighted)

		CF6-50	1979 Std
NO_x (as NO_2)	lb/1000 lb thrust-hr	7.7	3.0
CO	lb/1000 lb thrust-hr	14.9	4.3
HC (as CH_4)	lb/1000 lb thrust-hr	8.0	0.8

2. Draft 1981 Standards Calculation Method (takeoff thrust weighted)

		CF6-50	1979 Std
NO_x (as NO_2)	g/kN	60.4	39.3
CO	g/kN	117.6	36.1
HC (as CH_4)	g/kN	63.3	6.7





% Total Fuel Flow	In Pilot Stage	In Main Stage
At Idle	100	0
At Takeoff	20	80

Figure 5. Prototype Double Annular Combustor (Phase II Configuration D12).

2. Engine Demonstrator Combustor Design

The Double Annular combustor concept achieved program goals for CO and HC emissions at idle operating conditions early in the Phase II Program. As shown in Figure 6, these low levels of idle emissions were maintained throughout the combustor refinement test series. NO_x emission levels, shown in Table 6, did not meet the goal. The engine installation and performance requirements were most nearly met with configuration D12, which was selected as the prototype for the Phase III demonstrator engine combustor. A second-generation Phase III combustor configuration was needed because the prototype configuration used in Phases I and II was designed for component testing. As such, the features incorporated into this design to accommodate differential thermal growths, pressure loads, vibration loads, and mechanical assembly were not adequate to permit its use in engine tests.

The resulting demonstrator engine combustor design is shown in Figure 7. The aerothermal design features of this demonstrator engine combustor were patterned after those of the prototype combustor. Advanced aeromechanical design features derived from other General Electric programs were incorporated into its design. Machined-ring cooling-air slots were used throughout the dome and liners for improved cooling air effectiveness. Included in the mechanical arrangement were features for adequate thermal growth, assembly, and mechanical stiffness. With this design, both the pilot- and main-stage fuel nozzles can be installed through the existing fuel nozzle ports of the engine, wtih the combustor installed. This important design feature permits the existing engine outer casing to be used without modification. The main-stage fuel nozzles are connected to the existing engine fuel manifold. The pilot-stage fuel nozzles are connected to a new fuel manifold.

Key aerothermal design parameters of the two Double Annular combustors are compared in Table 7. Airflow distributions are very similar except that the demonstrator combustor dome cooling airflows are slightly higher. This is accomplished primarily by reducing profile trim airflow. Key velocities are also very similar except that inner and outer passage velocities of the demonstrator combustor are more nearly equalized to reduce parasitic pressure losses. Dome heights of the demonstrator combustor were increased about 20 percent to provide additional room within the cowl to accommodate the needed radial movements of the swirl-cup slip joints. Additional details of the swirl cup and dome construction are shown in Figures 8 and 9. Details of one of the crossfire slots in the centerbody are shown in Figure 10. Two of these slots located 180° apart were incorporated into the demonstrator combustor design to provide a positive flame path from the pilot stage for main-stage ignition.

Demonstrator engine combustor fuel nozzles are shown in Figure 11. Advanced aeromechanical design features derived from other General Electric programs were incorporated into the fuel nozzle design. The fuel nozzle tips incorporate air shrouds of the type in use with the production fuel nozzles to aid in fuel atomization and prevent carbon buildup. The fuel nozzle stems are designed with natural vibratory frequencies well above the range of engine

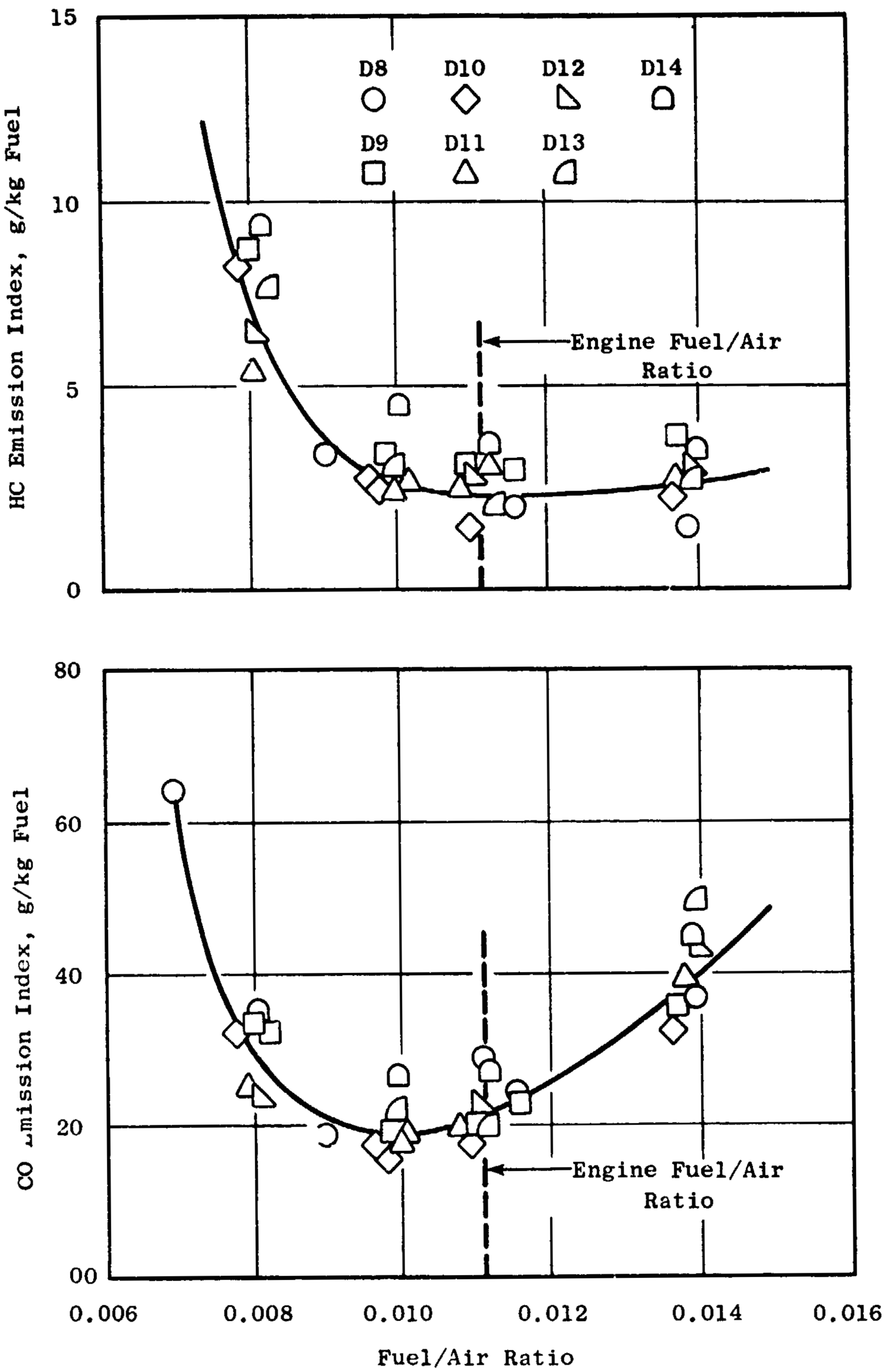


Figure 6. Phase II Prototype Double Annular Combustor - Idle Emission Characteristics.

Table 6. NO_x Emission Level Comparison, Phase II Prototype Double Annular Combustor Configurations.

Configuration Number	EI_{NO_x} at Takeoff (1) g/kg
D8	20.2
D9	19.7
D10	19.8
D11	20.3
D12	20.2
D13	18.8 (2)
D14	22.0 (3)
Current Production	33.9
ECCP Goal	10.0

(1) Corrected to current CF6-50C production engine cycle standard-day takeoff operating conditions.

(2) No profile trim air, high pressure drop.

(3) Increased liner cooling air, low pressure drop.

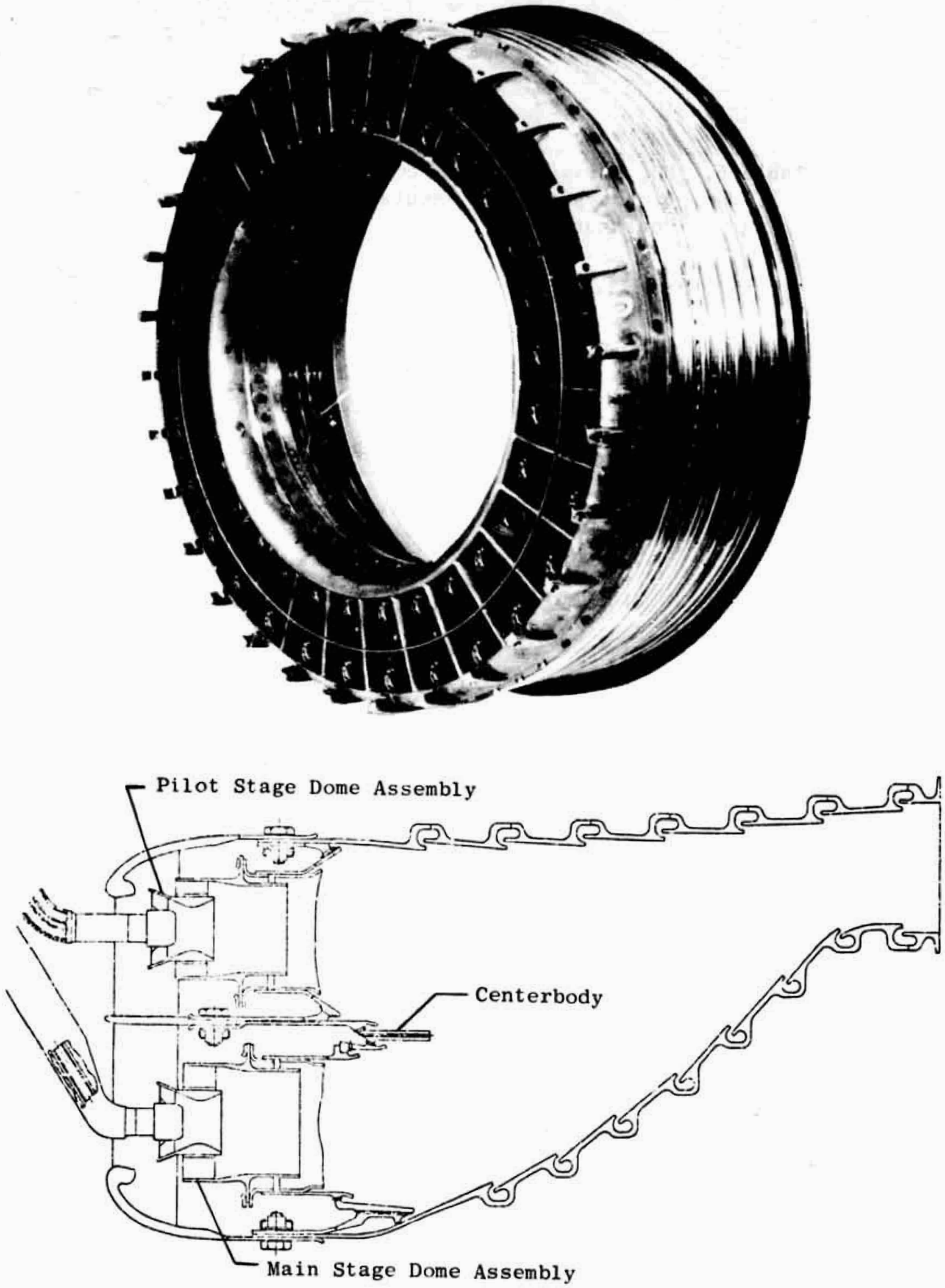


Figure 7. Phase III Demonstrator Double Annular Combustor.

Table 7. Double Annular Combustor Design Parameters.

	Phase II Prototype Combustor (D12)	Phase III Demonstrator Combustor
Airflow Distribution, % W_C		
Pilot Stage		
Swirlers	13.4	12.6
Dilution, Second Outer Panel	4.7	4.5
Dome Cooling	4.5	7.2
Main Stage		
Swirlers	33.1	33.0
Dilution, First Inner Liner Panel	10.8	10.6
Dome Cooling	4.1	5.4
Centerbody and Liner Cooling	23.1	23.3
Profile Trim	4.8	2.0
Aft Seal Leakage	1.5	1.4
	100.0	100.0
Key Velocities, m/s		
Pilot Stage Dome	11	10
Main Stage Dome	29	29
Outer Passage	24	37
Inner Passage	59	46
Reference	26	23
Key Dimensions, cm		
Pilot Stage Dome Height	5.7	7.1
Main Stage Dome Height	5.3	6.1
Combustion Length	32.5	32.5

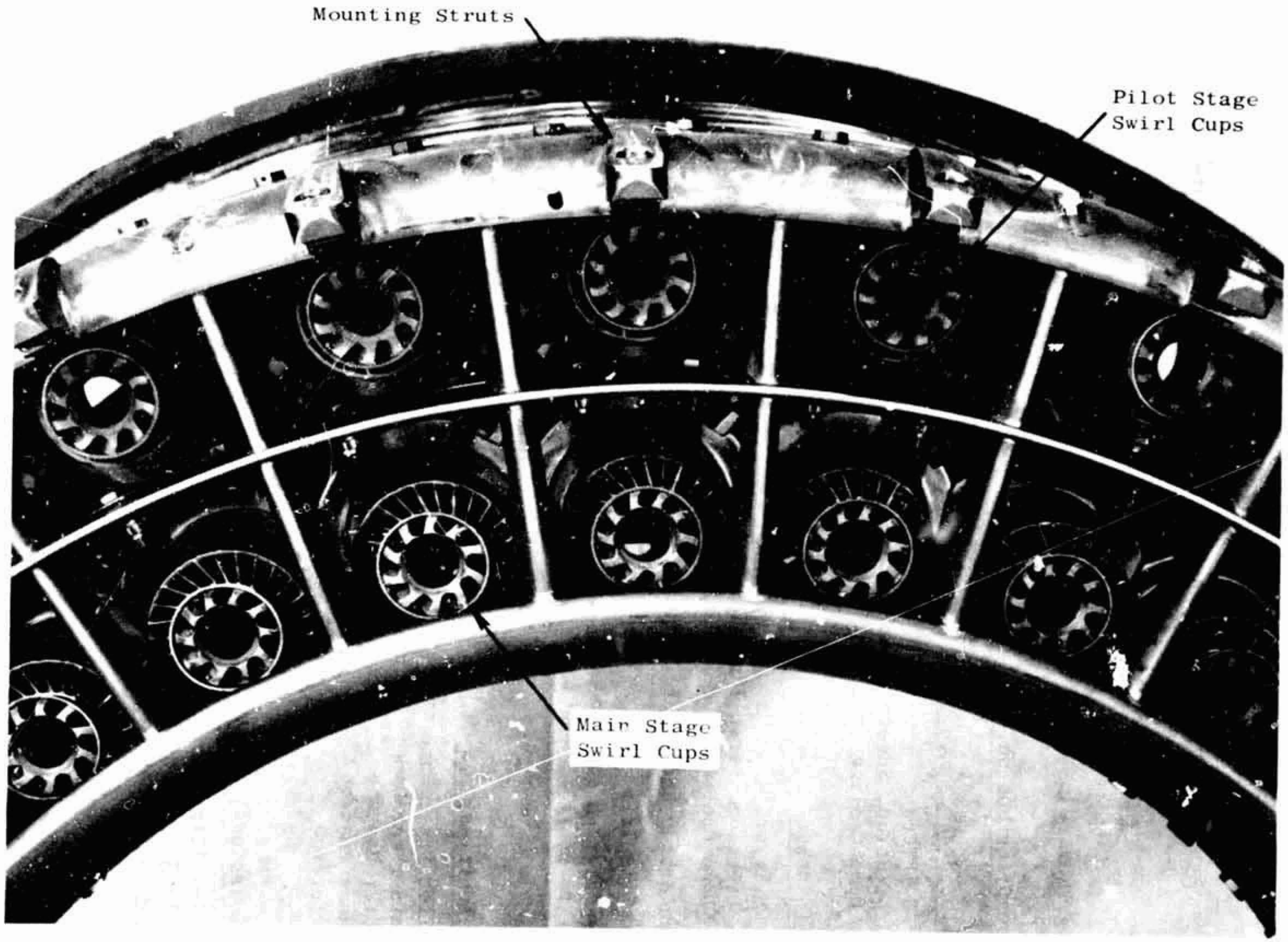


Figure 8. Demonstrator Combustor Overall Dome Details, Forward Looking Aft.

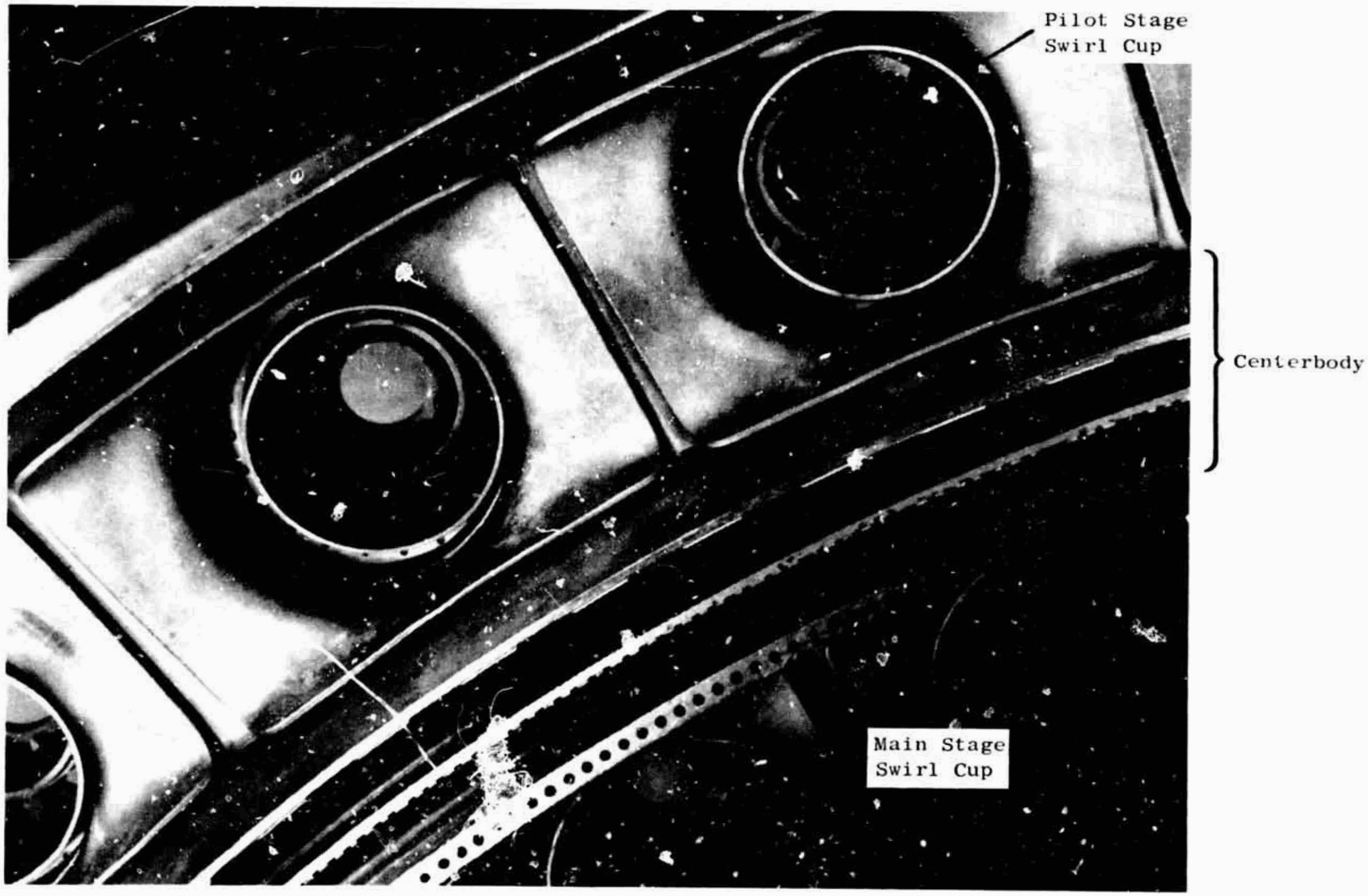


Figure 9. Demonstrator Combustor Pilot Stage Dome Details, Aft Looking Forward.

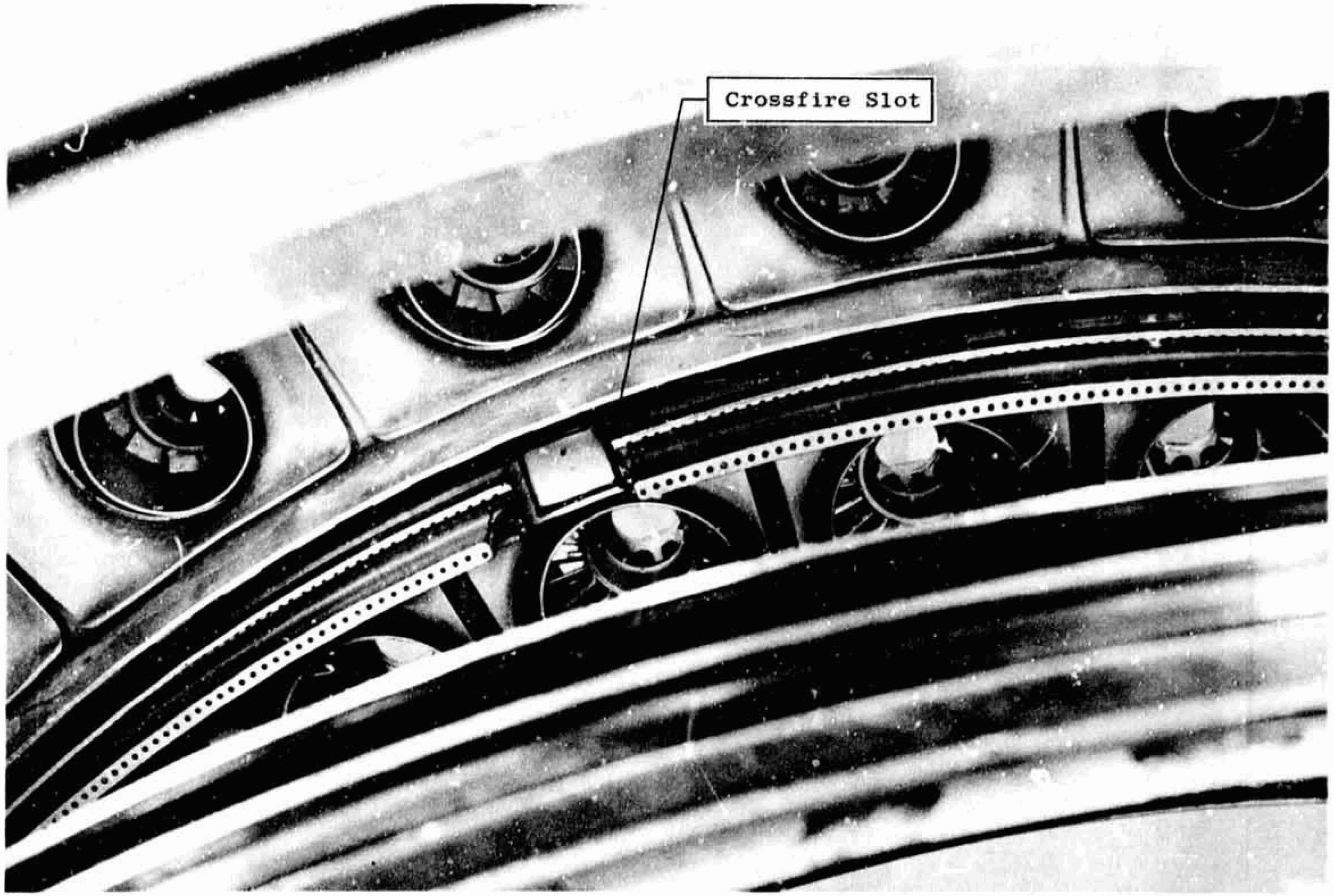
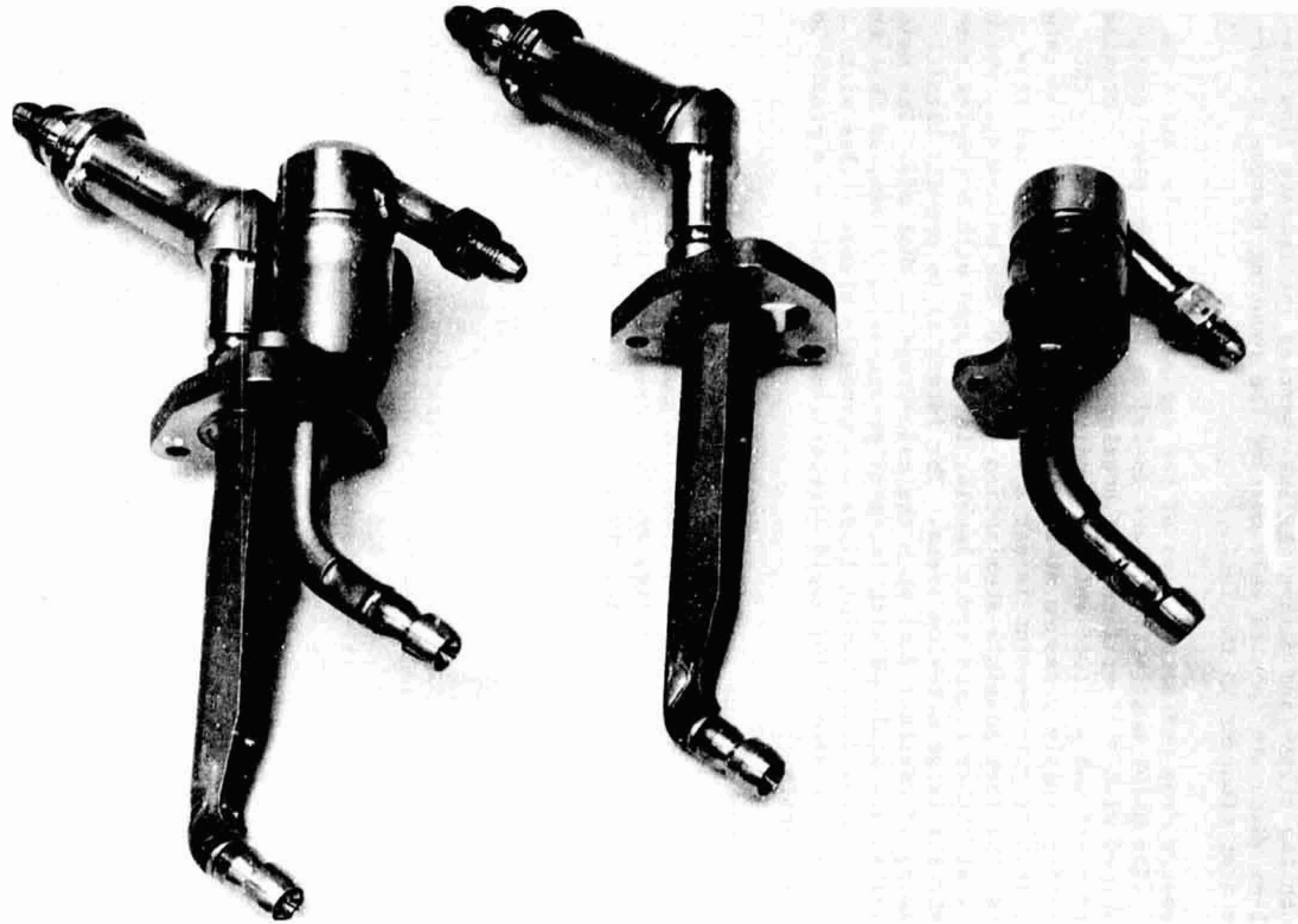


Figure 10. Demonstrator Combustor Centerbody/Crossfire Slot Detail, Aft Looking Forward.



Main and Pilot Stage Assembly — Main Stage — Pilot Stage

Figure 11. Engine Fuel Nozzles.

frequencies to prevent resonance. . stems are aerodynamically contoured in cross section to minimize pressure losses and incorporate double wall construction to minimize heat transfer from the hot compressor discharge air to the fuel. Both the pilot- and main-stage fuel nozzles incorporate flow distribution valves which are located well outside the mounting flanges to further minimize heat transfer to the fuel.

Flow-pressure drop characteristics of the engine fuel nozzles are shown in Figure 12. The pilot nozzles which are fueled at all engine power conditions are equipped with dual-orifice fuel nozzles to provide adequate atomization at ground start and altitude relight conditions without exceeding the current engine fuel supply pressure at the maximum pilot-stage fuel flow rate. The secondary orifice cut-in-point is set above the nominal idle fuel flow rate to provide the best possible atomization at idle. The main-stage, which is fueled only at higher engine power levels, is equipped with a simplex nozzle with relatively large metering areas. The intent is to prevent harmful carbon or gumming of residual fuel when the main-stage is shut off. The main-stage fuel nozzles are equipped with integral pressurizing valves, so that the main-stage manifold and distribution lines are normally always filled with fuel. This feature is needed for rapid acceleration from idle or approach to full power requirements.

Engine simulator fuel nozzles shown in Figure 13 were designed for use in rig tests. These nozzles duplicate the fuel spray angle and air shroud characteristics of the engine fuel nozzles, and approximate the atomization characteristics. The fuel nozzle tips are interchangeable simplex fuel nozzles sized as shown in Table 8 for rig tests at either atmospheric or elevated pressure.

3. Combustor Test Configurations

An extensive series of rig tests and modifications to the demonstrator engine combustor were conducted prior to its installation into the engine. The configuration designations, types and intent of the modifications, and types of tests conducted are listed in Table 9. Modifications were implemented for one or more of the following reasons:

1. Combustor Liner Temperature Improvement. Minor local adjustments to the liner cooling airflows were made in configurations E2 and E12 to reduce peak liner temperatures.

2. Combustor Exit Temperature Profile/Pattern Factor Improvement. The combustor was first tested without any profile trim airflow (Configuration E1A). The quantity and circumferential location of profile trim airflow was then varied in configurations E2, E8, and E12.

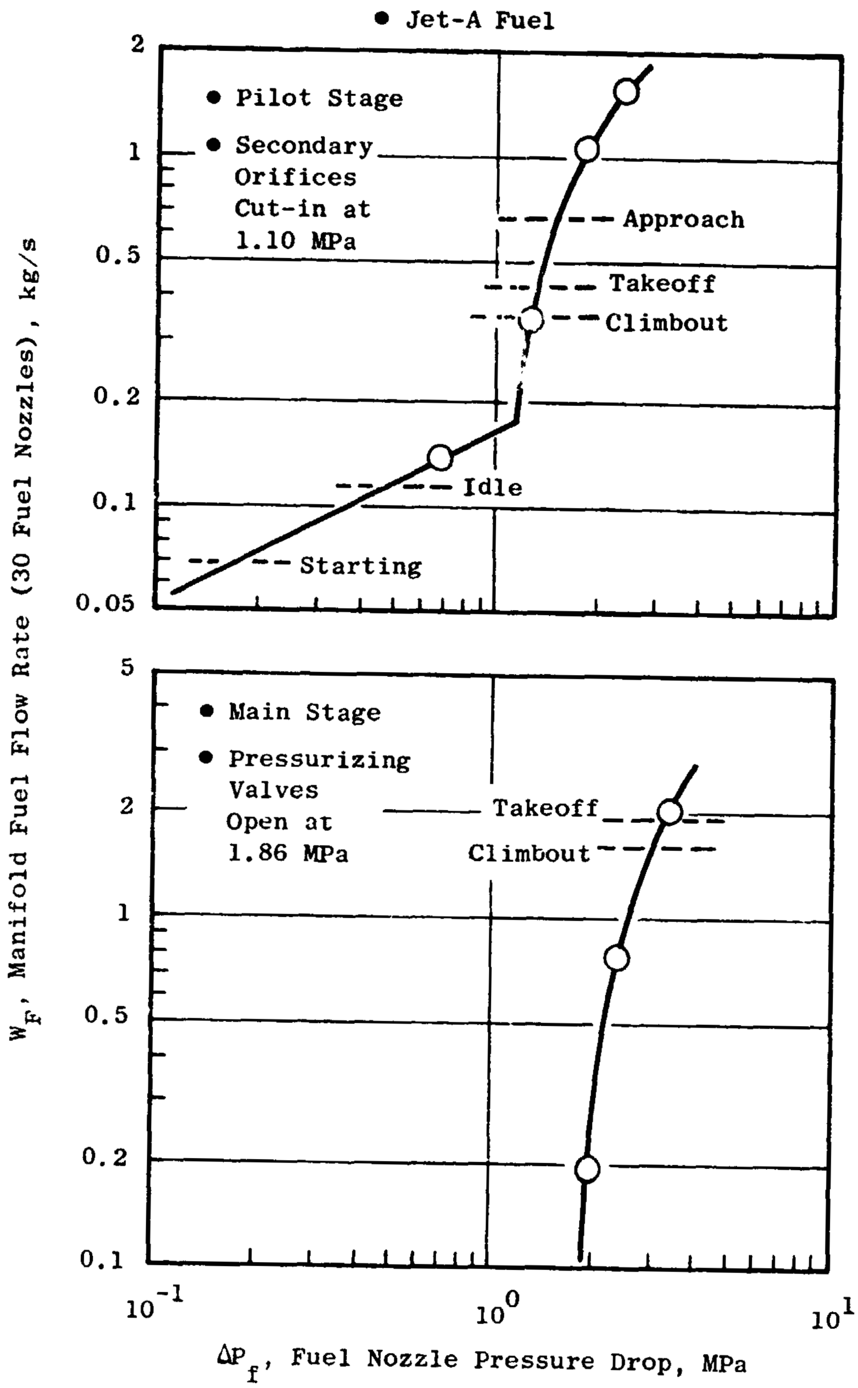


Figure 12. Flow Characteristics of the Engine Fuel Nozzles.

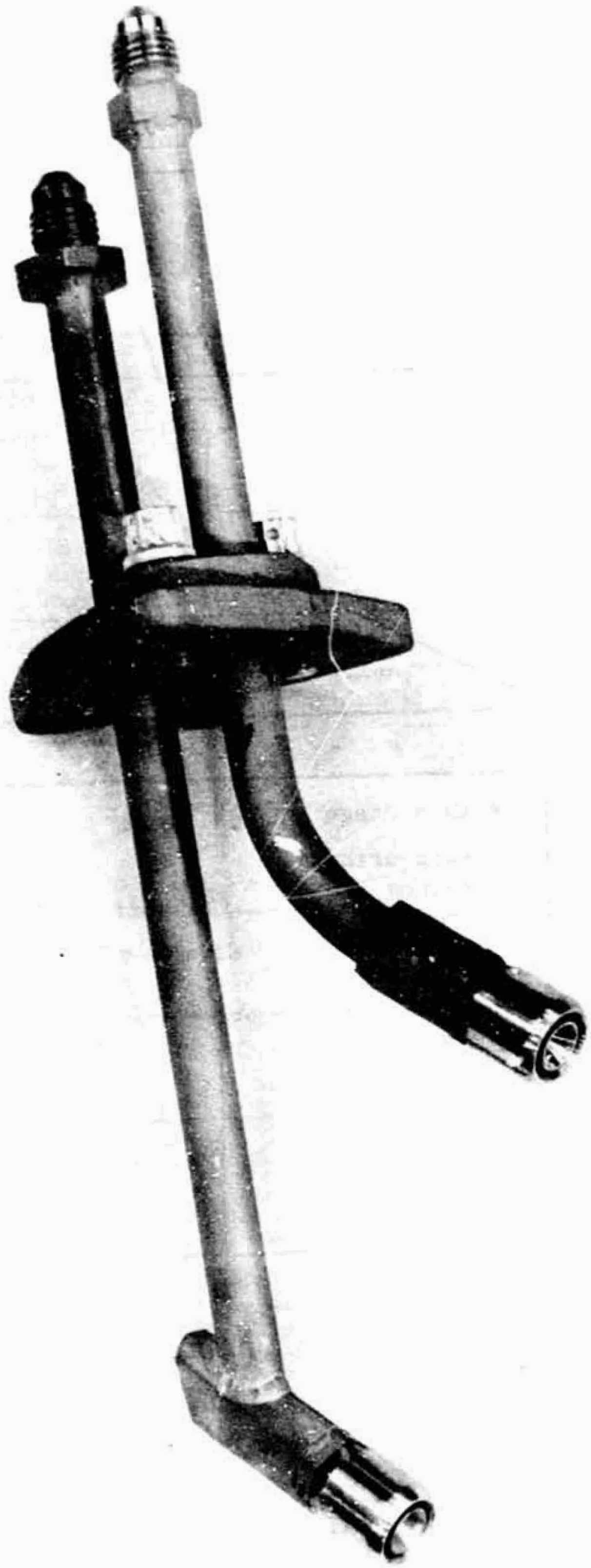


Figure 13. Rig Test Fuel Nozzles.

Table 8. Fuel Nozzle Design Parameters.

Intended Use	Combustor Stage	Type Nozzle	Flow Rate, Jet A Fuel @ 6.89 MPa Orifice Pressure Drop, kg/s (30 nozzles)
Engine Test (All)	Pilot	Dual Orifice with Integral Flow Divider Valve	Primary - 0.136 Secondary - 0.756
	Main	Simplex with Integral Pressurizing Valve	2.381
Rig Test, (Lightoff and Pressure Tests)	Pilot	Simplex	0.133
	Main	Simplex	0.464
Rig Test, (Atmospheric Pattern Factor Test)	Pilot	Simplex	0.0272
	Main	Simplex	0.0534

Table 9. Combustor Configurations and Rig Test Sequence.

Combustor Configuration Number	Run No.	Test Date	Final Reading Number	Type Test	Comments
E1A	1	3/11/76	10	Atmospheric Discharge, Pattern Factor	Combustor/Fuel Nozzles as Received
E1A	2	3/15/76	24	Atmospheric Discharge Ground Start/Subidle Performance	Combustor/Fuel Nozzles as Received
E1A	3	3/18/76	40	Low Power Emissions/Performance	Combustor/Fuel Nozzles as Received
E1B	4	3/24/76	51	Low Power Emission/Performance	Pilot Stage Fuel Nozzle Clearance Reduced
E2	5	4/1/76	60	Atmospheric Discharge, Pattern Factor	Combustor Airflow Distribution Modified
E2	6	4/5/76	72	Low Power Emissions/Performance	Fuel Nozzles Same as E1B
E3A-E3E	7	4/15/76	93	Idle Emissions, Diagnostic	Three Dilution Schemes and Two Fuel Nozzle Types
E4A-E4E	8	4/28/76	114	Idle Emissions, Diagnostic	Five Dilution Schemes
E5A-E5E	9	5/19/76	136	Idle Emissions, Diagnostic	Four Dilution Schemes and One Cup Modification
E6A-E6G	10	8/3/76	159	Emissions, Diagnostic	Five Pilot Fuel Nozzle/Cup and Two Main Fuel Nozzle Modifications
E7	11, 12	8/11/76 8/13/76	191	Emissions/Performance	Best Fuel Nozzle/Cup/Dilution Modification
E7	13	8/20/76	200	Atmoshperic Discharge, Pattern Factor	Basis for Profile Trim Air Modification
E8	14	8/27/76	209	Atmospheric Discharge, Pattern Factor	Profile Trim Air Added
E9A-E9C	15, 16	10/28/76 11/1/76	211	Idle Emissions, Diagnostic	Three-Cup Modifications
E10A-E10C	17	11/15/76	257	Idle Emissions, Diagnostic	Best Cup Modification from E9 and Three Dilution Schemes
E11	18	2/14/77	281	Emissions/Performance	Best Cup Modification from E9, E10 and Spray Tests
E11	19	2/17/77	290	Atmospheric Discharge, Pattern Factor	Basis for Profile Trim Air Modification
E12	20	2/25/77	298	Atmospheric Discharge, Pattern Factor	Profile Trim Air Modification

3. Combustor Pressure Drop Adjustment. As received, the combustor pressure drop was very close to the design intent (4.6 percent at engine takeoff operating conditions). Main-stage swirler airflow area was reduced in configurations E2 and E10 to compensate for other airflow area increases and maintain the intended pressure drop.

4. Idle CO and HC Emission Level Improvement. An extensive series of pilot-stage fuel nozzle, swirl-cup, and dilution modifications were made in configurations E1B through E11 in an effort to reduce the idle CO and HC emissions to the levels previously obtained with the Phase II prototype combustor.

Detailed descriptions of the combustor configuration modifications are presented in Appendix A. A comparison of the airflow distributions of the first and last configurations is contained in Table 10.

C. ENGINE FUEL SYSTEM

1. Engine Fuel Control Design Concept

Incorporating a Double Annular combustor in the CF6-50 engine requires a device for obtaining the desired fuel flow splits between stages over the entire range of engine operating conditions. Accordingly, a fuel flow splitter was designed in Phase II for use in the Phase III engine tests. The fuel splitter is shown in Figure 14, together with an operational schematic.

As shown in Figure 14, the splitter was designed for inclusion in the existing CF6-50 engine fuel control system. Overall fuel flow rate is scheduled by the production main engine control and throttle setting. The splitter schedules the split between the pilot and main stages automatically according to total fuel flow rate and predetermined settings of the main-stage cut-in point and the pilot-to-total split after cut-in. Both of these fuel scheduling parameters can be adjusted from the engine operating console. Remote adjustments were provided so that the effects of fuel scheduling on both exhaust emission levels and engine operating characteristics could be investigated. Fuel scheduling capabilities of the device are indicated in Figure 14. Pilot-to-total fuel flow split can be varied from about 50 to 100 percent at approach power operating conditions, and from about 10 to 30 percent at high-power operating conditions. The main-stage cut-in device incorporates a hysteresis feature to prevent flow instabilities.

Since the flow splitter schedules split as a function of total fuel flow rate, it is suitable only for sea level demonstration test use. Additional features are required also to accommodate cruise operating conditions.

Table 10. Demonstrator Engine Combustor Airflow Distributions.

Configuration	E1A (As Received, First Rig Test)	E11,12 (Final Rig Test And Engine Test)
Airflow Distribution (% W_c)		
Pilot Stage		
Swirlers	12.5	13.4
Dilution (Outer Second Liner Panel)	5.2	5.2
Dome Cooling	7.1	7.1
Main Stage		
Swirlers	33.7	29.0
Dilution (Inner First Liner Panel)	10.8	10.8
Dome Cooling	5.5	5.5
Centerbody Cooling	4.8	4.8
Liner Cooling	18.8	19.8
Profile Trim (Inner Sixth Liner Panel)	0	2.8
Seal Leakage	1.6	1.6
	100.0	100.0

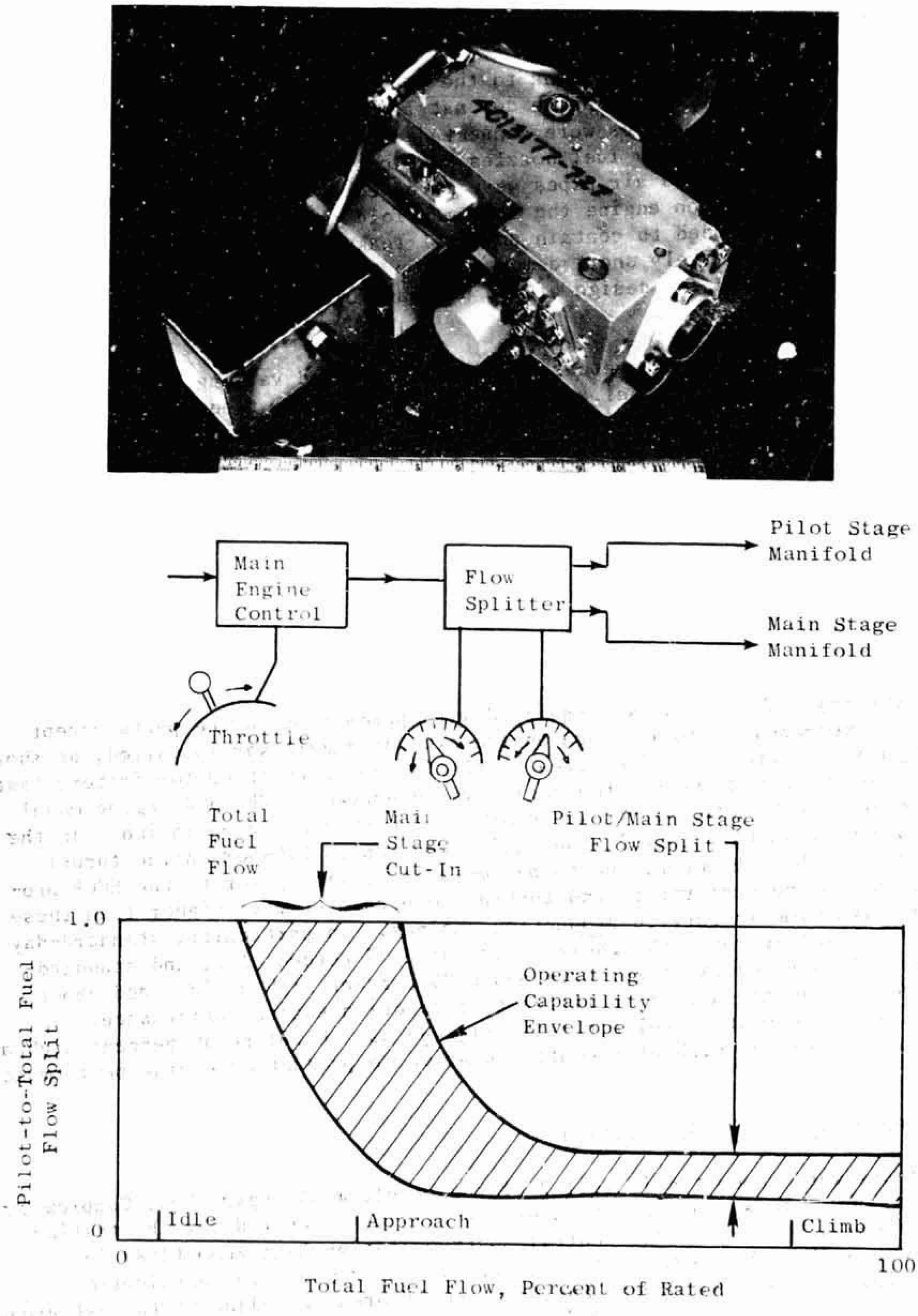


Figure 14. Demonstrator Engine Fuel Flow Splitter.

2. Engine Fuel Supply System

Relatively few modifications to the production engine fuel supply system were needed to conduct the engine demonstration tests. As shown in Figure 15, the main-stage fuel nozzles were connected directly to the existing fuel manifold, and the pilot-stage fuel nozzles were connected to a new manifold. Some of the compressor bleed air pipes were rerouted to accommodate this new manifold. In a production engine the fuel manifold and individual nozzle supply lines are all shrouded to contain any fuel leaks which might develop. However, for the relatively short demonstration test series, this safety requirement was waived and the design of the new manifold system was greatly simplified.

The fuel splitter, together with its associated valving and instrumentation, was mounted on a panel attached to the test cell floor directly under the engine, as shown in Figure 16.

D. ENGINE TEST APPARATUS

1. Demonstrator Engine Description

CF6-50 Engine Number 455-105/7 was used for the Double Annular Combustor engine demonstration tests. This engine is one of several factory engines which are used for all types of systems, mechanical, and performance development testing. The engine was equipped with production engine parts except that a fixed-area, conical, core engine exhaust nozzle was installed, as shown in Figure 17. Use of a fixed-area nozzle is common practice for factory testing. For these ECCP tests, the engine was operated to CF6-50C engine model thrust level (224 kN), but it was capable of higher-power operation. In the previous buildup (455-105/6), the engine was run to CF6-50M engine thrust levels (241 kN). However, due to accumulated testing prior to the ECCP program, the engine performance and turbine temperatures were higher than those of any high-time-in-service production engines. In particular, standard-day combustor airflow rates ($W_{36}\sqrt{\theta_2}/\delta_2$) were about 7 percent low, and standard-day fuel flow rates ($W_f/\theta_2\delta_2$) were about 25 percent high at idle and about 10 percent high at takeoff, relative to production engine performance. Standard-day combustor fuel-air ratio (f_4/θ_2) was therefore 30 percent high at idle and 15 percent high at takeoff, relative to production engine performance.

2. Engine Test Cell Description

Tests were conducted in Cell 7 of the Development Engine Test Complex of Building 500. This complex has extensive services required for the testing of development engines. The central Instrumentation Data Room (IDR) is located one floor below the test cell area. Instrumentation application facilities and the Development Engine Assembly area are adjacent to test area.

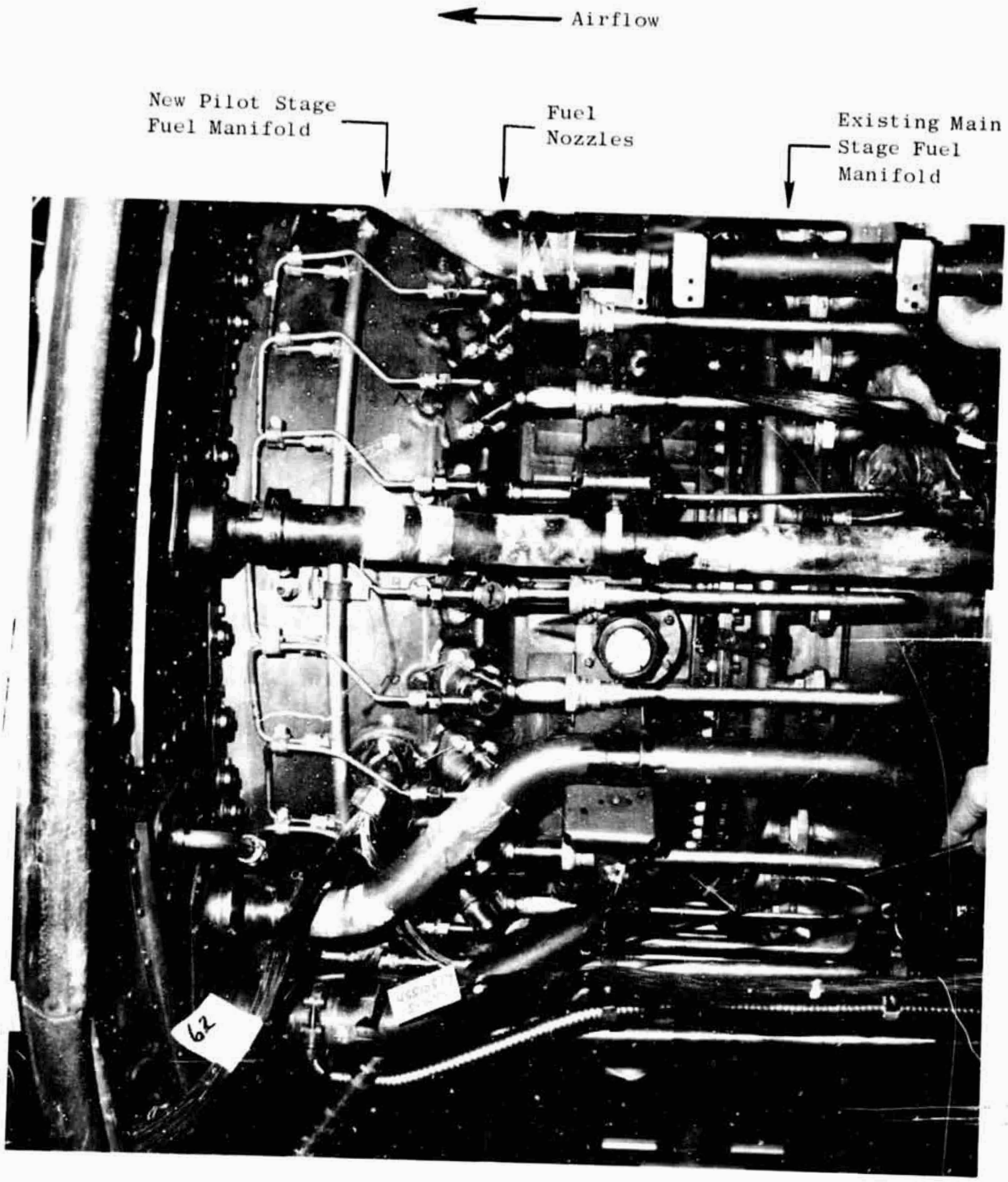


Figure 15. Engine Fuel Nozzle Manifolds.

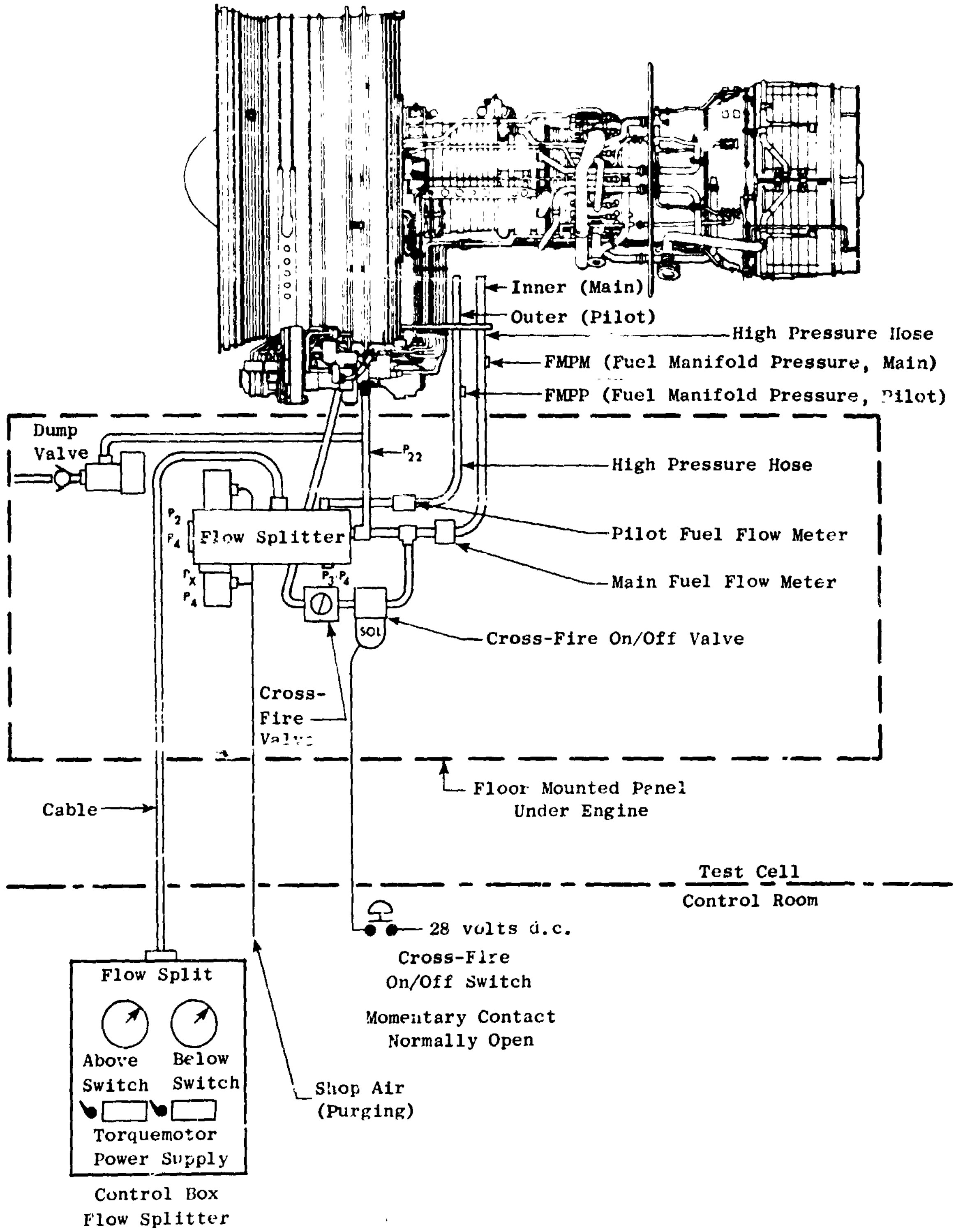


Figure 16. Engine Fuel System Setup.

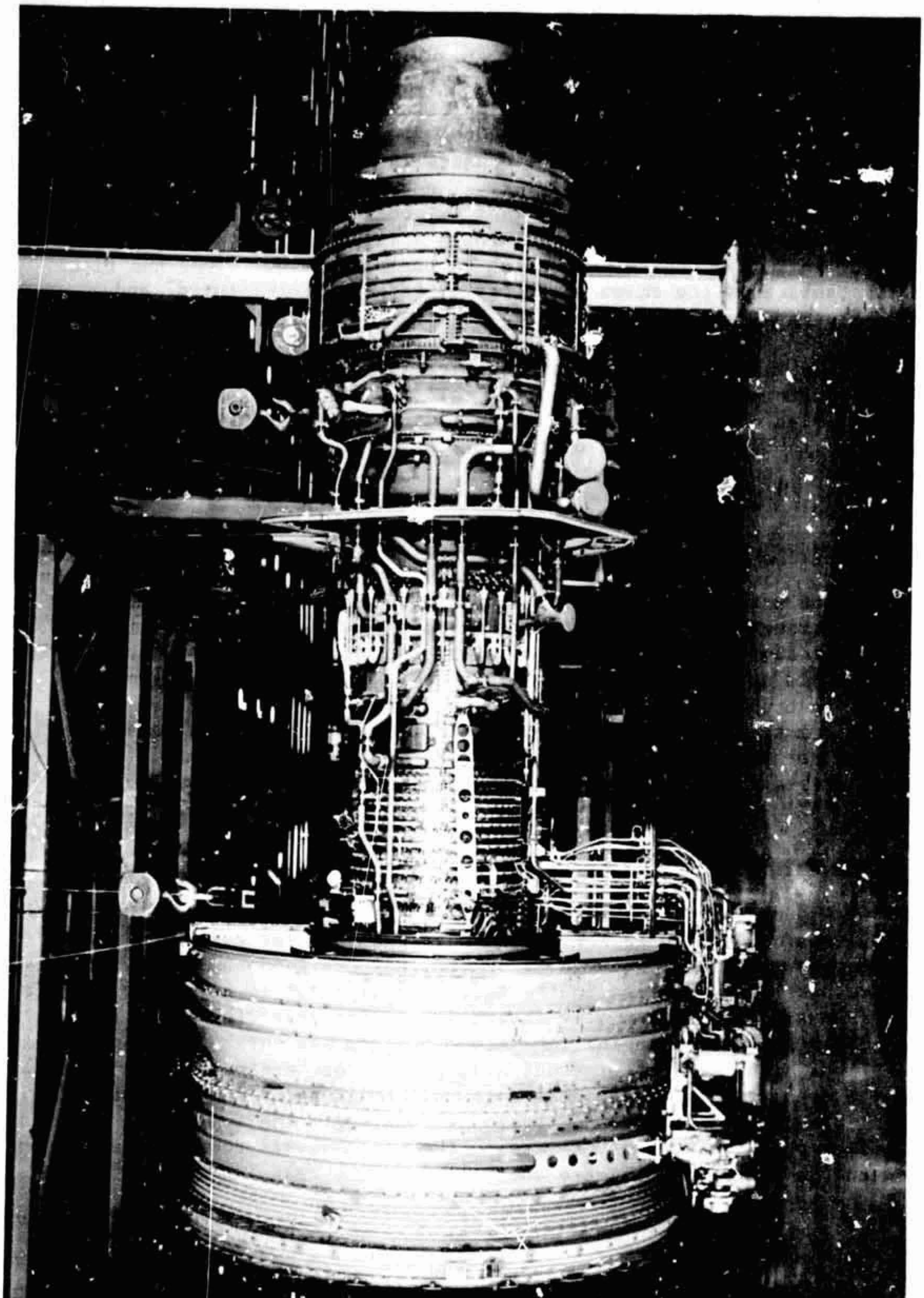


Figure 17. CF6-50 Development Engine with Factory Test Exhaust Nozzle.

Cell 7 was designed for development testing of large turbofan engines at sea-level-static conditions. The general arrangement of the cell is shown in Figure 18. Air enters the cell from an inlet mounted on the roof. An array of turning vanes provides uniform horizontal flow to the engine. The engine exhausts into an augmentor, where the exhaust is sound treated and exits into the atmosphere through a vertical stack. The augmentor pumps secondary air that flows around the engine and provides external cooling. The engine is suspended from a thrust measuring frame through a flight-type pylon and engine fan duct cowling. The engine centerline is nominally 3.05 m from the floor. Typical installations are shown in Figure 19 (aft looking forward) and Figure 20 (forward looking aft).

The engine is operated from an acoustically isolated control room located immediately adjacent to the test cell and on the left side, aft looking forward. The exhaust gas analysis equipment is located in a mezzanine room adjacent to the other side of the test cell and approximately in line with the exhaust nozzle. Gas sample lines are only about 8 meters long.

3. Performance Instrumentation

The engine and test cell were equipped with all of the normal development test instrumentation needed to safely operate the engine and determine the overall steady-state and transient operating characteristics. In addition, the Double Annular Combustor and its fuel supply/control system were extensively instrumented to characterize the performance of these new components. A summary of key measured and calculated parameters is shown in Table 11. A more detailed description of the types and locations of engine combustor instrumentation is presented in Appendix A.

4. Exhaust Gas Sampling Apparatus

One of the objectives of the demonstrator engine tests was to compare exhaust gas sampling techniques. A new exhaust gas sampling rake and traversing system, shown schematically in Figure 21, was designed and built for these tests. The assembly installed in the test cell is shown in Figure 22. Eight sampling arms are mounted radially inward from a traverse ring which is sized to clear the CF6-50 engine fan jet. Each arm has three sampling ports which are located on centers of equal area of the core engine exhaust nozzle. Alternate arms are manifolded together to collect 12-point mixed samples. The entire ring can be rotated for traverse sampling. The two sample lines and traverse motor controls are routed to the gas analysis room, where rake position and sample processing are controlled during test.

With this rake system, four different sampling techniques were utilized.

- 12-point fixed single-cruciform rake with the arms oriented vertically and horizontally and manifolded together to collect and analyze one mixed sample. This simple technique meets the Federal Register specifications (Reference 1).

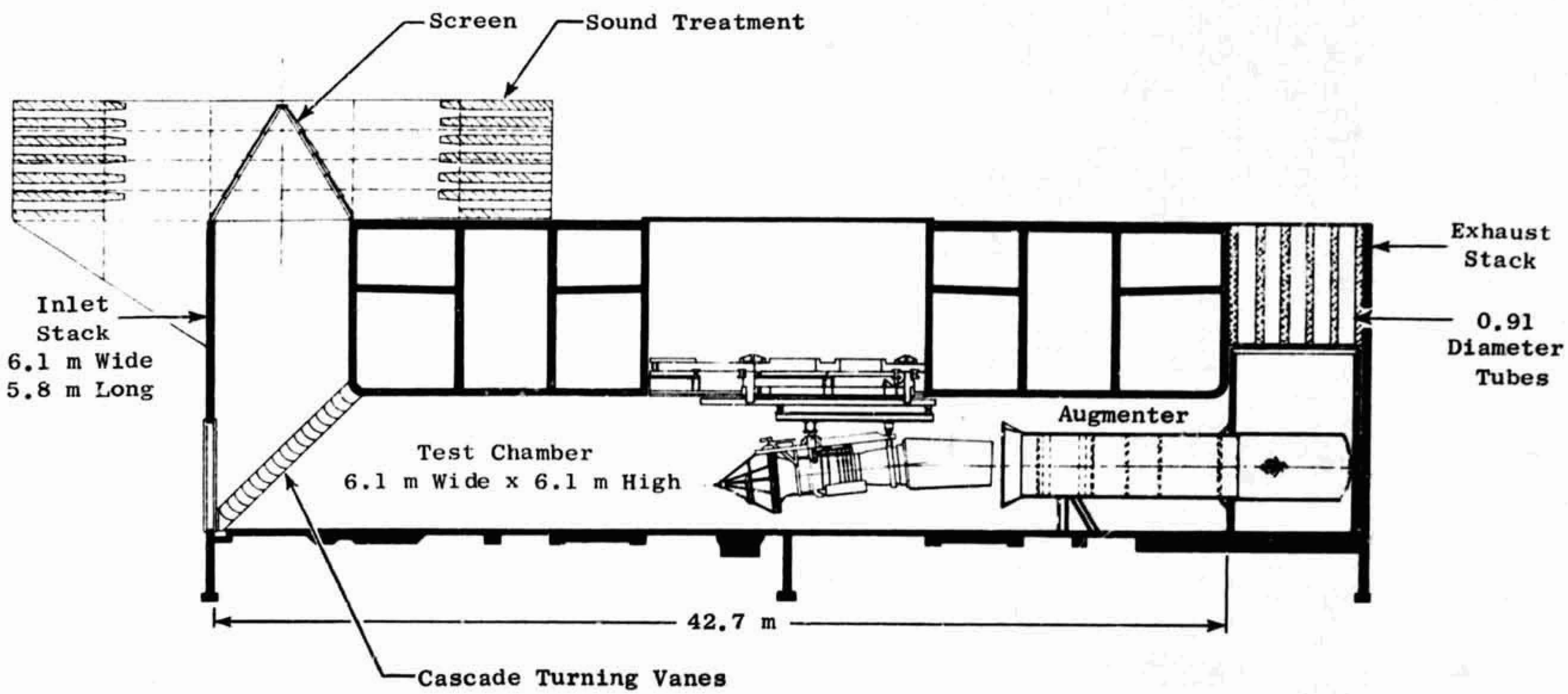


Figure 18. Development Engine Test Cell Cross Section.

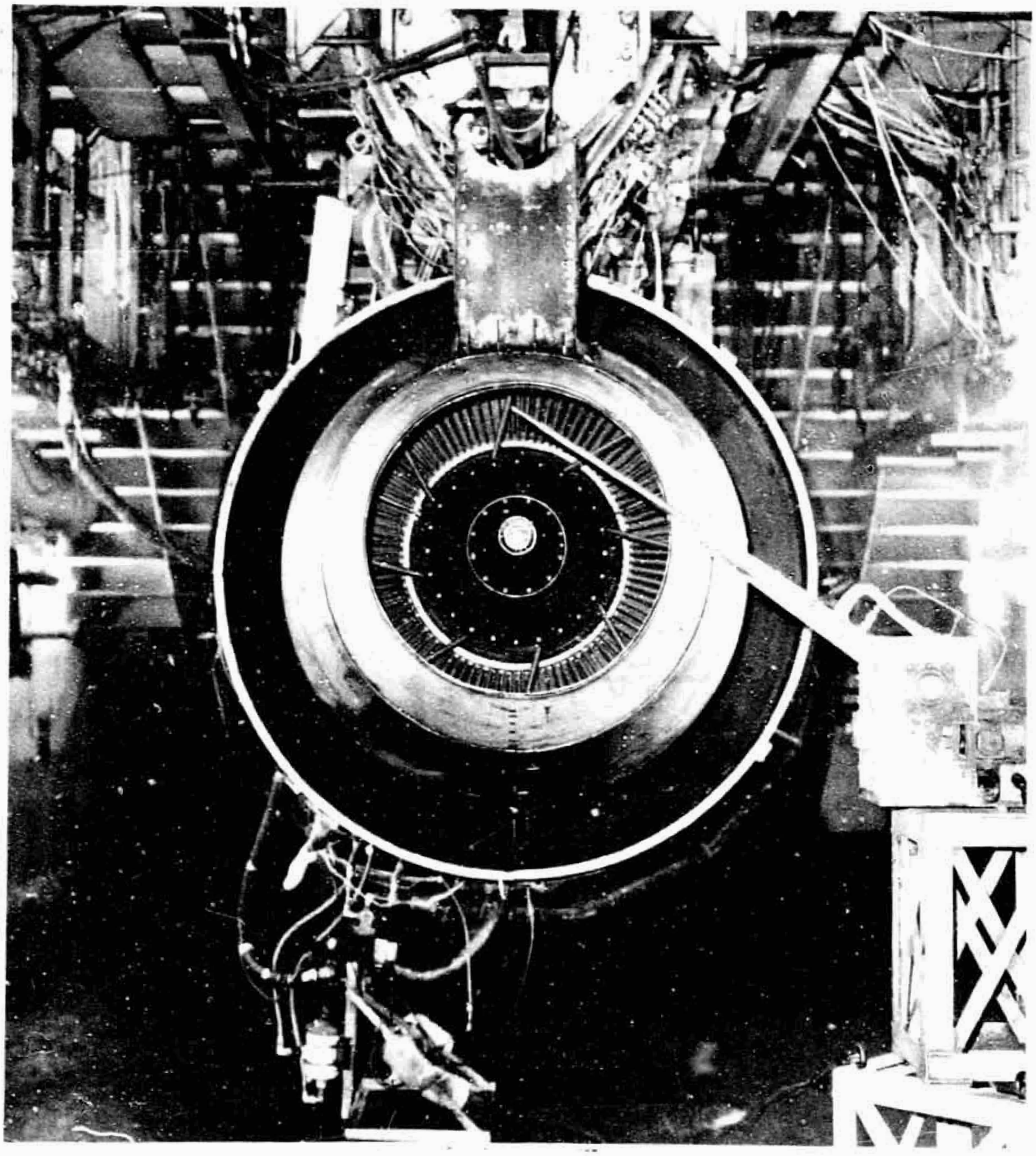


Figure 19. CF6 Engine Mounted in Development Engine Test Cell, Aft Looking Forward.

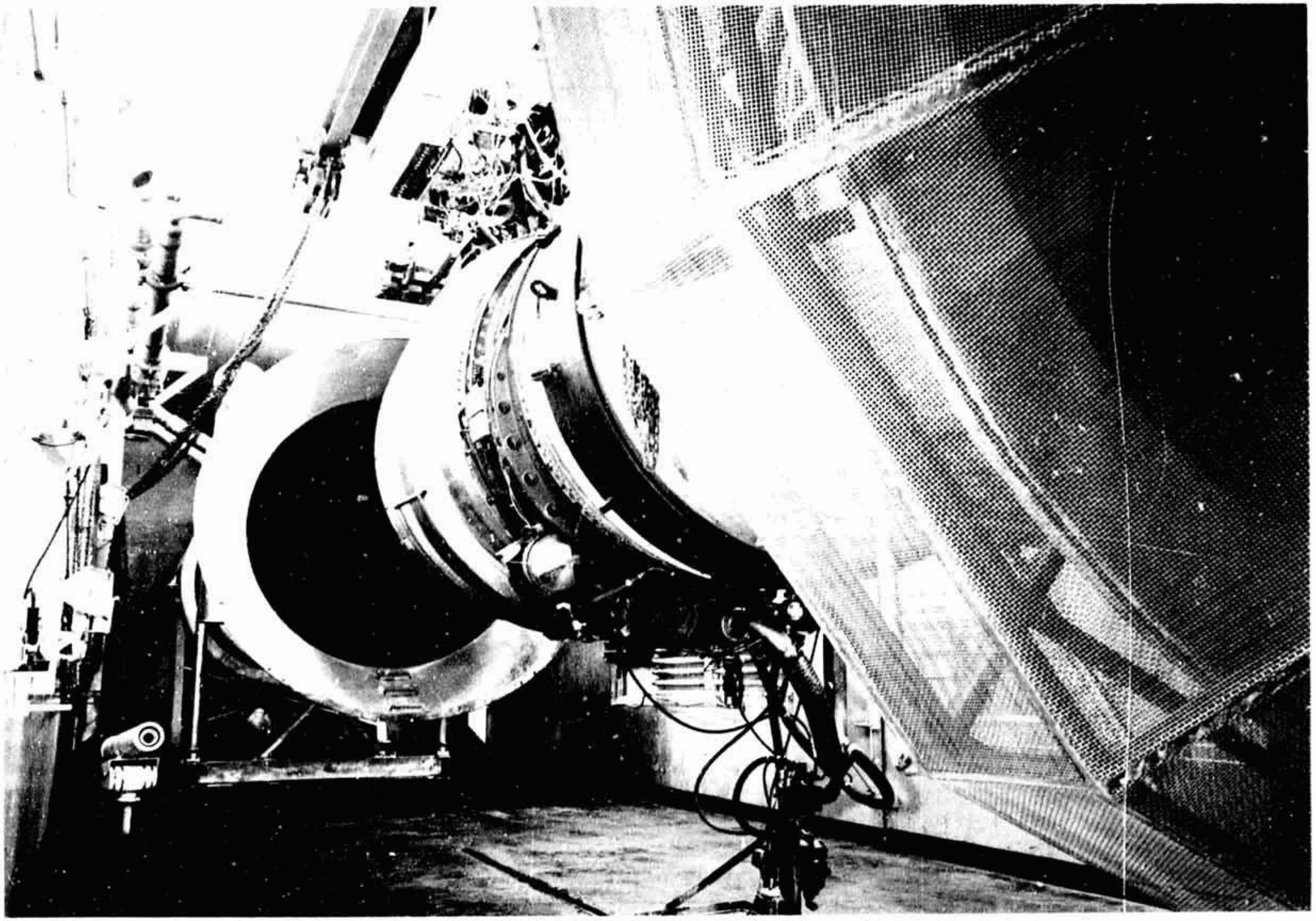


Figure 20. CF6 Engine Mounted in Development Test Cell 7, Forward Looking Aft.

Table 11. Summary of Key Measured and Calculated Engine/Combustor Performance Parameters.

Parameter	Measured	Calculated	Symbol	*Value Determined From*
Barometer	X		P_o	Continuously recording weather station.
Ambient Humidity	X		H_o	Continuously recording weather station.
Engine Inlet Total Pressure	X		P_2	Inlet Bellmouth rakes, 5 rakes, 5 immersions.
Engine Inlet Total Temperature	X		T_2	Inlet Bellmouth rakes, 5 rakes, 5 immersions.
Thrust	X		F_N	Three calibrated load Cell 5, corrected for Tare and cell factor.
Fuel Temperature	X		T_F	Thermocouples at 4 flow meters.
Fuel Specific Gravity	X	X	-	Calculated from pre-test sample and test temperature, and pre-test S.G.
Fuel Flow Rate	X		W_F	Four calibrated turbine meters total verification, and pilot and mainstages.
Low Pressure Rotor (Fan) Speed	X		N_1	Two tachometers.
High Pressure Rotor (Core) Speed	X		N_2	Two tachometers.
High Pressure Rotor Inlet Total Temperature Measured	X		T_{25}	
High Pressure Turbine Outlet Total Temperature	X		T_{49}	Eleven rakes, 5 immersions.
High Pressure Turbine Outlet Total Pressure	X		P_{49}	Two probes.
Total Engine Airflow Rate	X		W_{a1}	Calibrated inlet Bellmouth.
Core Airflow Rate		X	W_{a8}	Computed from core engine energy balance.
Engine Throttle Angle	X		α	
Compressor Variable Stator Setting	X		β	
Combustor Inlet Total Pressure	X		P_{T3}	Three probes on combustor cowl.
Combustor Inlet Total Temperature	X		T_3	Five immersion rakes in diffuser and 4 probes on combustor cowl.
Combustor Static Pressure	X		P_{16}	Twenty-four combustor wall taps.
Combustor Metal Temperature	X		T_M	Sixty surface and imbedded thermocouples.
Combustor Vibrations	X		-	Two borescope ports mounted dynamic pressure sensors Kulites.
Fuel Injector Vibrations	X		-	Eight strain gages on fuel nozzle stems.
Fuel Manifold Pressure	X		P_F	Static tap on each manifold.
Combustor Airflow Rate		X	W_{a36}	Computed from high pressure turbine energy balance.
Combustor Fuel-Air Ratio		X	f_{36}	$= W_{ft}/W_{a36}$
Fuel Nozzle Pressure Drop		X	ΔP_F	$= P_F - P_{36\ Dome}$
Combustor Total Pressure Drop		X	$\Delta P_T/P_3$	$= (P_{T3} - P_{36\ Dome}) / P_{T3}$
Combustor Reference Velocity		X	V_r	Computed from W_{a36}, T_3, P_3
Combustor Outlet Total Temperature		X	T_4	Computed from T_3, f_{36}
Core Engine Exhaust Fuel-Air Ratio		X	f_8	$= W_{ft}/W_{a8}$

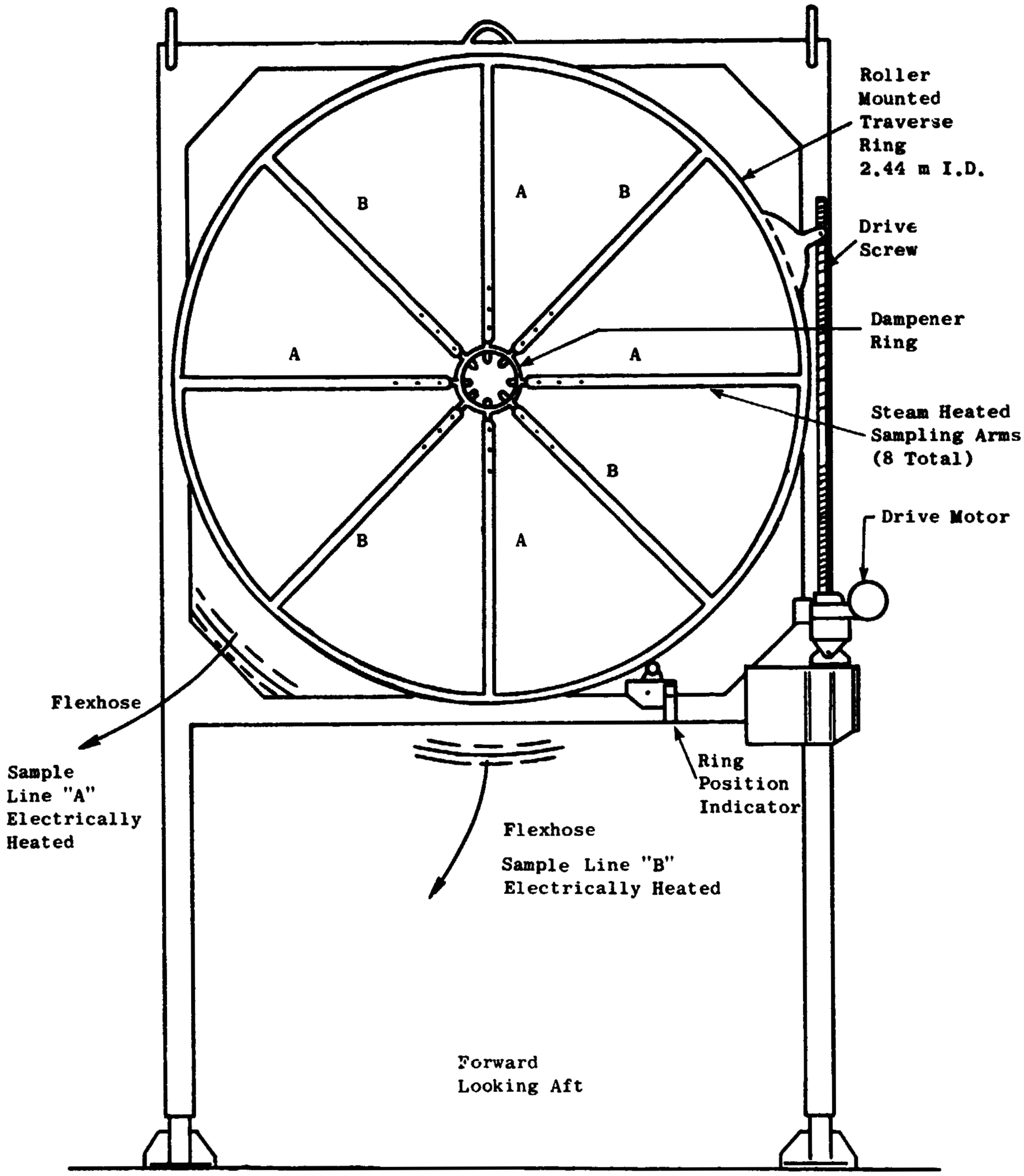


Figure 21. Exhaust Gas Sampling and Traverse Rake Diagram.

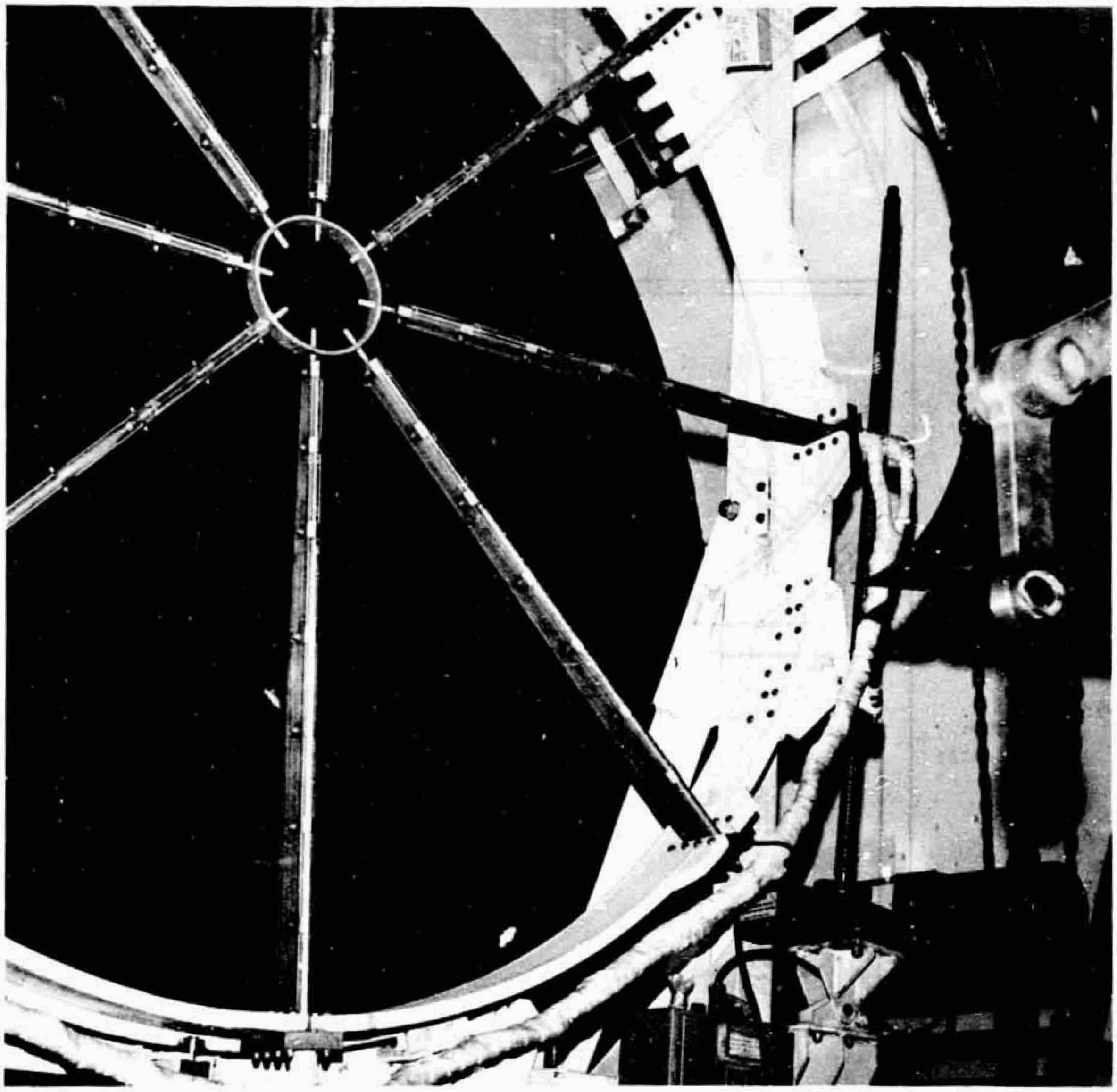


Figure 22. Exhaust Gas Sampling and Traversing System Installation.

- 12-point fixed single-cruciform rake as described above, except for the arms oriented 45° from the vertical and horizontal. This technique also meets the Federal Register specifications.

- 24-point fixed double-cruciform rake obtained by manifolding the two single cruciform rakes together. This was the primary technique for these tests.

- 216-point traverse. This technique consisted of rotating the 24-point double-cruciform rake and recording data at 5° intervals across the entire exhaust nozzle area.

In addition, the low pressure turbine exit total pressure rakes shown in Figure 23 were installed and manifold as shown in Figure 24 to provide a fixed 20-point, plane 5 emission sampling system. Additional details of the sampling equipment are presented in Appendix A, together with descriptions of the gas analysis equipment.

E. TEST CONDITIONS AND PROCEDURES

1. CF6-50C Production Engine Status Cycle Parameters

Both the component and engine tests were based on current CF6-50C production engine operating conditions, which are shown in Table 12. These status cycle parameters are based on analyses of acceptance test data for production engine serial numbers between -209 and -258. Power settings except for standard idle (3.31%) are based on percentages of the FAA-rated corrected thrust for CF6-50C engine, which is 224.2 kN (50,400 lb) and does not include scrubbing drag. Standard idle is based on a corrected high pressure rotor speed of 6249 rpm.

2. Component Test Conditions and Procedures

Combustor component tests were conducted in the same full annular test rig and facility, and using the same data acquisition systems, as were utilized in the Phase I and II Programs. Detailed descriptions are presented in References 1 and 13. The test rig exactly duplicates the aerodynamic flowpath and envelope dimensions of the CF6-50 engine. A new inner flowpath was used with the double annular demonstrator combustor in the Phase III tests to duplicate the engine flow-path modifications. The tests were conducted in Test Cell A3, which is equipped with an indirect-fired air heater and exhaust ducting systems for high pressure on vacuum operation. Flow capabilities are such that the CF6-50 engine combustor operating conditions can be exactly duplicated at all relight requirement and ground idle conditions. For higher-power simulation, temperature, velocity and fuel-air ratio are duplicated, but combustor inlet pressure is limited to about 0.97 MPa. As indicated in Table 9, four types of combustor rig tests were conducted in the Phase III Program. These were:

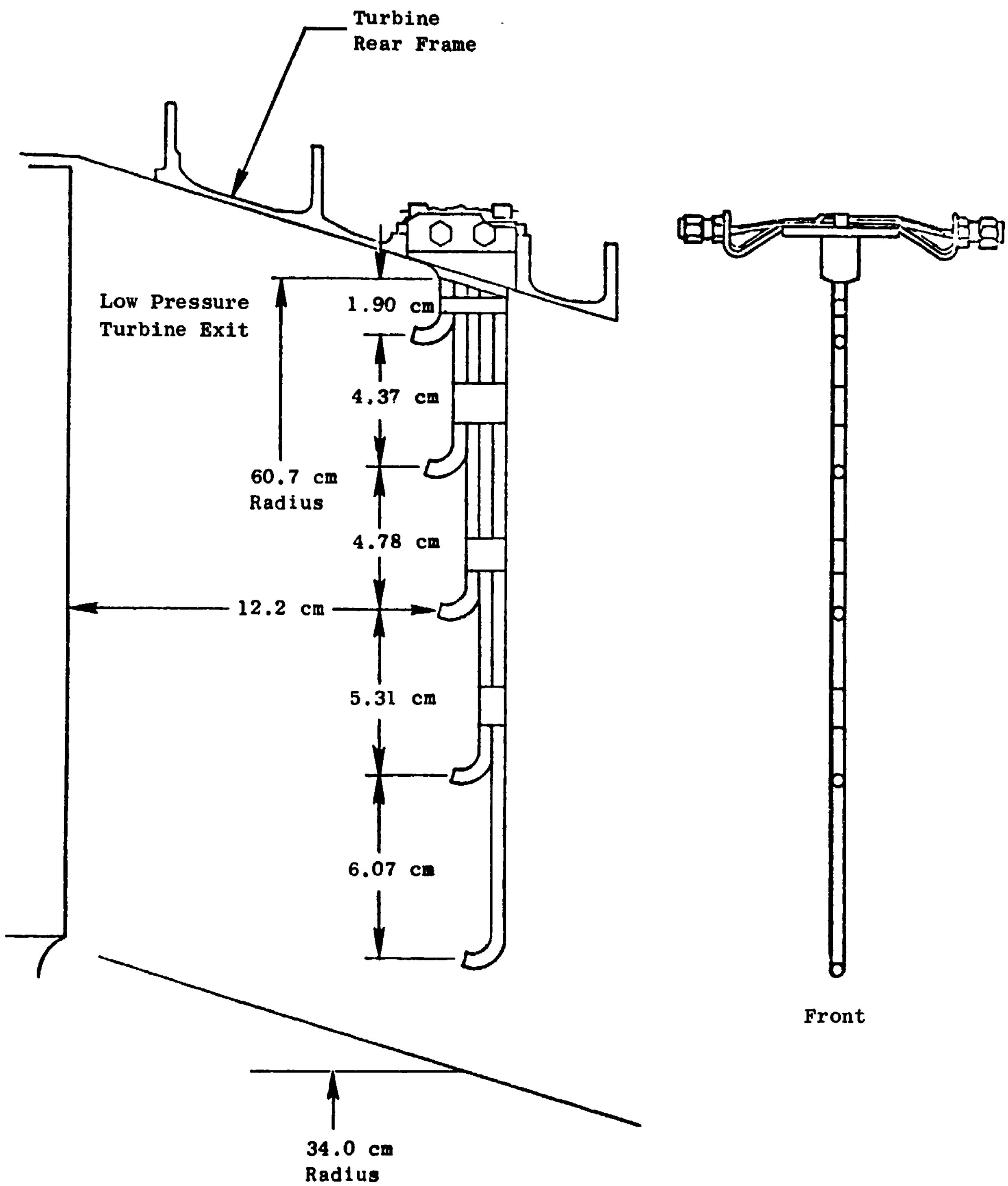


Figure 23. Turbine Exit (Plane 5) Total Pressure Rakes (Used for Exhaust Emission Sampling).

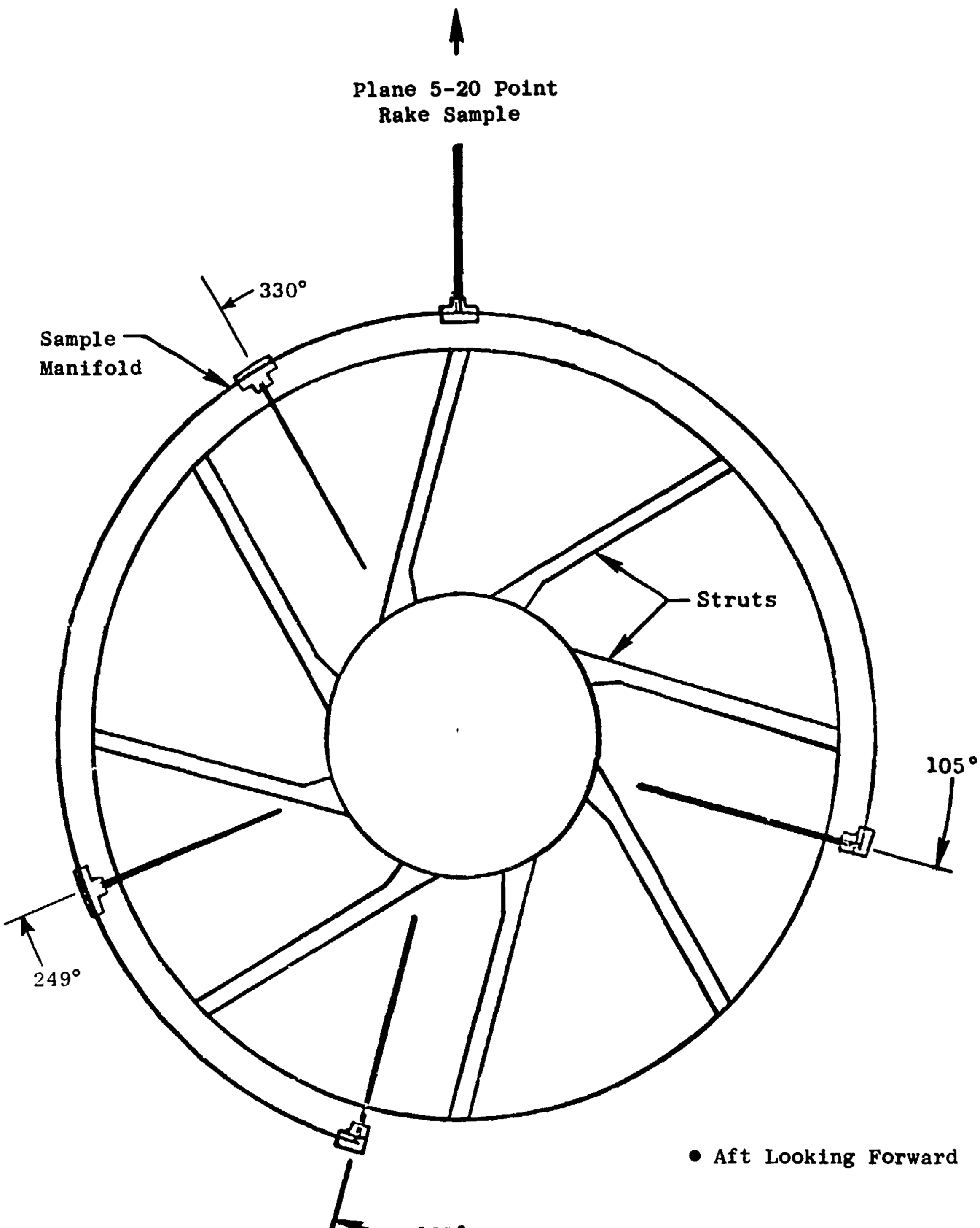


Figure 24. Turbine Exit Pressure Rake Sampling Array.

Table 12. CF6-50C Production Engine Cycle Parameters.

- T_{amb} = 288.2K
- P_{amb} = 0.1013 MPa
- Kerosene Fuel
- No Bleed

Rating			GIDL	--	--	FIDL	--	APPR	--	--	CLMB	-	TKOF
N_1	Fan Speed	rps	14.07	--	--	--	--	39.17	--	--	58.93	--	62.52
N_2	Core Speed	rps	104.7	--	--	--	--	143.8	--	--	164.4	--	169.1
W_{ft}	Fuel Flow Rate (Total)	kg/s	0.1526	0.1728	0.2130	0.7505	--	0.6645	--	--	1.953	--	2.376
T_3	Combustor Inlet Temperature	K	437.4	463	489	514	579	631.9	691	745	791.9	807	826.3
P_3	Combustor Inlet Pressure	MPa	0.300	0.374	0.461	0.561	0.917	1.197	1.606	2.117	2.616	2.785	2.983
W_{36}	Combustor Airflow Rate	kg/s	13.93	17.3	21.3	25.3	38.6	48.17	61.0	76.7	90.81	95.3	100.6
f_4	Combustor Fuel-Air Ratio	g/kg	10.96	10.3	10.0	9.9	11.6	13.79	16.4	19.0	21.51	22.4	23.62
V_r	Combustor Reference Velocity(1)	m/s	18.56	19.6	20.7	21.4	22.3	23.29	24.0	24.7	25.18	25.3	25.51
W_8	Core Exhaust Gas Flow Rate	kg/s	17.55	--	--	--	--	61.05	--	--	115.2	--	127.2
f_8	Core Exhaust Fuel-Air Ratio	g/kg	8.8	--	--	--	--	11.0	--	--	17.3	--	19.0
F_n	Uninstalled Net Thrust	kN	7.42	11.2	15.7	21.3	44.8	67.27	100.9	195.7	190.5	206.2	224.2
F_n/F_r	Percent of Rated Thrust	%	3.31	5.0	7.0	9.5	20.0	30.0	45.0	65.0	85.0	92.0	100.0

(1) Based on $A_r = 3729\ cm^2$ and $W_{36}/W_3 = 0.841$

a) High Pressure Performance/Emission Tests. These tests were conducted at actual idle and simulated higher power operating conditions to determine exhaust emission levels, liner temperature, pressure drop, crossfire, and combustor resonance characteristics. At each selected engine operating condition, data were obtained at a limited range of fuel-air ratios and/or a span of pilot-to-total fuel flow splits. Exhaust gases were sampled with a 25-point traversing rake assembly containing five rakes, each having five sampling elements. The 25 sample lines were steam heated and led out individually to a selector valve panel, and then to the emission analyzers. By manipulation of the valves, any desired individual element or combination of elements could be analyzed.

b) Ground Start Tests. Start tests were run at a range of actual engine ground starting conditions. For these tests, the combustor was exhausted to the atmosphere, allowing visual observation of the ignition attempts. Lightoff, propagation, and lean blowout were determined over a range of ambient temperature airflow rates corresponding to normal engine starting speeds.

c) Pattern Factor Tests. Combustor exit temperature profile characteristics were determined in atmospheric pressure tests. In these tests, very detailed temperature surveys were obtained by traversing an array of four thermocouple rakes, each having seven probe elements and recording temperatures at 1.5° intervals. From these tests results, the combustor airflow distributions were adjusted as needed to meet the engine installation requirements.

d) Idle Emissions Diagnostic Tests. A new diagnostic test technique was devised and utilized in some of the idle emission tests. For configurations E3 through E6, five different modifications were made in sectors of the combustor which were aligned with the area swept by each exit gas sample traverse rake. By traversing and sampling each rake individually, five configurations were effectively evaluated within the same test setup. The most promising modifications found in this series (E6A) were then uniformly incorporated into configurations E7 and 8 for more detailed evaluations. For configurations E9 and 10, the technique was again utilized, except that three instead of five modifications were made in order to better assess circumferential variations within each configuration. From these tests, sector configuration E9C was identified as most promising and incorporated uniformly into E11 and 12. Thus, overall, 26 combustor sector configurations were screened in only six test buildups using this sector/annular test technique.

3. Engine Test Conditions and Procedures

a) Steady-State Performance/Emissions Tests

The first series of engine tests were conducted to determine the steady-state performance and exhaust emissions characteristics according to the test point schedule shown in Table 13. Test points (1 through 10) were intended to provide the basic performance/emissions measurements, and to determine the effect of fuel flow split on performance and emissions at the EPA-specified operating conditions (idle, approach, climbout, and takeoff) using the 24-point double cruciform sampling technique. Test points (11 through 14) were intended to provide further data at the EPA operating conditions using the preferred fuel splits and the traverse sampling technique. Test points (12 through 15) were intended to provide data at additional operating conditions using the preferred fuel splits and the double cruciform sampling technique. Test points (21 through 24) were intended to provide additional measurements at the EPA operating conditions using the preferred fuel splits and the 12-point cruciform sampling technique.

As is usual in development engine tests, the engine was run to prescribed speeds corresponding to the desired thrust levels. In Table 13, the corrected fan speed which was actually used to set each test point (except standard idle) is shown. These speeds were selected from pretest engine performance predictions to provide the specified corrected thrust levels. Standard idle (3.3 percent thrust) was set by placing the throttle in the ground idle flat, where the engine control maintains corrected core speed.

All of the test points shown in Table 13 were run at least once, and a total of fifty-eight readings were obtained. Most of the test points were run at least twice. Tests were run in order of both increasing and decreasing power level. At each test point, the engine was stabilized about five minutes before reading. Each reading consisted of recording all of the engine/combustor performance parameters with the automatic data management system (DMS reading), and recording the smoke and gaseous emissions data. Usually, at each test point, emissions data were obtained with at least two and sometimes three different sampling techniques for direct comparison.

b) Acceleration/Deceleration Tests

A second and very important portion of the demonstrator engine tests was to determine the transient operating characteristics of the CF6-50 engine when equipped with a staged combustion system. In particular, there has been considerable speculation on the ability to meet the requirements specified in Reference 15 for power or thrust response when only the pilot-stage is fueled at idle and approach power levels.

Table 13. Demonstrator Engine Steady-State Performance and Emissions Test Schedule.

- Based on CF6-50C rated thrust (224.4 kN)
- No customer air bleed or power extraction.
- JP-5 Fuel

Test Point No.	Test Point Designation	F_N/δ_2, Corrected Thrust, % of Rated	$N_1/\sqrt{\theta_2}$, Corrected Fan Speed, rps	W_{fp}/W_{ft}, Pilot-to-Total Fuel Flow Split	Exhaust Gas Sampling Technique: 2[illegible]-Point Double Cruciform	Exhaust Gas Sampling Technique: 216-Point Traverse	Exhaust Gas Sampling Technique: 12-Point Single Cruciform
1,11,21	Standard Idle(1)	3.3	---	1.00	x	x	x
15	Secondary Power Point	5.0	16.3	1.00	x		
16	Secondary Power Point	7.0	19.3	1.00	x		
17	Secondary Power Point	20.0	32.8	1.00	x		
2,12,22	Approach	30.0	40.0	1.00	x	x	x
3	Approach	30.0	40.0	0.70	x		
4	Approach	30.0	40.0	0.45(2)	x		
18	Secondary Power Point	45.0	47.[illegible]	0.21(2)	x		
19	Secondary Power Point	65.0	53.8	0.18	x		
5	Climbout	85.0	59.0	0.23	x		
6,13,23	Climbout	85.0	59.0	0.18	x	x	x
7	Climbout	85.0	59.0	0.13	x		
20	Secondary Power Point	92.0	60.7	0.13	x		
8	Takeoff	100.0	62.8	0.23	x		
9	Takeoff	100.0	62.8	0.18	x		
10,14,24	Takeoff	100.0	62.8	0.13	x	x	x

(1) Standard idle is controlled to corrected corespeed $N_2/\sqrt{\theta_2}$ = 106.7 rps.

(2) Approximately minimum fuel splitter setting.

The test point schedule for this series of acceleration/deceleration tests is shown in Table 14. As shown, throttle bursts to and chops from takeoff power were specified, while systematically varying the initial/final power level and the two fuel splitter control parameters (flow split at approach and flow split at full power). The tests were conducted in general accordance with Reference 15 and standard General Electric practice. No emission measurements were made during these tests, but the engine exhaust plume was visually monitored for the presence of unburned fuel or smoke. For each test point, a full DMS engine performance reading was taken at the initial and final steady-state power level for correlation with the important parameters recorded transiently on high-speed multi-channel strip chart recorders.

c) Ground Start Tests

A ground start test series was conducted according to the test point schedule shown in Table 15. Included are variations in fuel control specific gravity setting, compressor stator vane setting, and starter air pressure to determine the starting times and stall characteristic of the engine when equipped with the Double Annular combustor.

F. DATA ANALYSIS PROCEDURES

1. Engine/Combustor Performance Data

All key engine and combustor performance data were recorded by digital data acquisition systems, and processed through standard test data reduction programs for converting data signals to engineering units, then calculating prescribed averages, flow rates, and performance parameters. Under normal conditions, computer printouts of these results were available for preliminary data analyses within about ten minutes after the test point was recorded. The engine data were also stored on magnetic tape for additional processing after the test was completed. This latter feature was used in these tests for compiling data obtained in different runs, and converting the data to SI units. The key engine and combustor performance parameters which were computed are listed in Table 11. Most of the parameters are self-explanatory. However, by General Electric convention, combustor reference velocity is based on compressor discharge total airflow (W_3), total density, and casing cross-sectional area at the combustor dome exit (A_r). Additional details of the performance data calculation and analysis procedures are presented in Appendix A.

2. Emission Data Reduction Procedure

In the combustor rig tests, the emission data acquisition, reduction, and calculation procedures were virtually identical to those utilized in Phases I and II, which are described in References 1 and 3. The same procedures were employed in the engine test except that fuel-air ratio corrections were also required.

Table 14. Demonstrator Engine Acceleration/ Deceleration Test Schedule.

- JP-5 Fuel.
- Fast Acceleration to Takeoff Power and Fast Deceleration from Takeoff at Each Test Point.

Test Point Number	Initial/Final Power Level		Fuel Splitter Control Setting, Pilot-to-Total Fuel Split at:	
	Flight Idle	Approach 30% F_N	Approach	Takeoff
57	x		1.00	0.23
58		x	1.00	0.23
59	x		1.00	0.18
60		x	1.00	0.18
61	x		1.00	0.13
62		x	1.00	0.13
63	x		0.70	0.23
64		x	0.70	0.23
65	x		0.70	0.18
66		x	0.70	0.18
67	x		0.70	0.13
68		x	0.70	0.13
69	x		0.45	0.23
70		x	0.45	0.23
71	x		0.45	0.18
72		x	0.45	0.18
73	x		0.45	0.13
74		x	0.45	0.13

Table 15. Demonstrator Engine Ground Start Test Schedule.

- JP-5 Fuel
- Normal Engine Automatic Start Sequence

Test Point Number	Compressor Stator Angle Setting Degrees Open from Normal	Fuel Specific Gravity Setting on Main Engine Control	Starter Air Pressure, kPa (absolute)
75	0	0.82	380
76	0	0.82	380
77	0	0.82	310
78	0	0.82	310
79	0	0.82	275
80	0	0.82	275
81	0	0.82	240
82	0	0.82	240
83	0	0.70	380
84	0	0.70	310
85	0	0.70	240
86	0	0.70	380
87	-4	0.70	380
88	+4	0.70	380
89	+4	0.82	380
90	0	0.82	380
91	-4	0.82	380
92	-4	Max	380
93	0	Max	380
94	+4	Max	380

A description of the emission data acquisition system used in the engine tests is presented in Appendix A. The gaseous emission analysis instruments were calibrated before and after each test run with calibration gases which had been checked against National Bureau of Standards SRM gas standards. The calibration data and emission test data were manually logged during the test, and subsequently input to a computer data reduction program where emission index, fuel-air ratio and combustion efficiency were calculated. The equations used for these calculations were basically those contained in SAE ARP 1256 (Reference 14), with the CO and CO_2 concentrations corrected for removal of water from the samples before analyses. Hydrocarbon emission levels were assumed to have the same molecular weight as the parent fuel in these emission index calculations. For use in the EPAP calculations, these hydrocarbon emission levels were converted to methane molecular weight as specified in the Federal Register (Reference 1).

Smoke samples were collected at four different soiling rates bracketing the quoted soiling rate, for subsequent reflectance measurement and data curve fitting in accordance with Reference 1.

3. Emission Data Correction Factors

Emission data are presented two ways:

(a) as measured, either from the combustor rig on the demonstrator engine, or

(b) as corrected to standard-day production CF6-50C engine operating conditions.

In the rig tests, the needed corrections usually involve only humidity, which is uncontrolled, and combustor inlet pressure, which, except for idle, is reduced from actual engine levels to be within the facility capabilities. In these development engine tests, the engine inlet pressure, temperature, and humidity are all uncontrolled and the engine performance is deteriorated from production engine status, so, in general, engine data must be corrected for pressure, temperature, humidity, velocity, and fuel-air ratio. Correction factors used in this report are presented in Table 10. Generally, these factors are based on correlations of rig test data where each of the operating parameters was independently varied. The validity of these correction factors was subsequently established by correlations of engine data, as described in the following chapter.

4. EPA Parameter Calculation Procedure

a) Current Standard Procedure

The gaseous exhaust emission standards in Reference 1 are expressed in terms of maximum allowable quantity of emission per 1000 thrust hours, for a prescribed takeoff-landing cycle:

$$EPAP_i = \frac{\sum^{j} \left(\frac{t_j}{60}\right) \left(\frac{W_{f_j}}{1000}\right) \left(EI_{ij}\right)}{\sum^{j} \left(\frac{t_j}{60}\right) \left(\frac{F_{N_j}}{1000}\right)} \tag{1}$$

where

EI = Emission index (lb/1000 lb fuel)

EPAP = Emission parameter (lb/1000 lb thrust-hr)

R_N = Net thrust (lb)

t = Prescribed time (minutes)

W_f = Fuel flow rate (pph)

and the subscripts are:

i = Type of emission (CO, HC, NO_x)

j = Prescribed power level (idle, approach, climbout, and takeoff)

For a particular engine cycle, Equation 1 can be reduced to:

$$EPAP_i = \sum^{j} (C_j) \quad (EI_{ij}) \tag{2}$$

where:

$$C_j = \frac{\left(\frac{t_j}{60}\right) \left(\frac{W_{f_j}}{1000}\right)}{\sum^{j} \left(\frac{t_j}{60}\right) \left(\frac{F_{N_j}}{1000}\right)} \tag{3}$$

For Class T2 engine (Rated Thrust $\geq$ 8000 lb), such as the CF6-50, the prescribed times are 26.0, 4.0, 2.2 and 0.7 minutes at idle, approach, climbout and takeoff power. The other parameters needed to evaluate the coefficients (C_j) for the CF6-50C engine cycle are shown in Table 12. The resulting EPAP equations for various assumed idle thrust settings are:

i) Standard (3.3%) idle thrust

$$EPAP_{i,3.3} = 0.1349 \, (EI_{i,idle}) + 0.0904 \, (EI_{i,approach}) + 0.1461 \, (EI_{i,climbout}) + 0.0565 \, (EI_{i,takeoff}) \tag{4}$$

ii) Increased (5.0%) idle thrust

$$EPAP_{i,5.0} = 0.1451\,(EI_{i,idle}) + 0.0826\,(EI_{i,approach}) + 0.1335\,(EI_{i,climbout}) + 0.0516\,(EI_{i,takeoff}) \quad (5)$$

iii) Further increased (7.0%) idle thrust

$$EPAP_{i,7.0} = 0.1562\,(EI_{i,idle}) + 0.0749\,(EI_{i,climbout}) + 0.1211\,(EI_{i,climbout}) + 0.0468\,(EI_{i,takeoff}) \quad (6)$$

For Class T2 engines, the allowable EPAP levels for CO, HC, and NO_x are 4.3, 0.8, and 0.3 lb/1000 lb thrust-hr, respectively, in these standards.

b) <u>Draft Revised Standard Procedure</u>

The draft revised gaseous emission standards in Reference 2 are expressed in terms of maximum allowable quantity of emission for the same prescribed takeoff-landing cycle normalized by rated thrust (instead of cycle summed thrust-hours). Also, the standards are expressed in SI units, so the EPA parameter calculation becomes:

$$EPAP_{i,draft} = \sum^{j} \frac{(60t_j)\ (W_{f_j})\ (EI_{ij})}{F_r} \quad (7)$$

where:

EI = Emission index (g/kg fuel)

EPAP = Emission Parameter, (g/kN)

F_r = Rated thrust (kN)

t = Prescribed time minutes)

W_f = Fuel flow rate, (kg/s)

and the subscripts are the same as before. As before, equation 7 can be reduced for a particular engine cycle to the form of equation 2, where now

$$\upsilon_{j,draft} = \frac{(60t_j)\ (W_{f_j})}{F_r} \quad (8)$$

The resulting EPAP equations for the CF6-50C engine cycle are:

i) Standard (3.3%) idle thrust

$$EPAP_{i,3.3,draft} = 1.062\,(EI_{i,idle}) + 0.711\,(EI_{i,approach}) + 1.150\,(EI_{i,climbout}) + 0.445\,(EI_{i,takeoff}) \quad (9)$$

ii) Increased (5.0%) idle thrust

$$EPAP_{i,5.0,draft} = 1.250\ (EI_{i,idle}) + 0.711\ (EI_{i,approach}) + 1.150\ (EI_{i,climbout}) + 0.445\ (EI_{i,takeoff}) \quad (10)$$

iii) Further increased (7.0) idle thrust

$$EPAP_{i,7.0,draft} = 1.483\ (EI_{i,idle}) + 0.711\ (EI_{i,approach}) + 1.150\ (EI_{i,climbout}) + 0.445\ (EI_{i,takeoff}) \quad (11)$$

For the CF6-50C engine, the allowable EPAP levels for CO, HC, and NO_x are 36.1, 6.7, and 39.3 g/kN, respectively, which include a 19 percent credit in the NO_x standard for the high pressure ratio (29.44:1) and associated high combustor-inlet temperature (826.3 K) at rated conditions.

CHAPTER III

RESULTS AND DISCUSSION

A. INTRODUCTION

The Phase III Program consisted of both component rig tests and CF6-50 engine tests of a new demonstrator Double Annular Combustor and its associated fuel supply/control system. Phase III rig tests were conducted to check the operating and performance characteristics with respect to engine installation requirements. The combustor and fuel supply/control system were then assembled into a CF6-50 development engine. The engine and a new exhaust gas sampling and traversing system were installed in an engine development test cell, and a series of emissions and performance tests were conducted. Results of these tests are summarized in the following sections of this chapter. Detailed results are continued in Appendix B.

B. COMPONENT TEST RESULTS

1. Combustor Rig Test Summary

The Phase III Program Plan was to conduct approximately six component rig tests of the new demonstrator Double Annular Combustor, prior to its assembly in the CF6-50 engine, to determine its operating and emission characteristics and to verify that all installation and performance requirements were satisfied. Initial component checkout tests of the combustor showed performance and operating characteristics to be, for the most part, satisfactory and virtually the same as those of the Phase II prototype configuration. However, the CO and HC emission levels were substantially higher.

After this finding, an extensive series of diagnostic and development tests of the combustor was conducted in an effort to reduce CO and HC emission levels at idle. Several pilot-stage modifications were defined and evaluated. Fuel spray characteristics, swirl cup geometry, and outer liner dilution airflow distribution were systematically varied to correct the deficiencies and to more precisely duplicate the pilot-stage design of the Phase II prototype combustor. Details of these modifications are contained in Appendix A, and test results are contained in Appendix B. Some CO and HC emission reductions were realized from these efforts, but levels equivalent to those of the Phase II prototype combustor were not attained. It appears that higher CO and HC emission levels at idle must be associated with some slight differences in the pilot-stage liner and centerbody cooling airflows and/or in the penetration and mixing characteristics of the swirl cup and dilution airflows. The exact causes of these higher CO and HC levels can probably be identified with additional testing and subsequently corrected.

However, the required corrections will involve some significant reworking of the pilot-stage dome assembly and its cooling liner assembly. Therefore, it was decided to proceed with the demonstrator engine tests to determine the overall performance and operating characteristics of the advanced combustor rather than further delay the program.

2. Emission Test Results

The final series of combustor rig checkout tests included a high pressure test to determine the performance/emission characteristics of the exact combustor configuration to be used in the engine demonstration tests. Test conditions were selected to show the effects of engine power setting, fuel flow split, and ambient temperature on emissions levels. Results, listed in Table B-6, were analyzed to establish the correlations of emissions indices with combustor operating parameters which are shown in Figures 25 through 30. In these figures, measured emission levels are plotted against the combustor operating parameters that are the bases for the emission correction factors shown in Table 16 and discussed in Chapter III, Section F3. The plotted symbols are the measured data, the lines are regression curve fits of the data, and, for reference, values of the operating parameters for the CF6-50 production engine on a standard day are indicated.

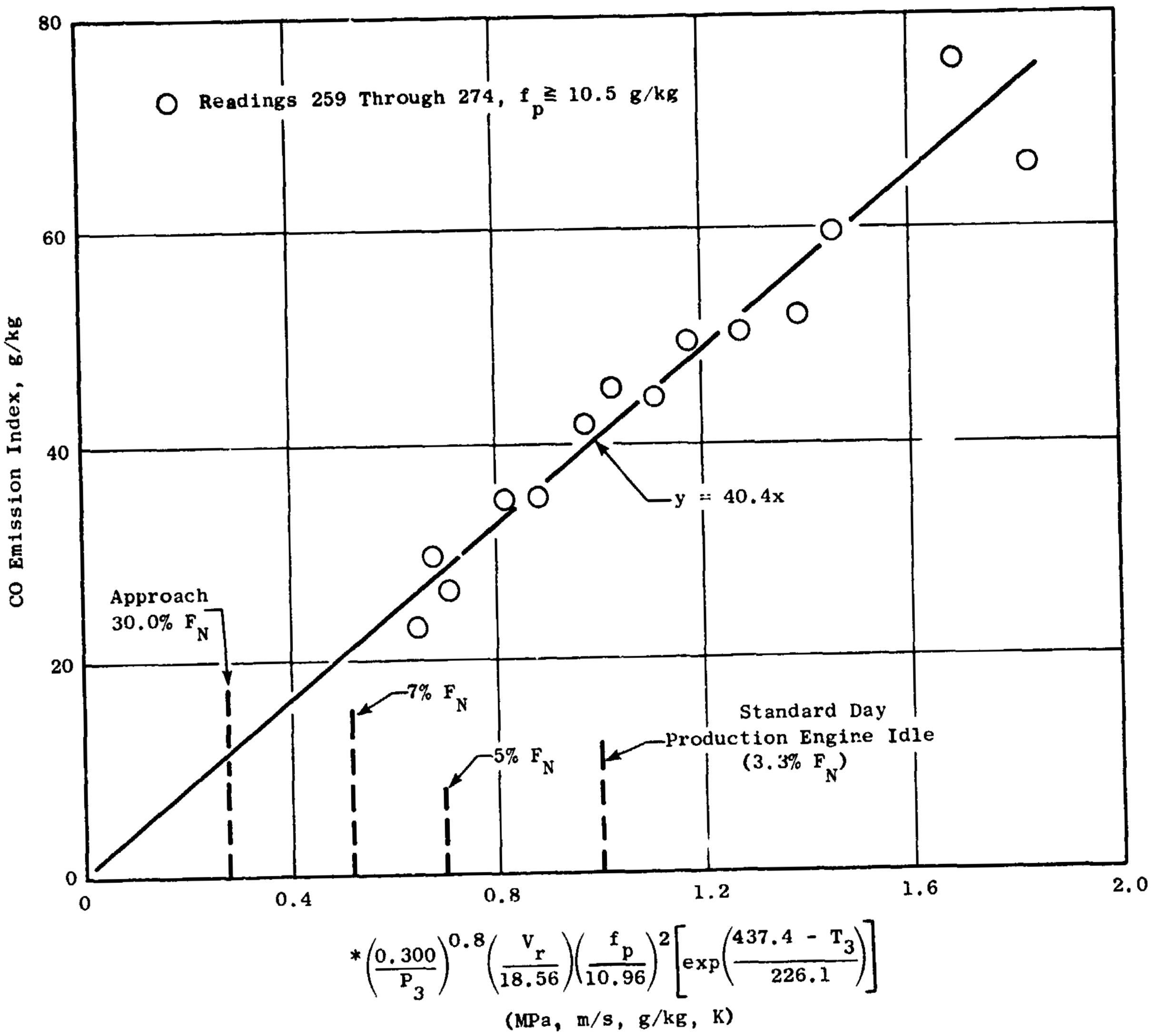
CO, HC, and NO_x emission levels with only the pilot stage fueled at simulated low-power engine operating conditions are shown in Figures 25, 26, and 27, respectively. Each of these plots correlates the data quite well over the range of simulated idle to approach power level engine operating conditions.

Emission levels of CO, HC, and NO_x with both stages fueled at simulated high-power engine operating conditions are shown in Figures 28, 29, and 30, respectively. The NO_x data, Figure 30, correlate quite well over the range of simulated 45 percent thrust to takeoff power level engine operating conditions. The CO and HC data, shown in Figures 28 and 29, are more difficult to correlate, as was found in Phase II (Reference 6).

Predicted engine emission indices and EPA parameters, based on the final series of combustor rig tests, are listed in Table 17. As in previous Phase II tests, it was found that the best combined EPA parameter results are obtained by fueling only the pilot stage at idle and approach power levels and supplying a high percentage of the fuel (80 to 90 percent) to the main stage at climbout and takeoff power levels. Using these fuel split schedules, the EPA parameters for CO, HC, and NO_x are:

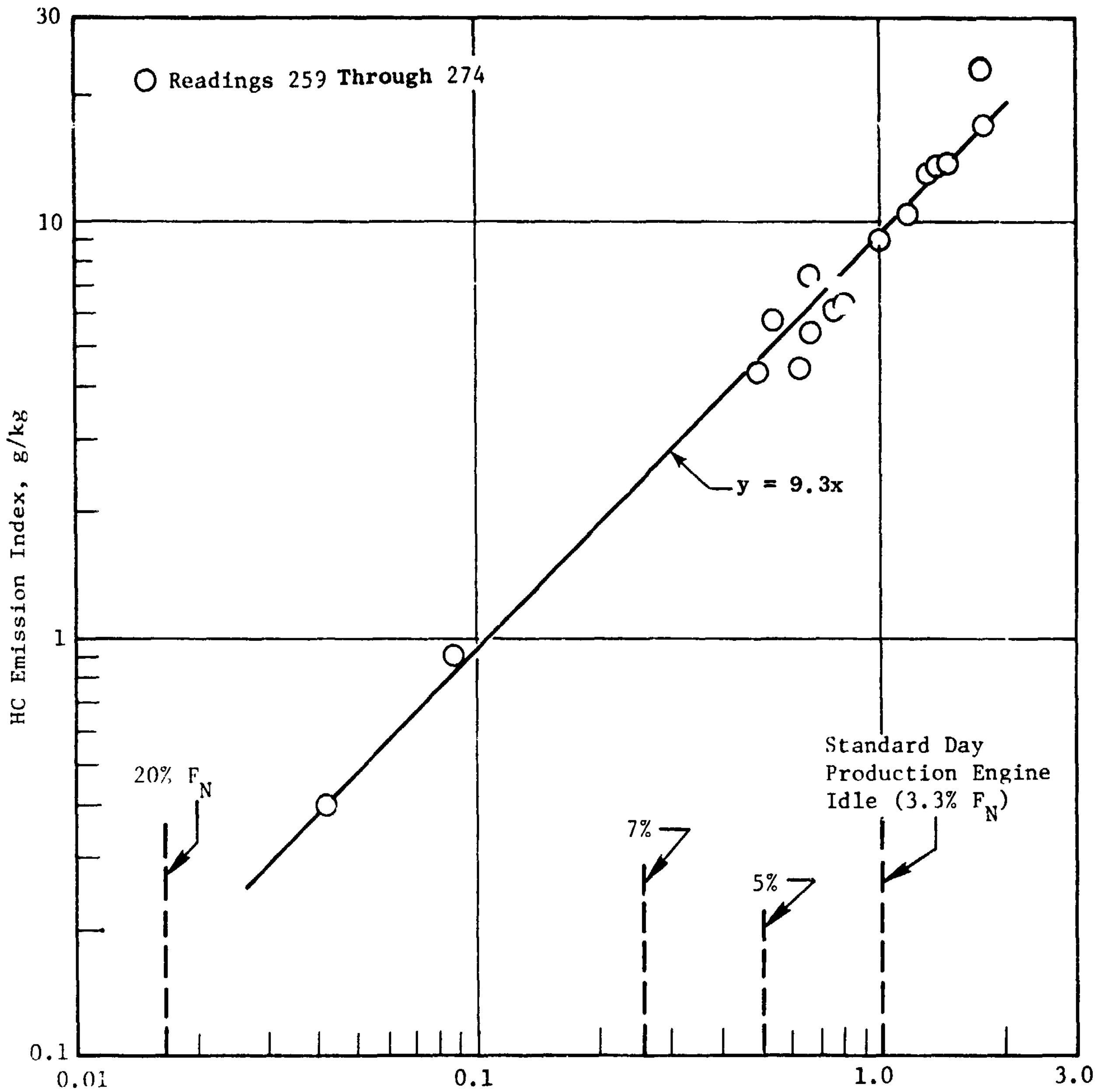
- Each about 160 percent of the current standard when the normal engine idle power setting (3.3 percent of takeoff thrust) is assumed.

- Reduced to about 103, 45, and 143 percent, respectively, of the current standard when 7.0 percent idle thrust setting is assumed.



* Parameter Number 2 from Table 16.

Figure 25. Effect of Combustor Operating Conditions on CO Emissions with Only Pilot Stage Fueled - Final Rig Test, Configuration E11.

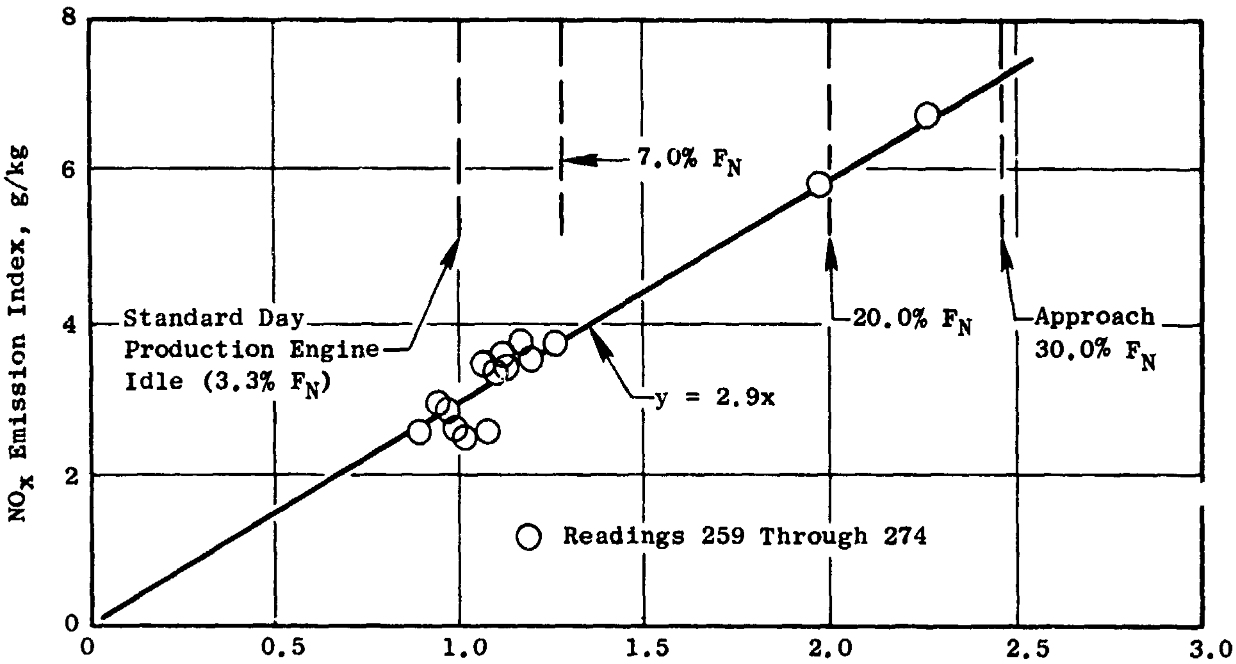


$$* \left(\frac{0.300}{P_3}\right)^2 \left(\frac{V_r}{18.56}\right) \left(\frac{10.96}{f_p}\right)^{1.2} \left[\exp\left(\frac{437.4 - T_3}{71.7}\right)\right]$$

(MPa, m/s, g/kg, K)

***Parameter Number 3 from Table 16.**

Figure 26. Effect of Combustor Operating Conditions on HC Emissions with Only Pilot Stage Fueled - Final Rig Test, Configuration E11.

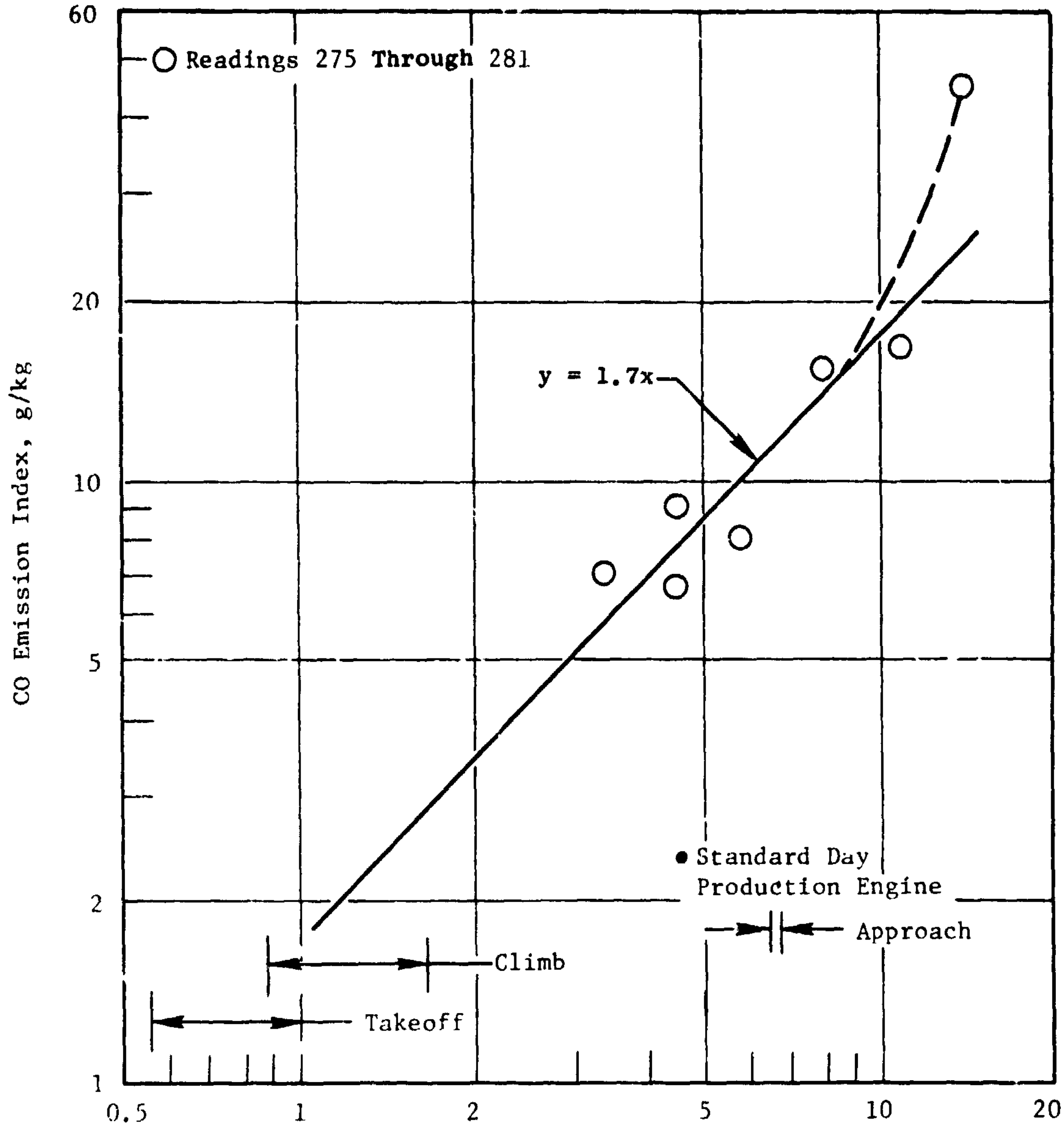


$$*\left(\frac{P_3}{0.300}\right)^{0.2}\left(\frac{18.56}{V_r}\right)\left(\frac{10.96}{f_p}\right)^{0.3}\left\{\exp\left[\left(\frac{T_3 - 437.4}{211.1}\right)+\left(\frac{6.29 - H_0}{53.2}\right)\right]\right\}$$

(MPa, m/s, g/kg, K, g/kg)

* Parameter Number 1 from Table 16.

Figure 27. Effect of Combustor Operating Conditions on NO_x Emissions with Only Pilot Stage Fueled - Final Rig Test, Configuration E11.



$$*\left(\frac{2.983}{P_3}\right)\left(\frac{V_r}{25.51}\right)\left(\frac{f_t}{23.62}\right)^{6.3}\left(\frac{3.07}{f_p}\right)^{1.7}\left(\frac{20.55}{f_m}\right)^{3.3}\left[\exp\left(\frac{826.3 - T_3}{83.3}\right)\right]$$

(MPa, m/s, g/kg, K)

*Paremeter No. 6 from Table 16.

Figure 28. Effect of Combustor Operating Conditions on CO Emissions, Both Stages Fueled - Final Rig Test, Configuration E11.

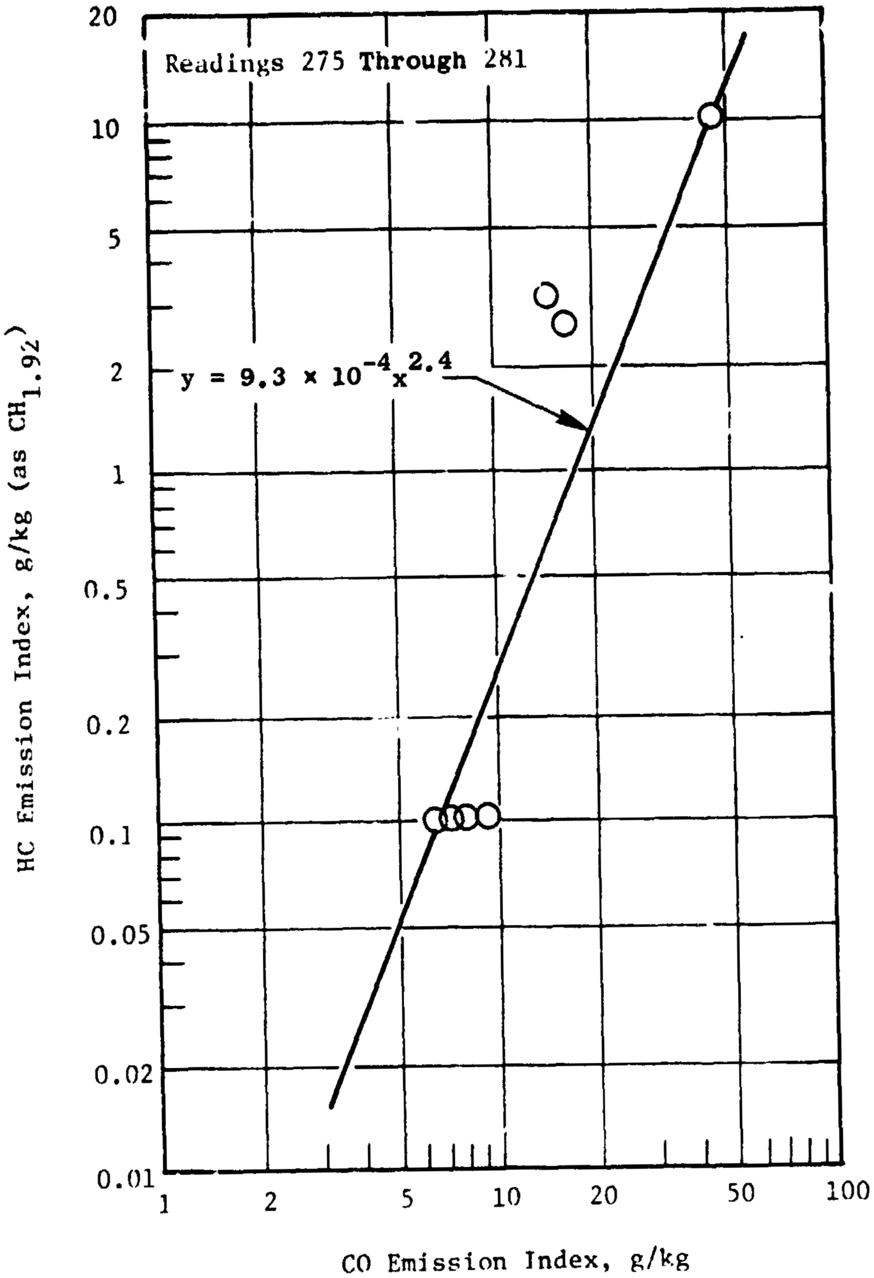
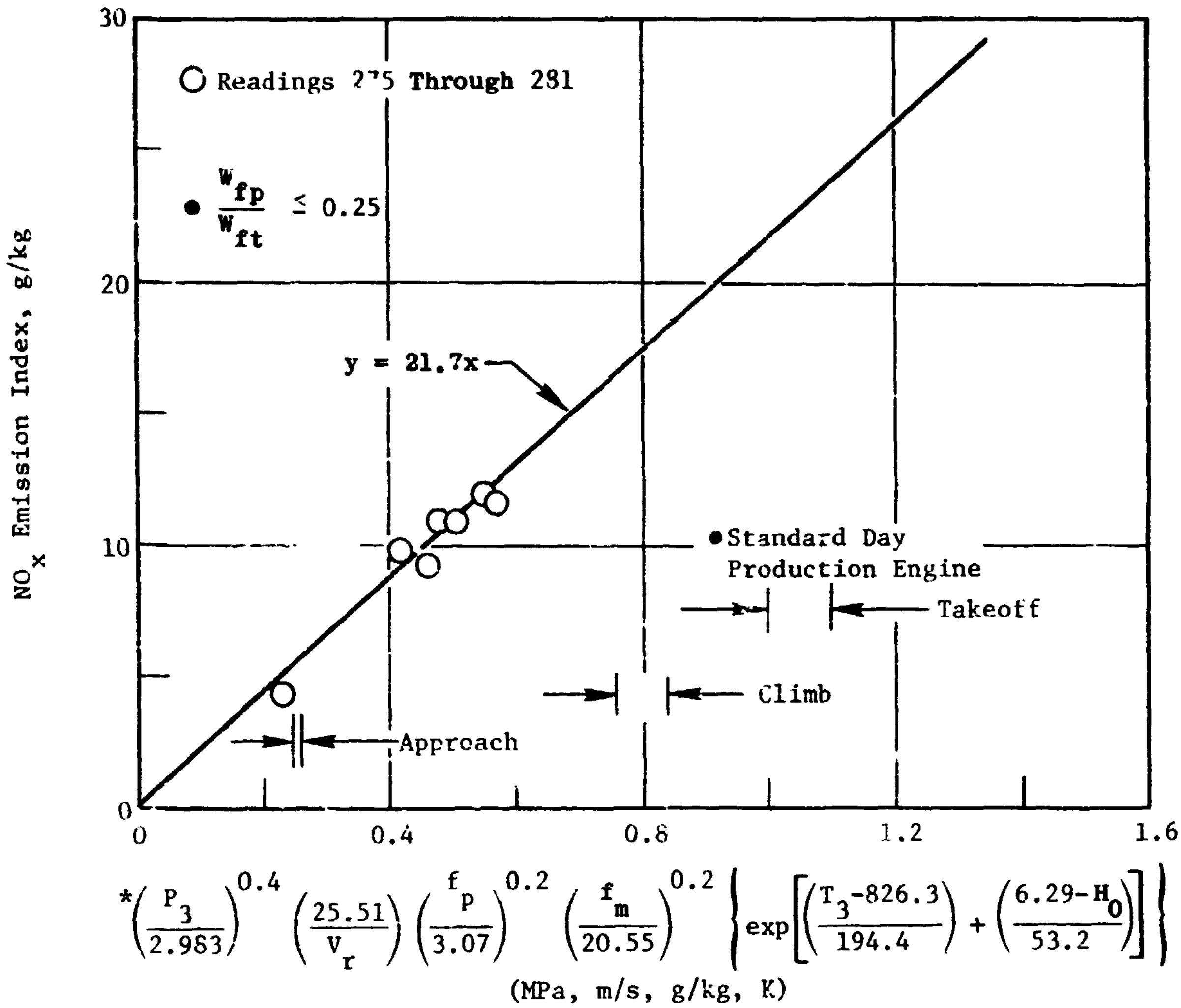


Figure 29. Variation of HC Emissions with CO Emissions, Both Stages Fueled - Final Rig Test, Configuration E11.



*Parameter No. 5 from Table 16.

Figure 30. Effect of Combustor Operating Conditions on NO_x Emissions, Both Stages Fueled, Final Rig Test, Configuration E11.

Table 16. Emissions Correction Factors.

Only Pilot Stage Fueled (Low Power)

$$EI_{NO_x\,corr} = \left(EI_{NO_x\,meas}\right)\left(\frac{P_{3\,std}}{P_{3\,test}}\right)^{0.2}\left(\frac{V_{r\,test}}{V_{r\,std}}\right)\left(\frac{f_{p\,test}}{f_{p\,std}}\right)^{0.3}\left\{\exp\left[\left(\frac{T_{3\,std} - T_{3\,test}}{211.1}\right) + \left(\frac{H_{o\,test} - 6.29}{53.2}\right)\right]\right\} \quad (1)$$

$$EI_{CO\,corr} = \left(EI_{CO\,meas}\right)\left(\frac{P_{3\,test}}{P_{3\,std}}\right)^{0.8}\left(\frac{V_{r\,std}}{V_{r\,test}}\right)\left(\frac{f_{p\,std}}{f_{p\,test}}\right)^{2.0}\left[\exp\left(\frac{T_{3\,test} - T_{3\,std}}{226.1}\right)\right], \qquad f_{p\,test} \geq 10.5 \quad (2)$$

$$EI_{HC\,corr} = \left(EI_{HC\,meas}\right)\left(\frac{P_{3\,test}}{P_{3\,std}}\right)^{2.0}\left(\frac{V_{r\,std}}{V_{r\,test}}\right)\left(\frac{f_{p\,test}}{f_{p\,std}}\right)^{1.2}\left[\exp\left(\frac{T_{3\,test} - T_{3\,std}}{71.7}\right)\right] \quad (3)$$

$$SN_{corr} = \left(SN_{meas}\right) - 11.54\left(f_{p\,test} - f_{p\,std}\right) \geq 0 \quad (4)$$

Both Stages Fueled (High Power)

$$EI_{NO_x\,corr} = \left(EI_{NO_x\,meas}\right)\left(\frac{P_{3\,std}}{P_{3\,test}}\right)^{0.4}\left(\frac{V_{r\,test}}{V_{r\,std}}\right)\left(\frac{f_{p\,test}}{f_{p\,std}}\right)^{0.2}\left(\frac{f_{m\,std}}{f_{m\,test}}\right)^{0.2}\left\{\exp\left[\left(\frac{T_{3\,std} - T_{3\,test}}{194.4}\right) + \left(\frac{H_{o\,test} - 6.29}{53.2}\right)\right]\right\} \quad (5)$$

$$EI_{CO\,corr} = \left(EI_{CO\,meas}\right)\left(\frac{P_{3\,test}}{P_{3\,std}}\right)\left(\frac{V_{r\,std}}{V_{r\,test}}\right)\left(\frac{f_{T\,std}}{f_{T\,test}}\right)^{6.3}\left(\frac{f_{p\,test}}{f_{p\,std}}\right)^{1.7}\left(\frac{f_{m\,test}}{f_{m\,std}}\right)^{3.5}\left[\exp\left(\frac{T_{3\,test} - T_{3\,std}}{85.3}\right)\right] \quad (6)$$

$$EI_{HC\,corr} = \left(EI_{HC\,meas}\right)\left(\frac{EI_{CO\,corr}}{EI_{CO\,meas}}\right)^{2.4} \quad (7)$$

$$SN_{corr} = \left(SN_{meas}\right) - 6.25\left(f_{m\,test} - f_{m\,std}\right) \geq 0 \quad (8)$$

Where

H_o, f_p and f_m are in (g/kg

T_3 is in (K)

(Others in consistent units)

Table 17. EPA Parameter Results, Final Combustor Rig Test, Configuration E11.

CF6-50C Engine Cycle				
Power Level, % of 50,410 lb	Fuel Split $\frac{W_{fp}}{W_{ft}}$	Emission Index* g/kg Fuel		
		CO	HC	NO_x
3.3	1.00	40.4	9.3	2.9
5.0	1.00	28.3	4.6	3.3
7.0	1.00	21.3	2.3	3.7
30.0	1.00	11.2	0.04	7.2
85.0	0.18	1.6	0	17.8
100.0	0.15	1.7	0	21.7

Assumed Idle Thrust percent	Current Federal Register Procedure EPA Emission Parameter lb/1000 lb thrust-hr			Revised Draft Procedure EPA Emission Parameter g/kN		
	CO	HC	NO_x	CO	HC	NO_x
3.3	6.79	1.26	4.87	53.5	9.9	38.3
5.0	5.34	0.67	4.57	45.9	5.8	39.4
7.0	4.43	0.36	4.29	42.1	2.0	40.7
EPA Standard	4.3	0.8	3.0	36.1	6.7	39.3

*Rig data are shown corrected to the standard-day production engine operating conditions listed in Table 12, using the correction factors shown in Table 16.

- 148, 148, and 97 percent, respectively, of the proposed revised standards, when the normal engine idle power setting (3.3 percent) is assumed.

3. Performance Test Results

Atmospheric pressure tests to provide detailed exit temperature pattern factor and profile characteristics were conducted with six different combustor configurations. Key results are shown in Figure 31 (average and peak radial profiles at nominal fuel flow split) and Figure 32 (variation of profile peak and pattern factor with fuel flow split). As shown in Figure 31, radial temperature profiles generally tend to be peaked inboard relative to limits specified for production engines. With conventional combustors, profiles can usually be adjusted to the desired shape by manipulation of location and quantities of dilution airflows. However, in the case of this low-emission lean-dome combustor, profile trimming is a much more difficult task because the quantities of airflow available are greatly reduced. In this design, 2 percent of the combustor airflow was budgeted for profile trim. Actual quantities used were:

Configuration E1	-	none
Configuration E2, E7	-	1.3%
Configuration E8, E11, E12	-	2.7%

and, as shown in Figure 31, very little change in location or magnitude of the average profile peak was achieved by these combustor modifications. However, as pilot-to-total fuel split was increased, profiles of all configurations tended to be peaked outboard and more nearly meet production engine limits, as shown in Figure 32. Production engine profile limits were mostly nearly met with Configuration E7, but pollutant emission levels were lower with Configuration E12 and the profile characteristics of configuration E12 were within the limits specified for short-time demonstration engine tests. Therefore, Configuration E12 was released for engine installation rather than further delay the program. However, the rig pattern factor test series did point out that the Double Annular low-emission combustor concept does require significantly more development effort in order to meet the production engine temperature profile requirements.

In all respects except profile and pattern factor, the combustor performance was quite good. Ground start/stability characteristics, shown in Figure 33, were excellent, as had been expected from Phase II Program prototype combustor tests. Lightoff, full propagation, and lean blowout all occurred at fuel flow rates well below the engine miniumum flow schedule, indicating that the normal starting and sub-idle acceleration procedures could be used in the demonstration engine tests. Furthermore, main-stage crossfire/stability characteristics at rig test pressure levels were in good agreement with Phase II results, and very low lean fuel-air ratio limits were predicted at actual engine crossfire pressure operating conditions (Figure 34). Low crossfire fuel-air ratio limits are needed to insure smooth and rapid engine acceleration characteristics.

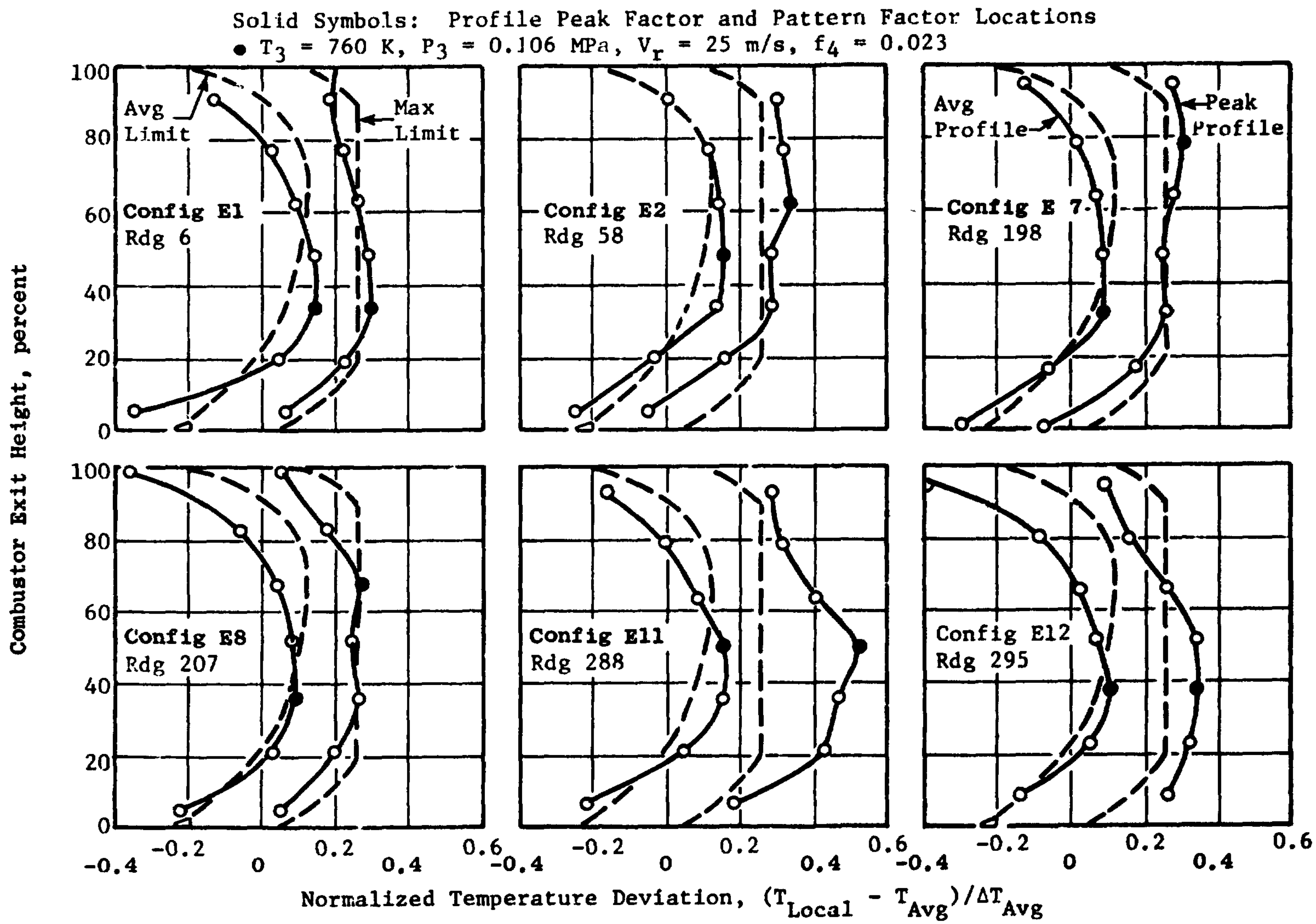


Figure 31. Combustor Exit **Radial** Temperature Profiles, Rig Tests at Simulated Takeoff Operating Conditions, $W_{fp}/W_{ft} \approx 0.2$.

- Profile Peak Factor = $(T_4$ Max. Avg Profile - T_4 Avg Overall$)/\Delta T_{Avg}$ Overall
- Pattern Factor = $(T_4$ Max. Local - T_4 Avg Overall$)/\Delta T_{Avg}$ Overall

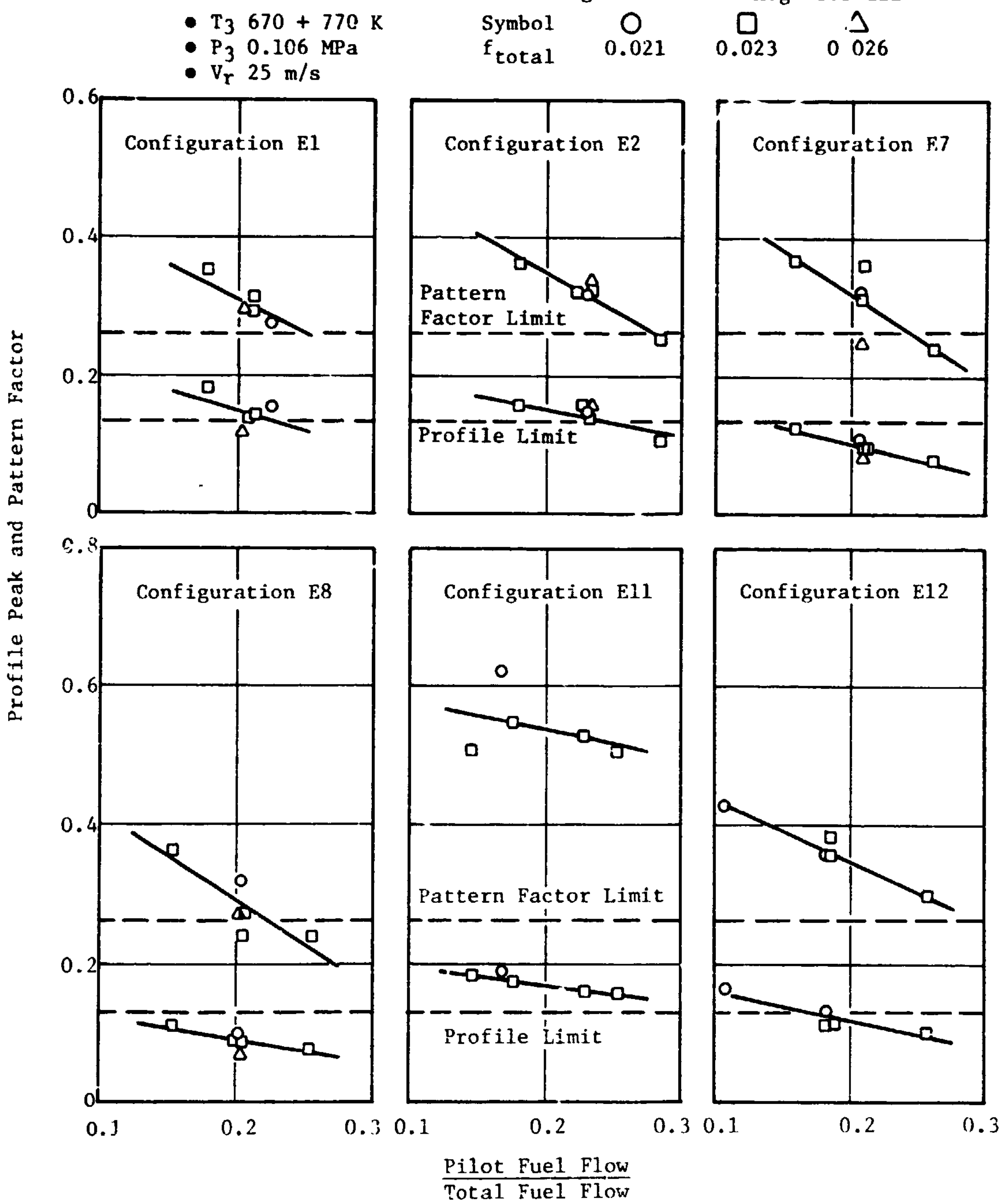


Figure 32. Combustor Exit Peak Temperature Characteristics, Rig Tests at Simulated High Power Operating Conditions.

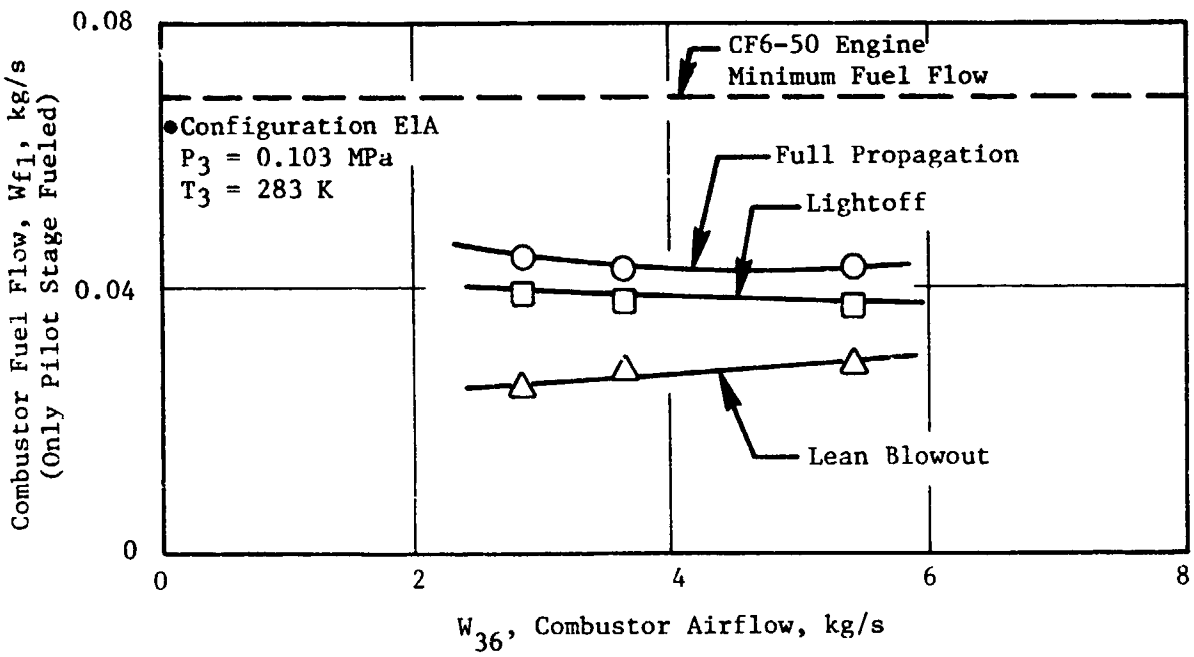


Figure 33. Ground Start/Stability Characteristics, Combustor Rig Tests.

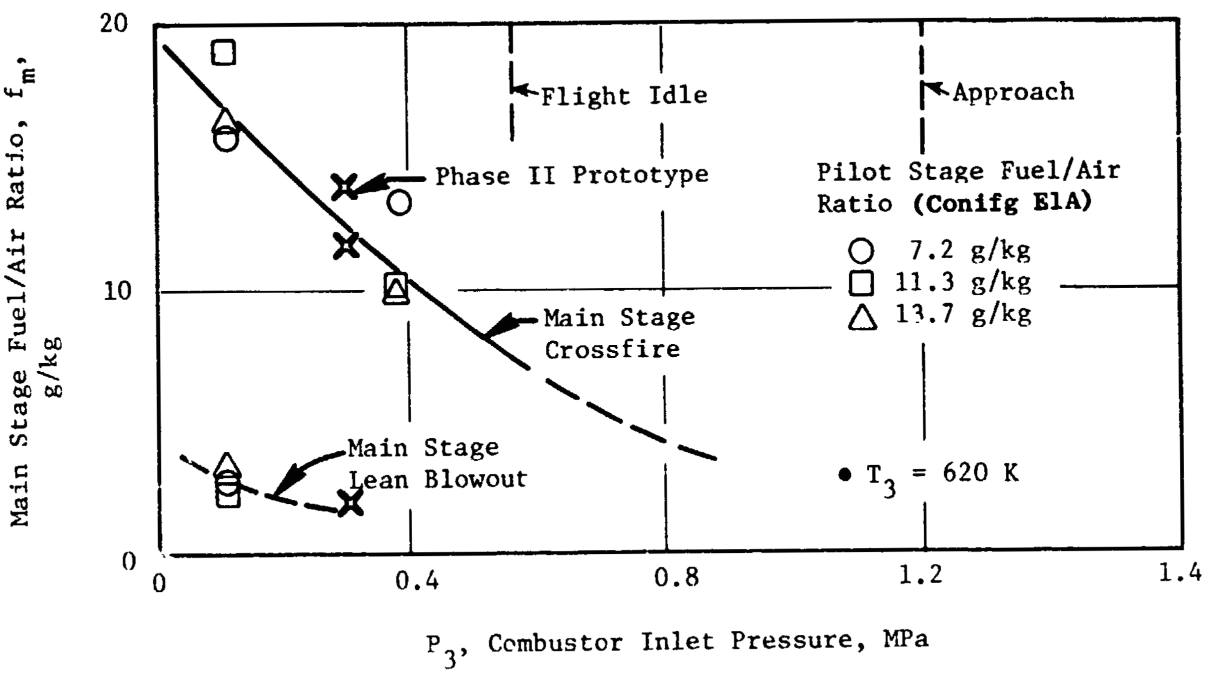


Figure 34. Main Stage Crossfire/Stability Characteristics, Combustor Rig Tests.

Combustor pressure drop characteristics, shown in Figure 35, were very close to the design intent (4.5 percent at takeoff conditions compared to 4.3 percent for the production combustor), and a correlation between pressure drop measured with inlet and exit impact pressure rakes and combustor-mounted pressure taps was established for use in calculating pressure drop in the engine tests.

Combustor dynamic pressure was monitored throughout these rig tests, and resonance was never detected. This was encouraging since some prototype combustor resonance had been encountered at both idle and high-power operating conditions in Phase II.

Combustor metal temperatures were for the most part very low, especially after small preferential cooling air modifications were made for Configuration E2. In the final high pressure test (Configuration E11), key regions were instrumented for direct comparison to engine tests. The liner temperature measurements indicated that the inner liner fourth panel would be the hottest region and the peak metal temperature at takeoff conditions would be about 1060 K (1450° F). This metal temperature level is close to the design intent and that which is generally needed for long-life production combustors.

4. Fuel System Test Results

A series of tests of the engine fuel control/supply system was conducted to determine the steady-state and transient operating characteristics of the new components and to insure that engine installation requirements were met.

A steady-state flow calibration of the fuel splitter was made; the results are shown in Figure 36. The unit functioned as intended. Both the main-stage cut-in point and the flow split after the cut-in point could be remotely and accurately set. The hysteresis loop, built in to prevent instability near cut-in, functioned as intended. A dynamic test of the fuel control/supply system was then conducted.

For the dynamic tests, the fuel splitter control together with fuel nozzle flow simulator valves, the standard engine pump and main fuel control unit, and associated supply/control elements were assembled and instrumented into a test loop where engine throttle bursts and chops were run. A typical transient data trace is presented in Figure 37, showing a fast acceleration and deceleration from simulated ground idle to takeoff to ground idle engine operating conditions for a preselected fuel splitter setting. In particular, data traces were examined for evidence of oscillations or instabilities, but none were found. The system responded as expected and satisfactory performance was demonstrated.

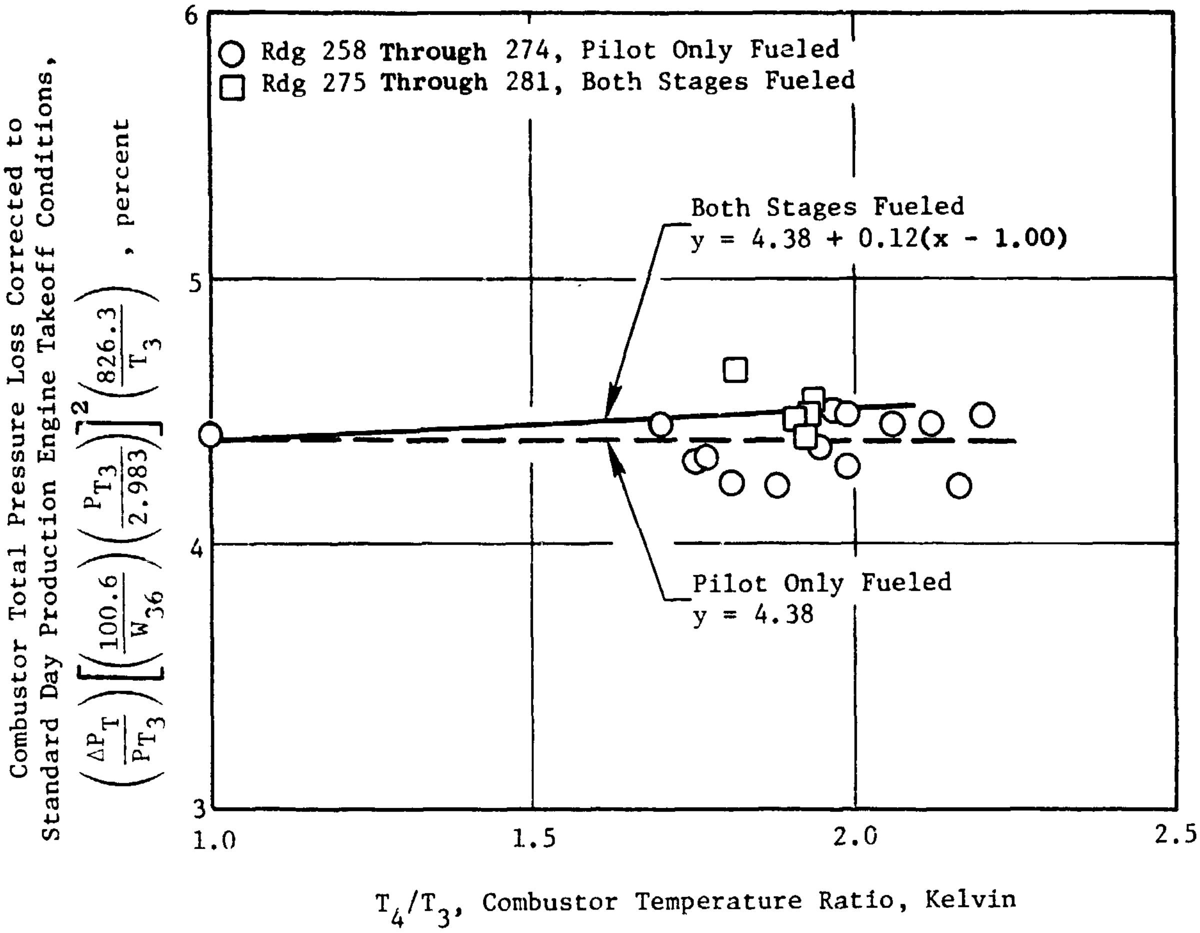


Figure 35. Pressure Loss Characteristics, Final Combustor Rig Test Configuration E11.

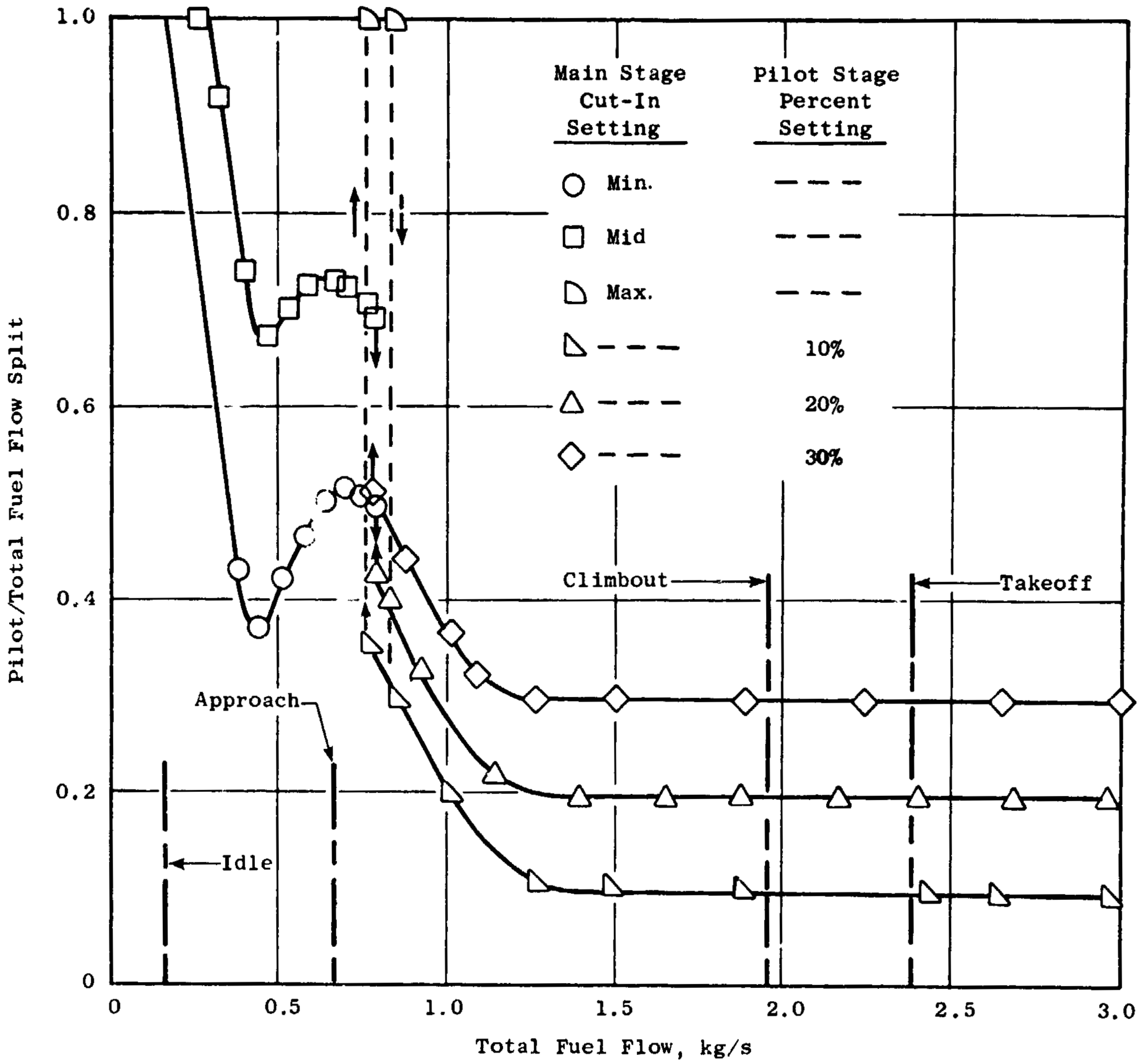
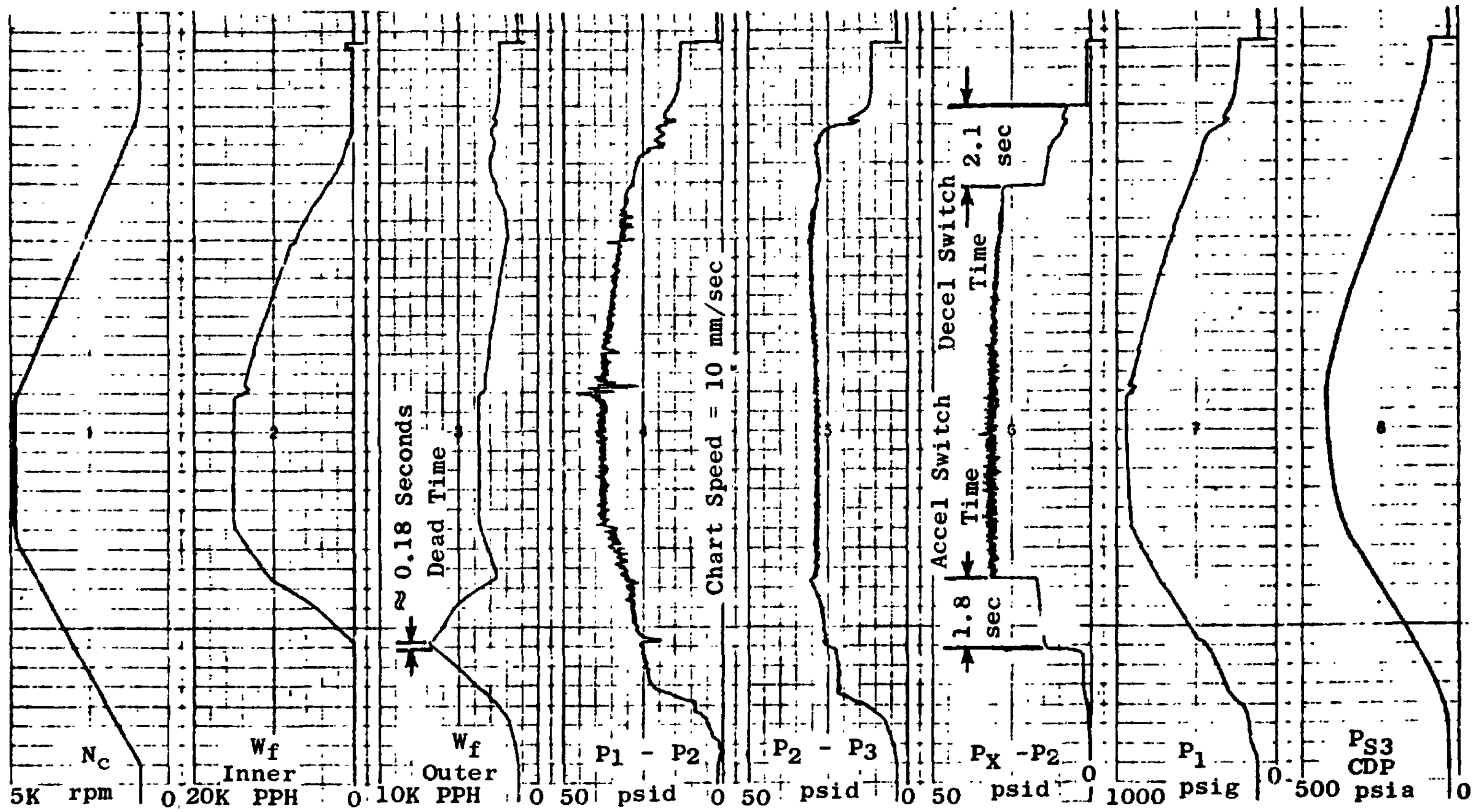


Figure 36. Fuel Splitter Control Steady State Flow Calibration.

P_1 = Splitter Fuel Inlet Pressure
P_2 = Mainstage Fuel Manifold Pressure
P_3 = Pilot Stage Throttling Valve Inlet Pressure
P_X = Control Piston Reference Pressure
P_{S3} = Compressor Discharge Static Pressure
N_c = Simulated Engine Speed
W_f = Fuel Flow Rate



- Fast Accel & Decel; Idle To Takeoff To Idle
- Approach Split = 1.0
- Pilot Split = 0.2

Figure 37. Typical Transient Da.a Trace, Engine Fuel System Checkout.

C. ENGINE TEST SUMMARY

A summary of the demonstrator engine test program is presented in Table 18. Eighteen test runs were made during the period between July 20, 1977, and August 29, 1977, to check out the engine/combustor instrumentation, establish operational procedures, and obtain all of the planned data for the basic Phase III Program and the four program addenda. As further shown in Table 18, over 200 steady-state data points were obtained, 67 starts were made, and over 55 hours of engine operation were accumulated. The test series generally went very smoothly, and no significant operational or instrumentational problems were encountered.

The tests were conducted in Development Engine Test Cell 7, which, as described in Chapter II, is located in the General Electric plant in Evendale, Ohio. The engine inlet ambient conditions are not controlled in this test cell, and during this test program, the weather was generally hot and humid. Engine inlet conditions varied as indicated below:

Ambient Temperature	295 to 306 K
Ambient Pressure	89 to 100 kPa
Ambient Humidity	6.4 to 14.3 g/kg

In some cases, the emissions data correction factors were quite large, due to the combined effects of the hot day ambient conditions and the deteriorated engine performance. Multipliers for correcting the measured emission levels to standard-day production engine combustor operating conditions were approximately of the following magnitudes:

Emission	Minimum Multiplier	Maximum Multiplier
CO	0.58 (at idle)	1.02 (at climb and takeoff)
HC	1.00 (at climb and takeoff)	1.46 (at idle)
NO_x	0.90 (at climb and takeoff)	1.14 (at idle)
Smoke Number	0.16 (at approach, with pilot only fueled)	0.93 (at idle)

JP-5 fuel with properties shown in Table 19 was used in all tests except the one on August 2, 1977, which was run with Diesel No. 2 fuel to fulfill the requirements of a program addendum described in Reference 12. As is quite often found, this lot of JP-5 fuel also met all of the ASTM specifications for Jet-A fuel.

D. ENGINE EMISSIONS TEST RESULTS

Sixty engine emission data points were obtained and are listed in Appendix B. Most of the planned power-level/fuel-split combinations were repeated several times. Further, two or more sampling techniques were usually employed on each test point, so that overall more than 123 power

Table 18. Demonstrator Engine Test Program Summary.

CF6-50 Engine No. 455-105/7, Cell 7, JP-5 Fuel Except 8/2/77

Test Date, 1977	Last Engine Log Reading	Lost DMS Reading	Last Start Number	Cumulative Engine Run Time	Cumulative Emissions Readings	Cumulative Turbulence Readings	Cumulative Accel/Decel Readings	Cumulative Start Readings	Type of Test
7/20	6	3	1	0:13	0	-	-	-	Checkout
7/22	17	9	2	2:02	5	-	-	-	Checkout
7/25	22	10	6	2:23	5	-	-	-	Checkout
7/26	35	32	8	6:55	11	-	-	-	Steady State Emissions & Performance
7/27	43	41	10	13:50	23	-	-	-	Steady State Emissions & Performance
7/28	44	53	12	17:[illegible]	33	-	-	-	Steady State Emissions & Performance
8/2	[illegible]	74	13	[illegible]:14	47	0	-	-	Turbulence Measurement & Diesel No. 2 Fuel
8/4	70	88	16	25:59	55	2	-	-	Turbulence Measurement & Sampling Technique
8/5	73	91	17	27:29	57	2	-	-	Turbulence Measurement & Sampling Technique
8/8	79	93	18	28:29	60	2	-	-	Turbulence Measurement & Sampling Technique
8/11	86	99	20	29:21	63	5	-	-	Turbulence Measurement & Sampling Technique
8/12	108	120	22	32:50	78	8	-	-	Turbulence Measurement & Sampling Technique
8/15	137	14[illegible]	2[illegible]	38:20	-	-	18	-	Acceleration/Deceleration (No Emission Rakes)
8/16	165	146	50	40:56	-	-	-	27	Starting/Sub-Idle Stall
8/23	177	158	52		-	-	-	-	Noise Measurement (8 readings)
8/24	192	169	54	47:39	-	-	-	-	Noise Measurement (8 readings)
8/25	207	176	64	49:34	-	-	26	34	Acceleeration/Starting (No Noise Rake)
8/2[illegible]	238	206	67	55:45	-	-	-	-	Engine Performance (Non-ECCP)

Table 19. Engine Test Fuel (JP-5) Analysis.

Fuel Property	Test Method	JP-5 Fuel, Engine Test
Composition:		
Aromatics, Vol. %	ASTMD1319	15.4
Olefins,m Vol. %	ASTMD1319	1.3
Napthalenes, Vol. %	ASTMD1840	1.6
Saturates, Vol. %	ASTMD1319	83.3
Hydrogen, Wt. %	ASTMD1018	14.0
Sulfur, Wt. %	ASTMD1266	0.08
Nitrogen, Wt. ppm	ASTMD3431	2.5
Volatility:		
Distillation Temperature, K	ASTMD86	
I.B.P.		450
10%		469
20%		475
50%		489
90%		516
F.B.P.		533
% at 478 K		25.5
Residue, %	ASTMD86	1.2
Loss, %	ASTMD86	0.8
Flashpoint, K	ASTMD93	330
Gravity, Specific (288.7/288.7 K)	ASTMD1298	0.8104
Fluidity:		
Viscosity at 310.9 K, mm^2/s	ASTMD445	1.53
Combustions:		
Net Heat of Combustion, MJ/kg	ASTMD2382	43.178
Smoke Point, mm	ASTMD1322	24.5

C-2

level/fuel-split sampling technique readings were obtained. The emission results of these tests are summarized in Figures 38 through 46 and Tables 20 and 21.

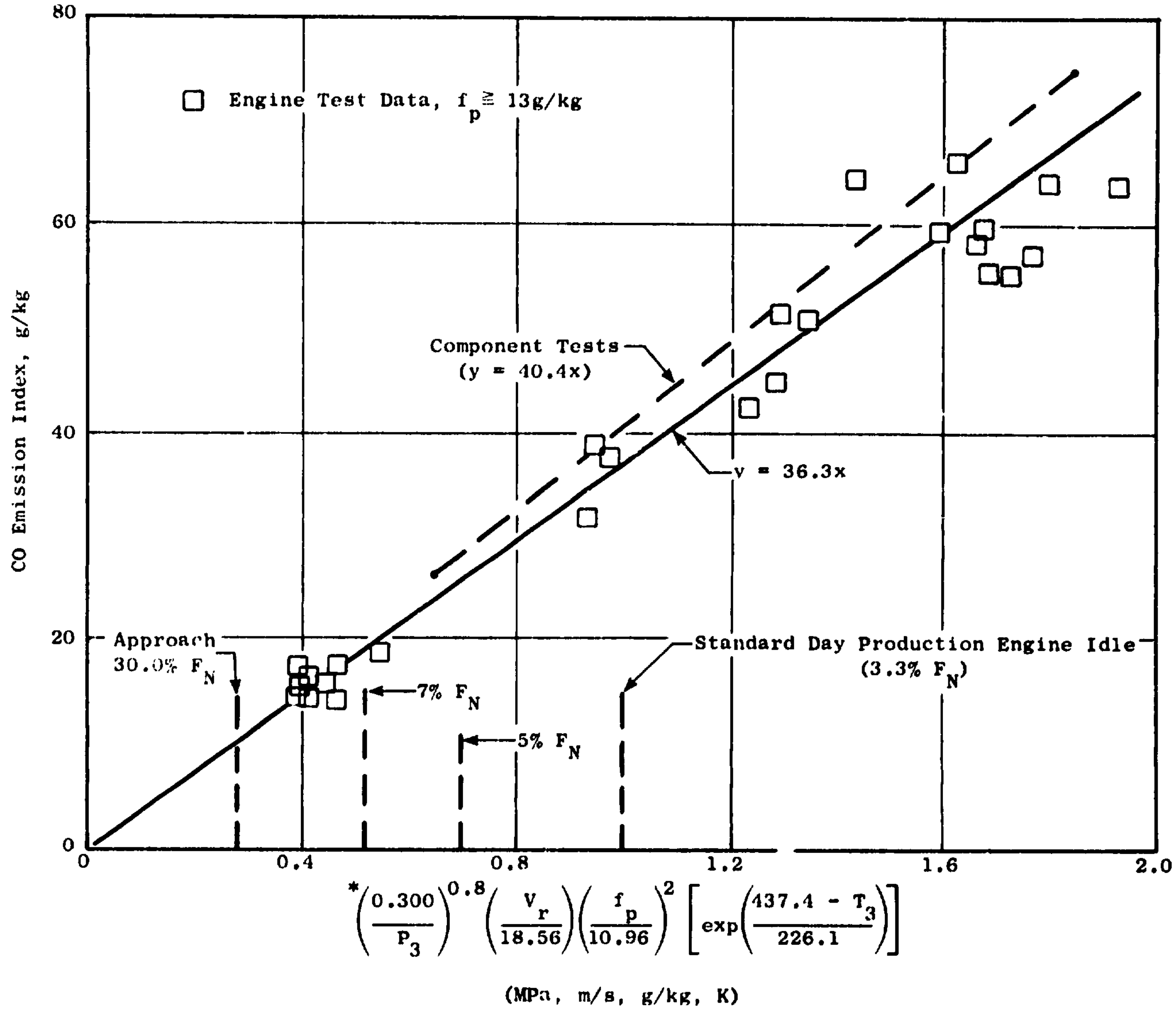
1. Corrected Emission Index and Smoke Number Results

As described in Chapter II, the gaseous emission correction factors were deduced from Phase II and Phase III rig test data and verified by the correlations shown in Figures 25 through 30. Identical plots of the engine gaseous emission data are shown in Figures 38 through 43. The following trends are indicated:

- CO emissions at low power operating conditions (Figure 38) correlate well with the rig-test-deduced parameter, but are about 10 percent lower.
- HC emissions (Figure 39) at standard idle conditions (X-1) were much lower in the engine than in the rig test.
- NO_x emissions at low power (Figure 40) correlate well with the component-deduced parameter, but are about 40 percent higher in the engine than in the rig test.
- CO emissions at high power (Figure 41) agree very well with the rig predictions, but as in the rig tests, the correlation deteriorates at intermediate powers (X>3).
- HC emissions (Figure 42) at high power agree quite well with component predictions.
- NO_x emissions at high power (Figure 43) correlate very well with the rig-deduced parameter, but levels were about 10 percent higher in the engine than in the rig test.

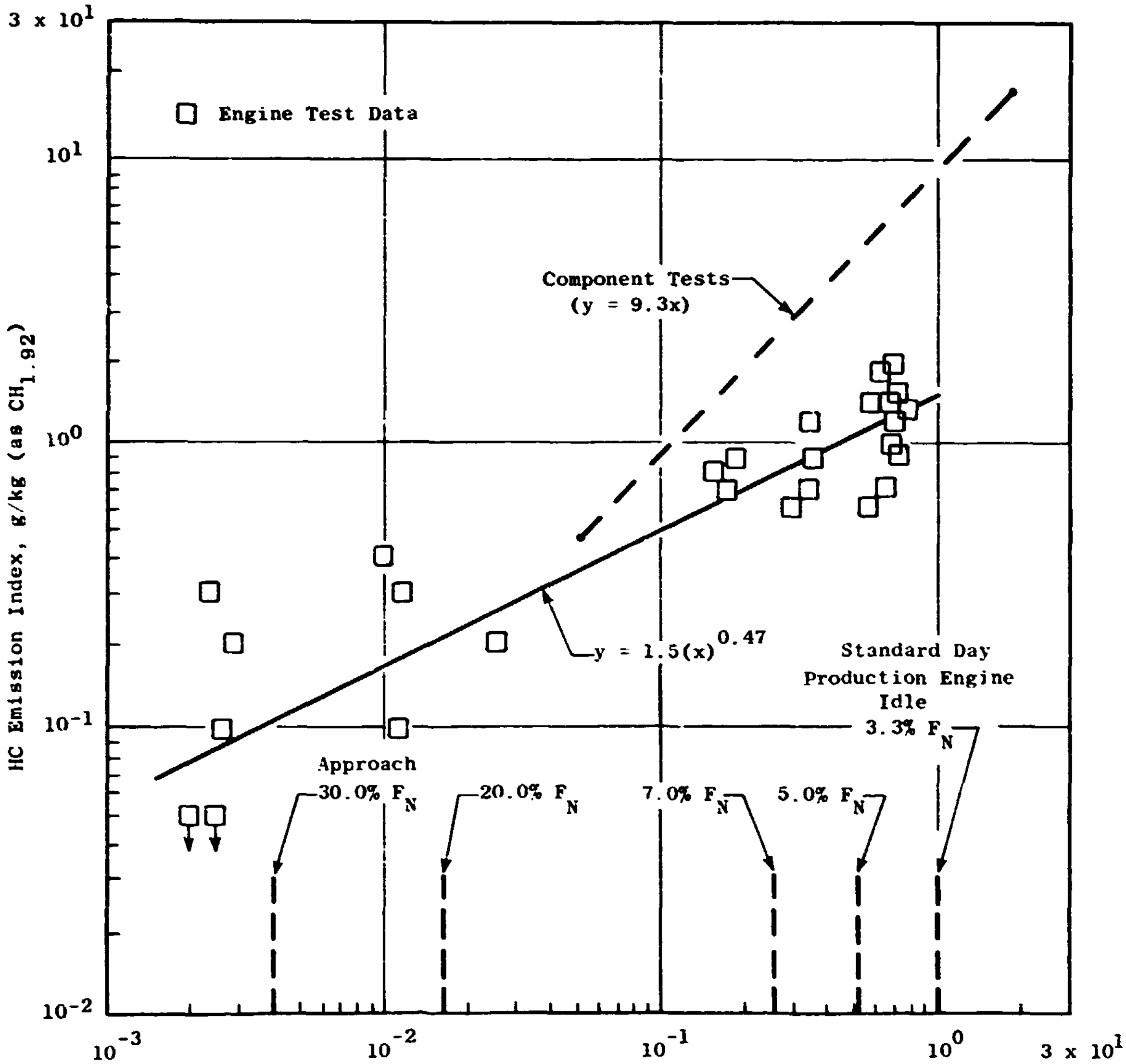
Thus, the engine data generally followed the trends expected, with changes in operating parameters indicating that the planned emission data correction procedures were valid. However, this analysis indicated that in some cases there were significant differences in rig and engine emission levels, particularly low-power NO_x and HC. The most probable explanation for these differences in emission levels is the lower combustor pressure drop in the demonstrator engine, at low-power operating conditions, relative to the rig tests. Combustor pressure drop data is presented in the Combustor Performance Characteristics section which follows.

Rig test smoke levels were generally extremely low, so in the final rig tests no measurements were made. However, as shown in Figure 44, engine smoke levels increased rapidly when a threshold fuel-air ratio in either the pilot or main stage was exceeded. As shown in Figure 44a, the threshold main-stage fuel-air ratio was 16.7 g/kg, and the EPA smoke requirement was exceeded at 19.5 g/kg. As shown in Figure 44b, the threshold pilot-stage fuel-air



* Parameter Number 2 from Table 16.

Figure 38. Effect of Combustor Operating Parameters on CO Emissions, Engine Tests with Only Pilot Stage Fueled.

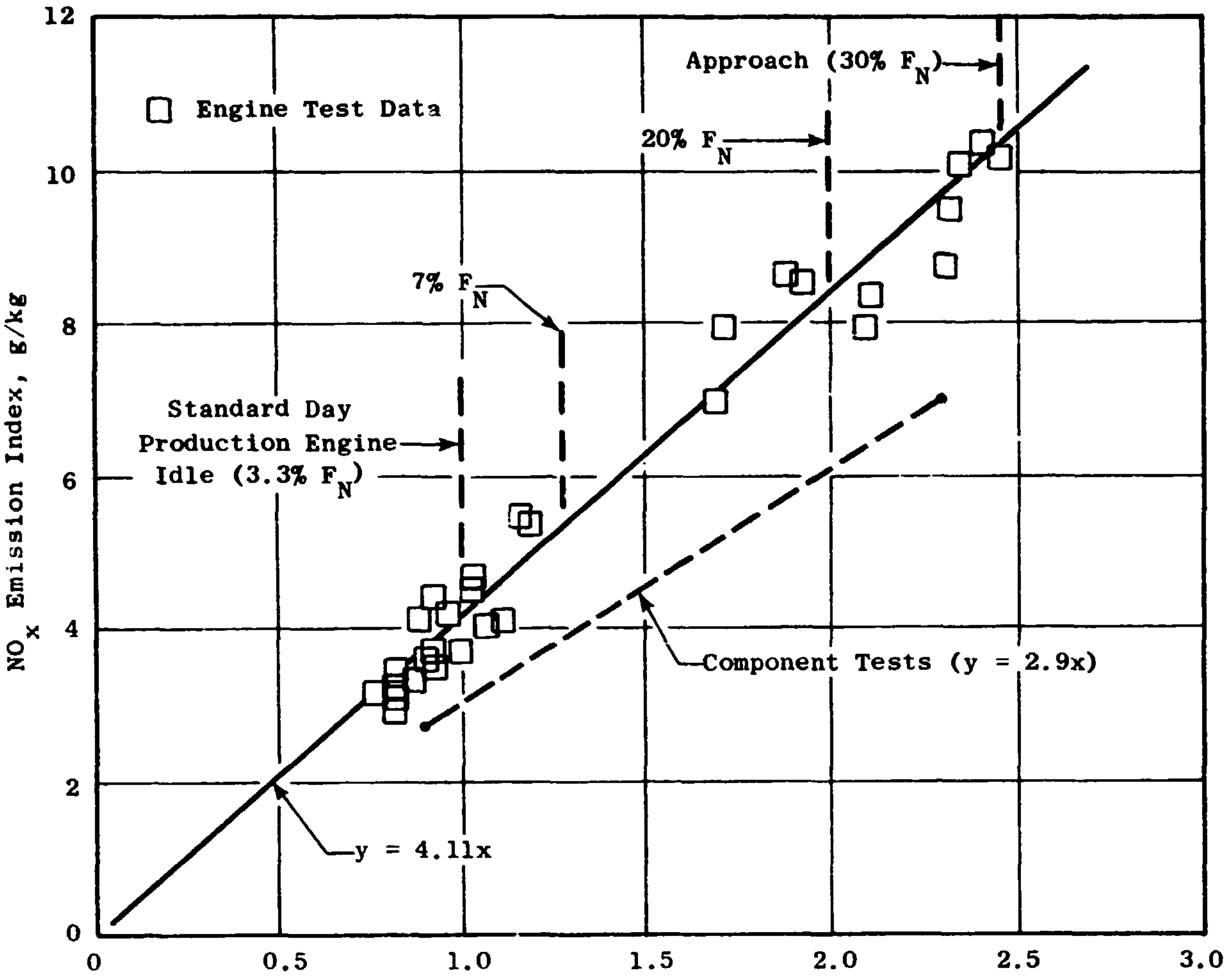


$$^{*}\left(\frac{0.300}{P_3}\right)^{2.0}\left(\frac{V_r}{18.56}\right)\left(\frac{10.96}{f_p}\right)^{1.2}\left[\exp\left(\frac{437.4 - T_3}{71.7}\right)\right]$$

(MPa, m/s, g/kg, K)

* Parameter Number 2 from Table 16.

Figure 39. Effect of Combustor Operating Parameters on HC Emissions, Engine Tests with Only Pilot Stage Fueled.

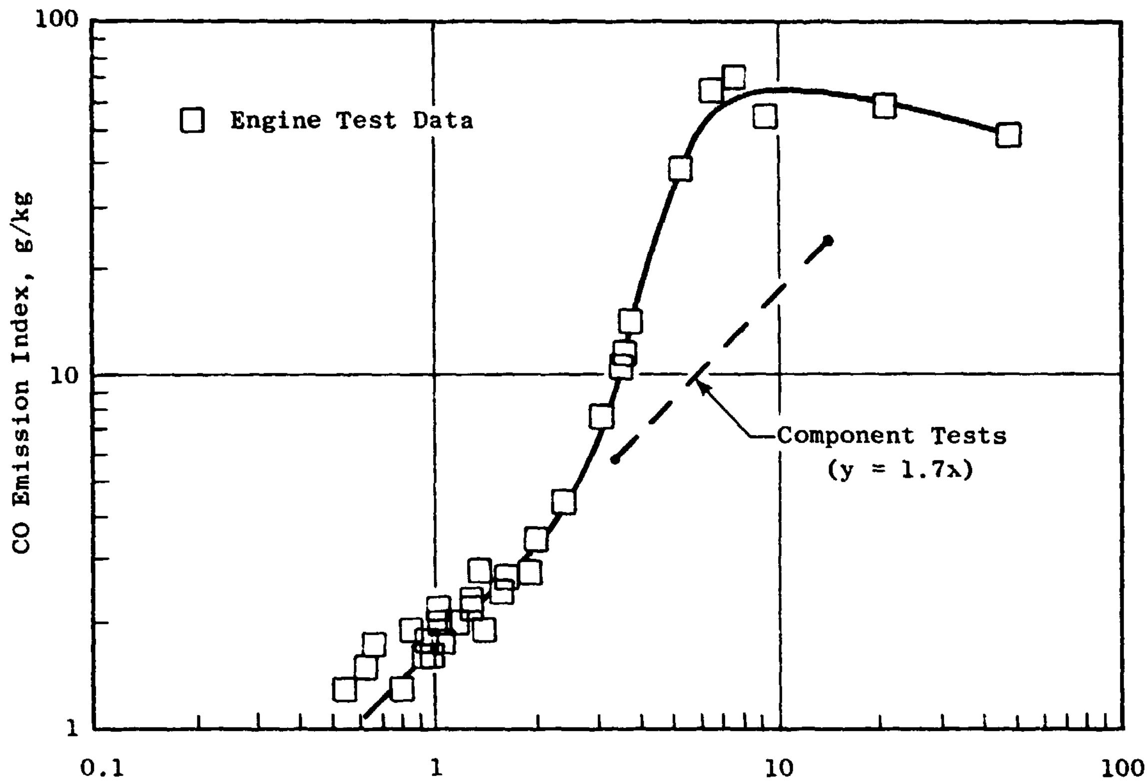


$$^{*}\left(\frac{P_3}{0.300}\right)^{0.2}\left(\frac{18.58}{V_r}\right)\left(\frac{10.96}{f_p}\right)^{0.3}\left\{\exp\left[\left(\frac{T_3-437.4}{211.1}\right)+\left(\frac{6.29-H_0}{53.2}\right)\right]\right\}$$

(MPa, m/s, g/kg, K)

* Parameter Number 1 from Table 16.

Figure 40. Effect of Combustor Operating Parameters on NO_x Emissions, Engine Tests with Only Pilot Stage Fueled.



$$^{*}\left(\frac{2.983}{P_3}\right)\left(\frac{V_r}{25.51}\right)\left(\frac{f_t}{23.62}\right)^{6.3}\left(\frac{3.07}{f_p}\right)^{1.7}\left(\frac{20.55}{f_m}\right)^{3.3}\left[\exp\left(\frac{826.3 - T_3}{83.3}\right)\right]$$

(MPa, m/s, g/kg, K)

* Parameter Number 6 from Table 16.

Figure 41. Effect of Combustor Operating Parameters on CO Emissions, Engine Tests with Both Stages Fueled.

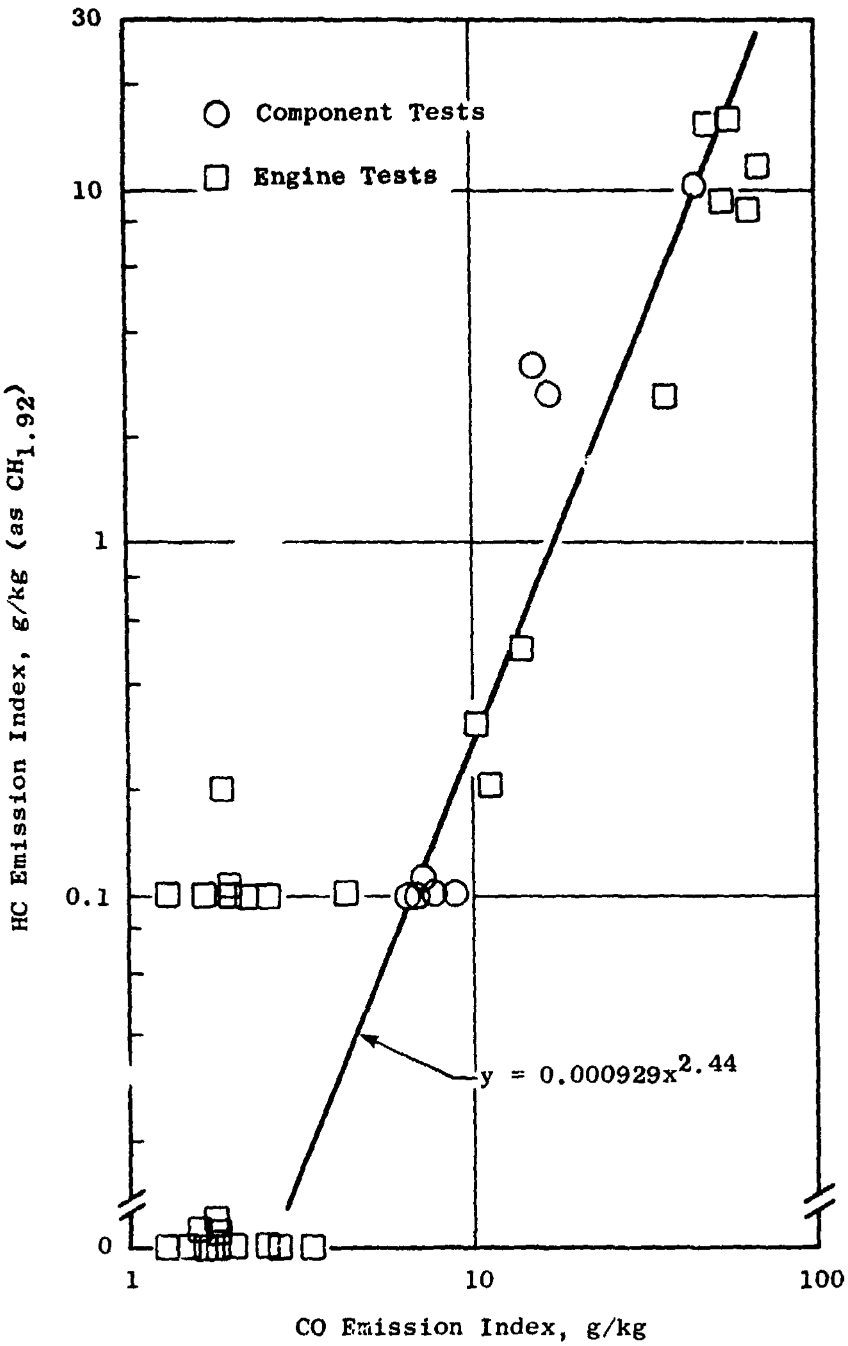
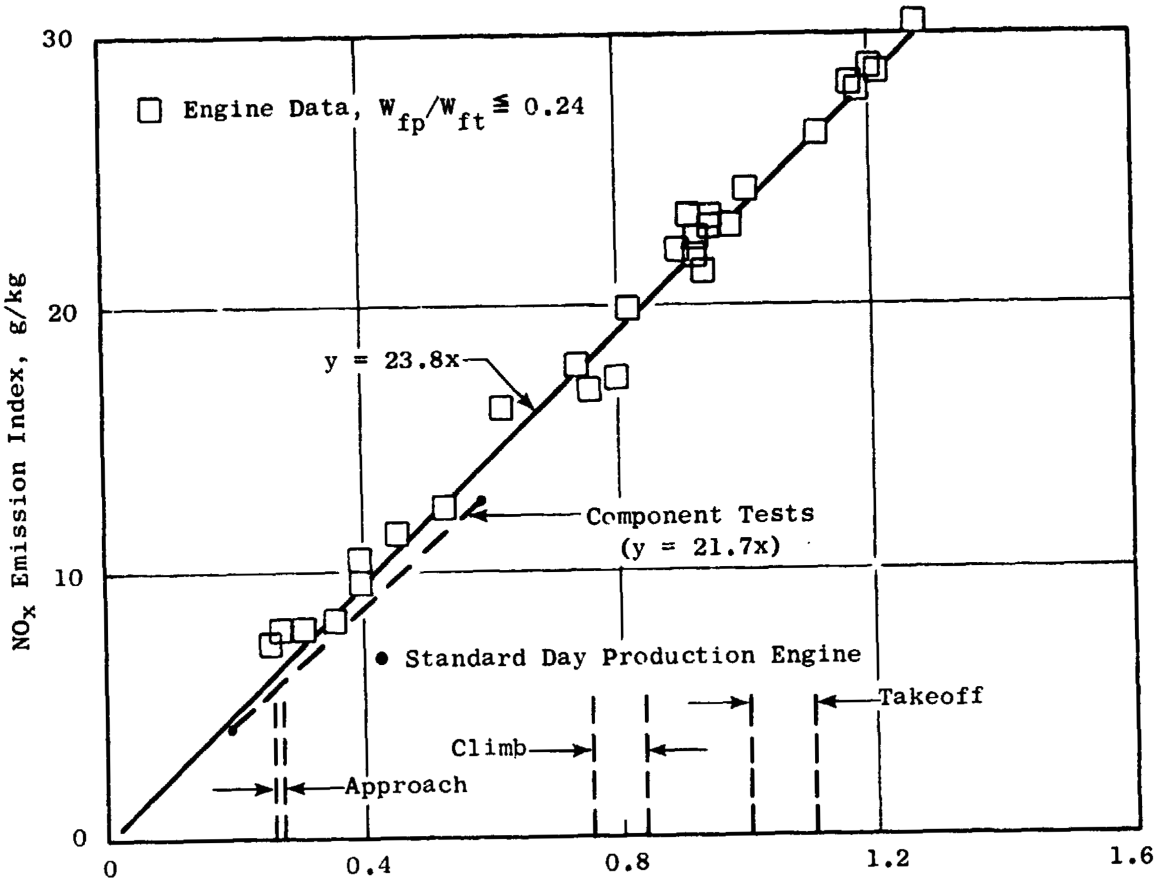


Figure 42. Variation of HC Emissions with CO Emissions, Engine and Component Tests with Both Stages Fueled.

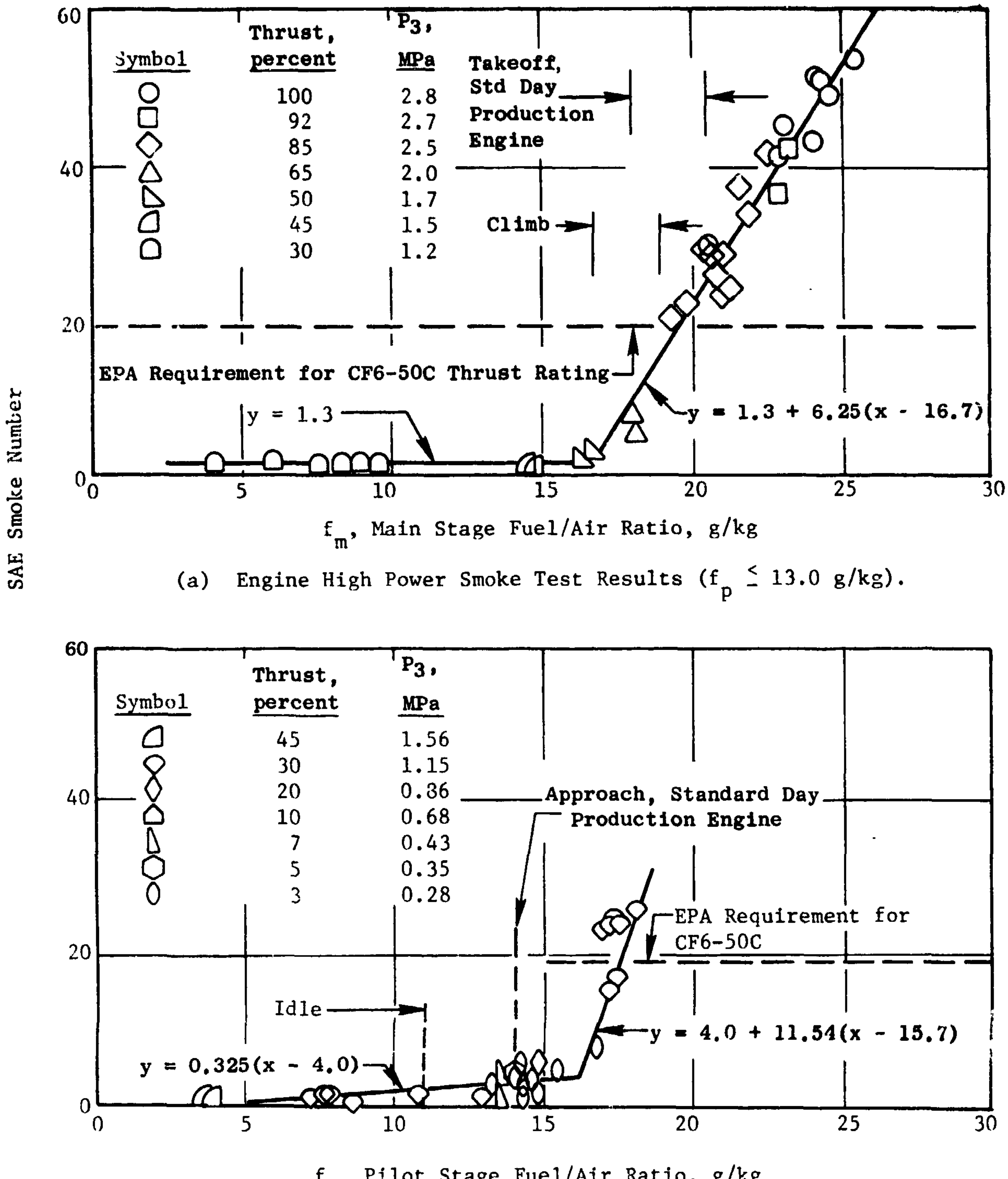


$$*\left(\frac{P_3}{2.983}\right)^{0.4}\left(\frac{25.51}{V_r}\right)\left(\frac{f_p}{3.07}\right)^{0.2}\left(\frac{f_m}{20.55}\right)^{0.2}\left\{\exp\left[\left(\frac{T_3 - 826.3}{194.4}\right) + \left(\frac{6.29 - H_0}{53.2}\right)\right]\right\}$$

(MPa, m/s, g/kg, K)

* Parameter Number 5 from Table 16.

Figure 43. Effect of Combustor Operating Parameters on NO_x Emissions, Engine Tests with Both Stages Fueled.



(a) Engine High Power Smoke Test Results ($f_p \leq 13.0$ g/kg).

(b) Engine Low Power Smoke Test Results ($f_m \leq 15.0$ g/kg).

Figure 44. Effect of Combustor Operating Parameters on Smoke Emission Levels, Engine Tests.

Note: The NO_x emission index and the SAE smoke number are corrected to standard day and production engine conditions.

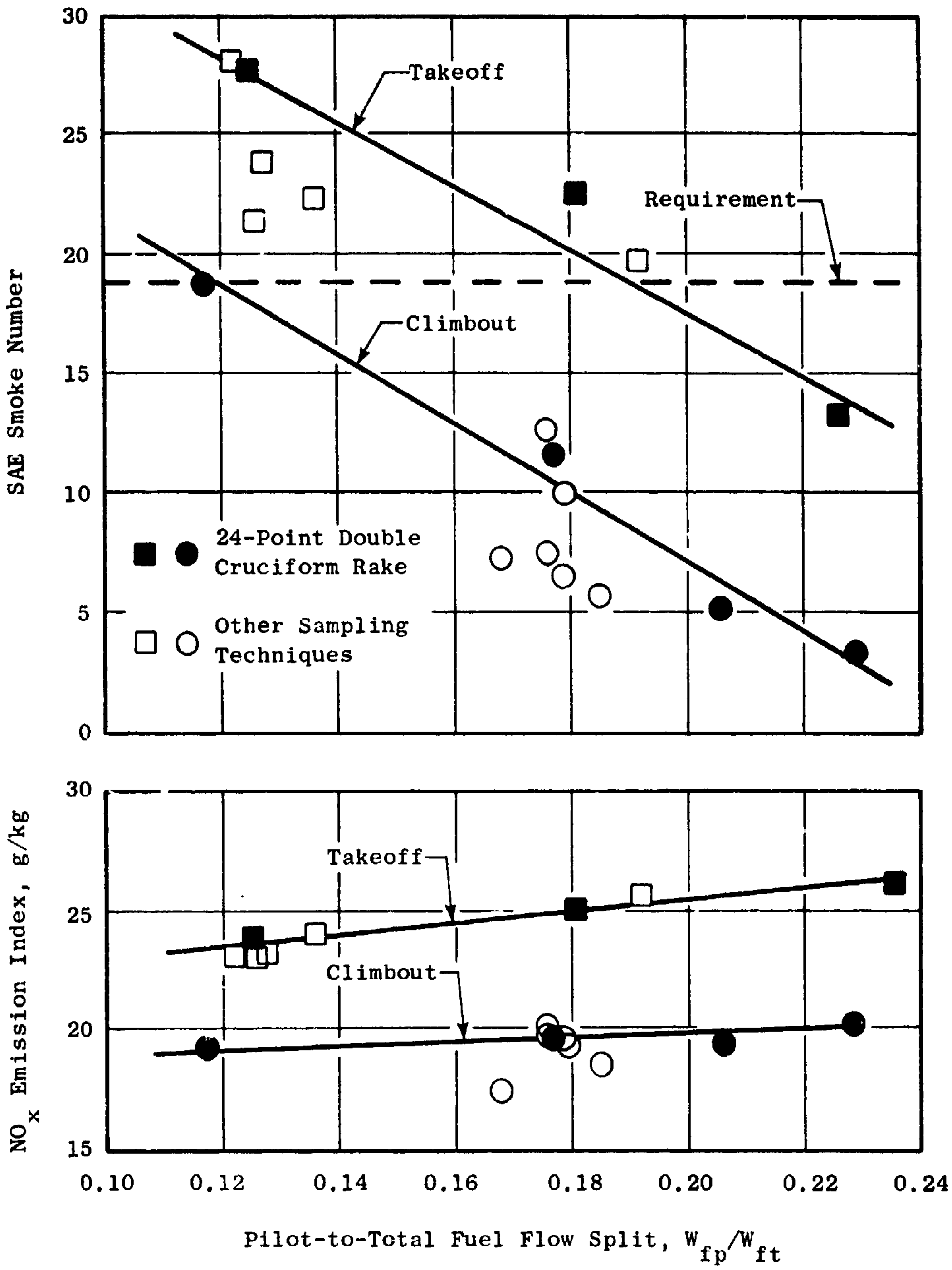


Figure 45. Effect of Fuel Split on High Power Smoke and NO_x Emission Levels, Engine Tests.

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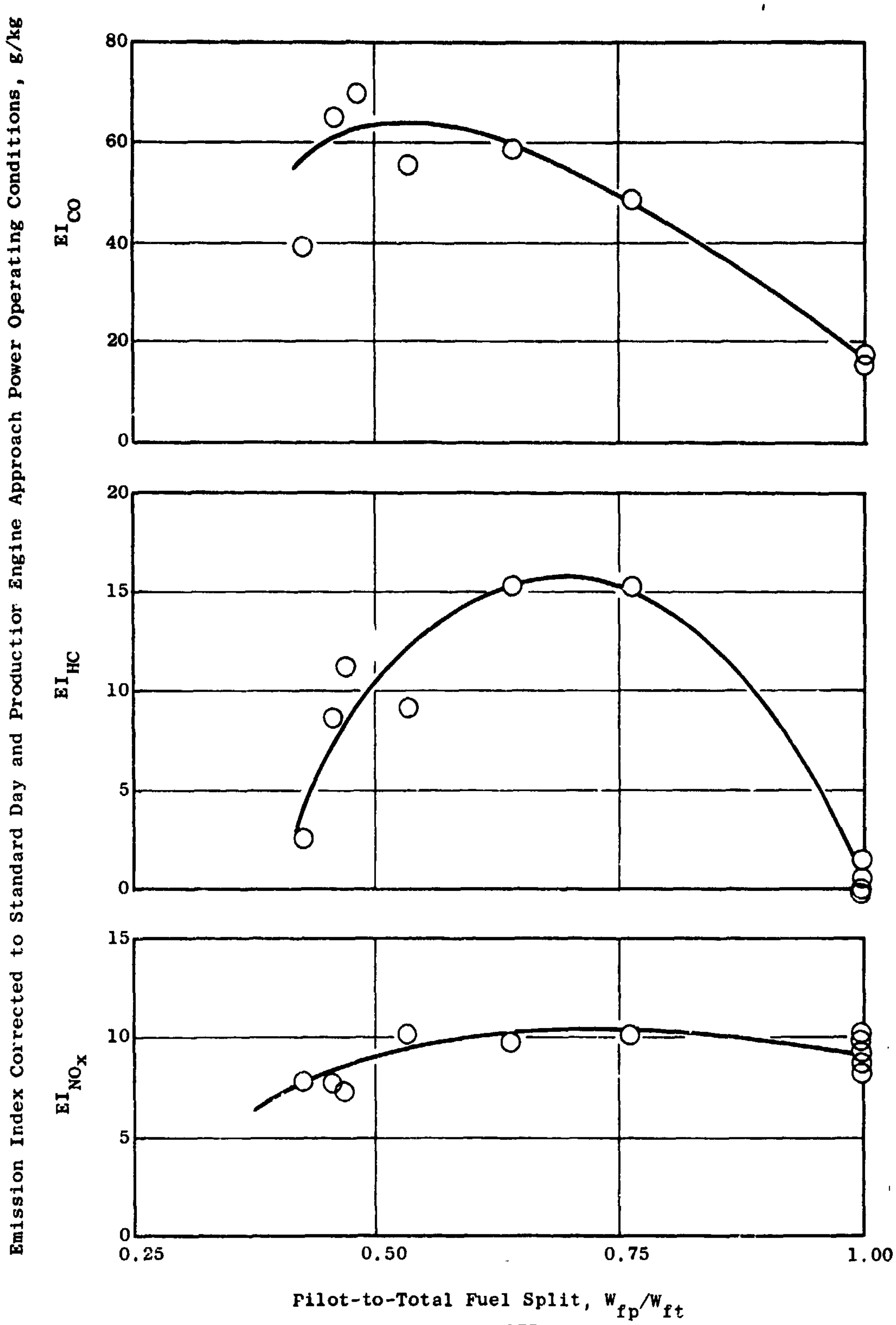


Figure 46. Effect of Fuel Split on Emission Levels at Approach Power Operating Conditions, Engine Tests.

Table 20. Corrected Average Emissions Levels, Demonstrator Engine Tests.*

Thrust, % of Takeoff Rating	P_3, MPa Combustor Inlet Total Pressure	T_3, K Combustor Inlet Temperature	V_r, m/s Combustor Reference Velocity	f_{36}, g/kg Overall Combustor Fuel-Air Ratio	W_{fp}/W_{ft} Pilot-to-Total Fuel Split	f_p, g/kg Pilot Stage Fuel-Air Ratio	f_m, g/kg Main-Stage Fuel-Air Ratio	n - Number of Test Points Run	Corrected Average SAE Smoke No.	Corrected Average Emission Index, g/kg CO	HC	NO_x
3.3 GIDL	0.300	437.4	18.56	10.96	1.00	10.96	0	9	35.3	1.7	4.1	2.8
5.0	0.374	463	19.6	10.3	1.00	10.3	0	4	25.4	1.3	4.7	3.3
7.0	0.461	489	20.7	10.0	1.00	10.0	0	3	19.1	1.2	5.3	3.2
9.5 FIDL	0.561	514	21.4	9.9	1.00	9.9	0	1	14.7	1.0	6.0	5.2
20.0	0.917	579	22.3	11.6	1.00	11.6	0	3	10.6	0.4	8.3	3.9
30.0 APPR	1.197	631.9	23.29	13.79	1.00	13.79	0	6	10.1	0.5	10.0	3.3
30.0 APPR	1.197	631.9	23.29	13.79	0.70	9.66	4.13	2	46.6	21.2	9.0	1.4
30.0 APPR	1.197	631.9	23.29	13.79	0.47	6.48	7.31	4	56.4	8.9	7.6	1.2
45.0	1.606	691	24.0	16.4	0.21	3.44	12.56	2	11.5	0.4	9.3	0.4
50.0	1.737	706	24.1	17.1	0.18	3.08	14.02	2	8.5	0.2	10.2	2.0
65.0	2.117	745	24.7	19.0	0.18	3.42	15.58	2	3.5	0.1	14.1	1.2
85.0 CLMB	2.616	791.9	25.18	21.51	0.22	4.73	16.78	2	1.5	0.1	19.9	4.4
85.0 CLMB	2.616	791.9	25.18	21.[illegible]	0.18	3.87	17.64	7	1.8	0	19.5	8.7
85.0 CLMB	2.616	791.9	25.18	21.51	0.12	2.58	18.93	1	2.7	0	19.3	18.7
92.0	2.785	807	25.3	22.4	0.13	2.91	19.49	2	2.4	0.1	20.9	17.5
100.0 TKOF	2.983	826.3	25.51	23.62	0.24	5.67	17.95	1	1.4	0	26.2	13.4
100.0 TKOF	2.983	826.3	25.51	23.62	0.19	4.49	19.13	2	1.6	0	25.5	19.0
100.0 TKOF	2.983	826.3	25.51	23.62	0.13	3.07	20.55	5	2.0	0	23.5	24.6

*Demonstrator engine data are corrected to the standard-day production engine operating conditions listed in Table 12, using the correction factors shown in Table 16.

Table 21. EPA Parameter Results, Demonstrator Engine Tests.

CF6-50C Operating Conditions

Assumed Idle Thrust, % of Rated	Pilot-to-Total Fuel Split at				Peak SAE Smoke Number	Current Federal Register Procedure EPA Parameter lb/1000 lb thrust-hr			Revised Proposed Procedure EPA Parameter g/kN		
	Idle	Approach	Climb	Takeoff		CO	($asCH_4$)	($asNO_2$)	CO	($asCH_4$)	($asNO_2$)
3.3	1.00	1.00	0.18	0.13	25	6.05	0.27	5.63	47.6	2.2	44.3
	1.00	1.00	0.18	0.19	19	6.03	0.27	5.75	47.5	2.2	45.2
	1.00	0.47	0.18	0.19	19	10.24	1.03	5.53	90.4	8.1	43.5
5.0	1.00	1.00	0.18	0.13	25	4.86	0.23	5.32	41.9	2.0	45.9
	1.00	1.00	0.18	0.19	19	4.84	0.23	5.43	41.7	2.0	46.8
	1.00	0.47	0.18	0.19	19	8.69	0.92	5.23	74.6	8.0	45.1
7.0	1.00	1.00	0.18	0.13	25	4.05	0.22	5.04	38.5	2.1	47.9
	1.00	1.00	0.18	0.19	19	4.03	0.22	4.50	38.3	2.1	48.7
	1.00	0.47	0.18	0.19	19	7.52	0.85	4.95	71.2	8.1	47.0
	EPA Standard				19	4.3	0.8	3.0	36.1	6.7	39.3

ratio was 15.7 g/kg and the EPA smoke requirement was exceeded at 17.0 g/kg. These fuel-air ratios would seldom be exceeded with a production engine on a standard day, but they were frequently exceeded in the demonstrator engine tests because of the hot-day conditions and the deteriorated engine performance.

As shown in Figure 44, the engine smoke data correlate simply with pilot- or main-stage fuel-air ratio each of which depends on both power level and fuel flow split. Significant variations in combustor inlet temperature and pressure are included in these data, but they do not appear to influence the smoke levels. Therefore, the smoke number correction factors shown in Table 16 are based only on the slope of the smoke number/fuel-air ratio lines in Figure 44.

In Table B-12, emissions data for each point in the engine test series are presented two ways:

a) as measured (and plotted in Figures 38 through 44).

b) as corrected to standard-day production CF6-50C engine operating conditions at the specified nominal power level and actual test fuel flow split.

In Table 20, the average corrected emission levels at each power level/fuel flow split combination are listed, and the number of engine test points obtained and included in the averages is indicated. For example, emissions at standard idle operating conditions (3.3 percent thrust) were measured nine times, and the average corrected CO, HC and NO_x emission indices were 35.3, 1.7 and 4.1 g/kg, respectively.

The effects of fuel split on emission levels are shown in Figure 45 (high power) and Figure 46 (approach power). As shown in Figure 45, smoke number was very sensitive to fuel flow split while NO_x emission index was virtually independent of fuel flow split. Therefore, the preferred fuel split at takeoff power is based on meeting the smoke number requirement ($W_{fp}/W_{ft} \geq 0.19$). As shown in Figure 46, the best all-around emission levels at approach power were obtained when only the pilot stage was fueled, based primarily on the high CO emission levels with two-stage burning throughout the fuel split range tested. The data do suggest that perhaps a pilot-to-total fuel split of about 0.25 might provide a significant reduction in NO_x levels and also produce acceptable CO levels if the idle CO emission level could be reduced.

2. EPAP Results

EPAP calculations for the engine test data corrected to standard day CF6-50 production engine operating conditions are presented in Table 21. Included are calculations to show the effect of idle power, fuel flow split schedule and current versus proposed draft procedure. These calculations are based on the emission indices listed in Table 20. EPA parameter values of 6.0, 0.3, and 5.8 lb/1000 lb thrust-hr were obtained for CO, HC, and NO_x, respectively, using the nominal CF6-50 engine idle power setting of 3.3 percent, the preferred fuel splits at high power, and the current EPA parameter calculation procedure. The approximate reductions in CO, HC, and NO_x were respectively 55, 95, and 30 percent, relative to the current production engine levels. At higher idle power settings, substantially lower EPAP's were obtained. The HC standard is met with an idle power setting of 3.3 percent, and the CO standard is met with an idle power setting of 7.0 percent. The current NO_x standard was not met, but the levels were only about 10 percent above the proposed revised standards for the high cycle pressure ratio of the CF6-50 engine.

3. Gas Sampling Technique Comparisons

Five different gas sampling techniques were employed in these engine exhaust emission tests using the apparatus and techniques described in Chapter II. One other sampling technique (FAA diamond rake) was investigated in a program addendum effort which is described in Reference 13.

Detailed results of these basic program sampling technique comparisons are presented in Appendix B. Fifty-five engine test points were included in these data, and generally two or more sampling techniques were utilized on a test point to measure smoke and each gaseous emission, so that a large number of comparisons can be made. Key trends are illustrated in Figures 47 through 54. Generally, these tests showed very consistent and close agreement between each of the sampling techniques.

The Federal Register specifies that in order to establish validity of the sampling technique, the fuel-air ratio calculated from the gas sample analysis must agree with the fuel-air ratio calculated from engine fuel and air flow measurements to within +15%. Figure 47 illustrates that for all 123 samples, the ratio of sample-to-metered fuel-air ratio is well within this limit, with a range of 0.89 to 1.04, and a mean of 0.951. The best agreement was obtained with the traverse sampling technique (0.982 mean), which is not surprising since this technique effectively samples the exhaust nozzle in 216 positions (72 circumferential locations X 3 radial immersions) and thus should average out any rich or lean regions. The traverses did reveal circumferential variations in fuel-air ratio which shifted with engine power setting as shown in Figure 48.

In Figures 49 through 54 sampling technique comparison plots for each of the emissions parameters are presented, with the parameter from the double cruciform rake taken as the independent variable. Generally very close agreement between all techniques is indicated. Virtually perfect agreement in both NO and NO_x emission indices is shown. Smoke number and CO emission index show the greatest variability (about +8%), but this variability seems to be more test point dependent than sampling technique dependent. Sample fuel-air ratio and HC emission index agreement is generally within about $\pm 4\%$, with the 12A sampling technique (+ oriented single cruciform rake) consistently indicating slightly higher levels.

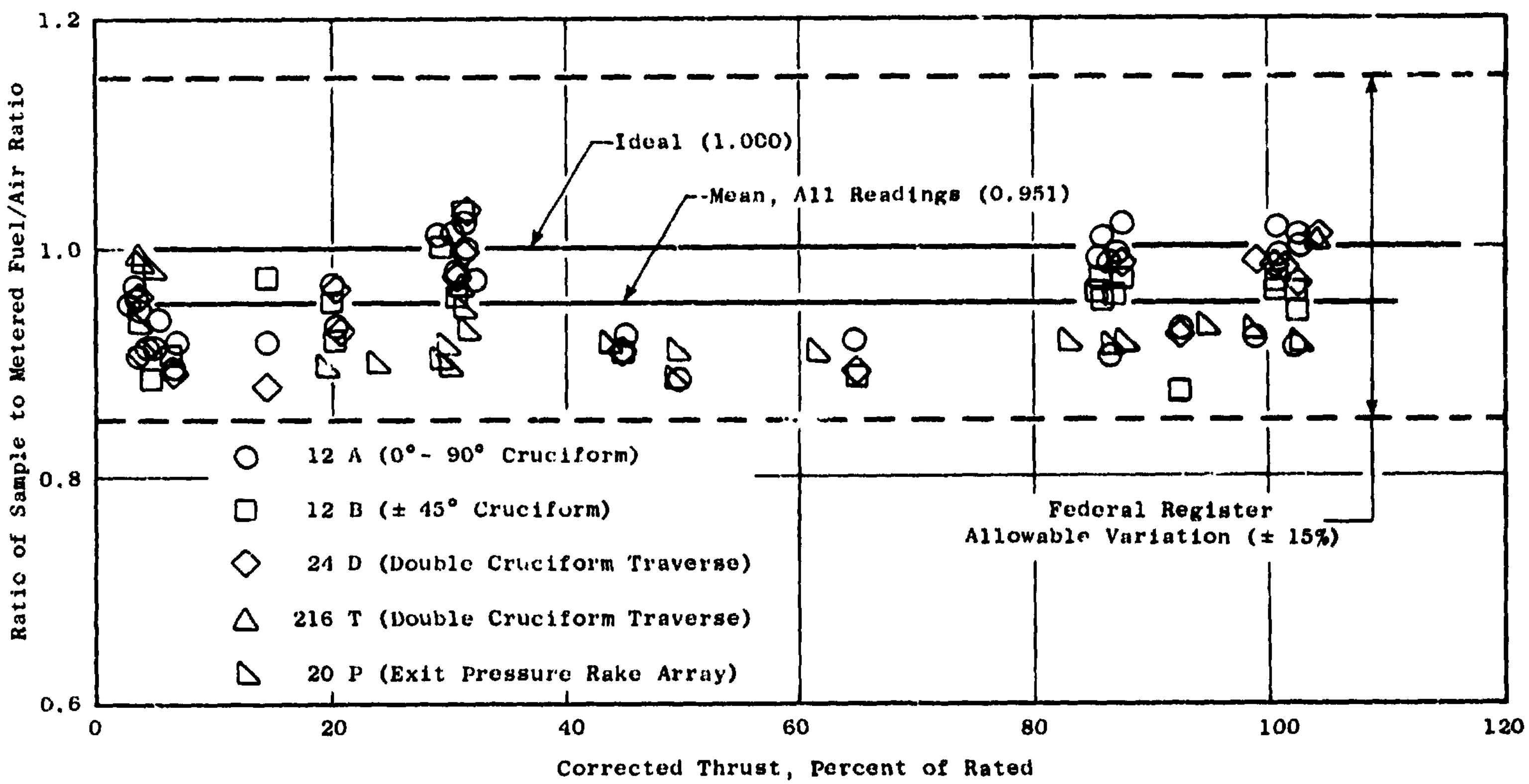


Figure 47. Comparison of Gas Sampling Techniques, Ratio of Sample-to-Metered Fuel/Air Ratio Versus Thrust.

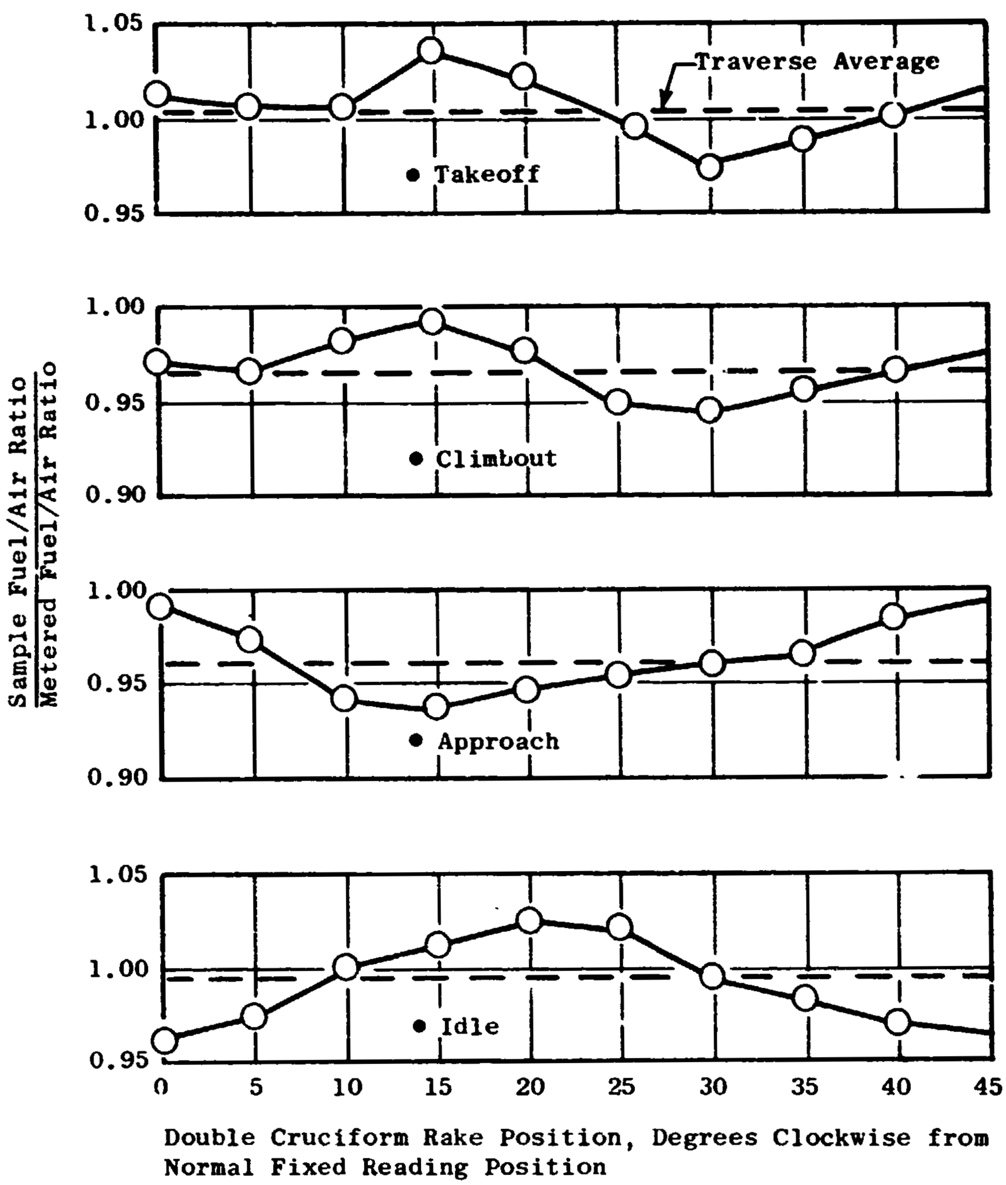
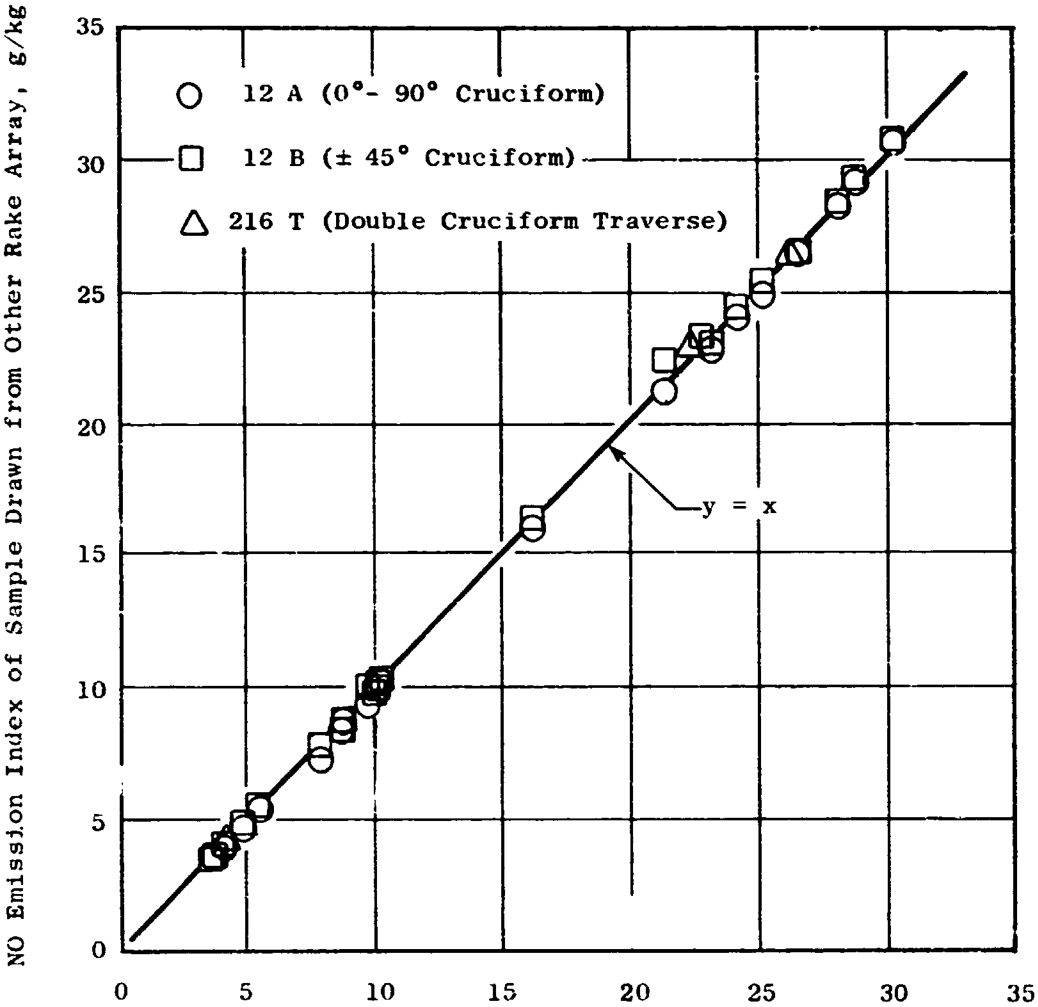


Figure 48. Circumferential Fuel/Air Ratio Variations, Double Cruciform Rake Traverse Tests.



. Emission Index of Sample Drawn from Double Cruciform Rake Array, g/kg

Figure 49. Comparison of Exhaust Sampling Techniques, Nitric Oxide Emission Index.

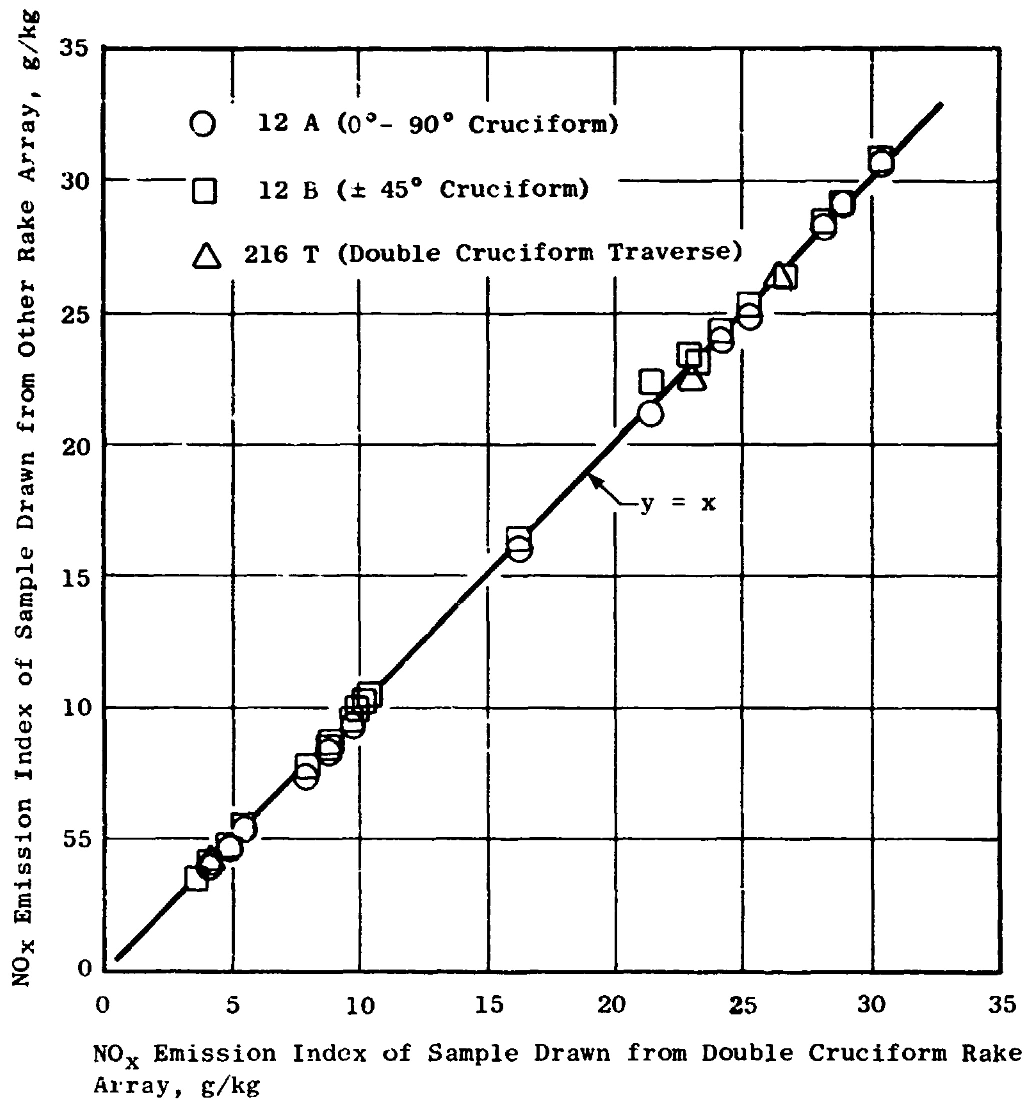


Figure 50. Comparison of Exhaust Sampling Techniques, Total Oxides of Nitrogen Emission Index.

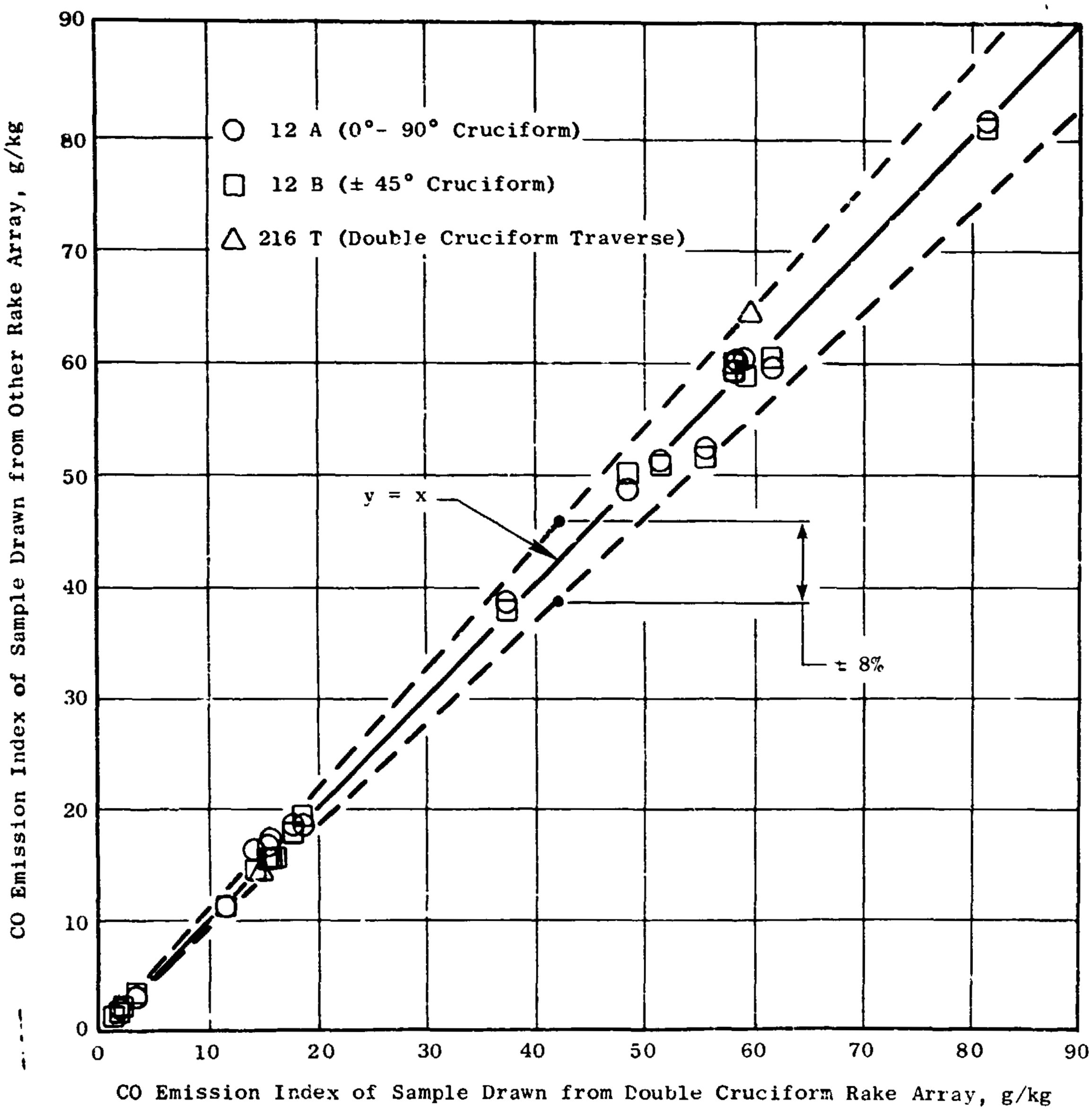


Figure 51. Comparison of Exhaust Sampling Techniques, Carbon Monoxide Emission Index.

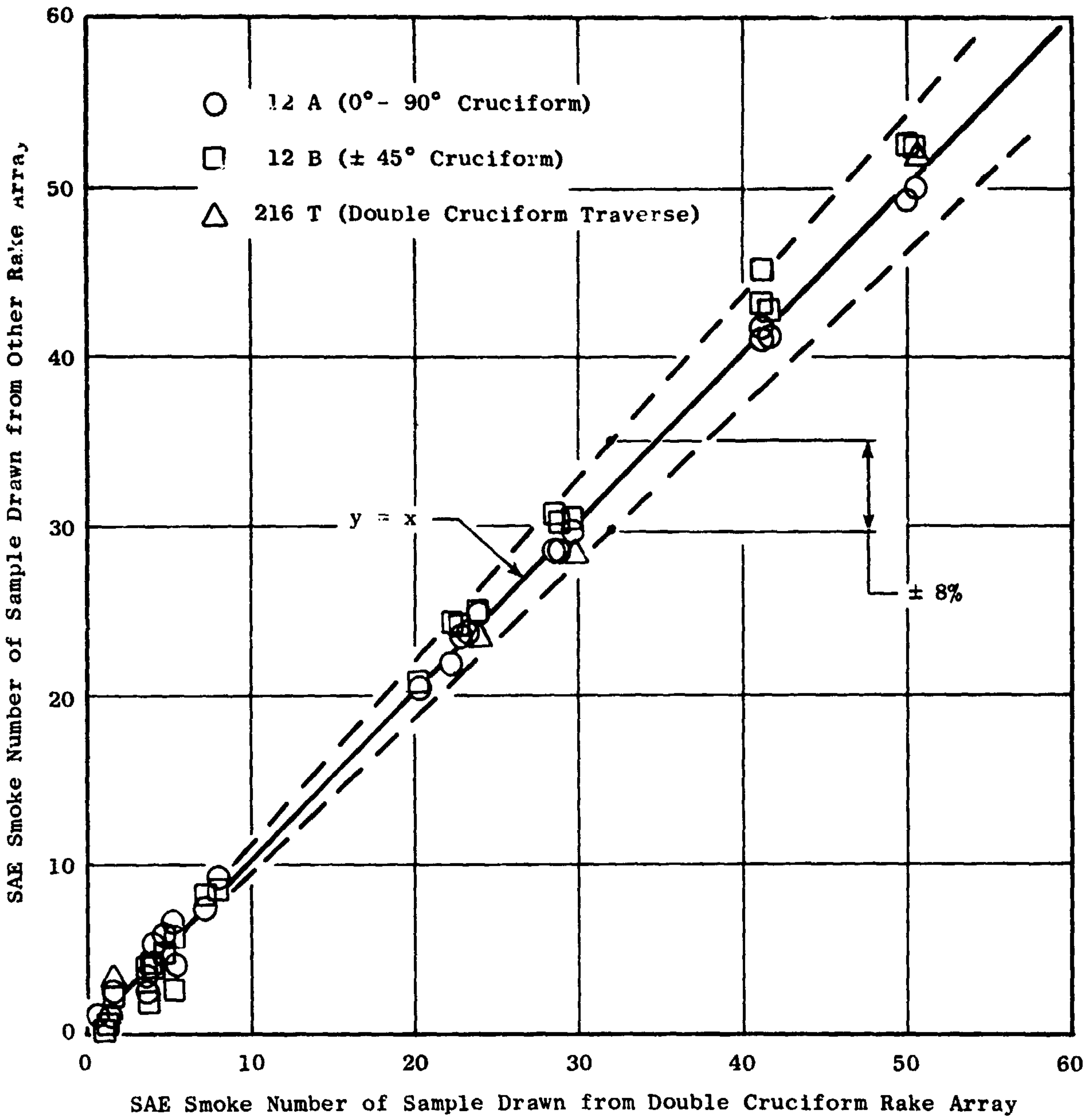


Figure 52. Comparison of Exhaust Sampling Techniques, SAE Smoke Number.

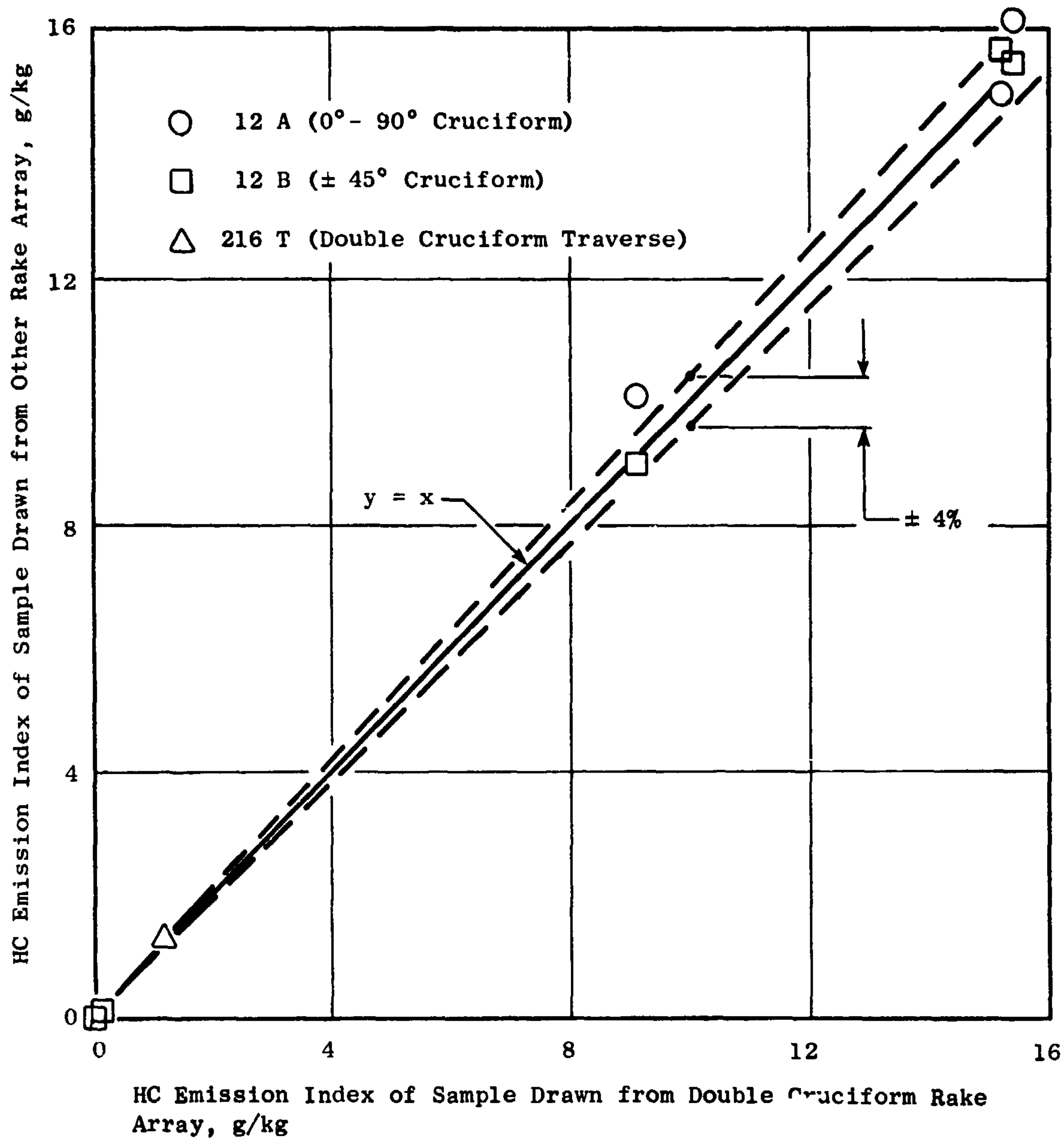


Figure 53. Comparison of Emission Sampling Techniques, Hydrocarbon Emission Index.

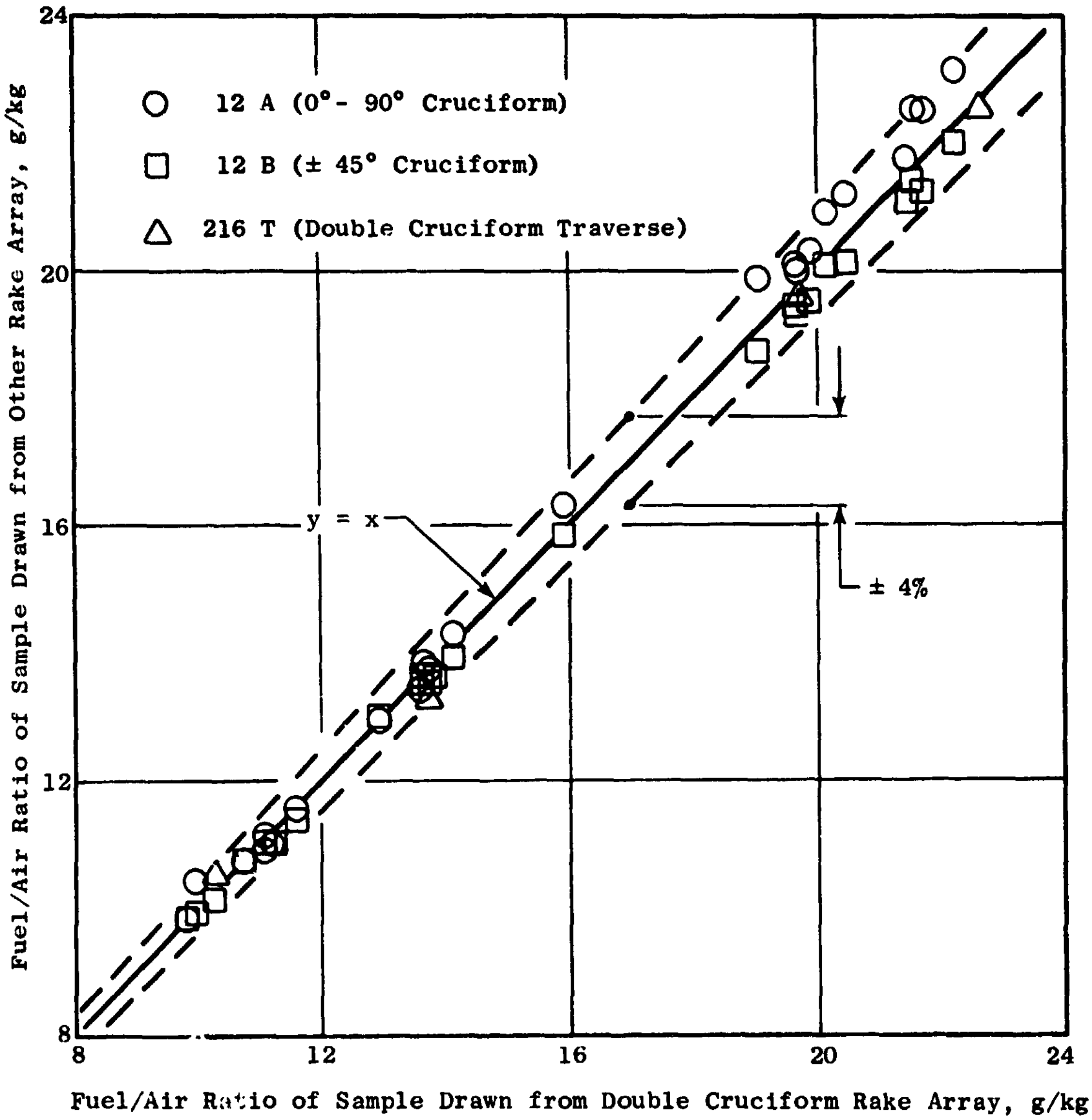


Figure 54. Comparison of Exhaust Sampling Techniques, Sample Fuel/Air Ratio.

These comparisons indicate that any of the gas sampling techniques used are about equally valid provided that the exhaust composition is nearly uniform. If this uniformity is known to exist, then the single cruciform fixed in either orientation (+ or X) is preferred because of its simplicity. However, these tests do indicate that biased results might be obtained with these simple rakes if spatial nonuniformities in exhaust composition do exist.

In these engine emission tests, nitric oxide (NO) as well as total oxides of nitrogen (NO_x) were measured. In the course of data consistency analyses, it was found that the ratio of NO to NO_x emissions was very nearly a function of combustion efficiency only (Figure 55) and independent of sampling technique or engine operating parameters. In particular, at approach power level combustion efficiency varied from about 97.2 to 99.6 percent (at about constant NO_x, temperature and pressure levels) as fuel flow split varied. The NO/NO_x ratio followed the same trend as when the power level was increased from 3.3 to 20.0 percent power (same range of combustion efficiency with varying NO_x, temperature and pressure levels). This trend is presented because it has not previously been noted and may be of some use for kinetic studies.

E. ENGINE PERFORMANCE TEST RESULTS

1. Engine Steady-State Performance

Detailed steady-state performance data of the demonstrator engine equipped with the Double Annular Combustor are contained in Appendix B, and key trends are illustrated in Figures 56 through 59. For comparison, also shown in these figures are (1) performance data of the same development engine from tests just prior to the ECCP when it was equipped with a production combustor, and (2) typical performance data for a new production engine, from Table 12. As shown in Figure 56, thrust characteristics of all three engines are nearly identical, indicating no fan deterioration. However, fuel flow rates, shown in Figure 57, were higher for the development engine, indicating some core engine deterioration. Fuel flow rates of the deteriorated development engine were about 25 percent high at idle and about 10 percent high at takeoff, relative to the fuel flow rates of a new production engine. Specific fuel consumption, shown in Figure 58, indicates about the same degree of development engine performance deterioration. However neither Figure 57 nor Figure 58 shows any effect of combustor type on the development engine fuel consumption. Combustor airflow rates of the development engine were about 7 percent low relative to those of a new production engine. This, in combination with the higher fuel flow rates, resulted in significantly higher combustor fuel-air ratios for the development engine. As shown in Figure 59, combustor fuel-air ratios in the deteriorated development engine were about 20 percent high at idle and about 15 percent high at takeoff, relative to those of a new production engine, at standard-day conditions.

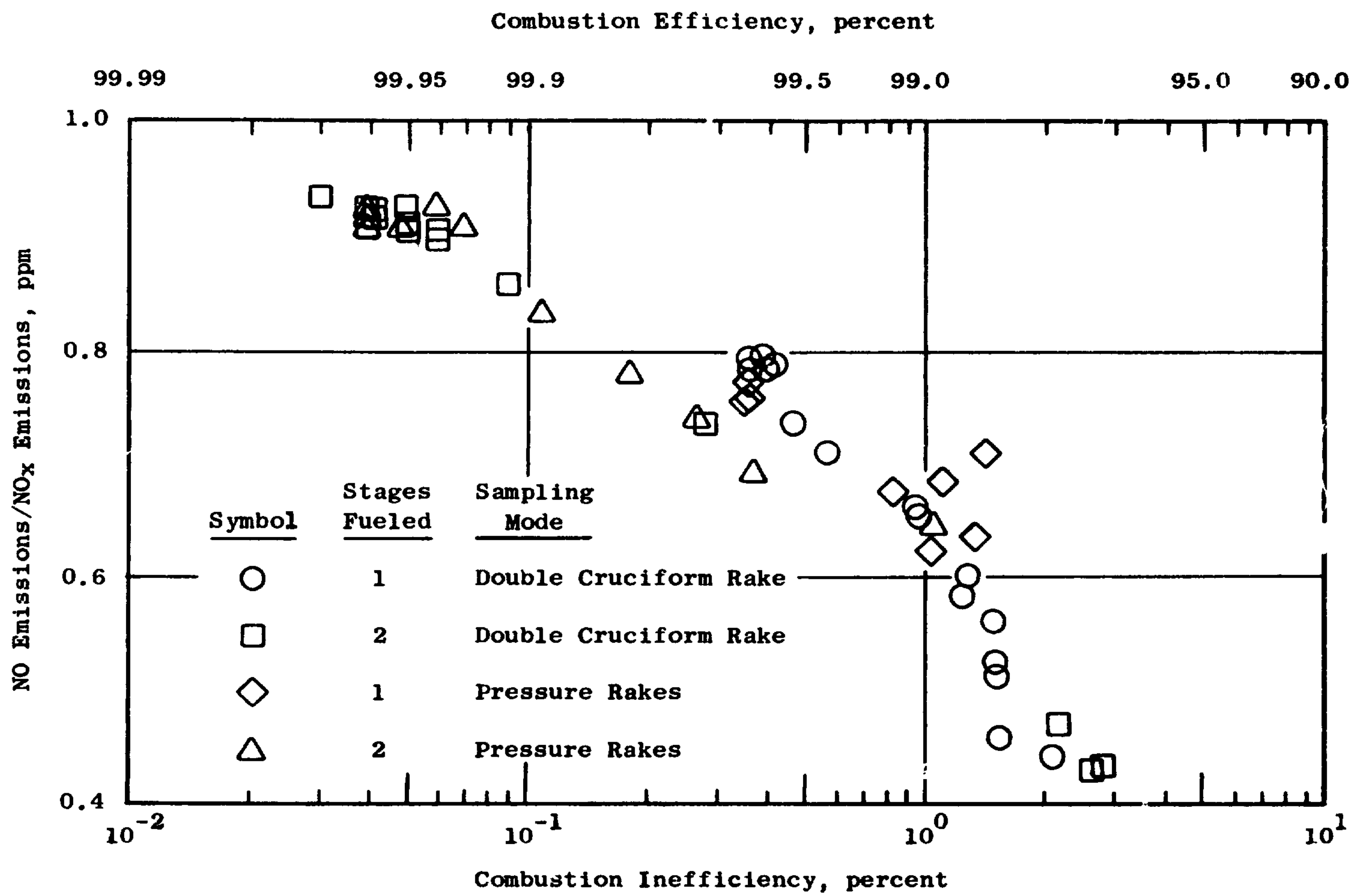


Figure 55. Relationship Between Nitric Oxide and Total Oxides of Nitrogen Emissions, Engine Tests.

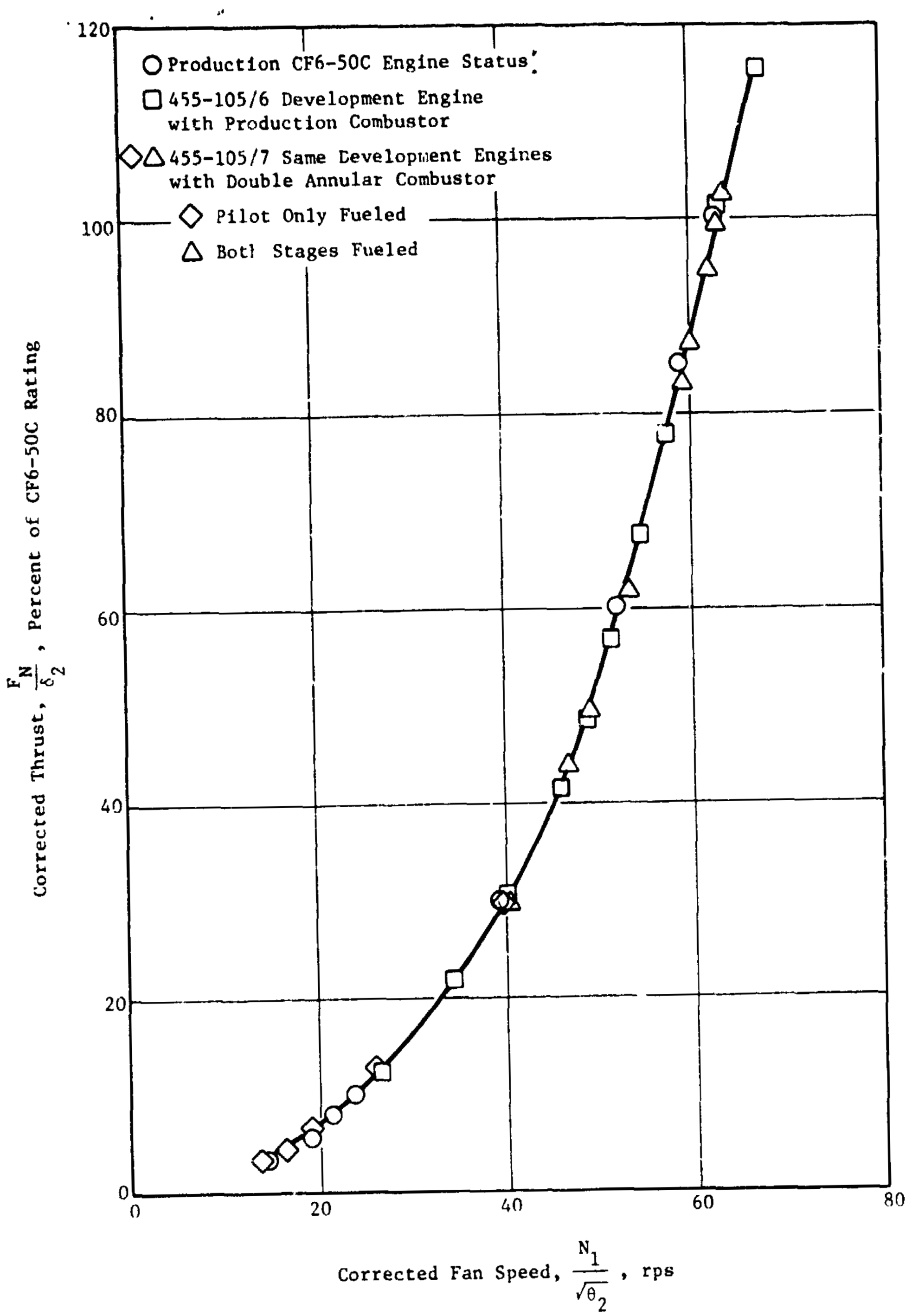


Figure 56. Comparison of Engine Thrust Characteristics.

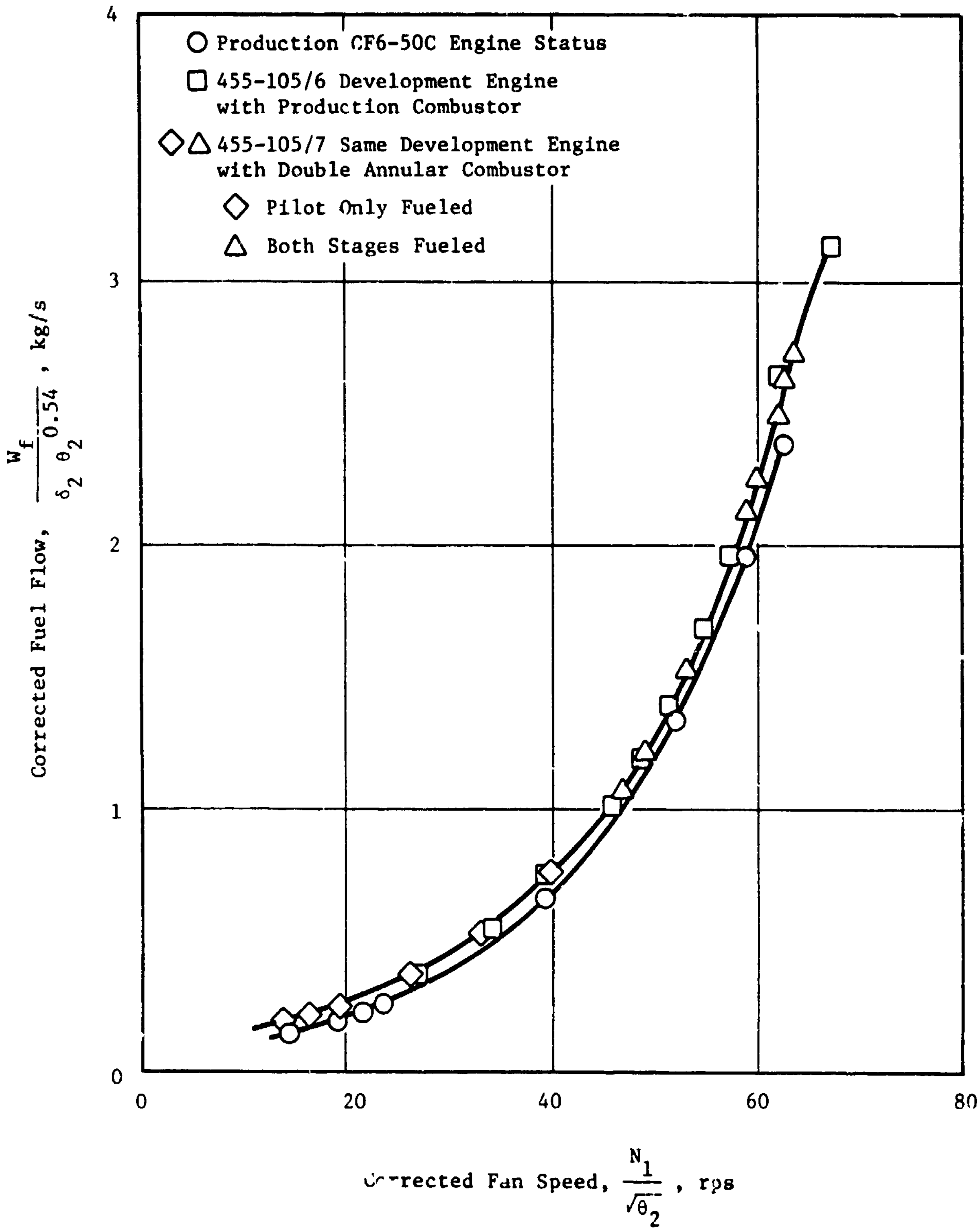


Figure 57. Comparison of Engine Fuel Flow Characteristics.

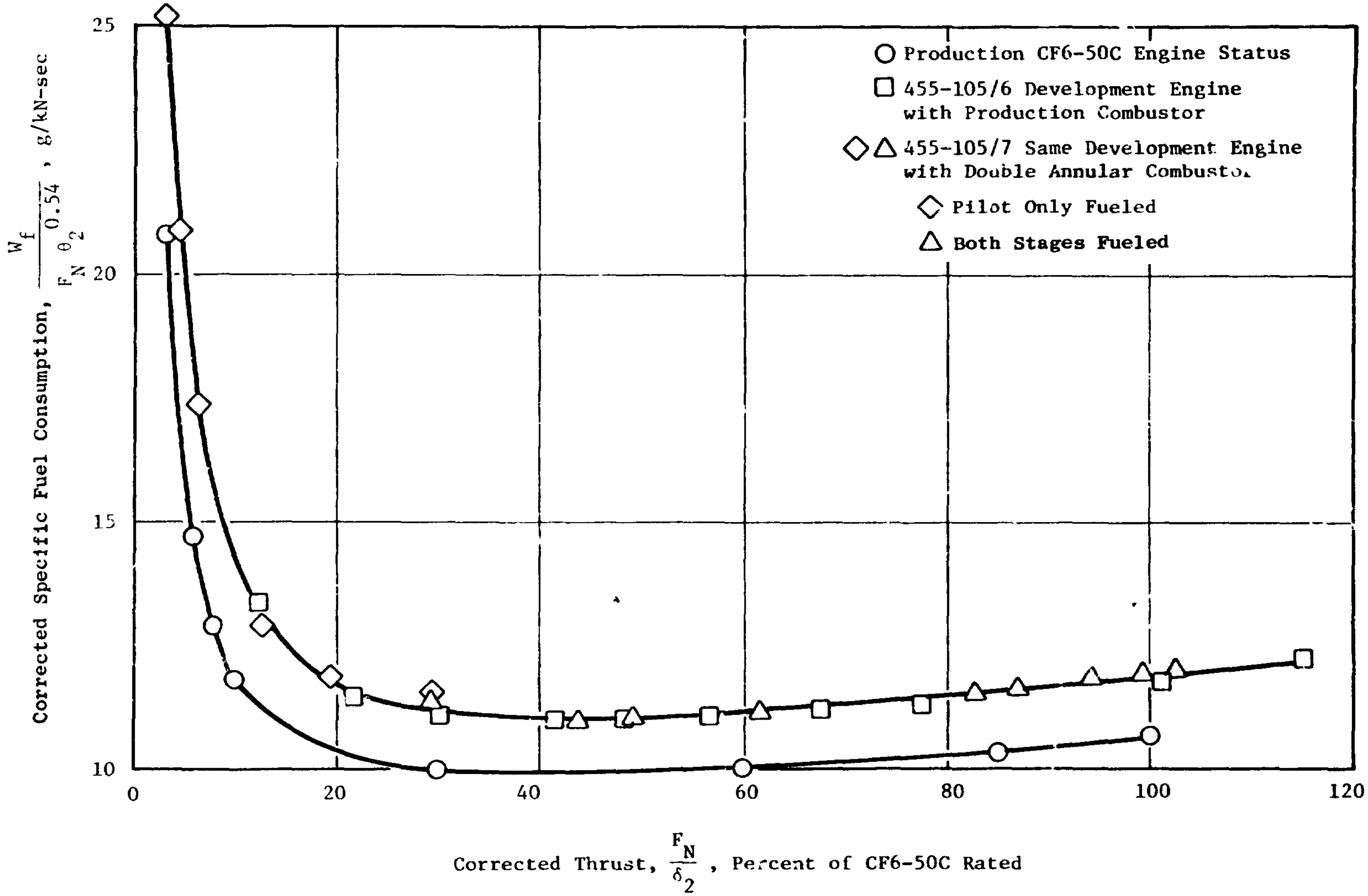


Figure 58. Comparison of Engine Specific Fuel Consumption Characteristics.

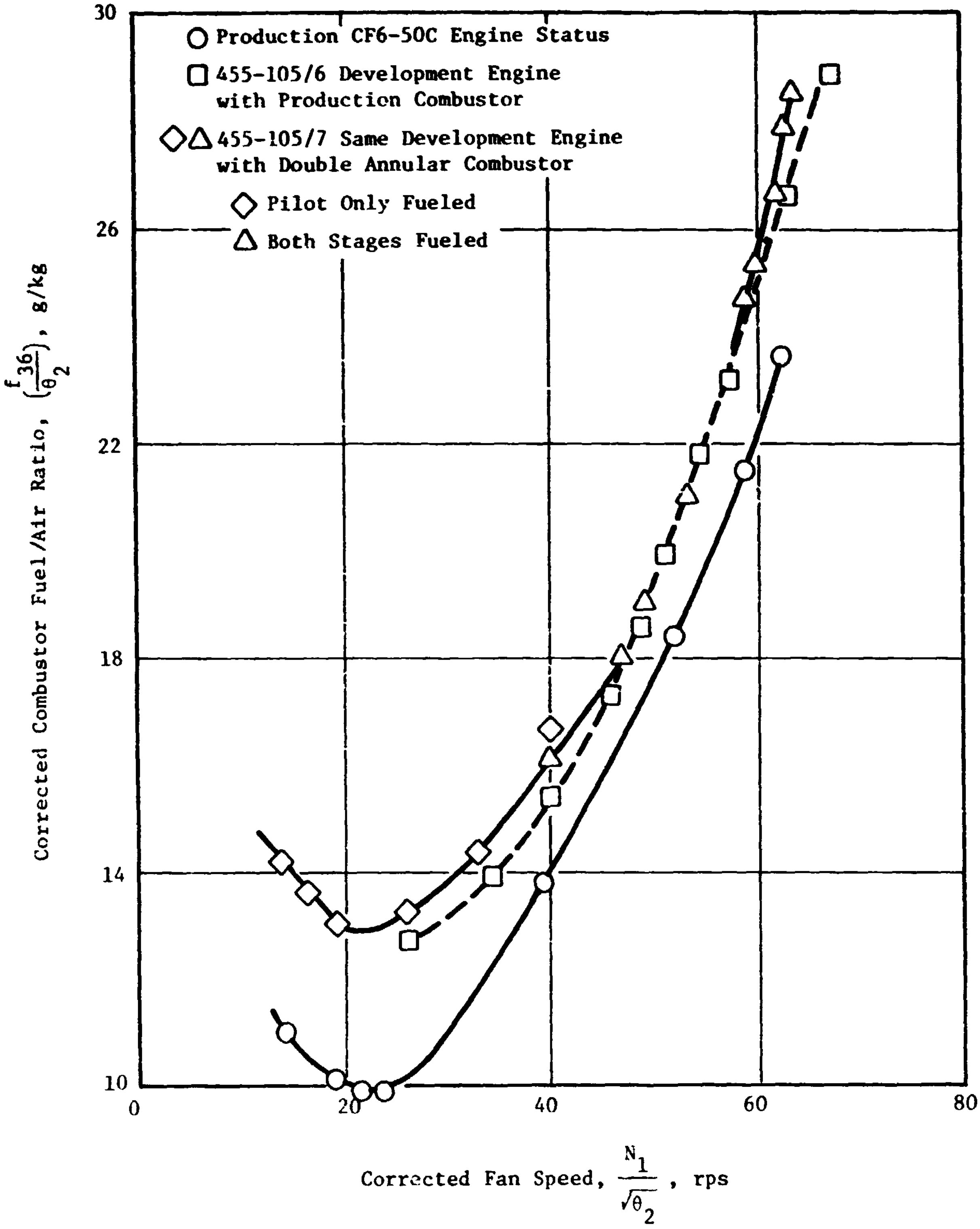


Figure 59. Comparison of Engine Fuel/Air Ratio Characteristics.

2. Thrust Response Characteristics

One of the greatest concerns prior to these demonstrator engine tests was the engine response with transition from one- to two-stage burning. A special momentary crossfire fuel enrichment feature was added to the control/supply system (Figure 60) in case speed falloff or pilot-stage blowout would occur. This feature was, however, never needed. The engine crossfired on the first attempt with no speed falloff, and no problems were ever encountered with fast or slow accelerations and decelerations.

Throttle burst results are shown in Figure 61. The times required to reach 95 percent rated thrust starting from flight idle conditions ranged from 3.7 to 5.4 seconds, as shown in Figure 61a. Eight of the nine fuel splitter settings that were tested met the 5-second airworthiness requirement (Reference 15), and, in general, were somewhat faster than the 4.7 seconds typical of a new CF6 production engine.

3. Ground Start Characteristics

The engine fired on the first attempt, and throughout the test program 67 starts were made with no problems. In the start/stall test series, characteristics were mapped and found to compare very well with those of production engines. Times to reach idle (Figure 62) were virtually the same as those of typical production engines and somewhat faster than those of this particular development engine when equipped with a production combustor.

4. Combustor Performance Characteristics

Combustor performance throughout the demonstrator engine tests was essentially as expected, and except for exit temperature profile characteristics compares very well with production engine requirements.

Combustor pressure drop (Figure 63) at high power was 4.5 percent, which is very close to rig test predictions for a production-quality engine. Idle pressure drop, however, was low (about 3.3 versus 4.4 percent predicted for a production engine) because of the low combustor airflow of the demonstrator engine at low power.

Combustor dynamic pressures were monitored throughout the engine test series and recorded for subsequent spectral analyses. As expected from the rig checkout tests, no resonance was ever detected.

Peak metal temperature characteristics of the outer liner centerbody and inner liner are shown in Figures 64, 65 and 66. In each case, the difference between metal temperature and combustor inlet air temperature correlates well with merely pilot-stage (outer liner) or main-stage fuel-air ratio (centerbody and inner liner). Both the level and location of peak temperatures

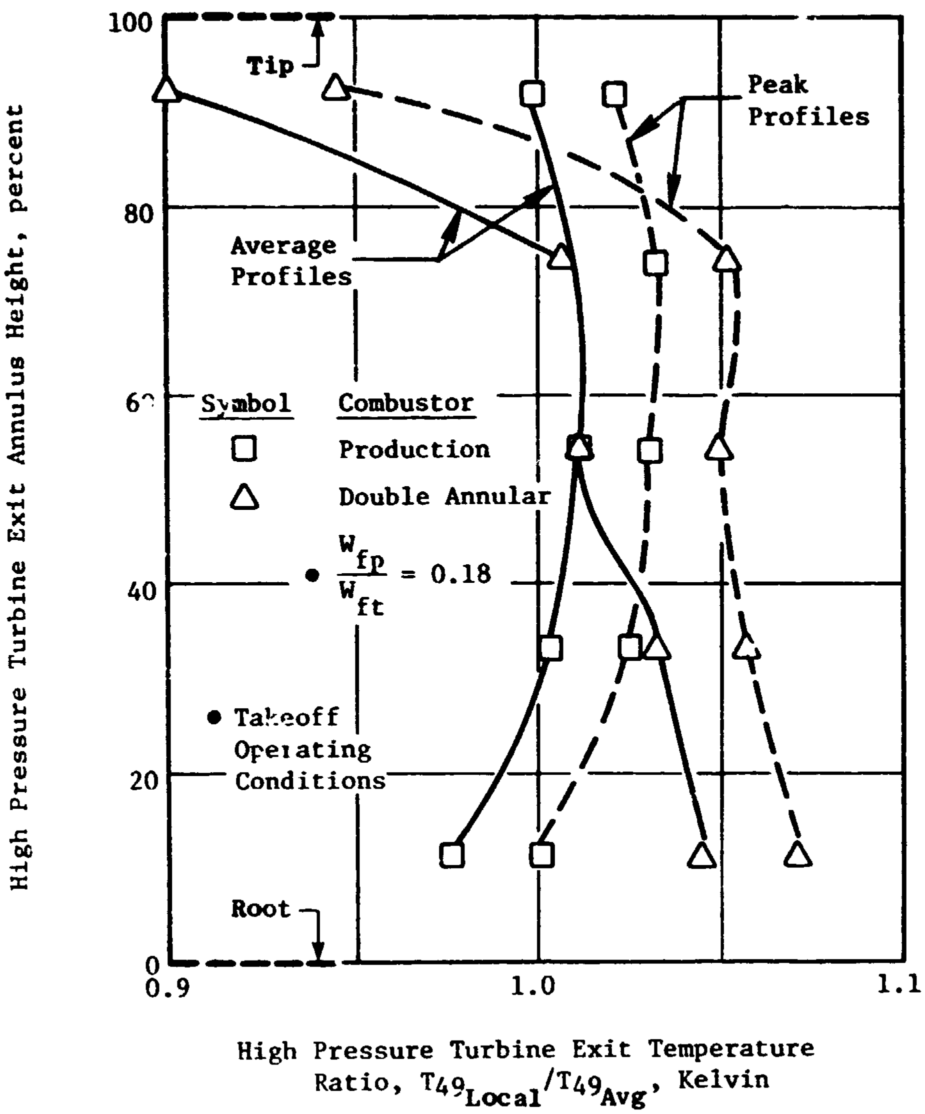
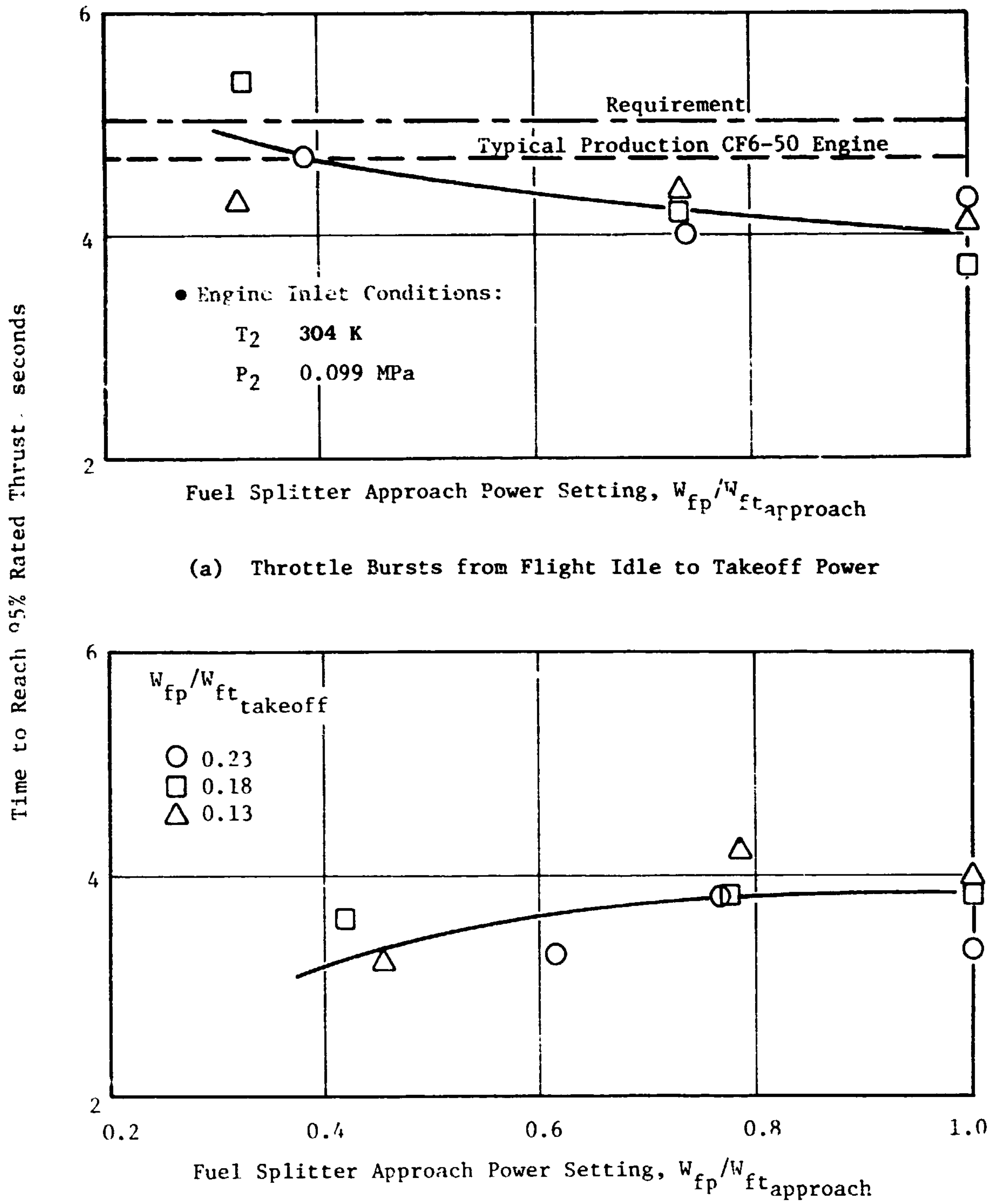


Figure 60. Engine Turbine Exit Temperature Profile Characteristics.



(a) Throttle Bursts from Flight Idle to Takeoff Power

(b) Throttle Bursts from Approach to Takeoff Power

Figure 61. Engine Power Response Characteristics.

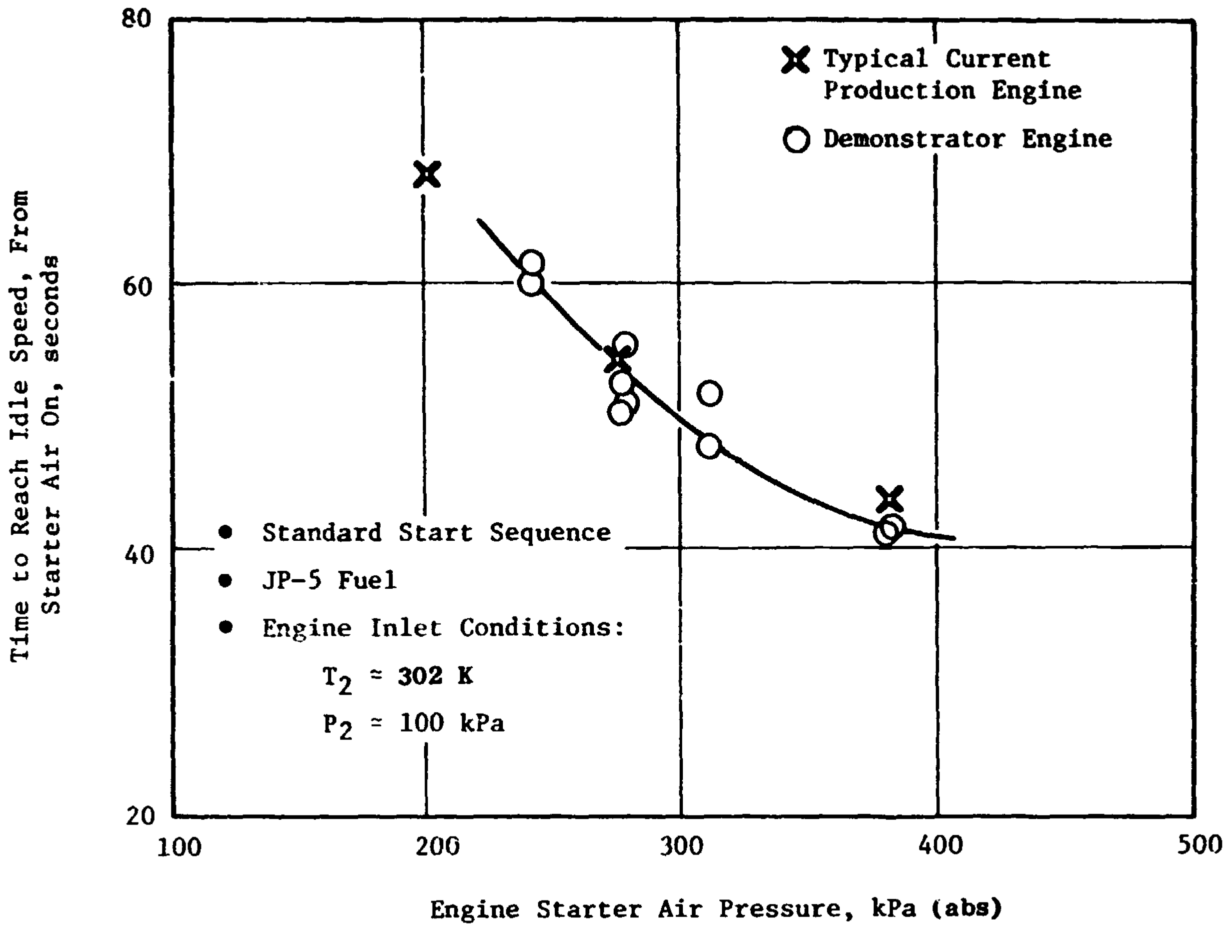


Figure 62. Engine Starting Characteristics.

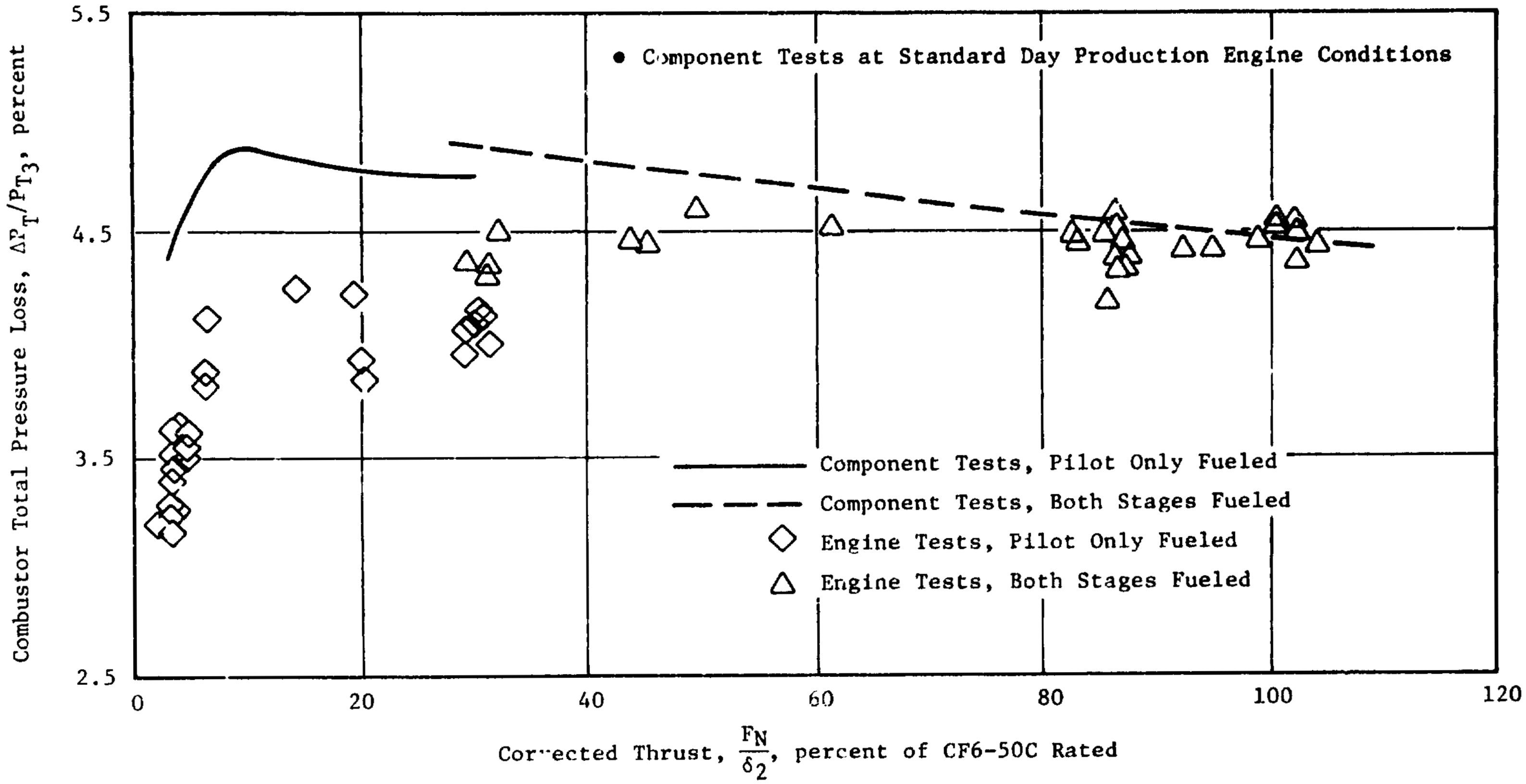


Figure 63. Combustor Pressure Loss Characteristics, Engine Tests.

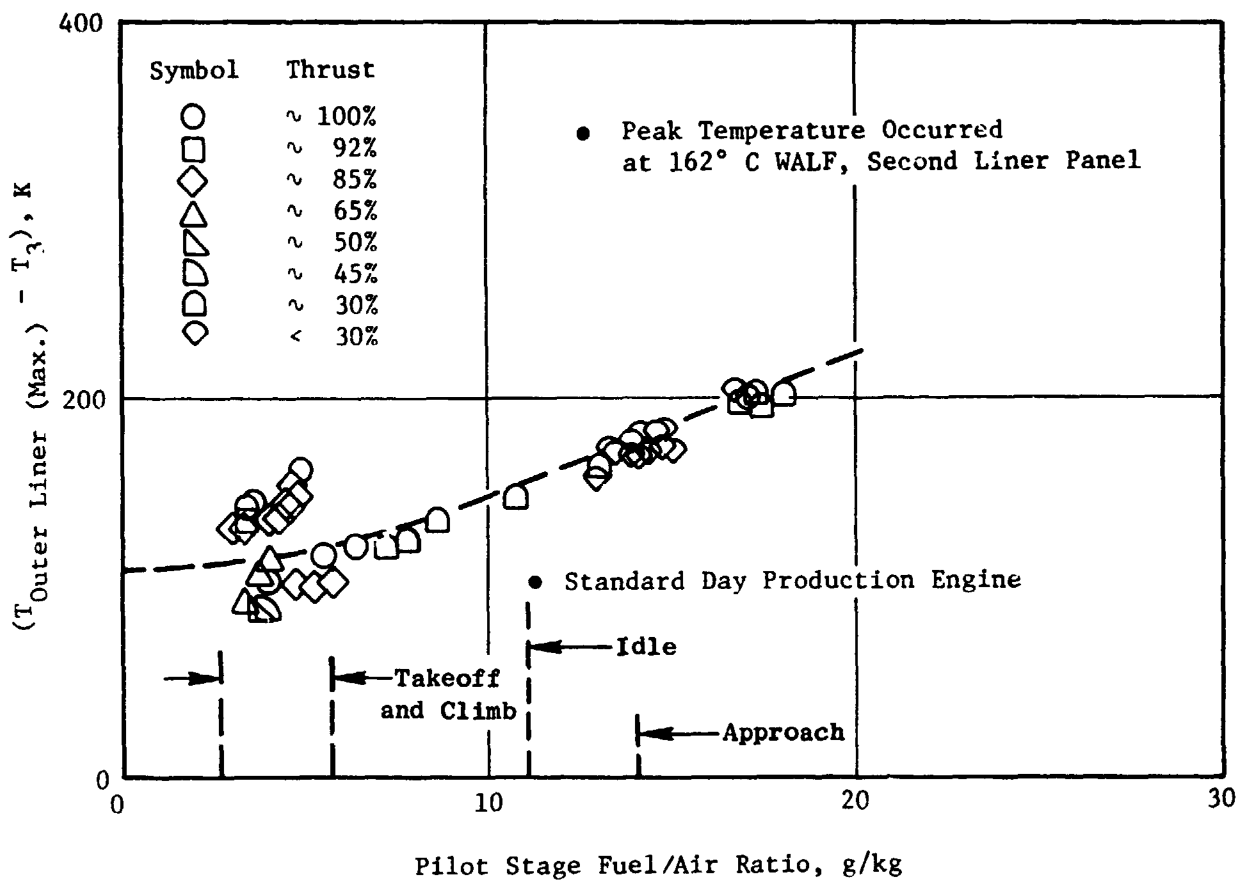


Figure 64. Variation of Peak Outer Liner Metal Temperature with Engine Operating Conditions.

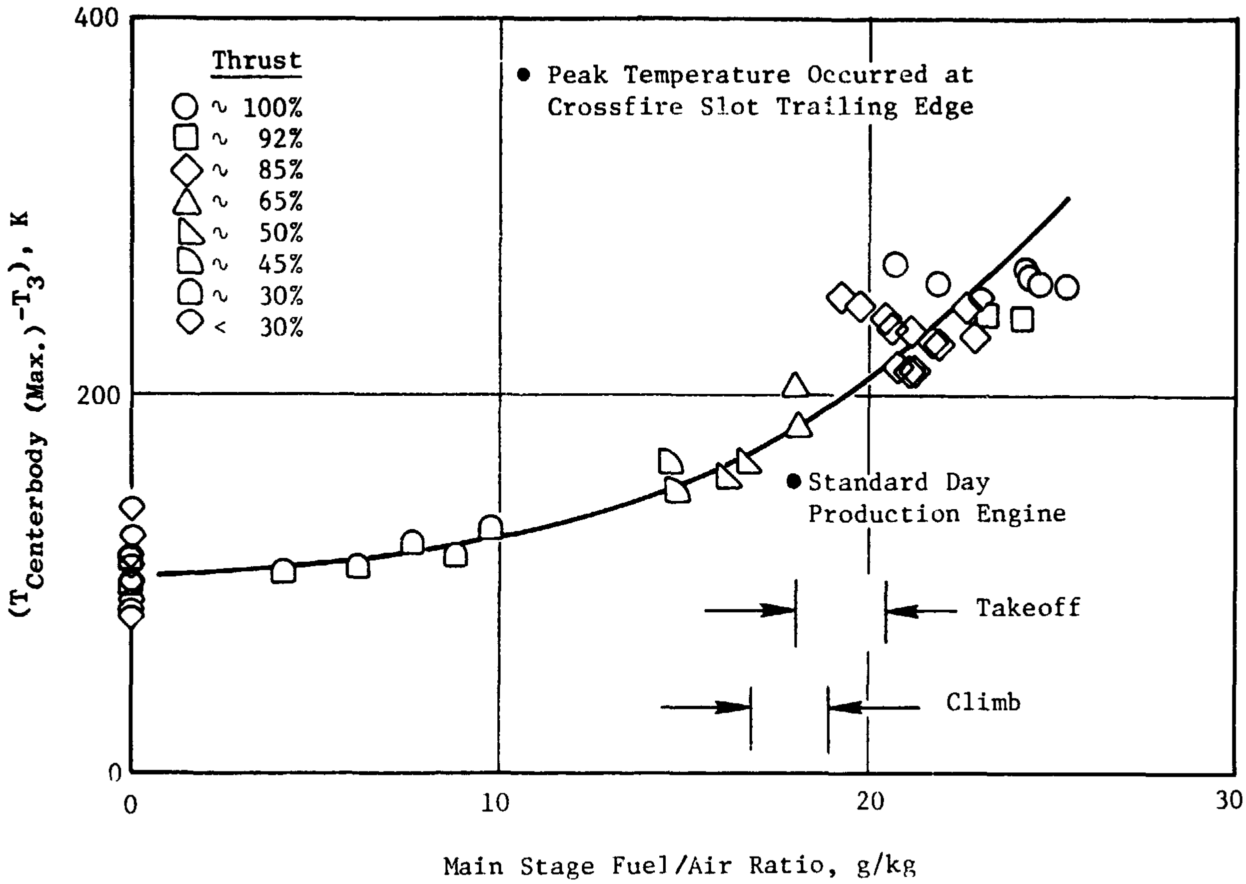


Figure 65. Variation of Peak Centerbody Metal Temperature with Engine Operating Conditions.

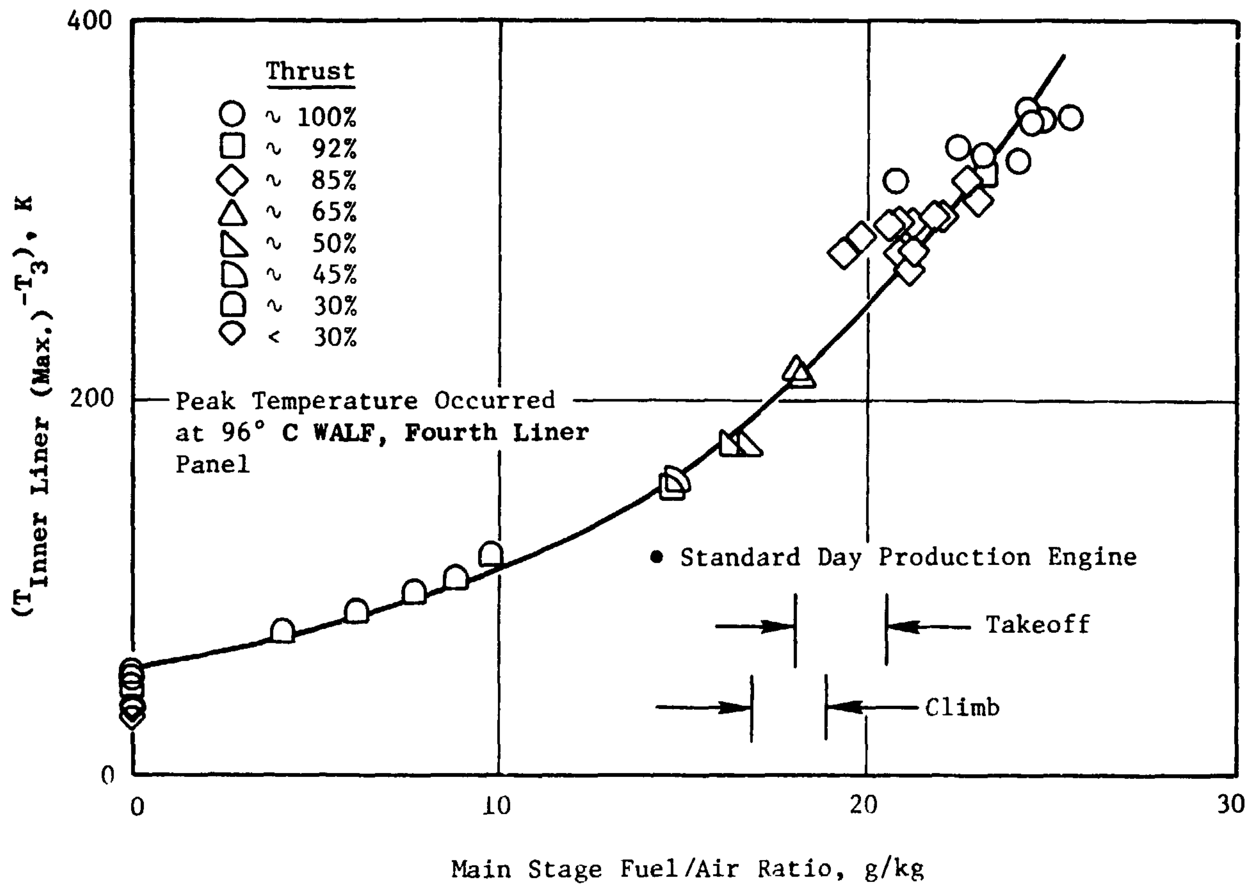


Figure 66. Variation of Peak Inner Liner Metal Temperature with Engine Operating Conditions.

agreed very well with rig test data, and are summarized in Table 22 for standard-day production engine operating conditions. The peak temperature was 1056 K, which is lower than that of production combustors. Generally 1088 K (1599° F) is considered to be the maximum temperature for long-life designs.

Periodically throughout the test series, borescope inspections at the combustor were made. No signs of carbon buildup or distress on any of the parts were detected. Posttest conditions of the combustor fuel nozzles and high-pressure turbine are shown in Figures 67 through 70. The combustor was in excellent condition, with only some very light carbon stains on the dome splash-plates. There was no carbon on the fuel nozzles, and spray quality/flow calibrations revealed no significant changes. However, for long-time service plugging or gumming of the main-stage nozzles is still a concern. The nozzles are not fueled at approach power with the preferred fuel schedule, and this problem may not appear until after several hundred hours of operation. Turbine distress was found, Figures 69 and 70, particularly in the area of the first-stage rotor blades. This was probably aggravated by (1) the high fuel consumption of the engine, (2) the high ambient temperatures which increased both combustor inlet temperature and combustor fuel-air ratio, and (3) considerable high-power run time with very low pilot-to-total fuel splits. Nonetheless, the need for improved temperature profile characteristics was clearly indicated to be the most significant performance problem associated with this Double Annular low-emission combustor design concept.

Table 22. Corrected Combustor Metal Temperature Results(1).

FNPC % Corrected Thrust	Rating	P_3, MPa	T_3, K	V_r, m/s	f_{36}, g/kg	WFP/NFT	f_p, g/kg	f_m, g/kg	Corrected Peak Metal Temperature, K: Outer Liner	Center-Body	Inner Liner
3.3	GIDL	0.[illegible]00	437.4	18.56	10.96	1.00	10.96	0	591	541	495
5.0		0.374	463	19.6	10.3	1.00	10.3	0	613	567	521
7.0		0.461	489	20.7	10.0	1.00	10.0	0	637	593	547
9.5	FIDL	0.561	514	21.4	9.9	1.00	9.9	0	662	618	572
20.0		0.917	579	22.3	11.6	1.00	11.6	0	739	683	637
30.0	APPR	1.197	631.9	23.29	13.79	1.00	13.79	0 (2)	810	736	690
30.0	APPR	1.197	631.9	23.29	13.79	0.70	9.66	4.13	779	740	704
30.0	APPR	1.197	631.9	23.29	13.79	0.47	6.48	7.31	754	749	723
45.0		1.606	691	24.0	16.4	0.21	3.44	12.56	804	829	824
50.0		1.737	706	24.1	17.1	0.18	3.08	14.02	819	854	855
65.0		2.117	745	24.7	19.0	0.18	3.42	15.58	858	903	915
85.0	CLMB	2.616	791.9	25.18	21.51	0.22	4.73	16.78	911	961	981
85.0	CLMB	2.616	791.9	25.18	21.51	0.18	3.87	17.64 (2)	909	969	994
85.0	CLMB	2.616	791.9	25.18	21.51	0.12	2.58	18.93	904	987	1018
92.0		27.85	807	25.3	22.4	0.13	2.91	19.49	919	1009	1045
100.0	TKOF	2.983	826.3	25.51	23.62	0.24	5.67	17.95	946	1008	1035
100.0	TKOF	2.983	826.3	25.51	23.62	0.19	4.49	19.13 (2)	944	1022	1056
100.0	TKOF	2.983	826.3	25.51	23.62	0.13	3.07	20.55	938	1044	1088

(1) Demonstrator Engine data are corrected to the standard day production engine operating conditions listed in Table 12, using the data correlations shown in Figures 68, 69, and 70.

(2) Preferred fuel splits for emissions.

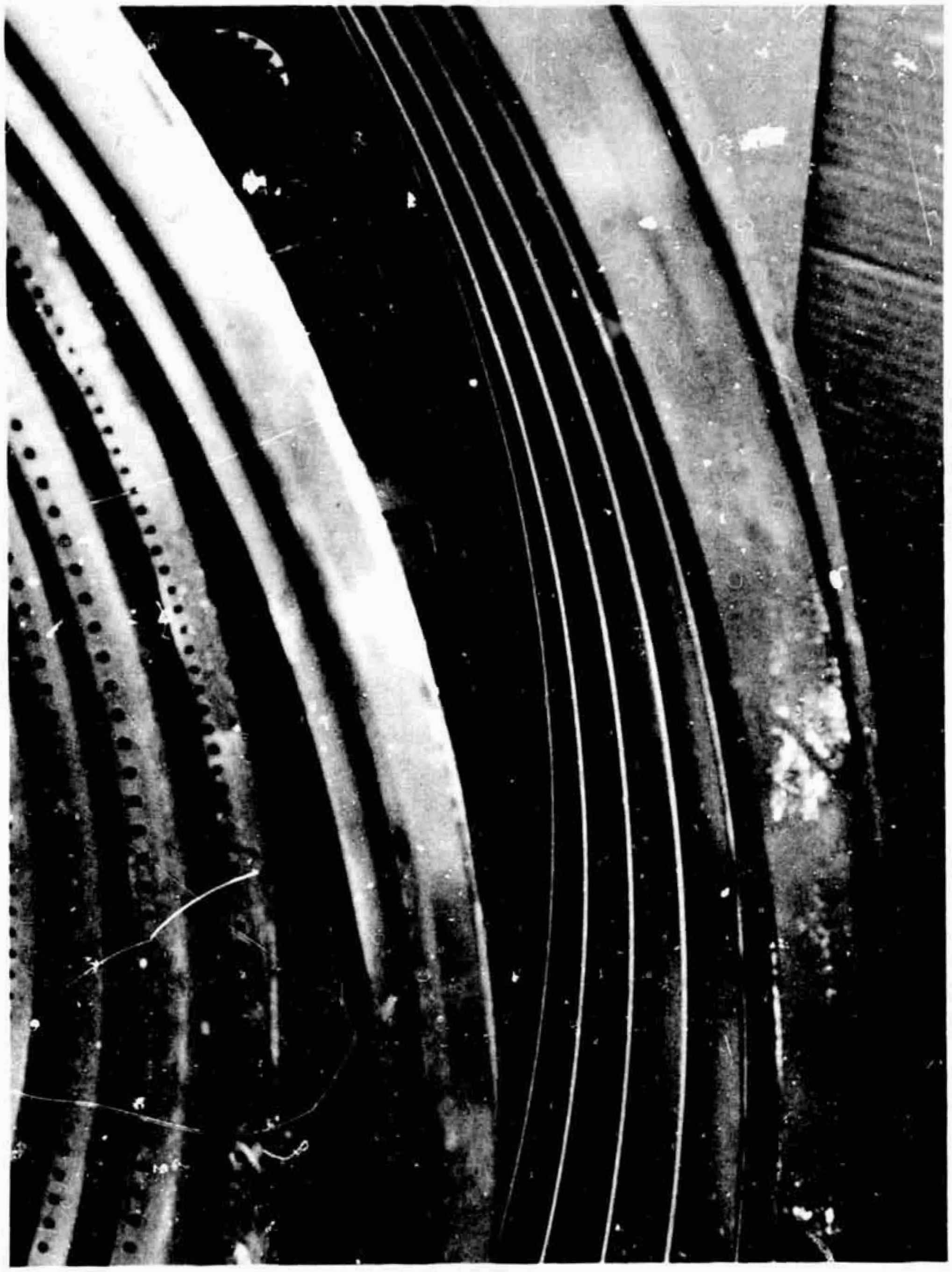


Figure 67. Combustor After Engine Test.

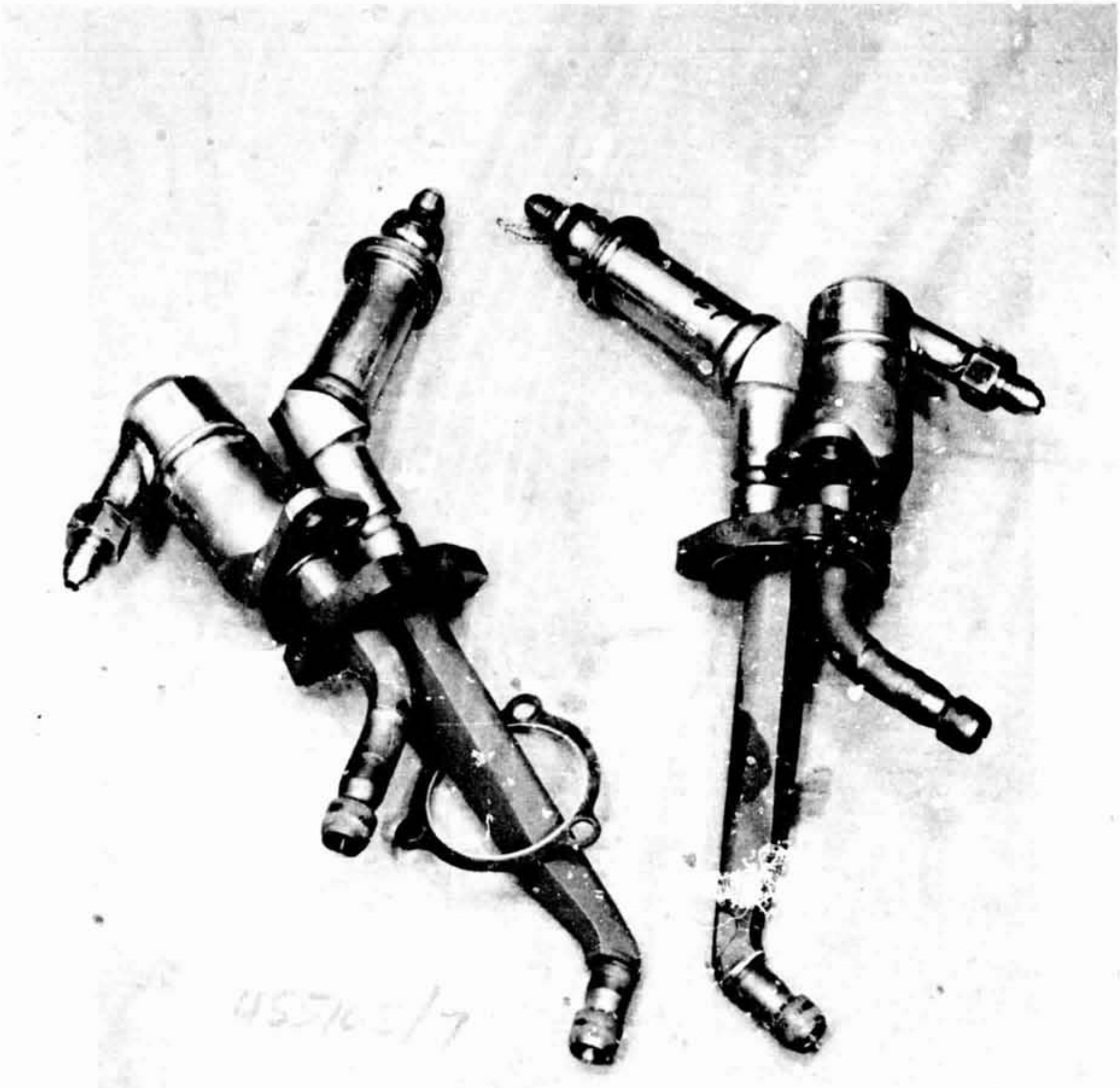


Figure 68. Fuel Nozzles After Engine Test.

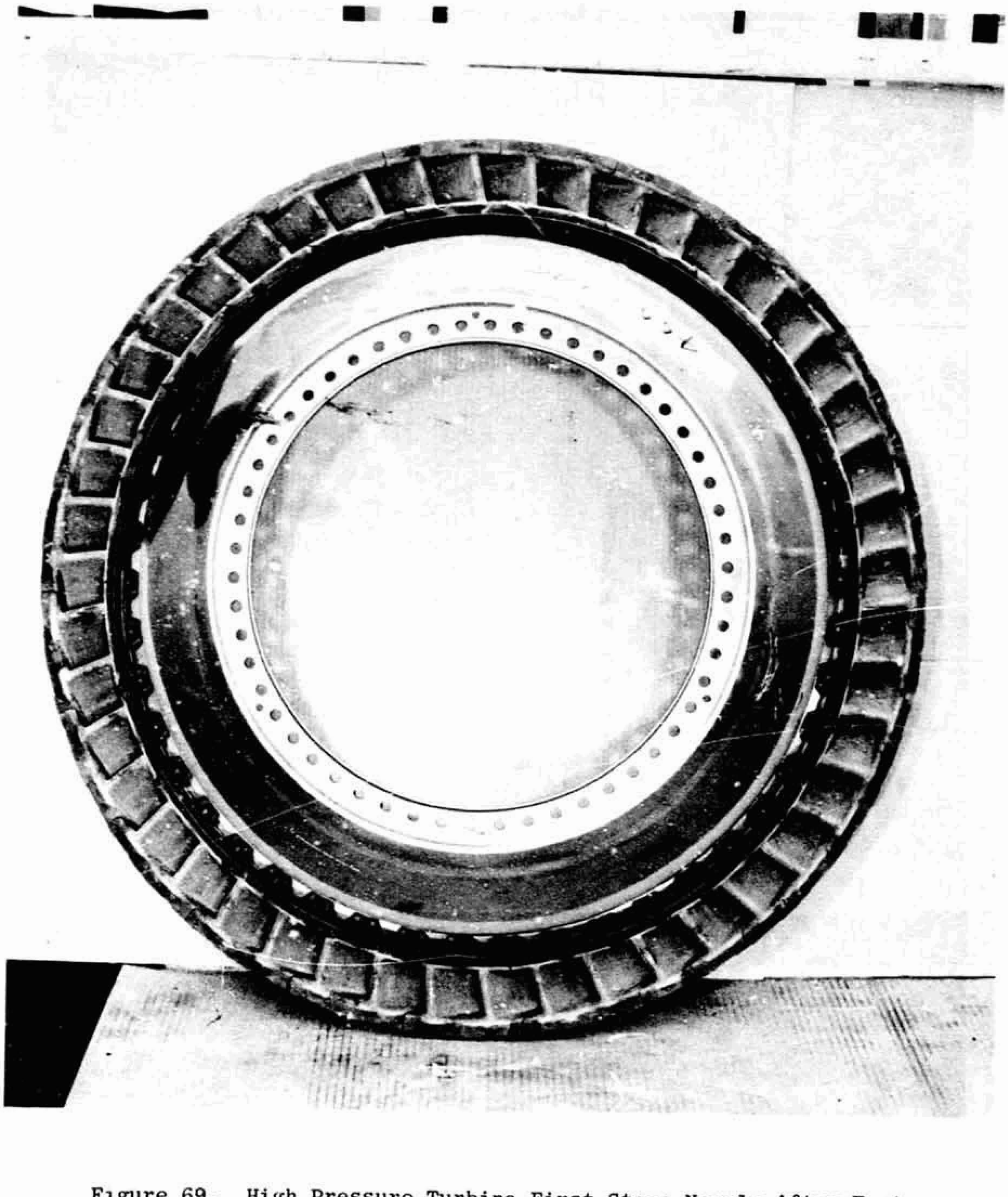


Figure 69. High Pressure Turbine First Stage Nozzle After Test.

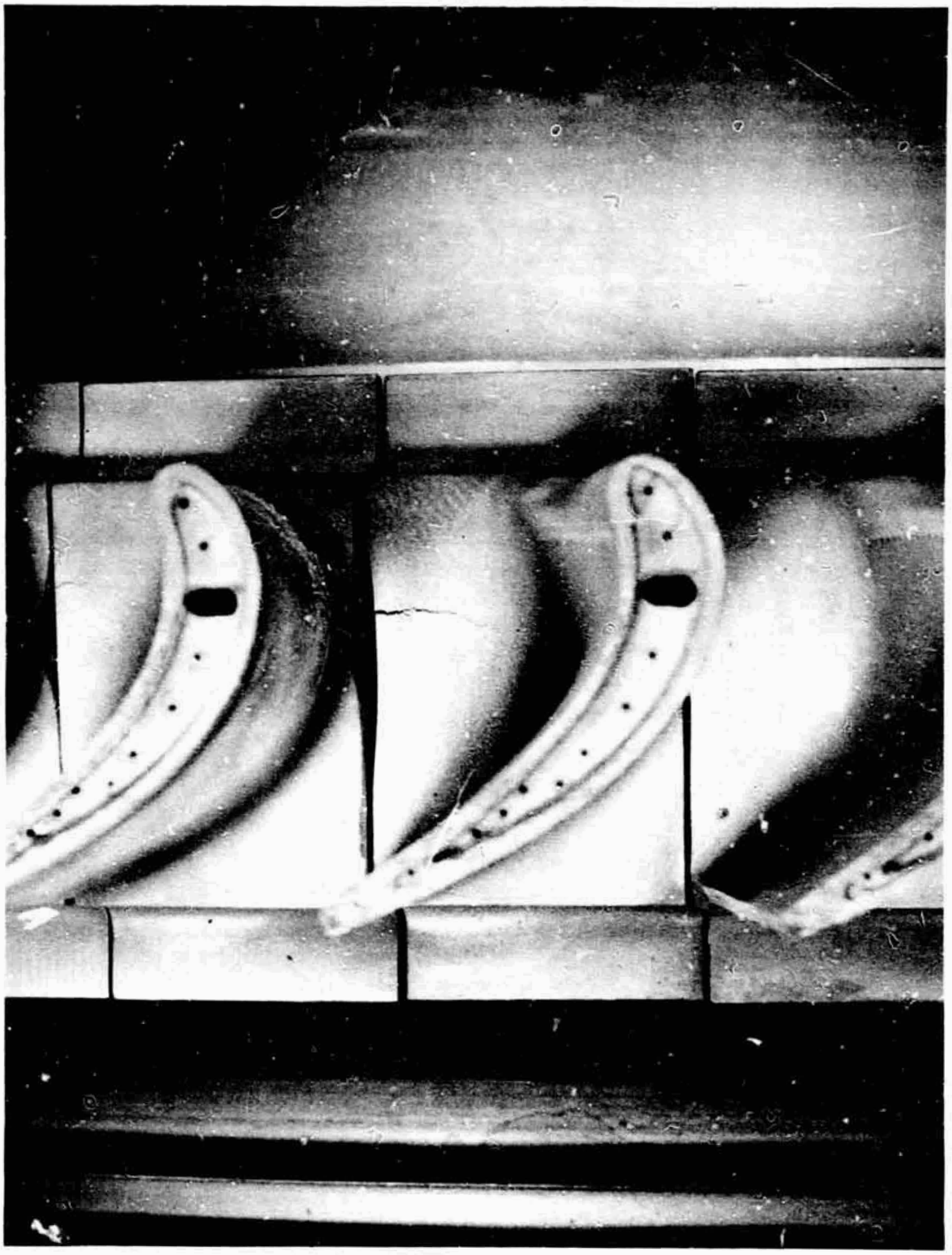


Figure 70. High Pressure Turbine First Stage Rotor Blade Platforms After Test.

CHAPTER

DEVELOPMENT STATUS SUMMARY

An assessment of the current development status of the CF6-50 Double Annular Combustor design concept, based on the combined results of Phases II and III of the program, is presented in Table 23. As is shown, the Double Annular Combustor has been found to meet or closely approach most of the key emission, performance, and operating requirements of the CF6-50 engine. Considering the relatively early state of the development of this advanced combustor design concept, this status is considered to be generally good. However, in its current form, the Phase III demonstrator engine combustor is still deficient in several key performance aspects. These are discussed below.

First, some additional improvement is needed to meet the applicable CO emission standard with the Phase III demonstrator engine combustor configuration at the nominal engine idle power setting of 3.3 percent of takeoff power. However, this emission standard was consistently met with the Phase II prototype combustor configuration and it is fully believed, therefore, that this standard can also be met with the Phase III demonstrator engine combustor configuration, with additional development effort.

To meet the applicable CO standard at the desired idle power setting, further reductions in the CO levels of the existing Phase III demonstrator engine combustor are particularly needed at the idle operating conditions. In addition, these needed development efforts must also be expanded to obtain lower CO emission levels at the approach operating mode, when both the pilot and main stages of the combustor are being operated. At present, operation of both stages of the existing Phase III demonstrator engine combustor at the approach condition results in relatively high CO emission indices at this operating mode and thus in high CO EPAP values. From an aircraft and engine operational standpoint, staging of the combustion process at any flight condition is undesirable. Preferably, the main stage should be in operation at power settings just above ground idle and before the aircraft is airborne. To accommodate this operational need, additional features will be required in the Double Annular Combustor design concept to provide lower CO emission levels at the approach mode with both the pilot and main stages in operation.

Secondly, as is shown in Table 23, additional reductions in its NO_x emission levels are needed to meet the applicable NO_x standard, as originally specified in Reference 1 by the EPA. Obtaining these additional large reductions in NO_x emission levels is not, however, considered to be a likely prospect with the existing Double Annular Combustor design concept. Thus, in this performance aspect, the development status is shown in Table 23 to be in the Major Further Development category. While it is believed that some small further reductions in NO_x emission levels of the Phase III demonstrator engine combustor can be realized, it is not expected that the currently applicable NO_x emission standard, as specified in Reference 1, will be met in the CF6-50 engine application even if these additional reductions in NO_x levels are realized.

Table 23. Assessment of Double Annular Combustor Development Status.

	Meets Requirements	Further Development Needed	Major Further Development Needed
• Emission Levels			
CO		X	
HC	X		
NO_x			X
Smoke	X		
• Ground Starting	X		
• Altitude Relight	X		
• Main Stage Crossfiring	X		
• Pressure Loss	X		
• Combustion Efficiency	X		
• Exit Temperature Profile/Pattern Factor			X
• Metal Temperature	X		
• Acoustic Resonance	X		
• Carboning	X		
• Fuel Nozzle Coking		X	

Based on the combined results of Phases II and III, it is believed the NO_x EPAP (as defined in Reference 1) of the CF6-50 engine can be reduced by up to 45 percent, relative to the NO_x EPAP of the current production CF6-50 engine, with the use of the Double Bypass Combustor design concept as is discussed in the preceding sections of this report. However, to meet the applicable EPA NO_x standard, as prescribed in Reference 1, a reduction of more than 60 percent is required. This large reduction is required because of the impacts of the high (30 to 1) cycle pressure ratios of the CF6-50 engine family on its NO_x emission characteristics. In general, it appears that, based on the parametric data obtained in Phases II and III, the use of a Double Annular Combustor in large turbofan engines with cycle pressure ratios greater than about 25 cannot be expected to result in full compliance with the applicable NO_x standard, as defined in Reference 1. However, in the case of large turbofan engines with cycle pressure ratios less than about 25 to 1, NO_x EPAP values closely approaching the applicable standard, as defined in Reference 1, can generally be expected with the use of the Double Annular Combustor design concept.

Recently, the EPA proposed a number of revisions to the standards prescribed in Reference 1. These proposed revised standards, which are presented in Reference 2, include a modest relaxation of the previously defined NO_x standard. Also included in the revised NO_x standard for existing engines is a pressure ratio adjustment which allows progressively higher NO_x levels for engines with cycle pressure ratios greater than 25. Based on the combined results obtained in Phases II and III of the program, it is believed that compliance with the revised NO_x standard can be attained by the CF6-50 with the use of the Double Annular Combustor.

Thirdly, as is shown in Table 23, substantial further improvements are needed in the exit temperature profile characteristics of the Phase III demonstrator engine combustor. Normally, this combustor development task would be relatively easy, but with this advanced combustor design concept, there is very little remaining combustor airflow available for exit temperature profile trimming. Accordingly, the attainment of fully satisfactory exit temperature distribution with the Double Annular Combustor is expected to be a formidable challenge, requiring major further development effort.

Finally, as is indicated in Table 23, the need is anticipated for additional features to prevent carbon deposition and, as a result, plugging within the main-stage fuel nozzles of the Double Annular Combustor. This problem was not encountered in the Phase III engine tests but is nevertheless still of concern. Possible problems of this latter kind are anticipated since the main-stage fuel nozzles are inoperative at some engine operating conditions. Without some added features, such as a nitrogen or air purge system, it is possible that any residual fuel in the nozzles might cause plugging problems when the main stage is shutdown.

Smoke levels are not listed as a deficiency, since the applicable standard was met for production engine operating conditions when the pilot-to-total fuel flow split was 0.18 or higher. However the smoke levels were still higher than those of the current production combustor. It is expected that with normal development smoke levels of the Double Annular Combustor will be reduced.

Apart from the combustor performance and operational problems indicated in Table 23, the fuel flow splitter represents still another area requiring further design and development effort. As is discussed in the preceding sections of this report, the existing fuel flow splitter device, which was used in the demonstrator engine tests, was designed for only sea level operation. Considerable added sophistication and complexity will be needed to also accommodate cruise operating conditions. The design and development of a suitable device to handle the necessary fuel flow splitting functions at all ground level and cruise operating conditions of the CF6 engines is expected to be a major undertaking.

Following these needed additional design and development efforts to provide a fully developed and demonstrated prototype combustion system for use in the CF6-50 and other CF6 engines, efforts can then be initiated to evolve versions of this prototype combustion system, including the necessary fuel flow control elements, for use in production CF6 engines. The major steps involved in the design, development, and demonstration of such combustion systems for use in production CF6 engines are summarized in Table 24. As is shown, the demonstration efforts must include flight service evaluation testing. These latter tests, which cannot be started until after certification of the engine with the new combustion system is completed, are expected to be quite extensive because of the magnitude of the combustor and engine design changes associated with the use of the Double Annular Combustor design concept. These latter demonstration tests are, therefore, expected to require a minimum of two years to complete. Accordingly, the total time span of the tasks outlined in Table 24 is expected to require several years to complete.

Table 24. Production Double Annular Combustion System Key Needs.

<u>Design/Development/Demonstration Steps</u>

- Design Definition
- Component Development Testing
- Engine Development Testing
  - Performance
  - Cyclic Endurance
- Engine Flight Testing
- Certification Testing
- Flight Service Evaluation Testing

APPENDIX A

EQUIPMENT AND EXPERIMENTAL PROCEDURES

1. Combustor Test Configurations

Modifications to the demonstrator Double Annular Combustor which were made during the Phase III Program rig tests are defined in Tables A-1 through A-4 and Figures A-1 through A-8. A brief description and purpose of each modification follows.

Configuration E1A was the "as-received" combustor which was tested for baseline performance and emission levels. There were no aft profile trim air dilution holes. All primary dilution and cooling hole patterns were circumferentially uniform.

Configuration E1B consisted of installing a 0.0127 cm bushing on the pilot-stage fuel nozzle tip to reduce the clearance between the fuel nozzle and the air swirler into which it is inserted. The intent was to reduce leakage airflow and improve fuel spray symmetry.

Configuration E2 consisted of general changes to the airflow distribution which are shown in Figure A-1. Modifications were aimed at reducing idle emission levels, preferentially increasing liner cooling in hottest regions, adding profile trim dilution air, and maintaining pressure drop.

Configuration E3 consisted of five sector combinations of pilot-stage fuel nozzle and dilution modifications shown in Figure A-2. The intent was to identify features which would reduce idle emission levels.

Configuration E4 consisted of five sector modifications to the pilot-stage dilution hole pattern, shown in Figure A-3. The intent again was to identify features which would reduce idle emission levels.

Configuration E5 consisted of five sector modifications to the pilot-stage dilution hole pattern and one swirl-cup modification shown in Figure A-4, which were again aimed at identifying idle emission reduction features.

Configuration E6 consisted of five pilot-stage sector modifications and two main-stage sector modifications, shown in Table A-4. Again pilot-stage modifications were aimed at idle emission level reductions. Main-stage modifications were aimed at determining any high power emission/stability sensitivity.

Configuration E7 (uniform all around) incorporated the most promising pilot- and main-stage modifications (E6A and E6F) from the previous series for a full performance and emission test series in preparation for engine installation.

Table A-1. Area/Airflow Distribution, Configurations E1 through E4.

Configuration	E1A A_e cm^2	E1A % W_c	E1B A_e cm^2	E1B % W_c	E2 A_e cm^2	E2 % W_c	E3A A_e cm^2	E3A % W_c	E3B A_e cm^2	E3B % W_c	E3C A_e cm^2	E3C % W_c
Outer Swirl Cups												
Primary Swirler	26.2	4.53	26.3	4.54	26.3	4.47	26.2	4.64	26.2	4.64	26.2	4.64
Secondary Swirler	38.8	6.69	38.8	6.71	38.8	6.60	38.8	6.86	38.8	6.86	38.8	6.86
Purge Holes	1.5	0.26	1.5	0.26	1.5	0.25	1.5	0.26	1.5	0.26	1.5	0.26
Nozzle Shroud/Leakage	6.1	1.06	5.1	0.89	5.2	0.88	0.4	0.07	5.1	0.91	5.1	0.91
Total	72.6	12.54	71.7	12.40	71.7	12.20	66.9	11.83	71.7	12.68	71.7	12.68
Inner Swirl Cups												
Primary Swirler	27.2	4.69	27.2	4.70	27.1	4.62	27.1	4.80	27.1	4.80	27.1	4.80
Secondary Swirler	160.3	27.68	160.4	27.73	147.0	25.01	147.0	26.00	147.0	26.00	147.0	26.00
Purge Holes	1.7	0.30	1.7	0.30	1.8	0.30	1.8	0.31	1.8	0.31	1.8	0.31
Nozzle Shroud/Leakage	6.2	1.07	6.2	1.07	6.2	1.06	6.2	1.10	6.2	1.10	6.2	1.10
Total	195.4	33.74	195.5	33.80	182.0	30.98	182.1	32.20	182.1	32.20	182.1	32.20
Dilution												
Outer Liner, Panel 2	29.9	5.16	29.9	5.17	40.1	6.83	40.1	7.10	40.1	7.10	18.7	3.31
Panel 3	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Inner Liner, Panel 1	62.7	10.82	62.6	10.83	62.6	10.66	62.6	11.08	62.6	11.08	62.6	11.08
Panel 6	0.0	0	0.0	0	7.8	1.33	7.8	1.38	7.8	1.38	7.8	1.38
Total	92.6	15.97	92.5	16.00	110.6	18.82	110.6	19.56	110.6	19.56	89.2	15.77
Cooling												
Outer Liner	52.1	9.00	52.1	9.01	52.1	8.87	52.1	9.22	52.1	9.22	52.1	9.22
Outer Dome	41.3	7.13	41.3	7.14	41.3	7.03	41.3	7.30	41.3	7.30	41.3	7.30
Centerbody	27.5	4.75	27.5	4.75	27.5	4.68	27.5	4.86	27.5	4.86	27.5	4.86
Inner Dome	31.8	5.48	31.7	5.49	31.7	5.40	31.7	5.61	31.7	5.61	31.7	5.61
Inner Liner	56.9	9.83	56.9	9.84	61.6	10.49	61.6	10.90	61.6	10.90	61.6	10.90
Seal Leakage	9.0	1.56	9.0	1.56	9.0	1.54	9.0	1.60	9.0	1.60	9.0	1.60
Total	218.6	37.75	218.6	37.80	223.3	38.00	223.3	39.50	223.3	39.50	223.3	39.50
Combustor Total	579.2	100.00	578.3	100.00	587.6	100.00	582.8	103.10	587.6	103.80	566.2	100.15

Configuration	E3D A_e cm^2	E3D % W_c	E3E A_e cm^2	E3E % W_c	E4A A_e cm^2	E4A % W_c	E4B A_e cm^2	E4B % W_c	E4C A_e cm^2	E4C % W_c	E4D A_e cm^2	E4D % W_c	E4E A_e cm^2	E4E % W_c
Outer Swirl Cups														
Primary Swirler	26.2	4.64	26.2	4.64	26.2	4.53	26.2	4.53	26.2	4.53	26.2	4.53	26.2	4.53
Secondary Swirler	38.8	6.86	38.8	6.86	38.8	6.69	38.8	6.69	38.8	6.69	38.8	6.69	38.8	6.69
Purge Holes	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26
Nozzle Shroud/Leakage	5.1	0.91	0.4	0.07	5.1	0.89	5.1	0.89	5.1	0.49	5.1	0.89	5.1	0.89
Total	71.7	12.68	66.9	11.83	71.7	12.37	71.7	12.37	71.7	12.37	71.7	12.37	71.7	12.37
Inner Swirl Cups														
Primary Swirler	27.1	4.80	27.1	4.80	27.1	4.69	27.1	4.69	27.1	4.69	27.1	4.69	27.1	4.69
Secondary Swirler	147.0	26.00	147.0	26.00	147.0	25.37	147.0	25.37	147.0	25.37	147.0	25.37	147.0	25.37
Purge Holes	1.8	0.31	1.8	0.31	1.8	0.30	1.8	0.30	1.8	0.30	1.8	0.30	1.8	0.30
Nozzle Shroud/Leakage	6.2	1.10	6.2	1.10	6.2	1.07	6.2	1.07	6.2	1.07	6.2	1.07	6.2	1.07
Total	182.1	32.20	182.1	32.20	182.1	31.43	182.1	31.43	182.1	31.43	182.1	31.43	182.1	31.43
Dilution														
Outer Liner, Panel 2	0.0	0	0.0	0	14.1	2.43	14.1	2.43	18.7	3.23	28.2	4.86	14.1	2.43
Panel 3	0.0	0	0.0	0	9.3	1.61	14.1	2.43	18.7	3.23	0.0	0	28.2	4.86
Inner Liner, Panel 1	62.6	11.08	62.6	11.08	62.6	10.81	62.6	10.81	62.6	10.81	62.6	10.81	62.6	10.81
Panel 6	7.8	1.38	7.8	1.38	7.8	1.35	7.8	1.35	7.8	1.35	7.8	1.35	7.8	1.35
Total	70.4	12.46	70.4	12.46	93.9	16.20	98.6	17.02	107.9	18.62	98.6	17.02	112.6	19.44
Cooling														
Outer Liner	52.1	9.22	52.1	9.22	52.1	9.00	52.1	9.00	52.1	9.00	52.1	9.00	52.1	9.00
Outer Dome	41.3	7.30	41.3	7.30	41.3	7.13	41.3	7.13	41.3	7.13	41.3	7.13	41.3	7.13
Centerbody	27.5	4.86	27.5	4.86	27.5	4.74	27.5	4.74	27.5	4.74	27.5	4.74	27.5	4.74
Inner Dome	31.7	5.61	31.7	5.61	31.7	5.48	31.7	5.48	31.7	5.48	31.7	5.48	31.7	5.48
Inner Liner	61.6	10.90	61.6	10.90	61.6	10.63	61.6	10.63	61.6	10.63	61.6	10.63	61.6	10.63
Seal Leakage	9.0	1.60	9.0	1.60	9.0	1.56	9.0	1.56	9.0	1.56	9.0	1.56	9.0	1.56
Total	223.3	39.50	223.3	39.50	223.3	38.54	223.3	38.54	223.3	38.54	223.3	38.54	223.3	38.54
Combustor Total	547.5	96.84	542.7	95.99	570.9	98.54	575.6	99.35	584.8	100.95	575.6	99.35	589.7	101.78

E3A through E3E: Overall = 565.4 cm^2

E4A through E4E: Overall = 579.4 cm^2

Table A-2. Area/Airflow Distribution, Configurations E5 Through E9.

Configuration	E5A		E5B		E5C		E5D		E5E		E6A		E6B	
	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c
Outer Swirl Cups														
Primary Swirler	26.2	4.38	26.2	4.38	26.2	4.38	26.2	4.38	26.2	4.38	26.2	4.59	26.2	4.59
Secondary Swirler	38.8	6.49	38.8	6.49	38.8	6.49	38.8	6.49	38.8	6.49	38.8	6.80	38.8	6.80
Purge Holes	1.5	0.25	1.5	0.25	1.5	0.25	1.5	0.25	1.5	0.25	1.5	0.26	1.5	0.26
Nozzle Shroud/Leakage	5.1	0.85	5.1	0.85	5.1	0.85	5.1	0.85	5.1	0.85	3.4	0.60	3.4	0.60
Total	71.6	11.97	71.6	11.97	71.6	11.97	71.6	11.97	71.6	11.97	69.9	12.25	69.9	12.25
Inner Swirl Cups														
Primary Swirler	27.1	4.53	27.1	4.53	27.1	4.53	27.1	4.53	27.1	4.53	27.1	4.75	27.1	4.75
Secondary Swirler	147.0	24.58	147.0	24.58	147.0	24.58	147.0	24.58	147.0	24.58	147.0	25.77	147.0	25.77
Purge Holes	1.8	0.30	1.8	0.30	1.8	0.30	1.8	0.30	1.8	0.30	1.8	0.32	1.8	0.32
Nozzle Shroud/Leakage	6.2	1.04	6.2	1.04	6.2	1.04	6.2	1.04	6.2	1.04	2.8	0.49	2.8	0.49
Total	182.1	30.44	182.1	30.44	182.1	30.44	182.1	30.44	182.1	30.44	178.7	31.32	178.7	31.32
Dilution														
Outer Liner, Panel 1	29.9	5.00	18.7	3.13	18.7	3.13	0	0	29.9	5.00	0	0	0	0
Panel 2	29.9	5.00	29.9	5.00	18.7	3.13	48.6	8.12	29.9	5.00	29.9	5.24	29.9	5.24
Panel 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Liner, Panel 1	62.6	10.47	62.6	10.47	62.6	10.47	62.6	10.47	62.6	10.47	62.6	10.97	62.6	10.97
Panel 6	7.8	1.30	7.8	1.30	7.8	1.30	7.8	1.30	7.8	1.30	7.8	1.37	7.8	1.37
Total	130.2	21.77	119.0	19.90	107.8	18.02	119.0	19.90	130.2	21.77	100.3	17.58	100.3	17.58
Cooling														
Outer Liner	52.1	8.71	52.1	8.71	52.1	8.71	52.1	8.71	52.1	8.71	52.1	9.13	52.1	9.13
Outer Dome	41.3	6.91	41.3	6.91	41.3	6.91	41.3	6.91	41.3	6.91	41.3	7.24	41.3	7.24
Centerbody	27.5	4.60	27.5	4.60	27.5	4.60	27.5	4.60	27.5	4.60	27.5	4.82	27.5	4.82
Inner Dome	31.7	5.30	31.7	5.30	31.7	5.30	31.7	5.30	31.7	5.30	31.7	5.56	31.7	5.56
Inner Liner	61.6	10.30	61.6	10.30	61.6	10.30	61.6	10.30	61.6	10.30	61.6	10.80	61.6	10.80
Seal Leakage	9.0	1.50	9.0	1.50	9.0	1.50	9.0	1.50	9.0	1.50	9.0	1.58	9.0	1.58
Total	223.2	37.32	223.2	37.32	223.2	37.32	223.2	37.32	223.2	37.32	223.2	39.12	223.2	39.12
Combustor Total	607.1	101.50	595.9	99.63	584.7	97.76	595.9	99.63	607.1	101.50	572.1	100.28	572.1	100.28
	Overall = 598.1 cm^2										Overall = 570.5 cm^2			

Configuration	E6C		E6D		E6E		E6F		E6G		E7		E8, E9	
	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c	A_{e_2} cm^2	% W_c
Outer Swirl Cups														
Primary Swirler	26.2	4.59	26.2	4.59	26.2	4.59	26.2	4.59	26.2	4.59	26.2	[illegible]	26.2	[illegible]
Secondary Swirler	38.8	6.80	38.8	6.80	38.8	6.80	38.8	6.80	38.8	6.80	38.8	6.75	38.8	[illegible]
Purge Holes	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26	1.5	[illegible]
Nozzle Shroud/Leakage	1.8	0.32	0.1	0.02	0.1	0.02	1.8	0.32	1.8	0.32	3.4	0.59	3.4	[illegible]
Total	68.3	11.97	66.6	11.67	66.6	11.67	68.3	11.97	68.3	11.97	69.9	12.16	69.9	[illegible]
Inner Swirl Cups														
Primary Swirler	27.1	4.75	27.1	4.75	27.1	4.75	27.1	4.75	27.1	4.75	27.1	4.72	27.1	[illegible]
Secondary Swirler	147.0	25.77	147.0	25.77	147.0	25.77	147.0	25.77	147.0	25.77	147.0	[illegible]	147.0	[illegible]
Purge Holes	1.8	0.32	1.8	0.32	1.8	0.32	1.8	0.32	1.8	0.32	1.8	0.31	1.8	0.31
Nozzle Shroud/Leakage	2.8	0.49	2.8	0.49	2.8	0.49	5.4	0.95	0.3	0.05	5.4	0.94	5.4	[illegible]
Total	178.7	31.32	178.7	31.32	178.7	31.32	181.3	31.78	176.2	[illegible]	181.3	31.86	181.3	[illegible]
Dilution														
Outer Liner, Panel 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panel 2	29.9	5.24	29.9	5.24	29.9	5.24	29.9	5.24	29.9	5.24	29.9	5.20	29.9	5.13
Panel 6	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.10
Inner Liner, Panel 1	62.6	10.97	62.6	10.97	62.6	10.97	62.6	10.97	62.6	10.97	62.6	[illegible]	62.6	[illegible]
Panel 6	7.8	1.37	7.8	1.37	7.8	1.37	7.8	1.37	7.8	1.37	7.8	1.36	15.6	[illegible]
Total	100.3	17.58	100.3	17.58	100.3	17.58	100.3	17.58	100.3	17.58	100.3	17.46	108.7	[illegible]
Cooling														
Outer Liner	52.1	9.13	52.1	9.13	52.1	9.13	52.1	9.13	52.1	9.13	52.1	9.07	52.1	[illegible]
Outer Dome	41.3	7.24	41.3	7.24	41.3	7.24	41.3	7.24	41.3	7.24	41.3	7.19	41.3	[illegible]
Centerbody	27.5	4.82	27.5	4.82	27.5	4.82	27.5	4.82	27.5	4.82	27.5	4.79	27.5	4.72
Inner Dome	31.7	5.56	31.7	5.56	31.7	5.56	31.7	5.56	31.7	5.56	31.7	5.52	31.7	5.44
Inner Liner	61.6	10.80	61.6	10.80	61.6	10.80	61.6	10.80	61.6	10.80	61.6	10.72	61.6	[illegible]
Seal Leakage	9.0	1.58	9.0	1.58	9.0	1.58	9.0	1.58	9.0	1.58	9.0	1.57	9.0	1.54
Total	223.2	39.12	223.2	39.12	223.2	39.12	223.2	39.12	223.2	39.12	223.2	[illegible]	223.2	[illegible]
Combustor Total	570.5	100.00	568.8	99.70	568.8	99.70	573	100.46	568.0	99.56	574.7	100.00	583.1	100.00
	Overall = 570.5 cm^2 (cont.)													

Table A-3. Area/Airflow Distribution, Configuration E9 Through E12.

Configuration	E9		E10A		E10B		E10C	
	A_e cm^2	% W_c	A_e cm^2	% W_c	A_e cm^2	% W_c	A_e cm^2	% W_c
Outer Swirl Cups								
Primary Swirler	26.2	4.49	26.2	4.58	26.2	4.58	26.2	4.58
Secondary Swirler	38.8	6.65	38.8	6.78	38.8	6.78	38.8	6.78
Purge Holes	1.5	0.26	1.5	0.26	1.5	0.26	1.5	0.26
Nozzle Shroud/Leakage	3.4	0.58	3.4	0.59	3.4	0.59	3.4	0.59
Total	69.9	11.98	69.9	12.22	69.9	12.22	69.9	12.22
Inner Swirl Cups								
Primary Swirler	27.1	4.65	27.1	4.74	27.1	4.74	27.1	4.74
Secondary Swirler	147.0	25.21	132.3	23.13	132.3	23.13	132.3	23.13
Purge Holes	1.8	0.31	1.8	0.31	1.8	0.31	1.8	0.31
Nozzle Shroud/Leakage	5.4	0.93	5.4	0.94	5.4	0.94	5.4	0.94
Total	181.3	31.10	166.6	29.12	166.6	29.12	166.6	29.12
Dilution								
Outer Liner, Panel 1	0.0	0.00	0.0	0.00	3.8	0.66	7.5	1.31
Panel 2	29.9	5.13	29.9	5.23	29.9	5.23	29.9	5.23
Panel 6	0.6	0.10	0.6	0.10	0.6	0.10	0.6	0.10
Inner Liner, Panel 1	62.6	10.74	62.6	10.94	62.6	10.94	62.6	10.94
Panel 6	15.6	2.67	15.6	2.73	15.6	2.73	15.6	2.73
Total	108.7	18.64	108.7	19.00	112.5	19.66	116.2	20.31
Cooling								
Outer Liner	52.1	8.94	52.1	9.11	52.1	9.11	52.1	9.11
Outer Dome	41.3	7.08	41.3	7.22	41.3	7.22	41.3	7.22
Centerbody	27.5	4.72	27.5	4.81	27.5	4.81	27.5	4.81
Inner Dome	31.7	5.44	31.7	5.54	31.7	5.54	31.7	5.54
Inner Liner	61.6	10.56	61.6	10.77	61.6	10.77	61.6	10.77
Seal Leakage	9.0	1.54	9.0	1.57	9.0	1.57	9.0	1.57
Total	223.2	38.28	223.2	39.01	223.2	39.01	223.2	39.01
Combustor Total	583.1	100.00	568.4	99.35	572.2	100.02	575.9	100.66
			Overall 572.1 cm^2					

Table A-4. Configuration E6 Modifications.

Sector	Stage	Swirl Cup No.	Nozzle Modification	Cup Modification
E6A	Pilot	1-6	Shroud flow reduced to engine nozzle level	None
E6B	Pilot	7-12	Shroud flow reduced to engine nozzle level	Cylindrical barrel extension
E6C	Pilot	13-18	Shroud flow reduced to 50% of engine nozzle level	None
E6D	Pilot	19-24	Shroud flow eliminated	None
E6E	Pilot	25-30	Shroud flow eliminated	Cylindrical barrel extension
E6F	Main	2-16	Leakage closed	None
E6G	Main	17-1	Leakage closed, shroud flow eliminated	None

Dilution Hole Patterns Uniform All Around
Pilot Stage: Same as E1
Aft Trim: Same as E2

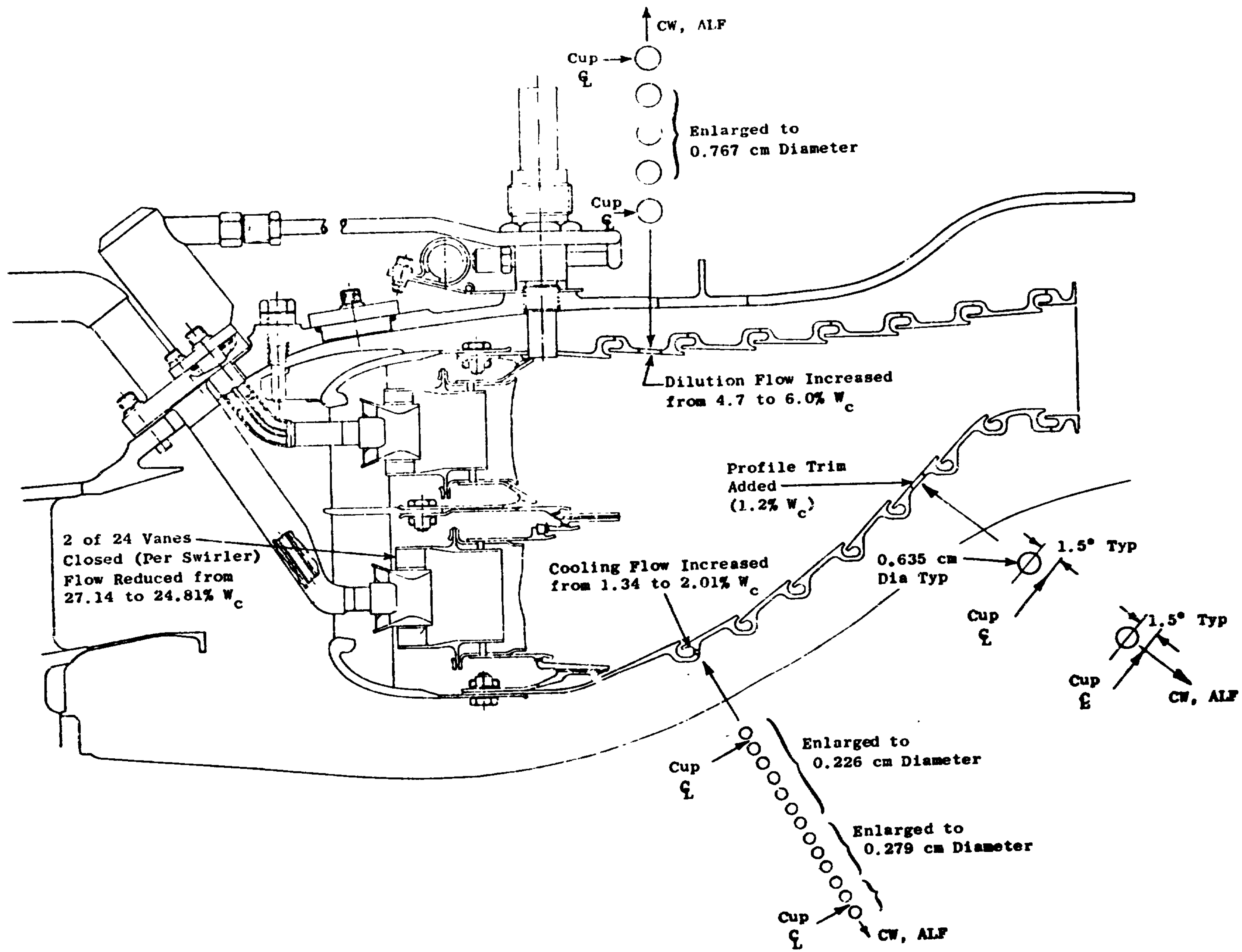
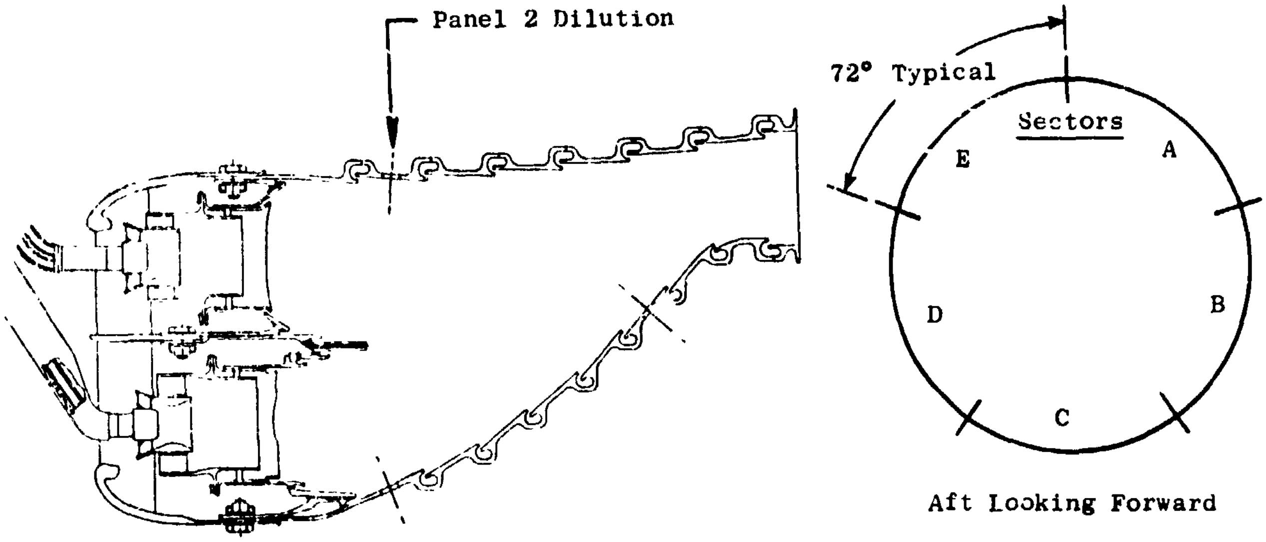


Figure A-1. Combustor Modifications, Configuration E2.

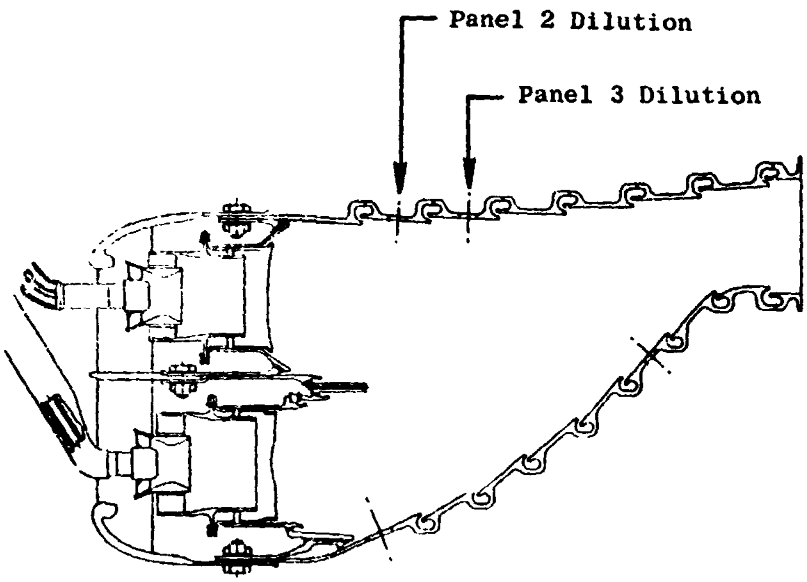


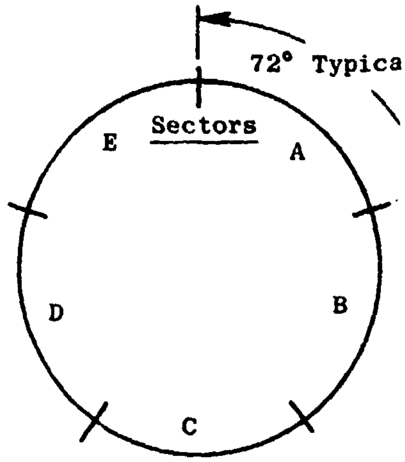
Config	Type Pilot Stage Nozzle	Outer Liner Panel Number	Outer Liner Dilution Hole Patterns * Hole Diameters, cm: ◇ = 0.50, ○ = 0.64, □ = 0.77					Equivalent Dilution Airflow % W_c
			Nozzle	← 12° →			Nozzle	
E3A	1	1						----
		2	○	□	□	□	○	7.10
		3						----
E3B	2	1						----
		2	○	□	□	□	○	7.10
		3						----
E3C	2	1						----
		2	◇	◇	◇	◇	◇	3.31
		3						----
E3D	2	1						----
		2	None					----
		3						----
E3E	1	1						----
		2	None					----
		3						----

Nozzle Type: 1 = Phase II Development
2 = Engine Simulator

* Patterns Repeated For 72° (6 Nozzles)

Figure A-2. Combustor Modifications, Configuration E3.





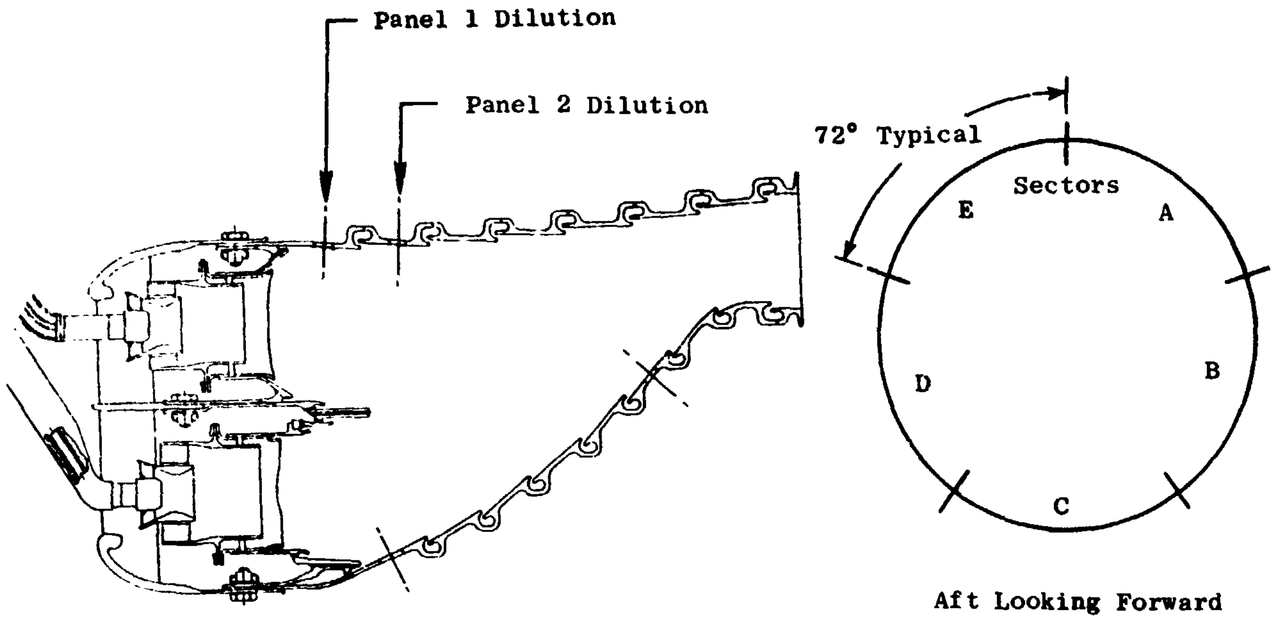
Aft Looking Forward

Config	Type Pilot Stage Nozzle	Outer Liner Panel No.	Outer Liner Dilution Hole Pattern * Hole Diameters (cm) ◇ = 0.50 (Nozzle ← 12° → Nozzle)	Equivalent Dilution Airflow % W_c
E4A	2	1		---
		2	◇ ◇ ◇	2.43
		3	◇ ◇	1.61
E4B	2	1		---
		2	◇ ◇ ◇	2.43
		3	◇ ◇ ◇	2.43
E4C	2	1		---
		2	◇ ◇ ◇ ◇ ◇	3.23
		3	◇ ◇ ◇ ◇ ◇	3.23
E4D	2	1		---
		2	◇ ◇ ◇ ◇ ◇ ◇ ◇	4.83
		3		---
E4E	2	1		---
		2	◇ ◇ ◇	2.43
		3	◇ ◇ ◇ ◇ ◇ ◇ ◇	4.86

Nozzle Type: 2 = Engine Simulator

* Patterns Repeated For 72° (6 Nozzles)

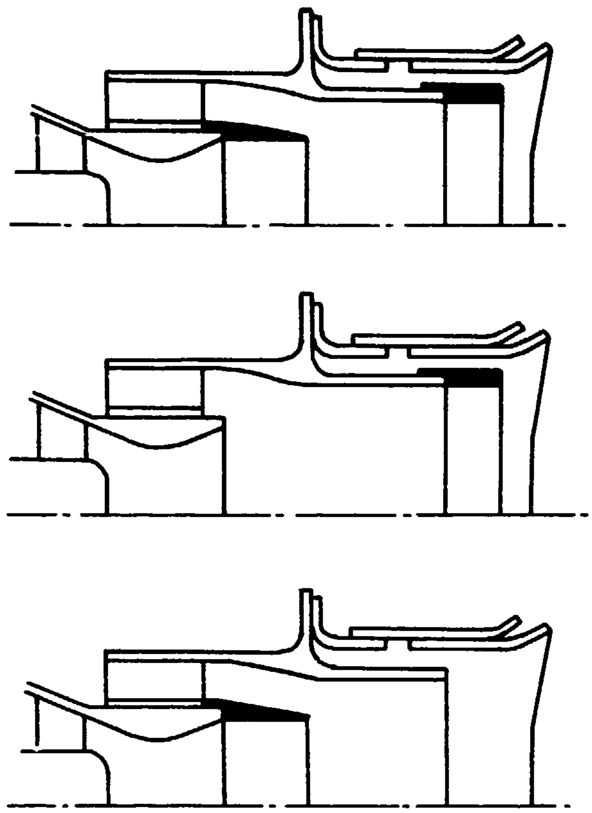
Figure A-3. Combustor Modifications, Configuration E4.



Config	Type Pilot Stage Nozzle	Outer Liner Panel Number	Outer Liner Dilution Hole Patterns * Hole Diameters, cm ◇ = 0.50, ○ = 0.64,					Equivalent Dilution Airflow % W_c
			Nozzle	← 12° →			Nozzle	
E5A	2	1	○	○	○	○	○	4.97
		2	○	○	○	○	○	4.97
		3						----
E5B	2	1	◇	◇	◇	◇	◇	3.12
		2	○	○	○	○	○	4.97
		3						----
E5C	2	1	◇	◇	◇	◇	◇	3.12
		2	◇	◇	◇	◇	◇	3.12
		3						----
E5D	2	1						----
		2	○	◇	○	◇	○	8.09
		3						----
E5E**	2	1	○	○	○	○	○	4.97
		2	○	○	○	○	○	4.97
		3						----
Nozzle Type: 2 = Engine Simulator								

* Patterns Repeated For 72° (6 Nozzles)
** With Pilot Stage Cup Barrel Extended 1.40 cm; Otherwise Same As E5A.

Figure A-4. Combustor Modifications, Configuration E5.

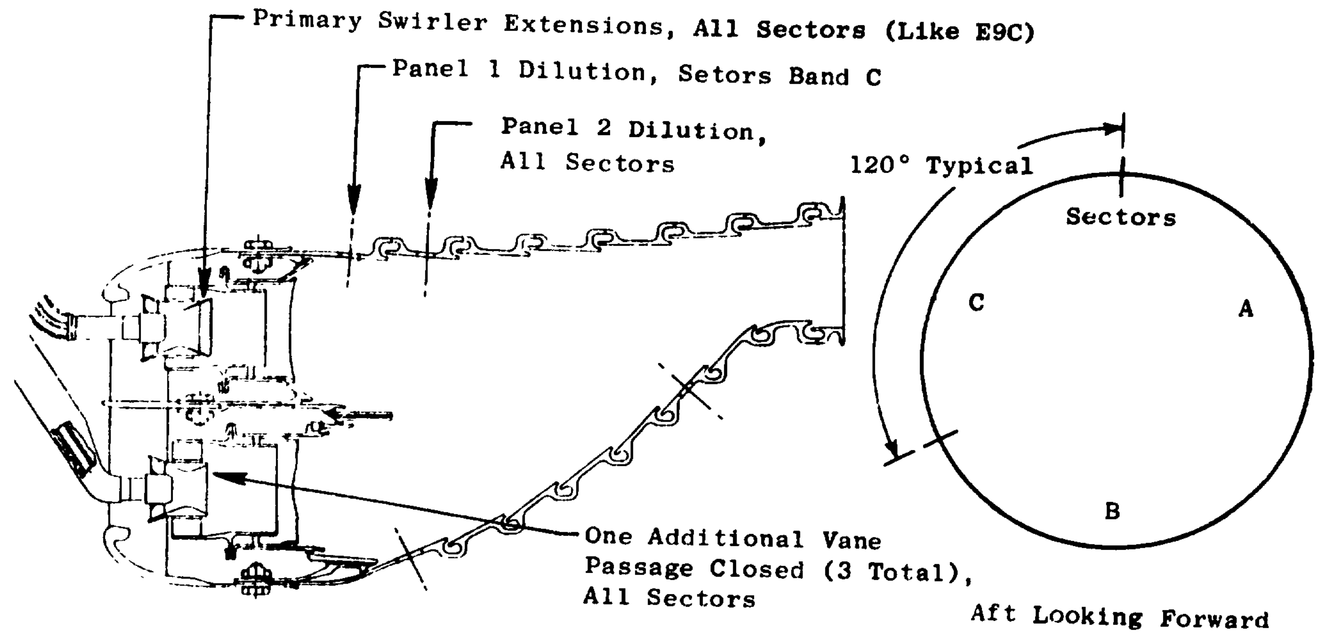


Configuration E9A
(Cup 1 - 10)

Configuration E9B
(Cup 11 - 20)

Configuration E9C
(Cup 21 - 30)

Figure A-5. Pilot Stage Modifications for Configuration E9



Configuration	Outer Liner Panel Number	Outer Liner Dilution Hole Patterns Hole Diameter, cm ◇ = 0.32 ○ = 0.64 (Nozzle ← 12° → Nozzle)	Equivalent Dilution Airflow % W_c	Swirler Plus Dilution Airflow % W_c
E10A	1 2	○ ○ ○ ○ ○	--- 5.23	17.45
E10B	1 2	○◇ ◇○ ○ ○ ○◇	0.66 5.23	18.11
E10C	1 2	◇○◇ ◇○◇ ○ ○ ◇○◇	1.31 5.23	18.76

Figure A-6. Combustor Modifications, Configuration E10.

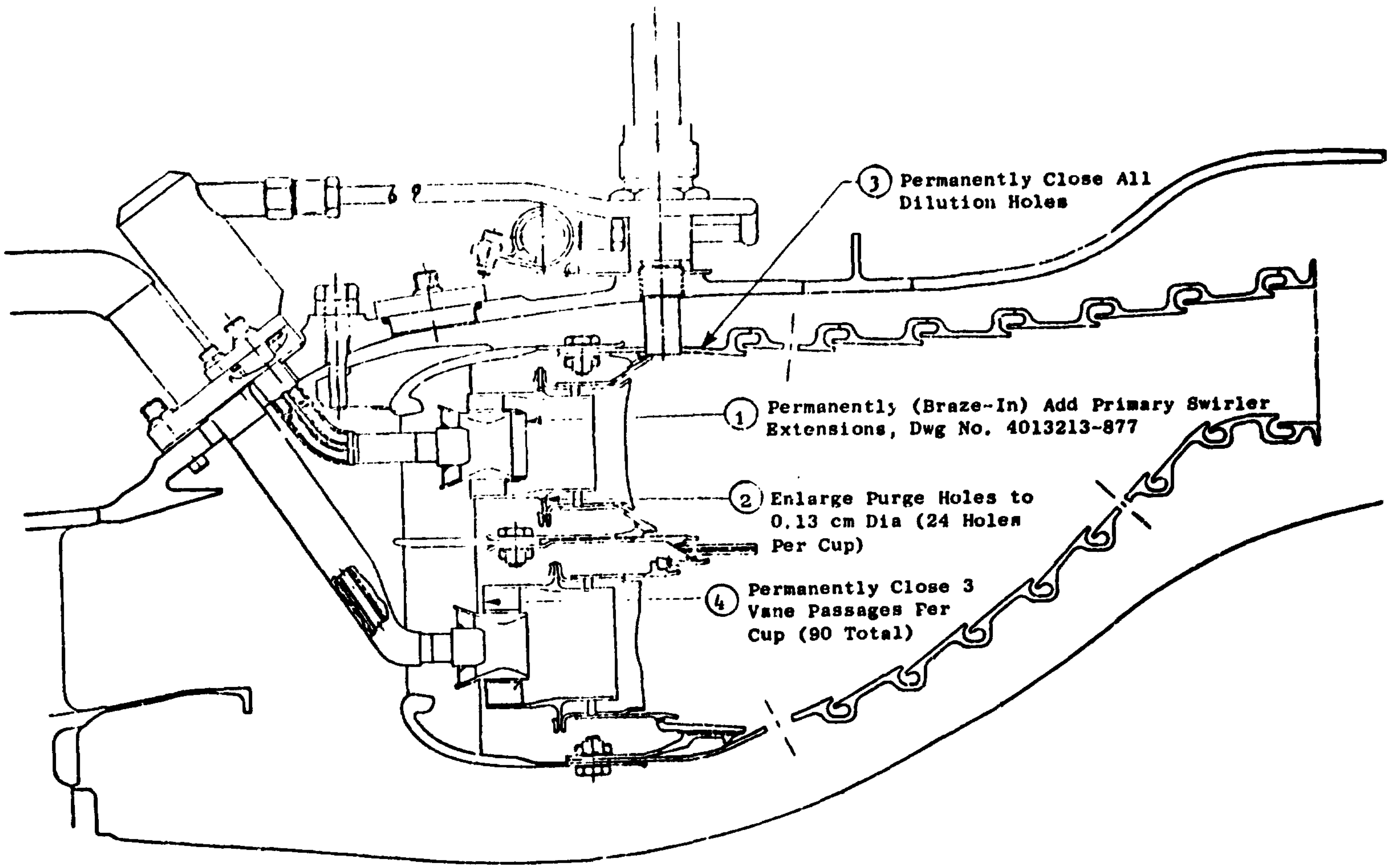
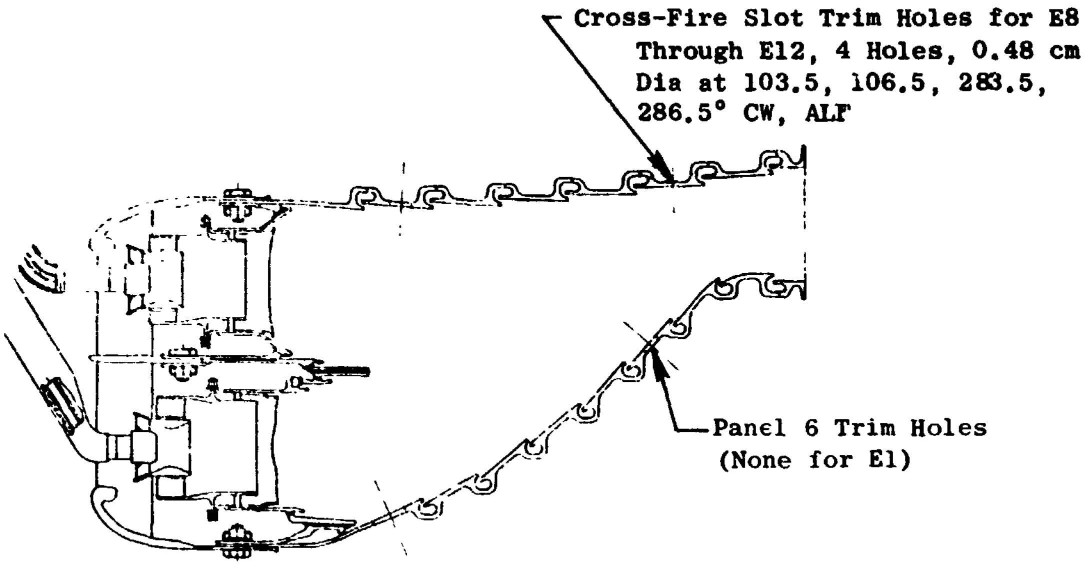


Figure A-7. Combustor Modifications, Configuration E11.



Config.	Inner Liner Panel 6 Trim Hole Patterns* (0.64 cm Diameter) — Nozzle ← 12° → Nozzle	Trim Airflow % W_c
E2-E7	○ ○	1.3
E8, E12	○ ○ ○ ○	2.7
E9-E11	○ ○ ○ ○	2.7

* Patterns Repeated for Entire Circumference

Figure A-8. Trim Hole Patterns, Configuration E1 Through E12.

Configuration E8 differed from E7 only in the aft trim air dilution hole pattern for changes to improve the exit temperature profile as shown in Figure A-8.

Configuration E9 incorporated three sector pilot-stage swirl cup modifications shown in Figure A-5. Modifications were again aimed at idle emission level reductions.

Configuration E10 incorporated the changes shown in Figure A-6. The E9C swirl cup modification all around, a reduction in main-stage swirl cup flow to balance pressure drop, and three pilot-stage dilution hole patterns were included.

Configuration E11 incorporated the E10A pilot-stage features (uniformly all around) together with increased pilot-stage swirl cup purge airflow, and general modifications shown in Figure A7 to meet engine installation requirements.

Configuration E12 (final rig and engine test configuration) differed from E11 only in location of aft profile trim dilution holes which is shown in Figure A-8.

2. Performance Instrumentation

The demonstrator Double Annular Combustor was extensively instrumented to characterize pressure and flow distribution, metal temperatures and acoustic and mechanical vibrations. The types, locations, and quantities of the sensors which were applied are shown in Figure A-9 and Table A-5.

A recently installed modernized test data system was utilized to acquire and process the engine and combustor data during these tests. The engine was operated from the control room console shown in Figure A-10 which is tied into the Instrumentation Data Room (IDR) shown in Figure A-11, located one floor below the test cell. A schematic diagram of the data processing system is shown in Figure A-12. With this system, fully reduced and corrected steady-state engine/combustor performance data were usually available for analysis in about ten minutes.

3. Exhaust Gas Sampling and Analysis Apparatus

A new exhaust gas sampling rake and traverse system, shown earlier in Figures 21 and 22, was designed and built for these tests. The design intent was to meet the Federal Register specifications and allow comparison of different sampling techniques. Some of the key design considerations/parameters were:

- The ring on which the rakes are mounted is 2.44 m I.D. to clear the fan stream of the CF6-50 engine.

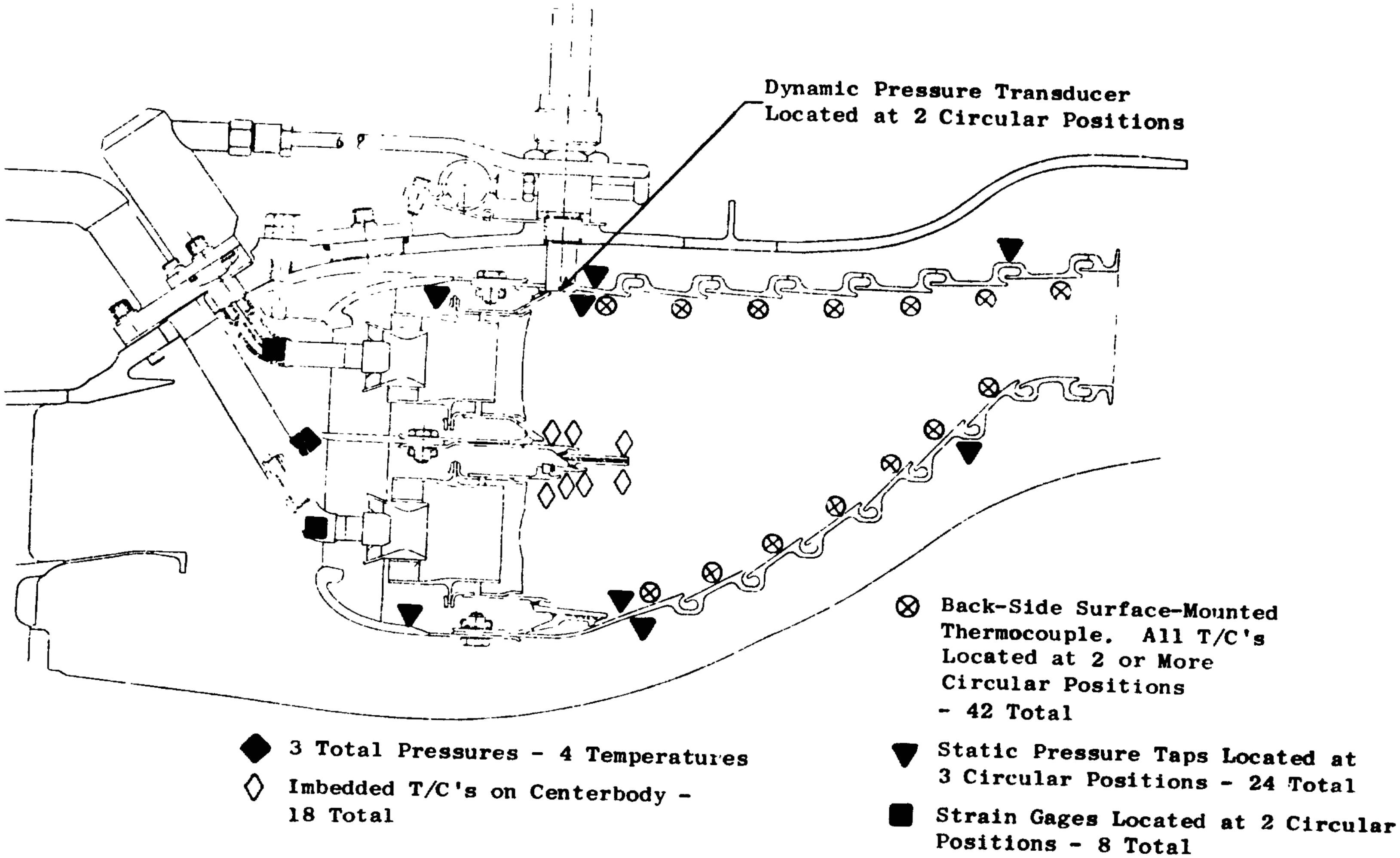


Figure A-9. Combustor Instrumentation Locations, Demonstration Engine Tests.

Table A-5. Engine Combustor Instrumentation List.

Parameter Name	Location, degrees CWALF	Parameter Name	Location, degrees CWALF	Parameter Name	Location, degrees CWALF
Outer-Liner Temperature, Panel 1	90	Inner-Liner Temperature, Panel 1	90	Air Pressure, Pilot Stage	0
Outer-Liner Temperature, Panel 1	93	Inner-Liner Temperature, Panel 1	93	Air Pressure, (Downstream)	90
Outer-Liner Temperature, Panel 1	96	Inner-Liner Tmeperature, Panel 1	96	Air Pressure, (Downstream)	180
Outer-Liner Temperature, Panel 1	99	Inner-Liner Temperature, Panel 1	99	Air Pressure, Main Stage	0
Outer-Liner Temperature, Panel 2	90	Inner-Liner Temperature, Panel 2	90	Air Pressure, (Upstream)	90
Outer-Liner Temperature, Panel 2	91.5	Inner-Liner Temperature, Panel 2	96	Air Pressure, (Upstream)	180
Outer-Liner Temperature, Panel 2	94.5	Inner-Liner Temperature, Panel 3	90	Air Pressure, Main Stage	0
Outer-Liner Temperature, Panel 2	96	Inner-Liner Temperature, Panel 3	96	Air Pressure, (Downstream)	90
Outer-Liner Temperature, Panel 2	97.5	Inner-Liner Temperature, Panel 4	90	Air Pressure, (Downstream)	180
Outer-Liner Temperature, Panel 2	100.5	Inner-Liner Temperature, Panel 4	96	Air Pressure, Outer Passage	0
Outer-Liner Temperature, Panel 2	167	Inner-Liner Temperature, Panel 5	90	Air Pressure, (Panel 1)	90
Outer-Liner Temperature, Panel 2	222	Inner-Liner Temperature, Panel 5	96	Air Pressure, (Panel 1)	180
Outer-Liner Temperature, Panel 3	90	Inner-Liner Temperature, Panel 6	90	Air Pressure, Outer Passage	0
Outer-Liner Temperature, Panel 3	96	Inner-Liner Temperature, Panel 6	96	Air Pressure, (Panel 7)	90
Outer-Liner Temperature, Panel 4	90	Inner-Liner Temperature, Panel 7	90	Air Pressure, (Panel 7)	180
Outer-Liner Temperature, Panel 4	96	Inner-Liner Temperature, Panel 7	93	Air Pressure, Inner Passage	0
Outer-Liner Temperature, Panel 5	90	Inner-Liner Temperature, Panel 7	96	Air Pressure, (Panel 1)	90
Outer-Liner Temperature, Panel 5	96	Inner-Liner Temperature, Panel 7	99	Air Pressure, (Panel 1)	180
Outer-Liner Temperature, Panel 6	90	Air Temperature, Madar Rake	90(5)	Air Pressure, Inner Passage	0
Outer-Liner Temperature, Panel 6	96	Air Temperature, Cowl Rake	6	Air Pressure, (Panel 7)	90
Outer-Liner Temperature, Panel 7	90	Air Temperature, Cowl Rake	77	Air Pressure, (Panel 7)	180
Outer-Liner Temperature, Panel 7	93	Air Temperature, Cowl Rake	186	Combustor Dynamic Pressure	102
Outer-Liner Temperature, Panel 7	96	Air Temperature, Cowl Rake	270	Combustor Dynamic Pressure	282
Outer-Liner Temperature, Panel 7	99	Air Pressure, Cowl Total	0	Fuel Nozzle Vibration, Pilot	232
Centerbody Temperature, Aft Edge	57	Air Pressure, Cowl Total	90	Fuel Nozzle Vibration, Pilot	294
Centerbody Temperature, Aft Edge	60	Air Pressure, Cowl Total	180	Fuel Nozzle Vibration, Main	234
Centerbody Temperature, Aft Edge	186 (2)	Air Pressure, Pilot Stage	0	Fuel Nozzle Vibration, Main	294
Centerbody Temperature, Aft Edge	192	Air Pressure, (Upstream)	90		
Centerbody Temperature, Aft Edge	336	Air Pressure, (Upstream)	180		
Centerbody Temperature, C/F Slot	102 (6)				
Centerbody Temperature, C/F Slot	282 (2)				

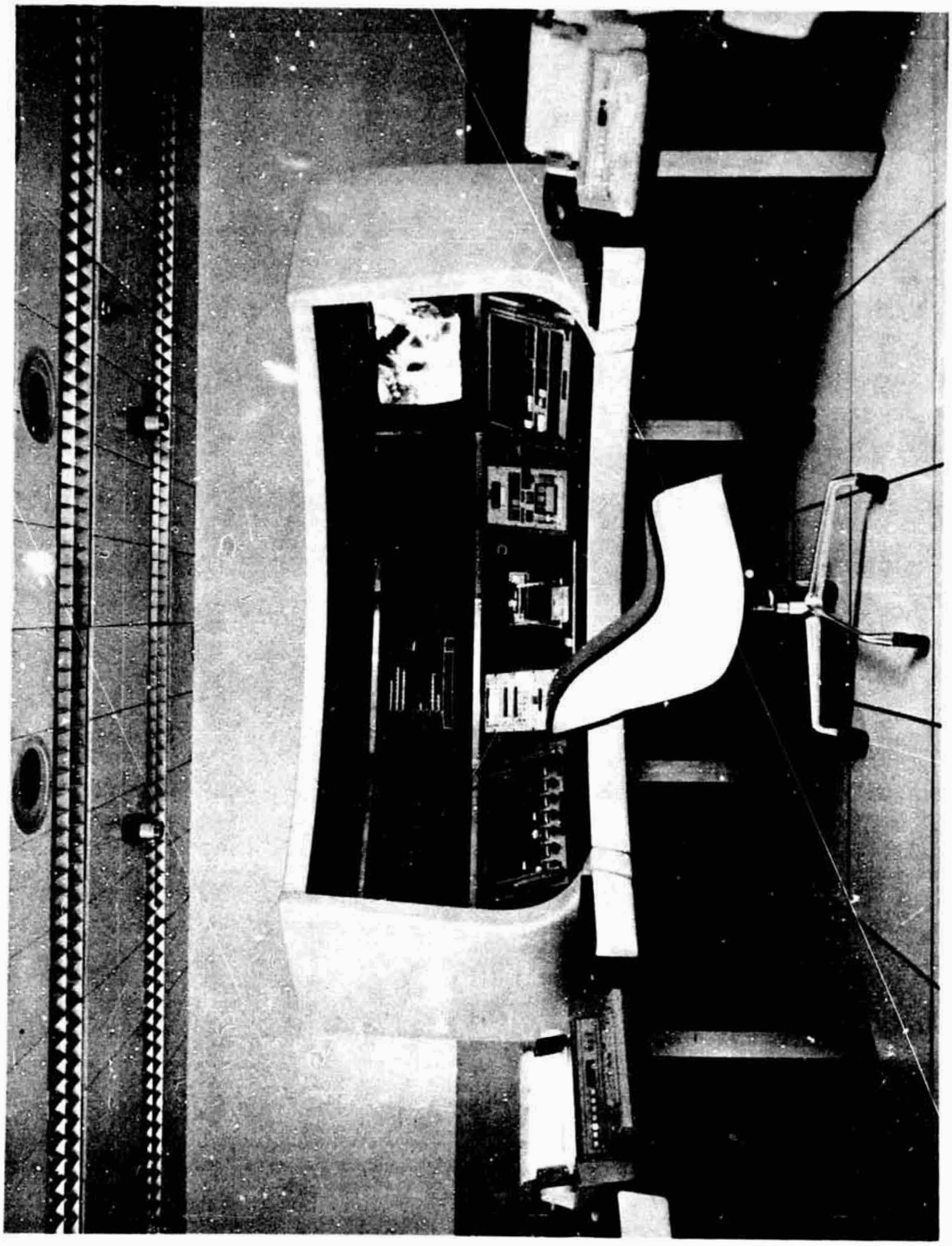


Figure A-10. Development Engine Test Cell Control Console.

Figure A-11. Instrumentation Data Room (IDR) for Development Engine Test Data Processing.

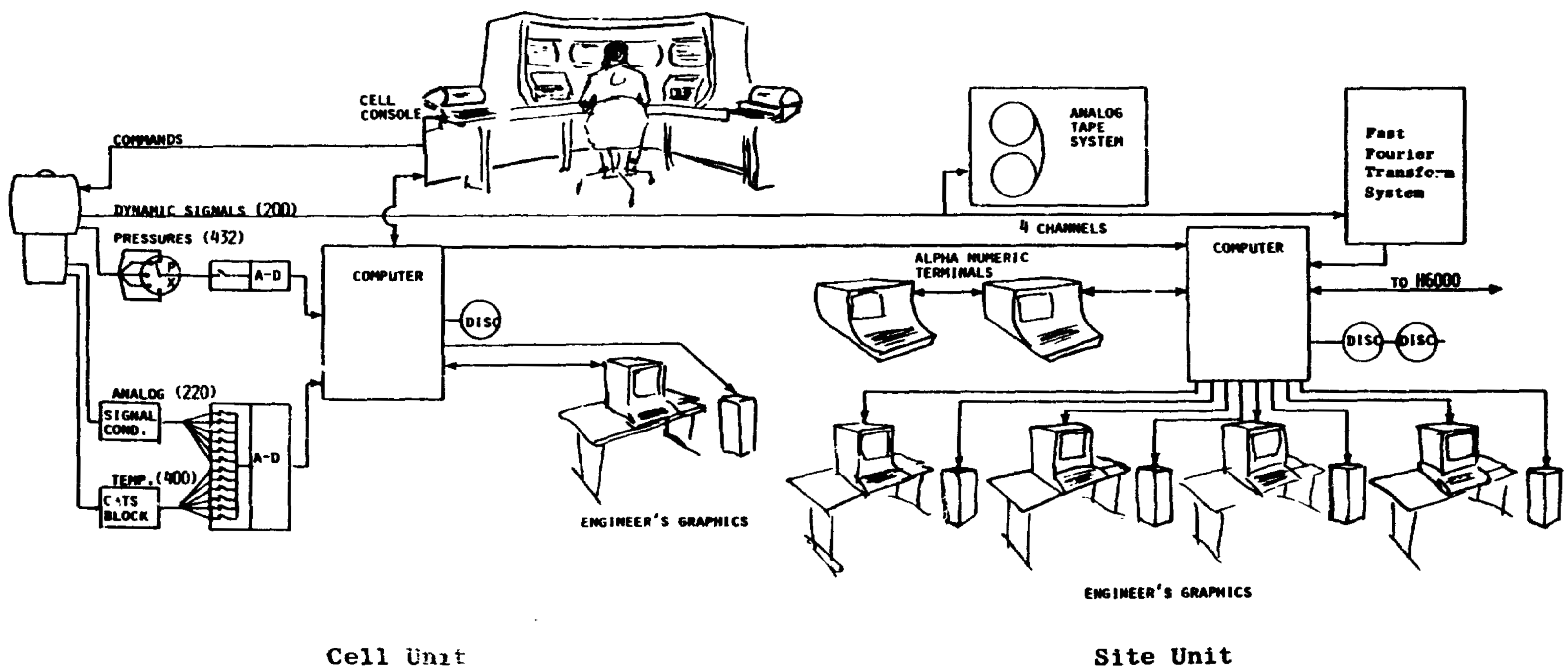


Figure A-12. Development Engine Test Data Processing Diagram.

- The structure is sized for an engine centerline of 3.05 m (10 ft), but can be varied between 1.83 and 3.96 m for use in other test sites.

- Angular rake positions can be set and varied to ±0.25 degree by a remote system.

- All sample-wetted parts are stainless steel or Teflon.

- All sample lines are steam heated outside the core engine exhaust stream.

- The three sampling ports in each rake arm are sized for a fixed conical engine exhaust nozzle 91.34 cm in diameter, cold. Orifices are at radial locations of 18.64, 32.28, and 41.68 cm, which correspond to 1/6, 1/2, and 5/6 of the cold nozzle areas. Orifices are 1.63 to 1.59 mm in diameter, have sharp edges, and are free of burrs to insure proper flow weighting.

- Connecting sample lines between individual arms and the manifolding point are 9.5 mm O.D. stainless steel tubing. Each flowpath length up to the manifolding point is the same to assure equal pressure drop in each line.

- Each of the two manifolded sample lines are connected to a .4 m length of flexible, Teflon core, electrically heated trans line to allow for rake rotation.

The structure was located in the test cell so that its centerline was within 3.2 mm of the axial centerline of the engine and the rake arms were 76.2 mm aft of the engine exhaust nozzles.

The exhaust gas analysis apparatus is shown in Figures A-13 and A-14, and a flow diagram for the system is shown in Figure A-15. The two sample lines from the rakes were connected to the sampling apparatus through a double three-way valve system. By manipulation of these valves, one line could be analyzed for smoke emissions while the other was analyzed for gaseous emissions, or one or both lines could be simultaneously analyzed for both smoke and gaseous emissions. In order to avoid fuel contamination of the system during engine starting, the rakes were backflushed with pure instrument air by opening the valve labeled "B" in Figure A-15. To maintain adequate velocity in the sample lines, the dump pump vented a nominal 20 liters/minutes flow rate.

The gaseous emissions analysis system consisted of four analyzers, each manufactured by Beckman Instruments, Inc. The CO (Model 865) and CO_2 (Model 864) analyzers were both nondispersive infrared (NDIR) instruments. To minimize water interference, the sample was passed through an ice trap before entering the NDIR instruments. The NO_x analyzer was a Model 951 heated chemiluminescence analyzer, and the HC analyzer was a Model 402 flame ionization detector (FID) instrument. No traps were used in the NO_x and HC lines ahead of the instruments.

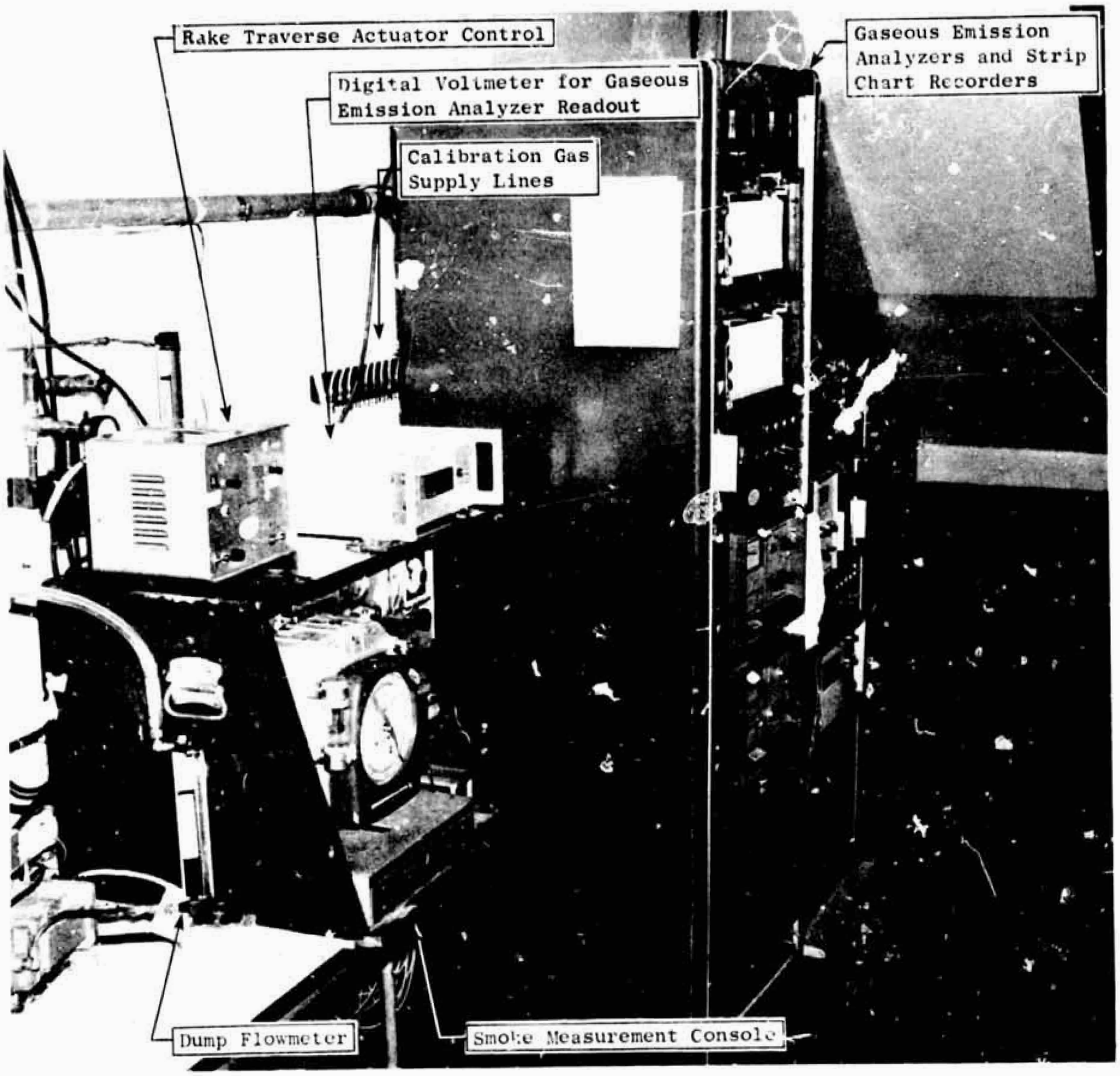


Figure A-13. Exhaust Gas Analysis Apparatus.

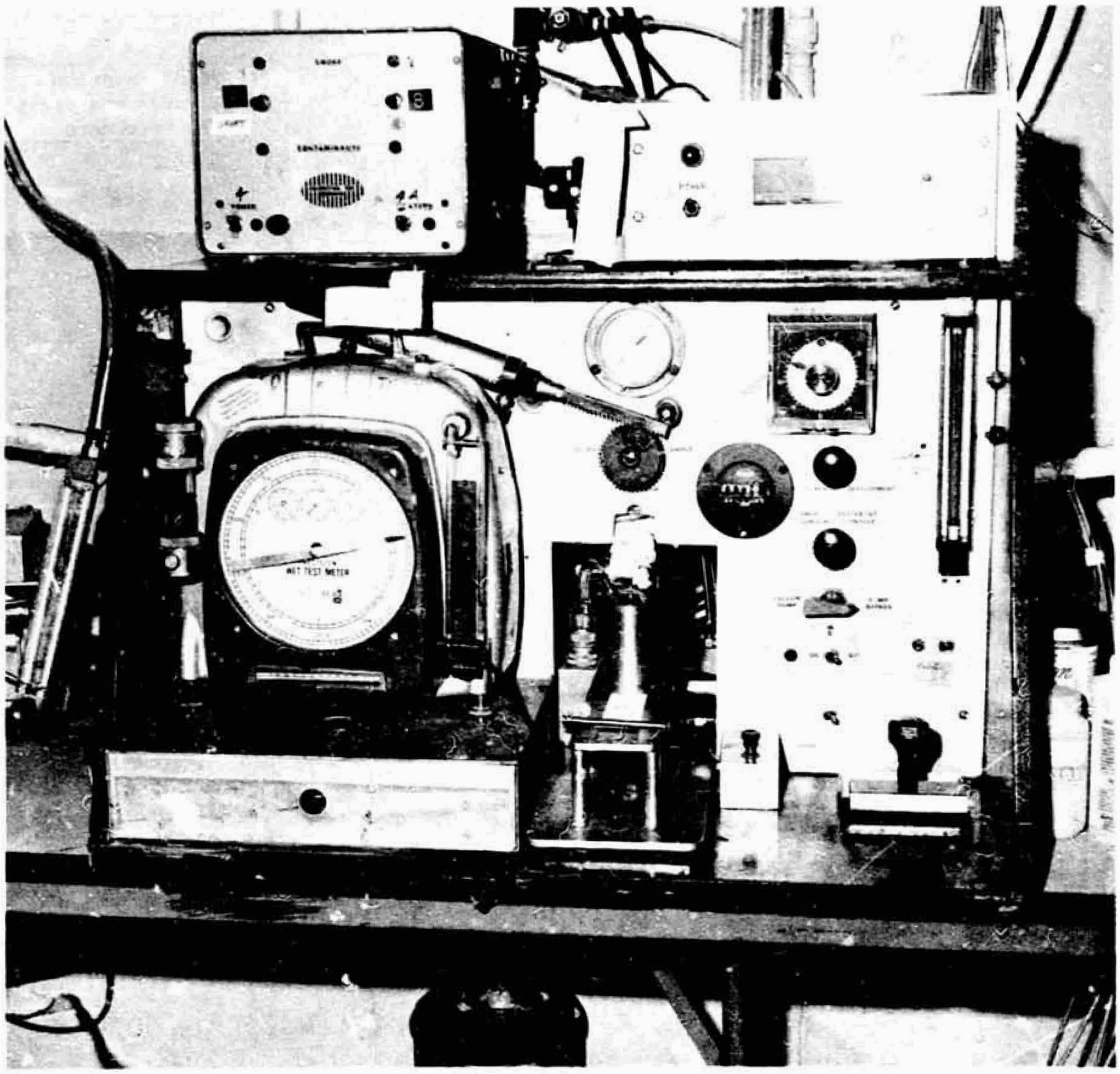


Figure A-14. Smoke Measurement Console.

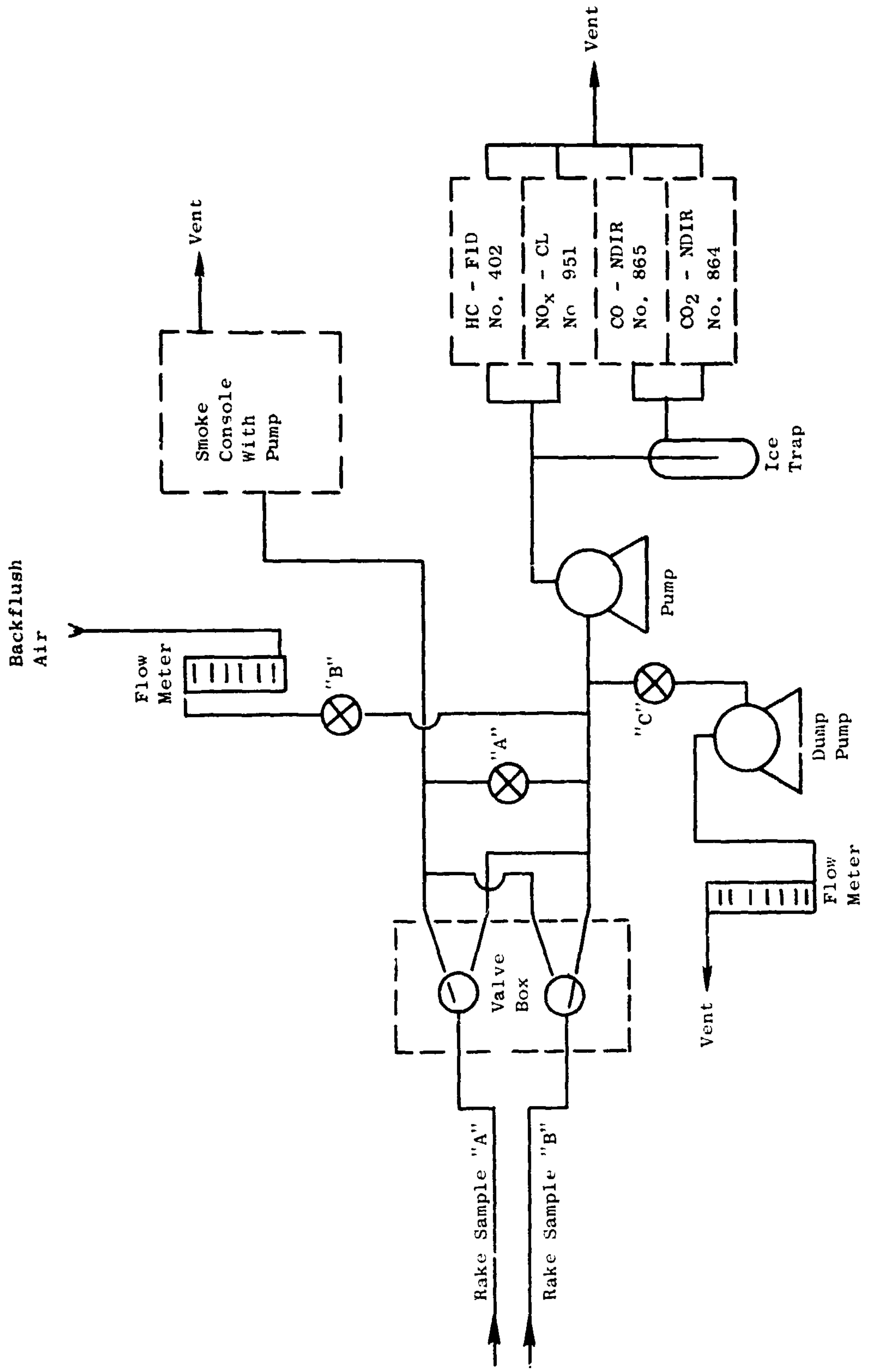


Figure A-15. Emissions Sampling and Analysis System Hookup Schematic.

The pumps, the flexible lines at the rakes, and the valve box were electrically heated. All other portions of the sample system were steam traced. Temperatures throughout the sample system were monitored with fourteen Chromel-Alumel thermocouples.

APPENDIX B

EMISSIONS AND PERFORMANCE DATA

1. Component Test Results

Combustor rig emissions test results are presented in Tables B-1 through B-6. Table B-6 contains the results for the final rig test of the engine configuration which are correlated in Figures 25 through 30. Combustor performance test results are presented in Tables B-7 and B-8 (Ignition/Stability Tests) and in Tables B-9, B-10, and B-11 (Pattern Factor Tests).

2. Engine Test Results

Engine emission test results are summarized in Table B-12. The table shows key engine/combustor operating parameters and emission results from the primary sampling techniques on each point. On nearly every test point, emissions were measured by at least two techniques, and the resulting detailed body of data is presented in Table B-13. For each of the sampling techniques and readings listed in Table B-13, a comparison of sample-to-metered fuel-air ratio is presented in Table B-14.

Engine/combustor performance data are listed in Table B-15 (Steady-State Tests), Table B-16 (Throttle Burst Tests), and Table B-17 (Start/Stall Tests).

Table B-1. Emissions Test Results, Configurations E1 and E2.

Config	Rdg Number	Inlet Total Press. Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air: Metered Outer Annulus	Metered Inner Annulus	Metered Over-all	Sample Over-all	Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE(3) Smoke Number	Total Press Loss %	Average Exit Temper-ature K	Notes
E1A	25	2.93	437	13.8	440	---	3.6	18.4	0	0	0	---	---	---	---	---	---	---	---	---	4.27	437	Idle
	26	2.94	429	13.7	836	1.0	3.6	17.8	0.0170	0	0.0170	0.0188	97.1	86.6	8.4	3.2	3.0	86.5	7.7	36	4.14	1051	
	27	2.93	431	13.6	738	1.0	3.6	17.9	0.0151	0	0.0151	0.0159	97.3	73.5	10.1	3.4	3.2	73.5	9.4	22	4.10	990	
	28	2.91	429	13.7	641	1.0	3.6	18.0	0.0130	0	0.0130	0.0132	97.4	59.8	12.0	3.6	3.5	58.6	10.6	8	4.28	917	
	32	2.93	423	13.7	542	1.0	3.6	17.6	0.0110	0	0.0110	0.0126	97.4	46.4	15.4	3.3	3.2	45.5	13.0	4	4.25	841	
	33	2.93	424	13.7	445	1.0	3.6	17.7	0.0090	0	0.0090	0.0100	95.9	56.0	28.2	3.5	3.4	54.9	24.0	1	4.11	765	
	34	3.39	631	13.8	672	1.0	3.6	22.8	0.0135	0	0.0135	0.0149	99.2	32.1	0.6	6.2	7.4	12.0	0.05	1	4.58	1124	Approach
	35	3.42	631	13.9	551	1.0	3.6	22.8	0.0110	0	0.0110	0.0118	99.6	16.8	0.6	6.6	7.9	6.3	0.05	0	4.54	1039	
	36	3.41	625	14.1	450	1.0	3.6	22.9	0.0089	0	0.0089	0.0098	99.7	8.9	0.7	6.4	7.9	3.2	0.05	0	4.61	959	
E1B	41	2.94	421	14.1	0	---	4.0	17.9	0	0	0	---	---	---	---	---	---	---	---	---	---	421	
	42	2.94	438	14.1	842	1.0	4.5	18.6	0.0166	0	0.0166	0.0216	97.9	68.9	5.3	2.8	2.7	68.6	5.3	20	4.65	1051	
	43	2.92	434	14.0	743	1.0	5.3	18.5	0.0148	0	0.0148	0.0192	97.9	59.8	7.3	2.8	2.8	58.5	6.8	15	4.50	986	
	44	2.93	435	13.9	643	1.0	5.0	18.3	0.0129	0	0.0129	0.0162	98.2	45.1	7.8	3.0	2.9	44.9	7.5	4	4.34	923	
	45	2.93	433	13.9	549	1.0	4.8	18.2	0.0110	0	0.0110	0.0144	98.61	31.5	6.5	3.0	2.9	31.2	6.1	1	4.31	354	
	46	2.93	429	13.9	548	1.0	4.8	18.1	0.0110	0	0.0110	0.0144	98.7	30.1	5.6	3.0	3.0	29.5	5.0	---	4.20	851	1
	48	2.95	432	14.1	451	1.0	4.9	18.3	0.0089	0	0.0089	0.0111	98.0	31.5	13.1	3.1	3.1	31.1	12.2	0	4.36	776	
E2	61	2.94	429	14.1	0	---	---	18.2	0	0	0	---	---	---	---	---	---	---	---	---	---	429	
	62	2.95	426	13.8	857	1.0	4.9	17.8	0.0172	0	0.0172	0.0188	97.0	75.0	13.0	3.1	3.1	74.2	11.5	---	3.98	1056	
	63	2.95	425	13.9	750	1.0	4.9	17.8	0.0150	0	0.0150	0.0178	97.1	69.0	12.6	3.1	3.1	67.9	11.2	---	4.04	981	
	64	2.95	426	13.8	649	1.0	4.9	17.8	0.0130	0	0.0130	0.0151	97.4	54.2	13.6	3.3	3.3	53.6	12.0	---	3.96	914	
	66	2.95	426	13.7	547	1.0	4.9	17.6	0.0111	0	0.0111	0.0127	97.4	44.2	15.4	3.2	3.1	44.2	13.8	---	3.98	948	
	67	2.95	425	13.8	552	1.0	4.9	17.7	0.0111	0	0.0111	0.0132	97.6	44.4	13.7	3.2	3.2	44.0	12.0	---	3.89	849	1
	68	2.96	425	13.7	450	1.0	4.9	17.5	0.0092	0	0.0092	0.0101	96.7	41.4	23.8	3.2	3.1	41.6	21.2	---	3.80	773	

Notes. 1. Radial Immersion Sampling Mode

Table B-2. Emissions Test Results, Configurations E3 and E4.

Config	Reading Number	Inlet Total Pressure Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Flow	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air: Metered Outer Annulus	Metered Inner Annulus	Metered Overall	Sample Overall	Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE Smoke Number	Total Pressure Loss %	Average Exit Temp K	Notes
E3A	73	2.93	424	13.3	0	1.00	5.9	17.[illegible]	0	0	0										4.44	424	
	74	2.92	432	13.7	639	1.00	5.9	18.0	0.0129	0	0.0129	0.0144	98.1	35.0	5.8							921	
	79	2.92	432	13.7	544	1.00	5.9	18.1	0.0110	0	0.0110	0.0139	98.1	34.4	11.2						4.53	849	
	84	2.92	430	13.9	546	1.00	5.9	18.2	0.0109	0	0.0109	0.0108	98.2	33.1	10.7						4.57	848	2
	89	2.93	431	13.9	444	1.00	5.9	18.2	0.0089	0	0.0089	0.0108	93.7	67.8	47.6						5.08	760	
E3B	75	2.92	434	13.7	638	1.00	5.9	18.2	0.0129	0	0.0129	0.0136	97.3	50.9	15.5						4.62	916	
	80	2.93	431	13.9	546	1.00	5.9	18.2	0.0109	0	0.0109	0.0109	96.5	49.7	23.2						4.63	840	
	85	2.92	430	13.8	546	1.00	5.9	18.2	0.0110	0	0.0110	0.0107	96.3	50.5	25.7						4.40	841	2
	90	2.91	433	13.7	444	1.56	5.9	18.1	0.0090	0	0.0090	0.0086	94.6	61.7	39.5						4.59	764	
E3C	76	2.93	434	13.7	641	1.00	5.9	18.1	0.0130	0	0.0130	0.0197	98.2	54.6	5.2						4.60	926	
	81	2.93	430	13.7	546	1.00	5.9	18.0	0.0110	0	0.0110	0.0160	98.6	37.5	5.1						4.64	854	
	86	2.93	431	13.9	546	1.00	5.9	18.2	0.0109	0	0.0109	0.0144	98.5	41.9	5.5						4.51	851	2
	91	2.91	433	13.7	442	1.60	5.9	18.2	0.0090	0	0.0090	0.0119	98.8	21.4	6.9						4.67	781	
E3D	77	2.93	433	13.7	641	1.00	5.9	18.1	0.0130	0	0.0130	0.0178	97.6	77.9	5.6						4.69	923	
	82	2.92	431	13.7	546	1.00	5.9	18.1	0.0110	0	0.0110	0.0147	98.0	57.0	6.5						4.51	853	
	87	2.92	431	13.8	545	1.00	5.9	18.2	0.0110	0	0.0110	0.0137	97.9	58.9	7.0						4.61	851	2
	92	2.93	433	14.0	443	1.00	5.9	18.3	0.0088	0	0.0088	0.0110	97.8	17.8	12.8						4.74	774	
E3E	78	2.93	432	13.7	642	1.00	5.9	18.0	0.0130	0	0.0130	0.0179	98.0	48.0	4.5						4.59	923	
	83	2.92	431	13.9	546	1.00	5.9	18.2	0.0110	0	0.0110	0.0142	98.1	52.5	6.6						4.78	850	
	88	2.91	431	13.8	545	1.00	5.9	18.2	0.0110	0	0.0110	0.0142	98.2	54.9	5.4						4.81	853	2
	93	2.93	436	14.0	442	1.90	5.9	18.3	0.0088	0	0.0088	0.0112	97.5	43.2	15.3						4.72	771	

Notes: 1. All Emissions Data are Averages for Sector Center 4 Traverse Positions.

2. Radial Immersion Sampling Mode.

3. NO_x and Smoke Not Measured.

Table B-2. Emission Test Results, Configurations E3 and E4 (Concluded).

Config	Reading Number	Inlet Total Pressure Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/ Total Fuel Flow	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air — Metered — Outer Annulus	Metered — Inner Annulus	Metered — Overall	Sample — Overall	Sample Combustion Efficiency %	Emission Indicies g/kg fuel — CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE Smoke Number	Total Pressure Loss %	Average Exit Temp K	Notes
E4A	94	2.93	427	13.9	0			18.1	0	0	0										3.96	427	
	95	2.93	428	14.0	643	1.00	6.2	18.2	0.0128	0	0.0128	0.0147	97.2	57.2	14.6						4.18	908	
	100	2.96	429	14.0	547	1.00	5.2	18.0	0.0108	0	0.0108	0.0123	97.1	49.8	17.7							840	
	105	2.93	426	13.8	547	1.00	5.7	17.9	0.0110	0	0.0110	0.0127	98.0	38.2	11.0						4.25	848	2
	110	2.93	427	13.9	446	1.00	3.8	18.0	0.0089	0	0.0089	0.0110	96.3	49.8	25.2						4.32	767	1
E4B	96	2.94	432	13.8	643	1.00	6.0	18.0	0.0129	0	0.0129	0.0155	97.5	61.7	10.8						4.19	918	
	101	2.96	428	13.9	547	1.00	4.7	18.0	0.0109	0	0.0109	0.0115	97.4	44.9	15.2						4.25	842	
	106	2.93	424	13.8	546	1.00	4.5	17.9	0.0109	0	0.0109	0.0108	97.9	41.8	10.9						4.34	843	2
	111	2.93	426	13.9	446	1.00	3.0	18.0	0.0089	0	0.0089	0.0093	96.1	44.0	28.5						4.36	764	1
E4C	97	2.94	431	14.0	643	1.00	5.3	18.2	0.0128	0	0.0128	0.0190	98.4	52.1	3.8						4.41	918	
	102	2.93	426	14.0	546	1.00	7.1	18.2	0.0108	0	0.0108	0.0149	98.8	34.4	4.5							843	
	107	2.93	429	13.9	547	1.00	5.2	18.1	0.0109	0	0.0109	0.0140	98.8	33.5	4.0						4.42	851	2
	112	2.93	425	13.9	446	1.00	2.8	18.0	0.0089	0	0.0089	0.0117	98.9	22.3	5.5						4.42	774	1
E4D	98	2.95	432	14.0	644	1.00	5.6	18.2	0.0128	0	0.0128	0.0164	98.0	54.9	7.6						4.27	917	
	103	2.93	426	14.0	547	1.00	6.4	18.1	0.0109	0	0.0109	0.0135	98.3	38.0	7.7						4.31	843	
	108	2.93	427	14.0	546	1.00	4.3	18.0	0.0109	0	0.0109	0.0143	98.6	33.2	6.7						4.27	845	2
	113	2.93	425	13.9	446	1.00	2.7	18.0	0.0089	0	0.0089	0.0110	98.3	27.5	10.7						4.20		1
E4E	99	2.94	428	13.9	645	1.00	5.2	17.9	0.0129	0	0.0129	0.0151	98.1	45.1	8.9						4.31	916	
	104	2.93	426	14.0	547	1.00	6.6	18.1	0.0108	0	0.0108	0.0134	98.0	35.2	11.4						4.46	841	
	109	2.93	428	13.9	546	1.00	3.9	18.0	0.0109	0	0.0109	0.0119	97.1	41.4	19.0						4.33	847	2
	114	2.93	425	13.9	446	1.00	2.6	18.0	0.0089	0	0.0089	0.0110	96.2	46.4	27.4						4.34	776	1

Notes: 1. Six Position Traverse (Position 5-10)
2. Radial Immersion Sampling Mode
3. NO_x and Smoke Not Measured

Table B-3. Emissions Test Results, Configurations E5 and E6.

Config	Rdg Number	Inlet Total Press. Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air – Metered – Outer Annulus	Metered – Inner Annulus	Metered – Over-all	Sample – Over-all	Sample Combustion Efficiency %	Emission Indices g/kg fuel – CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE(3) Smoke Number	Total Press Loss %	Average Exit Temperature K	Notes
E5A	136	2.91	431	13.7	0	---	---	18.0	0	0	0	---	---			---	---	---	---	---	4.11	431	
	131	2.93	429	13.8	441	1.0	3.6	18.1	0.0089	0	0.0089	0.0100	95.9	53.3	29.1	---	---	---	---	---	4.07	765	1
	127	2.93	430	13.9	539	1.0	3.6	18.1	0.0108	0	0.0108	0.0137	97.5	44.8	14.1	---	---	---	---	---	4.18	840	2
	122	2.95	430	13.7	540	1.0	3.6	17.8	0.0110	0	0.0110	0.0124	96.8	45.0	20.9	---	---	---	---	---	3.82	845	
	117	2.95	434	13.6	639	1.0	3.6	17.9	0.0130	0	0.0130	0.0148	97.3	50.7	15.4	---	---	---	---	---	3.94	922	
E5B	132	2.93	429	13.9	441	1.0	3.6	18.0	0.0088	0	0.0088	0.0077	95.0	50.9	38.3	---	---	---	---	---	4.11	760	1
	128	2.93	430	13.9	539	1.0	3.6	18.2	0.0108	0	0.0108	0.0105	97.5	36.2	16.3	---	---	---	---	---	4.22	840	2
	123	2.94	430	13.9	540	1.0	3.6	18.2	0.0108	0	0.0108	0.0100	97.1	40.5	19.4	---	---	---	---	---	4.22	840	
	118	2.95	435	13.7	639	1.0	3.6	18.0	0.0130	0	0.0130	0.0125	97.4	48.6	14.9	---	---	---	---	---	4.09	924	
E5C	133	2.93	429	13.8	442	1.0	3.6	18.0	0.0089	0	0.0089	0.0117	98.9	23.6	5.9	---	---	---	---	---	4.03	776	1
	129	2.93	430	13.9	540	1.0	3.6	18.2	0.0108	0	0.0108	0.0154	98.9	31.4	4.1	---	---	---	---	---	4.18	846	2
	124	2.95	430	14.0	539	1.0	3.6	18.2	0.0107	0	0.0107	0.0141	98.8	31.1	5.2	---	---	---	---	---	4.21	843	
	119	2.95	435	13.6	638	1.0	3.6	17.9	0.0130	0	0.0130	0.0177	98.4	49.9	4.2	---	---	---	---	---	4.27	929	
E5D	134	2.93	429	13.9	441	1.0	3.6	18.1	0.0088	0	0.0088	0.0113	97.3	33.7	18.8	---	---	---	---	---	4.09	768	1
	130	2.94	430	14.0	539	1.0	3.6	18.2	0.0107	0	0.0107	0.0120	97.6	31.3	16.8	---	---	---	---	---	4.28	838	2
	125	2.94	430	14.0	538	1.0	3.6	18.2	0.0107	0	0.0107	0.0133	97.7	38.0	14.1	---	---	---	---	---	4.21	839	
	120	2.94	430	13.7	638	1.0	3.6	17.9	0.0130	0	0.0130	0.0163	97.5	52.9	13.2	---	---	---	---	---	4.08	920	
E5F	135	2.93	429	13.9	441	1.0	3.6	18.1	0.0088	0	0.0088	0.0091	93.4	67.5	50.2	---	---	---	---	---	4.19	754	1
	126	2.94	430	13.9	539	1.0	3.6	18.1	0.0108	0	0.0108	0.0128	96.7	53.2	20.8	---	---	---	---	---	4.11	837	2
	121	2.95	430	13.6	539	1.0	3.6	17.8	0.0110	0	0.0110	0.0126	95.6	54.9	31.4	---	---	---	---	---	3.97	839	
	116	2.95	434	13.7	640	1.0	3.6	17.9	0.0130	0	0.0130	0.0154	95.9	59.0	27.2	---	---	---	---	---	3.97	916	
E6A	137	2.94	432	14.0	0	---	---	18.3	0	0	0	---	---	---	---	---	---	---	---	---	4.35	432	1
	138	2.95	433	13.9	646	1.0	3.6	18.2	0.0129	0	0.0129	0.0148	98.4	40.8	6.8	3.7	3.5	40.7	6.5	---	4.37	922	
	143	2.89	429	13.7	550	1.0	3.6	18.1	0.0112	0	0.0112	0.0128	98.4	31.6	8.3	3.3	3.2	30.6	7.2	---	4.36	856	
E6B	139	2.95	433	14.0	639	1.0	3.6	18.3	0.0127	0	0.0127	0.0122	94.7	66.6	37.1	3.0	2.9	66.1	35.1	---	4.59	896	1
	144	2.89	428	13.7	550	1.0	3.6	18.0	0.0112	0	0.0112	0.0102	94.1	62.5	44.7	2.6	2.5	60.6	38.5	---	4.35	839	
E6C	140	2.91	431	14.1	652	1.0	3.6	18.5	0.0129	0	0.0129	0.0164	98.1	53.0	6.8	3.2	3.1	51.0	6.0	---	4.43	919	1
	145	2.89	428	13.6	550	1.0	3.6	18.0	0.0112	0	0.0112	0.0147	96.7	51.9	20.6	3.0	2.9	[illegible].4	17.8	---	4.32	852	
E6D	141	2.92	431	13.9	650	1.0	3.6	18.2	0.0130	0	0.0130	0.0171	97.1	54.0	16.1	3.6	3.5	53.0	14.6	---	4.46	918	1
	146	2.89	428	13.7	550	1.0	3.5	18.0	0.0112	0	0.0112	0.0139	96.1	52.7	26.9	3.1	3.0	51.1	23.2	---	4.30	845	
E6E	142	2.89	426	13.9	650	1.0	3.6	18.2	0.0130	0	0.0130	0.0142	96.0	61.4	26.2	3.2	3.2	58.4	21.7	---	4.38	900	1
	147	2.90	429	13.7	650	1.0	3.6	18.0	0.0112	0	0.0112	0.0118	95.8	51.8	29.7	2.6	2.5	50.6	26.1	---	4.34	845	
E6F	154	4.76	734	17.3	1336	0.20	3.6	24.0	0.0042	0.0172	0.0214	0.0237	99.7	11.3	0.3	8.4	11.1	4.9	0.04	---	4.61	1473	3
	157	4.78	732	17.5	1333	0.15	3.6	24.2	0.0032	0.0180	0.0212	0.0241	99.6	15.4	0.3	7.9	10.6	6.4	0.04	---	4.63	1461	
E6G	156	4.77	734	17.3	1334	0.20	3.6	23.9	0.0042	0.0173	0.0215	0.0239	99.7	12.0	0.3	8.5	11.2	5.2	0.04	---	4.50	1474	3
	159	4.78	736	17.6	1334	0.15	3.6	24.4	0.0031	0.0179	0.0210	0.0238	99.6	16.0	0.4	7.3	9.7	7.0	0.05	---	4.69	1459	

Notes:

1. Six-Position Traverse
2. Radial Immersion Sampling Mode
3. Thirty-Position Traverse (180°), Simulated Cruise.

Table B-4. Emissions Test Results, Configuration E7.

Reading Number	Operating Mode	Inlet Total Pressure atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Flow	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Overall	Sample: Overall	Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE Smoke No.	Total Pressure Loss %	Average Exit Temperature K	Notes
160	Dry	2.94	434	14.2	0	---	---	18.7	0	0	0	---	---	---	---	---	---	---	---	---	3.98	434	---
168		2.94	433	14.3	0	---	---	18.7	0	0	0	---	---	---	---	---	---	---	---	---	4.26	433	---
191		2.90	421	13.8	0	---	---	17.7	0	0	0	---	---	---	---	---	---	---	---	---	4.35	421	---
161	Idle	2.97	432	14.2	734	1.00	---	18.3	0.0144	0	0.0144	0.0168	97.4	63.7	11.4	3.1	3.3	63.3	10.8	25.2	4.02	970	---
162		2.93	435	14.2	641	1.00	---	18.6	0.0126	0	0.0126	0.0146	97.8	51.7	9.5	2.9	3.1	50.6	9.0	11.6	4.13	910	---
163		2.91	429	14.0	539	1.00	---	18.3	0.0107	0	0.0107	0.0126	98.1	38.3	10.5	3.0	3.2	36.9	9.2	2.4	4.14	838	---
170		2.95	430	15.3	543	1.00	8.8	19.6	0.0099	0	0.0099	0.0111	98.1	34.7	11.4	3.3	3.8	31.7	9.7	0.5	4.80	810	---
164		2.91	429	14.1	441	1.00	---	18.3	0.0087	0	0.0087	0.0102	97.3	36.4	19.0	3.0	3.2	35.1	16.0	0.5	4.04	764	---
171	Approach	3.44	645	14.5	801	1.00	7.6	23.9	0.0153	0	0.0153	0.0167	99.0	42.4	0.2	5.7	7.2	16.3	0.02	---	4.58	1196	---
172		3.43	643	14.2	686	1.00	7.4	23.6	0.0134	0	0.0134	0.0134	99.4	26.5	0.2	6.3	7.9	10.2	0.02	0.7	4.56	1133	---
173		3.40	644	14.4	548	1.00	7.5	24.0	0.0106	0	0.0106	0.0106	99.8	9.8	0.2	6.9	8.8	3.7	0.02	---	4.71	1038	---
174		3.38	640	14.2	448	1.00	7.6	23.8	0.0087	0	0.0087	0.0089	99.9	4.8	0.3	7.4	9.6	1.8	0.03	---	4.56	968	---
178	Cruise	4.74	728	17.7	1311	0.25	4.1	24.2	0.0051	0.0155	0.0206	0.0232	99.8	10.2	0.1	7.4	10.3	4.0	0.01	---	4.13	1440	---
177		4.74	736	17.8	1307	0.20	4.0	24.6	0.0041	0.0163	0.0204	0.0232	99.7	11.2	0.1	6.9	9.3	4.8	0.01	---	4.14	1442	---
176		4.75	741	17.6	1314	0.15	4.4	24.5	0.0031	0.0176	0.0207	0.0235	99.6	15.6	0.2	6.5	8.6	7.1	0.03	0.3	4.16	1456	---
175		4.76	741	17.7	1324	0.10	4.3	24.6	0.0021	0.0187	0.0208	0.0240	99.4	23.5	0.8	7.1	9.4	10.7	0.12	---	4.04	1456	---
182	Climb	4.75	775	17.0	1282	0.25	---	24.7	0.0053	0.0157	0.0210	0.0241	99.9	5.7	0	8.4	18.0	0.9	0	---	4.61	1493	---
183		9.51	798	33.6	2561	0.20	---	25.2	0.0042	0.0169	0.0211	0.0255	99.9	3.7	0	10.6	15.6	1.5	0	1.1	4.38	1518	---
181		4.75	782	17.2	1280	0.20	---	25.2	0.0041	0.0166	0.0207	0.0237	99.8	6.9	0	7.8	16.4	1.1	0	---	4.35	1490	---
180		4.86	787	17.3	1279	0.15	---	25.1	0.0031	0.0174	0.0205	0.0243	99.8	8.7	0.1	8.8	17.8	1.5	0	0.5	4.92	1489	---
166		9.53	804	33.2	2591	0.15	7.2	25.1	0.0032	0.0184	0.0216	0.0240	99.9	5.0	0.1	10.6	15.0	2.1	0.01	1.9	3.97	1538	1
179		4.77	784	17.0	1284	0.10	3.8	25.0	0.0021	0.0188	0.0209	0.0241	99.5	17.2	1.3	8.7	16.9	2.9	0.02	---	4.29	1497	---
165		9.53	793	33.5	2592	0.10	7.7	24.9	0.0022	0.0193	0.0215	0.0247	99.8	7.6	0.2	10.7	16.1	2.9	0.02	2.3	4.09	1523	---
190	Takeoff	4.77	820	16.6	1346	0.25	---	25.7	0.0056	0.0169	0.0225	0.0268	99.9	5.7	0.2	9.9	21.3	0.8	0	1.0	4.41	1576	---
189		4.76	819	16.6	1352	0.20	---	25.5	0.0046	0.0181	0.0227	0.0269	99.8	7.2	0.2	9.4	20.2	1.1	0	0.8	4.32	1581	---
186		9.56	827	33.1	2708	0.20	---	25.7	0.0045	0.0182	0.0227	0.0276	99.9	3.3	0	13.5	21.3	1.1	0	---	4.48	1590	---
188		4.77	819	16.7	1357	0.15	---	25.4	0.0034	0.0192	0.0226	0.0269	99.8	9.2	0.2	8.8	18.8	1.4	0	0.7	4.31	1574	---
185		9.53	828	33.4	2715	0.15	---	25.9	0.0034	0.0192	0.0226	0.0275	99.9	4.4	0	12.1	19.1	1.4	0	---	4.48	1586	---
187		4.77	823	16.6	1345	0.10	---	25.3	0.0023	0.0202	0.0225	0.0267	99.6	13.4	0.7	8.9	18.6	2.1	0.01	1.0	4.48	1570	---
184		9.54	827	33.2	2694	0.10	---	25.8	0.0022	0.0203	0.0225	0.0272	99.8	7.1	0.1	11.9	18.8	2.3	0.01	---	4.10	1503	---

Note 1: Six-Position Traverse (Positions 1 - 6)

Table B-5. Emission Test Results, Configurations E9 and E10.

Config	Reading Number	Inlet Total Press Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Flow	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air: Metered Outer Annulus	Metered Inner Annulus	Metered Over-all	Sample Over-all	Sample Combustion Efficiency, %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x	Engine CO	Engine HC	SAE(3) Smoke Number	Total Press Loss %	Average Exit Temperature K
E9A	226	2.88	433	13.9	0	---	2.9	18.5	---	---	---	---	---	---	---	---	---	---	---	---	4.44	433
	227-228	2.91	429	12.6	646	1.0	3.7	16.8	0.0135	0	0.0135	0.0139	97.50	60.4	10.9	---	---	---	---	---	4.81	934
	232-233	2.97	425	13.7	541	1.0	3.1	17.8	0.0110	0	0.0110	0.0113	97.70	41.6	13.3	---	---	---	---	---	4.55	843
	237-238	2.96	430	13.8	442	1.0	2.9	17.9	0.0089	0	0.0089	0.0086	96.44	46.7	24.7	---	---	---	---	---	4.72	769
E9B	228-230	2.93	426	13.7	641	1.0	3.0	17.9	0.0129	0	0.0129	0.0155	97.46	59.2	11.6	---	---	---	---	---	4.51	913
	233-235	2.92	426	16.1	540	1.0	3.2	17.8	0.0109	0	0.0109	0.0127	97.78	43.3	12.1	---	---	---	---	---	4.51	844
	238-240	2.95	429	13.8	441	1.0	3.3	17.9	0.0089	0	0.0089	0.0103	97.36	37.1	17.7	---	---	---	---	---	4.46	769
E9C	230-231	2.94	425	13.7	640	1.0	2.9	17.7	0.0130	0	0.0130	0.0132	98.14	54.4	5.9	---	---	---	---	---	4.32	917
	235-236	2.92	428	13.8	541	1.0	2.7	17.9	0.0109	0	0.0109	0.0128	98.68	35.8	4.8	---	---	---	---	---	4.43	849
	240-241	2.95	429	13.8	441	1.0	3.6	17.9	0.0089	0	0.0089	0.0102	98.53	27.9	8.2	---	---	---	---	---	4.20	774
E10A	242	2.90	419	13.4	0	---	1.1	17.4	0	0	0	---	---	---	---	---	---	---	---	---	3.93	419
	243	2.90	428	13.9	647	1.0	1.1	18.1	0.0130	0	0.0130	0.0118	97.6	58.1	10.0	---	---	---	---	---	4.04	916
	248	2.92	426	13.8	549	1.0	1.3	18.0	0.0111	0	0.0111	0.0108	97.6	46.8	13.3	---	---	---	---	---	3.96	849
	253	2.92	426	13.8	447	1.0	1.2	17.9	0.0090	0	0.0090	0.0091	97.3	42.8	17.5	---	---	---	---	---	3.99	775
E10B	244	2.92	428	13.8	648	1.0	1.0	18.0	0.0131	0	0.0131	0.0108	97.5	63.6	10.2	---	---	---	---	---	4.04	918
	249	2.92	428	13.8	549	1.0	1.1	18.0	0.0111	0	0.0111	0.0109	97.6	45.9	13.6	---	---	---	---	---	4.41	848
	254	2.92	428	13.7	447	1.0	0.5	17.9	0.0091	0	0.0091	0.0095	97.3	39.0	18.4	---	---	---	---	---	3.91	774
E10C	246	2.92	427	13.7	647	1.0	0.9	17.9	0.0131	0	0.0131	0.0153	98.2	56.3	4.8	---	---	---	---	---	4.09	924
	251	2.92	428	13.6	549	1.0	1.1	17.8	0.0112	0	0.0112	0.0139	98.6	38.5	5.1	---	---	---	---	---	3.99	857
	256	2.91	430	13.7	447	1.0	1.7	18.0	0.0090	0	0.0090	0.0105	98.6	25.2	8.3	---	---	---	---	---	4.27	780

Table B-6. Emissions Test Results, Configuration E11.

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot Total Fuel Split	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel/g air: Metered Outer Annulus	Metered Inner Annulus	Metered Overall	Sample Overall	Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NO_x	Engine NO_x(1)	Engine CO	Engine HC	Total Pressure Loss %	Average Exit Temperature K	Peak Liner Temperature K	Notes
258	2.52	419	11.97	0	---	---	17.6	0	0	0	0	---	---	---	---	---	---	---	4.32	419	---	
265	2.54	415	12.29	480	1.00	7.1	17.8	0.0109	0	0.0109	0.0119	97.3	49.6	16.0	2.6	2.6	51.4	17.4	4.52	827	595	2.5% F_N
268	2.93	413	14.51	662	1.00	2.0	18.0	0.0127	0	0.0127	0.0130	97.6	59.4	10.3	2.9	---	---	---	4.45	891	622	Parametric
267	2.92	414	14.42	557	1.00	3.0	18.1	0.0107	0	0.0107	0.0111	97.6	45.0	13.4	2.8	---	---	---	4.49	825	595	Parametric
266	2.93	416	14.33	453	1.00	5.8	18.1	0.0088	0	0.0088	0.0089	96.6	49.0	22.7	2.0	---	---	---	4.36	751	574	Parametric
259	2.57	430	11.93	472	1.00	1.4	17.8	0.0110	0	0.0110	0.0119	97.7	44.1	13.3	2.6	---	---	---	---	849	618	Parametric
260	2.94	438	13.83	746	1.00	1.3	18.3	0.0150	0	0.0150	0.0163	97.7	65.7	7.3	2.5	---	---	---	---	997	688	Parametric
261	2.93	440	13.70	646	1.00	1.3	18.3	0.0131	0	0.0131	0.0131	98.2	51.8	6.1	3.4	---	---	---	4.44	935	649	Parametric
262	2.93	439	13.83	544	1.00	1.4	18.4	0.0109	0	0.0109	0.0112	98.1	41.8	8.8	3.6	3.2	42.1	8.9	4.49	856	624	34% F_N
263	2.93	439	13.88	445	1.00	1.4	18.4	0.0089	0	0.0089	0.0093	97.8	39.3	12.7	3.6	---	---	---	4.41	776	593	Parametric
264	3.75	436	17.64	699	1.00	1.0	18.2	0.0110	0	0.0110	0.0113	98.8	34.6	4.4	3.7	---	---	---	4.50	860	634	Parametric
271	2.94	457	13.74	733	1.00	0.6	18.8	0.0148	0	0.0148	0.0157	97.7	75.6	5.8	3.3	---	---	---	4.63	1007	688	Parametric
270	2.93	455	13.74	634	1.00	0.5	18.8	0.0128	0	0.0128	0.0132	98.3	50.0	5.4	3.4	---	---	---	4.61	939	661	Parametric
269	2.94	455	13.74	529	1.00	1.1	18.8	0.0107	0	0.0107	0.0109	98.6	35.0	6.3	3.5	---	---	---	4.67	864	634	Parametric
272	3.75	460	17.78	671	1.00	0.6	19.3	0.0105	0	0.0105	0.0111	99.0	26.3	4.3	3.7	3.3	26.7	0.3	4.52	863	638	50% F_N
273	3.38	598	14.24	621	1.00	0.4	22.3	0.0121	0	0.0121	0.0124	99.4	23.0	0.9	5.8	5.8	11.4	0.2	4.89	1048	780	200% F_N
274	3.42	645	14.38	693	1.00	0.4	23.9	0.0134	0	0.0134	0.0139	99.3	29.5	0.4	6.7	7.4	11.3	0.04	5.09	1133	831	Approach
275	3.41	688	13.43	778	0.253	0.4	24.0	0.0041	0.0120	0.0161	0.0170	98.0	45.0	10.0	4.4	7.4	9.4	0.2	5.14	1252	823	45% F_N
276	4.77	791	17.10	1314	0.104	0.6	25.3	0.0022	0.0191	0.0213	0.0238	99.4	16.8	2.6	9.7	17.3	3.1	0.04	4.72	1514	949	Climb
277	4.77	793	17.05	1313	0.176	0.6	25.3	0.0038	0.0176	0.0214	0.0227	99.8	6.0	0.1	9.1	16.1	1.5	0	4.65	1520	950	Climb
278	4.78	790	17.05	1308	0.254	0.6	25.2	0.0054	0.0159	0.0213	0.0220	99.8	6.6	0.1	10.9	19.4	1.2	0	4.65	1515	944	Climb
279	4.78	824	16.69	1382	0.104	0.5	25.7	0.0024	0.0206	0.0230	0.0249	99.3	15.4	3.2	10.8	20.4	2.4	0.04	4.66	1591	979	Takeoff
280	4.76	824	16.51	1380	0.178	0.8	25.5	0.0041	0.0191	0.0232	0.0255	99.8	9.0	0.1	11.8	22.3	1.4		4.66	1600	979	Takeoff
281	4.77	822	16.74	1378	0.251	0.5	25.8	0.0057	0.0171	0.0228	0.0250	99.8	7.0	0.1	11.5	22.1	1.1	0	4.62	1589	976	Takeoff

(1)Prer e Correction Exponent:

0.2 at Approach
0.4 at Climbout and Takeoff

Table B-7. Ground Start Test Results, Configuration E1A.

Config	Reading Number	Inlet Total Pressure atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Fuel-Air Ratio			Total Pressure Loss, %	Average Exit Temperature K	Fuel Flow, kg/hr					
							Pilot	Main	Total			Light off	½ Prop	Full Prop	1 Cup Out	½ Out	Blow Out
E1A	13	1.00	283	2.82	180	1.0	0.0117	0	0.0117	0.85	868	---	---	---	---	---	---
	12	1.00	280	2.82	224		0.0221		0.0221	0.89	813	---	---	---	---	---	---
	11	1.00	283	2.82	271		0.0267		0.0267	0.93	902	---	---	---	---	---	---
	--	1.[illegible]	283	2.82	---		---		---	---	---	130	146	152	127	117	91
	16	1.01	282	3.61	270		0.0208		0.0208	1.47	718	---	---	---	---	---	---
	15	1.01	281	3.63	315		0.0241		0.0241	1.48	749	---	---	---	---	---	---
	14	1.01	281	3.64	360		0.0275		0.0275	1.45	412	---	---	---	---	---	---
	--	1.01	282	3.61	---		---		---	---	---	136	143	153	147	129	98
	17	1.03	284	5.42	---		---		---	---	---	133	145	154	1[illegible]	122	108
	20	1.03	284	5.36	363		0.0188		0.0188	2.87	635	---	---	---	---	---	---
	19	1.03	282	5.33	405		0.0211		0.0211	2.87	692	---	---	---	---	---	---
	18	1.03	285	5.33	451		0.0235		0.0235	2.98	764	---	---	---	---	---	---
	21	1.04	283	5.37	543		0.0281		0.0281	3.18	893	---	---	---	---	---	---
	22	1.04	281	5.33	634		0.0330		0.0330	3.28	891	---	---	---	---	---	---
	23	1.04	283	5.34	724		0.0377		0.0377	3.39	955	---	---	---	---	---	---
	24	1.05	281	5.37	782		0.0405		0.0405	3.49	963	---	---	---	---	---	---

Table B-8. Main Stage Crossfire/Stability Test Results, Configurations E1 and E2.

Config	Reading Number	Inlet Pressure atm	Inlet Total Temp K	Combustor Airflow kg/sec	Pilot Stage Fuel Flow kg/hr	Pilot Stage Fuel-Air Ratio	Main Stage Crossfire Fuel Flow kg/hr	Main Stage Crossfire Fuel-Air Ratio	Main Stage Lean Blowout Fuel Flow kg/hr	Main Stage Lean Blowout Fuel-Air Ratio
E1A	9	1.05	619	4.1	107	0.0072	232	0.0156	39	0.0026
↓	↓	↓	↓	↓	166	0.0111	278	0.0186	33	0.0022
↓	↓	↓	↓	↓	206	0.0138	243	0.0163	46	0.0031
↓	10	1.04	512	4.6	116	0.0068	264	0.0160	44	0.0026
↓	↓	↓	↓	↓	201	0.0122	315	0.0191	61	0.0037
↓	38	3.76	623	13.5	659	0.0136	480	0.0099	---	---
↓	39	3.84	619	13.1	541	0.0115	535	0.0113	---	---
↓	40	3.95	624	13.0	343	0.0073	623	0.0132	---	---
E1B	49	3.84	516	15.1	792	0.0145	517	0.0094	---	---
↓	50	3.92	513	14.7	593	0.0111	655	0.0123	---	---
↓	51	3.93	513	15.0	389	0.0072	764	0.0142	---	---
E2	69	3.40	633	14.2	698	0.0137	504	0.0099	---	---

Table B-9. Pattern Factor Test Results, Configurations E1 and E2.

Config	Rdg Number	Inlet Total Press Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Fuel-Air Ratio Pilot	Fuel-Air Ratio Main	Fuel-Air Ratio Total	Total Pressure Loss percent	Avg Exit Temp K
E1	1	1.04	433	4.79	191	1.00	0.0111	0	0.0111	3.85	832
	2	1.05	647	4.21	204	1.00	0.0135	0	0.0135	4.26	1134
	3	1.05	631	4.20	297	0.22	0.0043	0.0153	0.0196	4.45	1249
	4	1.05	757	3.64	280	0.23	0.0048	0.0166	0.0214	4.19	1431
	5	1.05	751	3.60	302	0.21	0.0049	0.0181	0.0229	4.04	1458
	6	1.05	752	3.63	302	0.21	0.0049	0.0183	0.0231	4.16	1467
	7	1.05	750	3.67	302	0.15	0.0035	0.0193	0.0228	4.25	1468
	8	1.05	748	3.67	352	0.21	0.0053	0.0207	0.0260	4.32	1567
E2	53	1.04	467	4.79	191	1.00	0.0110	0	0.0110	4.02	865
	54	1.04	627	4.12	206	1.00	0.0139	0	0.0139	4.16	1129
	55	1.04	752	3.68	284	0.23	0.0049	0.0165	0.0214	4.35	1427
	56	1.04	749	3.63	308	0.28	0.0067	0.0169	0.0236	4.30	1493
	57	1.04	741	3.67	307	0.23	0.0054	0.0178	0.0232	4.10	1488
	58	1.04	739	3.66	306	0.23	0.0052	0.0180	0.0232	4.14	1500
	59	1.04	[illegible]	3.65	307	0.18	0.0042	0.0191	0.0233	4.24	1473
	60	1.04	[illegible]	3.80	366	0.23	0.0061	0.0205	0.0268	3.C2	1518

Exit Temperature Deviation, $(T_{local} - T_{avg})/\Delta T_{avg}$

Config	Rdg Number	Average Profile Tip 1	2	3	4	5	6	Root 7	Peak Profile Tip 1	2	3	4	5	6	Root 7
E1	1	+0.481	+0.620	+0.490	+0.285	+0.035	-0.263	-0.609	1.150	1.440	1.320	1.300	1.180	0.865	+0.189
	2	+0.369	+0.448	+0.343	+0.187	-0.021	-0.297	-0.642	0.865	1.011	0.973	1.110	0.992	0.696	+0.164
	3	-0.074	+0.108	+0.179	+0.225	+0.231	+0.059	-0.030	0.391	0.426	0.401	0.480	0.515	0.398	+0.075
	4	-0.119	+0.043	+0.100	+0.153	+0.148	-0.051	-0.350	0.204	0.275	0.257	0.279	0.279	0.236	-0.016
	5	-0.128	+0.038	+0.090	+0.142	+0.141	-0.056	-0.348	0.280	0.268	0.250	0.315	0.310	0.190	-0.089
	6	-0.130	[illegible]	+0.092	+0.141	+0.139	+0.044	-0.346	0.182	0.223	0.257	0.285	0.295	0.217	-0.065
	7	-0.167	+0.017	+0.103	+0.168	+0.183	+0.002	-0.312	0.248	0.304	0.334	0.350	0.357	0.280	-0.085
	8	-0.180	-0.047	+0.078	+0.117	+0.119	-0.075	-0.353	0.127	0.178	0.233	0.293	[illegible]	0.125	-0.107
E2	53	+0.409	+0.556	+0.479	+0.323	+0.112	[illegible]	-0.520	1.004	1.334	1.470	1.350	1.040	0.739	+0.029
	54	+0.284	+0.355	+0.306	+0.197	+0.047	-0.181	-0.520	0.737	0.808	0.952	0.922	0.781	0.557	0.015
	55	-0.002	+0.110	+0.138	+0.143	+0.129	-0.065	-0.261	0.287	0.318	0.303	0.292	0.305	0.230	-0.035
	56	-0.037	+0.084	+0.103	+0.095	+0.067	-0.115	-0.311	0.250	0.251	0.232	0.193	0.207	0.076	-0.181
	57	-0.096	+0.101	+0.131	+0.138	+0.139	-0.013	-0.254	[illegible]	0.298	0.264	0.256	0.264	0.200	-0.061
	58	+0.004	+0.115	+0.144	+0.154	+0.13	.033	-0.252	0.300	0.320	0.318	0.293	0.291	0.159	-0.049
	59	-0.016	+0.105	+0.104	+0.155	+0.154	0.031	-0.245	0.332	0.352	0.345	0.307	0.362	0.232	-0.033
	60	-0.001	+0.071	+0.127	+0.151	+0.129	-0.055	276	0.299	0.302	0.320	0.315	0.332	0.185	-0.139

Table B-10. Pattern Factor Test Results, Configurations E7 and E8.

Config	Rdg Number	Inlet Total Press Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Fuel-Air Ratio Pilot	Fuel-Air Ratio Main	Fuel-Air Ratio Total	Total Pressure Loss percent	Avg Exit Temp K	Exit Temperature Deviation, $(T_{local} - T_{avg})/\Delta T_{avg}$: Average Profile, Tip 1	2	3	4	5	6	Root 7	Peak Profile, Tip 1	2	3	4	5	6	Root 7
E7	192	1.04	435	4.79	0	0	0	0	0	3.85	435	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	193	1.05	432	4.90	190	1.00	0.0106	0	0.0106	3.98	814	0.312	0.512	0.374	0.347	0.149	-0.131	-0.465	1.064	1.231	1.390	1.370	1.160	0.820	0.304
	194	1.05	632	4.11	205	1.00	0.0137	0	0.0137	4.18	1127	0.183	0.315	0.295	0.219	0.082	-0.158	-0.471	0.621	0.646	0.850	0.873	0.769	0.546	0.160
	195	1.06	771	3.84	283	0.21	0.0042	0.0163	0.0205	4.57	1417	-0.119	0.025	0.077	0.101	0.106	-0.041	-0.276	0.293	0.318	0.282	0.274	0.294	0.216	-0.087
	196	1.06	765	3.67	307	0.26	0.0060	0.0172	0.0232	4.20	1496	-0.098	0.031	0.069	0.075	0.066	-0.087	-0.315	0.199	0.236	0.220	0.208	0.193	0.151	-0.084
	197	1.06	768	3.68	305	0.21	0.0048	0.0182	0.0230	4.23	1470	-0.121	0.034	0.070	0.092	0.088	-0.070	-0.294	0.269	0.357	0.313	0.279	0.271	0.182	0.008
	198	1.06	766	3.68	365	0.21	0.0048	0.0182	0.0230	4.16	1471	-0.122	0.020	0.071	0.093	0.093	-0.059	-0.295	0.282	0.310	0.280	0.248	0.263	0.180	-0.073
	199	1.06	769	3.67	303	0.16	0.0036	0.0193	0.0229	4.14	1487	-0.142	0.011	0.075	0.116	0.122	-0.023	-0.266	0.338	0.366	0.330	0.312	0.346	0.285	0.033
	200	1.06	763	3.6	345	0.21	0.0054	0.0207	0.0261	4.72	1586	-0.139	-0.003	0.048	0.077	0.066	-0.092	-0.324	0.209	0.243	0.237	0.242	0.241	0.190	-0.095
E8	201	1.03	431	4.74	0	0	0	0	0	3.60	431	---	---	---	---	---	---	---	---	---	---	---	---	---	---
	202	1.04	433	4.84	195	1.00	0.0110	0	0.0110	3.79	829	-0.114	0.433	0.483	0.370	0.163	-0.095	-0.418	0.742	1.158	1.279	1.360	1.240	0.935	0.523
	203	1.05	633	4.15	210	1.00	0.0138	0	0.0138	4.13	1131	-0.095	0.318	0.360	0.288	0.129	-0.084	-0.394	0.448	0.866	0.903	1.001	1.022	0.836	0.535
	204	1.05	761	3.63	279	0.20	0.0043	0.0171	0.0214	4.02	1436	-0.367	-0.054	0.049	0.089	0.038	0.035	-0.201	0.140	0.245	0.316	0.288	0.301	0.243	0.098
	205	1.05	759	3.65	301	0.25	0.0058	0.0171	0.0229	4.05	1481	-0.323	-0.038	0.048	0.072	0.067	-0.005	-0.239	0.085	0.178	0.228	0.226	0.236	0.199	0.065
	206	1.05	760	3.60	301	0.20	0.0047	0.0185	0.0232	3.95	1447	-0.353	-0.058	0.038	0.072	0.082	0.023	-0.224	0.126	0.188	0.254	0.277	0.258	0.272	0.068
	207	1.05	759	3.66	300	0.20	0.0047	0.0181	0.0228	4.06	1437	-0.356	-0.056	0.042	0.078	0.090	0.030	-0.219	0.054	0.179	0.267	0.244	0.263	0.203	0.049
	208	1.05	759	3.68	299	0.15	0.0035	0.0191	0.0226	4.09	1472	-0.390	-0.080	0.032	0.080	0.106	0.052	-0.192	0.154	0.278	0.362	0.322	0.359	0.300	0.126
	209	1.05	759	3.67	339	0.20	0.0052	0.0204	0.0256	4.08	1566	-0.360	-0.074	0.020	0.053	0.065	0.001	-0.242	0.103	0.196	0.251	0.240	0.268	0.248	0.051

Table B-11. Pattern Factor Test Results, Configurations E11 and E12.

Configuration	Reading Number	Inlet Total Pressure Atm.	Inlet Total Temp. K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Pilot/Total Fuel Split	Fuel-Air Ratio g Fuel/g Air			Total Pressure Loss %	Average Exit Temperature K	Exit Temperature Deviation, $(T_{local}-T_{avg})/\Delta T_{avg}$													
												Average Profile							Peak Profile						
												Tip						Root	Tip						Root
							Pilot	Main	Total			1	2	3	4	5	6	7	1	2	3	4	5	6	7
E11	282	1.04	426	4.91	0		0	0	0	3.76	426														
↓	283	1.05	428	4.79	192	1.000	.0109	0	.0109	3.85	819	+.185	+.398	+.353	+.203	+.018	-.240	-.545	0.844	1.176	1.218	1.148	1.125	0.942	0.548
↓	285	1.05	633	4.21	207	1.000	.0136	0	.0136	4.53	1124	+.175	+.302	+.280	+.191	+.067	-.133	-.418	0.677	0.889	1.049	1.049	0.888	0.741	0.406
↓	286	1.05	758	3.71	283	0.169	.0037	.0175	.0212	4.31	1425	-.167	+.016	+.106	+.164	+.186	+.080	-.176	0.303	0.373	0.409	0.506	0.622	0.431	0.227
↓	290	1.06	757	3.71	305	0.146	.0034	.0194	.0228	4.17	1476	-.199	-.008	+.094	+.170	+.182	+.077	-.187	0.340	0.363	0.448	0.506	0.477	0.421	0.205
↓	287	1.06	759	3.74	305	0.177	.0040	.0186	.0226	4.31	1471	-.186	+.012	+.102	+.170	+.162	+.105	-.185	0.356	0.343	0.407	0.538	0.546	0. .04	0.217
↓	288	1.06	758	3.73	307	0.178	.0041	.0188	.0229	4.38	1480	-.158	0	+.091	+.158	+.156	+.062	-.207	0.293	0.321	0.413	0.529	0.475	0.434	0.188
↓	289	1.06	757	3.72	307	0.253	.0058	.0171	.0229	4.26	1479	-.138	+.037	+.109	+.155	+.131	+.014	-.238	0.262	0.321	0.411	0.502	0.444	0.388	0.140
E12	292	1.04	433	4.82	197	1.000	.0114	0	.0114	3.63	899	+.004	+.457	+.464	+.386	+.245	+.077	-.191	0.745	1.306	1.342	1.233	1.242	1.228	1.060
↓	298	1.05	626	4.21	213	1.000	.0140	0	.0140	4.19	1131	-.056	+.260	+.288	+.249	+.154	+.032	-.220	0.558	0.919	0.976	0.923	0.913	0.909	0.720
↓	297	1.05	755	3.69	290	0.108	.0023	.0195	.0218	4.19	1442	-.395	-.092	+.040	+.118	+.161	+.141	-.069	0.217	0.307	0.404	0.425	0.404	0.363	0.312
↓	293	1.05	754	3.67	291	0.182	.0040	.0180	.0220	4.09	1447	-.372	-.065	+.048	+.106	+.129	+.093	-.107	0.126	0.239	0.314	0.347	0.339	0.364	0.313
↓	295	1.05	755	3.62	315	0.183	.0044	.0198	.0242	4.13	1517	-.377	-.082	+.031	+.072	+.110	+.064	-.132	0.096	0.159	0.265	0.353	0.353	0.333	0.267
↓	296	1.05	754	3.66	315	0.185	.0044	.0196	.0239	4.11	1507	-.374	-.081	+.034	+.090	+.111	+.072	-.128	0.120	0.198	0.296	0.329	0.380	0.348	0.285
↓	294	1.05	753	3.71	316	0.256	.0060	.0175	.0236	4.15	1496	-.336	-.041	+.054	+.090	+.099	+.035	-.168	0.060	0.163	0.258	0.294	0.286	0.317	0.228

Table B-12. Summary of Engine Emission Test Results.

Nominal Thrust Setting, % of 222.2 kN	Reading Number	Actual Corrected Thrust, % of 222.2 kN	$\delta_2 = P_2/P_{STD}$, Engine Inlet-to-Standard Pressure Ratio	$\theta_2 = T_2/T_{STD}$, Engine Inlet-to-Standard Temperature Ratio	H_v, Engine Inlet Humidity, g/kg	W_{ft} Total Fuel Flow kg/s	W_{a36}, Combustor Airflow, kg/sec	P_3 Compressor Exit Total Pressure, MPa	T_3, Compressor Exit Total Temperature, K	V_r, Combustor Reference Velocity, m/s	$\Delta P_t/P_3$, Combustor Total Pressure Drop, %	f_{36} Combustor Fuel-Air Ratio, g/kg	W_{fp}/W_{ft}, Pilot-to-Total Fuel Split	T_4, Combustor Exit Temperature, K	Sample Fuel-Air Ratio / Metered Fuel-Air Ratio	Sample Combustion Efficiency, %	Measured Emission Indices g/kg: CO	Measured Emission Indices g/kg: HC	Measured Emission Indices g/kg: NO_x	Measured SAE Smoke Number	Corrected Emission Indices g/kg: CO	Corrected Emission Indices g/kg: HC	Corrected Emission Indices g/kg: NO_x	Corrected SAE Smoke Number	Sampling Mode
3.3	5	3.63	0.9874	1.0574	9.71	0.192	13.00	0.295	452.6	18.35	3.26	14.72	1.000	1012.4	0.907	98.50	58.2	1.6	4.1	3.8	34.0	2.4	4.4	3.8	D
	12	2.92	0.9889	1.0399	7.43	0.190	11.26	0.261	441.1	17.38	3.18	16.84	1.000	1076.4	0.951	97.91	61.5	1.9	3.6	8.0	53.9	2.7	3.9	3.8	D
	16	3.22	0.9881	1.0367	8.71	0.187	13.30	0.294	440.2	18.20	3.16	14.06	1.000	977.7	0.972	98.48	59.1	1.5	3.7	3.9	46.9	2.1	4.0	3.9	D
	37	3.40	0.9867	0434	7.00	0.174	13.17	0.288	443.2	18.49	3.62	13.17	1.000	949.3	0.993	98.37	64.3	1.3	4.2	3.3	44.8	1.0	4.4	3.3	T
	49	3.37	0.9868	0402	10.71	0.183	12.77	0.286	443.7	18.12	3.45	14.36	1.000	992.1	0.955	98.51	59.6	1.0	4.1	3.3	35.6	1.4	4.6	3.3	A
	88	3.55	0.9836	.0594	12.86	0.191	12.83	0.291	453.2	18.28	3.27	14.92	1.000	1020.1	0.983	98.65	55.1	0.6	[illegible]	1.8	31.9	1.0	3.8	1.8	P
	89	3.39	0.9857	.0615	13.71	0.192	13.02	0.233	452.3	19.02	3.77	14.72	1.000	1012.3	1.011	98.83	63.7	0.7	3.2	3.0	35.6	1.1	3.9	3.0	P
	93	3.47	0.9806	1.0460	17.86	0.186	12.99	0.285	444.6	18.50	3.49	14.30	1.000	990.7	0.981	98.62	55.3	0.9	3.1	0.9	32.7	1.2	4.0	0.9	P
	118	3.32	0.9858	1.0356	14.29	0.187	12.69	0.286	440.5	17.88	3.38	14.72	1.000	1002.0	0.936	98.55	56.9	1.2	3.1	2.0	32.1	1.7	3.8	2.0	P
5.0	6	4.70	0.9872	1.0364	9.71	0.216	14.97	0.361	472.[illegible]	18.96	3.51	14.60	1.000	1018.7	0.914	98.70	50.6	1.2	4.5	3.6	26.3	1.8	5.0	3.6	D
	43	4.79	0.9866	1.0296	9.14	0.220	15.48	0.351	468.6	18.88	3.55	14.27	1.000	1009.0	0.911	98.74	51.2	0.7	4.6	4.1	27.6	1.0	5.1	4.1	A
	87	4.96	0.9835	1.0601	17.86	0.219	15.48	0.354	480.8	19.26	3.60	14.15	1.000	1017.3	0.960	98.96	42.2	0.6	3.7	2.4	23.9	1.0	4.2	2.4	P
	117	4.64	0.9853	1.0353	14.29	0.216	15.31	0.347	467.6	18.83	3.62	14.09	1.000	1003.5	0.938	98.86	44.8	0.9	3.5	3.1	26.3	1.3	4.3	3.1	P
7.0	7	6.70	0.9868	1.0567	9.71	0.257	18.35	0.425	504.1	19.87	4.13	14.02	1.000	1033.2	0.910	99.05	37.4	0.8	5.3	3.7	20.2	1.3	5.7	3.7	D
	44	6.69	0.9862	1.0321	9.14	0.255	18.68	0.428	496.9	19.84	2.88	13.63	1.000	1013.2	0.895	99.03	48.7	0.7	5.6	6.2	21.5	1.0	5.8	6.2	A
	116	6.51	0.9849	1.0350	14.29	0.251	18.63	0.426	494.9	19.79	3.81	13.48	1.000	1006.1	0.924	99.17	31.7	0.9	4.0	1.7	17.8	1.2	4.8	1.7	P
9.5	13	14.67	0.9871	1.0611	7.43	0.406	28.84	0.692	567.4	21.61	4.26	16.09	1.000	1091.3	0.878	99.56	18.8	0.2	7.9	5.2	10.3	1.0	6.7	5.2	D
20.0	8	20.06	0.9848	1.0565	9.71	0.521	35.15	0.863	603.0	22.43	3.94	14.83	1.000	1147.9	0.967	99.60	15.7	0.4	8.5	4.0	10.2	0.7	8	4.0	D
	45	20.16	0.9840	1.0330	9.14	0.519	35.08	0.857	594.0	22.41	3.84	16.81	1.000	1139.4	0.930	99.58	17.6	0.1	8.6	6.0	11.0	0.1	9.2	6.0	A
	115	19.65	0.9818	1.0352	14.29	0.518	34.86	0.857	590.2	21.96	4.24	16.85	1.000	1137.4	0.893	99.64	14.2	0.3	6.9	1.6	8.8	0.4	8.2	1.6	P
30.0	9	30.90	0.9833	1.0567	9.71	0.770	44.25	1.151	654.1	22.98	4.13	17.40	1.000	1278.1	0.977	99.61	15.4	0.3	10.3	23.0	10.5	0.5	10.5	3.0	D
	18	29.11	0.9860	1.0348	8.71	0.770	45.66	1.170	640.8	22.84	3.95	16.86	1.000	1268.9	1.010	99.63	17.7	1.5	10.0	22.8	12.4	2.1	10.5	3.0	D
	38	31.27	0.9825	1.0414	7.42	0.770	44.96	1.162	647.8	22.92	4.10	17.12	1.000	1263.5	0.962	99.65	16.8	0.1	10.1	23.5	10.3	0.2	10.1	3.0	T
	50	30.54	0.9828	1.0421	10.71	0.763	43.79	1.140	648.8	22.79	4.15	17.42	1.000	1274.7	1.015	99.61	16.3	0	9.4	24.0	10.9	0	10.0	3.0	A
	86	31.60	0.9772	1.0598	12.86	0.797	43.99	1.158	658.9	22.87	4.01	18.13	1.000	1306	0.929	99.66	15.2	0	8.7	25.6	9.9	0	9.3	4.0	P
	114	29.77	0.9795	1.0346	14.00	0.758	44.03	1.140	638.6	22.55	4.08	17.22	1.000	1258.9	0.899	99.63	14.7	0.2	8.3	14.7	9.7	0.3	9.7	4.0	P
30.0	21	31.42	0.9839	1.0232	8.71	0.785	46.06	1.188	641.0	22.71	4.11	17.06	0.761	1255.7	1.012	97.35	48.5	15.2	10.2	1.3	41.6	22.0	9.2	1.3	D
	22	31.3[illegible]	0.9840	1.0233	8.71	0.778	46.33	1.189	642.4	22.88	4.07	16.78	0.640	1267.6	1.015	97.10	58.1	15.4	9.9	1.6	51.7	20.4	8.9	1.6	D
	25	31.36	0.9855	1.0313	6.79	0.780	46.72	1.197	647.6	23.10	4.35	16.26	0.531	1234.8	1.035	97.79	55.7	9.[illegible]	10.2	0.5	54.7	9.5	8.7	0.5	D
	85	32.13	0.9768	1.0611	12.14	0.783	46.36	1.211	644.0	23.30	4.51	16.90	0.426	1271.9	0.968	98.83	38.8	2.6	7.9	1.3	45.2	1.7	6.8	1.3	P
	113	31.51	0.9794	1.0345	13.45	0.776	46.58	1.200	646.8	22.86	---	16.66	0.457	1249.1	0.897	97.63	65.0	8.6	7.8	1.6	63.8	9.9	7.5	1.6	P
	119	29.71	0.9793	1.0349	13.44	0.750	45.06	1.163	64[illegible].9	22.77	4.38	16.64	0.470	1263.4	0.913	97.26	69.7	11.6	7.4	1.6	61.7	15.3	7.5	1.6	P
[illegible]0	46	65.15	0.9805	1.0338	9.71	1.069	57.55	1.551	[illegible]01.8	23.79	4.65	18.58	0.213	1357.1	0.925	99.61	11.2	0.2	10.4	0.6	10.5	0.2	10.0	0.6	A
	112	63.95	0.9790	1.0365	16.00	1.066	57.36	1.547	696.8	23.60	4.67	18.58	0.206	1352.8	0.913	99.63	16.0	0.5	8.1	0.3	12.5	0.7	8.6	0.3	P
50.0	84	49.70	0.9763	1.0614	12.16	1.199	58.90	1.636	730.4	23.74	---	20.36	0.181	1437.7	0.886	99.82	7.4	0.1	11.3	2.8	7.6	0.1	10.6	2.8	P
	111	49.49	0.9780	1.0343	14.16	1.203	61.20	1.685	714.6	23.73	4.61	19.66	0.174	1402.4	0.908	99.73	10.3	0.3	9.5	1.6	9.6	0.4	9.9	1.3	P
65.0	47	64.89	0.9784	1.0364	9.71	1.554	70.73	2.029	760.1	24.22	---	21.98	0.182	1512.6	0.921	99.92	3.4	0	16.0	7.4	3.3	0	14.9	1.0	A
	110	61.78	0.9758	1.0351	14.14	1.514	69.54	1.900	750.6	24.10	4.52	21.77	0.169	1498.3	0.906	99.89	4.3	0.1	12.4	4.8	3.7	0.1	13.3	1.3	P
85.0	30	85.53	0.9795	1.0421	6.57	2.097	83.83	2.502	816.8	25.01	4.50	25.02	0.229	1650.1	0.972	99.96	1.3	0.1	24.2	20.2	1.4	0.1	20.3	3.4	D
	26	86.59	0.9790	1.0333	6.29	2.119	84.90	2.530	811.7	24.90	4.51	24.95	0.206	1644.0	0.977	99.96	1.6	0.1	22.9	22.2	1.6	0.1	19.5	5.1	D
	32	85.84	0.9790	1.0433	6.57	2.090	84.03	2.494	815.2	25.10	4.19	24.87	0.177	1664.4	0.990	99.96	1.7	0	22.9	28.9	1.8	0	19.6	11.6	D
	39	86.94	0.9761	1.0392	7.57	2.125	84.66	2.523	811.5	24.90	4.38	25.10	0.179	1668.2	0.967	99.96	1.8	0	22.5	28.4	1.8	0	19.7	10.0	T
	51	86.92	0.9763	1.0446	11.14	2.158	83.05	2.504	821.2	24.89	4.34	25.98	0.185	1681.7	0.995	99.96	1.9	0	21.2	28.5	1.7	0	18.6	5.7	A
	83	86.39	0.9713	1.0615	12.14	2.175	81.79	2.492	827.8	24.83	4.59	26.59	0.176	1704.6	0.912	99.96	1.8	0	23.2	33.7	2.0	0	19.9	7.5	P
	90	87.05	0.9734	1.0606	13.71	2.214	84.19	2.489	829.3	25.63	4.36	26.30	0.176	1697.4	0.9[illegible]1	99.96	1.7	0	22.0	31.2	1.9	0	20.0	12.6	P
	92	82.83	0.9681	1.0460	17.86	2.043	80.70	2.391	806.9	26.90	4.50	25.31	0.179	1650.7	0.950	99.95	2.0	0.1	17.6	25.9	1.8	0.1	19.5	6.5	P
	109	82.9[illegible]	0.9724	1.0345	14.14	2.101	82.33	2.468	803.8	24.51	4.46	25.52	0.168	1654.3	0.915	99.95	2.0	0.1	17.2	24.0	1.8	0.1	17.5	3.1	P
	33	87.64	0.9731	1.0436	7.00	2.156	84.15	2.522	818.6	24.96	4.39	25.62	0.117	1669.1	0.989	99.96	2.5	0	23.3	41.4	2.7	0	19.3	18.7	D
90.0	48	92.53	0.9760	1.0362	10.71	2.302	86.96	2.637	825.2	26.87	4.62	26.47	0.126	1699.1	0.876	99.96	2.8	0	---	41.9	2.7	0	---	[illegible]	A
	108	87.13	0.9720	1.0352	16.16	2.222	84.68	2.562	813.6	26.58	4.46	26.23	0.125	1682.9	0.916	99.93	2.6	0.1	19.7	36.2	2.2	0.2	20.9	15.3	P
100.0	31	100.71	0.9723	1.0424	6.57	2.514	93.00	2.850	847.[illegible]	25.28	4.57	27.02	0.236	1732.9	0.982	99.97	1.3	0	30.6	29.6	1.4	0	26.2	13.4	D
	35	100.69	0.9769	1.0444	7.43	2.527	92.50	2.841	846.8	25.20	4.53	27.31	0.181	1740.3	0.978	99.96	1.7	0	28.8	41.4	1.7	0	25.1	22.5	D
	80	99.03	0.9710	1.0601	11.57	2.546	89.02	2.775	857.1	25.13	4.47	28.60	0.192	1784.9	0.924	99.96	1.5	0	28.4	44.9	1.6	0	25.6	19.7	P
	82	102.24	0.9707	1.0604	12.00	2.652	90.06	2.833	861.4	25.03	4.56	29.44	0.136	1811.7	0.916	99.96	1.9	0	28.1	53.7	2.1	0	26.0	22.3	P
	107	94.95	0.9706	1.0340	14.00	2.448	88.89	2.730	830.3	24.71	4.41	27.54	0.126	1733.8	0.930	99.94	2.2	0.1	21.6	42.7	1.8	0.2	23.1	21.4	P
	36	102.55	0.9749	1.0439	7.00	2.586	93.08	2.867	849.3	25.20	4.37	27.78	0.125	1755.7	0.968	99.95	2.1	0	28.2	50.4	2.2	0	23.9	27.4	D
	40	104.08	0.9741	1.0283	7.57	2.624	94.56	2.910	843.4	25.05	4.44	27.75	0.122	1750.2	1.006	99.95	2.0	0	26.4	50.7	2.0	0	23.1	28.9	T
	52	102.37	0.9749	1.0456	11.14	2.607	92.13	2.864	843.4	25.10	4.51	28.30	0.127	1765.7	1.011	99.96	1.8	0	26.4	49.3	1.9	0	23.3	23.8	A

Table B-13. Sampling Technique Results.

RDG	NUM G/KG	RAKE (1)	EICO (G/KG)	EIHC (G/KG)	EINO (G/KG)	EINOX (G/KG)	FARS	COMEFF %	SMKNBR
5	9.71	A	59.3	1.1	0.	4.0	10.78	98.50	3.6
5	9.71	B	59.8	1.5	0.	4.1	10.75	98.46	4.0
5	9.71	D	58.2	1.4	2.3	4.1	10.78	98.50	3.8
6	9.71	A	50.1	1.0	2.7	4.6	10.62	98.73	3.3
6	9.71	B	51.0	1.3	2.7	4.5	10.67	98.68	3.8
7	9.71	A	36.7	0.7	3.4	5.3	10.36	99.07	3.4
7	9.71	B	39.0	0.9	3.5	5.4	10.26	99.02	3.9
8	9.71	A	17.4	0.4	6.4	8.4	11.40	99.55	5.3
8	9.71	B	15.6	0.3	6.7	8.5	11.40	99.60	3.9
8	9.71	D	15.7	0.4	6.8	8.7	11.59	99.60	4.0
9	9.71	A	16.5	0.2	8.1	10.2	13.79	99.59	24.9
9	9.71	B	[illegible]	0.3	8.3	10.3	13.50	99.60	25.0
9	9.71	D	[illegible]	0.3	8.2	10.3	13.74	99.61	23.9
12	7.43	A	[illegible]	1.7	1.5	3.5	12.96	97.93	9.2
12	7.43	B	[illegible]	1.9	1.6	3.6	13.00	97.92	8.5
12	7.43	D	81.5	1.9	1.6	3.6	12.93	97.91	8.0
13	7.43	A	19.6	0.2	5.5	7.4	10.43	99.53	6.8
13	7.43	B	18.6	0.2	5.7	7.9	9.95	99.55	2.6
13	7.43	D	18.8	0.2	5.8	7.9	9.99	99.54	5.2
16	6.86	A	60.2	1.4	1.5	3.6	10.95	98.46	3.3
16	6.86	B	58.8	1.5	1.5	3.6	11.09	98.48	2.9
16	6.86	D	59.1	1.5	1.7	3.7	11.02	98.48	3.9
18	6.86	A	18.7	1.7	6.9	9.8	13.76	99.40	23.6
18	6.86	B	18.0	1.5	7.0	9.9	13.64	99.43	24.1
18	6.86	D	17.7	1.5	7.1	10.0	13.75	99.43	22.8
21	6.86	A	48.7	15.0	4.2	10.3	13.85	97.36	1.1
21	6.86	B	50.1	15.7	4.2	10.1	13.83	97.26	0.6
21	6.86	D	48.5	15.2	4.4	10.2	13.93	97.35	1.3
22	6.86	A	60.1	16.2	4.0	10.1	13.59	96.98	2.4
22	6.86	B	58.9	15.5	4.2	10.0	13.73	97.08	2.1
22	6.86	D	58.1	15.4	4.3	9.9	13.76	97.10	1.6
25	6.29	A	57.4	10.1	4.6	10.2	13.42	97.65	1.1
25	6.29	B	56.4	9.0	4.8	10.3	13.56	97.79	1.6
25	6.29	D	55.7	9.1	4.8	10.2	13.60	97.79	0.5
26	6.29	A	1.6	0.	21.0	23.0	19.97	99.96	21.9
26	6.29	B	1.7	0.	21.3	23.3	19.32	99.96	24.3
26	6.29	D	1.6	0.1	21.1	22.9	[illegible]	99.96	22.2
30	6.57	A	1.3	0.1	22.0	24.0	[illegible]	99.96	20.4
30	6.57	B	1.3	0.1	22.4	24.4	19.42	99.96	20.9
30	6.57	D	1.3	0.1	22.2	24.2	19.65	99.98	20.3
31	6.57	A	1.3	0.	28.1	30.6	21.74	99.97	29.6
31	6.57	B	1.3	0.	28.6	30.7	21.05	99.97	30.2
31	6.57	D	1.3	0.	28.4	30.4	21.44	99.97	29.6
32	6.57	A	1.7	0.	20.9	22.9	20.32	99.96	28.5
32	6.57	B	1.8	0.	21.0	23.0	19.52	99.96	30.1
32	6.57	D	1.7	0.	20.9	22.9	19.89	99.96	28.9
33	7.00	A	2.4	0.	20.9	22.9	21.19	99.94	41.2
33	7.00	B	2.6	0.	20.9	23.1	20.13	99.94	42.7
33	7.00	D	2.5	0.	20.9	23.3	20.46	99.94	41.4
35	7.43	A	1.6	0.	27.0	29.1	22.47	99.96	41.0
35	7.43	B	1.7	0.	27.1	29.2	21.42	99.96	43.1
35	7.43	D	1.7	0.	26.7	28.8	21.57	99.96	41.1
36	7.00	A	2.0	0.	28.1	28.3	22.44	99.95	50.0
36	7.00	B	2.2	0.	28.1	28.5	21.24	99.94	52.3
36	7.00	D	2.1	0.	28.2	28.2	21.73	99.95	50.4
37	7.00	D	59.8	1.2	2.2	4.2	10.24	98.48	1.6
37	7.00	T	64.3	1.3	2.1	4.2	10.57	98.37	3.3
38	7.43	D	14.9	0.1	7.8	10.0	13.74	99.64	23.9
38	7.43	T	14.8	0.1	7.9	10.1	13.31	99.65	23.5
39	7.57	D	1.8	0.	21.0	23.0	19.72	99.96	29.9
39	7.57	T	1.8	0.	20.4	22.5	19.62	99.96	28.4
40	7.57	D	2.0	0.	28.0	28.4	22.67	99.95	52.0
40	7.57	T	2.0	0.	24.2	26.4	22.50	99.95	50.7

RDG	NUM G/KG	RAKE (1)	EICO (G/KG)	EIHC (G/KG)	EINO (G/KG)	EINOX (G/KG)	FARS	COMEFF %	SMKNBR
43	9.14	A	51.2	0.7	2.7	4.6	10.46	98.74	4.1
43	9.14	B	50.9	0.9	2.7	4.7	10.17	98.73	[illegible]
43	[illegible]	D	51.4	0.8	2.8	4.8	10.21	98.72	5.4
44	9.14	A	38.7	0.7	3.5	5.4	9.85	99.03	2.6
44	9.14	B	37.7	0.7	3.5	5.5	9.81	99.05	4.2
44	9.14	D	37.1	0.7	3.6	5.5	9.80	99.06	3.9
45	9.14	A	17.6	0.1	6.9	8.6	11.13	99.59	5.9
45	9.14	B	15.8	0.1	6.9	8.8	11.01	99.62	4.7
45	9.14	D	16.0	0.1	6.9	8.8	11.08	99.61	4.7
46	9.71	A	11.2	0.2	8.0	10.4	[illegible]	99.72	0.6
46	9.71	B	11.3	0.2	7.7	10.5	[illegible]	99.72	0.1
46	9.71	D	11.6	0.2	7.7	10.5	[illegible]	99.71	1.1
47	9.71	A	3.4	0.	13.7	16.0	[illegible]	99.92	7.5
47	9.71	B	3.6	0.	13.9	16.4	15.81	99.91	8.3
47	9.71	D	3.5	0.	13.9	16.2	15.94	99.91	7.2
48	10.71	A	2.6	0.	22.6	24.9	19.87	99.94	41.9
48	10.71	B	2.8	0.	23.0	25.4	18.72	99.93	45.2
48	10.71	D	2.8	0.	23.0	25.3	19.05	99.93	41.2
49	10.71	A	59.6	1.0	2.1	4.1	11.08	98.51	3.3
49	10.71	B	60.6	1.1	2.0	4.0	11.09	98.47	1.9
49	10.71	D	61.7	1.1	2.0	3.9	11.21	98.45	3.8
50	10.71	A	16.3	0.	7.3	9.4	14.28	99.61	[illegible]
50	10.71	B	14.5	0.	7.6	9.6	13.93	99.66	24.0
50	10.71	D	14.1	0.1	7.7	9.7	14.10	99.66	23.2
51	11.14	A	1.6	0.	19.3	21.2	20.89	99.96	29.5
51	11.14	B	1.7	0.	19.0	22.4	20.04	99.95	30.9
51	11.14	D	1.6	0.	19.4	21.4	20.14	99.96	28.4
52	11.14	A	1.8	0.	24.1	26.4	23.12	99.96	49.3
52	11.14	B	2.0	0.	24.4	26.4	21.96	99.95	52.7
52	11.14	D	1.9	0.	24.2	26.6	22.22	99.95	50.0
80	11.57	A	1.5	0.	26.4	28.4	21.29	99.96	41.3
80	11.57	P	1.5	0.	26.7	28.9	21.34	99.96	44.9
82	12.00	A	1.9	0.	25.7	27.9	21.73	99.96	50.9
82	12.00	P	1.9	0.	25.8	28.1	21.73	99.96	53.7
83	12.14	A	1.8	0.	20.7	23.0	19.48	99.96	31.2
83	12.14	P	1.8	0.	21.1	23.2	19.59	99.96	33.7
84	12.14	A	7.2	0.1	9.0	11.5	14.57	99.82	1.6
84	12.14	P	7.4	0.1	8.8	11.5	14.57	99.82	2.8
85	12.14	A	31.2	2.2	4.8	8.2	13.29	99.05	1.0
85	12.14	P	30.8	2.6	5.1	7.9	12.94	98.83	1.3
86	12.86	A	15.1	0.	6.8	8.8	14.65	99.64	25.1
86	12.86	P	15.2	0.	6.6	8.7	13.60	99.64	25.6
87	12.86	A	42.0	0.4	2.0	3.7	10.72	98.97	3.6
87	12.86	P	42.2	0.6	2.3	3.7	11.20	98.96	2.4
88	12.86	A	56.8	0.5	1.4	3.2	11.40	98.62	2.7
88	12.86	P	55.1	0.6	2.1	3.3	11.84	98.65	1.9
106	14.00	P	63.6	1.4	2.2	2.9	11.63	98.37	4.7
107	14.00	P	2.2	0.1	20.0	21.6	20.70	99.94	42.7
108	14.14	P	2.6	0.1	17.9	19.7	19.40	99.93	36.2
109	14.14	P	2.0	0.1	15.8	17.2	18.85	99.95	24.0
110	14.14	P	4.3	0.1	10.3	12.4	15.92	99.89	4.8
111	14.14	P	10.3	0.3	7.0	9.5	14.42	99.73	1.6
112	14.00	P	14.0	0.5	5.6	8.1	13.70	99.63	0.3
113	14.00	P	65.0	8.6	4.9	7.8	12.06	97.63	1.6
114	14.00	P	14.7	0.2	6.4	8.3	12.51	99.63	14.7
115	14.29	P	14.2	0.3	5.2	6.9	10.71	99.64	1.6
116	14.29	P	31.7	0.9	2.7	4.0	10.06	99.17	1.7
117	14.29	P	44.8	0.9	2.4	3.5	10.56	98.86	3.1
118	14.29	P	56.9	1.2	2.2	3.1	11.13	98.55	2.0
119	14.29	P	69.7	11.4	4.9	7.4	12.27	97.24	1.6

(1) A = + 12 Point Single Cruciform Rake
B = × 12 Point Single Cruciform Rake
C = ⊕ 24 Point Double Cruciform Rake
T = 336 Point Traverse
P = 20 Point Pressure Rake

Table B-14. Gas Sample Fuel-Air Ratio Comparisons.

Reading Number	FHPC Corrected Thrust % of Rated	FAR 8 Metered Core Exhaust Fuel-Air Ratio, g/kg	Ratio of Sample to Metered Fuel-Air Ratio: Double Cruciform Rake	0° - 90° Cruciform Rake	45° - 135° Cruciform Rake	Traverse	Pressure Rakes
5	3.6	11.89	0.907	0.907	0.904	---	---
6	4.7	11.64	---	0.912	0.917	---	---
7	6.7	11.33	---	0.914	0.906	---	---
8	20.1	11.98	0.967	0.968	0.952	---	---
9	30.9	14.06	0.977	0.981	0.960	---	---
12	2.9	13.60	0.951	0.953	0.956	---	---
13	14.5	11.38	0.878	0.917	0.874	---	---
16	3.2	11.34	0.972	0.966	0.978	---	---
18	29.1	13.62	1.010	1.010	1.001	---	---
21	31.4	13.78	1.011	1.005	1.004	---	---
22	31.3	13.56	1.015	1.002	1.013	---	---
25	31.4	13.14	1.035	1.021	1.032	---	---
26	86.6	20.16	0.977	0.991	0.958	---	---
30	85.5	20.21	0.972	0.991	0.961	---	---
31	100.7	21.83	0.982	0.996	0.964	---	---
32	85.8	20.09	0.990	1.011	0.972	---	---
33	87.6	20.69	0.989	1.024	0.973	---	---
35	100.7	22.06	0.978	1.019	0.971	---	---
36	102.6	22.45	0.968	1.000	0.946	---	---
37	3.4	10.64	0.962	---	---	0.993	---
38	31.3	13.83	0.993	---	---	0.962	---
39	86.9	20.28	0.972	---	---	0.967	---
40	104.1	22.41	1.012	---	---	1.004	---
43	4.8	11.48	0.889	0.911	0.886	---	---
44	6.7	11.01	0.890	0.895	0.891	---	---
45	20.2	11.97	0.926	0.930	0.920	---	---
46	45.2	15.01	0.909	0.925	0.909	---	---
47	64.9	17.75	0.898	0.921	0.891	---	---
48	92.5	21.38	0.891	0.929	0.876	---	---
49	3.4	11.60	0.966	0.955	0.956	---	---
50	30.5	14.07	1.002	1.015	0.990	---	---
51	86.9	20.99	0.960	0.995	0.955	---	---
52	102.4	22.86	0.972	1.011	0.961	---	---
80	99.0	23.10	---	0.922	---	---	0.924
82	102.2	23.78	---	0.914	---	---	0.914
83	86.4	21.48	---	0.907	---	---	0.912
84	49.7	16.44	---	0.886	---	---	0.886
85	32.1	13.65	---	0.973	---	---	0.948
86	31.6	14.64	---	1.001	---	---	0.929
87	5.0	11.43	---	0.938	---	---	0.980
88	3.6	12.05	---	0.946	---	---	0.983
106	3.2	12.42	---	---	---	---	0.936
107	94.6	22.25	---	---	---	---	0.930
108	87.1	21.19	---	---	---	---	0.916
109	82.9	20.62	---	---	---	---	0.915
110	61.8	17.58	---	---	---	---	0.906
111	49.5	15.88	---	---	---	---	0.908
112	44.0	15.01	---	---	---	---	0.913
113	30.0	13.45	---	---	---	---	0.897
114	29.8	13.91	---	---	---	---	0.899
115	19.6	11.99	---	---	---	---	0.893
116	6.5	10.89	---	---	---	---	0.924
117	4.6	11.38	---	---	---	---	0.928
118	3.3	11.89	---	---	---	---	0.936
119	29.7	13.44	---	---	---	---	0.913

	Double Cruciform Rake	0° - 90° Cruciform Rake	45° - 135° Cruciform Rake	Traverse	Pressure Rakes	Overall
Number of Observations	31	37	29	4	22	123
Mean Value	0.962	0.961	0.947	0.982	0.922	0.951
Standard Deviation	0.0428	0.0432	0.0425	0.0202	0.0244	0.0419

Table B-15. Demonstrator Engine Steady State Performance Results.

(a) Key Overall Performance Parameters.

Reading Number	δ_2, Ratio of Engine Inlet to Standard Pressure, dimensionless	θ_2, Ratio of Engine Inlet to Standard Temperature, dimensionless	H_o, Engine Inlet Air Humidity, g/kg	$N_1/\sqrt{\theta_2}$, Corrected Fan Speed, rps	$N_2/\sqrt{\theta_2}$, Corrected Core Speed, rps	F_n/δ_2, Corrected Installed Thrust, kN	F_n/δ_2, Corrected Installed Thrust, % of 221.2 kN	$W_f/\delta_2\theta_2$, Corrected Fuel Flow, kg/s	$W_f/F_n\theta_2^{0.54}$, Corrected Specific Fuel Consumption	P_{49}/P_2, Engine Pressure Ratio, dimensionless	T_{49}/θ_2, Corrected High Pressure Turbine Exit Temperature, K
5	0.98743	1.0574	8.8571	14.201	105.58	8.1144	3.6680	0.18086	23.380	1.1930	703.84
6	0.98719	1.0564	8.2857	16.186	112.12	10.436	4.0880	0.21287	20.380	1.2430	693.65
7	0.98684	1.0567	8.2857	19.893	120.12	14.894	6.7033	0.26378	17.030	1.3460	688.03
8	0.98480	1.0565	8.2857	33.237	136.98	44.572	20.060	0.51561	11.568	2.0383	730.97
9	0.98332	1.0555	8.2857	38.787	143.64	68.667	30.986	0.76338	11.117	2.6088	804.44
12	0.98806	1.0380	8.8571	12.868	105.41	6.4002	2.8810	0.18030	28.087	1.1584	703.07
13	0.98708	1.0411	8.8571	27.790	134.08	32.152	14.471	0.40430	12.575	1.7462	718.61
16	1.0061	1.0367	6.4286	13.875	105.11	7.1574	3.2213	0.17424	24.344	1.1084	701.90
18	1.0030	1.0348	6.4286	38.804	144.18	64.684	29.112	0.72198	11.162	2.4804	803.23
21	0.98391	1.0232	6.4286	40.118	144.89	69.817	31.402	0.75213	11.346	2.6703	803.81
22	0.98401	1.0233	6.4286	38.987	146.15	69.580	31.316	0.78437	11.273	2.0643	797.52
25	0.98640	1.0313	7.8571	38.986	145.19	69.676	31.360	0.76150	10.989	2.6636	793.07
29	0.97800	1.0333	7.8571	58.752	166.82	192.30	86.587	2.1353	11.088	5.5670	1045.1
30	0.97951	1.0421	7.8571	58.530	166.53	190.04	85.529	2.1030	11.066	5.5002	1046.2
31	0.97239	1.0424	6.5714	62.023	171.74	223.77	100.71	2.5406	11.364	6.3161	1105.1
32	0.97342	1.0433	6.5714	58.645	166.02	190.73	85.842	2.1000	11.066	5.5363	1048.5
33	0.97387	1.0436	6.5714	58.978	167.00	194.73	87.642	2.1755	11.178	5.6337	1080.7
35	0.97485	1.0444	7.1429	61.950	171.46	223.73	100.69	2.5436	11.380	6.2857	1114.3
36	0.97403	1.0439	7.1429	62.303	171.69	227.86	102.55	2.6042	11.429	6.3830	1123.4
37	0.98674	1.0434	7.1429	13.732	104.17	7.5829	3.4038	0.17264	22.828	1.2000	704.55
38	0.98254	1.0414	7.1429	39.929	144.48	69.476	31.269	0.77002	11.083	2.0640	815.56
39	0.97611	1.0302	7.1429	58.702	166.17	193.18	86.945	2.1486	11.091	5.5789	1058.8
40	0.97408	1.0283	7.5714	62.977	172.62	231.24	104.08	2.6651	11.525	6.4670	1135.1
43	0.98658	1.0296	8.5714	16.431	115.16	10.637	4.7876	0.22040	20.719	1.3546	721.42
44	0.98616	1.0321	8.5714	19.387	121.67	14.875	6.6947	0.25473	17.125	1.3615	702.70
45	0.98399	1.0330	8.5714	32.680	137.64	44.797	20.162	0.52061	11.622	2.0496	747.93
46	0.98051	1.0336	9.7143	46.781	151.86	100.32	45.152	1.0746	10.711	3.4219	871.54
47	0.97840	1.0344	9.7143	53.446	156.32	144.18	64.893	1.5652	10.856	4.4625	970.16
48	0.97598	1.0362	9.7143	60.301	168.82	205.59	92.529	2.3215	11.292	5.8643	1080.3
49	0.98677	1.0402	10.714	13.773	105.27	7.4910	3.3715	0.18243	24.353	1.1988	732.83
50	0.98275	1.0421	10.714	38.674	144.51	67.859	30.541	0.76157	11.223	2.6113	820.62
51	0.97629	1.0446	11.143	58.949	166.77	193.13	86.923	2.1647	11.208	5.5791	1073.5
52	0.97492	1.0454	11.143	62.068	172.18	227.45	102.37	2.6181	11.510	6.3806	1135.1
80	0.97102	1.0601	11.143	61.856	171.28	220.03	99.029	2.5474	11.577	6.1923	1119.8
82	0.97067	1.0604	11.143	62.460	171.57	227.12	102.24	2.6538	11.682	6.3676	1134.8
83	0.97133	1.0615	12.143	58.945	165.98	191.95	86.391	2.1726	11.319	5.5657	1065.0
84	0.97631	1.0614	12.143	48.194	152.36	110.42	49.695	1.1919	10.795	3.6696	890.50
85	0.97684	1.0611	12.143	40.655	145.53	71.393	32.132	0.77838	10.903	2.7157	796.69
86	0.97725	1.0598	12.143	40.380	144.55	70.217	31.602	0.79255	11.287	2.6723	823.30
87	0.98348	1.0601	12.143	16.542	114.27	11.030	4.9641	0.21626	19.607	1.2695	707.64
88	0.98363	1.0594	12.143	14.008	106.24	7.5900	3.5510	0.18900	23.966	1.1976	723.38
89	0.98573	1.0615	13.714	13.838	106.72	7.5400	3.3936	0.20844	27.645	1.1880	746.79
90	0.97338	1.0604	13.714	58.129	166.26	193.41	87.047	0.93080	4.8561	5.8824	1077.5
91	0.98672	1.0697	13.714	13.800	103.06	7.8334	3.5256	0.19823	24.540	1.1945	711.54
92	0.96887	1.0460	14.284	58.210	163.77	184.03	82.826	1.4311	7.7765	5.3769	1062.0
93	0.98042	1.0460	14.284	13.970	106.57	7.7069	3.4682	0.20606	26.610	1.1912	724.24
95	0.98306	1.0417	14.143	14.411	108.42	8.0682	3.6312	0.22063	27.333	1.1955	740.8
97	0.97731	1.0412	14.271	40.315	144.50	67.677	30.460	0.81432	12.032	2.6398	819.79
98	0.97060	1.0386	14.271	58.407	163.46	179.54	80.806	1.3897	7.7402	5.3745	1046.2
107	0.97864	1.0340	14.000	62.008	169.84	210.29	94.647	2.4806	11.796	6.1120	1106.1
108	0.97801	1.0362	14.000	60.247	166.72	193.59	87.130	2.2462	11.603	5.7180	1070.6
109	0.97844	1.0346	14.000	59.140	164.26	184.30	82.946	2.1242	11.526	5.5803	1064.5
110	0.97604	1.0351	14.000	53.327	156.83	137.28	61.784	1.5245	11.105	4.3016	951.63
111	0.97706	1.0343	14.000	49.162	153.27	109.96	49.489	1.2096	11.001	3.7034	897.96
112	0.97897	1.0345	14.000	46.850	150.86	97.059	43.953	1.0703	10.980	3.4075	880.93
113	0.528244E+24	1.0345	14.000	40.764	145.29	0.128308E-08	.577443E-08	144207E-03	11.240	0.488803E-03	794.24
114	0.97961	1.0346	14.000	38.915	143.80	66.151	29.773	0.79091	11.503	2.8081	810.51
115	0.98181	1.0352	14.000	32.847	136.90	43.654	19.647	0.51610	11.868	2.0427	740.07
116	0.98486	1.0360	14.000	19.809	120.93	14.454	6.5053	0.25668	17.343	1.3445	694.05
117	0.98534	1.0363	14.000	16.380	114.08	10.386	4.6386	0.21513	20.874	1.2476	711.05
118	0.98582	1.0356	14.000	13.875	105.62	7.3737	3.2187	0.18611	25.230	1.1804	731.58
119	0.97932	1.0349	14.000	38.879	144.35	66.016	29.712	0.75242	11.308	2.6070	788.34

Table B-15. Demonstrator Engine Steady State Performance Results (Continued).

(b) Supplementary Overall Performance Parameters.

Reading Number	δ_{25}, Ratio of Core Engine Inlet to Standard Pressure, dimensionless	θ_{25}, Ratio of Core Engine Inlet to Standard Pressure, dimensionless	$\frac{W_{25}\sqrt{\theta_{25}}}{\delta_{25}}$, High Pressure Rotor Inlet Corrected Airflow, kg/s	T_{41}, First Stage Turbine Rotor Inlet Temperature, K	T_{49}, High Pressure Turbine Exit Temperature, K	$\frac{W_2\sqrt{\theta_2}}{\delta_2}$, Total Engine Inlet Airflow, kg/s	P_3/P_2, Compression Ratio, dimensionless	T_{49}/T_{25}, Core Engine Temperature Ratio, dim.	α, Throttle Angle, degrees
5	1 0336	1 0072	17 241	924 24	736 41	-0 442348E+31	2 9478	2 3897	49 600
6	1 0465	1 0077	19 724	938 06	785 83	-0 442111E+31	3 4071	2 3617	56 934
7	1 0711	1 0032	23 681	969 51	780 09	-0 442383E+31	4 2469	2 3338	58 938
8	1 2740	1 1519	37 805	1081 1	764 92	-0 443198E+31	8 6491	2 3099	64 973
9	1 4251	1 1944	43 442	1203 4	841 13	-0 443864E+31	11 554	2 5625	67 745
12	1 0862	1 0693	14 573	976 17	818 91	-0 430036E+31	2 6065	2 6288	47 666
13	1 1798	1 1063	33 341	1026 5	742 77	-0 430089E+31	6 9218	2 3723	47 483
16	1 1000	1 0662	15 500	894 62	743 60	-0 400082E+31	2 7464	2 4185	47 531
18	1 5006	1 1714	41 211	1178 2	886.18	-0 410807E+31	10 981	2 5786	67 138
21	1 4365	1 1597	43 609	1184 1	819 00	-0 436136E+31	11 915	2 6049	68 779
22	1 4360	1 1589	43 666	1177 3	812.61	-0 438809E+31	11 923	2 5900	69 438
25	1 4382	1 1602	44 197	1185 2	813 31	-0 437487E+31	11 900	2 5282	69 940
26	2 1386	1 3256	58 806	1546 7	1073 5	-0 440806E+31	25 583	2 9418	87 472
30	2 1267	1 3348	57 975	1552 7	1082 3	-0 442447E+31	25 214	2 9204	87 662
31	2 2945	1 3665	60 086	1632 6	1143 7	-0 445498E+31	28 933	3.0218	94 583
32	2 1191	1 3371	58 149	1549 2	1085 8	-0 446174E+31	25 286	2 9238	89 708
33	2 1359	1 3404	58 349	1571 6	1098 8	-0 445381E+31	25 583	2 9643	91 011
35	2 2913	1 3685	60 035	1638 3	1156 0	-0 444890E+31	28 764	3 0316	94 171
36	2 3120	1 3718	60 107	1662 4	1163 8	-0 444738E+31	29 027	3 0621	94 771
37	1 0383	1 0729	17 343	870 82	729 70	-0 438381E+31	2 8862	2 2686	56 426
38	1 4278	1 1792	43 965	1191 1	843 29	-0 440763E+31	11 670	2 5556	71 085
39	2 1283	1 3324	58.297	1561 4	1092 8	-0 443198E+31	25 494	2 9438	87 894
40	2 3316	1 3571	60 090	1645 9	1161 2	-0 441894E+31	29 486	3 0774	94 315
43	1 0459	1 0808	19 945	930 90	738 71	-0 436798E+31	3 5126	2 4022	59 669
44	1 0701	1 0680	23.783	942 41	721 04	-0 437515E+31	4 2797	2 3410	61 514
45	1 2633	1 1228	37 943	1073 3	768 02	-0 438675E+31	8 5932	2 4254	67 195
46	1 6329	1 2232	49 641	1277 2	895 45	-0 440670E+31	15 614	2 6217	74 216
47	1 8817	1 2803	54 538	1421 6	997 28	-0 441757E+31	20 465	2 7840	78 891
48	2 1957	1 3435	58 684	1546 0	1121 4	-0 443829E+31	26 666	3 0036	90 236
49	1 0297	1 0697	16 808	904 04	756 76	-0 439455E+31	2 8589	2 3783	56 638
50	1 4183	1 1784	43 444	1197 3	848 70	-0 441648E+31	11 443	2 5674	70 457
51	2 1292	1 3422	58 174	1577 2	1112 4	-0 445210E+31	25 316	2 9596	88 782
52	2 3103	1 3770	59 851	1663 0	1177 0	-0 446082E+31	28 989	3 0861	95 701
80	2 2622	1 3085	59 218	1673 6	1174 8	648 46	28 288	3 0699	96 616
82	2 2961	1 3044	59 572	1698 2	1190 9	657 60	28 807	3 1012	96 736
83	2 1204	1 3638	57 885	1596 8	1117 5	608 11	25 319	2 9680	92 241
84	1 8824	1 2682	51 107	1349 1	950 6	464 48	16 741	2 6866	83 715
85	1 4431	1 2076	44 800	1195 8	835 48	372 30	12 236	2 5121	77 979
86	1 4280	1 2028	43 885	1224 9	863 63	351 73	11 697	2 5868	70 547
87	1 0443	1 0919	20 597	936 64	742 39	139 75	3 5400	2 3284	58 862
88	1 0282	1 0892	17 119	928 55	764 79	117 94	2 9211	2 3977	57 328
89	1 0284	1 0911	15 842	1007 6	784 19	117 00	2 8337	2 6424	56 386
90	2 1368	1 3643	77 912	1126 1	1130 5	606 90	25 233	1 6783	89 568
91	1 0286	1 0893	16 440	965 44	746 12	115 69	2 8272	2 4659	56 787
92	2 0771	1 3378	66 544	1296 6	1082 1	596 27	24 371	2 2114	85 550
93	1 0241	1 0756	16 296	974 85	751 14	116 64	2 8725	2 5766	57 252
95	1 0296	1 0714	16 421	1010 2	765 07	121 24	2 9722	2 6789	55 235
97	[illegible] 347	1 1824	42 706	1223 4	846 97	368 85	11 617	2 6732	67 254
98	2 0915	1 3310	66 936	1267 8	1078 6	601 77	24 463	2 1672	84 372
107	2 2008	1 3577	58.872	1620 8	1135 1	640 92	27 762	3 0382	91 802
108	2 1720	1 3424	57 957	1573 3	1100 8	623 80	26 000	2 9796	88 586
109	2 1225	1 3317	57 617	1546 7	1083 6	609 48	25 044	2 9433	87 563
110	1 8692	1 2807	54 049	1402 8	978 41	528 47	20 024	2 7639	82 683
111	1 7092	1 2440	50 899	1314 2	915 43	474 95	17 003	2 6719	80 754
112	1 6360	1 2251	49 454	1268 8	884 67	448 93	15 599	2 6181	79 350
113	0 702072E+24	1 1779	0 913113E-02	0 643808E+78	816 13	0 00000	0 00000	2 5335	76 544
114	1 4192	1 1719	43 330	1179 4	832 96	348 63	11 482	2 5645	69 757
115	1 2634	1 1265	37 942	1066 7	780 92	283 64	8 6187	2 4124	66 568
116	1 0806	1 0710	23 820	931 61	713 50	162 29	4 2689	2 3152	60 943
117	1 0444	1 0665	19 982	980 00	731 11	137 45	3 4802	2 3652	59 812
118	1 0299	1 0651	16 602	989 39	752 48	115 99	2 8598	2 4203	57 774
119	1 4221	1 1720	43 403	1186 3	810 34	349 67	11 719	2 5427	71 067

Table B-15. Demonstrator Engine Steady State Performance Results (Continued).

(c) Combustor Emissions Correlation Parameters.

Reading Number	P_3, Compressor Exit Pressure, MPa	T_3, Compressor Exit Temperature, K	W_{c36}, Combustor Airflow, kg/s	W_{ft}, Total Fuel Flow, kg/s	W_{fp}/W_{ft}, Pilot-to-Total Fuel Split, percent	f_{36}, Combustor Fuel-Air Ratio, g/kg	f_8, Core Engine Exit Fuel-Air Ratio, g/kg	$\Delta P_T/P_3$, Combustor Pressure Loss, percent	V_r, Combustor Reference Velocity, m/s
5	0.29493	462.52	13.075	0.19247	98.418	14.780	11.880	3.2831	18.337
6	0.34000	472.81	14.972	0.21568	98.207	14.300	11.631	3.5106	18.986
7	0.42465	504.06	18.334	0.25606	98.708	14.015	11.321	4.1280	19.800
8	0.86306	603.19	35.146	0.52082	99.523	14.822	11.972	3.9447	22.462
9	1.1512	654.06	44.246	0.78069	99.529	17.306	14.062	4.1337	22.977
12	0.26116	441.12	11.256	0.18986	98.416	16.841	13.604	3.1814	17.376
13	0.60829	567.60	28.837	0.40631	99.317	14.080	11.381	4.2649	21.614
16	0.28380	440.23	13.297	0.18671	98.341	14.041	11.342	3.1088	18.206
18	1.1706	640.76	45.657	0.76984	98.940	16.861	13.620	3.9542	22.844
21	1.1878	641.04	46.041	0.78518	76.001	17.054	13.776	4.3066	22.711
22	1.1808	642.36	46.334	0.77758	64.014	16.782	13.566	4.0705	22.804
25	1.1972	647.60	46.722	0.75978	53.114	16.262	13.136	4.3524	23.100
28	2.5292	811.74	84.904	2.1106	20.653	24.963	20.156	4.5100	24.901
30	2.5065	816.82	83.830	2.0972	22.853	25.018	20.200	4.5014	25.010
31	2.8504	847.81	93.000	2.5137	23.585	27.029	21.833	4.5746	25.284
32	2.4940	815.18	84.029	2.0890	17.675	24.872	20.091	4.1915	25.103
33	2.5225	818.57	84.146	2.1556	11.676	25.617	20.693	4.3029	24.969
35	2.8412	846.85	92.505	2.5266	18.115	27.313	22.063	4.6347	25.201
36	2.8674	849.32	93.079	2.5863	12.500	27.786	22.445	4.3718	25.199
37	0.28847	443.16	13.171	0.17350	97.730	13.173	10.641	3.6241	18.424
38	1.1619	647.84	44.964	0.76974	99.445	17.119	13.828	4.0872	22.916
39	2.5214	811.47	84.662	2.1253	17.879	25.103	20.278	4.3774	24.904
40	2.9103	843.39	94.556	2.6237	12.227	27.748	22.414	4.4354	25.046
43	0.35114	468.60	15.476	0.22001	98.496	14.217	11.484	3.5500	18.877
44	0.42764	496.89	18.679	0.25452	98.645	13.626	11.006	3.8760	19.838
45	0.85677	594.03	35.044	0.51928	99.402	14.818	11.969	3.8409	22.208
46	1.5513	701.75	57.548	1.0691	21.317	18.578	15.007	4.4475	23.794
47	2.0288	760.09	70.727	1.5544	18.261	21.977	17.752	4.9835	24.220
48	2.6370	825.21	86.962	2.3019	12.624	26.470	21.382	4.4230	24.874
49	0.28585	443.66	12.769	0.18335	97.376	14.359	11.599	3.4532	18.115
50	1.1395	648.75	43.794	0.76305	99.393	17.423	14.074	4.1541	22.790
51	2.5043	821.24	83.046	2.1579	18.476	25.984	20.990	4.3355	24.892
52	2.8637	853.41	92.130	2.6073	12.696	28.300	22.860	4.5078	25.095
80	2.7753	857.14	89.015	2.5458	19.195	28.599	23.102	4.4713	25.128
82	2.8333	861.37	90.060	2.6516	13.568	29.443	23.783	4.5641	25.026
83	2.4919	827.78	81.787	2.1746	17.551	26.589	21.478	4.5889	24.833
84	1.6561	730.36	58.896	1.1900	18.090	20.359	16.445	5.4876	23.730
85	1.2110	665.98	46.365	0.78336	42.590	16.899	13.650	4.5089	23.301
86	1.1582	658.92	43.986	0.79743	90.504	18.129	14.644	4.0141	22.872
87	0.35366	480.75	15.482	0.21901	98.407	14.146	11.427	3.6042	19.242
88	0.29114	453.22	13.833	0.19146	98.112	14.980	12.052	3.2732	18.259
89	0.28302	462.27	11.936	0.21188	0.176430E+27	17.753	14.340	3.2152	17.432
90	2.4006	829.27	88.797	0.94223	0.404315E+26	9.5370	7.7037	4.3610	30.001
91	0.28277	462.08	12.186	0.19522	0.1[illegible]E+27	16.016	12.938	3.6784	17.837
92	2.3006	806.89	87.785	1.4178	25.841	16.154	13.049	4.4968	27.076
93	0.28536	444.57	12.223	0.20573	88.671	16.880	13.619	3.4880	17.376
95	0.29630	[illegible]	12.447	0.22153	363.69	17.804	14.381	3.4586	17.380
97	1.1504	[illegible]	43.636	0.81242	0.602146E-04	18.616	15.030	3.9482	22.313
98	2.4057	[illegible]	89.402	1.3750	0.358128E-04	15.380	12.423	4.4730	27.144
107	2.7304	[illegible]	88.886	2.4404	12.619	27.545	22.250	4.4088	24.706
108	2.5615	813.56	84.685	2.2216	12.532	26.234	21.191	4.4599	24.584
109	2.4676	803.75	82.329	2.1011	16.778	25.521	20.615	4.4613	24.511
110	1.9790	750.59	69.545	1.5137	16.911	21.766	17.582	4.5210	24.090
111	1.6848	714.64	61.199	1.2021	17.401	19.659	15.880	4.6003	23.726
112	1.5474	696.82	57.340	1.0657	20.574	18.586	15.014	4.4654	23.602
113	0.00000	648.83	-0.68333	0.77627	45.863	-1136.0	-917.64	0.578960E+77	-0.578960E+77
114	1.1386	638.59	44.028	0.75813	99.79	17.219	13.909	4.0839	22.950
115	0.85741	590.23	34.862	0.51758	99.314	14.847	11.993	4.2427	21.936
116	0.40590	494.94	18.632	0.25118	98.557	13.481	10.890	3.8453	19.787
117	0.34746	467.55	16.307	0.21570	98.324	14.001	11.323	3.6221	18.827
118	0.28586	440.46	12.688	0.18672	98.051	14.716	11.887	3.3795	17.882
119	1.1628	642.87	45.061	0.74964	46.925	16.636	13.438	4.3794	22.770

Table B-15. 'emonstrator Engine Steady State Performance Results (Continued).

(d) Combustor Heat Transfer Parameters

Reading Number	P_3, Compressor Exit Pressure, MPa	T_3, Compressor Exit Temperature, K	f_{36}, Combustor Fuel-Air Ratio, g/kg	W_{fp}/W_{ft}, Pilot-to-Total Fuel Split, percent	ΔT_m OL, Peak Outer Liner Temperature Rise, K	ΔT_m CB, Peak Centerbody Temperature Rise, K	ΔT_m IL, Peak Inner Liner Temperature Rise, K	f_p, Pilot Stage Fuel-Air Ratio, g/kg	f_m, Main Stage Fuel-Air Ratio, g/kg
5	0 29497	452 52	14 720	98 418	181 74	33 991	100 08	14 487	0 23294
6	0 34080	472 81	14 399	98 297	170 32	34 194	124 43	14 154	0 24522
7	0 42465	504 02	14 015	98 708	171 53	32 729	115 56	13 834	0 18101
8	0 86306	603 19	14 822	99 523	180 59	36 587	92 603	14 751	0 070721
9	1 1512	654 05	17 396	99 529	202 85	57 322	113 08	17 314	0 081940
12	0 26116	441 12	16 841	98 416	205 61	36 440	138 79	16 574	0 26682
13	0 69229	567 59	14 090	99 317	176 32	33 262	91 892	13 994	0 096298
16	0 29390	440 23	14 041	98 341	179 00	34 959	108 24	13 808	0 23396
18	1 1705	640 76	16 861	98 940	198 86	56 493	100 65	16 683	0 17870
21	1 1978	641 04	17 054	76 091	163 88	77 067	106 47	12 977	4 0775
22	1 1813	642 36	16 782	64 014	149 44	87 949	109 20	10 743	6 0391
25	1 1972	647 60	16 262	53 114	136 07	97 807	120 82	8 6372	7 6243
26	2 5298	811 74	24 953	20 653	150 86	286 15	248 13	5 1534	19 799
30	2 5805	816 82	25 018	22 853	154 49	278 72	250 85	5 7174	19 300
31	2 8504	847 81	27 029	23 585	173 16	316 77	269 58	6 3748	20 654
32	2 4940	815 18	24 872	17 675	146 93	290 94	242 30	4 3960	20 476
33	2 5225	818 57	25 617	11 676	133 44	314 60	247 28	2 9911	22 626
35	2 8412	846 85	27 313	18 115	162 00	331 15	260 02	4 9477	22 336
36	2 8674	849 32	27 786	12 500	145 54	351 24	267 65	3 4732	24 313
37	0 28847	443 16	13 173	97 739	159 28	34 781	105 90	12 876	0 29780
38	1 1619	647 84	17 119	99 445	200 27	54 908	104 82	17 024	0 095047
39	2 5214	811 47	25 103	17 879	144 71	292 70	237 45	4 4881	20 615
40	2 9103	843 39	27 748	12 227	143 13	346 89	264 04	3 3926	24 355
43	0 35114	468 60	14 217	98 496	170 09	32 069	114 27	14 003	0 21375
44	0 42464	496 59	13 626	98 645	171 56	31 495	110 21	13 441	0 18460
45	0 85677	594 03	14 818	99 408	176 96	33 728	87 407	14 730	0 087711
46	1 5513	701 75	18 578	21 317	89 279	150 53	163 79	3 9602	14 618
47	2 0288	760 09	21 977	18 261	117 14	215 58	204 87	4 0133	17 964
48	2 6370	825 21	26 470	12 624	136 02	319 96	243 58	3 3414	23 128
49	0 28585	443 66	14 359	97 976	176 13	34 036	116 19	14 068	0 29060
50	1 1396	648 75	17 423	99 393	197 20	51 752	101 39	17 318	0 10571
51	2 5043	821 24	25 984	18 476	149 01	290 85	235 93	4 8010	21 183
52	2 8637	853 41	28 300	12 696	146 29	348 03	259 76	3 5931	24 707
80	2 7753	857 14	28 599	19 195	168 23	329 56	252 69	5 4897	23 110
82	2 8333	861 37	29 443	3 568	153 66	349 61	259 00	3 9948	25 448
83	2 4919	827 72	26 589	17 551	151 69	296 15	228 95	4 6665	21 922
84	1 6561	730 35	20 369	18 098	97 628	177 42	166 23	3 6830	16 676
85	1 2110	665 98	16 899	42 580	122 58	118 37	128 93	7 1955	9 7033
86	1 1582	658 92	18 129	99 564	202 15	53 605	103 58	18 040	0 089943
87	0 35356	480 75	14 146	98 407	175 64	34 484	107 74	13 921	0 22540
88	0 29114	453 22	14 920	98 112	178 29	34 280	96 575	14 638	0 28164
89	0.28302	452 27	17 753	0 176430E+27	183 60	34 131	96 074	0.313230F+06	-0 313230E+06
90	2 4886	829 27	9 5370	0 404315E+26	156 06	296 61	230 79	0 385574E+06	-0 385594E+06
91	0 28237	452 08	16 016	0 188627E+27	167 51	37 076	95 213	0 301940E+06	-0 301946E+06
92	2 3806	806 89	16 154	25 841	140 36	276 63	217 36	4 1744	11 980
93	0 28536	444 59	16 860	88 671	174 45	34 435	102 06	14 950	1 9101
95	0 29530	451 24	17 804	363 69	182 78	32 864	97 030	64 751	-46 947
97	1 1504	643 58	18 618	0 602146E-04	195 56	49 935	95 592	0 112106E-04	18 618
98	2 4067	799 13	15 380	0 358128E-04	138 72	269 13	214 90	0 550788E-05	15 380
107	2 7304	830 31	27 545	12 619	136 94	326 34	241 12	3 4760	24 069
108	2 5615	813 56	26 234	12 532	130 73	305 40	231 24	3 2875	22 946
109	2 4676	803 75	25 521	16 778	137 74	278 50	217 37	4 2819	21 239
110	1 9790	750 59	21 766	16 911	108 77	211 73	184 42	3 6809	18 085
111	1 6848	714 64	19 659	17 401	92 122	175 86	159 39	3 4210	16 238
112	1 5474	696 82	18 586	20 574	89 954	156 27	149 82	3 8240	14 762
113	0 00000	648 83	-1136 0	45 663	125 75	106 70	119 28	-518 73	-617 28
114	1 1306	638 59	17 219	99 439	195 68	47 564	92 662	17 122	0 096626
115	0 85741	590 23	14 847	99 314	177 25	34 025	83 429	14 745	0 10178
116	0 42599	494 94	13 481	98 557	174 53	32 249	97 989	13 287	0 19454
117	0 34746	467 56	14 091	98 324	170 99	33 108	93 880	13 856	0 23615
118	0 28566	440 46	14 716	98 051	172 12	34 120	95 262	14 479	0 28687
119	1 1628	642 87	16 636	46 925	126 43	103 82	115 46	7 8066	8 8296

Table B-15. Demonstrator Engine Steady State Performance Results (Concluded).

(e) Combustor Fuel Nozzle Parameters.

Reading Number	W_{ft}, Total Fuel Flow, kg/s	W_{fv}, Verification Fuel Flow, kg/s	W_{fp}, Pilot Stage Fuel Flow, kg/s	W_{fm}, Main Stage Fuel Flow, kg/s	T_{fp}, Pilot Stage Fuel Temperature, K	T_{fm}, Main Stage Fuel Temperature, K	γ_{man}, Fuel Specific Gravity at Manifolds, dim.	ΔP_{fp}, Pilot Stage Fuel Nozzle Pressure Drop, MPa	ΔP_{fm}, Main Stage Fuel Nozzle Pressure Drop, MPa
5	0 19247	0 19080	0 18942	0 782147E-04	348 22	310 36	0 79274	0 536258E+23	0 536258E+23
6	0 21568	0 21543	0 21191	0 827678E-04	363 85	315 80	0 79198	0 536258E+23	0 536258E+23
7	0 25696	0 25682	0 25363	0 827706E-04	354 42	315 76	0 79169	0.536258E+23	0 536258E+23
8	0 52092	0 52009	0 51844	0 840558E-04	345 88	312 08	0 79113	0 536258E+23	0 536258E+23
9	0 76569	0 76949	0 76686	0 882975E-04	343 17	308 94	0 79050	0 536258E+23	0 536258E+23
12	0.18966	0 18973	0 18654	0 767618E-04	350 04	310 49	0 79306	1 1205	1 1315
13	0 40631	0 40610	0 40353	0 807707E-04	345 42	309 88	0 79158	1 2544	1 3428
16	0 18671	0 18687	0 18361	0 897749E-04	348 01	308 95	0 80049	1 1049	1 1128
18	0 76984	0 76971	0 76168	0 863278E-02	335 16	326 42	0 80146	1 4890	1 6481
21	0 78618	0 78528	0 59745	0 18445	333 44	334 71	0 80398	1 3691	1 9117
22	0 77758	0 77772	0 49776	0 27548	334 29	335 80	0 80434	1 2998	1 9720
25	0 75978	0 75979	0 40365	0 35068	334 52	336 13	0 79496	1 2470	2 0194
26	2 1186	2 1211	0 43755	1 6957	327 09	328 15	0 79416	1 2544	3 2370
30	2 0972	2 1011	0 47929	1 5922	333 70	335 05	0 78835	1 2822	3 1624
31	2 5137	2 5167	0 59285	1 8502	335 95	336 95	0 78581	1 3536	3 5212
32	2 0899	2 0936	0 36939	1 6832	336 75	337 13	0 78755	1 2307	3 3192
33	2 1556	2 1589	0 25168	1 8364	333 90	335 84	0 78719	1 1692	3 5568
35	2 5266	2 5294	0 45769	1 9674	332 14	333 08	0 78929	1 2754	3 7096
36	2 5863	2 5889	0 32328	2 1162	331 25	332 48	0 79004	1 2064	3 9836
37	0 17350	0 17351	0 16958	0 747330E-04	361 21	324 74	0 79094	1 0661	0 59566
38	0 76974	0 77087	0 76547	0 836751E-04	338 25	310 63	0 79125	1 5172	1 4534
39	2 1253	2 1284	0 37997	1 7102	330 06	331 38	0 79183	1 2252	3 3175
40	2 6237	2 6262	0 32079	2 1499	327 37	328 70	0 79289	1 1975	4 0261
43	0 22001	0 22019	0 21671	0 826776E-04	340 04	300 13	0 79615	1 1513	1 6861
44	0 25452	0 25460	0 25107	0 830236E-04	347 15	308 45	0 79660	1 1728	1 7277
45	0 51928	0 51911	0 51620	0 847773E-04	337 33	303 95	0 79699	1 3221	1 4575
46	1 0691	1 0689	0 22790	0 83211	331 18	333 53	0 79706	1 1453	2 4117
47	1 5544	1 5540	0 28385	1 2549	328 97	330 70	0 79653	1 1795	2 8086
48	2 3019	2 3015	0 29058	1 9333	327 18	328 61	0 79591	1 1842	3 6407
49	0 18335	0 18366	0 17964	0 762689E-04	352 56	319 23	0 79411	1 1163	0 073119
50	0 76305	0 76302	0 75842	0 878727E-04	337 56	300 92	0 79380	1 5121	-0 067862
51	2 1579	2 1573	0 39870	1 7189	332 28	333 51	0 79140	1 2388	3 3468
52	2 6073	2 6046	0 33103	2 1292	334 37	335 71	0 78894	1 2072	3 9922
80	2 5458	2 5386	0 48867	1 9577	339 26	340 11	0 79623	1 2890	3 6920
82	2 6E16	2 6432	0 35977	2 1022	337 83	338 89	0 79637	1 2213	4 0140
83	2 1746	2 1695	0 38166	1 7424	337 53	338 63	0 79811	1 2340	3 4087
84	1 1900	1 1964	0 21691	0 97241	342 24	344 67	0 79911	1 1656	2 5968
85	0 78336	0 78239	0.33356	0 44397	345 33	347 15	0 79970	1 2110	2 1261
86	0 79743	0 79636	0 79347	0 837625E-04	342 76	311 77	0 80015	1 5444	-0.80240
87	0 21901	0 21911	0 21552	0 151188E+17	357 81	-0 193968E+24	0 80036	1 1536	0 087388
88	0 19146	0 19142	0 18784	0 812629E-04	357 77	318 17	0 80022	1 1209	-0 16107
89	0 21188	0 380000E+24	0 373830E+24	0 850561E-04	354 04	318 58	0 79010	1 1230	-0 16811
90	[illegible]	[illegible]	[illegible]	1 [illegible]	[illegible]	[illegible]	0 [illegible]	1 [illegible]	[illegible]
91	0 19622	0 380086E+24	0 368040E+24	0 741742E-04	369 83	331 67	0 79618	1 0900	1 0899
92	1 4178	1 0282	0 36637	1 0622	330 72	331 68	0 80169	1 2213	3 2456
93	0 20673	0 093188	0 18243	0 760717E-04	355 76	318 68	0 80191	1 1712	1 1464
95	0 22153	0 20257	0.00667	0 874308E-04	336 26	300 70	0 80007	1 1430	1 1537
97	0 81242	0 78449	0 489194E-06	0 884817E-02	335 08	330 31	0 80.21	1 5245	1 7031
98	1 3750	2 0320	0 492415E-06	1 6386	328 26	329 11	0 80277	1 2114	3 2270
107	2 4484	2 4437	0 30897	2 0188	326 40	327 40	0 80502	1 1899	-2 6102
108	2 2216	2 2176	0.27840	1 8534	327 03	328 29	0 80509	1 1757	-2 4473
109	2 1011	2 0073	0 35253	1 6981	325 75	327 62	0 80503	1 2140	-2 2086
110	1 5137	1 5106	0 25699	1 2436	329 78	331 54	0 80475	1 1695	-1 7954
111	1 2031	1 2008	0 20036	0 98352	331 70	334 08	0 80396	1 1367	-1 5083
112	1 0657	1 0643	0 21927	0 83923	333 42	336 93	0 80342	1 1432	-1 3821
113	0 77627	0 77520	0 35446	0 41564	338 29	340 01	0 80289	2 3784	0 080115
114	0 75813	0 75717	0 75387	0 814062E-04	337 29	313 87	0 80274	1 5202	-1 0061
115	0 51758	0 51628	0 51404	0 831416E-04	342 24	304 42	0 80276	1 3338	-0 73677
116	0 25118	0 25067	0 24756	0 800415E-04	350 03	305 44	0 80281	1 1802	-0 32457
117	0 21570	0 21564	0 21208	0 797619E-04	350 84	309 16	0 80290	1 1562	-0 24787
118	0 18672	0 18643	0 18308	0 776110E-04	350 17	311 13	0 80209	1 1196	-0 18876
119	0 74964	0 74829	0 35177	0 39208	336 72	338 43	0 80308	1 2214	-1 0773

Table B-16. Demonstrator Engine Throttle Burst Test Results.

Bursts from Flight Idle to Takeoff Power									
DMJ Reading Number at Flight Idle	DMJ Reading Number at Takeoff	θ_2, Engine Inlet-to-Standard Temperature Ratio at Flight Idle	θ_2, Engine Inlet-to-Standard Temperature Ratio at Takeoff	δ_2, Engine Inlet-to-Standard Pressure Ratio at Flight Idle	δ_2, Engine Inlet-to-Standard Pressure Ratio at Takeoff	W_{fp}/W_{ft}, Fuel Splitter Setting at Approach	W_{fp}/W_{ft}, Fuel Splitter Setting at Takeoff	Time to Reach 95% Rated Thrust, seconds	
---	123	---	1.0537	---	0.9739	1.000	0.234	4.3	
---	126	---	1.0543	---	0.9706	1.000	0.180	3.7	
---	128	---	1.0559	---	0.9707	1.000	0.126	4.1	
129	130	1.0554	1.0557	0.9836	0.9707	0.741	0.244	4.0	
131	132	1.0553	1.0560	0.9836	0.9709	0.733	0.185	4.2	
133	134	1.0561	1.0564	0.9835	0.9703	0.733	0.127	4.4	
136	137	1.0571	1.0565	0.9844	0.9707	0.384	0.209	4.7	
138	139	1.0573	1.0571	0.9835	0.9709	0.331	0.188	5.4	
140	141	1.0572	1.0571	0.9836	0.9706	0.322	0.127	4.3	

Bursts from Approach to Takeoff Power								
Engine Log Reading at Approach	Engine Log Reading at Takeoff	θ_2 at Approach	θ_2 at Takeoff	δ_2 at Approach	δ_2 at Takeoff	W_{fp}/W_{ft}, Fuel Splitter Setting at Approach	W_{fp}/W_{ft}, Fuel Splitter Setting at Takeoff	Time to Reach 95% Rated Thrust, seconds
---	113	---	1.053	---	0.9759	1.000	0.238	3.3
---	118	---	1.054	---	0.9737	1.000	0.188	3.8
121	122	1.053	1.053	0.9818	0.9737	1.000	0.130	4.0
123	124	1.052	1.052	0.9820	0.9741	0.768	0.246	3.8
[illegible]	[illegible]	[illegible]	[illegible]	0.9822	[illegible]	0.774	0.189	3.8
129	130	1.052	1.052	0.9823	0.9737	0.782	0.131	4.2
131	132	1.052	1.052	0.9821	0.9731	0.621	0.214	3.3
133	134	1.05[illegible]	1.050	0.9817	0.9742	0.420	0.192	3.6
135	136	1.051	1.050	0.9821	0.9740	0.459	0.132	3.2

Table B-17. Demonstrator Engine Start/Stall Test Results.

Test Intent	Engine Log Reading Number	Compressor Stator Angle, degrees open from normal	Main Engine Control Fuel Specific Gravity Setting	Engine Starter Air Pressure kPa (absolute)	θ_2, Engine Inlet-to-Standard Temperature Ratio	σ_2 Engine Inlet-to-Standard Pressure Ratio	Time to Reach Idle Speed, seconds	$T_{4.9}$ max - Highest Turbine Outlet Temperature Recorded During Start Sequence, K
Normal Start Mapping	140	0.6	0.82	379	1.045	0.9847	41.7	951
	141	0.6	0.82	379	1.046	0.9847	41.5	966
	142	0.7	0.82	310	1.046	0.9843	51.8	958
	143	0.6	0.82	310	1.047	0.9849	47.8	976
	144	0.6	0.82	276	1.048	0.9847	55.4	988
	145	0.6	0.82	241	1.048	0.9848	61.4	989
	146	1.0	0.82	241	1.050	0.9841	60.2	1026
	147	0.7	0.82	276	1.050	0.9841	50.1	999
	148	1.2	0.82	276	1.053	0.9843	50.8	1000
	149	0.7	0.82	276	1.052	0.9842	52.5	999
	150	0.8	0.70	379	1.056	0.9841	41.6	1001
	151	0.7	0.70	310	1.055	0.9840	45.8	1024
	152	0.7	0.70	241	1.053	0.9848	Aborted, $T_{4.9}$ Limit Exceeded	
Sub-Idle Stall Mapping(1)	153	-1.1	0.70	379	1.058	0.9842	39.2	
	154	-3.5	0.70	379	1.058	0.9842	37.4	
	155	4.5	0.70	379	1.058	0.9841	30.4	
	156	4.1	0.837	379	1.056	0.9839	29.4	
	157	5.6	0.837	379	1.057	0.9840	29.4	
	159	0	0.837	379	1.059	0.9842	32.6	
	160	-4.0	0.837	379	1.057	0.9841	35.1	
	161	-5.8	0.837	379	1.056	0.9842	35.4	
	---	-5.8	Max	379	1.057	0.9843	45.2	
	162	0	Max	379	1.057	0.9843	[illegible].5	
	---	0	Max	379	1.056	0.9841	38.7	
	163	6.0	Max	379	1.056	0.9840	33.8	

(1) No Stalls/Temperature Limits Encountered

APPENDIX C

NOMENCLATURE

Symbol		Units
A_e	Combustor effective flow area (Geometric area x flow coefficient)	cm^2
A_r	Combustor reference area	cm^2
CO	Carbon monoxide pollutant emission	
CO_2	Carbon dioxide emission	
EI	Emission index	g/kg fuel
EPAP	Environmental Protection Agency emission parameter	
	Current procedure:	lb emission/1000 thrust-hrs
	Proposed procedure:	g emission/kN thrust
f_t, f_{36}	Total combustor metered fuel-air ratio	g/kg
f_m	Main-stage metered fuel-air ratio	g/kg
f_p	Pilot-stage metered fuel-air ratio	g/kg
f_8	Engine exit metered fuel-air ratio	g/kg
f_s	Fuel-air ratio calculated from gas sample	g/kg
H	Engine/combustor inlet air humidity	g/kg
HC	Total unburned hydrocarbon pollutant emission	
NO	Nitric oxide pollutant emission	
NO_x	Total oxides of nitrogen pollutant emission	
N_1	Low pressure (fan) rotor speed	rps
N_2	High pressure (core engine) rotor speed	rps
P_2	Engine inlet total pressure	MPa
P_{25}	High pressure rotor inlet total temperature	MPa

NOMENCLATURE (Concluded)

Symbol		Units
P_3, P_{T3}	Compressor discharge (combustor inlet) pressure	MPa
T_2	Engine inlet total temperature	K
T_{25}	High pressure rotor inlet total temperature	K
T_3	Compressor discharge (combustor inlet) temperature	K
T_{49}	High pressure turbine exit temperature	K
T_f	Fuel temperature	K
W_f	Fuel flow rate	kg/s
W_{ft}	Total fuel flow rate	kg/s
W_{fp}	Pilot-stage fuel flow rate	kg/s
W_{fm}	Main-stage fuel flow rate	kg/s
W_2	Engine inlet total airflow rate	kg/s
W_3	Compressor discharge total airflow rate	kg/s
W_{36}, W_c	Combustor airflow rate	kg/s
W_8	Core engine exit gas flow rate	kg/s
ΔP_f	Fuel manifold pressure drop	MPa
ΔP_t	Combustor total pressure drop	MPa
α	Throttle angle	degrees
β	Stator angle	degrees
δ	Ambient-to-standard pressure ratio (=P/0.191325)	
θ	Ambient-to-standard temperature ratio (=T/288.3)	

APPENDIX D

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