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EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

Phase I Final Report

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

The primary objective of this program was to identify, define and develop technology for the design of low emissions combustors for use in advanced CTOL commercial engines. Full annular versions of our advanced combustor designs, sized to fit within the CF6-50 engine, were defined, manufactured, and tested at high pressure conditions. Thirty-four configurations, in all, were screened, and significant reduct.ons in CO, HC and NO_x emissions levels were achieved with two of these advanced combustor design concepts. Emissions and performance data at a typical AST cruise condition were also obtained as part of an addendum to the basic program. In addition, combustor noise data were also obtained as a part of another addendum to the basic program.

The two promising combustor design approaches evolved in these efforts were the Double Annular Combustor and the Radial/Axial Staged Combustor. With versions of these two basic combustor designs, CO and HC emissions levels at or near the target levels were obtained. Although the low target NO_x emissions level was not obtained with these two advanced combustor designs, significant reductions were obtained relative to the NO_x levels of current technology combustors. In addition, smoke emission levels below the target value were obtained.

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FOREWORD

The program described herein was conducted by the General Electric Aircraft Engine Group under NASA Contract NAS3-16830. The data in this report were compiled in July 1974 and published in June 1975. The work was done under the direction of the NASA Project Manager, Mr. Richard W. Niedzwiecki, Aerospace Engineer, Airbreathing Engines Division, NASA-Lewis Research Center. The report has also been issued as General Electric Document TIS 74AEG380.

Execution of this major program required a significant team effort. The key contributors to this effort were:

AE Schexnayder - Program Management

DW Rogers - Program Element I Investigations and Emissions Data Acquisition Techniques

CC Mandeville - Program Element II Investigations

JA Jasper - Combustor Testing

GL Converse - AST Investigations

JJ Emmerling - Noise Investigations

JR Taylor - Conceptual Combustor Design Studies

HM Maclin and JS Kelm - Mechanical Designs and Hardware Procurement

Important contributions were also made by:

WT Martin and EJ Rogala, Combustor Testing; CM Stanforth and RC Williamson, Emissions Analysis Equipment; SB Kazin, Noise Investigations; VM Cecil, Data Calculations and Graphics; and EV Zettle, Final Data Analysis and Reporting.

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CC Gleason, Principal Investigator
DW Bahr, Technical Program Manager

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NOMENCLATURE

Symbol	Quantity	Unit
A_E	Effective area	cm^2
B	Fuel nozzle spacing	cm
EI_x	Emission Index of constituent x (x = CO, HC or NO_x)	g of x/kg fuel
f	Fuel-air ratio, fuel flow rate/airflow rate	-
f_m	Metered fuel-air ratio	-
f_s	Sample fuel-air ratio	-
$f_{3.9}$	Fuel-air ratio at the combustor exit plane	-
H	Inlet air humidity	g water/kg air
H_D	Dome height	cm
L_B	Burner length	cm
L_C	Combustor length	cm
L_{Dil}	Distance from dome to first dilution station	cm
n	Fuel hydrogen-to-carbon atom ratio	-
P_{S_3}	Static pressure at the combustor inlet	atm
P_3, P_{T_3}	Total pressure at the combustor inlet	atm
$P_{3.9}$	Total pressure at the combustor exit	atm
ΔP_T	Total combustor pressure drop	atm
T_{S_3}	Static temperature at the combustor inlet	°K
T_3, T_{T_3}	Total temperature at the combustor inlet	°K
$T_{3.9}$	Total temperature at the combustor exit	°K
ΔT_{local}	Local combustor temperature rise	°K
ΔT_{avg}	Average combustor temperature rise	°K

NOMENCLATURE (concluded)

Symbol	Quantity	Unit
t_{res}	Residence time	sec
V_R	Reference velocity	m/s
W_C	Combustor airflow rate	kg/s
W_3	Compressor exit airflow rate	kg/s
W_{a_1}	Pilot stage airflow rate	kg/s
W_{a_2}	Main stage airflow rate	kg/s
W_{f_1}	Pilot stage fuel flow rate	kg/hr
W_{f_2}	Main stage fuel flow rate	kg/hr
W_{f_T}	Total fuel flow rate	kg/hr
x	abscissa	-
y	ordinate	-
η_o	Overall combustion efficiency	-
η_1	Pilot stage combustion efficiency	-
η_2	Main stage combustion efficiency	-
ρ	Density	g/cm^3

SUMMARY

The primary objective of this Phase I Program was to identify, define and develop technology for the design of advanced combustors, with significantly lower pollutant exhaust emissions levels than those of current technology combustors, for use in advanced CTOL commercial aircraft engines. The efforts in this 18-month program were specifically directed toward screening and evaluating a large number and variety of combustor design approaches for obtaining low carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x) and smoke emissions levels.

The key task elements of these efforts involved the definition of advanced combustor design approaches for obtaining the objective low pollutant emissions levels, the aeromechanical design of CF6-50 engine-size versions of these approaches, the fabrication of full annular versions of these combustor designs and the developmental evaluation of the combustor test configurations. These test configurations were designed to fit within the combustor housing of the current production version of the General Electric CF6-50 engine and were evaluated, at elevated pressures, in a test rig which exactly duplicates the combustor housing of the CF6-50 engine In addition to detailed emissions level data, detailed data on the other important performance characteristics of each test configuration were also obtained. Also, data were obtained on the noise characteristics of several of the combustor test configurations.

Versions of four basic advanced combustor design concepts, involving a total of 34 test configurations, were evaluated in these development efforts. Specifically, CF6-50 engine-size versions of NASA Swirl-Can-Modular Combustors, Lean Dome Single Annular Combustors, Lean Dome Double Annular Combustors and Radial/Axial Staged Combustors were evaluated. Encouraging results were obtained with versions of the latter two design concepts. Both of these concepts feature the use of two discrete zones within the combustor, with which the combustion process may be appropriately staged, to minimize CO and HC emissions levels at low engine power operating conditions as well as NO_x and smoke emissions levels at high engine power operating conditions. With versions of these two designs, CO and HC emissions levels at or near the target levels were obtained. Significant reductions in NO_x emissions levels were also obtained with these two advanced combustor design concepts, although the low target level was not attained. In addition, smoke emission levels below the target value were obtained. In addition, the other important performance characteristics of these advanced combustor designs were found to be generally satisfactory, considering the early stage of their development.

Based on these results, it is concluded that significantly lower CO, HC and NO_x emissions levels than those of current technology combustors, along with low smoke emission levels, are obtainable with staged combustor design concepts, such as the two concepts evolved in this program. It is further concluded that acceptable ground ignition and altitude relight performance can be expected with versions of these two staged combustor designs. However, it is anticipated that obtaining acceptable exit temperature characteristics, combustion stability characteristics and combustion efficiencies with these

advanced designs at all engine operating conditions, particularly at the intermediate power operating conditions, will necessitate substantial additional development efforts. Extensive further development efforts appear to be especially needed to define the preferred means of staging the combustion process within these complex and sophisticated combustors and to define the additional engine fuel control and supply systems capabilities needed to operate such combustors. Thus, it is concluded that significant additional development efforts will be required to provide versions of these staged combustor designs suitable for use in engines.

INTRODUCTION

Within recent years, the number of turbine engine-powered aircraft in both commercial and military service has increased at an extremely rapid rate. This rapidly increasing usage of turbine engine-powered aircraft has logically resulted in increased interest in assessing the contributions of aircraft turbine engines to the air pollution problems confronting many metropolitan areas throughout the world. Therefore, several studies to define the extent of these contributions have already been conducted and others are in progress. In general, the studies conducted to date have shown that the overall contributions of aircraft turbine engine operations to the air pollution problems of metropolitan areas are quite small, as compared to those of other contributors (Reference 1). These studies have also shown that the exhausts of aircraft turbine engines generally contain low concentrations of gaseous and particulate emissions considered to be in the category of air pollutants. The typically low concentrations of pollutant emissions are due to the continuous, well controlled and highly efficient nature of the combustion processes in turbine engines and to the use of fuels which contain very small quantities of impurities.

Nonetheless, even though relatively low concentrations and total amounts are generated in most instances, the exhaust emissions in the category of air pollutants resulting from the operations of aircraft turbine engines are of concern. The specific aircraft turbine engine exhaust emissions which are of possible concern from an air pollution standpoint consist of carbon monoxide (CO), unburned or partially oxidized hydrocarbons (HC), carbon smoke particulate matter and oxides of nitrogen (NO_x). The foremost concern associated with these engine exhaust emissions appears to be their possible impacts on the immediate areas surrounding major metropolitan airports. Because of the operating characteristics of most current turbojet and turbofan engines, the highest levels of these various objectionable exhaust constituents are typically generated at engine operating modes that occur in and around airports. Further, because large numbers of daily aircraft operations can occur in and around a given airport, the cumulative exhaust emissions resulting from these localized aircraft operations tend to be concentrated to some extent in the airport vicinity.

For these reasons, the U.S. Environmental Protection Agency (EPA) concluded that standards to regulate and minimize the quantities of CO, HC, NO_x and smoke emissions discharged by aircraft, when operating within or near airports, are needed. Based on this finding, such standards were defined for several different categories and types of fixed-wing, commercial aircraft engines and were issued in July 1973. For the most part, these standards become effective in 1979 (Reference 2).

The introduction of aircraft engine exhausts into the stratosphere is another possible area of concern. Because of the relatively slow mixing rates between the stratosphere and the troposphere, and the resulting tendencies for materials introduced into the stratosphere to accumulate, it is believed that the continuous introduction of some engine exhaust products into the stratosphere by large aircraft fleets might, after extended time periods, result in adverse environmental impacts. The introduction by aircraft engines of NO_x emissions into the stratosphere has, for example, been identified as a particular area of possible concern. The possible impacts of the introduction of these and other engine exhaust products into the stratosphere have been the subject of the Climatic Impact Assessment Program, which has been conducted by the U.S. Department of Transportation (Reference 3). The preliminary findings of this very extensive program indicate that very low NO_x emissions levels at high altitude cruise operating conditions may become an important need in future transport aircraft engines (Reference 4).

To minimize these possible adverse environmental effects, significant development efforts to provide technology for the control and reduction of the levels of the pollutant exhaust emissions of aircraft turbine engines have already been conducted by both government and industry organizations and major additional development efforts of this kind are currently underway. Significant advances have already been made in the development of technology for the design of engines with greatly reduced smoke emission levels. As a result of these latter efforts, advanced transport aircraft engines, such as the General Electric CF6 engines, with virtually invisible smoke emission levels, have already been developed and placed into service. These latter engines are, thus, already in compliance with the smoke emission standards which have been issued by the EPA.

At the present time, therefore, the primary pollutant exhaust emissions reduction technology needs of nonafterburning engines appear to involve the reduction of CO and HC emissions levels at idle operating conditions and the reduction of NO_x emissions levels during takeoff, climbout and, possibly, cruise operations. In any nonafterburning engine, the source of these emissions is, of course, its combustor. The attainment of these more favorable exhaust emissions characteristics in future engines, thus, primarily involves providing improved and modified main combustors for use in these engines. Major combustor design technology advances appear to be needed to obtain significant reductions in the levels of these gaseous pollutant emissions.

To provide these needed combustor design technology advances, the Experimental Clean Combustor Program was initiated by the U.S. National Aeronautics and Space Administration (NASA) in 1972 (Reference 5). The overall objective of this major program is to define, develop and demonstrate technology for the design of low pollutant emissions combustors for use in advanced commercial CTOL aircraft engines. The intent of these efforts is to generate combustor design technology which is primarily applicable to advanced commercial 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 focus of this major program is on reducing the CO, HC and NO_x emissions levels of these engines. The overall program is being conducted in three sequential phases:

Phase I: Combustor Screening

Phase II: Combustor Refinement and Optimization

Phase III: Combustor-Engine Testing

The NASA/General Electric Experimental Clean Combustor Program is one of the programs that comprise the overall program. This program is being carried out by the General Electric Aircraft Engine Group under contract to the NASA-Lewis Research Center. A description of the NASA/General Electric Phase I Program, together with the results of this initial program phase, are presented in this report. This Phase I Program was initiated in January 1973, and its design and development activities were completed in June 1974.

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CHAPTER I. DESCRIPTION OF EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

OVERALL PROGRAM DESCRIPTION

The Experimental Clean Combustor Program is a multiyear effort which is being conducted by the NASA-Lewis Research Center. The primary objectives of the overall program are:

- To generate and demonstrate the technology required to design and develop advanced commercial CTOL aircraft engines with significantly lower pollutant exhaust emissions levels than those of current technology engines.
- To demonstrate the attainment of the target emissions level reductions in tests of advanced commercial aircraft turbofan engines.

The intent of this major program is to obtain the objective pollutant emissions level reductions by the development of advanced combustor designs, rather than by the use of special engine operational techniques and/or water injection methods. The program is aimed at generating advanced combustor design 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 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 focus of the program is on reducing the levels of the gaseous pollutant emissions of these engines.

The NASA/General Electric Experimental Clean Combustor Program is one of the programs that comprise the overall program. This program is being conducted by the General Electric Aircraft Engine Group under contract to the NASA-Lewis Research Center. The design and development efforts of this NASA/General Electric program are specifically directed toward providing advanced combustors for use in the General Electric CF6-50 engine. This engine is an advanced, high bypass turbofan engine in the 218 kN (50,000 lb) rated thrust class. This engine is in commercial service in the McDonnel-Douglas DC-10 Series 30 aircraft and in the Airbus Industrie A300B aircraft. While the CF6-50 engine is the specific intended application of the advanced combustor technology development efforts of this program, this technology is also considered to be generally applicable to all advanced engines in the large thrust size category.

PROGRAM PLAN

The NASA/General Electric Experimental Clean Combustor Program is being conducted in three sequential, individually funded phases:

Phase I: Combustor Screening

Phase II: Combustor Refinement and Optimization

Phase III: Combustor-Engine Testing

Phase I Program

The Phase I Program, which has been completed, was an 18-month effort specifically directed toward screening and evaluating a large number and variety of combustor design approaches for obtaining low CO, HC, NO_x and smoke emissions levels. The objective of these efforts was to identify, define and develop promising combustor design approaches for obtaining the objective pollutant exhaust emissions level reductions. This program phase is the subject of this final report.

The key task elements of these Phase I Program efforts involved the identification and definition of various advanced combustor design approaches for obtaining the objective low pollutant emissions levels, the detailed aeromechanical design of several CF6-50 engine-size versions of these approaches, the fabrication of full annular versions of these various combustor designs and the developmental evaluation of these full annular combustor test configurations. All of these various full annular combustor test configurations were designed and sized to fit within the existing combustor housing of the production CF6-50 engine and to operate with the same combustor inlet diffuser as in the production engine. The various low emissions combustor test configurations were evaluated in a high pressure combustor test rig, which exactly duplicates the aerodynamic flowpath and envelope dimensions of the combustor housing of the CF6-50 engine. These evaluations were conducted with combustor operating conditions identical to those of the CF6-50 engine, except for combustor pressure level at some high engine power test conditions. Lower pressures were used at these high engine power test conditions because of air supply facility limits. However, the measured emissions data were adjusted to correct for the effects of the lower combustor pressure levels. In these evaluations, detailed measurements of the emission characteristics of these various combustor test configurations were obtained with an on-line, rapid data acquisition exhaust gas sampling and analysis system. Along with these emissions data, detailed data on the other important performance characteristics of each combustor test configuration were also obtained.

In the basic Phase I Program, primary attention was directed toward the development of low pollutant emissions combustor design technology for use in advanced subsonic transport aircraft engines. In conjunction with this major program effort, additional efforts were also carried out in two program addendums, 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 emissions 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 basic acoustic characteristics of these advanced low emissions combustors and, thereby, to enable comparisons of their noise characteristics with those of current technology combustors.

Descriptions of the basic Phase I Program, along with the results obtained in these investigations, are presented in Chapter III of this report. Descriptions of the efforts associated with the AST Addendum, together with the results of these investigations, are presented in Chapter IV of this report. The results obtained in the Combustion Noise Measurement Addendum will be presented in a separate report.

Phase II Program

The Phase II Program, which is currently underway, is a 15-month effort to develop further the most promising advanced combustor designs evolved in the Phase I Program. The development efforts of this phase involve both full annular and sector combustor component tests. Also included as a part of the Phase II Program efforts is the detailed aeromechanical design of versions of these advanced combustors for possible use in demonstrator CF6-50 engine tests. The primary objective of these design and development efforts is to define and provide at least one advanced combustor design which meets the performance and installation requirements of the CF6-50 engine and which also meets or closely approaches the objective low pollutant emissions level goals of the program.

Phase III Program

The Phase III Program, which is planned for the future, will consist of detailed evaluations of the most promising Phase II Program combustor design in a demonstrator CF6-50 engine. The objective of these efforts will be to demonstrate the successful attainment of significant pollutant emissions level reductions with an advanced combustor which meets the performance, operational and installation requirements of the engine. The Phase III Program is expected to be a 16-month effort.

PROGRAM SCHEDULE

The overall schedule plans of the NASA/General Electric Experimental Clean Combustor Program are presented in Figure 1. In this chart, the solid bars indicate completed efforts and the striped bar indicates efforts currently under contract. The open bar, shown for the Phase III Program, indicates possible future contract effort.

PROGRAM GOALS

Pollutant Emissions Level Goals

The pollutant emissions level goals of the NASA/General Electric Experimental Clean Combustor Program-Phase I are presented in Table I. As is shown by the comparison of the goals with the status levels of the current production CF6-50 engine, the attainment of these goals involves significant pollutant emissions level reductions. These goals are intended to be optimistic projections of the pollutant emissions level reductions that are practically attainable with combustor design technology advancements. Thus, the prime intent of the program was to generate and develop advanced combustor design technology, rather than to refine and/or verify already available combustor

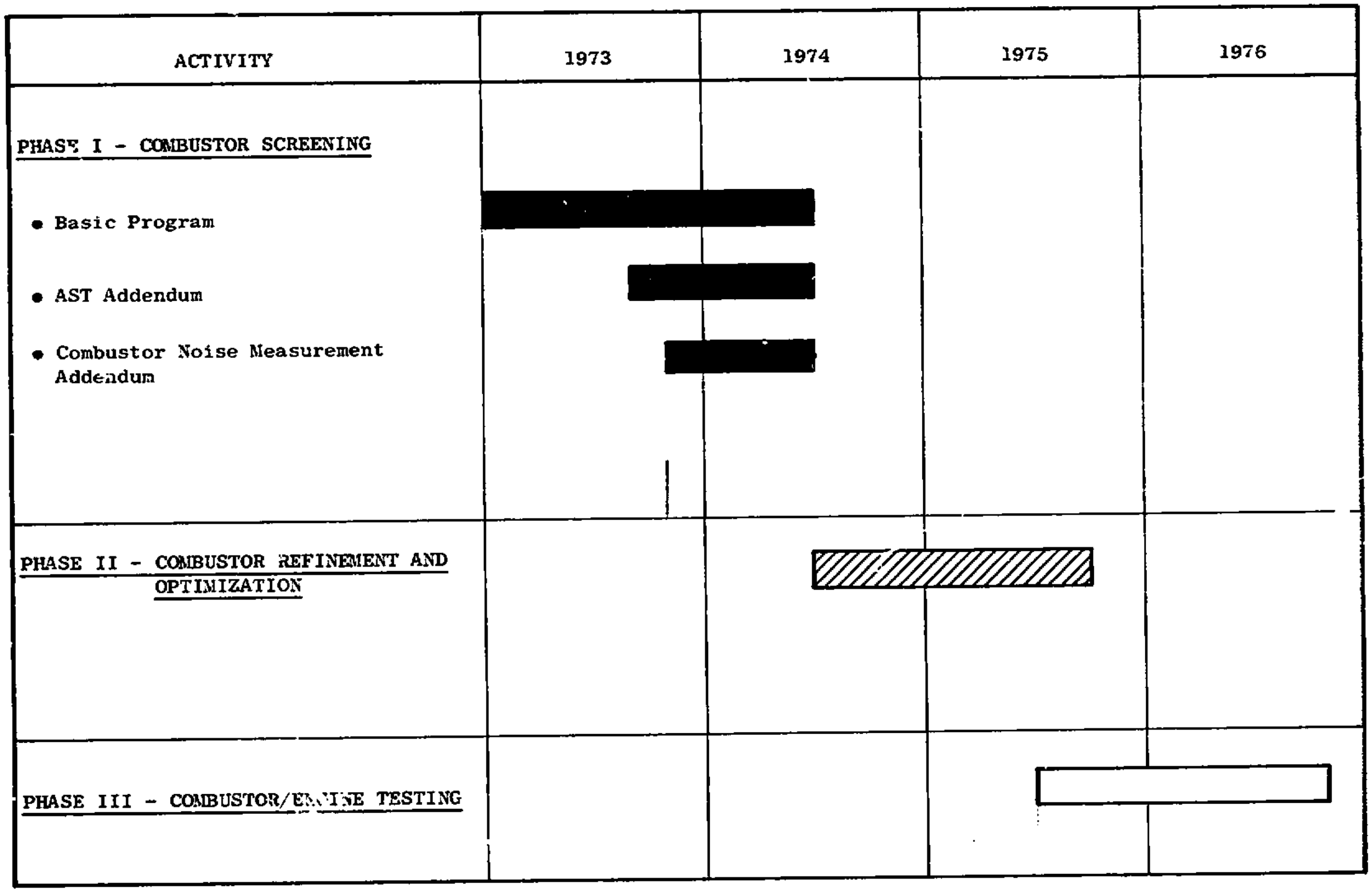

Figure 1. NASA/General Electric Experimental Clean Combustor Program.

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Table I. Pollutant Emissions Level Goals of the NASA/General Electric Experimental Clean Combustor Program.

A. Basic Program Goals

- Sea Level Static Engine Operating Conditions
- Aviation Kerosene Fuel

Pollutant Emission		Engine Operating Mode	Program Goal	Current CF6-50 Engine Status
NO_x (As NO_2)	- g/kg Fuel	Hot Day Takeoff	10	44
NO_x (As NO_2)	- g/kg Fuel	Standard Day Takeoff	-	35
CO	- g/kg Fuel	Standard Day Ground Idle	20	67
HC (As $C_nH_{1.9n}$)	- g/kg Fuel	Standard Day Ground Idle	4	27
Smoke	- (SAE SN)	Hot Day Takeoff	15	12

B. AST Addendum Goals

- AST Cruise Engine Operating Conditions
- Aviation Kerosene Fuel

Pollutant Emission		Program Goal	Level of Current CF6-50 Combustor (Approximate)
NO_x (As NO_2)	- g/kg Fuel	5	17
CO	- g/kg Fuel	5	1
HC (As $C_nH_{1.9n}$)	- g/kg Fuel	1	0.1
Smoke	- (SAE SN)	15	5

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 Phase I Program.

As is shown in Table I, the emissions level goals of the basic Phase I Program, which are intended to apply to advanced subsonic transport aircraft engines like the CF6-50 engine, are related to the specific steady-state engine operating modes, where the peak levels of each emissions category are generated. Each of the gaseous emissions level goals is defined in terms of an emission index, which is the ratio of the grams of pollutant emission formed per kilogram of fuel consumed. The smoke emission level goal is expressed to terms of the SAE ARP 1179 Smoke Number.

As is shown in Table I, the NO_x emissions level goal of the basic Phase I Program is defined at a hot day engine operating mode. The selection of this operating mode, rather than a standard day takeoff operating mode, was made to provide an extra degree of severity in terms of NO_x emissions formation. At the hot day takeoff mode, the combustor inlet air temperature of the CF6-50 engine is 39° K higher than at the standard day takeoff mode (858° K versus 819° K). Since inlet air temperature is the dominant parameter affecting the degree of NO_x emissions formation, the use of the higher combustor inlet air temperature in the basic Phase I Program investigations thereby provided NO_x emissions level reduction technology applicable over a wide range of simulated engine cycle pressure ratios. A combustor inlet air temperature of about 860° K would be the nominal value expected at standard day takeoff conditions with a turbofan engine having a cycle pressure ratio of 35.

Also included in Table I are the pollutant emissions level goals of the AST Addendum. These goals are defined at a specific set of combustor operating conditions that would nominally be associated with an AST engine operating at a specific high altitude-supersonic cruise condition. The key goal of this set of goals is the target NO_x emissions level. The CO and HC emissions level goals are intended primarily to set limits within which trade offs can be made between attainable NO_x emissions levels and attainable CO and HC emissions levels. Because of the lower combustor pressure associated with the defined AST cruise operating condition, this NO_x goal is roughly comparable in terms of attainment difficulty to the basic Phase I Program NO_x emissions goal, which is defined for subsonic transport engines at hot day takeoff operating conditions.

Combustor Performance Goals

The key combustor performance goals of the NASA/General Electric Experimental Clean Combustor Program are presented in Table II. Except for its 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 those specified as goals for the basic Phase I Program. Thus, the major challenge of this program was to identify and define advanced

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

	Performance Parameter	Engine Operating Mode	Program Goal
A.	Basic Program Goals		
	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
B.	AST Addendum Goals		
	Minimum Combustor Efficiency - %	AST Cruise	99.8
	Maximum Pressure Drop - %	AST Cruise	6.0
	Maximum Exit Temperature Pattern Factor	AST Cruise	0.25

combustor designs which have performance characteristics similar to those of the current CF6-50 engine combustor, as well as reduced pollutant emissions levels.

The specified combustion efficiency goal at idle of 99 percent is higher than the combustion efficiency provided by the current CF6-50 engine combustor at idle operating conditions. This goal is specified as 99.0 percent to be consistent with the CO and HC emissions level goals of the basic Phase I Program. Combined, these latter two goals are equivalent to a combustion efficiency at idle of 99.1 percent.

Also included in Table II are the combustor performance goals of the AST Addendum. At the specified combustor operating conditions associated with this addendum investigation, the current production CF6-50 engine combustor also operates with performance levels equal to or better than these goals. Thus, as in the basic program investigations, the key development problem is retaining these excellent performance characteristics while also obtaining more favorable pollutant emissions characteristics. The combustion efficiency goal is specified as 99.8 percent to be consistent with the AST Addendum goals for CO and HC emissions.

CHAPTER II. PHASE I PROGRAM - DESIGN AND DEVELOPMENT APPROACHES

The CF6-50 engine, for use in which the various Phase I Program combustor test configurations were specifically sized and designed, is briefly described in this chapter. Also described is the current production CF6-50 engine combustor which was used in this program as the baseline design, to which the performance and emissions characteristics of the various test configurations were compared. In addition, the test facilities and equipment, including the pollutant emissions sampling and analysis equipment, are described herein. Further, the various testing methods and the test data processing and analysis methods used in conducting this program are also described in this chapter.

CF6-50 COMBUSTOR DESIGN AND PERFORMANCE CHARACTERISTICS

CF6-50 Engine - General Description

The CF6-50 engine is the higher power version of two models of the CF6 high bypass turbofan engines which have been designed and developed by General Electric. The other model is the CF6-6D engine. The CF6-50 engine is in commercial service as the power plant for the McDonnell-Douglas DC-10 Series 30 Tri-Jet long range intercontinental aircraft and the Airbus Industrie A300B aircraft.

The CF6-50 engine is a dual-rotor, high bypass ratio turbofan 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 turbine. Basically, the engine consists of a fan section, compressor section, combustor section, turbine section and accessory drive section. These basic sections are shown in Figure 2. This high bypass turbofan engine has a high thrust-to-weight ratio and favorable fuel economy characteristics. The key overall specifications of the CF6-50 engine are presented in Table III.

Table III. Key Specifications of the CF6-50 Engine.

Weight	3780 kg
Length (cold)	482 cm
Max. Dia. (cold)	272 cm
Fan/Comp. Stages	1-(3)/14
HPT/LPT Stages	2/4
Thrust/Weight	5.95
Pressure Ratio	30:1
Airflow	660 kg/s
Max. SLS Thrust	218 kN
SFC	0.389
Cruise Mach No./Alt	0.85/10.5 km
Thrust	48 kN
SFC	0.654

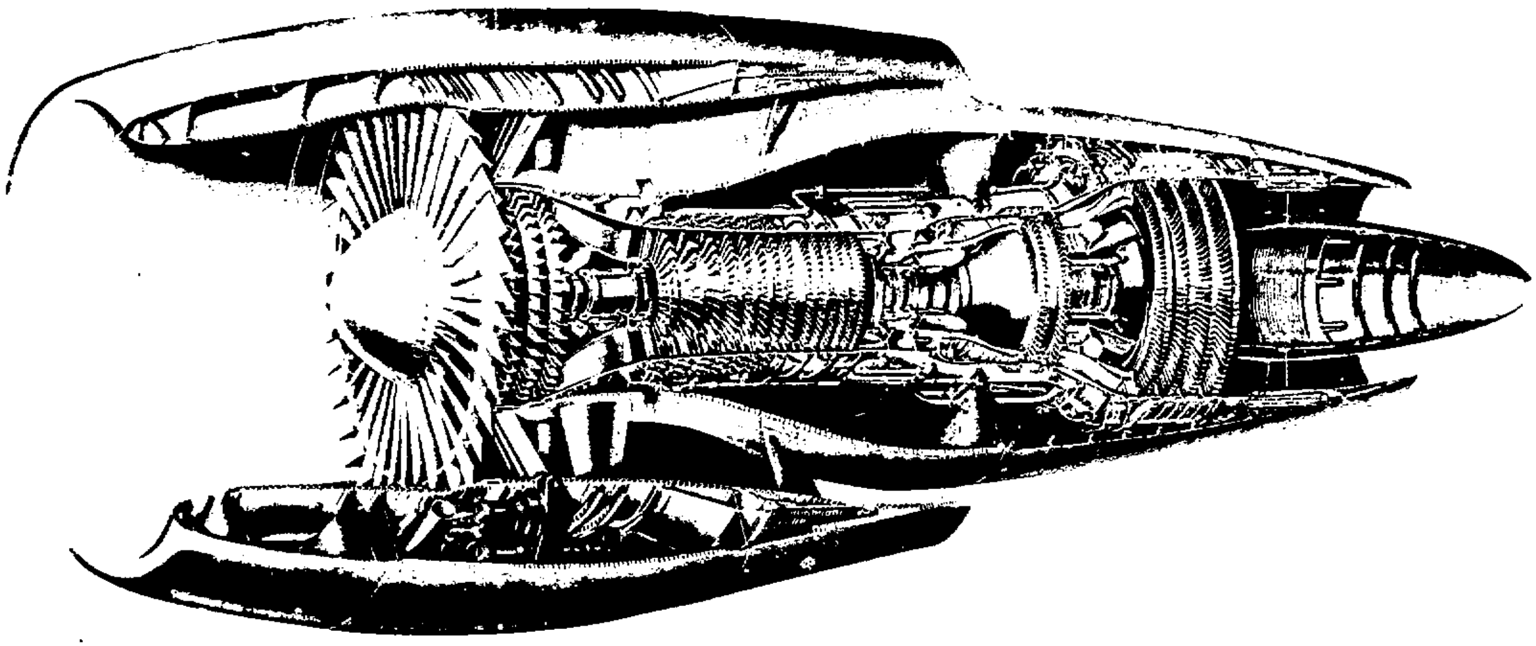


Figure 2. General Electric CF6-50 High Bypass Turbofan Engine.

The CF6-50 engine is considered to be an attractive selection for use in this program as the baseline vehicle for developing and evaluating advanced combustor configurations with reduced levels of exhaust pollutant emissions. The smoke emission levels of this engine are already very low, virtually invisible at all operating conditions.

CF6-50 Combustor - General Description

The CF6-50 engine combustor is a high performance design with demonstrated low exit temperature pattern factors, low pressure loss, high combustion efficiency and low smoke emission performance at all operating conditions. A cross-sectional drawing of this combustor, as installed in the engine, is presented 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 which, in turn, improves its 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 swirler cups, 1 for each fuel nozzle. The combustor consists of four major sections which are riveted together into one unit and spot welded to prevent rivet loss: the cowl assembly, the dome, and the inner and outer liner skirts. The combustor is mounted at the cowl assembly by 30 equally-spaced radial mounting pins. A photograph of this combustor assembly is shown in Figure 4. The inner and outer skirts each consist of a series of circumferentially stacked rings which are joined by resistance welded and brazed joints. The liners are film-cooled by air which enters each ring through closely spaced circumferential holes. Three axial planes of dilution holes on the outer skirt and five planes on the inner skirt are employed to promote additional mixing and to lower the exit temperatures at the turbine inlet. Several of the more important design parameters of this combustor are presented in Table IV.

Additional material relating to the design of this CF6-50 combustor, and the fuel supply and control systems used with this combustor, are presented in Appendix A of this report.

Some of the important measured performance characteristics of this combustor at sea level static takeoff operating conditions are as follows:

Exit Temperature Pattern Factor	0.26
Exit Temperature Profile Factor	1.09
Combustion Efficiency	99.9%

More detailed data on the pattern factor and profile factor performance and requirements are shown in Figure 5. The altitude relight and ground start characteristics of the combustor are presented in Figure 6.

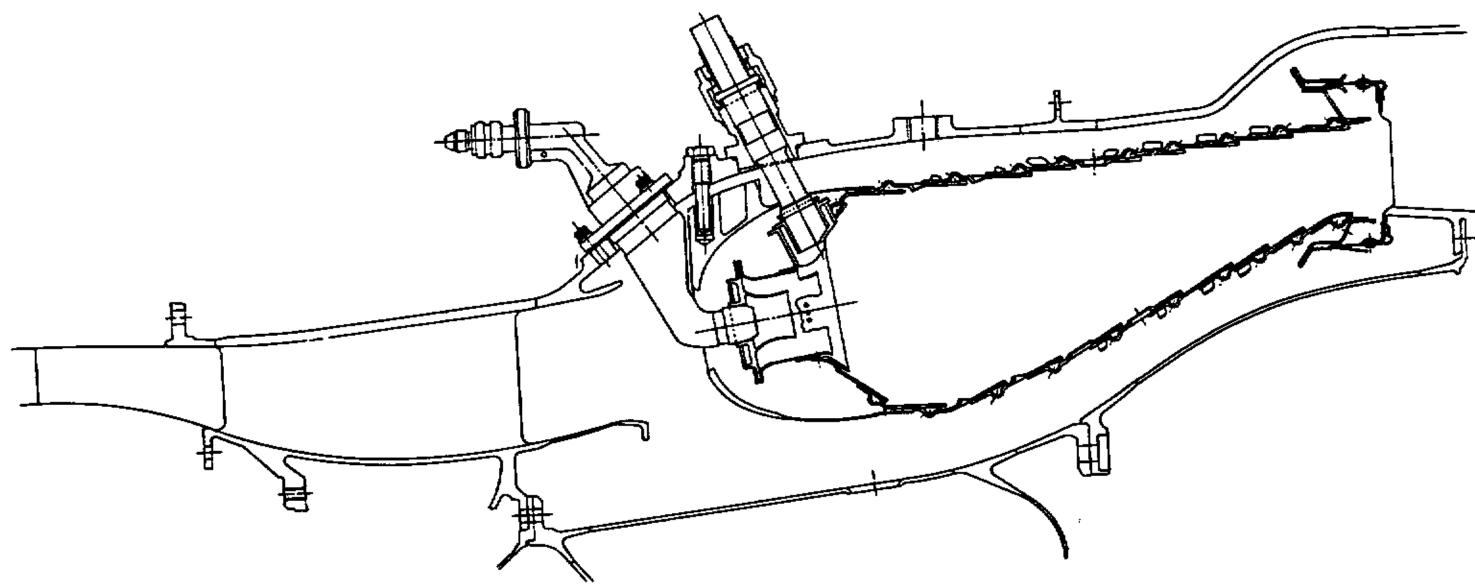


Figure 3. Production CF6-50 Engine Combustor.

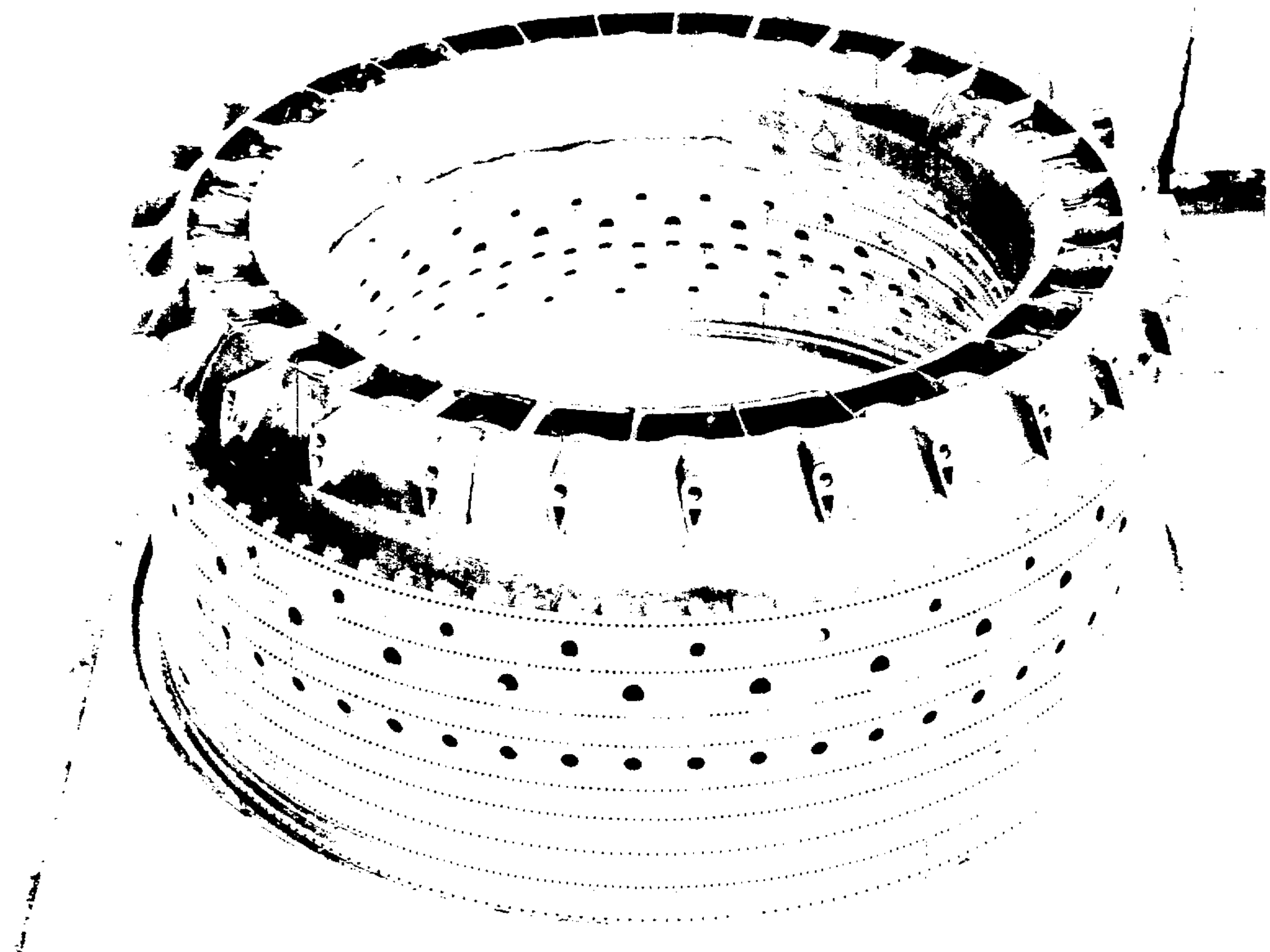


Figure 4. CF6-50 Combustor Assembly.

Table IV. CF6-50 Combustor Key Design Parameters.

Combustor Airflow (W_C)	103.42 kg/s
Compressor Exit Mach Number	0.27
Overall System Length	75.95 cm
Burning Length (L_B)	34.8 cm
Dome Height (H_D)	11.43 cm
L_B/H_D	3.0
Reference Velocity	25.9 m/s
Space Rate	2.2×10^{11} J/hr-m^3-atm
$\Delta P_T/P_{T_3}$	4.3% (Total)
Number of Fuel Nozzles	30
Fuel Nozzle Spacing (B)	6.91 cm
L_B/B	5.0
B/H_D	0.60
Design Flow Splits (Outer-Center-Inner)	33-32-35% of W_C
Liner Cooling Flow	30% of W_C

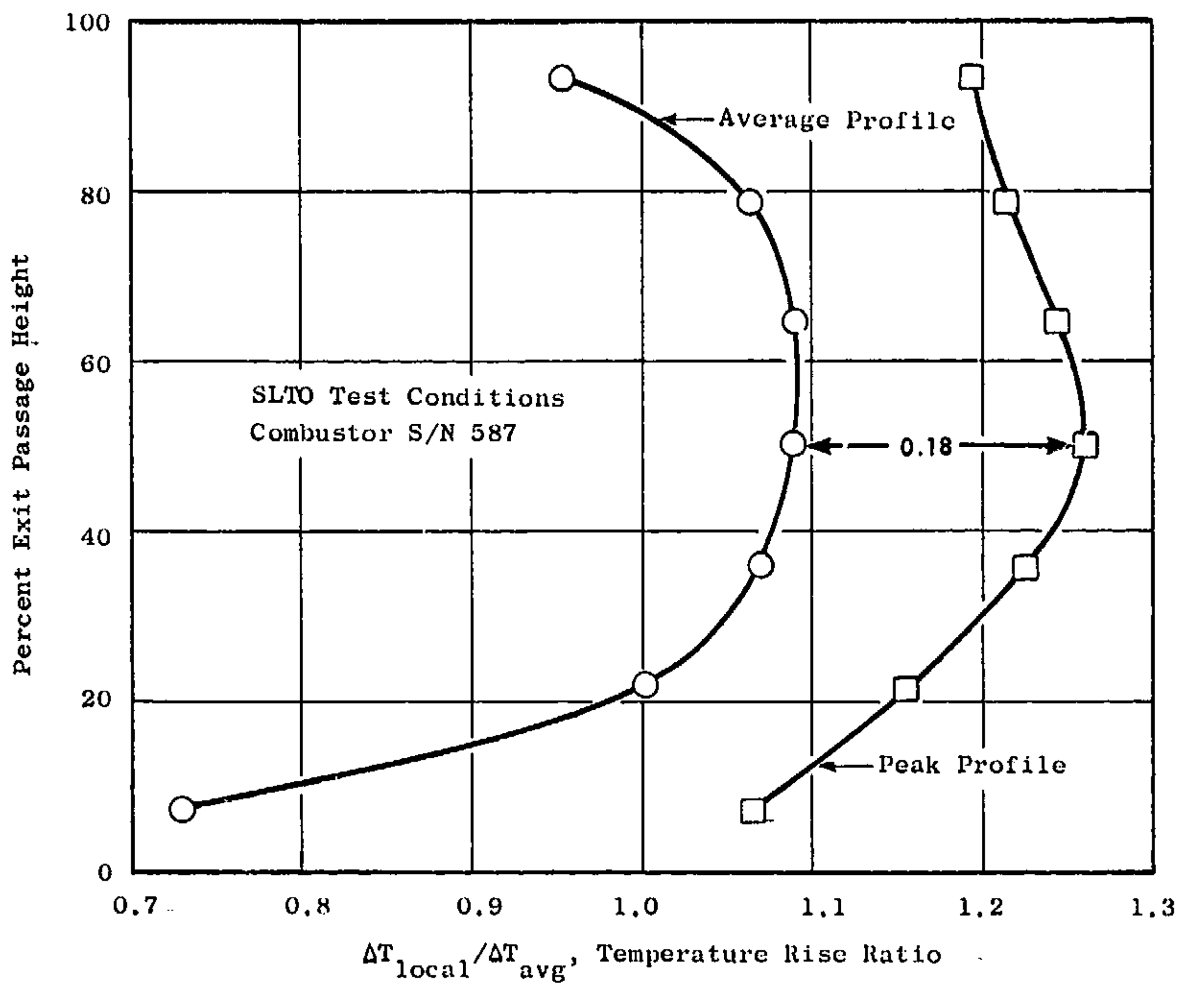
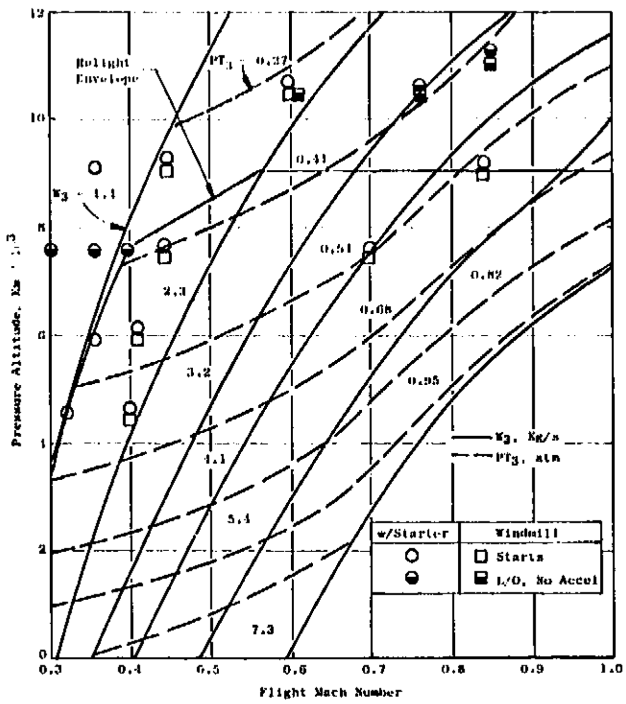
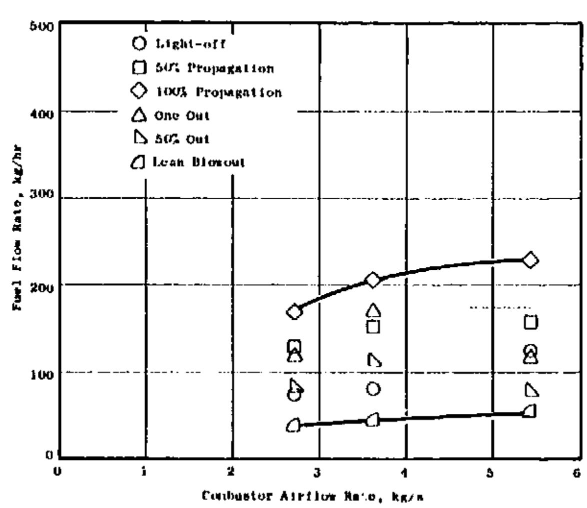


Figure 5. Exit Temperature Profile Characteristics, Typical CF6-50 Production Combustor.



a) Altitude Relight Characteristics



b) Sea Level Ignition Characteristics

Figure 6. Altitude Relight and Ground Start Ignition Characteristics, Typical CF6-50 Production Combustor.

CF6-50 Combustor - Exhaust Emissions Characteristics

The CF6-50 combustor was originally designed and developed to meet low smoke requirements. The basic design feature used to obtain the objective low smoke levels was the axial swirl cup combustor dome design approach which was originally developed for use in the CF6-6 and TF39 engines. This carbureting swirl cup design permits the introduction of large amounts of the combustor airflow (up to 20 percent) through the swirl cups and provides very effective fuel and air mixing. These features result in low smoke levels and, in addition, a combustor design that meets the altitude relight requirements of the engine. Low smoke levels have been demonstrated with the existing CF6-50 combustor design. The measured smoke levels obtained in an engine test are presented in Figure 7. With these low smoke levels, the CF6-50 engine exhaust plume is virtually invisible at all operating conditions.

The gaseous emissions characteristics of the CF6-50 engine combustor are illustrated in Figures 8, 9 and 10. In these figures, the results of emissions tests of CF6-50 Engine No. 455-508/6A at 7 SLS engine operating conditions, ranging from ground idle to 100 percent SLS takeoff power are presented. In this test series, jet kerosene fuel was used. The test points were chosen to correspond to the EPA power settings (ground idle, 30, 85, and 100 percent rated power) with 2 additional points at low power (6 and 12 percent) to better define the idle emissions levels. These points were obtained with zero CDP bleed. An additional point was obtained with three percent bleed, which was the maximum bleed obtainable with this particular engine buildup without repiping the engine. The data are plotted against inlet temperature (T_3) in order to adjust the data to standard day operating conditions. The measured NO_x emission levels are shown corrected to an inlet air humidity level of 6.30 g/kg of air.

The key emissions level data presented in Figures 8, 9 and 10 are summarized in Table V, where they are compared to the Phase I Program goals.

Table V. CF6-50 Engine/Combustor Gaseous Pollutant Emissions Levels.

	Emission Index, g/kg Fuel	
	Current Engine Status	Experimental Clean Combustor Program Goal
HC - At Idle (Standard Day)	27	4
CO - At Idle (Standard Day)	67	20
NO_x - At Takeoff (Standard Day)	35	-
NO_x - At Takeoff (Hot Day)	44*	10

*Extrapolated value, based on standard T_3 correction factor.

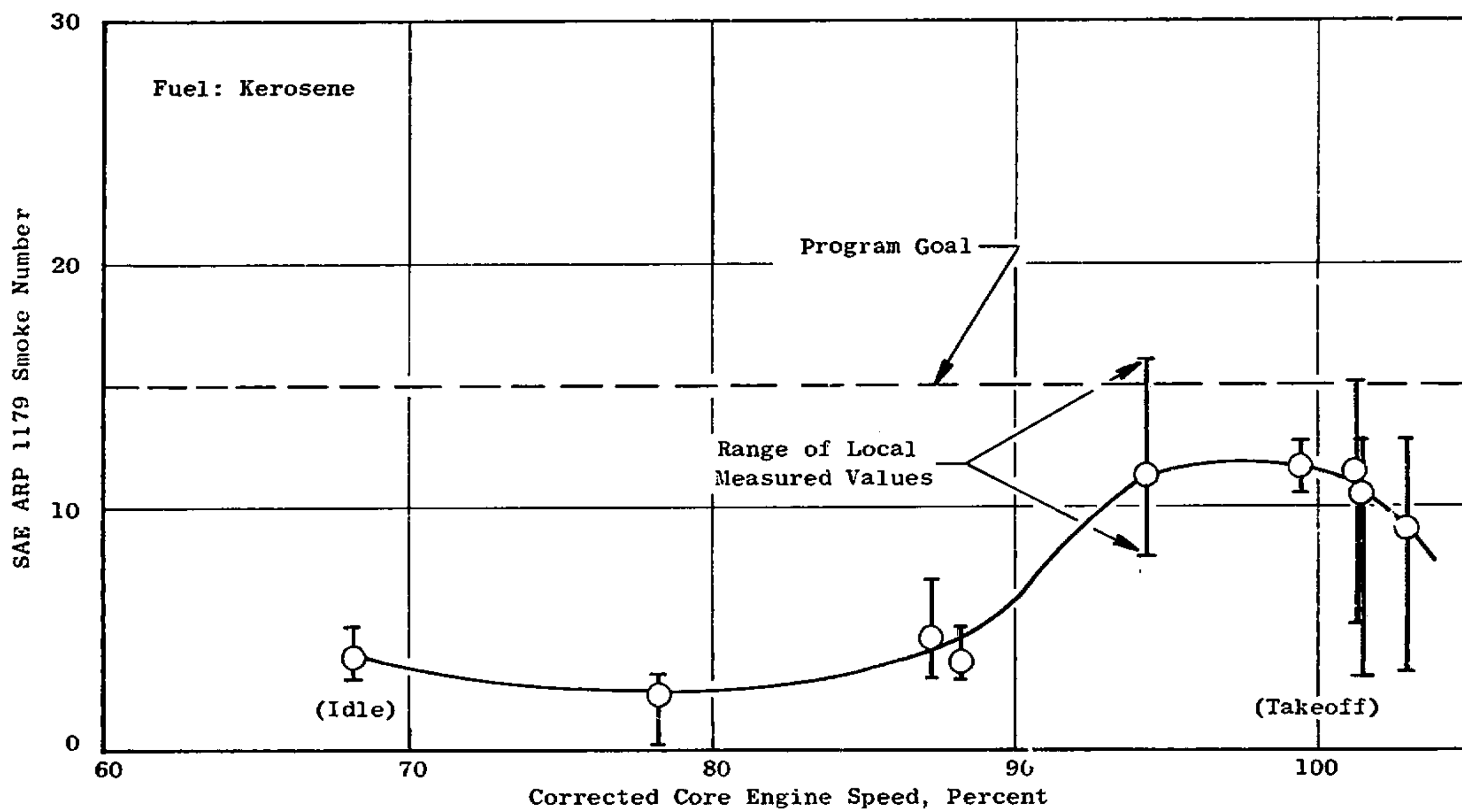


Figure 7. Smoke Emission Characteristics, CF6-50 Engine/Combustor.

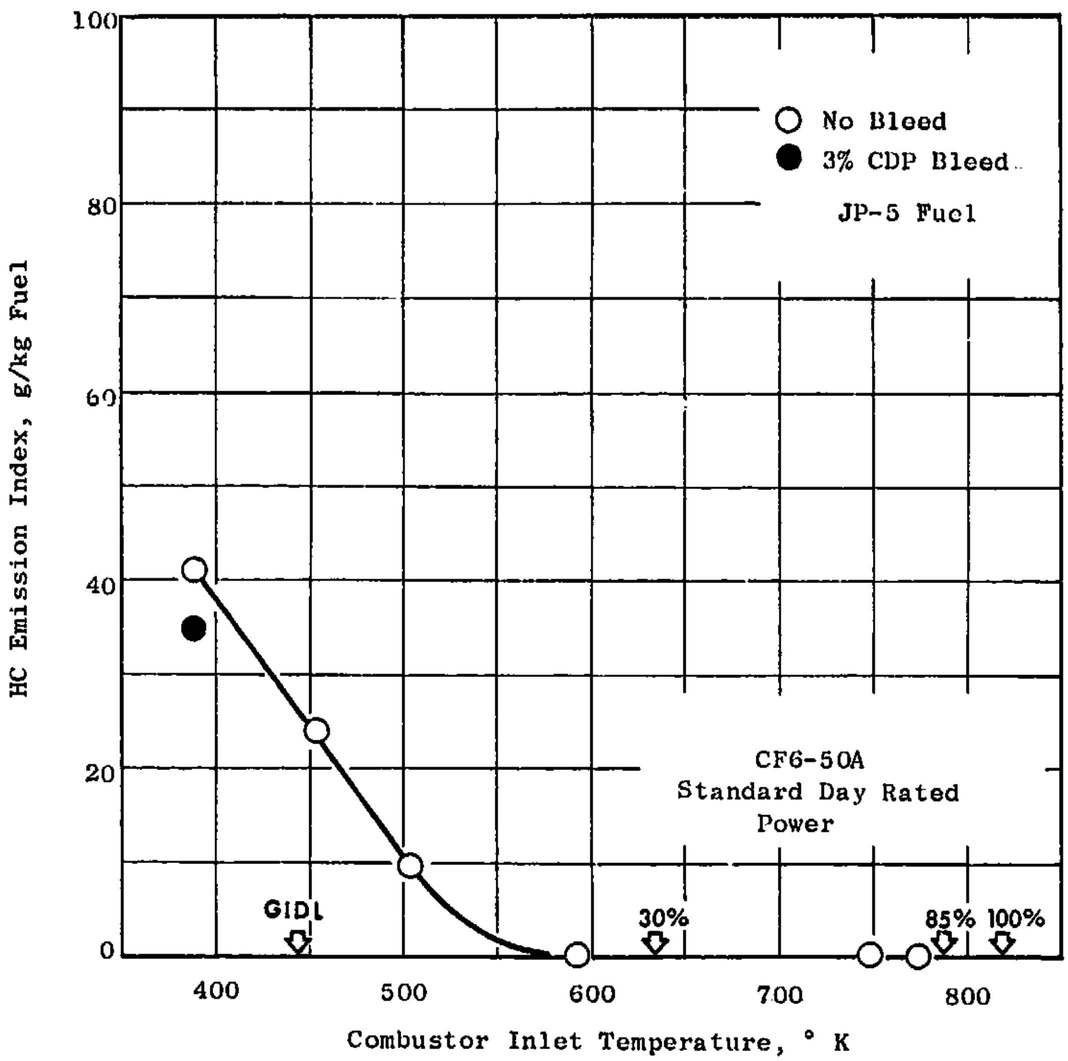


Figure 8. HC Emission Characteristics, CF6-50 Engine/Combustor.

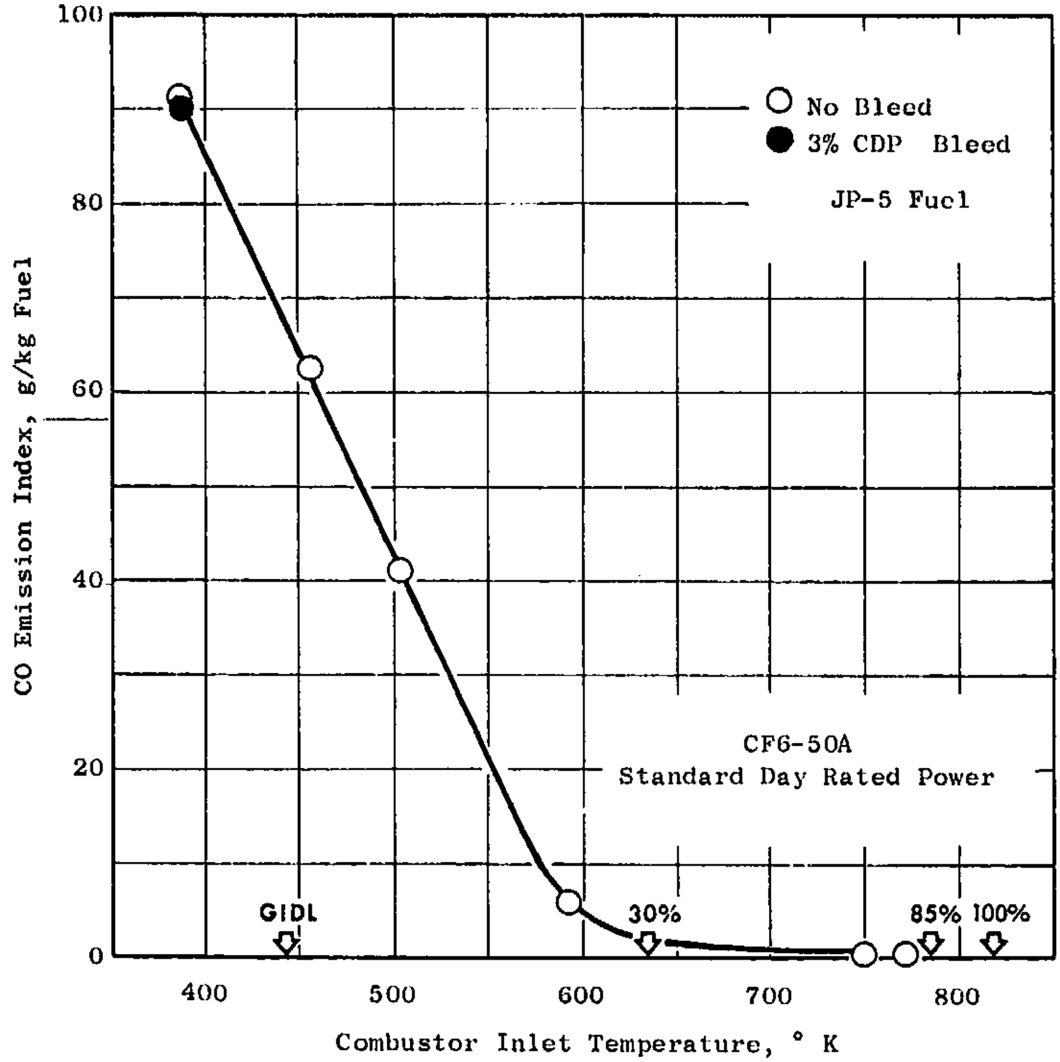


Figure 9. CO Emission Characteristics, CF6-50 Engine/Combustor.

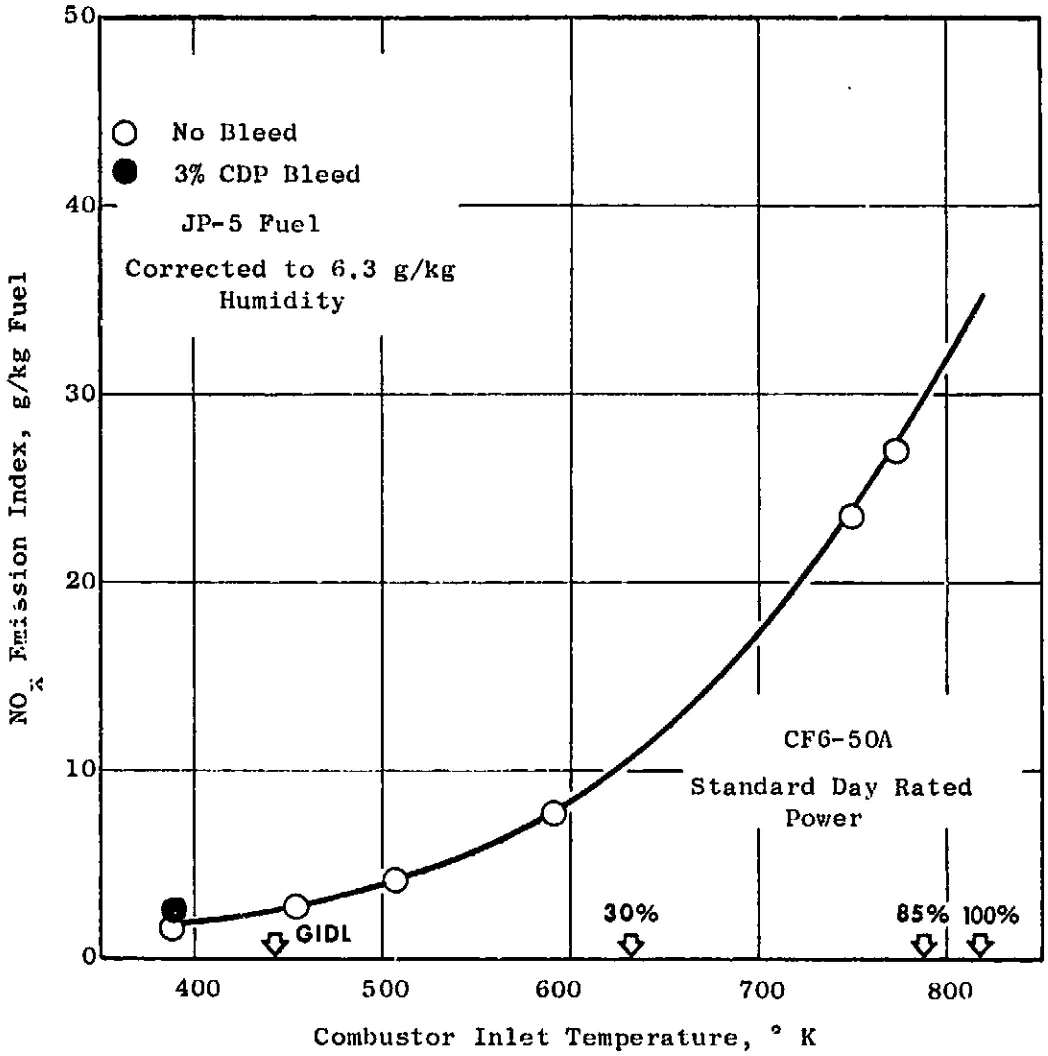


Figure 10. NO_x Emission Characteristics, CF6-50 Engine/Combustor.

TEST FACILITIES AND EQUIPMENT

Test Cell and Related Facilities

The Phase I Program combustor evaluations were performed in Test Cell A3, which is located in the General Electric Evendale Plant. This facility is fully equipped with the necessary inlet ducting, exhaust ducting, controls and instrumentation required for conducting full-scale combustor component tests over wide ranges of operating conditions. A view of the interior of the cell is shown in Figure 11. The cell itself is a rectangular chamber with reinforced concrete blast walls on three sides and a lightweight roof. The installed ventilation and safety equipment are designed specifically for tests involving combustible fluids. This cell contains the necessary air piping to accommodate two test vehicles.

In operating this test cell, its utilization is maximized by mounting the test rigs on portable dollies with quick-change connections so that build-up operations are accomplished in another area and the resulting test vehicle occupies the cell only for the duration of its actual testing. This cell operational concept allows the installation of a typical test vehicle in about four hours. The turnaround time from the completion of a test with one vehicle to the start of a test with another is, therefore, only about eight hours. The instrumentation reliability is improved since the sensors are prewired to multiple quick-connect panels and checked out in the favorable environment of the vehicle build-up area.

The control consoles and data recording equipment are located in the adjacent control room. This room is insulated to muffle test noise and facilitate communication and is environmentally controlled for the benefit of the electronic equipment.

Air is supplied to this test cell from a central air supply system. This system has a nominal capacity of 45 kg/s of continuing airflow at a delivery pressure of up to 20 atm. The system may also be used for exhaust suction to simulate a pressure altitude up to 8.9 km, with flow rates reduced in proportion to density.

Auxiliary equipment in the air distribution network provides for further conditioning of the delivered air, when required. This conditioning includes 10-micron filtration, drying to a 233° K dewpoint and temperature control. Cold air, down to 217° K, can be provided by piping connections to a turbo-refrigeration unit. Warm air, up to 450° K, can be supplied directly by bypassing the aftercooler. Further heating, up to 922° K, is accomplished with a gas-fired heat exchanger. The gas-fired indirect air heater is designed to accept 36 kg/s of air from the central air supply system at 450° K and 9.5 atm and to discharge the air unvitiated at 933° K and 8.3 atm. The heater is capable of accommodating higher flows and higher pressures at reduced outlet temperatures. The heater is a refractory-lined shell 8.2 m in diameter and 13.7 m tall, containing a conical radiating furnace baffle and a heat exchanger.

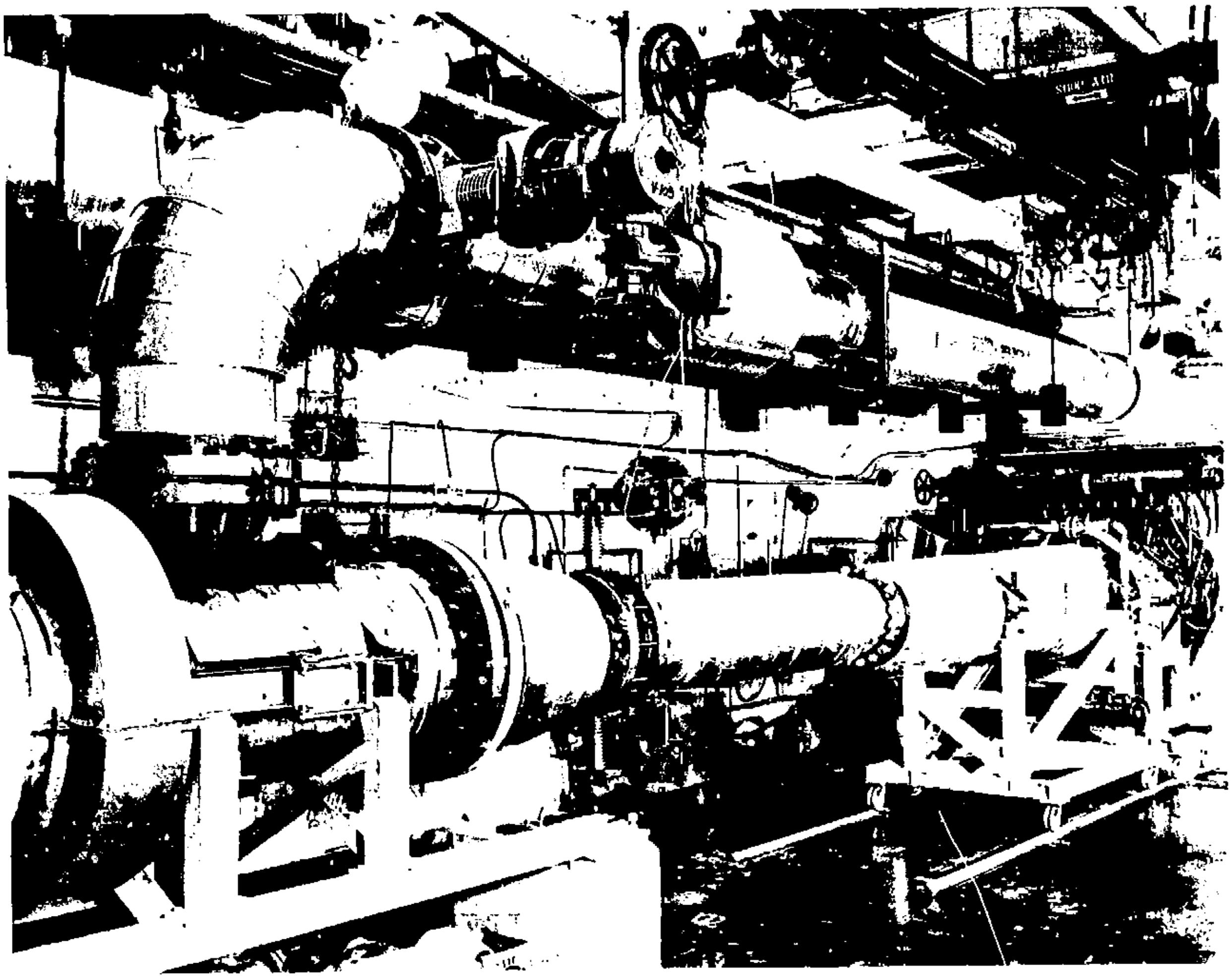


Figure 11. Interior View of Test Cell A3.

Combustors being tested in this cell can be exhausted directly to the atmosphere or can be connected to the facility exhaust system for pressure control. When connected to the facility exhaust system, the combustor pressure can be regulated from the upper limit, imposed by the pressure or flow capacity of the air supply system, down to about 0.2 atm. Exhaust suction is provided either by the centrifugal compressors of the air supply system or by a two-stage steam ejector system with an interstage condenser.

Liquid fuels are supplied to Cell A3 from two large above-ground tanks, each having a capacity of 114 cubic meters. Each tank is provided with a centrifugal pump to transfer the fuels through 10.2-cm pipelines. The high pressure fuel pumps, located in Cell A3, boost the fuel pressure as high as 826 newtons/cm^2. The available fuel pressures and flows with these pumps were adequate for all tests of the Phase I Program, with ample margin for metering and control.

Test Rig

The Phase I Program combustor evaluations were conducted with an existing full annular combustor test rig. This full annular combustor test rig exactly duplicates the aerodynamic combustor flowpath and envelope dimensions of the CF6-50 engine. The test rig consists of an inlet plenum chamber, an inlet diffuser section and a housing for the combustor. Included as a part of this rig is an exit plane rotating rake assembly for obtaining measurements of combustor outlet temperatures and pressures and for extracting gas samples.

A drawing of this CF6-50 combustor test rig is presented in Figure 12. Photographs of the test rig are presented in Figure 13. The combustor test rig is basically a cylindrical pressure vessel designed for high-temperature service and fitted with inlet and exit flanges. The rig is equipped with ports and bosses to accommodate fuel nozzles/injectors, igniters and boroscope inspection devices. These ports are located exactly as in the engine design. The rig is also equipped with provisions to extract both turbine cooling air and customer bleed air. These provisions also duplicate those in the engine. In this program, the engine design turbine cooling air bleed flows were extracted from the inner and outer bleed ports shown in Figure 12. The total bleed flow was metered with a sharp-edged orifice and the flow rates were recorded. The bleed flow split was controlled by fixed area ratios between the inner and outer bleed ports.

The air inlet connection of the test rig consists of an 81.3-cm diameter pipe flange of special design which is bolted to the air supply plenum of the test cell. In the supply plenum, the flow is mixed and then straightened by grates and screens. Within the test rig, a bullet-nosed centerbody directs the entering airflow into an annular passage. This annular passage simulates the compressor discharge passage of the engine. The inner and outer walls are formed to the contour of the engine's diffuser and the gap is spanned by 10 streamlined struts, identical to those in the engine, which support the centerbody. The struts also provide access for instrumentation leads into the

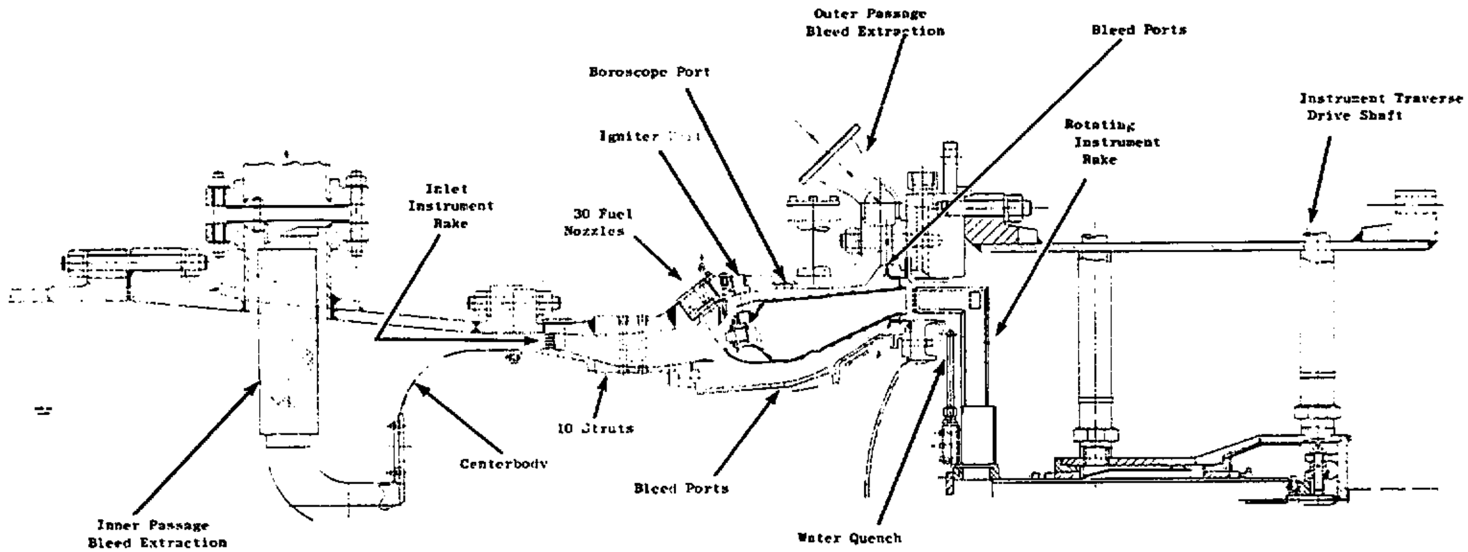
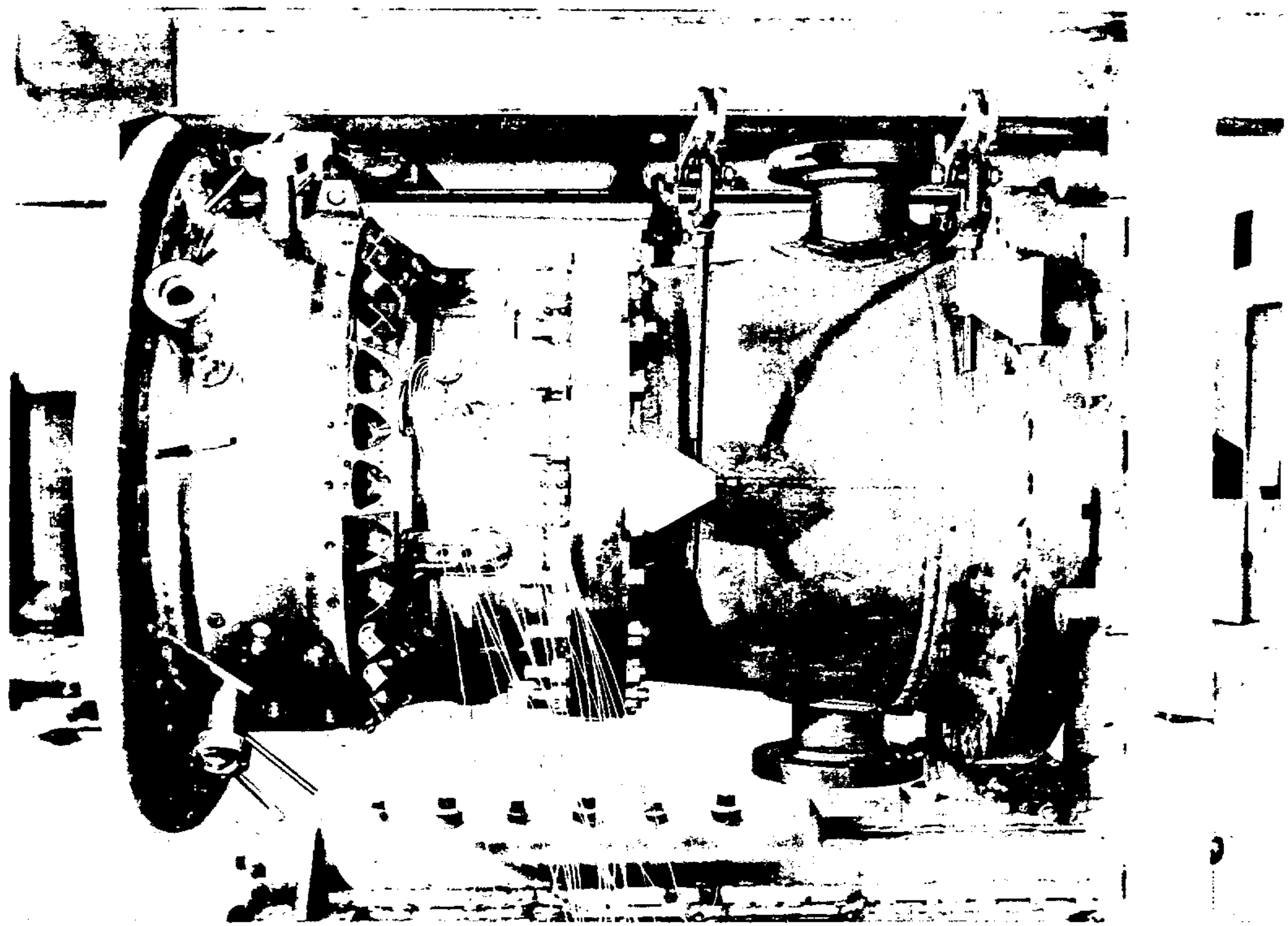
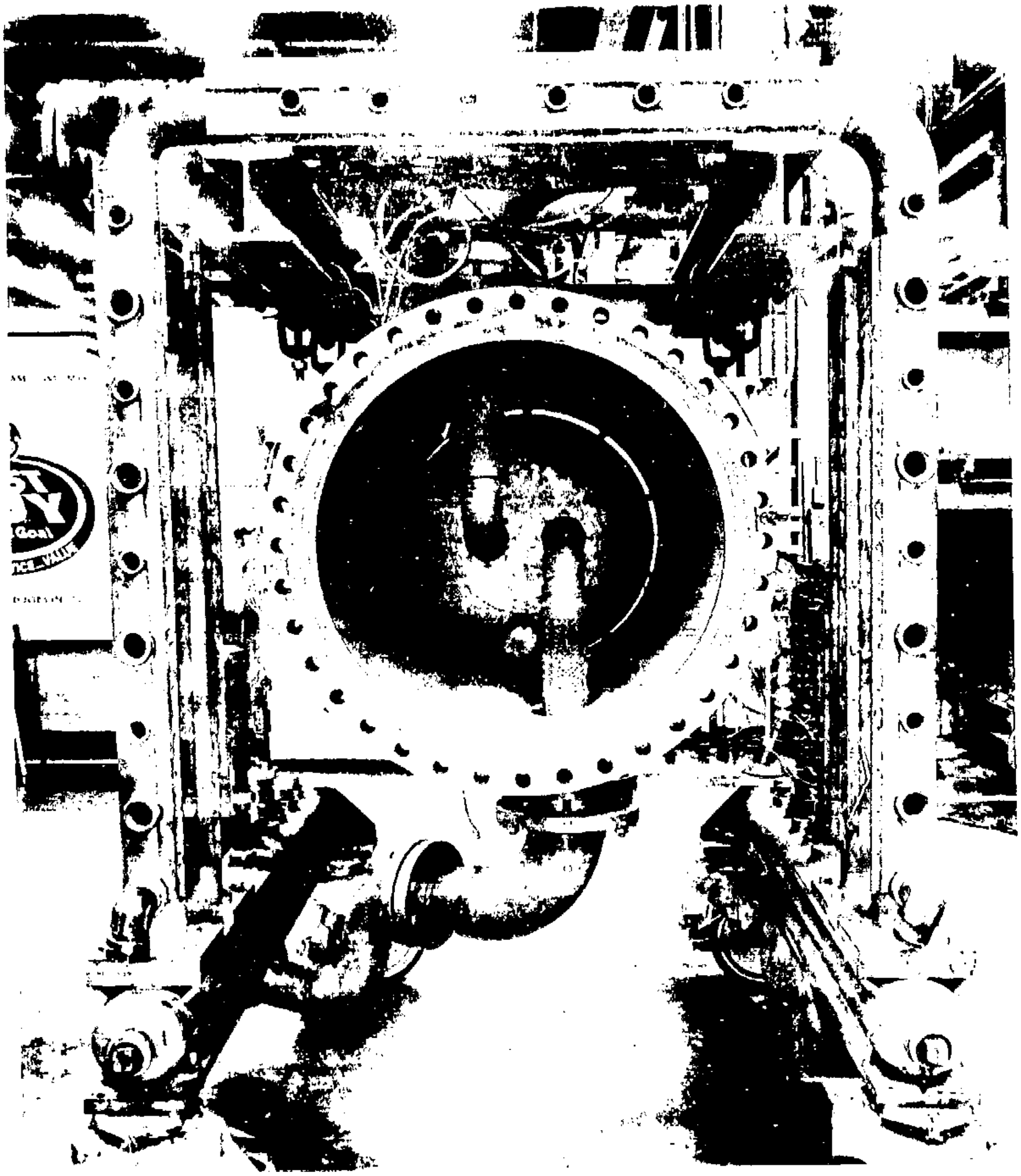


Figure 12. Full Annular CF6-50 Combustor Test Rig, Axial Cross Section View.



a) Side View

Figure 13. CF6-50 Combustor Test Rig Photographs.



b) View Looking Downstream Illustrating Centerbody Simulation of Compressor Discharge Passage

Figure 13. CF6-50 Combustor Test Rig Photographs (Concluded).

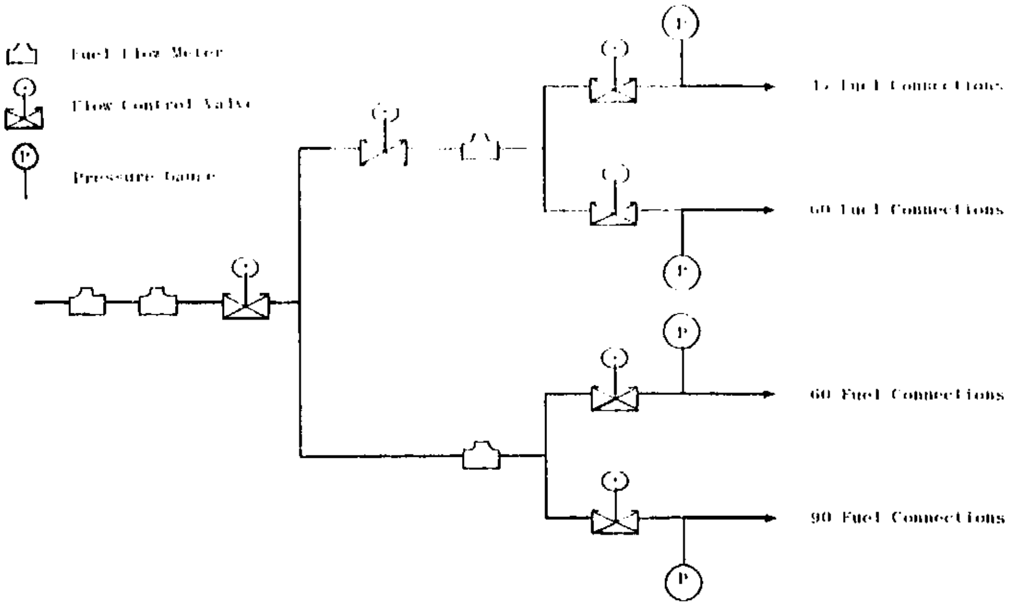
centerbody. Aft of the step diffuser, the centerbody forms the inner wall of the combustor housing. The inner wall is provided with bleed ports, through which a portion of the airflow can be extracted as customer bleed air. Additional ports are provided to simulate turbine rotor cooling air extraction. The air extracted from both of these sets of ports is routed through 2 10.2-cm pipes, forward through the centerbody nose, then radially out of the rig.

The combustor test rig is equipped with 30 fuel nozzle ports, spaced 12 degrees apart. The various fuel injection assemblies used in this program were all installed through these existing ports and, thus, 30 fuel injection assemblies were used with all of the combustor test configurations, even though some of the configurations featured the use of more than 30 fuel injection points. Arrays of 30, 60, 72 and 90 fuel injection points were used in the various test configurations. Fuel injection assemblies with up to four supply tubes were used to accommodate the increased number of injection points.

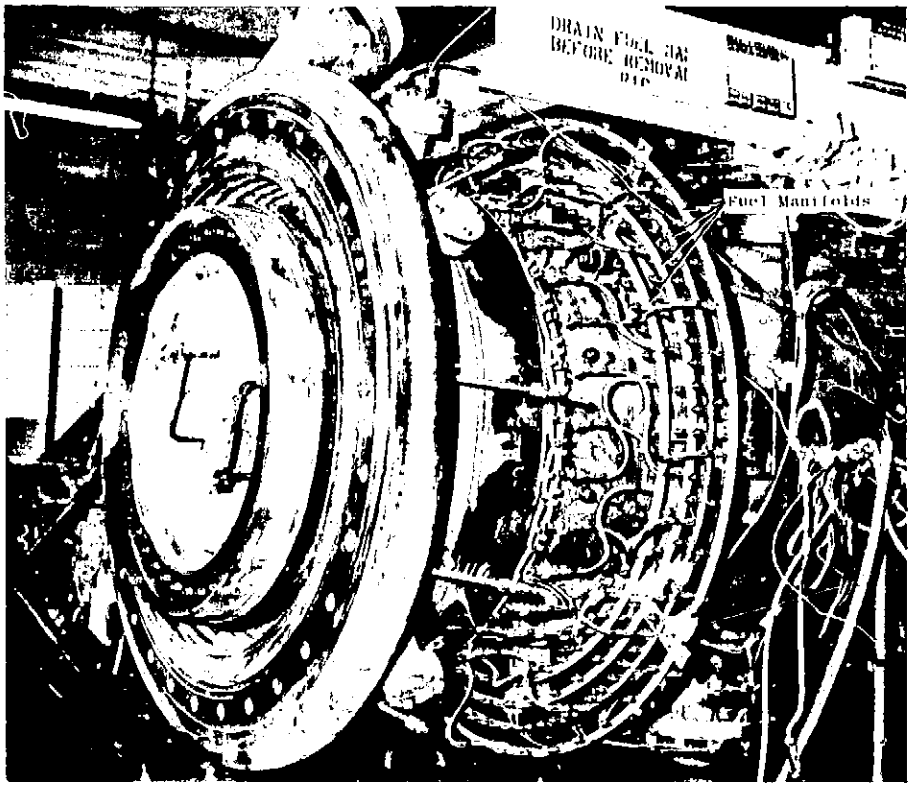
The fuel was supplied to these injection assemblies through 4 manifolds which had 45, 45, 60 and 90 fittings. A diagram showing the basic four-manifolded fuel feed system is presented in Figure 14, along with a photograph showing the four-manifold hookup on the test rig. The available hookups were numerous. Alternate injectors, or sectors of injectors in each of the two combustor dome annuli, could be fueled. Each manifold fitting was equipped with Leejets (fixed orifices) which were used to provide reliable and uniform circumferential fuel metering. There was a permanently attached filter incorporated into the Leejet. The Leejets calibrated within ±3 percent of the desired flow and were spot checked during the program. Two Leejet sizes were selected to cover the full range of required fuel flows. Operation of the combustor at very low fuel flows was accomplished by the use of only the small (9.8 kg/hr) Leejet. For middle flow requirements, the larger Leejet (18.6 kg/hr) was employed and for the maximum flow requirements, both Leejets were utilized. A typical hookup, where either or both Leejets could be used, is shown in Figure 15.

The exhaust end of this combustor test rig is provided with a large diameter flange to which an instrumentation spool section can be joined. The instrumentation spool section used in this program consisted of an existing short-flanged pipe with a water-cooled centerbody supported by radial pipes. Water-cooled radial combustor exit passage survey rakes were attached to an axial shaft in the centerbody. In the array used in the program, five gas sampling rakes and five thermocouple rakes were mounted to this rotating shaft. Each thermocouple rake contained five thermocouple elements of Platinum 30/Platinum 6 Rhodium wire. A typical thermocouple rake, as used in this program, is shown in Figure 16. Inside the thermocouple rake body, each thermocouple wire was spliced to a copper lead wire and led out of the instrumentation section through the centerbody. The gas sampling rakes are described in detail in the following section.

In this spool section, the shaft and its ten attached rakes are rotated by a bevel gear set at the aft end, driven by an external drive motor through a shaft inside a centerbody support pipe. Instrumentation lines are brought



a) Schematic of the Four-Manifold Fuel Supply and Control System



b) Photograph Showing the Four Fuel Manifolds Installed

Figure 14. Combustor Test Rig, Fuel Supply System.

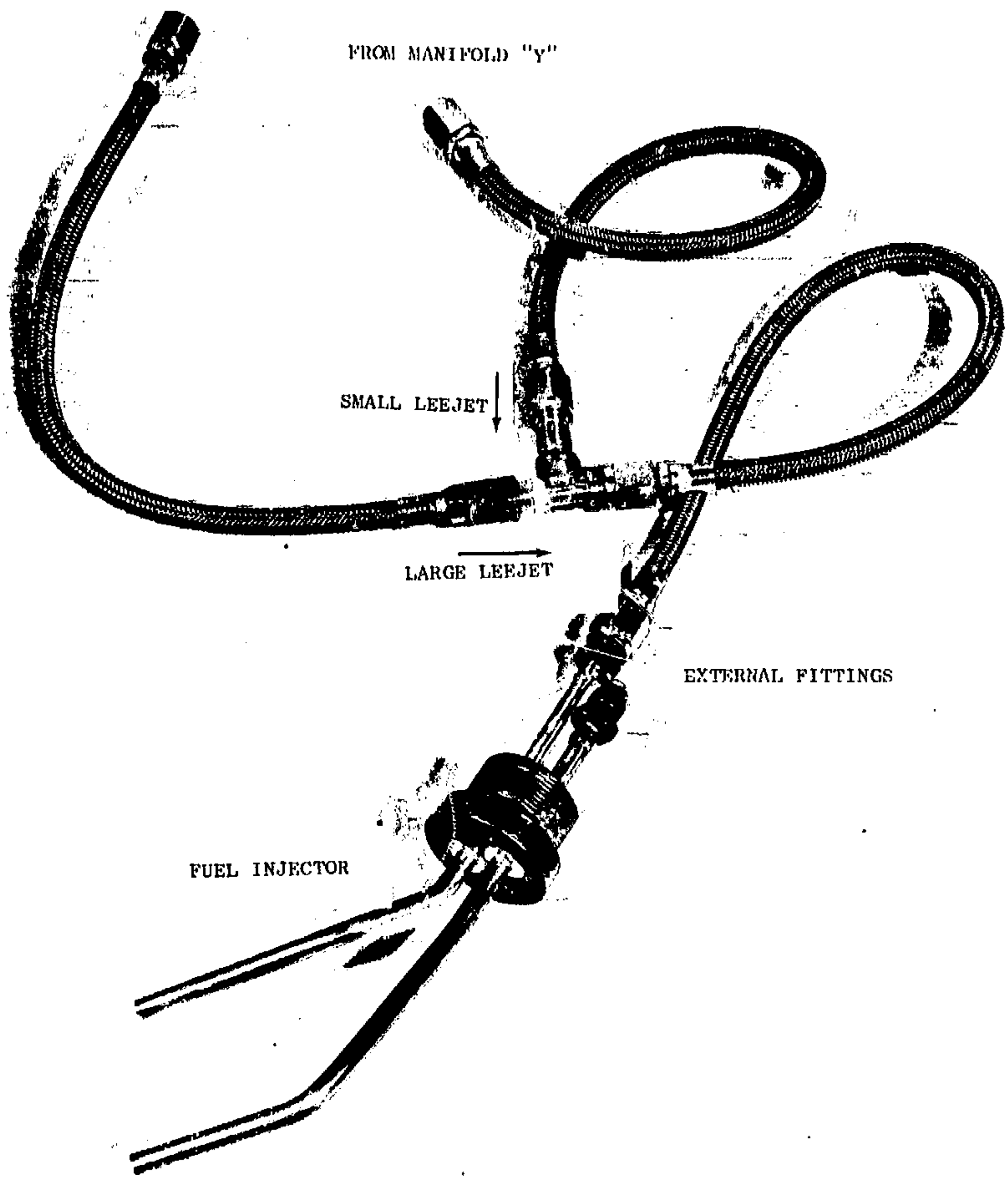


Figure 15. Typical Fuel Metering Hookup.

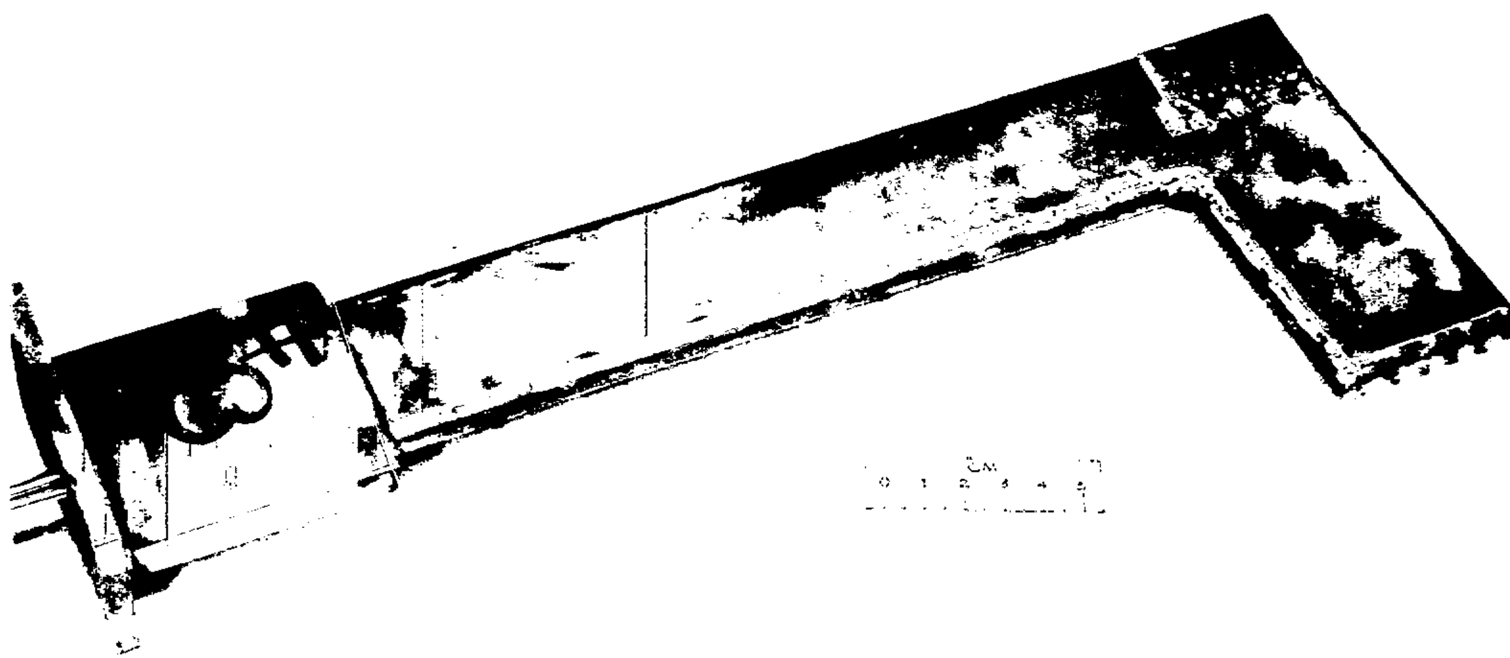


Figure 16. Combustor Exit Thermocouple Rake.

through other support pipes. This instrumentation spool also contains water spray rings to cool the combustion gases downstream of the measurement plane. A photograph of the instrumentation spool section with the ten rakes installed is presented in Figure 17. Local gas samples were extracted and total pressures were measured using the five gas sampling rakes.

Pollutant Emissions Sampling and Analysis System

The exhaust gas sampling and analysis system used in the Phase I Program experimental investigations was designed to provide a rapid determination of the emission levels of the various combustor configurations at a wide variety of test conditions. The sampling system consisted of a rotating rake traverse assembly, multielement gas sampling probes, heated transfer lines, a manifolding valve panel and the various gaseous and smoke emissions analyzers. The outputs from the CO, CO_2, HC and NO_x analyzers were electronically integrated with the test cell digital data acquisition system, which allowed all emissions data to be automatically recorded and reduced in the test cell in a matter of minutes.

One of the key components of this system was the rake traversing assembly. This traverse assembly, shown in Figure 17, contained 5 thermocouples and 5 gas sample rakes and was capable of rotating 72 degrees. Thus, gas samples could be extracted from any desired location within the combustor exhaust plane. The normal test procedure used in the Phase I Program investigations was to extract gas samples (and exit thermocouple data) at six-degree intervals in the exit plane. In this manner, 12 rake traverse positions were required to sample the entire combustor exhaust stream annulus.

The gas sample rakes used in this program contained five elements, or probes, with quick-quenching probe tips. In this design, both water cooling of the probe body and steam heating of the sample lines within the probe are used. A photograph of one of these rakes is shown in Figure 18. The assembly is shown schematically in Figure 19. Each of the five individual sampling elements was led out of the rake separately; there was no common manifolding of these sample lines within the sampling rake. The tips of each of these sampling elements were designed to quench the chemical reactions of the extracted gas sample as soon as the sample entered the rake. This quenching, or freezing, of the reactions was necessary to eliminate the possibility of further reactions within the sample lines. Water cooling of the rake body was required to maintain the mechanical integrity of the rakes in the high temperature, high pressure environment in which they operated. Steam heating of the sample lines within the rake, on the other hand, was needed to maintain these sample lines at a temperature high enough to prevent condensation of hydrocarbon compounds and water vapor within the sample lines.

With 5 sampling rakes with 5 elements each, a total of 25 gas sampling locations existed within the combustor exit plane at each angular position of the traverse assembly. Of the 25 available probe elements, however,

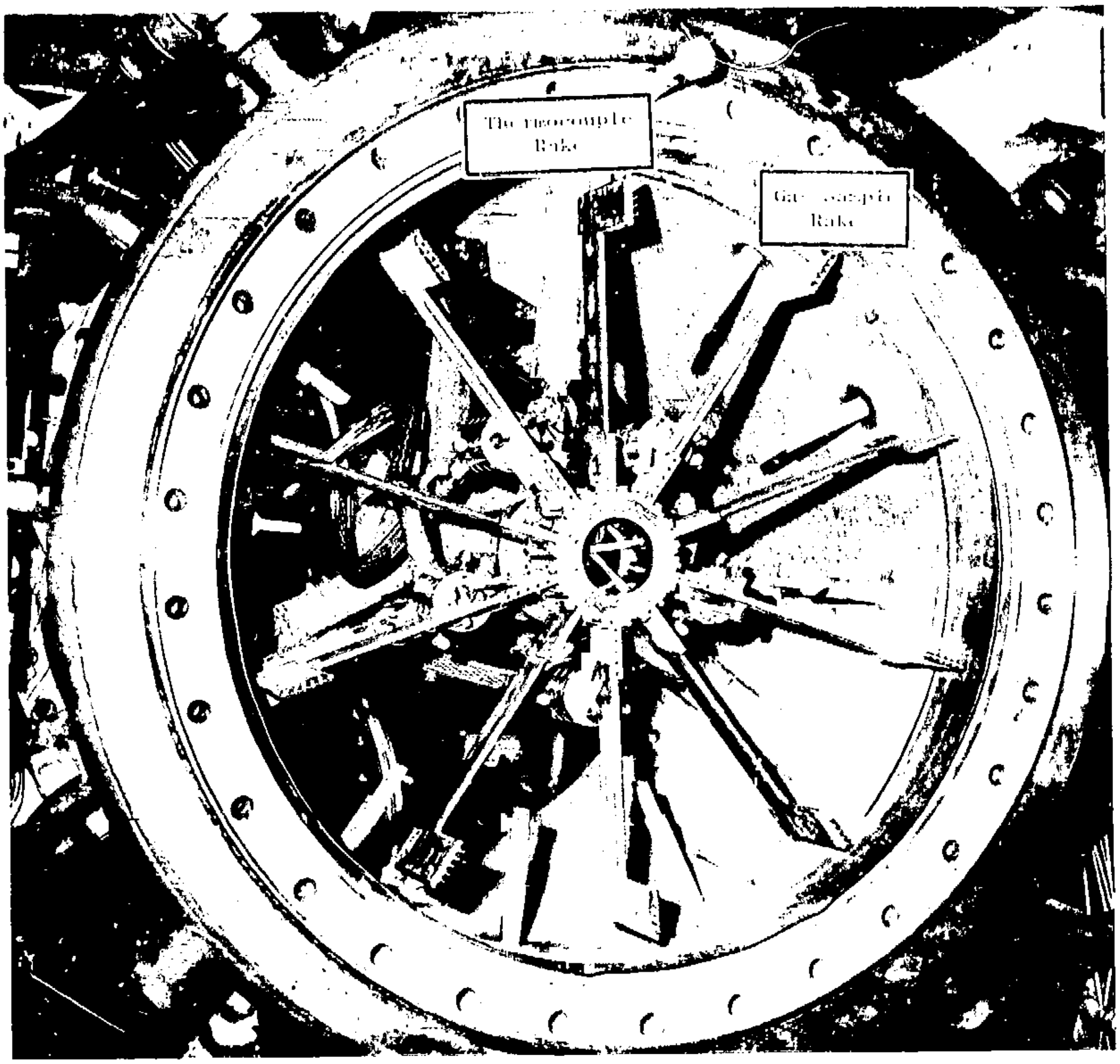


Figure 17. CF6-50 Combustor Exit Rake Traverse Assembly, with Phase 1 Program Rakes Installed.

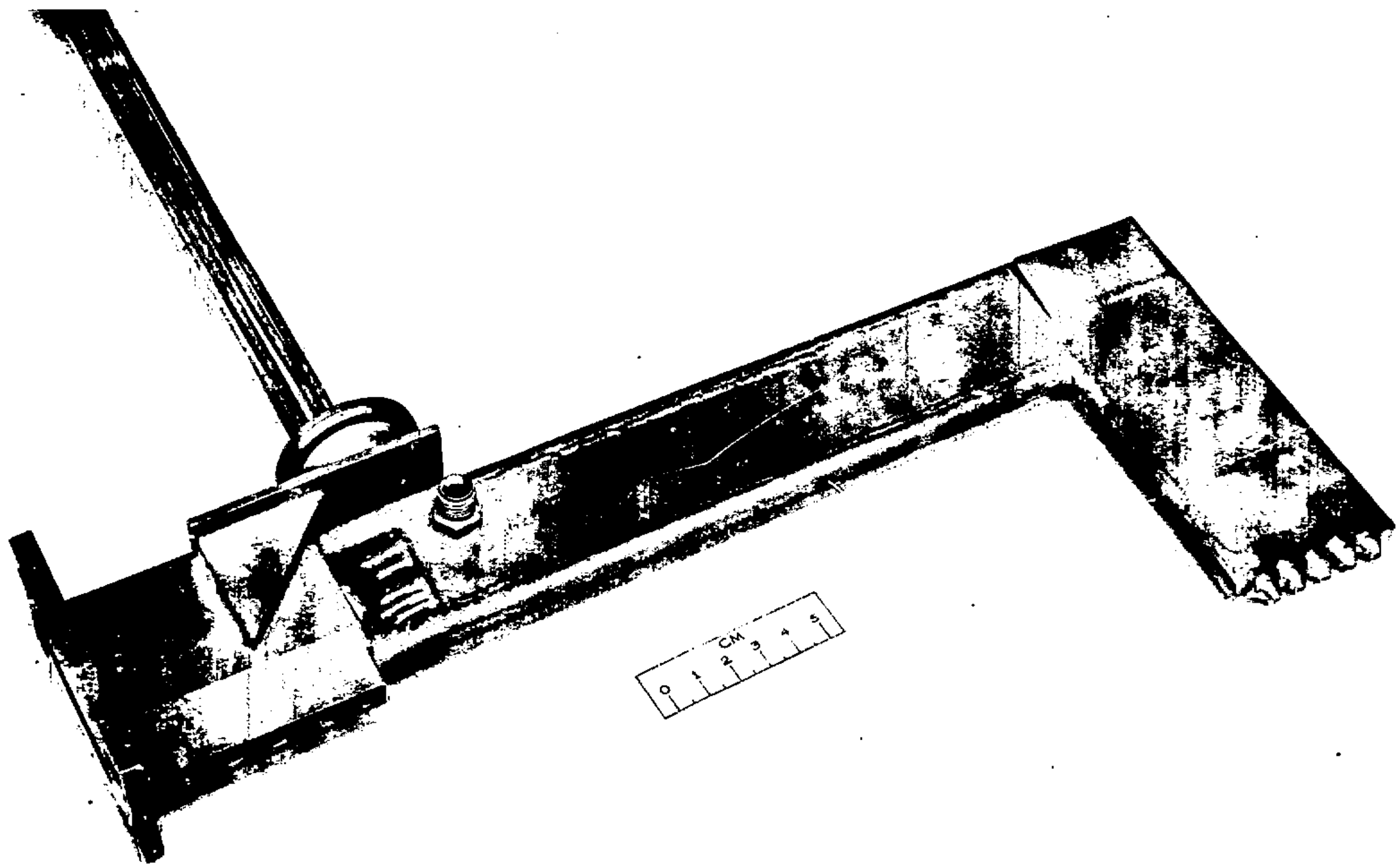


Figure 18. Steam-Heated, Water-Cooled Gas Sample Rake.

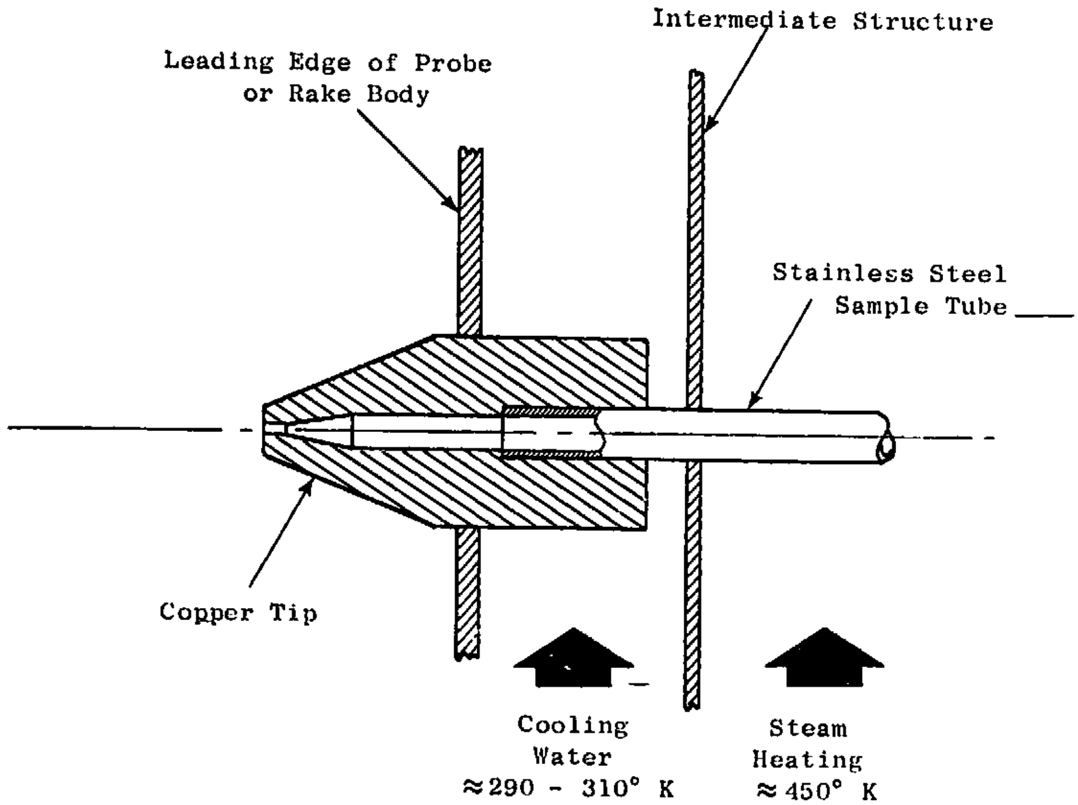


Figure 19. Steam-Heated, Water-Cooled Gas Sample Rake, Schematic.

only 15 were normally used for gaseous emissions sampling, with the remaining 10 elements used for combustor exit pressure measurements and smoke emission sampling. A selector valve in each of these latter ten sample lines allowed either smoke level or exit pressure data to be obtained at any selected angular position. The individual rake elements normally used for the various types of measurements are shown in Figure 20.

After leaving the rakes, the individual gas sample lines were led to a series of selector valves and then to the emissions analyzers. These lines were grouped into bundles of 5 lines (1 bundle for each gas sample rake) and each bundle was steam-traced from the individual rakes to the analyzers in order to maintain the sample line temperatures near 422° K. Each sample line was constructed of 0.64-cm diameter, 0.089-cm wall stainless steel tubing. Two thermocouples were installed in each tube bundle to monitor the temperature of the steam used for heating the sample lines. In addition, one sample line from each bundle was instrumented to provide a measurement of the pressure within the sample line. This pressure measurement provided assurance that sufficient flow was being drawn through the sample lines to quench the reactions at the probe tips.

In the test cell control room, the 25 individual sample lines were connected to a group of 3-way selector valves. At this panel, the selected sample streams for providing smoke level or pressure data were separated, by the valving arrangement, from those selected for gaseous emissions level determinations. By manipulation of the appropriate valves, any individual element or any desired combination of elements could be selected for the various types of measurements. The normal procedure used was to manifold the 15 selected streams shown in Figure 20 for gaseous emissions level determinations together at this control valve panel, thereby supplying one average gas sample to the emissions analyzers at each traverse position. This manifolding procedure was a very fast method of determining the average level of each of the various emissions of interest at each circumferential traverse position and alleviated the need to analyze each sample individually at every traverse position of a given test condition.

An existing on-line exhaust gas analysis system was used for determining the CO_2, CO, HC, NO and NO_2 concentrations of the exhaust gas sample streams. With this on-line system, the sample streams were continuously processed. A flow diagram of this system is shown in Figure 21.

The four basic gas analysis instruments of this on-line system are a flame ionization detector for HC emissions, two nondispersive infrared analyzers for CO and CO_2 emissions and a heated chemiluminescence analyzer for NO and NO_2 emissions. This analysis equipment is in general conformance with SAE ARP 1256 (Reference 1), except for the use of a chemiluminescence analyzer for NO_x emissions. The output signals of these analyzers were recorded both on a printed paper tape and into the digital data acquisition system of the test cell. With this latter data processing system, the output signals of the analyzers were continuously scanned and fed into an on-line computer.

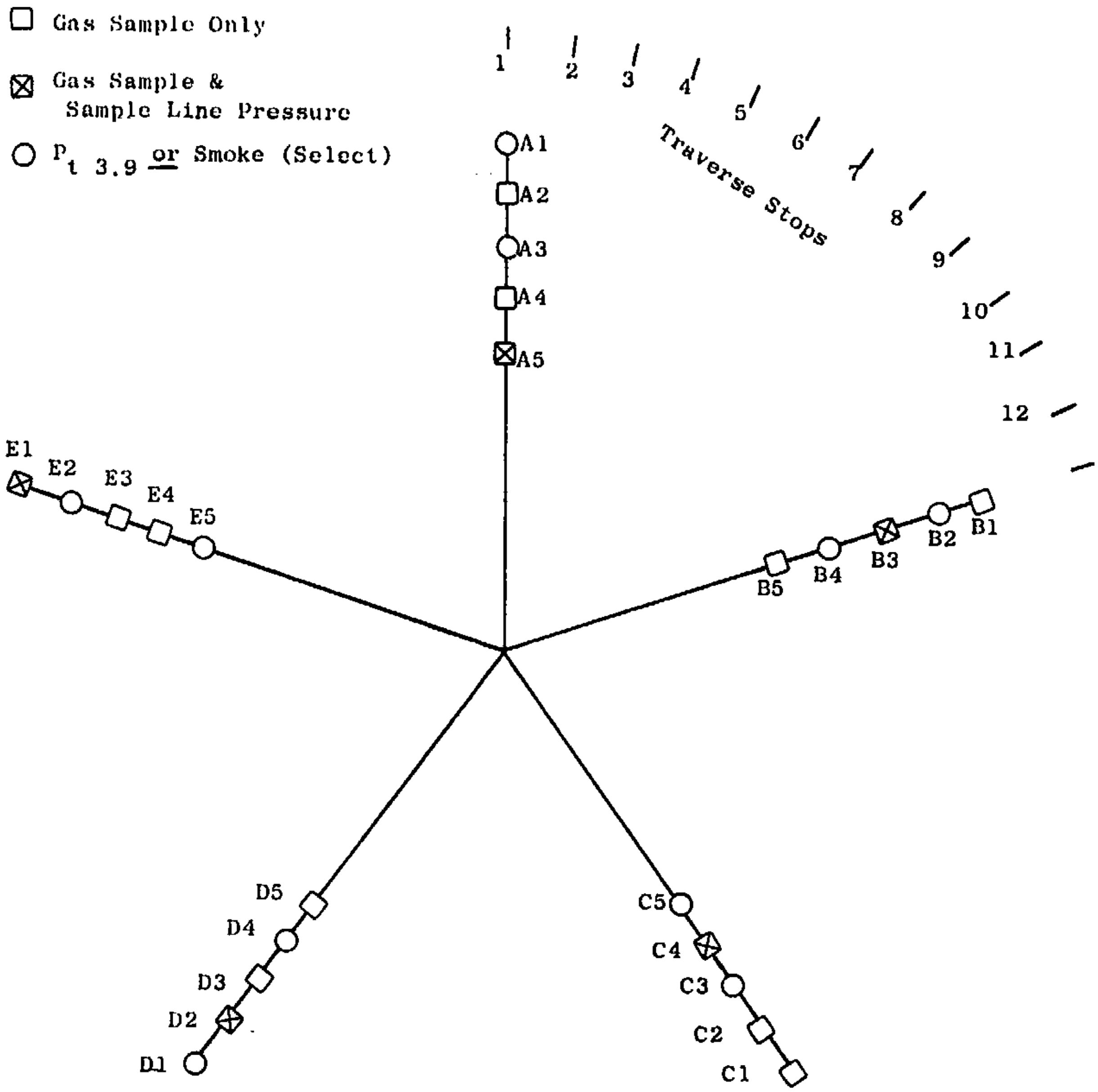
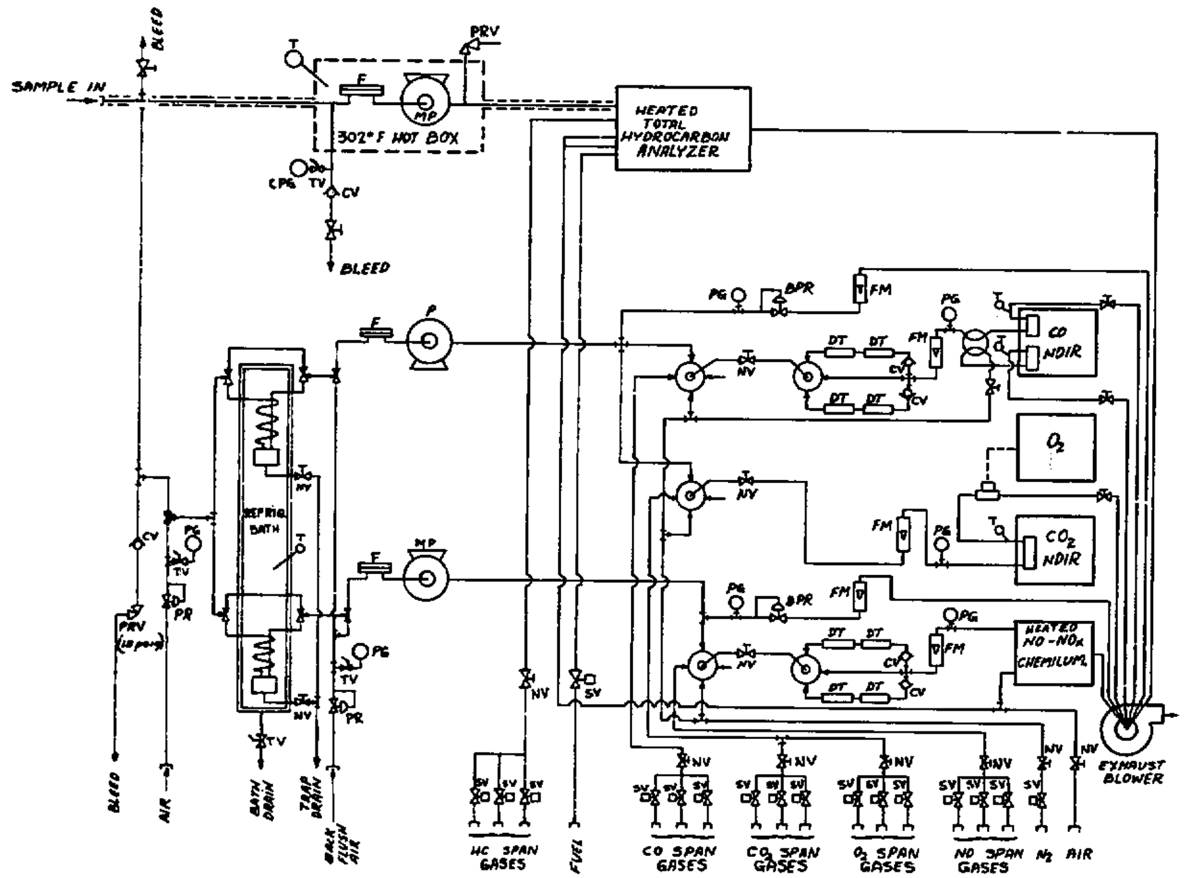


Figure 20. Gas Sample Rake Locations, Combustor Exit Plane, Aft Looking Forward.



LEGEND

BPR	-	Back Pressure Regulator
CPG	-	Compound Pressure Gage
CV	-	Check Valve
DT	-	Dryer Tube
F	-	Filter
FM	-	Flowmeter
MP	-	High Temperature Metal Bellows Pump-Mounted in Inverted Position
NV	-	Needle Valve
P	-	Pump
PG	-	Pressure Gage
PR	-	Pressure Regulator
PRV	-	Pressure Relief Valve
SV	-	Solenoid Valve
T	-	Temperature Indicator
TV	-	Toggle Valve

Figure 21. General Electric On-Line Exhaust Emissions Analysis System, Flow Diagram.

The smoke emissions data were obtained in this program using the standard General Electric filter stain method. The equipment used for these measurements is in conformance with SAE ARP 1179 (Reference 2).

More detailed information on the entire gaseous and smoke emissions sampling and analysis system is presented in Appendix B of this report.

Data Processing Systems

The data processing equipment permanently installed in Test Cell A3 includes a 900-channel digital data acquisition system, strip-chart recorders for continuous recording of up to 24 test parameters, displays of 22 pressures, displays of 24 temperatures and displays of 4 fuel flows for use by the operators in controlling test parameters, plus a small analog computer generally programmed to compute airflows and fuel-air ratios. Portable equipment includes a teletype terminal for the time-sharing computers. The valves used to regulate fuel flows, airflows, combustor air temperatures and combustor air pressures are remotely operated from the control room by means of pneumatic operators. Various elements of this control and data processing equipment were used in the tests of the Phase I Program.

Throughout the program, the combustor test data were recorded by the test cell digital data acquisition system. This apparatus scans each of the measured parameters in sequence, controlling the position of pressure scanning valves when required, converts the amplified DC signal of the measurement to digital form and records the value on a perforated paper tape suitable for input to the time-sharing computer through the teletype terminal. During each scan, the overall voltage accuracy is checked against a precision potentiometer that has been calibrated in a standards laboratory. The digital voltmeter and low level amplifier are of sufficient quality that voltages are accurate to 0.02 percent of full-scale in the 0-10 millivolt range.

All connections between data sensors and readout instrumentation, and all programming of the sequencing and control circuitry, were accomplished through interchangeable program boards. Thus, each test setup included its own prewired, preprogrammed front panel for rapid changeover from one circuit configuration to the next. A schematic of the data acquisition installation setup is shown in Figure 22.

As is mentioned above, the CO_2, CO, HC, NO and NO_2 analyzers of the gaseous emissions analysis system were also electronically integrated into this test cell digital data acquisition system. These emissions data from these analyzers were, therefore, transmitted to an on-line computer, as well as recorded on a printed paper tape.

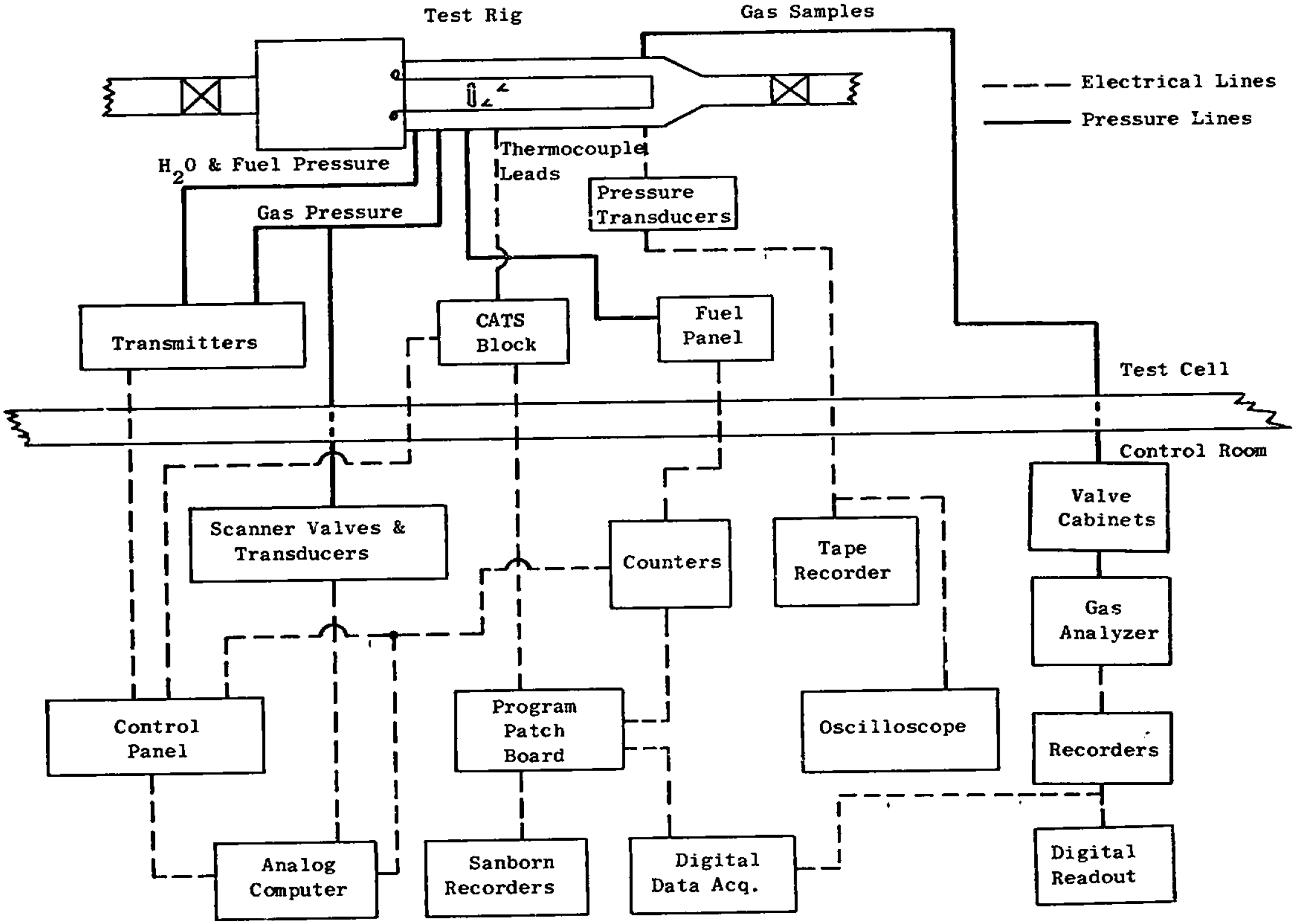


Figure 22. Test Facility Data Acquisition Schematic.

TEST AND DATA ANALYSIS PROCEDURES

The procedures employed in these Phase I Program investigations were designed for rapid screening of the various candidate combustor configurations. Each combustor configuration was tested over a range of simulated engine operating and parametric test conditions. The gas sampling system developed for these tests incorporated the latest in gas sample extraction and automated data processing systems technology and was based on the experience gained in numerous combustor component test programs conducted at General Electric. Detailed surveys were made of the combustor exit plane at all test conditions to accurately determine the emissions and performance characteristics of the experimental combustor configurations. These test procedures, along with the analytical procedures used to reduce and adjust the test data to standard CF6-50 engine operating conditions, are described in the following sections.

Test Conditions

The test conditions selected for the various combustor evaluations of these investigations represented actual engine operating conditions, simulated engine operating conditions and parametric variations about these operating conditions. The points which were most important during these tests were the CF6-50 engine standard day idle condition and the hot day takeoff condition, since the program goals for emissions and performance were specified at these cycle points. Other points of particular interest during testing were the CF6-50 hot day 30 percent power, hot day 85 percent power and standard day cruise conditions. In addition, selected configurations were tested at a typical AST supersonic cruise condition.

In these tests, the combustor inlet temperatures, reference velocities and turbine cooling air extraction rates of the CF6-50 engine were exactly duplicated. Combustor inlet pressure levels were also duplicated at the idle condition, but reduced pressure levels (relative to those of the engine) consistent with the air supply capacity were used at the higher power conditions. In these cases, the airflow rates were correspondingly reduced to maintain the true reference velocities. At the hot day takeoff condition, the air supply limit in these tests was 9.5 atm, compared to the engine pressure of 29.1 atm.

Turbine cooling airflow extraction rates, as in the CF6-50 engine, were duplicated in these tests. The extraction rates were 6 and 10 percent of the compressor discharge airflow from the outer and inner combustor flow passages, respectively.

Selected combustor configurations were tested over ranges of test conditions around the nominal idle and takeoff operating conditions. The following ranges of test conditions were investigated:

Idle

Inlet temperature: 366 - 589° K

Inlet pressure: 2.72 - 4.76 atm

Reference velocity: 14.6 - 21.3 m/s*

Takeoff

Inlet temperature: 644 - 866° K

Inlet pressure: 3.06 - 9.53 atm

Reference velocity: 18.9 - 29.6 m/s*

*Maximum attainable reference velocity

The purpose of these parametric tests was to better define the effects of combustor operating conditions on the pollutant emissions characteristics of the combustors. In addition, at all test conditions, data were obtained over ranges of combustor fuel-air ratios. At some fuel-air ratios, the effect of varying the fuel flow splits between combustor annuli or stages was also examined.

A matrix of the important test conditions is shown in Table VI. From this list of test conditions, a test point schedule was established for each combustor test configuration. In this manner, each test was tailored to the specific combustor under investigation in order to obtain the maximum benefit from the test. Very infrequently, test conditions not contained in Table VI were run if, during the course of a test, the need for an alternate point was apparent.

Test Procedures

In the elevated pressure tests, the test points were usually run in order of increasing combustor inlet temperature for safety considerations and to expedite testing. As test conditions were changed, the combustor pressure drop and the various combustor metal temperatures were monitored on multi-channel strip chart recorders to ensure that the established transient safety limits were not exceeded. When each test condition was set and stabilized, the data were recorded in two phases. First, the fixed combustor instrumentation (inlet air pressure and temperature, airflow, fuel flow, metal temperatures, exit pressure, etc.) was recorded. Then a survey of the numerous positions in the combustor exit plane was made, collecting detailed exit temperature and pollutant emissions data. The scope of the test instrumentation read on each test point is shown in Table VII.

Table VI. Experimental Clean Combustor High Pressure Test Conditions.

	Cycle Condition	P_{T3} atm	T_{T3} °K	W_3 kg/s	W_{comb} kg/s	W_f kg/hr	f	V_R m/s	$T_{T3.9}$ ideal °K	Comments
Engine Operating Conditions	Standard Day Idle	3.39	454	19.1	16.1	811	0.0140	19.5	970	True Engine Conditions
	Hot Day 30% Power	6.80	661	35.9	30.3	1526	0.0142	26.5	1172	P_{T3} cycle = 11.6 atm
	Standard Day Cruise	9.53	733	41.6	35.1	2649	0.0210	24.4	1449	P_{T3} cycle = 14.4 atm
	Hot Day 85% Power	9.53	825	40.3	34.0	2752	0.0225	26.5	1572	P_{T3} cycle = 25.3 atm.
	Std Day Takeoff	9.53	820	39.0	32.9	2742	0.0231	25.6	1586	P_{T3} Cycle = 29.8 atm
	Hot Day Takeoff	9.53	858	38.7	32.7	2880	0.0245	26.5	1659	P_{T3} cycle = 29.1 atm
Idle Parametric Test Conditions	-	3.38	454	23.9	20.1	1014	0.0140	24.4	970	Increased V_R
	-	3.38	454	14.3	12.1	608	0.0140	14.6	970	Reduced V_R
	-	3.38	454	19.1	14.9	862	0.0149	19.5	1022	Simulated 6% CDP Bleed
	-	3.38	454	19.1	13.8	911	0.0157	19.5	1044	Simulated 12% CDP Bleed
	-	3.38	366	23.6	20.0	1005	0.0140	19.5	883	Reduced T_{T3}
	-	3.38	589	14.7	12.4	626	0.0140	19.5	1105	Increased T_{T3}
Take-off Parametric Test Conditions	-	6.80	858	27.7	23.3	2057	0.0245	26.5	1559	Reduced P_{T3}
	-	6.30	858	19.7	16.6	1467	0.0245	18.9	1659	Reduced V_R
	-	6.80	858	32.4	27.4	2411	0.0245	31.1	1659	Increased V_R
	-	3.06	858	12.5	10.5	926	0.0245	26.5	1659	Reduced P_{T3}
	-	6.80	755	31.4	26.5	2337	0.0245	26.5	1583	Reduced T_{T3}
	-	6.80	644	36.9	31.1	2742	0.0245	26.5	1500	Reduced T_{T3}
AST Cruise Test Conditions	-	6.80	833	34.4	29.0	2400	0.023	32.0	1589	Typical AST V_R
	-	6.80	833	28.9	24.4	2021	0.023	26.5	1589	CF6-50 V_R

At above conditions, the following ranges of parametric fuel-air ratios were investigated:

Idle	f = 0.006 to 0.032
30% Power	f = 0.014 to 0.030
Cruise	f = 0.012 to 0.025
Climbout	f = 0.014 to 0.025
Takeoff	f = 0.012 to 0.025
AST	f = 0.018 to 0.025

Table VII. Combustor/Rig Instrumentation.

Parameter	Instrumentation
Total Airflow	Standard ASME Orifice
Bleed Airflow	Standard ASME Orifice
Fuel Flow	Turbine Flow Meters
Fuel Injector Pressure Drop	Pressure Tap in Each Fuel Manifold
Fuel Temperature	Thermocouple in Fuel Manifold
Diffuser Inlet Total Pressure	4 5-Element Fixed Impact Rakes
Diffuser Inlet Static Pressure	4 Wall Static Taps
Diffuser Inlet Total Temperature	2 Thermocouples on Each P_T Rake
Combustor Exit Total Temperature	5 5-Element Thermocouple Traverse Rakes
Combustor Exit Emissions Levels	5 5-Element Impact Traverse Rakes
Combustor Exit Total Pressure	2 Elements on Each Emissions Rake
Combustor Metal Temperature	Minimum of 12 Thermocouples on Dome and Liners Plus Temperature Sensitive Paints
Inlet Air Humidity Level	Dew Point Hygrometer
Combustor Passage Static Pressure	3 Wall Taps in Each Passage (6 Total)
Combustor Dome Pressure Drop	4 Pressure Taps
Gas Sample Line Pressure	Pressure Tap in One Gas Sample Line from Each Rake at Rig/Cell Interface (5 Total)
Gas Sample Line Temperature	2 Thermocouples in Each Steam-Heated Tube Bundle, One at Rake/Tube Bundle Interface, One at Rig/Cell Interface (10 Total)

The normal test procedure was to obtain exit thermocouple and emissions data at six-degree intervals around the combustor exit annulus. With the rake traversing assembly used in this program, 12 traverse positions were required to sample the entire exhaust plane. On those tests where acoustic measurements were taken, this procedure was altered somewhat. With the downstream acoustic probe installed in the combustor exit plane, the travel of the rotating rake assembly was limited to 30 degrees. Therefore, on these tests, data were taken in three-degree increments around the exit annulus, at 10 rake positions.

In addition to these elevated pressure tests, the ground start ignition characteristics of three combustor test configurations were also evaluated. The ignition tests were originally planned to be conducted in two parts. Initially, the sea level ignition capabilities were to be investigated over a range of airflows. Then, with promising configurations, the altitude relight characteristics were to be determined over a range of windmilling conditions associated with the CF6-50 altitude flight map. However, of the three configurations eventually selected for sea level ignition testing, none was deemed sufficiently promising at this stage of their development to warrant the altitude relight investigations.

To determine the sea level ignition characteristics of the selected designs, the combustor test vehicle was exhausted to the atmosphere, thus allowing visual observation of the ignition attempts. A prescribed combustor airflow, within the range of starting airflows of the CF6-50 engine, was set with ambient temperature inlet air. The fuel flow was slowly increased and ignition attempted. The fuel flow was recorded where one cup was lit, where 50 percent propagation occurred and where 100 percent propagation occurred. The fuel flow was then decreased and the condition where one cup was out, where 50 percent of the cups were out and where lean blowout occurred was recorded. While maintaining the same inlet conditions, this process was repeated several times with both the hydrogen torch and the electrical spark ignitor. When sufficient data repeatability was achieved, a second, third, and sometimes fourth combustor airflow was set, and the entire procedure was repeated at each new condition. This test procedure is identical to that employed during the ground start testing currently conducted on the current production CF6-50 engine combustor.

Pollutant Emissions Measurement Procedures

As is described in the preceding section, 15 individual elements (3 elements per rake) were usually used for the gaseous emissions level measurements. Because of the extensive amount of time that would have been required to individually analyze samples obtained from each of these elements at every traverse position of every combustor test point, some type of sample manifolding was always employed. Previous combustor component test programs at General Electric have shown that, when done properly, the sample manifolding concept provides emissions levels that are in close agreement with those determined from measurements of many individual samples.

Because of the wide variations in fuel staging techniques which were investigated as a part of this program, various exhaust gas sample manifolding techniques were employed. The normal procedure was to manifold together only gas samples which had nearly equal sample emissions concentrations, in order to provide properly weighted results. During normal fueling points (combustor fueled uniformly) all the various gas samples could be manifolded together. On points where only one annulus or stage was fueled, only samples from the same radial immersion were combined, due to the large radial emissions concentration gradients which could exist. On points where only a sector of the combustor was fueled, only samples taken from the same circumferential position were manifolded together because of the strong circumferential variations.

CO, CO_2, HC and total NO_x emissions levels were determined in all instances. At some special test conditions, NO and NO_2 emissions levels were also separately determined. Additional details on these gaseous emissions sampling procedures are presented in Appendix B of this report.

During some of these combustor tests, smoke emissions levels were also measured at selected test points of interest. These levels were generally not measured in tests where the maximum combustor inlet pressure level was less than seven atm since the smoke levels at such low pressure levels would be too low to be accurately determined. The smoke levels of the CF6-50 production combustor are already very low and the smoke levels of the various Phase I Program combustor configurations were expected to be even lower. Thus, smoke emissions characteristics were generally not considered to be of major concern. At those conditions where smoke data were acquired, samples were usually extracted from the combustor exit plane with ten elements, as shown in Figure 20. These ten elements were manifolded together to provide one average sample to the smoke measurement console. At least three smoke spots were taken at each test condition and the average SAE Smoke Number for this operating point was determined from the average of these three spots.

The normal General Electric procedure for measuring smoke levels is to extract several 0.0057 cubic meter samples, but due to the low smoke levels of most of the combustor configurations of this program, larger samples of 0.0198 cubic meter were used. With this size sample, more accurate reflectance measurements of the smoke spots could be obtained because the spots were darker.

Combustor Performance Data Processing Procedures

A summary of the important combustor operating performance parameters which were measured or calculated is shown in Table VIII. Most of the parameters and equations of this table are self-explanatory, but a few items require further clarification:

- By General Electric convention, reference velocity is based on total inlet airflow, total inlet density and casing cross-sectional

Table VIII. Summary of Measured and Calculated Combustor Parameters.

Parameter	Symbol	Units	Measured	Calculated	Value Determined From
Inlet Total Pressure	P_{T3}	atm	X		Average of measurements from 5 immersions on 4 rakes (20 total)
Exit Total Pressure	$P_{T3.9}$	atm	X		Average of measurements from 2 immersions on 5 rakes (10 total)
Total Pressure Loss	$\Delta P_T/P_{T3}$	%		X	$100\ (P_{T3} - P_{T3.9})/P_{T3}$
Total Pressure Loss @ SLTO	$\Delta P_T/P_{T3}$@ SLTO	%		X	$(\Delta P_T/P_{T3})(99.6/W_c)^2\ (P_{T3}/29.06)^2\ (858/T_{T3})$
Total Inlet Airflow	W_3	kg/s	X		ASME orifice
Combustor Bleed Airflow	W_{bleed}	kg/s	X		ASME orifice
Combustor Airflow	W_c	kg/s		X	$W_3 - W_{bleed}$
Reference Velocity	V_R	m/s		X	$W_3/\rho_{T3}\ A_R = 0.0248\ W_3\ T_{T3}/P_{T3}$
Total Fuel Flow	W_f	kg/hr	X		Turbine flowmeter
Outer Annulus Fuel Flow	W_{f_o}	kg/hr	X		Turbine flowmeter
Inner Annulus Fuel Flow	W_{f_i}	kg/hr	X		Turbine flowmeter
Overall Metered Fuel-Air Ratio	f_m	–		X	$W_f/3600\ W_c$
Outer Annulus Fuel-Air Ratio	f_{m_o}	–		X	$W_{f_o}/3600\ W_c$
Inner Annulus Fuel-Air Ratio	f_{m_i}	–		X	$W_{f_i}/3600\ W_c$
Inlet Air Humidity	H	g/kg	X		Dew point hygrometer
Inlet Total Temperature	T_{T3}	° K	X		Average of measurements from 2 immersions on 4 rakes (8 total)
Exit Total Temperature	$T_{T3.9}$	° K		X	Combustion temperature rise curves, using P_{T3}, T_{T3}, f_m, G/S
Pattern Factor	PF	–		X	$(T^{*}_{T3.9,\ max} - T_{T3.9,\ avg})/(T_{T3.9\ avg} - T_{T3})$ - from thermocouples
Profile Factor	Pr F	–		X	$(T^{**}_{T3.9,\ immersion\ average,\ max} - T_{T3})/(T_{T3.9\ avg} - T_{T3})$ - from thermocouples

*Maximum individual exit temperature measured.

**Maximum of the average exit temperatures calculated at each radial immersion.

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area at the dome exit. For the CF6-50 flowpath, this reference area is 3729 cm^2.

- Each combustor exit temperature was computed from the metered fuel-air ratio and averaged gas sample combustion efficiency (with measured inlet temperature and standard thermodynamic charts). Thermocouple data, when available, were used to compute exit temperature profile factors and pattern factors. No radiation or convection corrections were applied to these thermocouple data. Correction factors could now be deduced from the gas sample data.

Emissions Data Processing Procedures

The voltage responses of the CO, CO_2, HC and NO_x analyzers were read at each traverse position of a given test condition with the test cell digital data acquisition system, as described previously. These data were transmitted directly to an on-line data reduction computer for calculation of the emissions concentrations, the emission indices, the combustion efficiency and the fuel-air ratio of the gas sample at each traverse position. A new emissions data processing and reduction program was specifically developed for this purpose as a part of the Phase I Program. With these capabilities, a normal 12-position manifolded traverse could be connected in about 15 minutes and reduced gaseous emissions data were available within another 10 to 15 minutes.

The equations used for these calculations were basically those contained in SAE ARP 1256 (Reference 1). In these calculations, the CO and CO_2 concentrations were corrected for the removal of water from the sample before its analysis. Aviation kerosene (JP-5 fuel) was used throughout these tests. Therefore, a typical value for n (fuel hydrogen-to-carbon atom ratio) of 1.92 was used in these calculations. Frequent fuel analyses, obtained throughout the test series, confirmed this value.

Based on the individual gas sample emission index, fuel-air ratio and combustion efficiency values at each traverse location, the overall average emission indices, sample fuel-air ratio, and combustion efficiency for the test condition were then determined by mass averaging. These averaged values are the values presented in the numerous data tables and figures throughout this report.

Pollutant Emissions Data Adjustment Procedures

Correlations relating pollutant emissions levels to combustor operating conditions were used in this program to:

- Extrapolate data from the reduced pressure test conditions to the full engine operating pressure.

- Extrapolate test data to combustor inlet air temperatures, which could not be obtained during a test due to combustor safety limitations.

- Normalize a range of test data to a single standard test condition.

In studies conducted at General Electric and elsewhere, NO_x levels have been found (empirically) to increase: (1) exponentially with increases in combustor inlet temperature; (2) exponentially with decreases in inlet air humidity; (3) linearly with increases in combustor residence time; and, (4) directly with the square root of combustor inlet pressure. In the General Electric studies, the following functional relationships have been found to best describe the NO_x formation processes:

$$NO_x \propto \exp(T_{T3}/169) \qquad (T_{T3} \text{ in } ^\circ K)$$

$$\propto \exp(-0.0188H) \qquad (H \text{ in g water/kg air})$$

$$\propto t_{res} \qquad (\text{or } \frac{1}{V_R} \text{ for a fixed combustor length})$$

$$\propto (P_{T_3})^{0.5}$$

These empirical correlations have been found to be in excellent agreement with the relationships predicted by a complex, analytical NO_x emissions computer model developed at General Electric.

It has also been found experimentally that NO_x levels, at a given set of inlet conditions, are highly dependent upon combustor fuel-air ratio and combustor design. The NO_x emissions characteristics of rich primary zone combustor designs, such as the production CF6-50 engine combustor, have been found to decrease with increases in fuel-air ratio. However, the NO_x levels of lean primary zone designs, such as those tested in this program, have been found to increase with fuel-air ratio. The slope of this increase is highly dependent upon specific combustor design features. Thus, no generalized fuel-air-ratio correlation factors have been developed.

Using the pressure, temperature, reference velocity and humidity relationships shown above, NO_x emissions data acquired at any test condition can be extrapolated to any other test condition of interest (at the same fuel-air ratio). In this program, the conditions of most importance from a NO_x emissions standpoint were the hot day takeoff and AST cruise operating conditions. The combustor inlet conditions for these cycle points are:

	P_{T3} atm	T_{T3} °K	V_R m/s	H* g/kd
Hot Day SLSTO	29.06	858	26.5	6.29
AST Cruise	6.80	833	26.5	6.29

*General Electric's procedure is to adjust NO_x data to a humidity level of 6.29 g/kg (corresponding to 60 percent relative humidity on a standard day).

The above relationships were used in this program to extrapolate the measured data to these test conditions. The general procedure used in this program was to extrapolate all NO_x emissions data to the hot day takeoff condition, plot it versus fuel-air ratio and then determine the true takeoff level at the correct fuel-air ratio (0.0245).

The effects of combustor operating conditions on CO and HC emissions levels are not as predictable as those for NO_x. Both CO and HC levels are known to decrease with increasing inlet temperature and pressure and to increase with increasing reference velocity. In previous studies conducted at General Electric, the CO and HC levels have been found to correlate well with an exponential function of inlet temperature, a power function of inlet pressure and a linear function of reference velocity. However, the exact functional relationships describing these changes have been found to be highly dependent upon the combustor configuration being evaluated. Some combustor configurations have been found to be very sensitive to changes in inlet conditions, while other configurations were much less sensitive.

In the Phase I Program, the engine operating conditions of most interest from a CO and HC emissions standpoint were the standard day idle conditions. This operating condition was exactly duplicated in the tests. Thus, no extrapolation of these data was required. At most of the simulated high power operating conditions of interest, the various test configurations operated with very high combustion efficiencies and correspondingly low CO and HC levels. Extrapolation to true engine conditions would have resulted in even lower CO and HC levels. Some tests of the Radial/Axial Staged Combustor, however, produced higher quantities of CO and HC at the simulated high power operating conditions. Because of the significant levels of these emissions, in some cases, at these conditions an empirical method of extrapolating the data to the actual engine pressure levels was developed.

REFERENCES

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

2. "Aircraft Gas Turbine Engine Exhaust Smoke Measurement," SAE Aerospace Recommended Practice 1179, May 1970.

CHAPTER III. BASIC PHASE I PROGRAM

INTRODUCTION

The objective of the basic Phase I Program was to identify, define and develop promising combustor design approaches with significantly lower CO, HC, NO_x and smoke emissions levels than those of current technology combustors for use in advanced CTOL commercial transport aircraft engines. Thus, the efforts of this program were involved with the screening and evaluation of a large number and variety of combustor design concepts. These efforts were specifically directed toward defining advanced combustors for use in the General Electric CF6-50 engine, although the resulting combustor design technology was intended to be generally applicable to all advanced engines in the large thrust size category.

The pollutant emissions objectives of these efforts were each defined at specific CF6-50 engine operating modes. The target levels are shown in Table I, where they are compared to the emissions levels of the current production CF6-50 engine at the same operating modes. As is shown by this comparison, major reductions in the levels of the three gaseous pollutant emissions are needed to meet these target values. The key combustor performance objectives of these efforts were, essentially, to maintain the same high performance levels in the low emissions combustors as are obtained with the current production CF6-50 combustor.

The key task elements of the basic Phase I Program involved the definition of advanced combustor design approaches, the aeromechanical design of CF6-50 engine-size versions of these approaches, the fabrication of full annular versions of these designs and the development testing of these full annular combustor configurations. The combustor configurations were all designed to fit within the combustor housing of the current production CF6-50 engines and were evaluated, at elevated pressures, in a test rig which exactly duplicates the combustor housing of the engine.

The basic Phase I Program effort was comprised of two program elements, which were carried out in parallel. Program Element I involved the design, fabrication and test of CF6-50 engine-size combustors with various NASA Swirl-Can-Modular dome configurations. A schematic illustration of this family of combustor test configurations is presented in Figure 23. Versions of this type of combustor design with arrays of 60, 72 and 90 swirl cans, with various types of swirl-can flameholder devices, with various fuel injection devices and with various types of fuel injection staging were evaluated. In total, 17 combustor configurations were tested as a part of Program Element I.

Program Element II involved the design, fabrication and test of CF6-50 engine-size combustors with other types of advanced dome configurations. The three basic families of configurations which were evaluated in this program element were the Lean Dome Single Annular Combustor, the Lean Dome Double

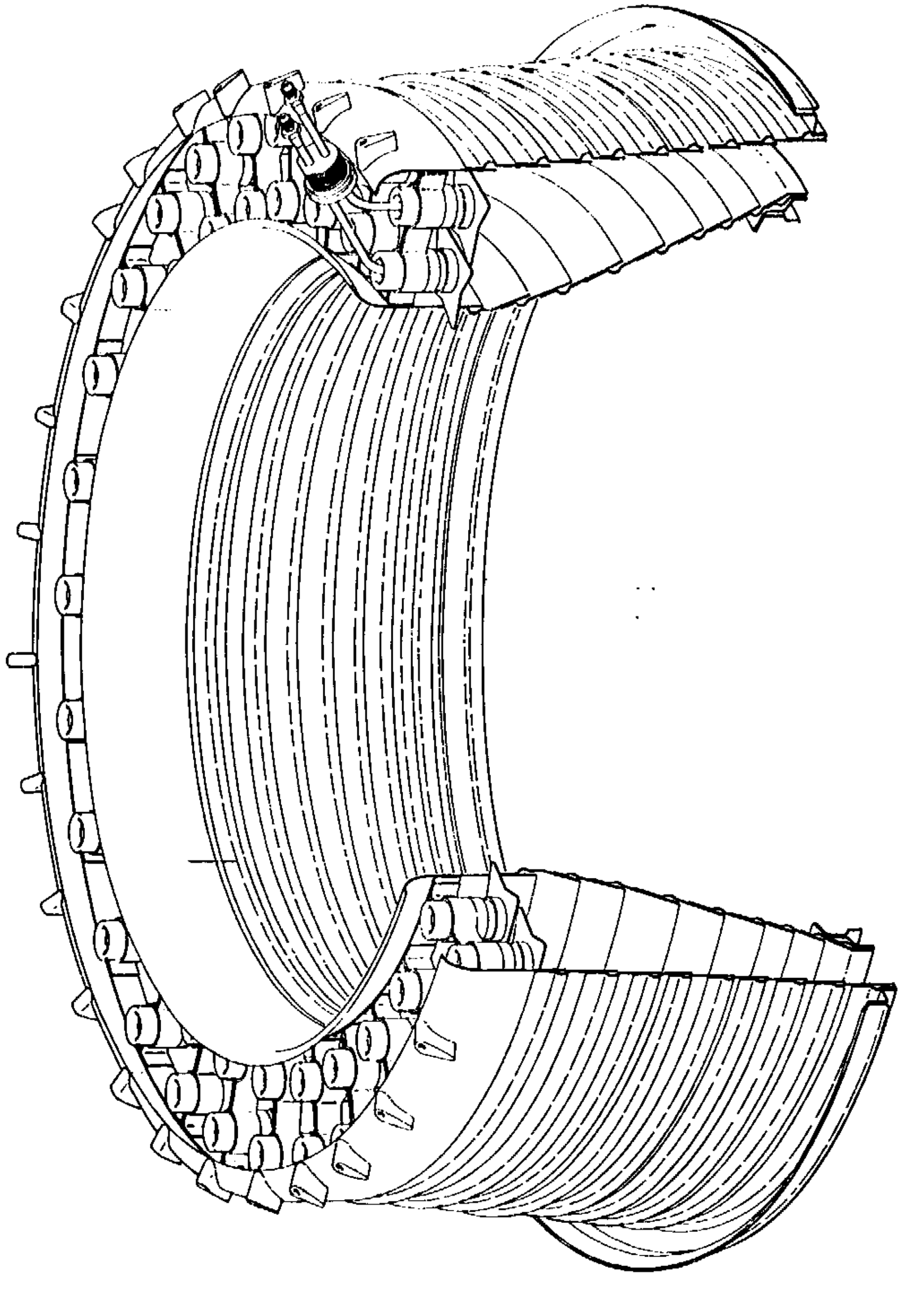


Figure 23. Swirl-Can-Modular Combustor for CF6-50 Engine.

Annular Combustor and the Radial/Axial Staged Combustor. Schematic illustrations of these CF6-50 combustor design approaches are presented, respectively, in Figures 24, 25 and 26. Versions of each of these combustor types with various combustor airflow splits and with various other configuration modifications were evaluated. In total, 17 combustor configurations were tested as a part of Program Element II.

An extensive quantity of testing was completed in this basic Phase I Program. In each program element, 17 combustor test configurations were evaluated. Combined, data were obtained at a total of 733 individual test points in 43 individual test runs. The total test data acquisition time involved in obtaining these data was over 220 hours.

In the following sections of this chapter, descriptions of the various combustor test configurations, descriptions of the measured pollutant and performance characteristics of these combustors and assessments of the results of these design and development efforts are presented.

COMBUSTOR TEST CONFIGURATIONS

Program Element I Combustor Test Configurations

The Program Element I combustor configurations consisted of various versions of Swirl-Can-Modular Combustors, all sized for use in the CF6-50 engine. The Swirl-Can-Modular Combustor design concept was developed at the NASA-Lewis Research Center for application in advanced turbojet engines. This combustor design concept consists of a modular array of carbureting swirl cans, each with an axial air swirler and a flame-stabilizing plate. Each module contains features to premix the fuel with air in the carburetor, swirl the fuel-air mixture, stabilize combustion in the swirl-can wake and provide interfacial mixing areas between the bypass air through the swirl-can array and the hot gases in the wake of the swirl-can modules. In such Swirl-Can-Modular Combustor designs, a large number of swirl cans, arranged in several annuli within the dome, are utilized.

The various Program Element I designs were intended to build upon the NASA Swirl-Can-Modular Combustor experience and to identify design features capable of providing further reduced CO, HC and NO_x emissions levels for this combustor design approach. They were, however, constrained to fit into the current CF6-50 engine flowpath envelope and to use the production CF6-50 combustor cooling liners. The Program Element I Swirl-Can-Modular Combustors were, thus, designed for a significantly different engine application and engine cycle than those of the previously conducted NASA investigations. Therefore, some differences in design were necessary. A comparison of several key design features of the CF6-50 size designs with those of typical NASA designs is shown in Table IX.

The most significant differences in the two sets of designs are in the number of dome annuli, the size of the swirl cans and the module air loading.

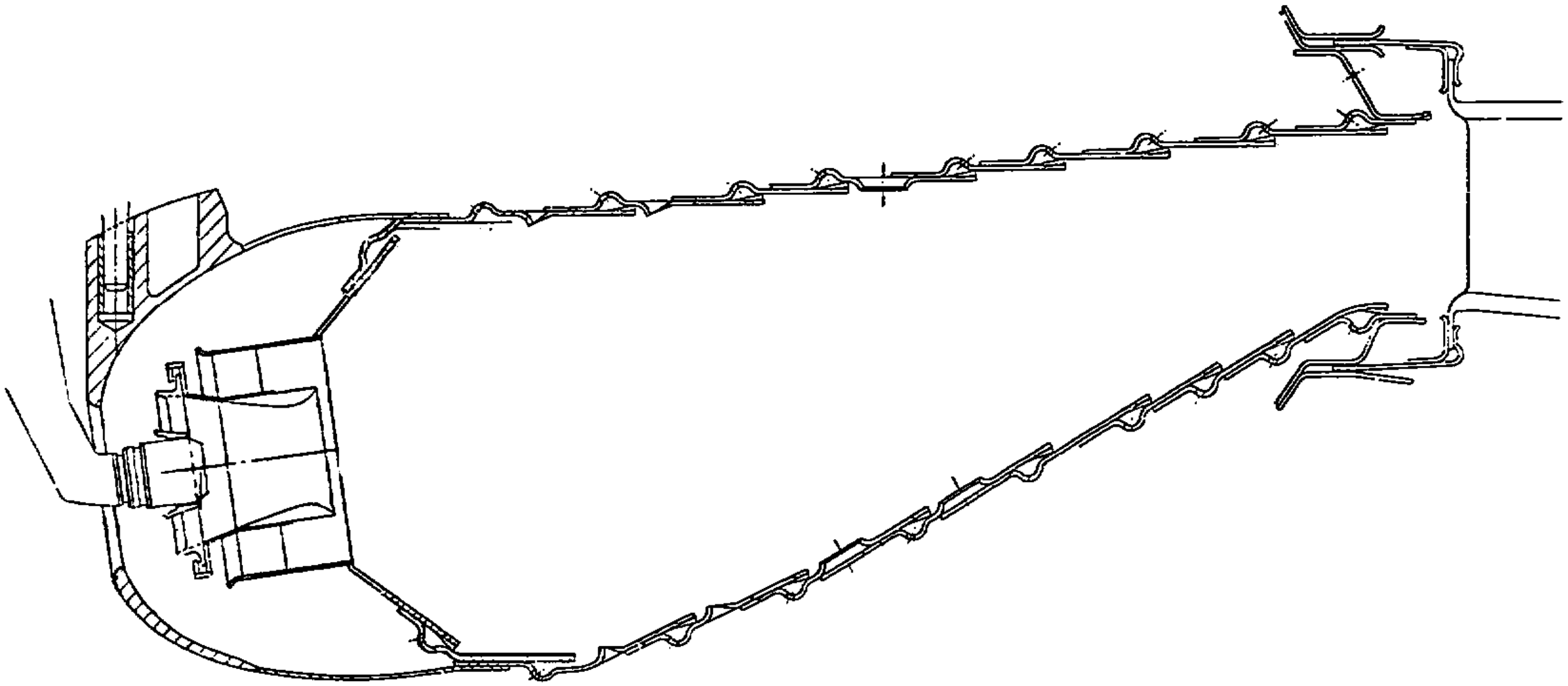


Figure 24. Lean Dome Single Annular Combustor for CF6-50 Engine.

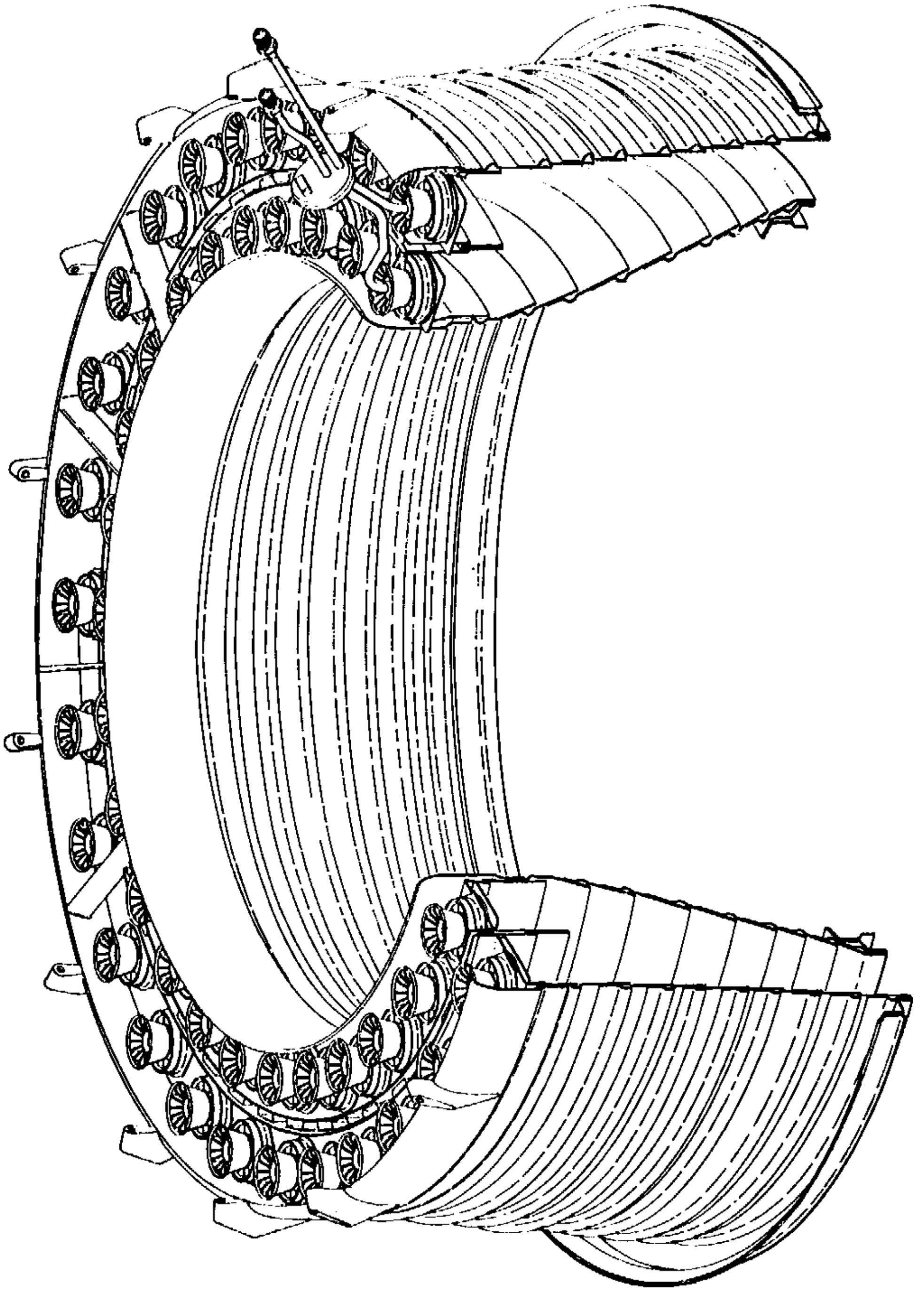


Figure 25. Lean Dome Double Annular Combustor for CF6-50 Engine.

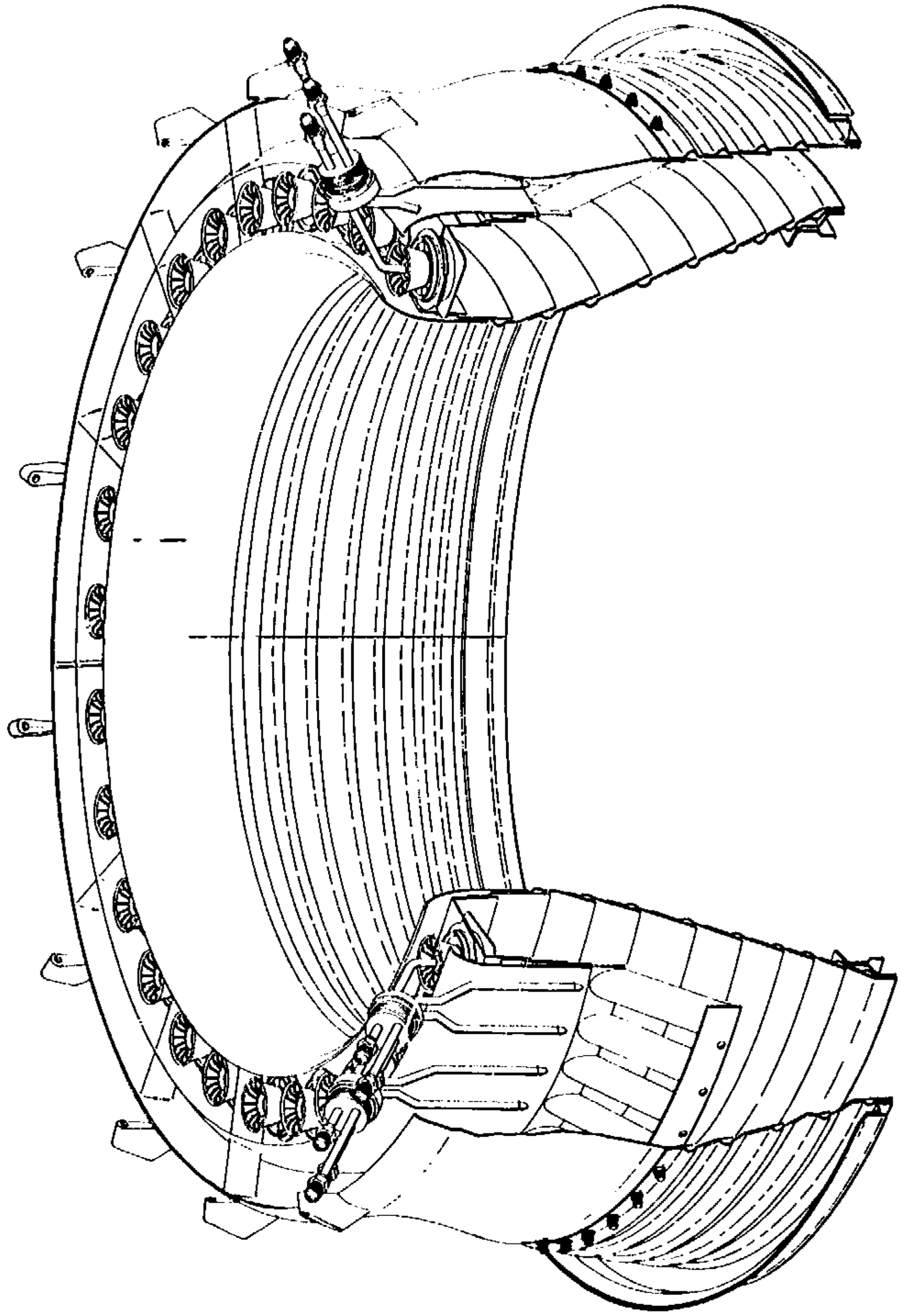


Figure 26. Radial/Axial Staged Combustor for CF6-50 Engine.

Table IX. Comparison of GE Swirl-Can Combustors with Typical NASA Designs.

	NASA*	GE	Basis
Number of Dome Annuli	3 or 4	2	Use of CF6-50 production cooling liners
Number of Swirl Cans per Annulus	Varied	Equal	Fuel injection system complexity
Diameter of Swirl Cans, cm	3.81	3.18	Common diameter for all GE Swirl-Can Combustors. Largest diameter to accommodate 45 cans on inner annulus. Largest diameter to accommodate counterswirl on 72-Swirl-Can Combustor.
Length of Swirl Cans, cm	3.81	6.35	Additional margin for fuel containment (per NASA suggestion)
Flame Stabilizer Shape	Flat, Hex, Star Conical	Flat, Star Conical	Required dome blockage, extended flameholder perimeter
Swirl-Can Air Loading, kg/s-atm-can	0.094	0.056	CF6-50 cycle requirement
Fuel Injector Source Spacing	Approximately Square	Approximately Square	GE and NASA experience
Type Air Swirler	Axial, Windmill	Axial, Windmill	GE and NASA experience, ease of fabrication
Fuel Injection Technique	Tangential Low Pressure	Axial Low Pressure	Installation considerations

*References 1, 2, 3

The use of a two-row dome design in the CF6-50 combustor configuration (rather than three or four rows, as in the earlier NASA designs) was dictated by the geometric constraints of the CF6-50 engine flowpath and the diameters of the combustor cooling liners. To obtain an approximately square array of fuel sources, an array in which each swirl-can flameholder is approximately square in shape, the baseline CF6-50 Swirl-Can-Modular Combustor design incorporated 72 swirl cans, 36 in each row. This provided a radial spacing of 5.87 cm, and a circumferential spacing of 5.38 cm on the inner annulus and 6.40 cm on the outer annulus. The use of fewer fuel injection sources than those used in this baseline design was expected to improve the idle emissions (CO and HC) levels of this baseline combustor, while the use of more injectors was expected to reduce the NO_x emissions. Consequently, a 60-swirl-can configuration and a 90-swirl-can configuration were also defined. With the 60-swirl-can dome array, the dome frontal area per swirl can was approximately equal to that of the combustor designs used in earlier NASA investigations. The 72 and 90-swirl-can dome arrays, therefore, provided slightly less frontal area per swirl can, and required smaller flameholders than the earlier NASA design.

The size of the swirl can (3.18-cm diameter) used in the CF6-50 combustor design was chosen so as to be common to all three combustor designs (60, 72, 90 cans). The limiting case was the 90-swirl-can combustor where the swirl-can spacing was only 4.31 cm in the inner annulus. This factor precluded the use of a larger sized can, as was used in the earlier NASA investigations, since there would have been insufficient circumferential space for the flameholder. In addition, some of the 72-swirl-can combustor configurations were designed to accommodate a counterrotating air swirler around the swirl cans and the 3.18-cm diameter swirl can was the largest that could be used with this counterrotating air swirler. In addition to being a smaller diameter, the Program Element I swirl cans were also longer than those used in the NASA design to provide further protection against fuel escapement upstream of the swirl cans.

The various Program Element I swirl-can combustor designs were intended to permit investigations of the effects of the various design parameters on the pollutant emissions and performance characteristics of this combustor concept. Design parameters such as number of swirl cans, flameholder geometry, fuel injection technique, swirl-can airflow and combustor pressure loss were extensively evaluated in these tests. Since the combustors were of modular construction, most of the hardware was interchangeable among the various designs. A description of the combustor hardware common to all swirl-can combustor configurations tested in this program is presented in the following section.

Common Design Features - The baseline combustor configuration design contained 72 swirl cans and featured flat flame-stabilizing plates, axial air swirlers and low pressure fuel injection devices. Modified CF6-50 production combustor cooling liners and newly designed inner and outer cowls completed the combustor assembly. A schematic illustration of this baseline Swirl-Can-Modular Combustor, with the key dimensions indicated, is shown in Figure 27. A photograph of this combustor is presented in Figure 28. Some of its important geometric parameters are listed in Table X.

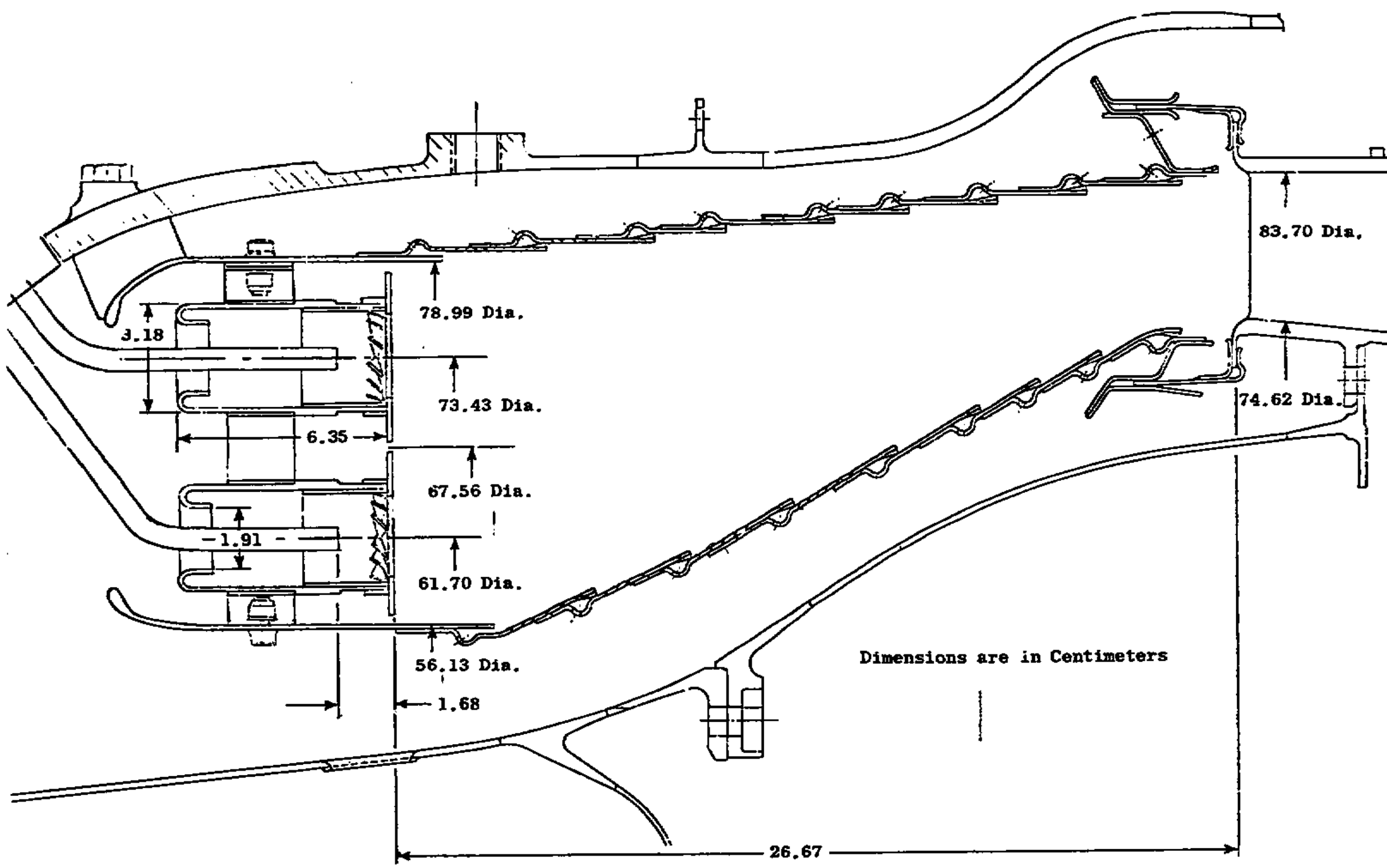


Figure 27. Baseline Swirl-Can-Modular Combustor Design.

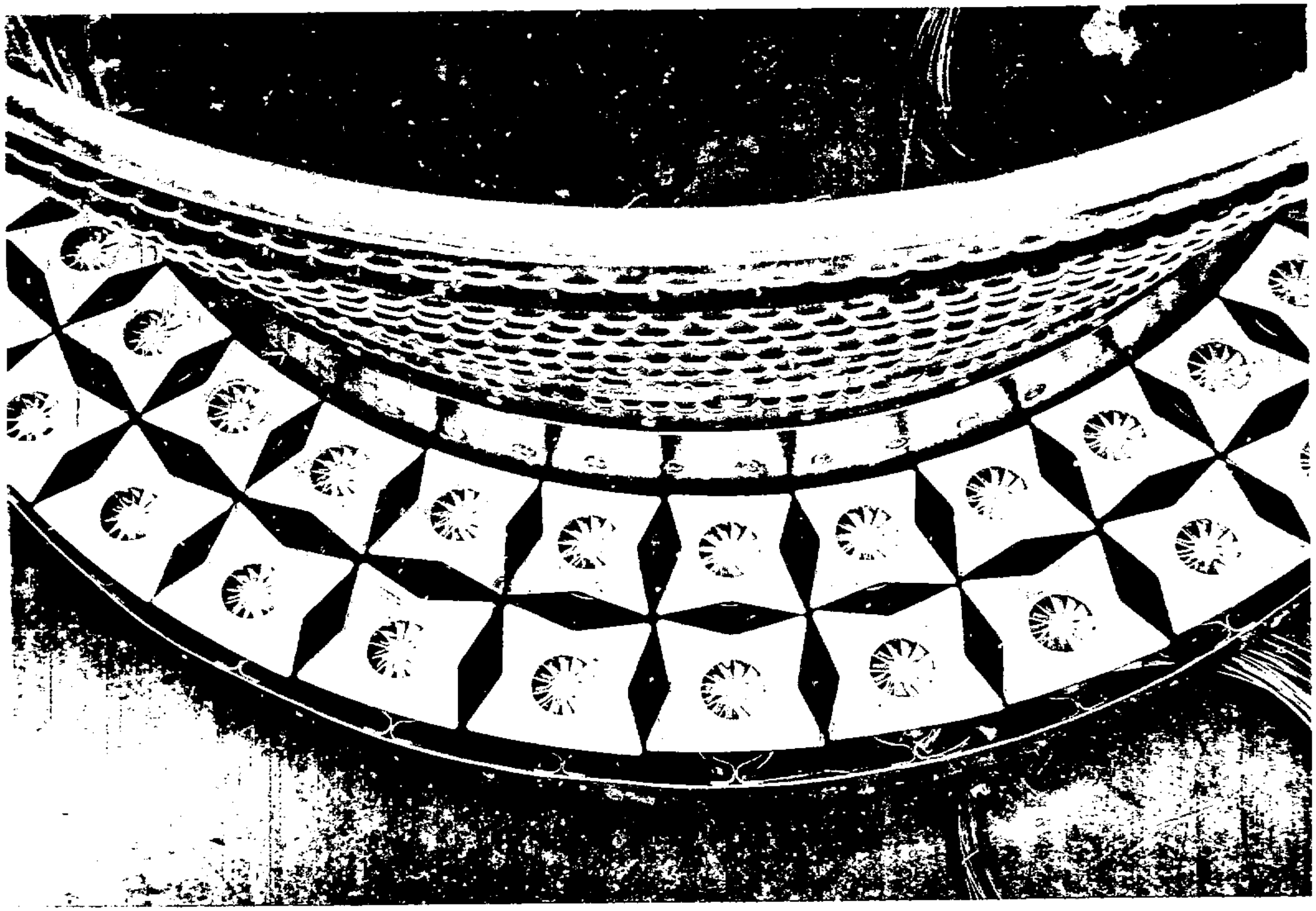


Figure 28. Photograph of Baseline Swirl-Can-Modular Combustor.

Table X. Swirl-Can Combustors, Geometric Design Parameters.

	Inner Annulus	Outer Annulus	Overall
Dome Height[(1)], cm	5.715	5.715	11.43
Burning Length, cm	-	-	26.67
Fuel Injector Spacing, cm			
60 can	6.46	7.69	-
72 can	5.38	6.41	-
90 can	4.31	5.13	-
Area, cm^2	-	-	2426
Volume, cm^3	-	-	47,183

(1) At plane of flameholders

The basic dome support structure used in all Program Element I combustors consisted of networks of sheet metal "spectacles" welded to an inner and an outer ring. The swirl-can assemblies were tack-welded into these dome mounting brackets, and the resulting dome assemblies were bolted to the inner and outer cowls. To determine the effects of varying the number of swirl cans on emissions and performance levels, three dome mounting brackets were designed to accommodate 60, 72, or 90 swirl cans.

The modular swirl-can assembly (shown in Figure 29), which was common to all Program Element I configurations, consisted of a cast cylindrical can and a sheet metal swirler and flameholder. These components were tack-welded together to allow for easy removal of any of the pieces.

Three different types of flameholders were designed. These designs are shown in Figure 30. The flat flameholders were designed in 3 sizes to permit their use in the 60, 72 and 90-swirl-can dome arrays. These flameholders were all designed with equal amounts of air on all sides of the flameholders. The flameholder extended over the exit of the swirl can (see Figure 27) and served as a fuel trip ring to help provide a more uniform fuel distribution. A variation of the flat flameholder design, with a multitude of radial slots cut into each flameholder to increase the flameholder wetted perimeter, was also designed for the 60-swirl-can dome array as part of the AST Addendum evaluations. This latter configuration, which is shown in a partially assembled dome array in Figure 31, was subsequently evaluated at both CF6-50 engine and AST engine operating conditions. The counterswirl flameholders were designed only for the 72-swirl-can dome array because the counterswirler resulted in flameholders too large for use in the 90-swirl-can dome. The sheltered flameholders were designed only for the 90-swirl-can dome array. All of these flameholders were intended to provide the high blockage necessary to maintain the combustor pressure drop at the CF6-50 design level.

The amount of airflow passing through the swirl cans was controlled by using different sized air swirlers. Three sizes were designed (Figure 32) with different flow areas obtained by changing the pitch angle of the swirler vanes. The swirler was brazed to a sheet metal sleeve to allow the axial position of the swirler in the swirl can to be easily changed.

The standard fuel injectors used with all Program Element I configurations were open-ended 0.46-cm inside diameter stainless steel tubes, with fuel metering accomplished external to the combustor (using fixed fuel metering orifices). To accommodate 60, 72 or 90 fuel tubes from the existing 30 fueling ports in the CF6-50 combustor test rig, a variety of fuel tube configurations was required. During most of the combustor tests, these fuel tubes were connected to the fuel manifolds in a manner allowing individual control of the fuel flow to each annulus. With this setup, the effects of radial fuel staging could be investigated. Upon occasion, the fuel tubes were also hooked up to investigate circumferential sector fuel staging at idle.

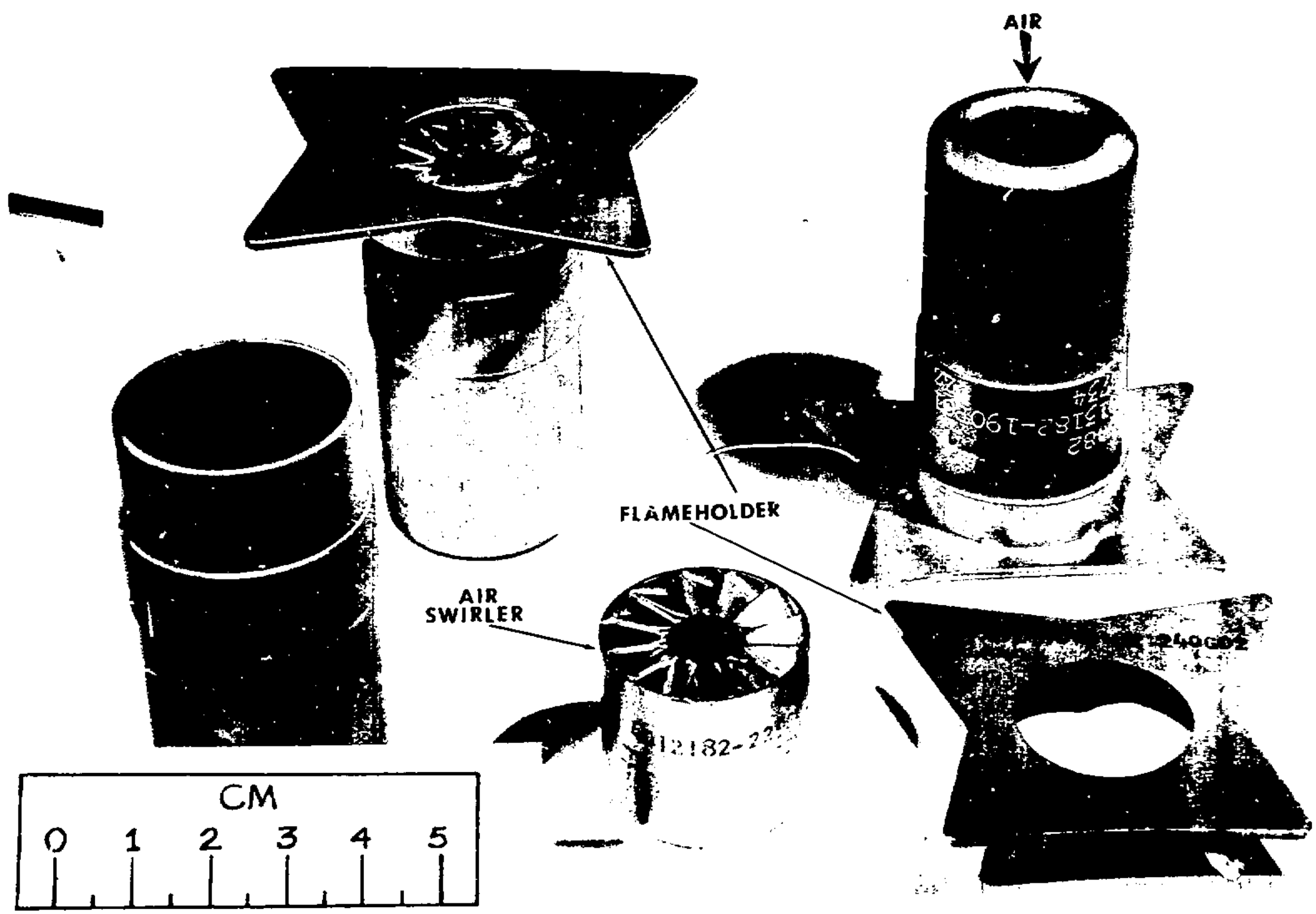


Figure 29. Modular Swirl-Can Assembly.

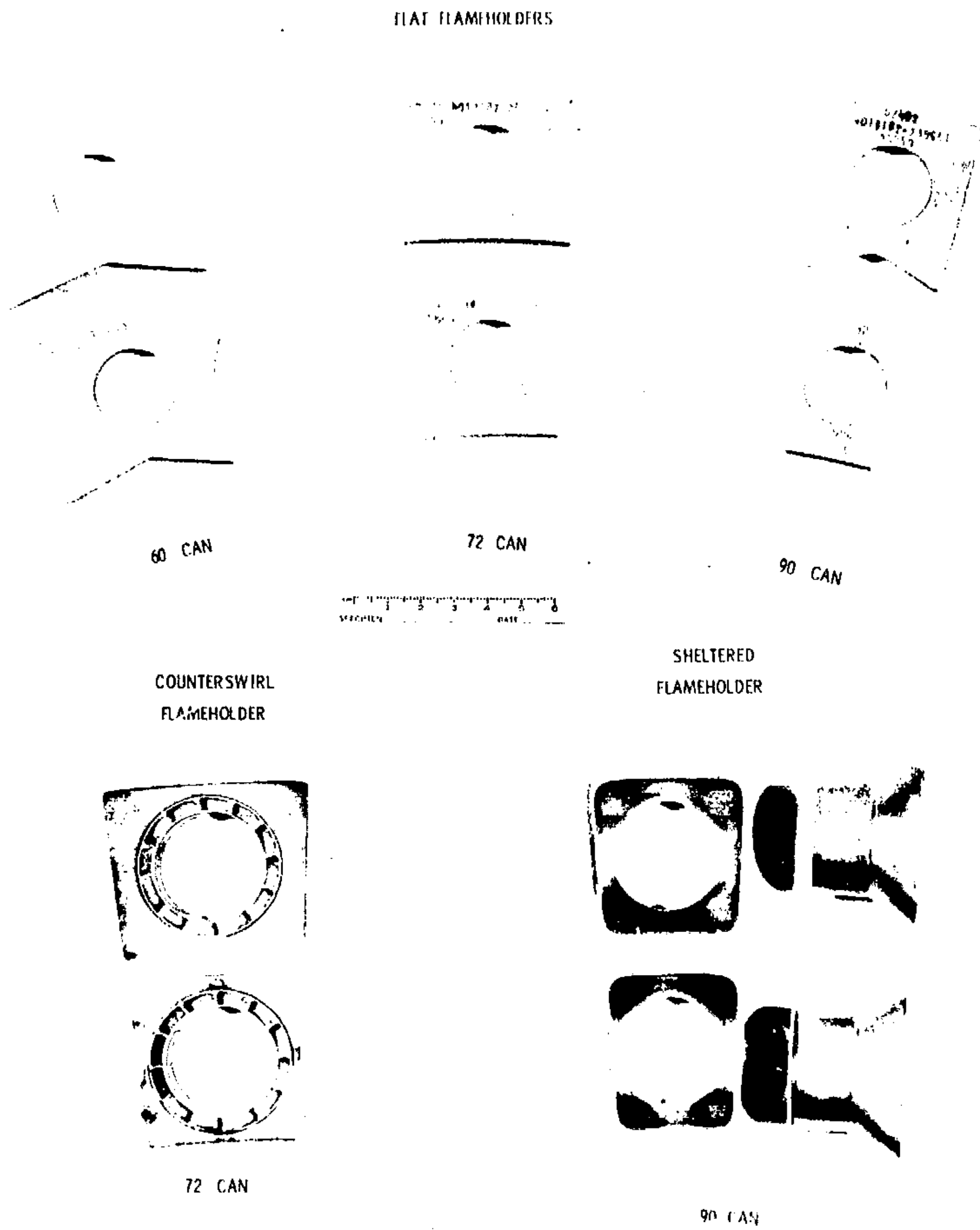


Figure 30. Swirl-Can Combustor Flameholder Designs.

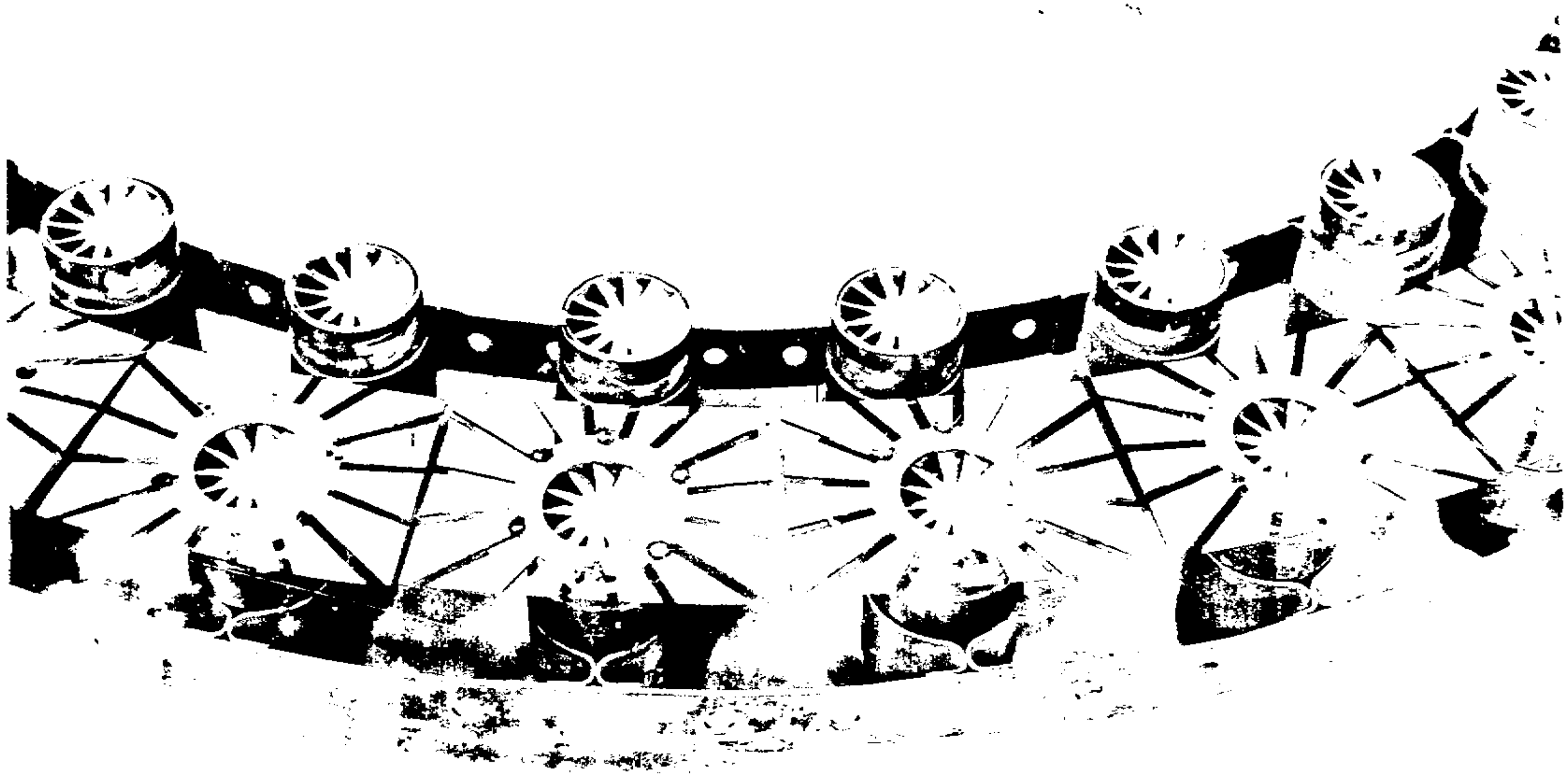


Figure 31. Partial Dome Assembly, 60-Swirl-Can/Slotted Flat Flameholder Combustor.

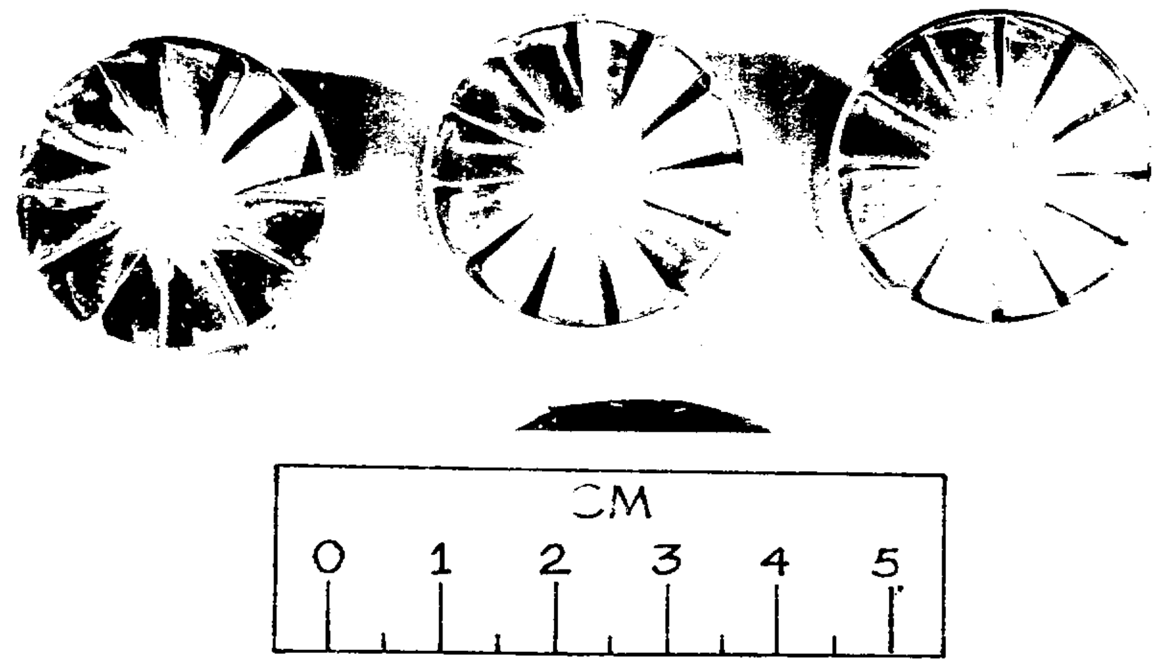


Figure 32. Swirl-Can Air Swirlers.

The combustor inner and outer sheet metal cowls used with all of these test configurations were designed with the aid of a General Electric aerodynamic analysis computer program to ensure that the proper combustor airflow distribution was obtained with a minimum of disturbance to the airflow. The inner and outer cooling liners were modified CF6-50 production combustor liners, with all the dilution airflow eliminated and the cooling air reduced by flamespraying the cooling holes. The cowls and liners were interchangeable among all the Swirl-Can-Modular Combustor configurations tested.

The various test configurations may be categorized into three classifications according to flameholder type. The various test configurations, in this classification, are briefly described in the following sections.

Flat Flameholder Configurations - Seven combustor configurations with flat flameholder designs were tested. A summary of the key geometric features of each of these test configurations is shown in Table XI.

In the first three Program Element I tests, flat flameholder combustor configurations (I-1, I-2 and I-3) with 72, 90 and 60-swirl-can dome arrays, respectively, were evaluated to investigate the effects of the number of swirl cans on the emissions and performance characteristics of the CF6-50 Swirl-Can-Modular Combustor design approach. With the fourth test configuration (I-4), the benefits of sector fuel staging on idle emissions were investigated with the same 60-swirl-can combustor as used for Test Configuration I-3. Test Configuration I-11 also consisted of a 60-swirl-can combustor, modified to produce a higher combustor pressure loss, to determine the effect of changes in this important combustor design parameter on the emissions levels. It was also used to investigate sector fuel staging as an idle emissions reduction technique. Test Configuration I-14 was a re-creation of I-2 in order to obtain more data with this configuration and to permit a more confident extrapolation of its measured NO_x emissions levels to engine operating conditions. The final flat flameholder test configuration (III-1) was designed as a part of the AST Addendum program. With this configuration a large increase (about a factor of 3) in the wetted perimeter of the flat flameholders of the 60-swirl-can combustor was obtained. The high airflow swirlers were also used in this configuration.

Counterswirl Flameholder Configurations - The counterswirl flameholder combustor configurations featured the use of a counterrotating air swirler mounted around the swirl can (Figure 33) to improve the fuel and air mixing within the flameholder wakes. In this approach, the outside swirler airstream was intended to create an intense shearing zone with the fuel-air mixture from the swirl can, allowing more intense mixing and providing leaner, more homogeneous dome mixtures. All counterswirl flameholder test configurations used the 72-swirl-can dome array. A summary of the key geometric design features is shown in Table XI.

The main design parameter investigated with this series of test configurations was the fuel injection technique. In each of the four test configurations, a different injection technique was used in an effort to further improve the dome fuel-air mixing. The four techniques employed are shown schematically in Figure 34.

Table XI. Summary of Design Parameters, Swirl-Can Modular Combustors.

Test Configuration	Number of Swirl Cans	Flameholder Type	Swirler Angle	Fuel Injector	Pressure Loss (1)	Wetted Perimeter	Airflow Distribution: Swirl Can	Flameholder	Array	Dome	Liner
			°		%	cm	% of Combustor Total				
I-1	72	Flat	30	Std	3.52	1588	9.4	----	70.9	80.3	19.7
I-3,4	60	Flat	30	Std	4.20	2019	8.4	9.1 [2]	61.4	78.9	21.1
I-2	90	Flat	30	Std	4.32	1656	12.5	----	66.5	79.0	21.0
I-11	60	Flat	20	Std	5.35	1539	8.0	----	73.4	81.4	18.6
I-14	90	Flat	30	Std	4.20	1656	13.1	----	69.3	82.4	17.6
III-1	60	Flat (2)	45	Std	4.22	4361	16.4	42.7 [3]	25.7	84.8	15.2
I-5	72	Counterswirl	45	Std	3.85	1212	19.4	13.8	47.7	80.9	19.1
I-6	72	Counterswirl	45	18 cm Or.	4.42	1028	21.4	15.3	45.4	82.2	17.8
I-9	72	Counterswirl	30	Shortened	4.22	1417	11.8	15.7	55.1	82.6	17.4
I-16	72	Counterswirl	None	Atomizer	3.98	1549	30.2	14.1	40.3	84.6	15.4
I-7	90	Sheltered	20	Std	2.80	1613	8.7	----	74.4	83.1	16.9
I-8	90	Sheltered	45	Std	3.85	1613	24.8	----	57.8	82.6	17.4
I-10,15	90	Sheltered	30	Std	4.55	1613	15.1	----	66.5	81.6	18.4
I-12	90	Sheltered	30	Std	4.00	1613	14.0	---- [4]	61.6	75.6	24.6 [5]
I-13	90	Sheltered	30	Std	3.90	1613	14.0	6.9	61.6	82.5	17.5

Superscripts:
1 -- Pressure loss at sea level static takeoff.
2 -- Corner holes drilled through flameholders.
3 -- Radial slots cut into each flameholder.
4 -- Dilution holes drilled through flameholders.
5 -- Liner dilution air, 6.9% of combustor airflow.

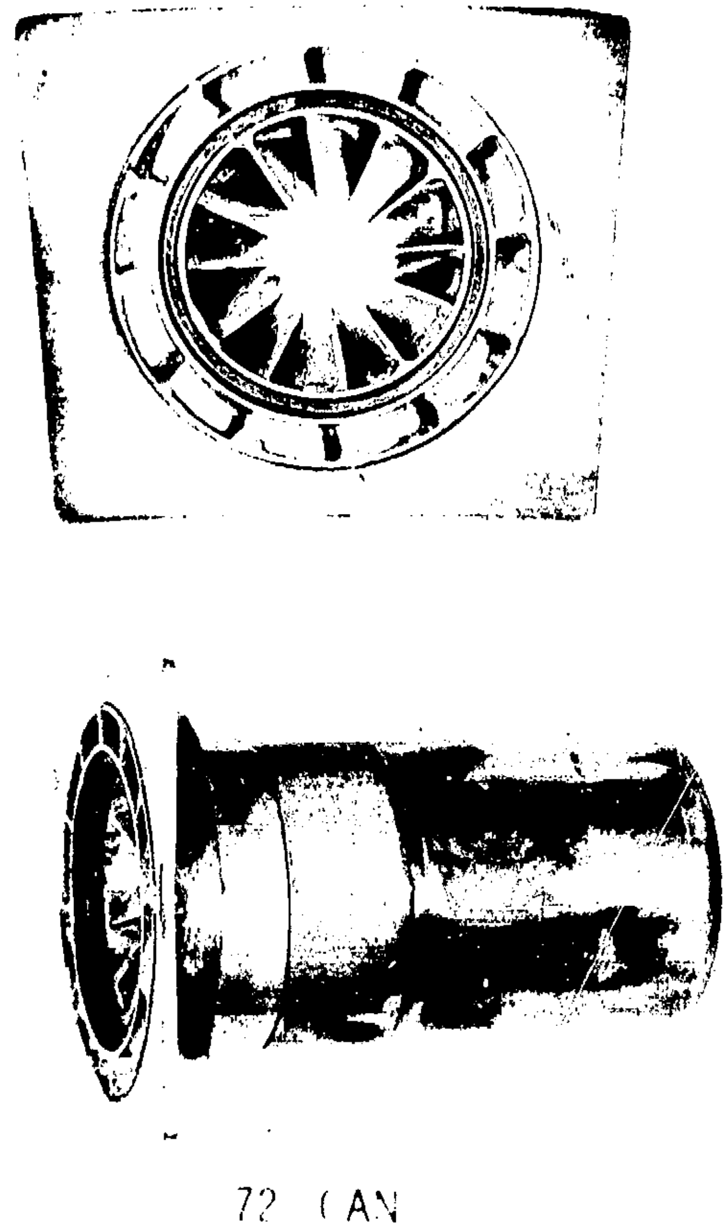


Figure 33. Swirl-Can/Counterswirl Flameholder Assembly.

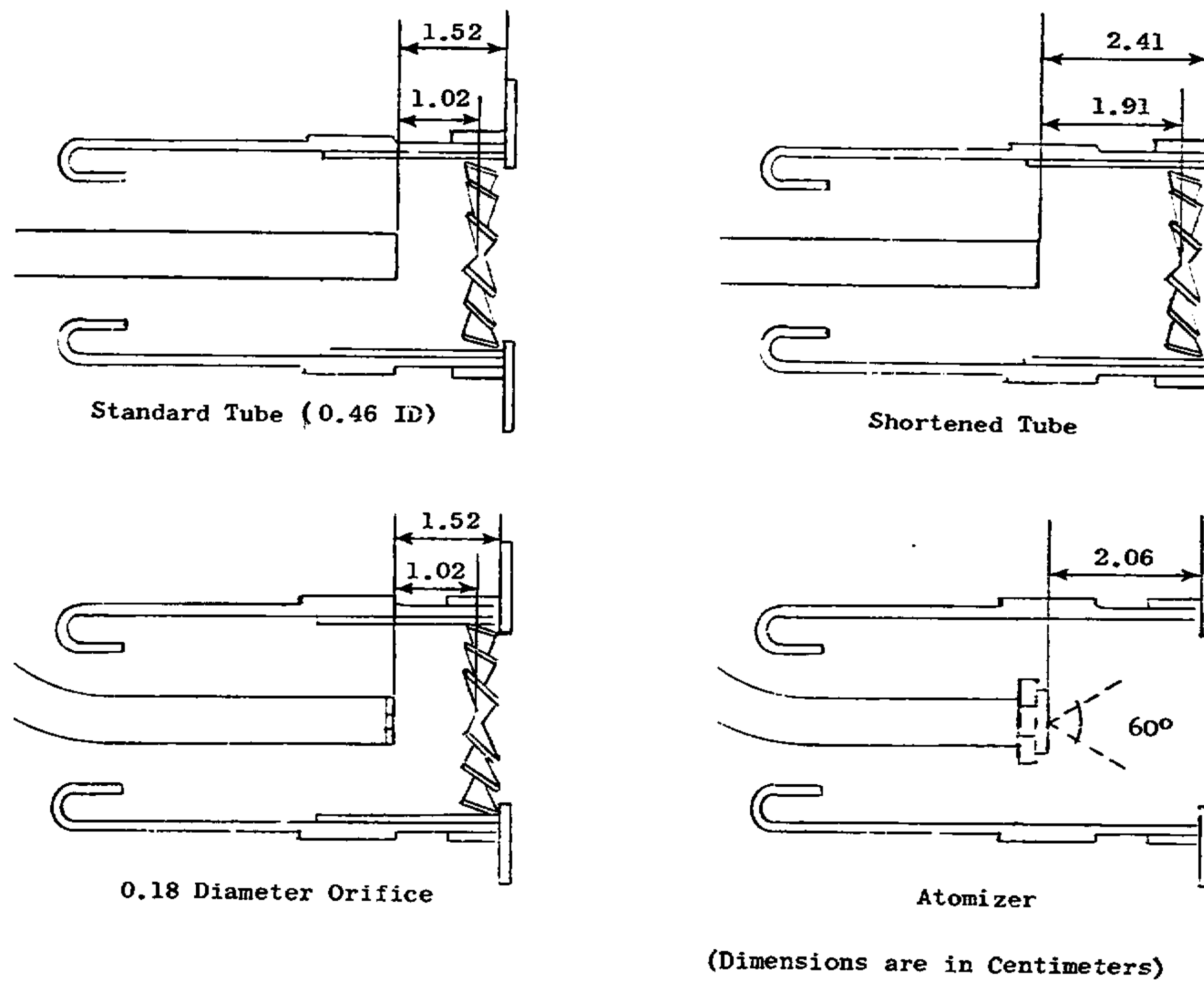


Figure 34. Fuel Injector Configurations, Swirl-Can Combustor.

The initial counterswirl flameholder combustor test configuration (I-5) used the standard, open-ended fuel tubes. With these standard fuel tubes, very low fuel injection velocities were obtained, even at high power (high fuel flow) operating conditions. It was felt that increasing this fuel velocity might improve fuel atomization quality. Therefore, Test Configuration I-6 featured the use of the standard fuel tubes, each with a small diameter orifice installed in its end. This orifice increased the velocity of the injected fuel by a factor of almost seven. Flow visualization studies showed that, by shortening the standard fuel tube by about one cm, a much improved fuel spray pattern could be obtained. This modification was incorporated into Test Configuration I-9. The final counterswirl flameholder test configuration (I-16) incorporated small, pressure-atomizing simplex spray nozzles to provide very good fuel atomization and distribution at all test conditions. In addition, the air swirlers inside the swirl cans were removed in order to obtain the highest airflow possible through the swirl cans.

Sheltered Flameholder Configurations - Six combuster test configurations featured the use of sheltered flameholders. This flameholder device was designed with the axial dimension of the flameholder extended 1.27 cm downstream from the plane of the swirl cans (Figure 35). This created a "sheltered" region in the wake of the cans, and was intended to provide more time for the swirl-can air and fuel to mix before entering the primary combustion zone. All configurations used the 90-swirl-can dome array. The key geometric features of each configuration are shown in Table XI.

The first three sheltered flameholder test configurations were intended to determine the effects of varying the swirl-can airflow on the emissions and performance characteristics of this combustor design. Test Configuration I-7 used the lowest flow area air swirlers, while Test Configuration I-8 incorporated the highest flow area swirlers, and Test Configuration I-10 utilized the intermediate flow area swirlers. In addition, Test Configurations I-8 and I-10 (and all succeeding sheltered flameholder configurations) incorporated a modification of the flameholders to raise the combustor pressure loss to the correct level. For Test Configuration I-12, dilution holes were added to the second cooling panel of the outer cooling liner in line with and between each swirl can, in an effort to direct that portion of the dome airflow passing between the flameholders and the outer cowl into the primary combustion zone. It was felt that a large amount of available combustion air was being allowed to escape the combustion zone along the outer liner. For Test Configuration I-13, this liner dilution air was eliminated and four small holes were added to each flameholder just aft of the air swirler plane. These latter flameholder dilution holes were found to provide improved fuel atomization quality from the swirl cans during fuel spray visualization tests. The final sheltered flameholder test configuration (I-15) was a rebuild of Test Configuration I-10 and was evaluated in a more extensive test series, including sea level ignition testing.

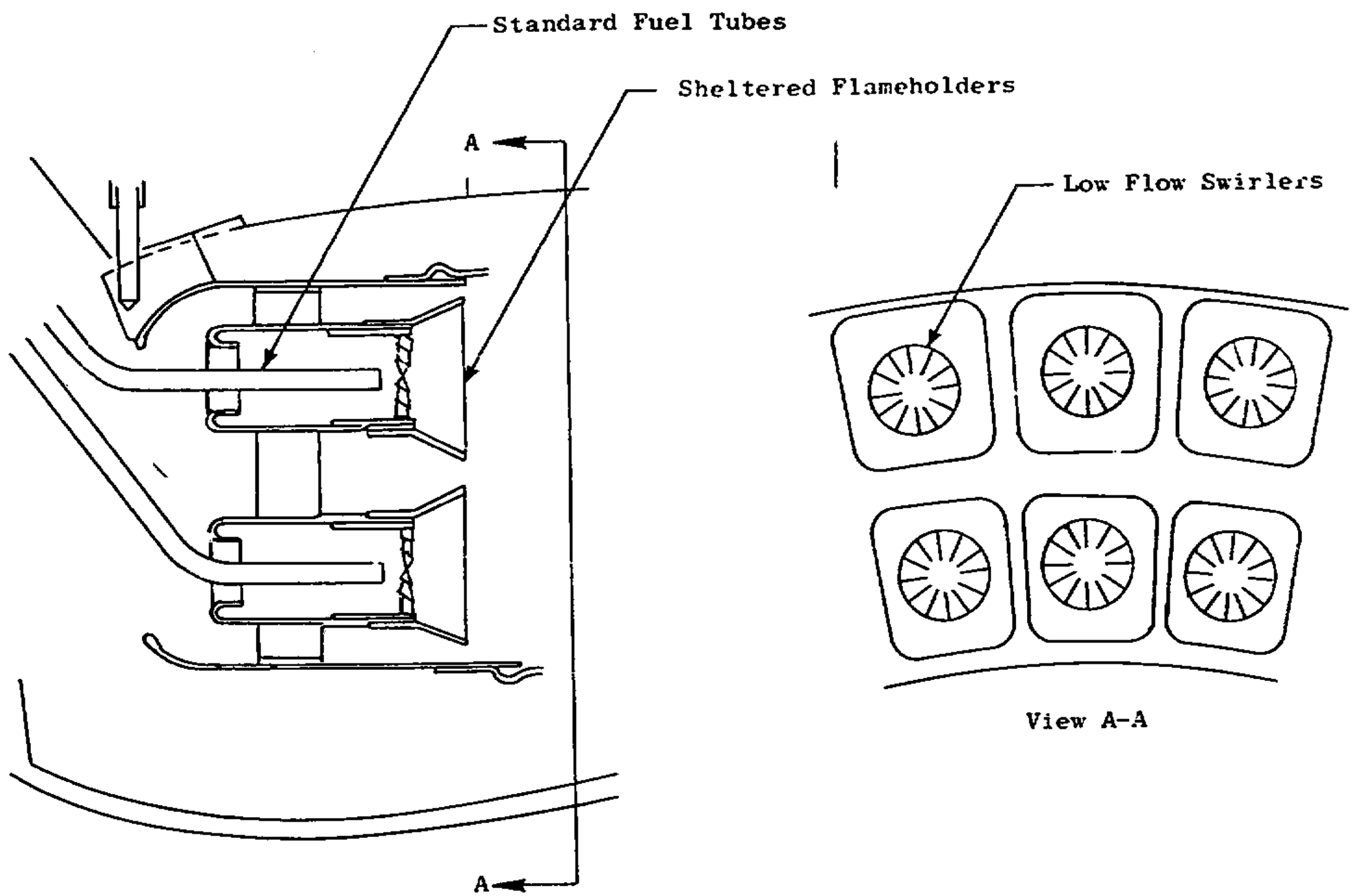


Figure 35. 90-Swirl-Can/Sheltered Flameholder Combustor Design.

Program Element II Combustor Test Configurations

In Program Element II, three basic combustor design concepts were investigated; a Lean Dome Single Annular approach, a Lean Dome Double Annular approach and a Radial/Axial Staged approach. The general arrangements of these three design approaches are shown in Figures 24, 25 and 26. All were designed for use with the existing CF6-50 production combustor cooling liners.

In the Lean Dome Single Annular Combustor approach, greatly increased percentages of the total combustor airflow were introduced into the iome, or primary combustion zone. This lean dome approach involved the least degree of design modification of the production CF6-50 engine combustor. However, to obtain satisfactory operation at low power with this lean dome design, variable geometry features to reduce the amounts of airflow into the primary combustion zone would probably be needed. Many variable geometry approaches involving a mechanical and/or fluidic modulation are conceivable. Variable geometry modulations and actuation techniques were not investigated in this program, but the potential advantages were assessed by testing fixed geometry combustors with first a rich and then with a lean dome. In all, four Single Annular Combustor configurations were investigated. Their design details are described in a following section.

The second of the basic concepts consisted of a Lean Dome Double Annular Combustor approach. As in the Single Annular Dome approach, a key design feature was the use of increased percentages of the total combustor airflow into the dome, or primary zone. However, with this design approach all of the fuel could be concentrated into one of the annuli at low power operating conditions, thereby providing improved low power operation without variable geometry. In all, six Double Annular Combustor configurations were investigated. Their design details are described in a following section.

The third of these basic concepts consisted of a design in which beneficial axial and radial fuel staging provisions were important features. In this latter design, the pilot stage was specifically sized for low power operation. In this design approach, all of the fuel is supplied to this pilot stage at low power operating conditions. At the higher engine power operating conditions, the second or main stage is also fueled. This latter stage, which handles a high percentage of the total combustor airflow, is displaced not only radially but axially from the pilot stage. The main stage fuel is premixed, to some degree, with its airflow and, therefore, the resulting fuel-air mixtures that flow into its combustion zone are lean and relatively uniform. The burning of these lean mixtures is stabilized by the pilot stage of the combustor. In all, seven Radial/Axial Staged Combustor configurations were investigated and their design details are described in a following section.

Except for the Single Annular Combustor configuration, all of the combuster design concepts investigated within Program Element II utilized airblast fuel injection techniques. Figure 36 illustrates the general features of these fuel injection devices. In previously conducted General Electric development

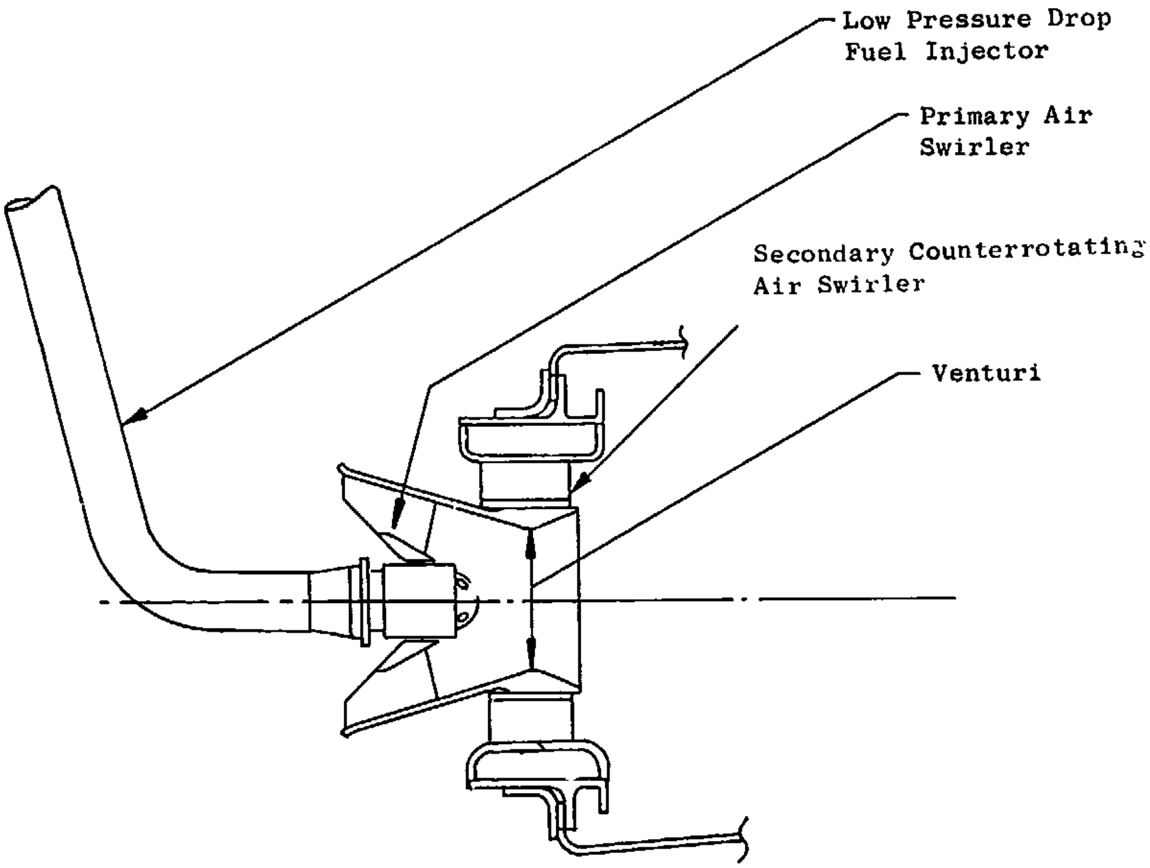


Figure 36. General Features, General Electric Airblast Fuel-Air Atomization/Mixing Device.

programs, the use of fuel injection techniques of this kind resulted in significant reductions in both CO and HC emissions levels, as compared to the levels obtained with more conventional pressurized fuel spray nozzle atomization. With airblast fuel injection methods of this kind, the fuel is injected at low pressures and is atomized in swirl-cup devices by a portion of the combustor airflow. Since the fuel atomization process is primarily dependent on the air kinetic energy rather than on fuel pressure, very effective fuel atomization and fuel-air mixing may be attained over wide ranges of engine operating conditions, including idle. In the Single Annular Combustor configurations, fuel injection was accomplished by use of standard pressure-atomizing CF6-50 engine fuel nozzles. These nozzles produce good fuel atomization with low fuel flows by using a small primary orifice, as well as with high fuel flows through the utilization of an additional larger secondary orifice. The dual-orifice operation is accomplished by a pressure-activated valve. This method provides good fuel atomization over the entire range of engine operating conditions.

Single Annular Combustor Configurations - The general arrangement of the Single Annular Combustor test configurations is shown in Figure 37. The combustor assembly consisted of a dome, a cowl and cooling liners. The first test configuration (II-1) consisted of a production CF6-50 engine combustor. For the three lean dome combustor configurations, these same basic configurations, but modified, were used. The dome modifications consisted of installing counterrotating high airflow secondary swirlers and dome dilution holes. The dome dilution holes were used only because the swirler airflow could not be increased further. The key design parameters of these combustors are shown in Table XII. A photograph of the dome in the assembled combustor is shown in Figure 38. The cooling modifications consisted of reducing the cooling flow metering hole areas and closing the dilution holes.

The production cowl assembly was used for Test Configuration II-2, but the pressure drop was higher than planned. This cowl was found to excessively throttle the airflow into the dome array. For the last two tests, the cowl was cut back, which eliminated this airflow throttling.

Double Annular Combustor Configurations - The general arrangement of the Double Annular Combustor design approach is shown in Figure 39 and its key design parameters are tabulated in Table XIII. The combustor assembled for the first test is shown in Figure 40. The fuel injector assemblies used in all test configurations are shown in Figure 41. The combuster assembly consisted of a dome assembly, a cowl and modified CF6-50 production combustor cooling liners.

The dome assembly consisted of two annular spectacle plates separated by a small centerbody. Assembled in the spectacle plates was an array of 60 air swirlers (30 in each annulus). The air swirler components consisted of a primary air swirler/venturi casting, a counterrotating secondary air swirler, a flameshield and a retainer ring. The air swirler assemblies were attached to the dome spectacle plates with a radial slip joint arrangement to accommodate mechanical stackup and thermal growth between the fuel injectors and the combustor assembly. The flameshields were impingement cooled. The centerbody and dome panels were film cooled using wiggle strip construction.

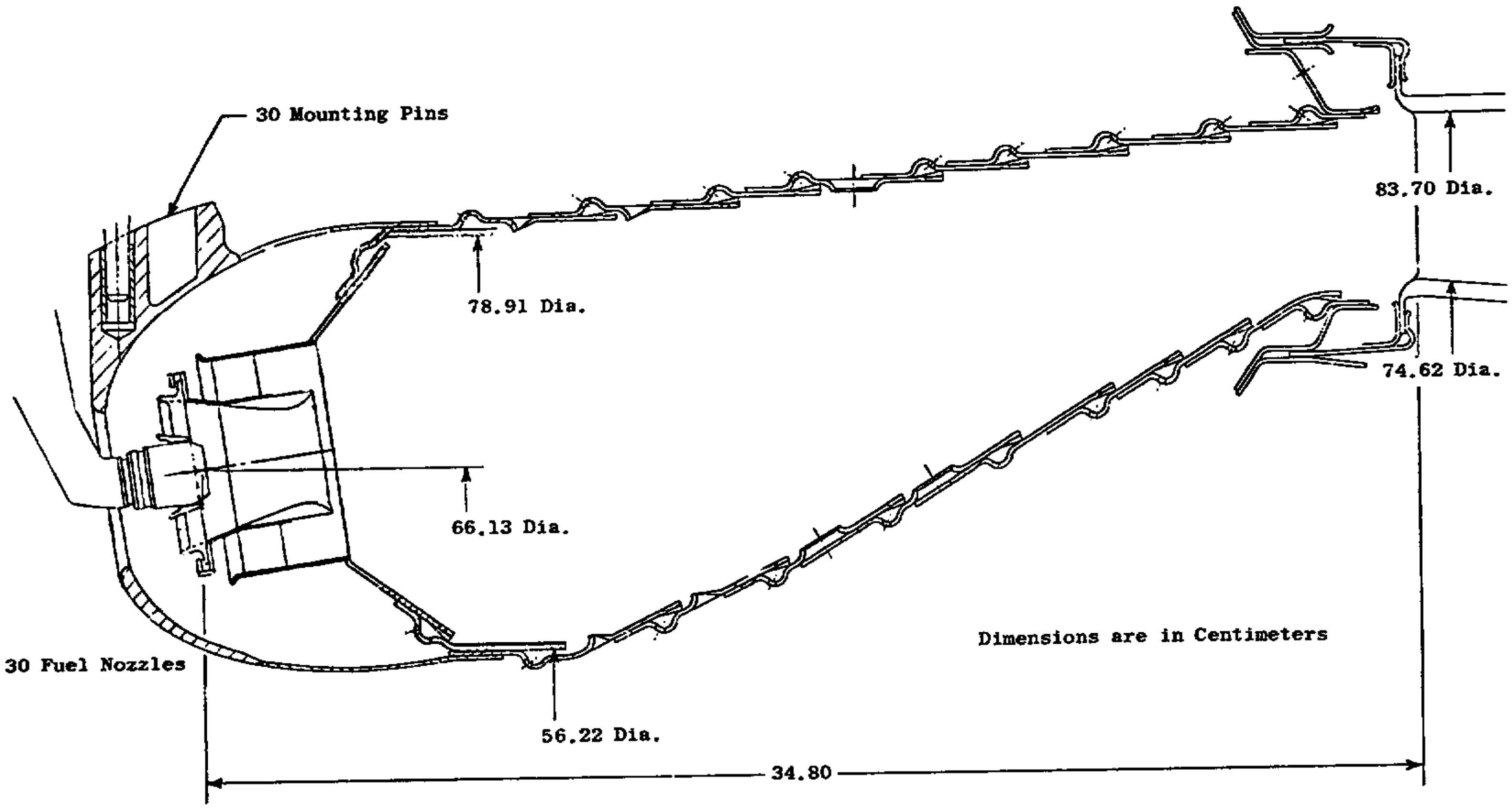


Figure 37. General Arrangement, Single Annular Combustor.

Table XII. Summary of Design Parameters, Single Annular Combustor Test Configurations.

Test Configuration	II-1	II-2	II-3,5
Combustor Type	Production CF6-50	Single Lean Dome	Single Lean Dome
Pressure Loss-% at SLSTO	4.30	5.90	4.80
Dome Airflow % Combustor Total			
Swirler	17.1	67.8	69.2
Dilution	-0-	5.3	6.5
Total	17.1	73.1	75.7
Liner Dilution Airflow, %			
Panel 1	6.0	-0-	-0-
Panel 2	11.6	-0-	-0-
Panel 4-6	19.4	-0-	-0-
Cooling Airflow % of Total			
Dome	14.2	4.1	5.1
Liner	31.7	22.8	19.2
Total	45.9	26.9	24.3

Geometry ---- Common to all Configurations.

Dome Height, cm------------11.34
Burning Length, cm---------34.80
Fuel Inj. Spacing, cm------ 6.93
Dome Exit Area, cm^2--------2409
Volume, cm^3----------------67,960

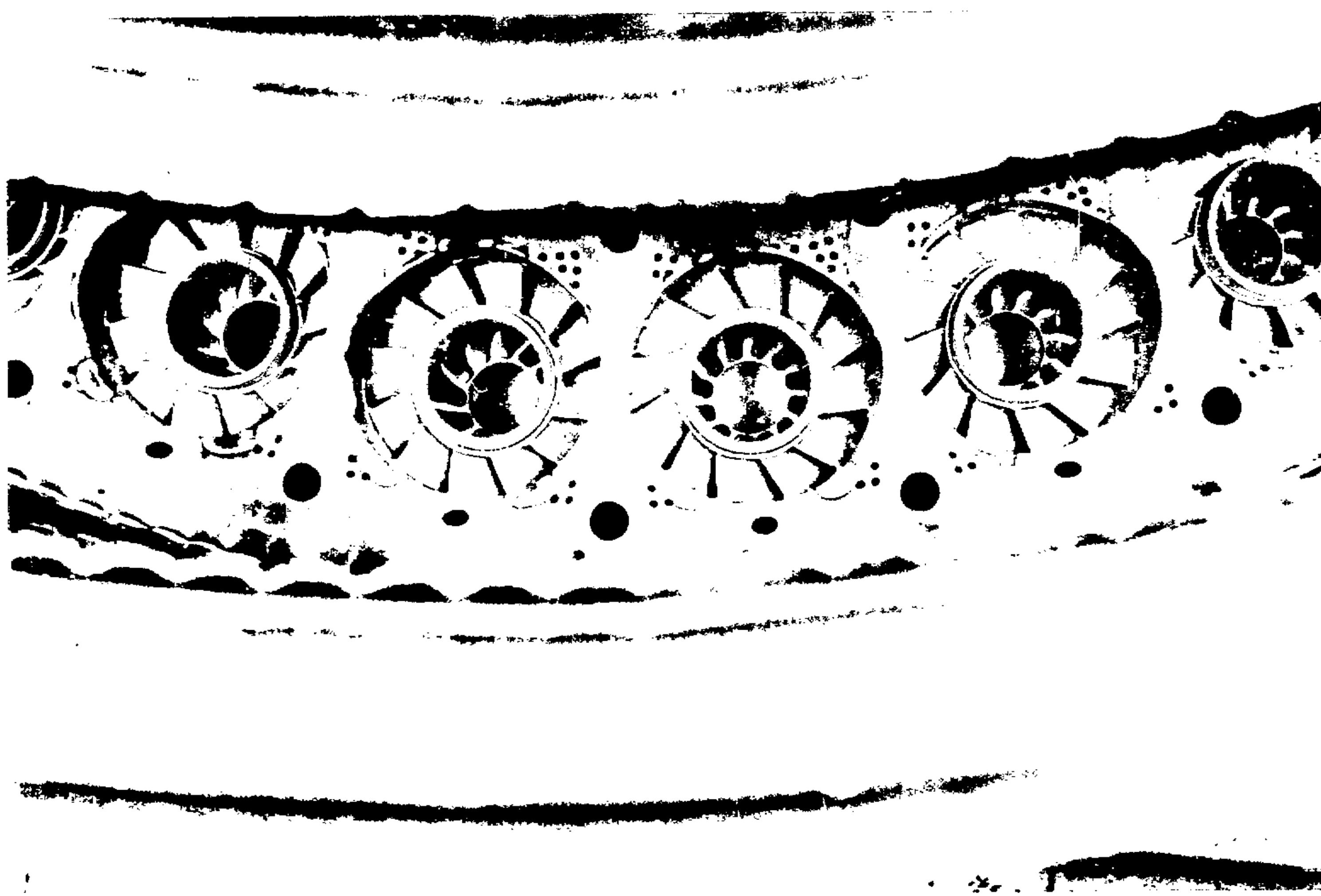


Figure 38. Single Annular Lean Dome Combustor Assembly, Aft Looking Forward.

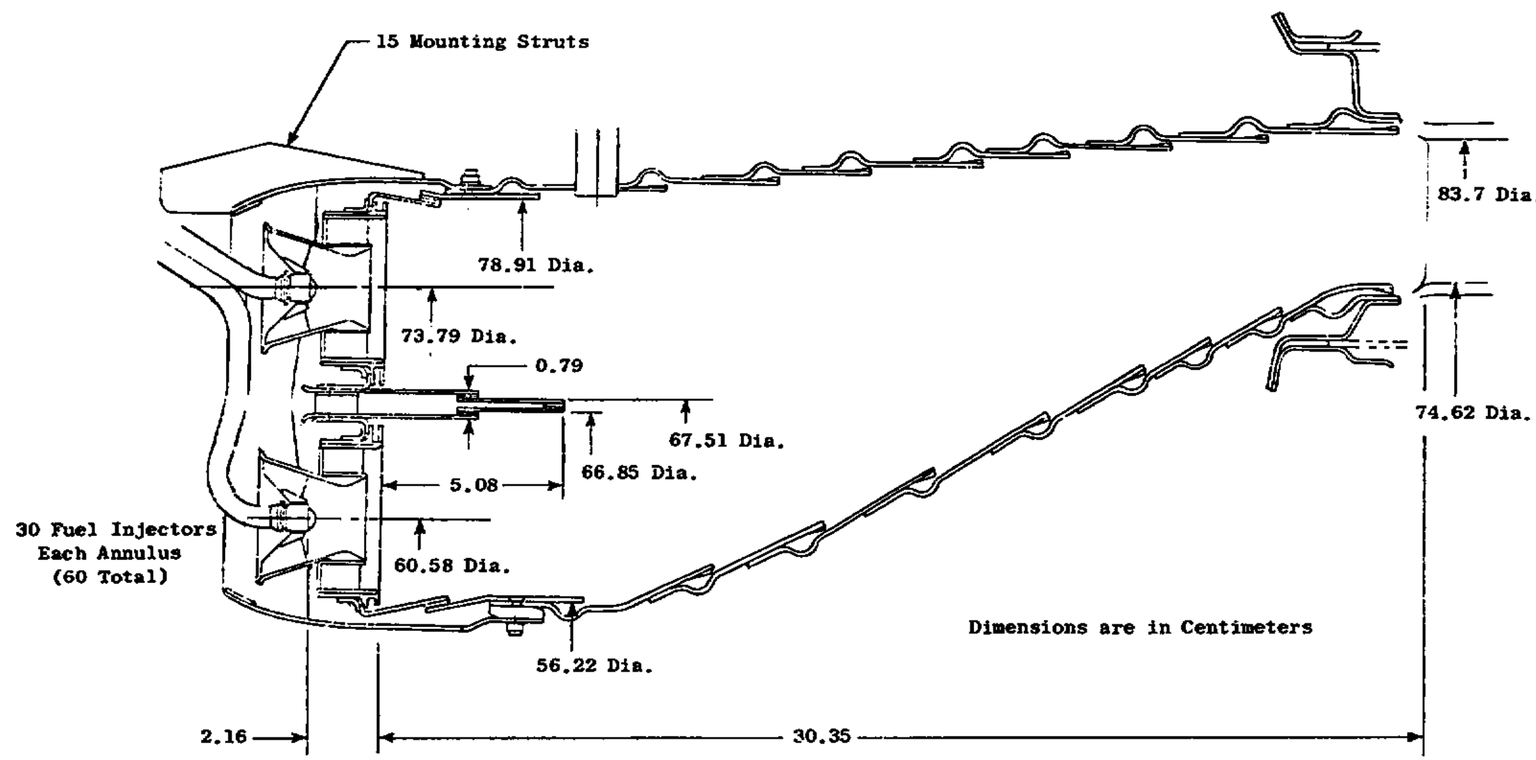


Figure 39. General Arrangement, Double Annular Dome Combustor.

Table XIII. Summary of Design Parameters, Double Annular Dome Combustor Test Configurations.

Test Configuration	II-4	II-8	II-9	II-11	II-13	II-16	All
Pressure Loss Total, at SLTO, %	4.75	4.65	4.32	4.72	5.42	5.80	-----
Airflow Distributions, % of Combustor Airflow							
Outer Annulus							
Swirler	32.7	18.4	18.4	18.4	18.0	12.2	-----
Dilution	none	14.9	none	none	none	none	-----
Total	32.7	33.3	18.4	18.4	18.0	12.2	-----
Inner Annulus							
Swirler	32.7	18.4	33.0	33.0	34.5	37.0	-----
Dilution	none	13.7	13.8	13.8	17.5	18.7	-----
Total	32.7	32.1	46.8	46.8	52.0	55.7	-----
Cooling Airflows, Both Annuli							
Dome							7.8 to 9.0
Centerbody							3.3 to 3.7
Liner							17.2 to 23.6
Dome Height[1], cm							
Outer Annulus							5.69
Inner Annulus							5.33
Overall							11.35
Burning Length, cm							
Outer Annulus[1]							5.08
Inner Annulus[2]							5.08
Overall							30.35
Fuel Inj. Spacing, cm							
Outer Annulus							7.73
Inner Annulus							6.34
Area[1], cm^2							
Outer Annulus							1311
Inner Annulus							1028
Overall							2409
Volume, cm^3							
Outer Annulus[2]							6541
Inner Annulus[2]							5097
Overall							54,991

Superscripts:

(1) --- At trailing edge of centerbody

(2) --- From flameshields to trailing edge of centerbody

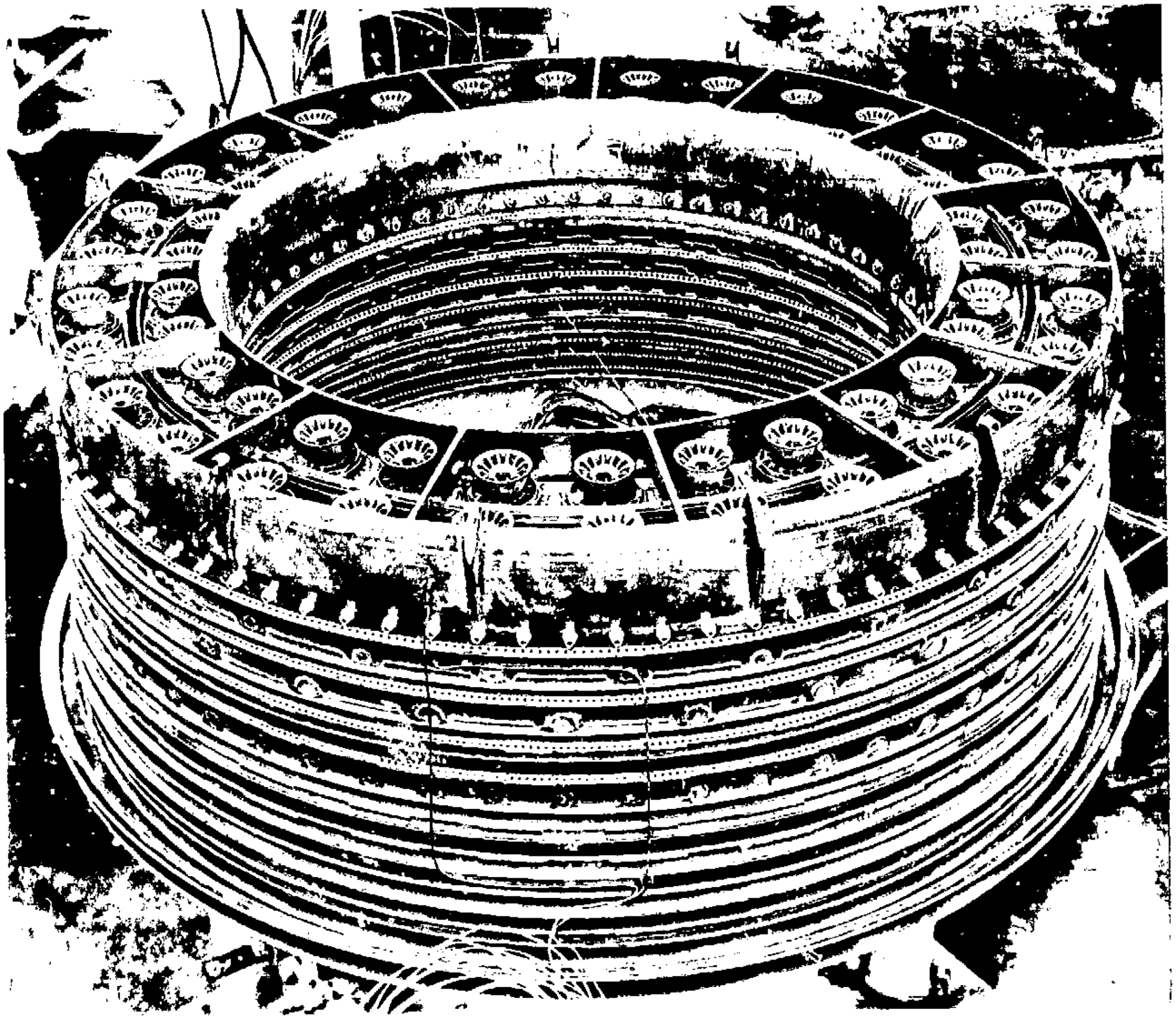


Figure 40. Double Annular Combustor Assembly.

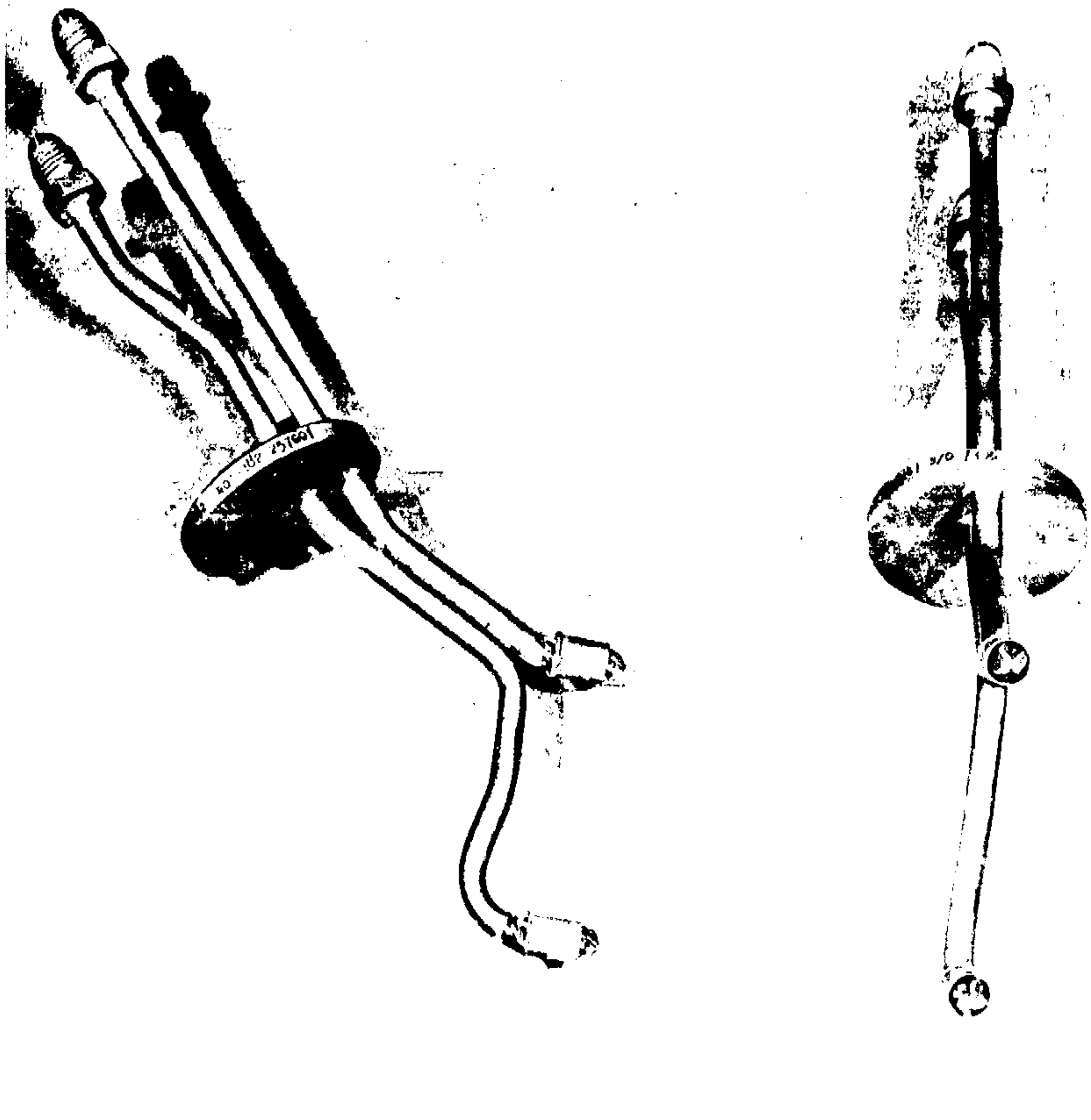


Figure 41. Fuel Injector Assemblies, Double Annular Combustor.

The cooling liners were modified in that the cooling flow metering hole areas were reduced and the standard dilution holes were closed. However, new dilution holes were added for some of these test configurations.

The 60 fuel injectors (30 assemblies) consisted of low pressure drop devices which were inserted in the normal manner (externally) after the combuster was installed in the test rig. The fuel injector tip and counterrotating air swirler combination used in these combustors is an airblast fuel atomization/mixing device previously developed at General Electric for use in advanced engine combustors. For this program, the fuel injector tip/primary air swirler design was used intact, but new higher airflow secondary air swirlers were designed. The key dimensions of the fuel injector/air swirler assembly are shown in Figure 42.

Six Double Annular Combustor test configurations were investigated. Each change was systematically made to more nearly approach the exhaust emissions goals. The key design parameter variations, as shown in Figure 43 and Table XIII, were:

- Airflow split between dome air swirlers and liner dilution holes.
- Airflow split betwen inner and outer annuli.
- Location and type of dilution holes.

In the first two test configurations (II-4 and II-8), all of the combustor airflow (except that required for cooling) was equally split between the inner and outer annuli, and the split between dome air swirlers and liner dilution holes was varied. In the last four test configurations (II-9, II-11, II-13, II-16), the airflow was highly biased to the inner annulus and the location and type of dilution holes were also varied. In each case where liner dilution holes were used, they were located in line and between each fuel injector (60 holes per liner). Simple flush holes were used in Test Configurations II-8, II-9 and II-11. Thimbled holes (Figure 43) were utilized in Test Configurations II-13 and II-16 to provide better penetration of the dilution air jets. In test configurations where the dome swirler airflows were reduced, the reductions were made by blocking vanes of the secondary air swirlers.

Radial/Axial Staged Combustor Configurations - The general arrangement of the Radial/Axial Staged Combustor is shown in Figure 44. The combustor assembled for the first test is shown in Figure 45. The fuel injector assemblies are shown in Figure 46. The combustor assembly consisted of a pilot stage dome assembly, a main stage flameholder/chute assembly, a cowl, and modified CF6-50 production combustor cooling liners.

The pilot dome assembly consisted of an annular spectacle plate and an array of 30 air swirlers similar to those in the Double Annular Combustor configurations. The air swirler components consisted of a primary air swirler/venturi casting, a counterrotating secondary air swirler, a flameshield and a retainer ring. The air swirler assemblies were attached to the dome with a radial slip joint arrangement to accommodate mechanical stackup

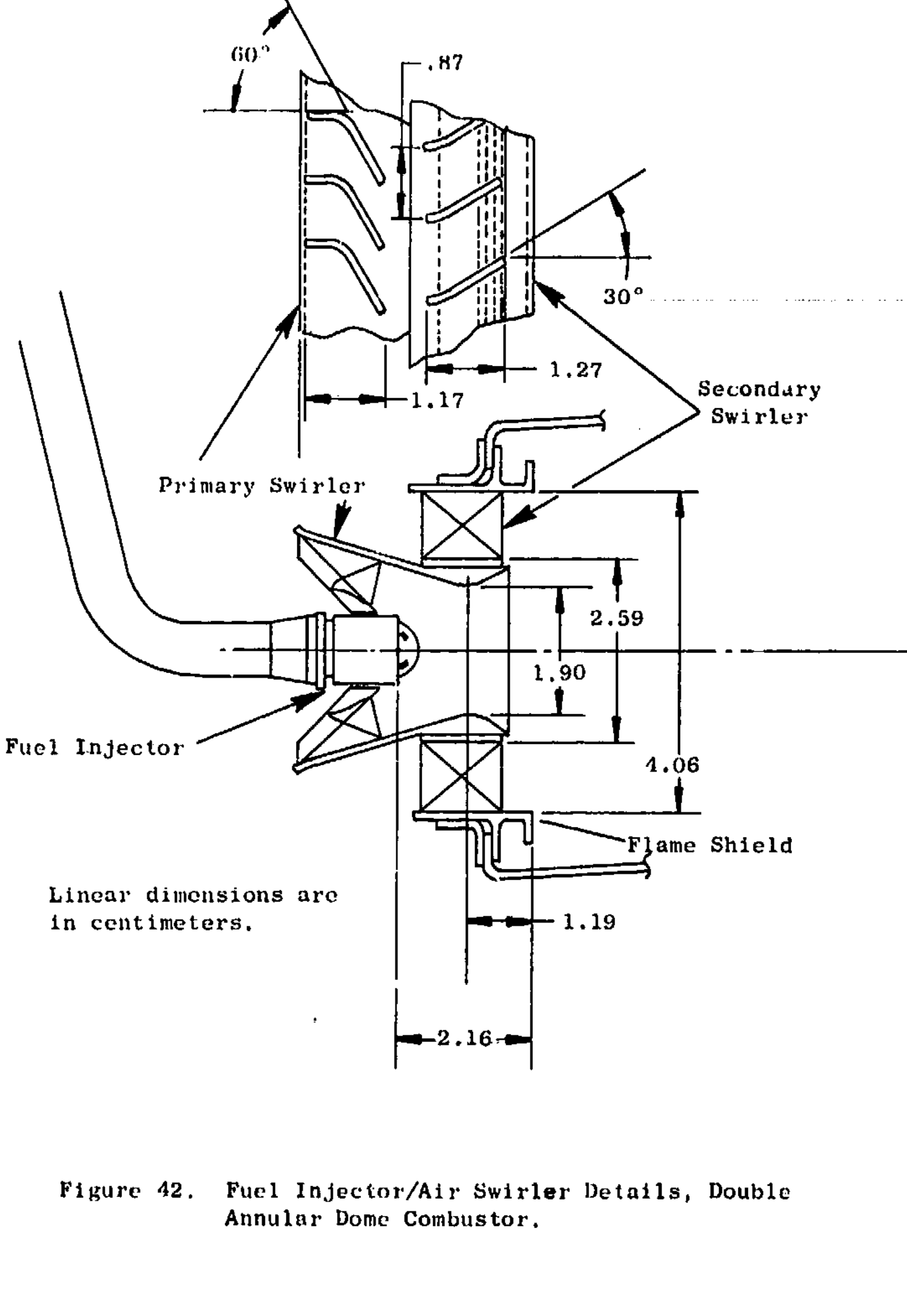


Figure 42. Fuel Injector/Air Swirler Details, Double Annular Dome Combustor.

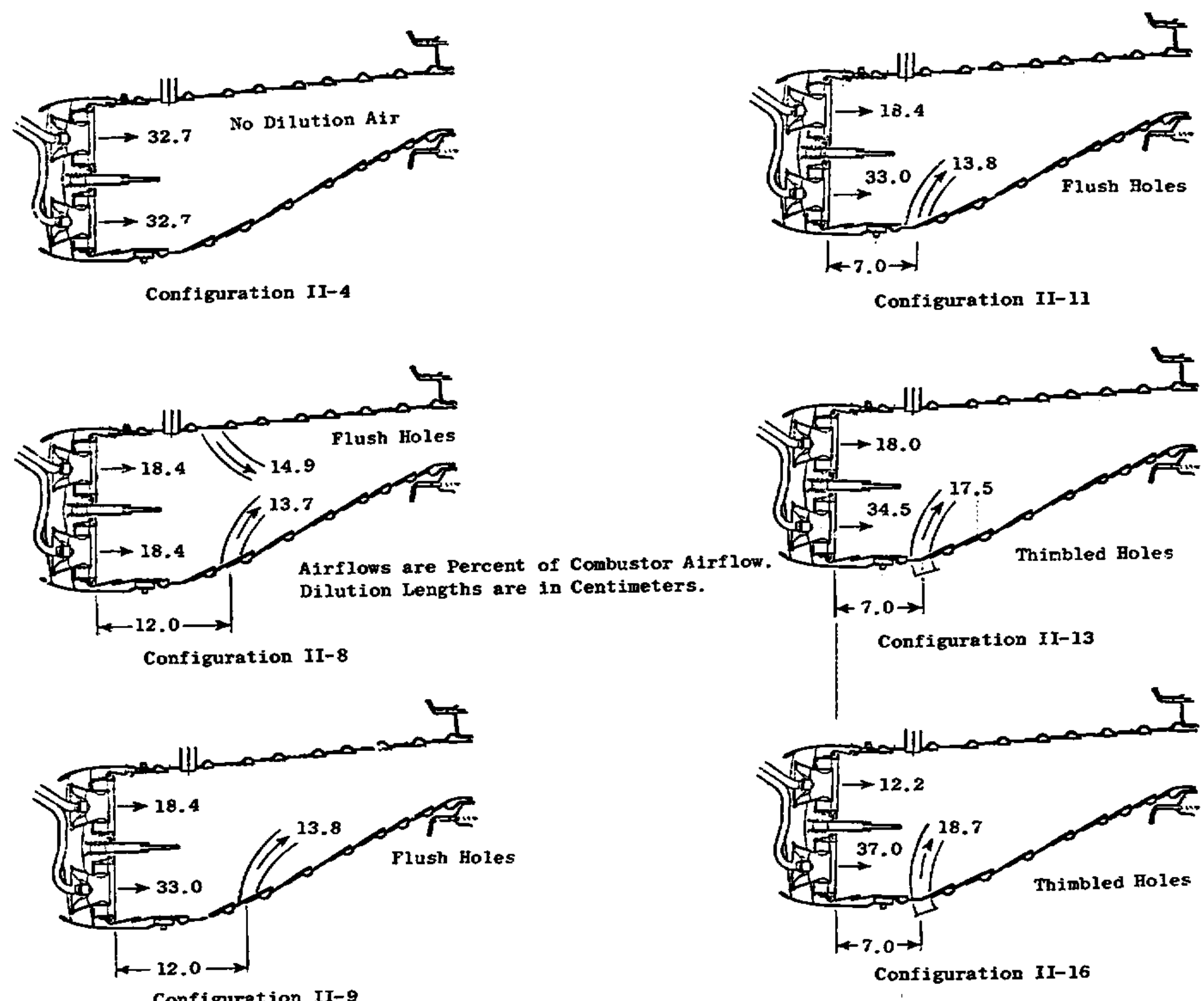


Figure 43. Design Parameter Variations, Double Annular Dome Combustors.

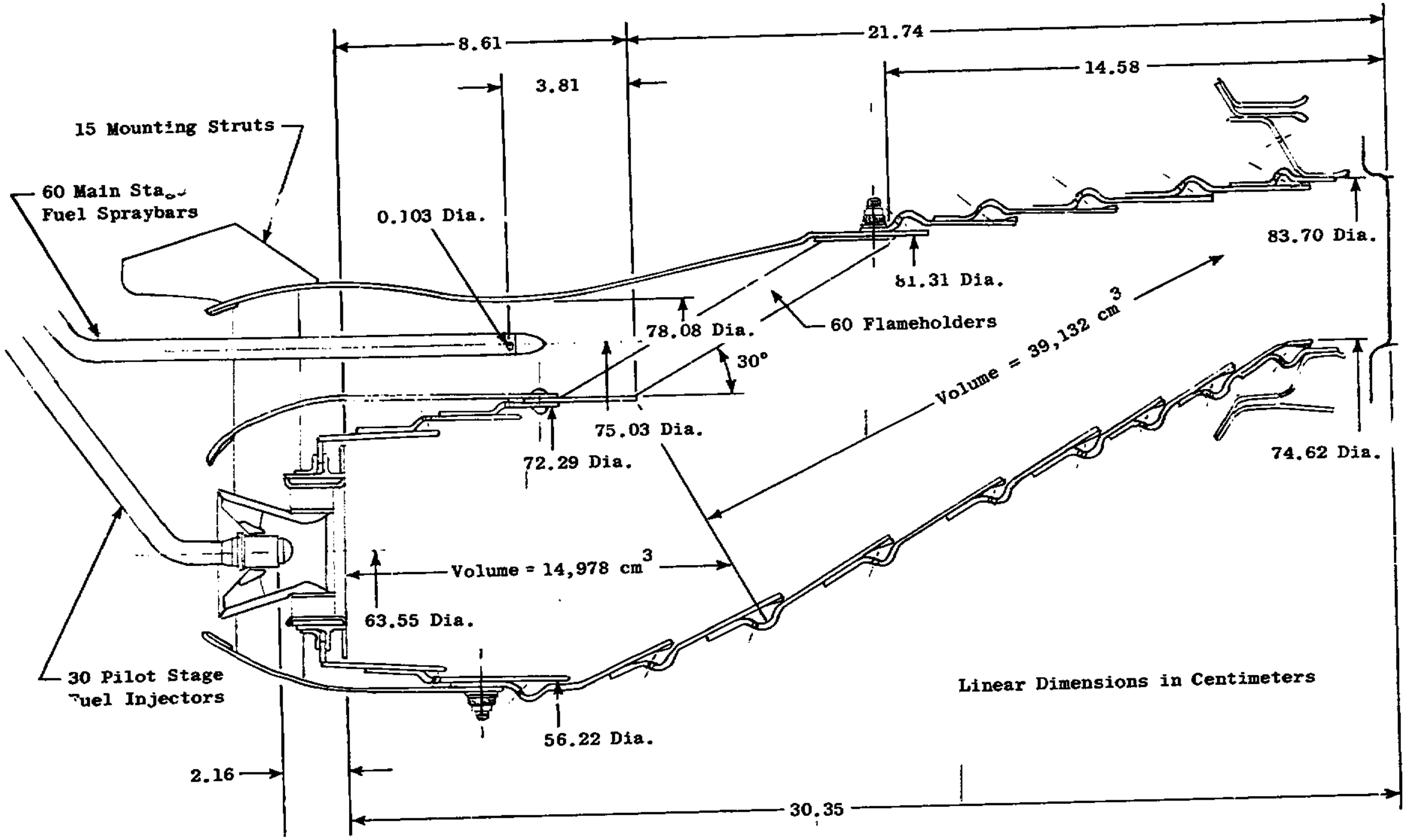


Figure 44. General Arrangement, Radial/Axial Staged Combustor.

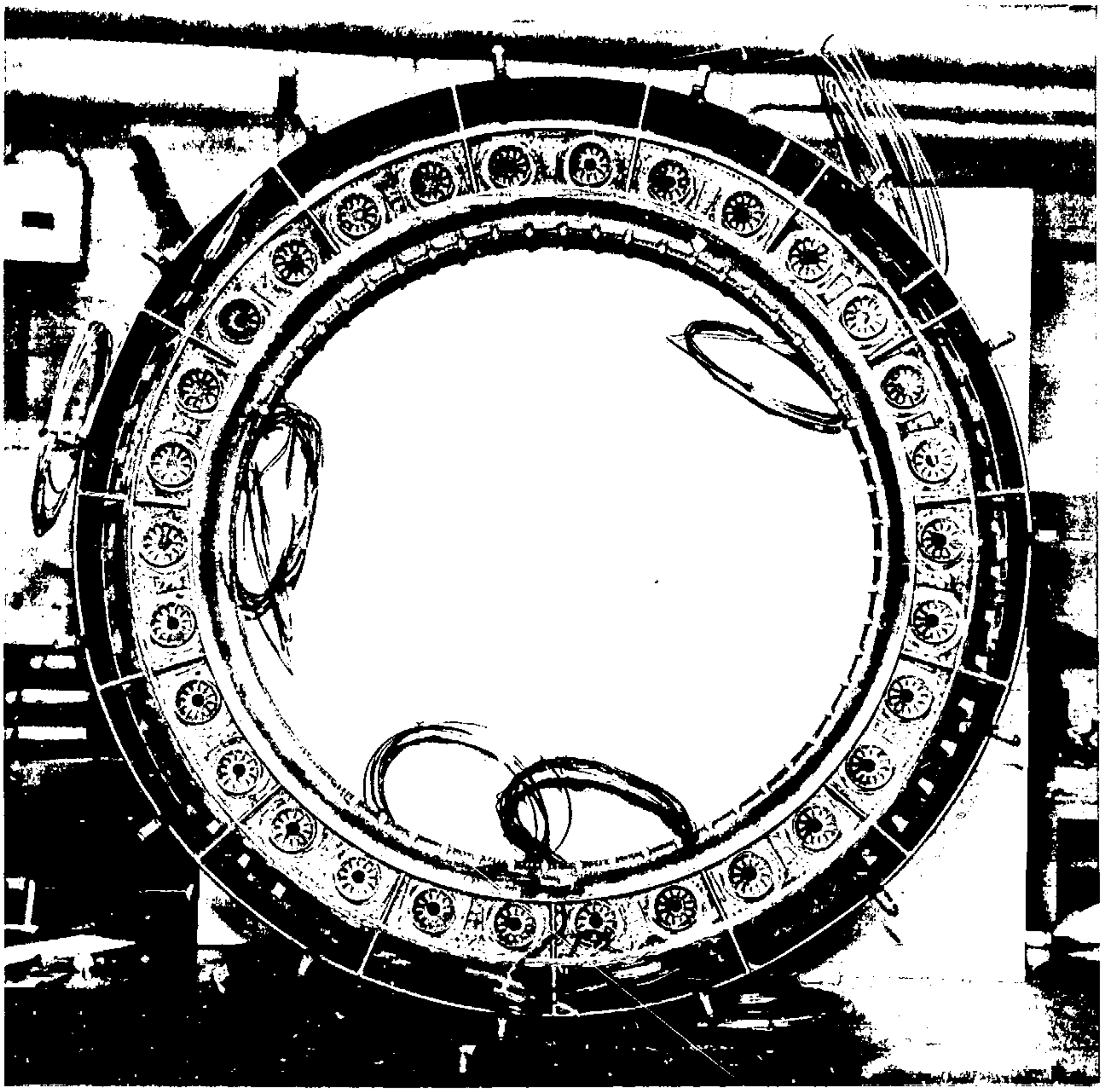


Figure 45. Radial/Axial Staged Combustor Assembly, Forward Looking Aft.

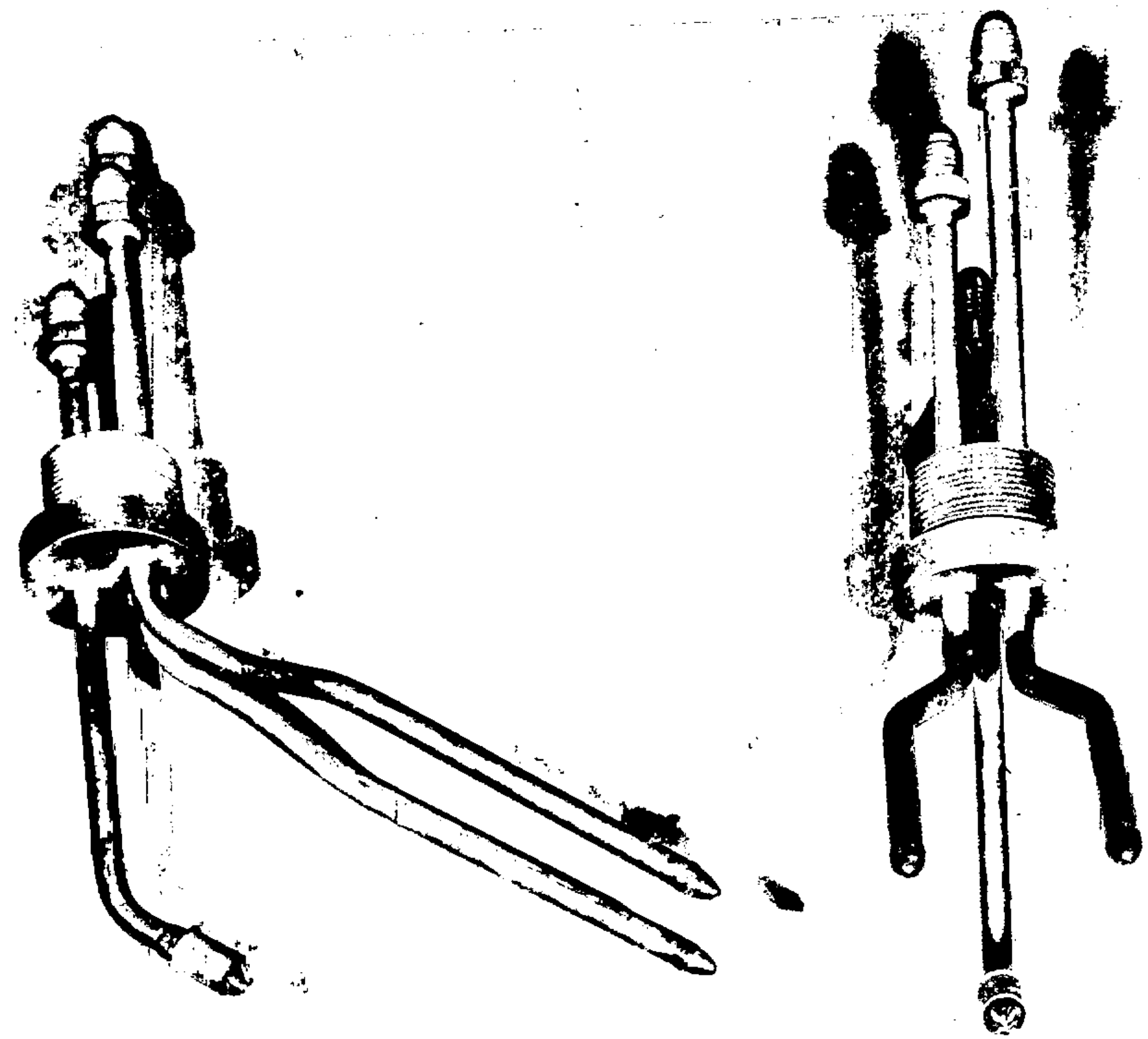


Figure 46. Fuel Injector Assemblies, Radial/Axial Staged Combustor.

and thermal growth between the fuel injectors and the combustor assembly. The flameshields were impingement cooled. The dome panels were film cooled using a stacked ring construction.

The main stage flameholder assembly (Figure 47) consisted of an array of 60 sloping high blockage (about 80 percent) flameholders which were semicircular in cross section. The flameholder width was constant from base to tip so the main stage air admission gap or "chute" width varied slightly from the inner to outer diameter. In this design approach, the base of the flameholders opens to permit the pilot combustion products to flow radially outward in the flameholder wakes and pilot the main stage combustion process. An array of cooling air holes at the tip of the flameholders was used to cool the outer flameholder/cowl/liner joint which was followed immediately by a film cooling slot in the outer liner.

The cowl contained a flow splitter to: (1) form a smooth flowpath for the main stage air, and (2) isolate the main stage fuel-air mixture from the pilot outer film cooling air. The main stage flowpath was designed to smoothly accelerate the main stage air from about 46 m/s at the inlet to about 91 m/s at the fuel injection station and to about 137 m/s at the chute exit surface.

The pilot stage fuel injector/air swirler combination consisted of an airblast fuel atomization/mixing device, as was previously described. The main stage fuel injectors consisted of 60 simple low pressure drop spraybars, each having a pair of opposed circumferentially-directed orifices (0.103-cm diameter). The fuel injector assemblies were installed in the rig from the inside before the combustor was installed. This design was selected for screening tests so that the main stage fuel injector location and/or configuration could be changed readily. In actual engine application, these injectors might be mounted radially from new pads in the outer casing.

The cooling liners were modified in that cooling flow metering hole areas were reduced and dilution holes were closed. The outer liner was also shortened.

Seven Radial/Axial Staged Combustor test configurations were evaluated. The key design parameter variations are shown in Table XIV and Figure 48. The emissions goals of the Phase I Program were very nearly approached with the first test configuration, but with somewhat reduced combustion efficiency levels at high power operating conditions. The design variations that were investigated included:

- Adding splash plates (Figure 49) to the main stage fuel injectors. Flow visualization tests showed the original fuel injectors provided good circumferential but limited radial fuel spreading. The splash plates increased the radial extent of fuel spread at some expense to circumferential spreading.

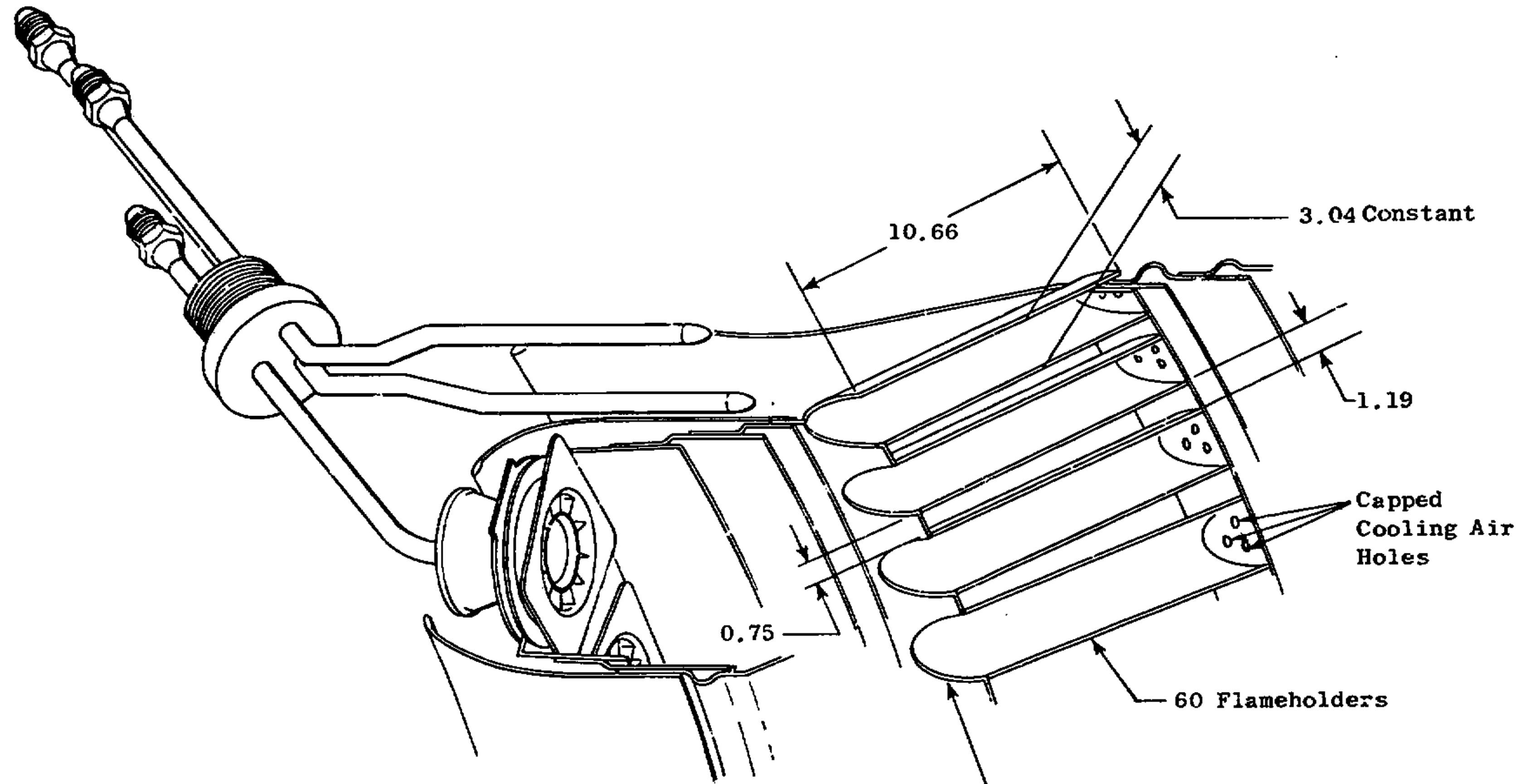
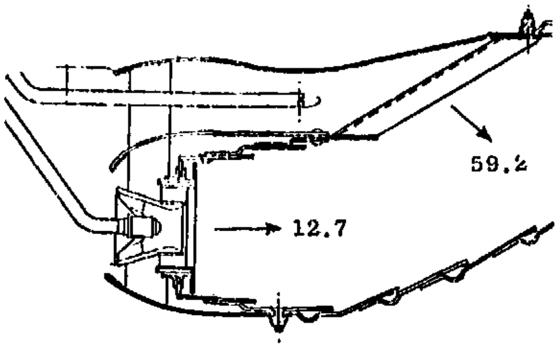


Figure 47. Flameholder Details, Radial/Axial Staged Combustor.

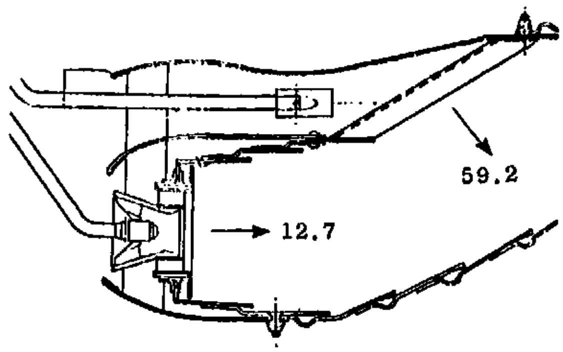
Table XIV. Summary of Design Parameters, Radial/Axial Staged Combustor Test Configurations.

Test Configuration	II-6,7	II-10	II-12,15	II-14	III-2	All
Pressure Loss						
Total, at SLTO, %	4.75	4.75	5.15	5.16	3.95	----
Airflow Distributions, % of Combustor Airflow						
Pilot Stage Swirler	12.7	12.7	10.8	8.2	9.3	----
Main Stage Chutes	59.2	59.2	60.4	62.3	64.5	----
Cooling Flows						
Pilot	---	---	---	---	---	10.8 to 12.3
Liners	---	---	---	---	---	15.4 to 17.2
Fuel Injectors						
Pilot Stage						
Type	---	---	---	---	---	Fuel Nozzle
Spacing, cm	---	---	---	---	---	6.65
Main Stage-Type	Plain	Splash Plates	Splash Plates	Splash Plates	Splash Plates	----
Burning Length, cm						
Pilot Stage(1)	---	---	---	---	---	8.61
Overall	---	---	---	---	---	30.35
Volume, cm^3						
Pilot Stage	---	---	---	---	---	14,978
Overall	---	---	---	---	---	54,110
Pilot Stage Dome						
Height, cm	---	---	---	---	---	8.04
Area at Exit, cm^2	---	---	---	---	---	1,491

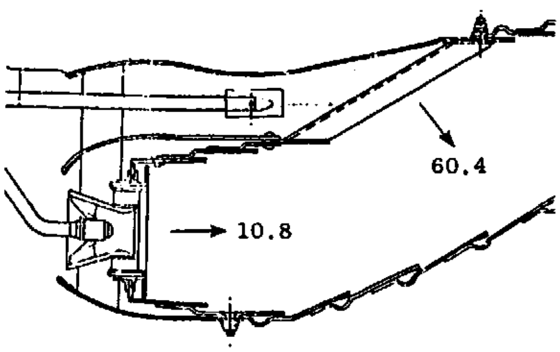
Superscript: (1) --- From dome flameshields to main stage flameholders.



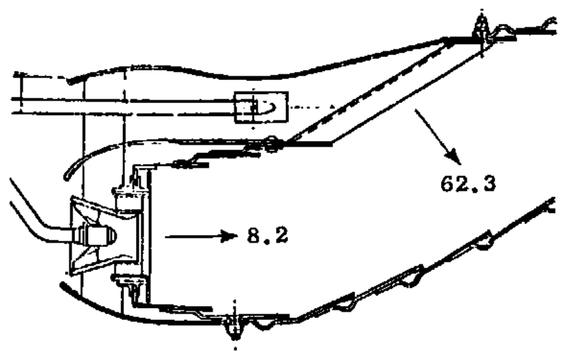
Configurations II-6, 7



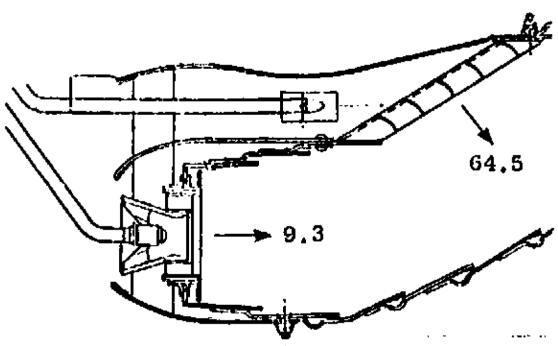
Configuration II-10



Configurations II-12, 15



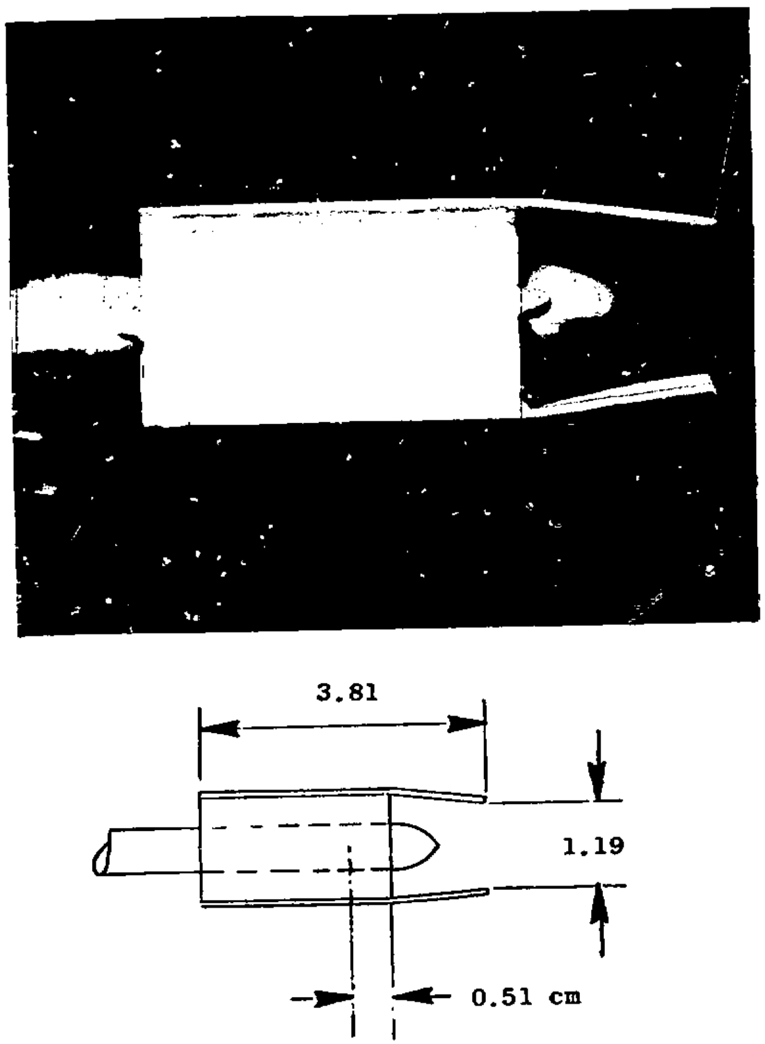
Configuration II-14



Configuration III-2

Airflows are Percent of Combustor Airflow

Figure 48. Design Parameter Variations, Radial/Axial Staged Combustor.



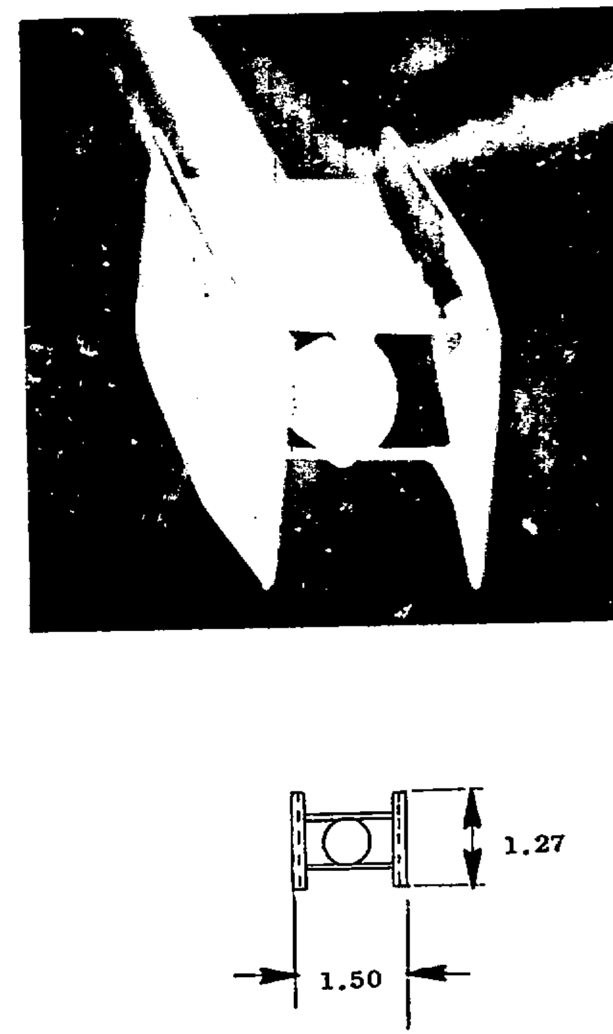


Figure 49. Splash Plate Modifications to the Main Stage Fuel Spraybar, Radial/Axial Staged Combustor.

- Reducing the pilot stage airflow. The intent was to bias the fuel further to the main stage while holding or increasing the pilot stage outlet temperature. Pilot stage airflow was reduced by closing off some of the secondary air swirler flow passages.

- Adding turning vanes to the main stage chutes (Figure 50) to promote more intense mixing between the pilot and main stage flows.

Throughout these tests, the fuel injectors were manifolded so that various fueling modes and wide variations in fuel flow splits could be investigated.

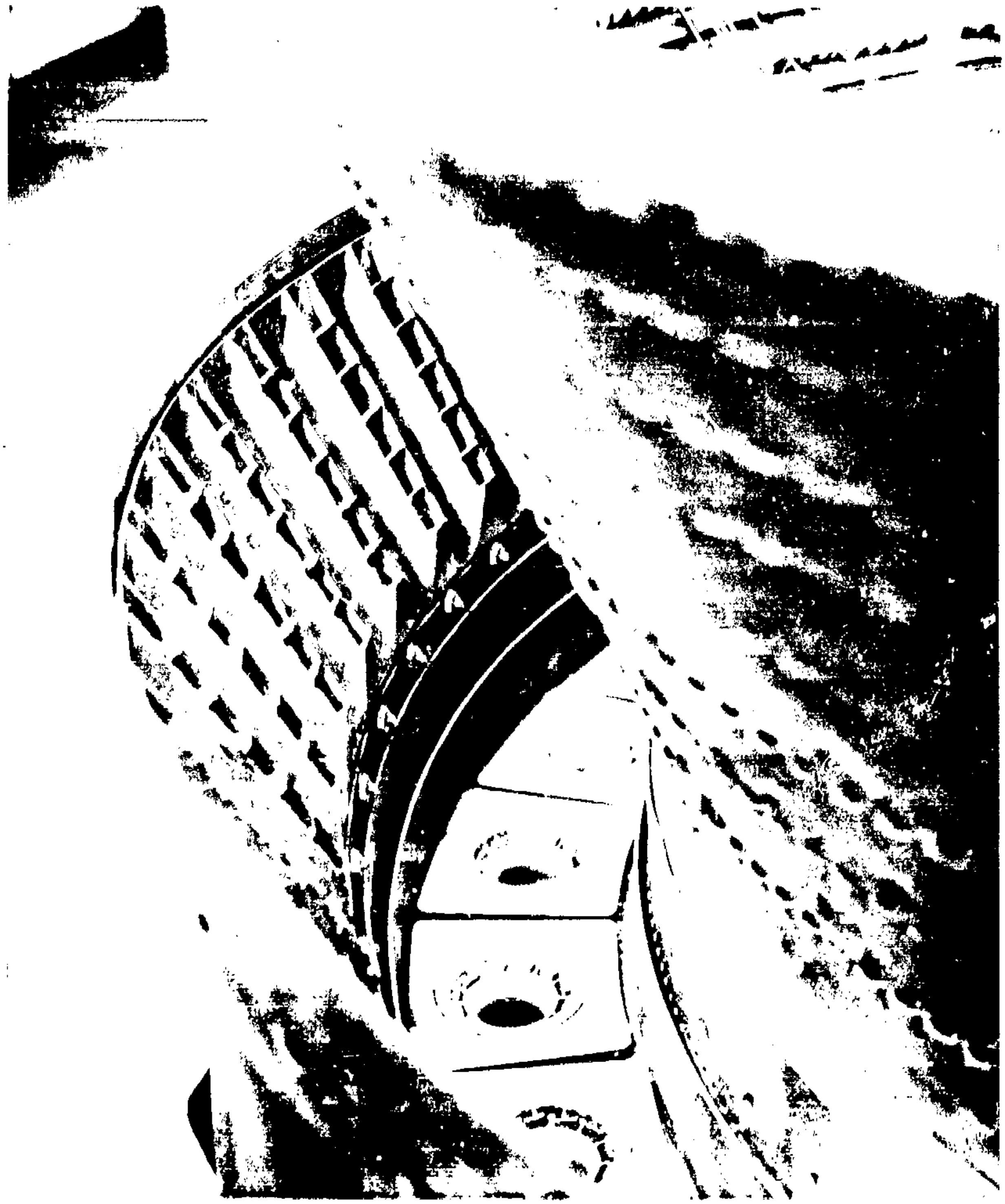


Figure 50. Turning Vanes Installed in Chutes, Test Configuration III-2.

EXPERIMENTAL RESULTS

In the basic Phase I Program, 34 combustor configurations were evaluated. In the following sections of this chapter, the results of these tests, categorized by combustor design type, are presented. The actual sequencing of these various tests that was used in conducting this development effort is presented in Appendix C. An extensive quantity of data was accumulated in these tests. These data, particularly the pollutant emissions level data, were consistently found to be of high quality. This assessment of the data quality is based on several factors including the generally excellent instrumentation calibration consistency, metered-to-sample fuel-air ratio agreement, data repeatability and consistency of data trends.

In each program element of the basic Phase I Program, 16 test configurations were defined and evaluated. As a part of these tests, piggybacked evaluations of several of these test configurations were also conducted at combustor operating conditions which would be associated with an AST engine at supersonic cruise. These piggybacked tests were carried out as a part of the AST Addendum. Also as a part of this addendum, a special version of a Program Element I test configuration and a Program Element II test configuration was defined. These two configurations were then evaluated at the AST cruise conditions. In these latter two tests, piggyback evaluations at the combustor operating conditions of the CF6-50 engine were also included. Thus, in each element of the basic program 17 combustor configurations were tested at the operating conditions of the CF6-50 engine.

Detailed summaries of the results of these tests are presented in Appendix C. In the following discussions, the key results, with emphasis on the pollutant emissions results, are presented.

Program Element I Results

The key pollutant emissions level results obtained with the 17 NASA Swirl-Can-Modular CF6-50 combustor configurations at standard day idle, hot day approach, hot day climbout, hot day takeoff and standard day cruise operating conditions of the CF6-50 engine are presented in Tables XV, XVI, XVII, XVIII and XIX, respectively. In general, only relatively small reductions in pollutant emissions levels were obtained with this CF6-50 combustor design approach. However, at the idle and intermediate engine power operating conditions, significant NO_x emissions level reductions with high combustion efficiency levels were obtained. The significant findings of these Program Element I tests follow.

Flat Flameholder Combustor Configurations - Seven Flat Flameholder test configurations were evaluated. In this series of test configurations, the lowest CO and HC emissions levels at idle operating conditions of any of the Program Element I test configurations were obtained (Configurations I-3 and I-4). However, excessive flameholder metal temperatures generally limited the high power testing of this series of test configurations.

Table XV. Standard Day Idle Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors.

Engine Combustor Conditions: P_{T3} 3.39 atm, T_{T3} 454° K, V_{ref} 19.5 m/s, Fuel-Air Ratio 0.0140

Engine Conditions Duplicated In Test Rig

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %
Program Goals	----	20	4	99+
CF6-50 Engine	2.8	67	27	95.7
CF6-50 Combustor Rig Data	2.69	76	24	95.8
Swirl-Can Combustor Configurations:				
72-Module Flat Plate Array				
Configuration I-1				
All Modules Fueled	1.76	116.5	85	88.8
O.D. Row Only Fueled	2.35	94.5	59	91.9
90-Module Flat Plate Array				
Configuration I-2				
All Modules Fueled	0.90	132.	262	70.7
O.D. Row Only Fueled	2.50	89.	34.5	94.4
O.D. Row Only Fueled 6% Air Bleed Simulation, F/A = 0.0149	2.58	84	28.5	95.1
O.D. Row Only Fueled 12% Air Bleed Simulation, F/A = 0.0157	2.65	81	25.0	95.6
Configuration I-14				
O.D. Row Only Fueled	2.24	89	28.8	95.0
I.D. Row Only Fueled	2.32	74.5	33.	95.0
All Modules Fueled, 180° Sector Burning Simulation at F/A = 0.0280	2.11	64.	15.	97.0
60-Module Flat Plate Array				
Configuration I-3,4				
All Modules Fueled	1.47	117.	80.	89.3
2 Alternate 90° Sectors Fueled, Outer Row Fuel 2x Inner Row Fuel	2.41	69.2	11.8	97.2
O.D. Row Only Fueled	2.23	116	80.5	89.2
I.D. Row Only Fueled	2.51	61.	12.6	97.3
Configuration I-11				
All Modules Fueled	1.65	128.	83.5	89.6
Outer Row Fuel 1/2 Inner Row Fuel	2.37	71.4	15.5	96.8
1 240° Sector Fueled, Outer Row Fuel 1/3 Inner Row Fuel	1.95	87.5	39.	94.0
All Modules Fueled, 180° Sector Burning Simulation at F/A = 0.0280	2.26	68.	7.5	98.7
Configuration III-I AST Design				
All Modules Fueled	0.98	147.	155.	81.1
All Modules Fueled, 180° Sector Burning Simulation, F/A = 0.0280	1.65	77.	30.5	95.1
I.D. Row Only Fueled	1.71	103	60.	91.6
72-Module Counterswirl Flameholder Array				
Configuration I-5				
O.D. Row Only Fueled	1.82	109	89.	88.6
I.D. Row Only Fueled	2.15	100	29.	94.8
Configuration I-6				
O.D. Row Only Fueled	2.17	100	51.	92.6
I.D. Row Only Fueled	2.32	91.5	40	93.9
Configuration I-9				
I.D. Row Only Fueled	2.11	83.	36.	94.5
All Modules Fueled, 180° Sector Burning Simulation, F/A = 0.0280	1.90	70.	22.4	96.1
Configuration I-16				
I.D. Row Only Fueled	1.84	92.1	90.5	88.8
All Modules Fueled, 180° Sector Burning Simulation	1.73	77.5	46.	93.6
90-Module Sheltered Flameholder Array				
Configuration I-7				
O.D. Row Only Fueled	1.75	108.	85.	89.0
I.D. Row Only Fueled	2.17	102.	59.	91.7
Configuration I-8				
O.D. Row Only Fueled, P_{T3} = 3.39 atm	2.07	108.	75.	90.0
O.D. Row Only Fueled, P_{T3} = 4.5 atm	2.94	92.7	55.6	92.2
I.D. Row Only Fueled, P_{T3} = 2.75 atm	3.14	105	60.4	91.5
I.D. Row Only Fueled, P_{T3} = 4.5 atm	2.68	90.1	51.4	92.8

Table XV. Standard Day Idle Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors. (concluded)

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %
Configuration I-10,15				
All Modules Fueled	1.50	110.	106.	86.8
I.D. Row Only Fueled	1.87	91.9	88.6	88.9
O.D. Row Only Fueled	1.80	105.	67.5	90.8
O.D. Row Only Fueled, V_{ref} increased to 22.1 m/s	2.68	112.	91.8	88.1
O.D. Row Only Fueled, V_{ref} decreased to 14.7 m/s	2.07	90.9	60.1	91.9
Configuration I-12				
All Modules Fueled	1.20	106.5	110.	86.5
I.D. Row Only Fueled	2.33	86.4	33.2	84.7
Configuration I-13				
All Modules Fueled	1.95	78.	75.	90.7
All Modules Fueled, 180° Sector Burning Simulation At F/A = 0.0280	2.1	76.	75	90.8

Table XVI. Hot Day Approach Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors.

Engine Combustor Conditions: P_{T3} 11.6 atm; T_{T3} 661° K; V_{ref} 26.5 m/s; Fuel-Air Ratio 0.0142

Rig Testing At Reduced Pressures Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	-------
CF6-50 Engine	12.0	4.0	0.1	99.9	5
CF6-50 Engine Rig Data	10.7	7.5	0.3	99.8	-------
Swirl-Can Combustor Configurations:					
72-Module Flat Plate Array					
Configuration I-1	8.2	28.0	8.9	98.4	-------
90-Module Flat Plate Array					
Configuration I-2	5.8	31.0	2.8	99.0	-------
Configuration I-14	5.35	57.5	6.5	98.0	-------
180° Sector Burning Simulation at F/A = 0.0284	9.30	27.0	0.65	99.3	
60-Module Flat Plate Array					
Configuration I-3,4					
P_{T3} = 3.4 atm	6.15	40.0	2.44	98.8	2
P_{T3} = 6.8 atm	6.74	22.4	1.32	99.4	-------
Configuration I-11	5.90	60.0	5.0	98.1	-------
180° Sector Burning Simulation at F/A = 0.0284	8.69	24.5	0.6	99.4	-------
Configuration III-1 AST Design	6.30	79.0	14.6	96.6	1
180° Sector Burning Simulation at F/A = 0.0284	8.95	37.0	1.2	99.0	
72-Module Counterswirl Flameholder Array					
Configuration I-5	6.2	79.0	11.5	96.9	1
Configuration I-6	6.55*	----	----	----	-------
Configuration I-9	4.15	107.	41.5	93.2	-------
180° Sector Burning Simulation at F/A = 0.0284	8.55	24.0	1.5	99.3	-------
Configuration I-16	2.0	131.	262.	70.7	-------
180° Sector Burning Simulation at F/A = 0.0284	8.9	28.0	1.0	99.3	-------
90-Module Sheltered Flameholder Array					
Configuration I-7	7.2	81.5	26.0	95.5	1
Configuration I-8	6.6	79.0	21.5	96.1	-------
180° Sector Burning Simulation at F/A = 0.0284	9.8	36.0	2.0	99.0	-------
Configuration I-10,15	6.7	71.0	16.0	96.7	-------
180° Sector Burning Simulation at F/A = 0.0284	9.8	33.0	2.0	99.0	-------
Configuration I-12	6.7	73.0	131.	85.2	-------
180° Sector Burning Simulation at F/A = 0.0284	9.4	30.0	7.0	98.6	-------
Configuration I-13	6.1	80.0	16.0	96.6	-------
180° Sector Burning Simulation at F/A = 0.0284	9.8	31.0	1.8	99.1	-------

Note: *No Hot Day Approach Rig Data Obtained for This Configuration. The NO_x Data Presented Above Were Extrapolated From CTOL Cruise Rig Data.

Table XVII. Hot Day Climbout Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	25.3 atm	825° K	26.5 m/s	0.0225

Rig Testing at Reduced Pressure Up to 9.6 atm. – Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	-------
CF6-50 Engine	36.0	0.3	0.1	99.9	12
CF6-50 Engine Combustor, Rig Data	32.0	0.3	0.1	99.9	2
Swirl-Can Combustor Configurations:					
72-Module Flat Plate Array					
Configuration I-1	31.6*	---	---	----	-------
90-Module Flat Plate Array					
Configuration I-2	23.85	1.1	-0-	100	-------
Configuration I-14	27.2#	---	---	99.9+#	-------
60-Module Flat Plate Array					
Configuration I-3,4 -- No High Power Data Obtained					
Configuration I-11	30.4*	---	---	---	-------
Configuration III-1 AST Design	27.6@	---	---	---	-------
72-Module Counterswirl Flameholder Array					
Configuration I-5	28.6	9.9	-0-	99.8	8
Configuration I-6	28.0@	---	---	99.5+	-------
Configuration I-9	26.2@	---	---	99.6+	-------
Configuration I-16	24.6	10.0	1.25	99.6	-------
90-Module Sheltered Flameholder Array					
Configuration I-7	28.7	9.2	2.3	99.6	3
Configuration I-8					
P_{T3} = 4.76 atm	30.0	8.7	6.4	99.2	-------
P_{T3} = 6.80 atm	30.0	6.0	4.6	99.4	-------
Configuration I-10,15					
P_{T3} = 4.76 atm	30.8	74.	0.1	98.3	
P_{T3} = 6.80 atm	30.8	5.4	0.3	99.8	-------
Configuration I-12	30.1	6.6	1.4	99.8	-------
Configuration I-13	34.6	3.4	2.3	99.9	-------

Notes: For the Above Models, Data at Hot Day Climbout Conditions Were Not Obtained. The Data Presented Above Were Extrapolated From the Following Conditions:

*From Hot Day Approach Rig Data.

#From CTOL Cruise Rig Data.

@From Hot Day Takeoff Rig Data.

Table XVIII. Hot Day Takeoff Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors.

Engine Combustor Conditions: P_{T3} 29.1 atm; T_{T3} 858° K; V_{ref} 26.5 m/s; Fuel-Air Ratio 0.0245

Rig Testing At Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	10	----	----	99+	15
CF6-50 Engine	44.0	0.2	0.1	99.9	12
CF6-50 Combustor Rig Data	41.2	0.4	-0-	99.9	1
Swirl-Can Combustor Configurations:					
72-Module Flat Plate Array					
Configuration I-1	44.1*	----	----	----	-----
90-Module Flat Plate Array					
Configuration I-2	33.6#	----	----	100#	-----
Configuration I-14	38.1@	----	----	99.9@	-----
60-Module Flat Plate Array					
Configuration I-3,4 -- No High Power Data Obtained.					
Configuration I-11	39.7*	----	----	99.4+*	-----
Configuration III-1, P_{T3} = 4.8 atm	37.5	9.0	0.1	99.8	2
Configuration III-1, P_{T3} = 6.3 atm	37.5	9.1	0.1	99.8	-----
72-Module Counterswirl Flameholder Array					
Configuration I-5	37.6	12.0	-0-	99.7	25
Configuration I-6	37.0	12.7	0.4	99.7	6
Configuration I-9	37.2	3.2	0.9	99.9	-----
Configuration I-16	34.6¢	----	---	99.7+¢	-----
90-Module Sheltered Flameholder Array					
Configuration I-7	38.5#	----	---	99.6¢	-----
Configuration I-8	39.7	8.6	0.3	99.8	-----
Configuration I-10,15	39.1	5.9	-0-	99.9	-----
Configuration I-12	38.5	9.1	0.3	99.8	-----
Configuration I-13	46.1#	---	---	99.9+#	-----

Notes -- * No Hot Day Takeoff Data Taken For This Configuration. The NO_x and Combustion Efficiency Data Presented Above Were Extrapolated From Hot Day Approach Rig Data.

-- # No Hot Day Takeoff Data Obtained For This Configuration. The NO_x Combustion Efficiency Data Presented Above Were Extrapolated From Hot Day Climbout Rig Data.

-- @ No Hot Day Takeoff Data Obtained For This Configuration. The NO_x And Combustion Efficiency Data Presented Above Were Extrapolated From CTOL Cruise Rig Data.

-- ¢ No Hot Day Takeoff Data Taken For This Configuration. The NO_x and Combustion Efficiency Data Presented Above Were Extrapolated From Hot Day Approach, Climbout, and CTOL Cruise Data.

Table XIX. Standard Day Cruise Emissions Data, NASA Swirl-Can-Modular CF6-50 Combustors.

Engine Combustor Conditions: P_{T3} = 14.4 atm, T_{T3} = 733° K, V_{ref} = 34.4 m/s, Fuel-Air Ratio = 0.0210

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	-----
CF6-50 Combustor - Rig Test Data	17.6	0.9	0.3	99.9	7
Swirl-Can Combustor Configurations:					
72-Module Flat Plate Array					
Configuration I-1	15.05*	----	----	98.4+	-----
90-Module Flat Plate Array					
Configuration I-2	12.29	2.3	-0-	100.	7
Configuration I-14	12.48	6.5	0.1	99.8	-----
60-Module Flat Plate Array					
Configuration I-3,4	14.15*	----	----	99.7+	-----
Configuration I-11	13.15*	----	----	99.3+	-----
Configuration III-1	15.2	17.8	0.6	99.5	1
72-Module Counterswirl Flameholder Array					
Configuration I-5	14.8	16.7	0.1	99.6	-----
Configuration I-6	14.6	16.9	1.1	99.5	3
Configuration I-9	11.8	13.6	0.8	99.6	-----
Configuration I-16	10.56	37.0	19.0	97.2	-----
90-Module Sheltered Flameholder Array					
Configuration I-7	15.0	17.8	4.3	99.2	3
Configuration I-8	14.8	18.5	2.7	99.3	-----
Configuration I-10,15	13.9	14.5	1.1	99.6	-----
Configuration I-12	14.6*	----	----	----	-----
Configuration I-13	15.8	13.4	1.0	99.6	-----

Note * CTOL Cruise Rig Data Were Not Obtained For These Configurations. The NO_x and Combustion Efficiency Data Presented Above Were Extrapolated From Hot Day Approach Rig Data.

The first tests in this series were aimed at determining the effect of the number of swirl-can modules (60, 72, or 90) on emissions levels. The NO_x emissions levels at the takeoff condition were found to be about the same as those of the CF6-50 production engine combustor and no strong effect of number of modules was found. The 90-swirl-can combustor (Configuration I-2) tended to provide lower NO_x levels, but very limited data were obtained because of excessive flameholder temperatures. A retest of this configuration (Configuration I-14) with a slightly reduced liner cooling airflow, in which more extensive data were obtained, indicated that the effect of the number of modules was very weak. Two other parameters were varied in this series in an effort to reduce NO_x emissions levels: increased combustor pressure drop, with no improvement (Configuration I-11); and increased flameholder perimeter (Configuration III-1).

As expected, the idle emissions levels were highly dependent upon fueling mode. For a common fueling mode these levels tended to increase with the number of swirl-can modules. When only the inner annulus was fueled, the idle emissions levels of the 60-swirl-can combustor (Configuration I-3) were slightly lower than those of the CF6-50 production engine combustor. Various modes of fueling the 60-swirl-can combustor were evaluated. Sector burning with half the modules fueled produced about the same CO and HC emissions levels as inner annulus burning. The results of varying the sector size showed that the HC emissions levels continued to decrease as sector size was decreased, but that a minimum CO emission level was obtained with a sector size of about 180 degrees (for the nominal overall fuel-air ratio of about 0.014).

Combustion efficiency levels at all higher engine power test conditions were consistently high (generally above 99.5 percent) and smoke emission levels were very low, as anticipated. The exit temperature profile characteristics were also generally favorable considering the development nature of the hardware. Relatively heavy carbon buildups on the downstream face of the swirlers and flameholders of the swirl-can modules were generally observed in posttest inspections of these test configurations.

Counterswirl Flameholder Configurations - Four Counterswirl Flameholder test configurations, all with 72-swirl-can modules, were evaluated. In this series of test configurations, no tests were limited by flameholder metal temperatures. One of the configurations (Configuration I-16) produced the lowest NO_x emissions level of any of the Swirl-Can-Modular Combustors that were tested.

The main design parameter investigated in this series was fuel injection technique. Some small effects on NO_x emissions characteristics were found. In the first configuration (Configuration I-5), the standard fuel injector was used. In the second configuration (Configuration I-6), an orifice was added to the end of each fuel injector tube, which produced no change. The last two configurations (Configuration I-9, with a shortened fuel tube, and Configuration I-16, with pressure-atomizing fuel nozzles and increased swirl-can flow) produced reductions at the hot day takeoff conditions. The hot day takeoff NO_x emission index of Configuration I-16 was 35g/kg fuel, which was the lowest obtained with any Swirl-Can-Modular Combustor in this program.

The idle emissions levels of this series of test configurations were relatively unaffected by the fuel injector changes and were generally higher than those of the CF6-50 production engine combustor. Annulus burning was the only fuel staging mode investigated. The Flat Flameholder combustor test results suggest that somewhat lower idle emissions levels might have been obtained with these Counterswirl Flameholder configurations with the use of sector burning.

The combustion efficiency levels at the higher power test conditions were consistently high in this series (generally above 99.8 percent). Relatively high smoke levels were obtained with Configuration I-5, but low levels were measured with Configuration I-6, indicating that the fuel injector modification was somewhat effective. Carbon accumulation on the swirlers and flameholders of the modules was relatively heavy in this series.

Sheltered Flameholder Configurations - Six Sheltered Flameholder test configurations, all with 90-swirl-can modules, were evaluated. Only one test configuration (Configuration I-13) in this series was limited by flameholder metal temperatures. This latter configuration also produced the highest NO_x level of any Swirl-Can-Modular Combustor tested.

The design variables investigated in this series included swirl-can airflow quantity, overall pressure drop and alternate dilution air introduction methods. Except for the use of flameholder dilution (Configuration I-13), these changes had virtually no effect on NO_x emissions levels. Higher pressure drop (Configuration I-10) was somewhat effective at lower fuel-air ratios, but at the hot day takeoff conditions the NO_x level was relatively unaffected. The idle emissions levels were also relatively insensitive to these configuration changes. Sector burning again was found to be the best fueling mode, especially with respect to HC emissions.

Again in this series, the combustion efficiency levels at the higher power test conditions were consistently high (generally above 99.8 percent) and the smoke levels were low. The exit temperature profile characteristics were somewhat poorer than those of the Flat Flameholder configurations, due mainly to the difficulty in maintaining dimensional uniformity of the dome arrays. Carboning tendencies were less noticeable in this series than in either the Counterswirl or Flat Flameholder configuration test series.

One of these configurations (Configuration I-10) was selected for more extensive investigations. This selection was made primarily because operation was possible at all required high engine power modes with this test configuration. In these additional evaluations (as Configuration I-15), the sea level ignition characteristics of the combustor were measured (Figure 51). The fuel flow rates required for both lean blowout and full flame propagations were found to be higher than those of the CF6-50 production engine combustor, indicating that further development would be required to meet the CF6-50 altitude relight requirements.

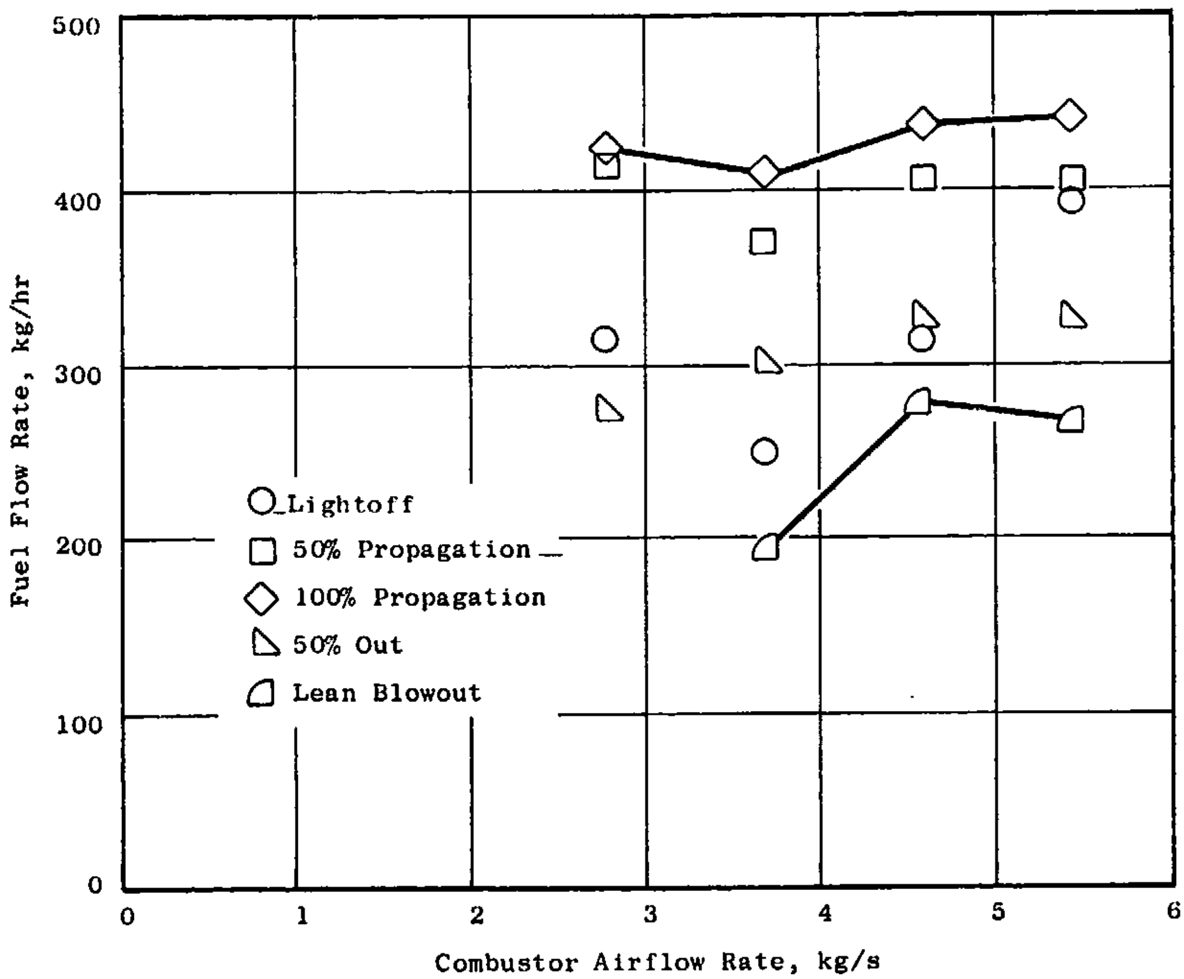


Figure 51. Sea Level Ignition Characteristics, 90-Swirl-Can/Sheltered Flameholder Combustor, Configuration I-15.

Program Element II Results

Single Annular CF6-50 Combustor Configurations - Four single annular configurations were evaluated in Program Element II. The key pollutant emissions level results obtained with these test configurations are presented in Tables XX, XXI, XXII, XXIII, XXIV and XXV.

The first configuration (Configuration II-1) in this series consisted of a production CF6-50 engine combustor with modified fuel supply plumbing arrays. The objectives of this first test were threefold:

- Check out all testing procedures, including the emissions data acquisition procedures, for use throughout the program.
- Obtain baseline pollutant emissions and combustor performance data.
- Determine the degree of idle emissions reductions obtainable in a conventional single annular combustor by the use of fuel staging or CDP bleed air extraction methods at idle operating conditions.

All three objectives were achieved. The newly defined exhaust gas sampling equipment and procedures designed specifically for this program performed as planned. The measured emissions levels agreed closely with the levels predicted from CF6-50 engine tests. The NO_x emissions levels decreased linearly with fuel-air ratio at takeoff operating conditions, which is typical of conventional (rich) combustor dome designs.

With CDP bleed air extraction or sector burning at idle operating conditions, significant CO and HC emissions level reductions were obtained, as shown in Table XX. The use of increased bleed air extraction reduces the combustor reference velocity, which itself is effective (increased residence time), but more importantly increases the fuel flow rate required to maintain engine speed. Combined, these effects significantly increase the combustor fuel-air ratio. Fueling alternate nozzles at idle compared to fueling all of the nozzles produced virtually no change in emissions levels. However, sector burning (15 nozzles fueled in 2 opposed sectors) provided significant reductions. The results indicate that further reductions might have been achieved by fueling fewer nozzles and/or grouping the fueled nozzles into one continuous sector (rather than two sectors), since a major portion of the emissions occurred in the interface region. It appears that the lean interface quenching effect is the reason why fueling alternate nozzles is ineffective and sector burning is effective.

Three Lean Dome Single Annular Combustor configurations (Configurations II-2, II-3 and II-5) were tested. In these configurations all of the combustor airflow, except that required for liner cooling, was introduced into the dome. The first configuration (Configuration II-2) produced a large reduction in NO_x levels at low fuel-air ratios, but at the hot day takeoff conditions, the NO_x level was the same as that of the CF6-50 production engine combustor. Apparently, the fuel-air mixing rate was slow compared to the combustion rate. The idle emissions were very high, even with sector burning, and the high

Table XX. Standard Day Idle Emissions Data, Single Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	3.39 atm	454° K	19.5 m/s	0.0140

Test Conditions Duplicated in Test Rig

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %
Program Goals	---	20	4	99+
CF6-50 Engine	2.8	67	27	95.7
CF6-50 Combustor Rig Tests:				
II-1 Baseline Std Engine Combustor				
Normal Operational Mode	2.69	76	24	95.8
Simulated 6% Air Bleed; F/A = 0.0149	2.74	71	20	96.3
Simulated 12% Air Bleed; F/A = 0.0157	2.78	67	17	96.7
Fuel Supplied Only to Alternate Nozz.	2.56	71	24	95.9
Fuel Supplied to Alternate 90° Sectors	3.90	41	2.4	98.8
Lean Dome CF6-50 Combustor Configurations:				
II-2				
2 Alternate 90° Sectors Fueled	3.04	79	65	91.6
Sectors with 6% Bleed Simulation F/A = 0.0149	3.07	80.5	63	91.8
Sectors with 12% Bleed Simulation F/A = 0.0157	3.09	84	62	91.8
2 120° Sectors Fueled	2.65	96.5	102	87.5
2 Opposed 60° Sectors Fueled	3.82	103	60	91.6
II-3,5				
2 Alternate 90° Sectors Fueled	1.46	92.5	75	90.3

Table XXI. Hot Day Approach Emissions Data, Single Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	11.6 atm	661° K	26.5 m/s	0.0142

Rig Testing at Reduced Pressures up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	----
CF6-50 Engine	12.0	4.0	0.1	99.9	5
CF6-50 Combustor Rig Tests :					
II-1 Baseline Std Engine-Combustor: P_{T3} = 6.8 atm	10.7	7.5	0.3	99.8	----
Lean Dome CF6-50 Combustor Configurations:					
II-2 P_{T3} = 6.8 atm	5.6	101	29.6	94.7	----
II-3,5 P_{T3} = 9.53 atm*	4.10	----	----	----	----

Note: * For Models II-3,5, rig data were not obtained at the approach conditions. The NO_x engine data presented above were extrapolated from CTOL cruise data.

Table XXII. Hot Day Climbout Emissions Data, Single Annular CF6-50 Combustors.

	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
Engine Test Conditions:	25.3 atm	825° K	26.5 m/s	0.0225

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	--
CF6-50 Engine	36.0	0.3	0.1	99.9	12
CF6-50 Combustor Rig Tests:					
II-1 Baseline Std Engine-Combustor: P_{T3} = 9.53 atm	32.0	0.3	0.1	99.9	2
Lean Dome CF6-50 Combustor Configurations:					
II-2					
P_{T3} = 9.53 atm	28.6	9.2	0.8	99.7	--
P_{T3} = 6.8 atm	28.6	13.5	0.8	99.6	2
II-3,5 P_{T3} = 9.53 atm*	26.1	----	----	----	--

Note * For Models II-3,5, rig data were not obtained at the climbout conditions. The NO_x engine data presented above were extrapolated from hot day takeoff data.

Table XXIII. Standard Day Takeoff Emissions Data, Single Annular CF6-50 Combustors.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	819° K	26.0 m/s	0.0245

....Oxides of Nitrogen Engine Values Obtained by Extrapolating Hot Day Takeoff Rig Data.

....Combustion Efficiency Values are Hot Day Takeoff Rig Data.

	Oxides of Nitrogen g/kg fuel	Combustion Efficiency %
Program Goals	10	99+
CF6-50 Engine	35.4	99.9
CF6-50 Combustor Rig Tests:		
II-1 Baseline: Std Engine-Combustor: P_{T3} = 9.53 atm	32.6	99.9
Lean Dome CF6-50 Combustor Configurations:		
II-2		
P_{T3} = 9.53 atm	33.0	99.8
P_{T3} = 3.04 atm	33.0	99.4
II-3,5 P_{T3} = 9.53 atm	29.3	99.7

Table XXIV. Hot Day Takeoff Emissions Data, Single Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	858° K	26.5 m/s	0.0245

Rig Testing At Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	10	———	----	99+	15
CF6-50 Engine	44.0	0.2	0.1	99.9	12
CF6-50 Combustor Rig Tests:					
II-1 Baseline: Std Engine-Combustor: P_{T3} = 9.53 atm	41.2	0.4	-0-	99.9	1
Lean Dome CF6-50 Combustor Configurations:					
II-2					
P_{T3} = 9.53 atm	41.5	6.5	0.5	99.8	2
P_{T3} = 3.04 atm	41.5	22.0	13.0	99.4	1
II-3,5 P_{T3} = 9.53 atm	35.5	6.5	1.6	99.7	12

Table XXV. Standard Day Cruise Emissions Data, Single Annular CF6-50 Combustors.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	14.4 atm	733° K	24.4 m/s	0.0210

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	----
CF6-50 Combustor Rig Tests:					
II-1 P_{T3} = 9.53 atm	17.6	0.9	0.3	99.9	7
Lean Dome CF6-50 Combustor Configurations:					
II-2 P_{T3} = 9.53 atm	12.7	23.0	2.5	99.2	----
II-3,5 P_{T3} = 9.53 atm	11.95	31.0	3.0	99.0	10

power combustion efficiency levels had all of the characteristics of a truly lean dome combustor. Also, its pressure drop was high. Posttest data analyses and flow calibrations showed that the combustor cowl was undersized. The cowl flow area was then increased which lowered the overall combustor pressure drop while increasing both the dome pressure drop and dome airflow. The combustor was retested as Configurations II-3 and II-5. This modification provided a modest reduction in NO_x levels at all fuel-air ratios. However, at this point, the Lean Dome Single Annular Combustor design approach was abandoned because:

- Relatively little progress had been made in reducing NO_x emissions levels.
- The data indicated that, even if significant NO_x reductions were achieved, the idle emissions goals would be very difficult to approach even with conventional dome flows at idle, as in Configuration II-1.
- Both the Double Annular and Radial/Axial Staged Combustor design approaches indicated more promise.

Double Annular Combustor Configurations - Six Lean Dome Double Annular Combustor configurations were evaluated. The key pollutant emissions level results obtained with these configurations are presented in Tables XXVI, XXVII, XXVIII, XXIX, XXX and XXXI.

In this series, significant effects of airflow distribution and fuel flow split between the two dome annuli on emissions levels were found. No significant reductions in emissions levels were obtained when the airflow was split equally between the annuli, as was used in the initial configuration (Configuration II-4). Idle and NO_x emissions levels very similar to those of the Lean Dome Single Annular Combustor were obtained, indicating that doubling the number of fuel injection points was not of itself a great enough change. A lower dome flow configuration (Configuration II-8) improved the idle emissions levels somewhat, but the NO_x emissions levels were even higher than those of the CF6-50 production engine combustor. These trends together with the favorable results obtained with the Radial/Axial Staged Combustor led to the biased airflow approach utilized in the subsequent Double Annular Combustor test configurations.

Significant reductions in both idle and NO_x emissions levels were obtained when the airflow was heavily biased to the inner annulus. In tests of these types of configurations (Configurations II-9, II-11, II-13 and II-16), the fuel flow split between annuli (at high power) and the location and type of the inner dome dilution air entry holes were found to be important parameters in addition to the overall airflow split between annuli. As is shown in Figure 52, the NO_x levels were progressively reduced when the inner liner dilution holes were moved forward (Configuration II-11 versus II-9), when thimbles were added to increase the dilution air jet penetration (Configuration II-13 versus II-11) and when the airflow was further biased to the inner annulus (Configuration II-16 versus II-13). These trends strongly

Table XXVI. Standard Day Idle Emissions Data, Double Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	3.39 atm	454° K	19.5 m/s	0.0140

Engine Conditions Duplicated in Test Rig

	Oxides of Nitrogen g/kg fuel	Carbon Monoxide g/kg fuel	Unburned Hydrocarbons g/kg fuel	Combustion Efficiency %
Program Goals	----	20	4	99+
CF6-50 Engine	2.8	67	27	95.7
CF6-50 Combustor Rig Data	2.69	76	24	95.8
Double Annular Combustor Configurations:				
II-4				
Pilot Only Fueled	1.36	125	130	84.1
Main Burner Only Fueled	1.23	112	120	85.4
Main Burner Only Fueled, F/A = 0.0149 6% Air Bleed Simulation	1.41	103	109	86.7
II-8				
Both Burners Equally Fueled	1.42	132	86	88.3
Main Burner Only Fueled	2.95	49	5.0	98.4
Pilot Only Fueled	2.88	44	8.2	98.2
Pilot Only Fueled, 1 168° Sector Fueled	2.85	75	2.6	97.9
II-9 -- Pilot Only Fueled	3.41	46	4.4	98.5
II-11 -- Pilot Only Fueled	3.30	36.5	7.2	98.5
II-13 -- Pilot Only Fueled	2.84	68	31	95.3
II-16 -- Pilot Only Fueled	3.29	45.2	4.9	98.4

Table XXVII. Hot Day Approach Emissions Data, Double Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	11.6 atm	661° K	26.5 m/s	0.0142

Rig Testing at Reduced Pressures Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	----
CF6-50 Engine	12.0	4.0	0.1	99.9	5
CF6-50 Combustor Rig Data (At P_{T3} = 6.8 atm)	10.7	7.5	0.3	99.8	----
Double Annular Combustor Configurations:					
II-4 P_{T3} = 3.40 atm					
Pilot F/A = 0.0071	3.85	146	48	91.8	----
II-8 P_{T3} = 3.40 atm					
Pilot F/A = 0.0071	6.45	31	1.7	99.1	----
180°-Sector Burning Simulation Total F/A = 0.0284; Pilot F/A = 0.0142	10.3	1.0	-0-	100	----
II-9 P_{T3} = 3.40 atm					
Pilot Only Fueled	12.7	26.0	0.2	99.4	----
II-11 P_{T3} = 3.40 atm					
Pilot Only Fueled	17.0	2.0	0.1	99.9	----
Pilot F/A = 0.006	5.1	106	15.7	95.9	----
Pilot F/A = 0.006 Total F/A = 0.0284 Sector Burning Simulation	7.2	1.0	-0-	100	----
Pilot F/A = 0.004	4.8	115	14.8	95.8	----
Pilot F/A = 0.004 Total F/A = 0.0284 Sector Burning Simulation	7.5	7.0	-0-	99.9	----
II-13 P_{T3} = 4.76*					
Pilot Only Fueled Sector Burning Simulation, Total F/A = 0.0284	6.9	----	----	----	----
Pilot F/A = 0.005	5.05	----	----	----	----
II-16 P_{T3} = 4.76 atm*					
Pilot F/A = 0.005	4.2	----	----	----	----
Pilot F/A = 0.005: Sector Burning Simulation, Total F/A = 0.0284	4.8	----	----	----	----

Note: * For Models II-13 and II-16, rig data were not obtained at the approach condition. The NO_x engine data presented above were extrapolated from CTOL cruise data.

Table XXVIII. Hot Day Climbout Emissions Data, Double Annular CF6-50 Combustors.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	25.3 atm	825° K	26.5 m/s	0.0225

Rig Testing at Reduced Pressures Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	----
CF6-50 Engine	36.0	0.3	0.1	99.9	12
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	32.0	0.3	0.1	99.9	2
Double Annular Combustor Configurations:					
II-4 P_{T3} = 4.76* atm Pilot F/A = 0.006 to 0.010	24.6	----	----	----	----
II-8 P_{T3} = 4.76 atm* Pilot F/A = 0.012	37.5	----	----	----	----
II-9					
At P_{T3} = 4.76 atm Pilot F/A = 0.010	28.0	6.0	0.3	99.8	----
Pilot F/A = 0.006	23.1	3.5	0.2	99.9	----
At P_{T3} = 6.76 atm Pilot F/A = 0.005	23.3	3.5	0.1	99.9	----
At P_{T3} = 7.2 atm Pilot F/A = 0.004	23.9	6.6	1.3	99.8	----
II-11 P_{T3} = 6.8 atm Pilot F/A = 0.006	20.6	2.5	0.1	99.9	----
Pilot F/A = 0.004	20.9	3.7	0.1	99.9	----
II-13 P_{T3} = 4.72 atm Pilot F/A = 0.005	17.9	2.0	0.1	99.9	----
Pilot F/A = 0.004	16.9	3.2	0.2	99.9	----
Pilot F/A = 0.003	18.3	5.3	0.2	99.9	----
II-16 P_{T3} = 4.76 atm Main Burner Only Fueled	17.1	6.5	0.1	99.8	----

Note * For Models II-4 and II-8, the NO_x engine data at climbout condition were extrapolated from rig data obtained at the hot day takeoff conditions.

Table XXIX. Standard Day Takeoff Emissions Data, Double Annular CF6-50 Combustors.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	819° K	26.0 m/s	0.0245

....Oxides of Nitrogen Engine Values Obtained by Extrapolating Hot Day Takeoff Rig Data Unless Otherwise Specified.

....Combustion Efficiency Values are Hot Day Takeoff Rig Data.

	Oxides of Nitrogen g/kg Fuel	Combustion Efficiency %
Program Goals	10	99+
CF6-50 Engine	35.4	99.9
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	32.6	99.9
Double Annular Combustor Configurations:		
II-4 P_{T3} = 4.76 atm		
Pilot F/A = 0.0122	27.8	99.3
Pilot F/A = 0.006 to 0.011	28.0	99.4
II-8 P_{T3} = 4.76 atm*		
Pilot F/A = 0.012	40.3	----
II-9 P_{T3} = 4.76 atm		
Pilot F/A = 0.0100	30.0	99.9
Pilot F/A = 0.008	25.9	99.9
Pilot F/A = 0.006	24.4	99.9
Pilot F/A = 0.005	23.6	99.9
II-11 P_{T3} = 4.76 atm		
Pilot F/A = 0.006	21.6	99.9
Pilot F/A = 0.005	21.2	100
Pilot F/A = 0.004	22.2	99.9
Pilot F/A = 0.003	22.6	99.8
Main Burner Only Fueled	25.6	99.8
II-13 P_{T3} = 4.76 atm		
Pilot F/A = 0.005	19.9	99.9
Pilot F/A = 0.004	18.6	99.9
Pilot F/A = 0.003	19.3	99.9
Main Burner Only Fueled	22.7	99.8
II-16		
Pilot F/A = 0.005; P_{T3} = 6.8 atm	17.8	100
Pilot F/A = 0.005; P_{T3} = 4.76 atm	17.8	99.9
Pilot F/A = 0.004; P_{T3} = 4.76 atm	17.7	99.9
Pilot F/A = 0.003; P_{T3} = 6.8 atm	17.6	100
Pilot F/A = 0.003; P_{T3} = 4.76 atm	17.6	99.9

Note * For Model II-8, the NO_x engine data at standard day takeoff condition were extrapolated from rig data obtained at the hot day climbout conditions.

Table XXX. Hot Day Takeoff Emissions Data, Double Annular CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	858° K	29.5 m/s	0.0245

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	10	----	----	99+	15
CF6-50 Engine	44.0	0.2	-0.1	99.9	12
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	41.2	0.4	-0-	99.9	1
Double Annular Combustor Configurations:					
II-4 P_{T3} = 4.76 atm					
Pilot F/A = 0.0122	34.2	8.2	5.0	99.3	1
Pilot F/A = 0.006 to 0.011	34.6	8.0	4.6	99.4	2
II-8 P_{T3} = 4.76 atm*					
Pilot F/A = 0.0122	49.7	----	----	----	--
II-9 P_{T3} = 4.76 atm					
Pilot F/A = 0.0100	37.1	3.5	0.1	99.9	--
Pilot F/A = 0.008	32.0	3.0	0.1	99.9	--
Pilot F/A = 0.006	30.2	3.8	-0-	99.9	--
Pilot F/A = 0.005	29.2	4.8	0.1	99.9	--
II-11 P_{T3} = 4.76 atm					
Pilot F/A = 0.006	26.7	2.5	0.2	99.9	--
Pilot F/A = 0.005	26.2	-0-	-0-	100	--
Pilot F/A = 0.004	27.4	4.1	0.2	99.9	--
Pilot F/A = 0.003	27.9	6.8	0.2	99.8	--
Main Burner Only Fueled	31.6	7.0	0.2	99.8	--
II-13 P_{T3} = 4.76 atm					
Pilot F/A = 0.005	24.6	2.0	0.5	99.9	--
Pilot F/A = 0.004	22.95	3.1	0.5	99.9	--
Pilot F/A = 0.003	23.8	4.6	0.2	99.9	--
Main Burner Only Fueled	28.0	5.9	0.3	99.8	--
II-16					
Pilot F/A, 0.005; P_{T3} = 6.8 atm	22.0	0.7	0.4	100	--
Pilot F/A, 0.005; P_{T3} = 4.76 atm	22.0	1.3	0.4	99.9	--
Pilot F/A, 0.004; P_{T3} = 4.76 atm	21.9	1.6	0.3	99.9	0
Pilot F/A, 0.003; P_{T3} = 6.8 atm	21.8	1.9	0.1	100	1
Pilot F/A, 0.003; P_{T3} = 4.76 atm	21.8	2.5	0.3	99.9	1

Note: * For Model II-8, rig data were not obtained at the hot day takeoff conditions. The NO_x engine data presented above were extrapolated from CTOL cruise data.

Table XXXI. Standard Day Cruise Emissions Data, Double Annular CF6-50 Combustor.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	14.4 atm	733° K	24.4 m/s	0.0210

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	--
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	17.6	0.9	0.3	99.9	7
Double Annular Combustor Configurations:					
II-4 P_{T3} = 4.76 atm, Pilot F/A = 0.006 to 0.010	11.1	26.0	3.9	99.0	--
II-8 P_{T3} = 4.76 atm, Pilot F/A = 0.0105	17.3	1.6	0.2	100	--
II-9 P_{T3} = 4.76 atm, Pilot Only Fueled	31.0	5.0	1.0	99.8	--
Pilot F/A = 0.006	11.6	14.5	1.0	99.6	--
II-11 P_{T3} = 3.40 atm*, Pilot F/A = 0.006	10.72	----	----	----	--
Pilot F/A = 0.004	11.0	----	----	----	--
II-13 P_{T3} = 4.76 atm, Pilot F/A = 0.005	8.60	20.5	3.2	99.2	--
II-16 P_{T3} = 4.76 atm, Pilot F/A = 0.005	8.07	23.0	3.9	99.1	0

Note: * For Model II-11, rig data were not obtained at the CTOL cruise condition. The NO_x engine data presented above were extrapolated from rig hot day approach data.

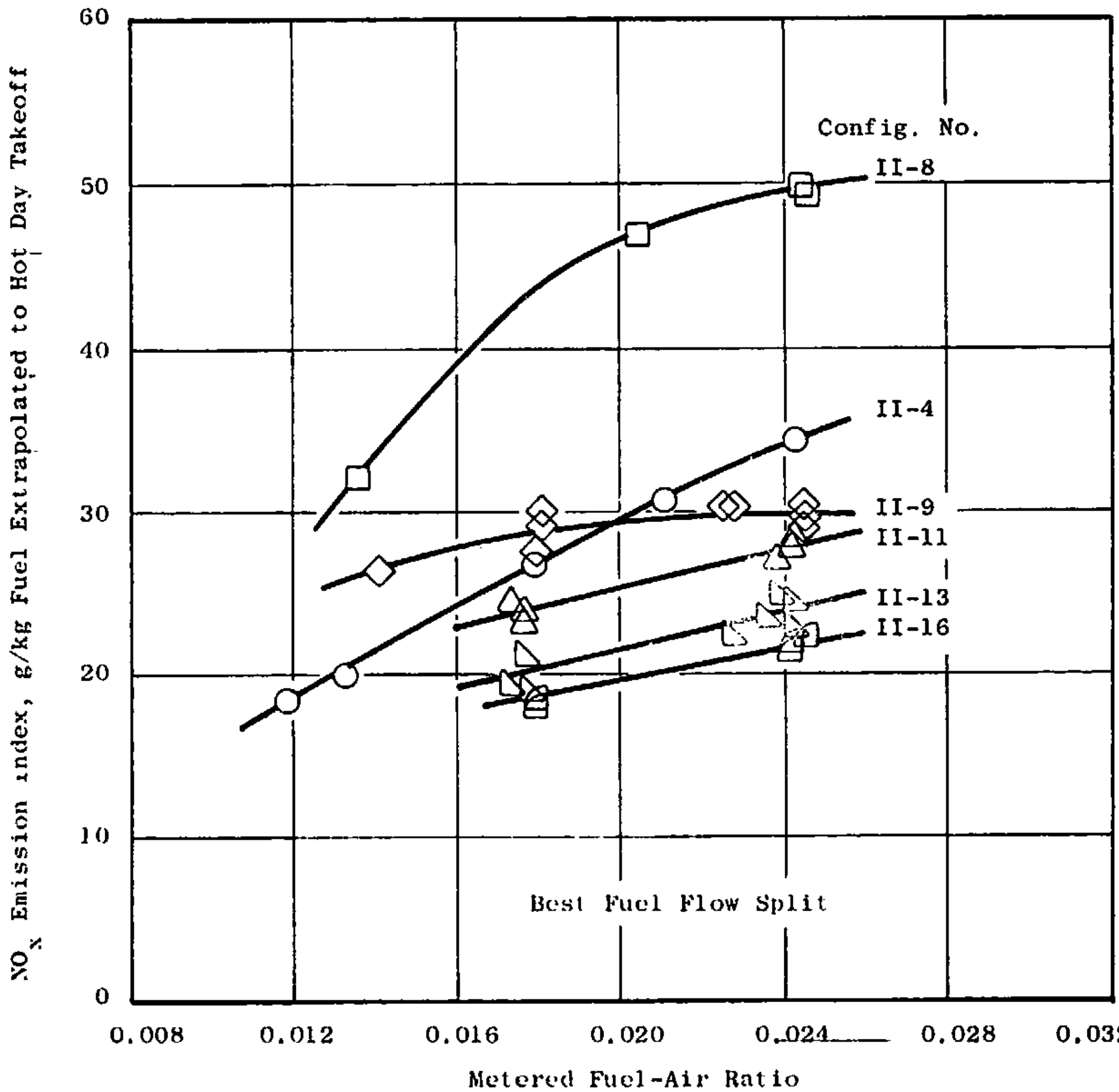


Figure 52. NO_x Emissions Levels, Double Annular Combustors.

suggest further reductions in NO_x levels could be obtained by moving the inner liner dilution air holes even farther forward. In order to accomplish this, the inner liner/cowl/dome joint would need to be redesigned. As is shown in Figure 53, the minimum NO_x levels at takeoff operating conditions were obtained with about 80 percent of the fuel supplied to the inner dome.

The NO_x reductions obtained in this test series were achieved with no sacrifice in high power combustion efficiency. Generally, at all test conditions above idle in this series, the combustion efficiency levels were well above 99.0 percent. Thus, at true engine pressure levels, combustion efficiency levels approaching 99.9 percent would be projected.

The lowest idle emissions levels were obtained with Configurations II-9, II-11 and II-16, with only the outer annulus fueled, as shown in Table XXVI. The common characteristics of these configurations were a biased dome airflow split and no outer liner dilution air holes to cause quenching of the combustion products. Configurations II-9 and II-11 had the same outer annulus swirler airflow (18 percent) and differed only in the location of the inner liner dilution air holes. Configuration II-16 had lower outer annulus swirler airflow (12 percent), which in the Radial/Axial Staged Combustor configurations produced the lowest idle emissions levels obtained in this program. However, in the Double Annular Combustor configurations, the levels were higher, suggesting that high penetration of the inner liner dilution air jets produced a quenching effect. These trends strongly suggest that idle emissions might be further reduced by lengthening the centerbody, thus providing a longer sheltered region in the outer annulus for low power operation. Configuration II-16, which provided the lowest NO_x emissions level and nearly the lowest idle emissions levels in this series, was selected for additional evaluations which included ignition testing.

The results of this ignition testing are shown in Figure 54. Compared to the CF6-50 production engine combustor, the fuel flow rates required for sea level ignition were higher, especially at low combustor airflow rates, so altitude relight testing was not attempted. The results did, however, suggest that satisfactory relight characteristics could be obtained with further development. Lengthening the centerbody alone would be expected to provide a significant improvement.

Typical exit temperature profile characteristics at high power conditions compared well with those of the CF6-50 production engine combustor. At low power conditions where only the outer annulus is fueled, the profiles were, however, more peaked. Overall, the results suggest that acceptable exit temperature profile characteristics should be attainable with this design.

The mechanical and cooling characteristics of the Double Annular Combustor configurations were very satisfactory. Over 86 hours of combustor operation were accrued in this series and the hardware was still in good condition. As received, the centerbody cooling flow area was lower than intended, and in some early tests, high metal temperatures were indicated. Each time, however, posttest inspection revealed no significant damage. The impingement-cooled dome flameshield was still in excellent condition and indicates that some cooling air to this region could be reapportioned to the centerbody. Throughout the test series, dome carbon buildup was very light.

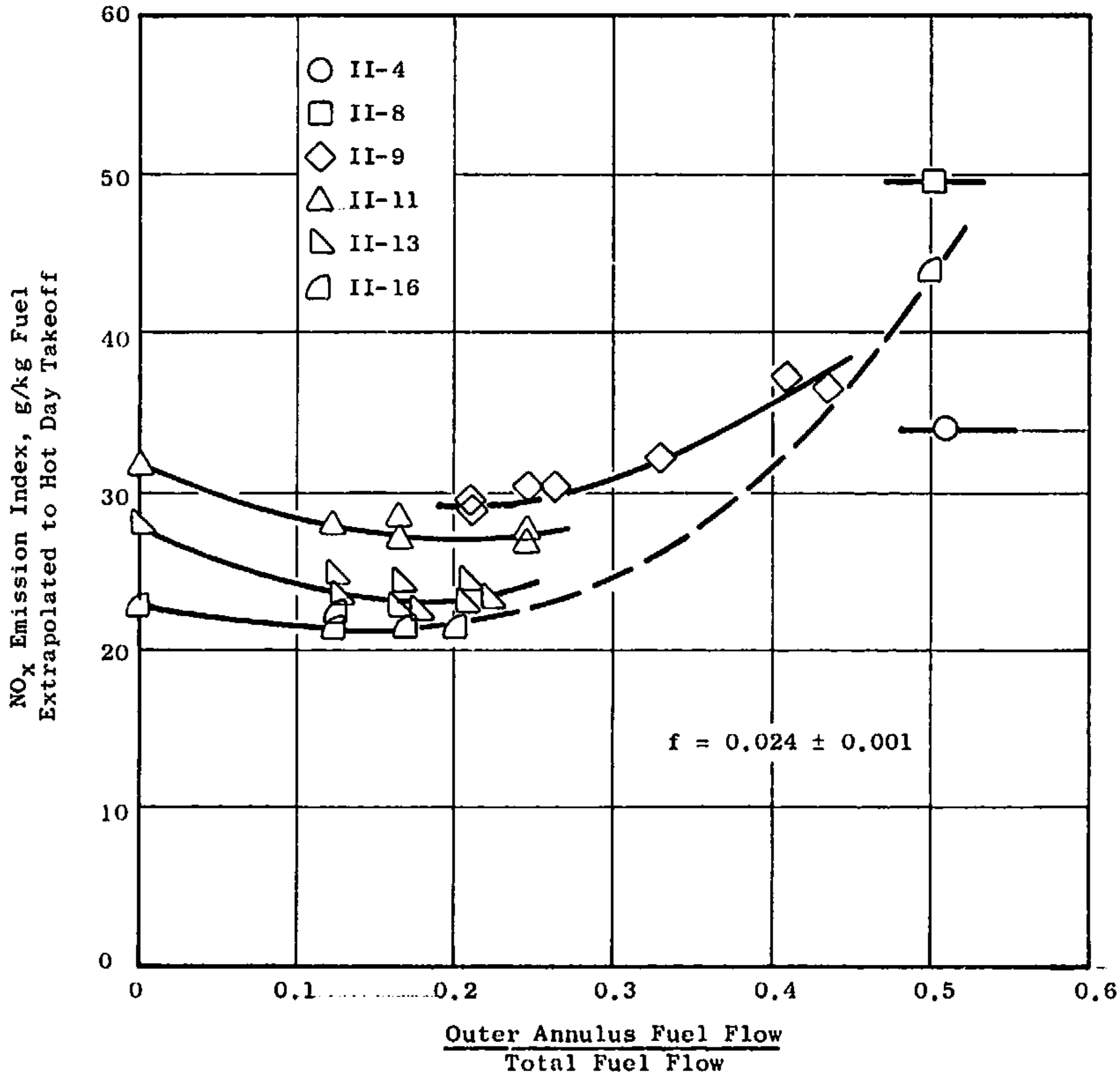


Figure 53. Effect of Fuel Flow Split on NO_x Emissions Levels, Double Annular Combustors.

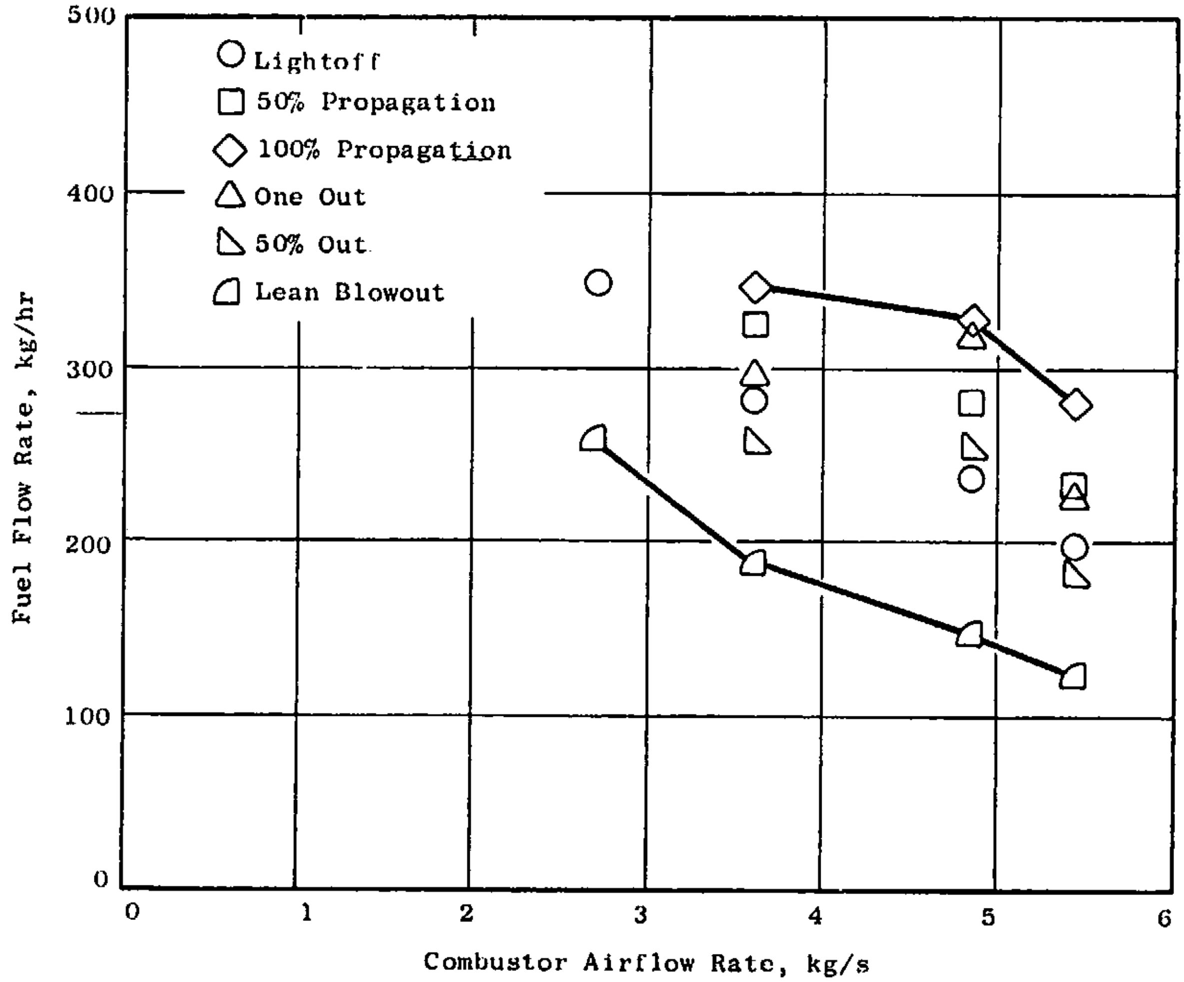


Figure 54. Sea Level Ignition Characteristics, Double Annular Combustor, Configuration II-16.

Radial/Axial Staged Combustor Configurations - Seven Radial/Axial Staged Combustor configurations were evaluated. The exhaust emissions goals of this program were very closely approached with this novel design concept. The key pollutant emissions characteristics obtained with these configurations are presented in Tables XXXII, XXXIII, XXXIV, XXXV, XXXVI and XXXVII.

As is shown in Table XXXII, the CO and HC emissions goals were very nearly achieved with the first test configurations (Configurations II-6, II-7, II-10). The HC levels were found to decrease exponentially with fuel-air ratio and the CO levels were found to be relatively insensitive to fuel-air ratio. One point where 12 percent CDP bleed air extraction was simulated with Configuration II-7 resulted in HC and CO emissions indices of 1.5 and 23.7, respectively, which are by far the lowest levels obtained with any combustor configuration tested in the Phase I Program. These low idle emissions levels were achieved with 12.7 percent of the combustor airflow apportioned to the pilot stage air swirlers. In later configurations, the pilot stage swirler airflow was reduced to more nearly approach the high power combustion efficiency and NO_x emissions goals.

The first decrease in swirler airflow (Configuration II-12) produced idle emissions results very much as expected: the HC levels increased very slightly and virtually no change was obtained in the CO levels. The next decrease in swirler airflow (Configuraton II-14) resulted in increased emissions levels, especially CO. Analyses suggest that the manner in which the swirler airflow was reduced was a greater factor than was the absolute level of reduction. (Increasing fuel flow in the earlier test configurations an equivalent amount did not cause as much increase in emissions as did the decrease in airflow and Configuration II-14 had a weak secondary air swirl strength). Configuration III-2 had a stronger swirl strength and an airflow level intermediate to those of Configurations II-10 and II-14, but its emissions levels were much higher suggesting that the chute air turning vanes that were incorporated into this particular configuration caused severe quenching of the pilot stage combustion gases. These vanes produced a significant improvement in high power combustion efficiency, but their impact upon idle emissions levels must be further evaluated.

As is shown in Tables XXXV and XXXVI, the first Radial/Axial Staged Combustor configuration (Configuration II-6) also showed very encouraging results with respect to high power NO_x emissions levels. The first test was run at moderate conditions (T_3 = 730° K, P_3 = 4.8 atm) and the effects of fuel staging mode were investigated. It was found that the transition from pilot-only to two-stage burning was very smooth and that both the NO_x emissions levels and combustion efficiency levels were highly sensitive to fueling mode. Also tried with this first test configuration was fueling alternate main stage injectors. This type of fuel staging resulted in higher combustion efficiencies. However, the NO_x levels were also higher with only the alternate injectors fueled versus all 600 injectors. No metal temperature problems were encountered and posttest inspection showed no distress. Thereafter, the combustor was progressively subjected to more severe operating conditions and configuration changes. As noted above, idle emissions levels were nearly the same for Configurations II-6, II-7, II-10 and II-12 but increased with Configuration II-15. The combustor was then reconfigured to the Configuration

Table XXXII. Standard Day Idle Emissions Data, Radial/Axial Staged CF6-50 Combustors.

Engine/Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	3.39 atm	454° K	19.5 m/s	0.0140

Test Conditions Duplicated in Test Rig

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %
Program Goals	----	20	4	99+
CF6-50 Engine	2.8	67	27	95.7
CF6-50 Combustor Rig Data	2.69	76	24	95.8
Radial/Axial Combustor Configurations - Pilot Only Fueled				
II-6,7	3.05	29	1.5	99.2
V_{ref} reduced 6%	3.05	25.5	1.1	99.3
V_{ref} reduced 11%	3.05	24	1.4	99.3
II-10	3.17	18	0.7	99.5
II-12	3.39	28.3	1.7	99.1
II-14	2.89	40.4	2.7	99.0
II-15	3.65	26.5	1.5	99.2
V_{ref} reduced 8%; P_{T3} reduced 15%; T_{T3} reduced 7%	4.19	39.2	4.3	98.7
III-2	2.56	60.7	8	97.8

Table XXXIII. Hot Day Approach Emissions Data, Radial/Axial Staged CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{rel}	Fuel-Air Ratio
	11.6 atm	661° K	26.5 m/s	0.0142

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

		Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals		----	----	----	99+	--
CF6-50 Engine		12.0	4.0	0.1	99.9	5
CF6-50 Combustor Rig Data (At P_{T3} = 6.8 atm)		10.7	7.5	0.3	99.8	--
Radial/Axial Combustor Configurations:						
II-6,7 P_{T3} = 4.76 atm*	Alternate					
Pilot Only Fueled	Secondary	11.7	----	----	----	--
Pilot F/A = 0.012	Chute	11.9	----	----	----	--
Pilot F/A = 0.008	Fueling	7.6	----	----	----	--
II-10 P_{T3} = 4.76 atm						
Pilot Only Fueled		13.24	9.1	0.2	99.8	--
Pilot F/A = 0.007*		5.3	----	----	----	--
Pilot F/A = 0.005*		3.5	----	----	----	--
II-12 P_{T3} = 3.39 atm Pilot Only Fueled		13.4	14.5	-0-	99.7	--
II-14 - No Data Obtained						
II-15 P_{T3} = 6.80 atm						
Pilot Only Fueled		10.88	5.8	0.6	99.8	--
Pilot F/A = 0.007		7.22	90.5	66.5	91.2	1
III-2 P_{T3} = 3.39 atm						
Pilot Only Fueled		8.6	3.2	2.1	99.7	2
Pilot F/A = 0.0079		9.0	106	85.7	89.0	--

Note * For Models II-6, 7 (all data) and II-10 (pilot F/A = 0.005, 0.007), rig data were not obtained at the hot day approach conditions. The NO_x engine data presented above were extrapolated from rig CTOL cruise data.

Table XXXIV. Hot Day Climbout Emissions Data, Radial/Axial Staged CF6-50 Combustors.

	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
Engine Test Conditions:	25.3 atm	825° K	26.5 m/s	0.0225

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	--
CF6-50 Engine	36.0	0.3	0.1	99.9	12
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	32.0	0.3	0.1	99.9	2
Radial/Axial Combustor Configurations:					
II-6,7 P_{T3} = 6.8 atm					
Pilot Only Fueled	28	6.5	-0-	99.8	--
Pilot F/A = 0.006	14.55	78	5.7	97.6	--
Pilot F/A = 0.005	12.3	87.5	13	96.6	--
II-10					
Pilot F/A = 0.007, P_{T3} = 6.8 atm	18.0	36.5	2.0	98.9	--
Pilot F/A = 0.007, P_{T3} = 4.76 atm	18.0	49.0	4.5	98.3	--
Pilot F/A = 0.005, P_{T3} = 6.8 atm	11.1	59.0	15.0	97.1	--
Pilot F/A = 0.005, P_{T3} = 4.76 atm	11.1	69.0	25.0	95.9	--
II-12 P_{T3} = 6.8 atm					
Pilot F/A = 0.007	19.6	29.0	1.4	99.2	--
Pilot F/A = 0.005	12.2	46.0	4.4	98.5	--
II-14 P_{T3} = 6.8 atm					
Pilot F/A = 0.005	16.5	33.3	3.0	98.9	--
Pilot F/A = 0.003	8.5	69.0	42.5	94.1	--
II-15 P_{T3} = 9.53 atm					
Pilot F/A = 0.006	16.15	19.0	1.5	99.4	1
Pilot F/A = 0.005	12.6	28.3	2.9	99.1	1
Pilot F/A = 0.004	11.75	37.5	4.0	98.7	1
III-3 P_{T3} = 6.8 atm					
Alternate Secondary Chutes Fueled					
Pilot F/A = 0.008	28.9	25.6	1.2	99.3	1
All Secondary Chutes Fueled					
Pilot F/A = 0.008	30.1	9.7	0.3	99.7	1
Pilot F/A = 0.006	24.24	9.7	0.3	99.7	1
Pilot F/A = 0.005	18.87	15.0	0.5	99.6	--
V_{ref} increased 15% at 0.005	19.56	16.0	0.6	99.6	--
Pilot F/A = 0.004	14.88	20.0	1.1	99.4	1
Pilot F/A = 0.003	11.89	33.8	5.2	98.7	1
V_{ref} increased 15% at 0.003	11.58	48.1	9.9	97.9	--

Table XXXV. Standard Day Takeoff Emissions Data, Radial/Axial Staged CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	819° K	26.0 m/s	0.0245

.... Oxides of Nitrogen Engine Values Obtained by Extrapolating Hot Day Takeoff Rig Data to Standard Day Conditions, Unless Noted Otherwise

.... Combustion Efficiency Values are Hot Day Takeoff Rig Data.

	Oxides of Nitrogen g/kg Fuel	Combustion Efficiency %
Program Goals	10	99+
CF6-50 Engine	35.4	99.9
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	32.6	99.9
Radial/Axial Combustor Configurations:		
II-6,7 P_{T3} = 6.8 atm*		
Pilot Only Fueled	29.0	----
Pilot F/A = 0.006	24.1	----
Pilot F/A = 0.005	18.2	----
II-10 P_{T3} = 6.8 atm*		
Pilot F/A = 0.007	19.66	----
Pilot F/A = 0.0054	14.6	----
Pilot F/A = 0.005	12.95	----
II-12 P_{T3} = 4.76 atm		
Pilot F/A = 0.007	21.28	99.4
Pilot F/A = 0.006	16.58	99.2
Pilot F/A = 0.005	13.35	98.9
Pilot F/A = 0.004	11.57	98.7
II-14 P_{T3} = 4.65 atm		
Pilot F/A = 0.0105	28.08	99.5
Pilot F/A = 0.005	16.91	99.1
Pilot F/A = 0.004	12.88	98.3
Pilot F/A = 0.003	10.1	94.8
Pilot F/a = 0.0019	8.5	90.9
II-15		
Pilot F/A = 0.006, P_{T3} = 9.53 atm	22.0	99.6
Pilot F/A = 0.006, P_{T3} = 4.76 atm	18.37	99.5
Pilot F/A = 0.006, P_{T3} = 3.06 atm	19.58	98.8
Pilot F/A = 0.004, P_{T3} = 9.53 atm	13.45	99.3
Pilot F/A = 0.004, P_{T3} = 4.76 atm	12.95	97.1
Pilot F/A = 0.004, P_{T3} = 3.06 atm	12.82	96.4
Pilot F/A = 0.003, P_{T3} = 9.53 atm	10.84	98.4
III-2 P_{T3} = 4.76 atm		
Pilot F/A = 0.005	16.75	99.8
Pilot F/A = 0.004	14.40	99.7
Pilot F/A = 0.003	12.95	99.5

Note * For Models II-6,7 and II-10, the NO_x engine data at standard day takeoff conditions were extrapolated from rig data obtained at the hot day climbout conditions

Table XXXVI. Hot Day Takeoff Emissions Data, Radial/Axial-Staged CF6-50 Combustors.

Engine Combustor Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	29.1 atm	858° K	26.5 m/s	0.0245

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	10	----	----	99+	15
CF6-50 Engine	44.0	0.2	0.1	99.9	12
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	41.2	0.4	-0-	99.9	1
Radial/Axial Combustor Configurations:					
II-6,7* P_{T3} = 6.8 atm					
Pilot Only Fueled	35.9	----	----	----	--
Pilot F/A = 0.006	29.8	----	----	----	--
Pilot F/A = 0.005	22.5	----	----	----	--
II-10* P_{T3} = 6.8 atm					
Pilot F/A = 0.007	24.3	----	----	----	--
Pilot F/A = 0.0054	18.0	----	----	----	--
Pilot F/A = 0.005	16.0	----	----	----	--
II-12 P_{T3} = 4.76 atm					
Pilot F/A = 0.007	26.3	25.5	0.5	99.4	--
Pilot F/A = 0.006	20.5	30	0.95	99.2	--
Pilot F/A = 0.005	16.5	39.7	2.1	98.9	--
Pilot F/A = 0.004	14.3	52.5	0.8	98.7	
II-14 P_{T3} = 4.65 atm					
Pilot F/A = 0.0105	34.7	9.8	2.6	99.5	--
Pilot F/A = 0.005	20.9	23.5	3.3	99.1	--
Pilot F/A = 0.004	15.9	37	7.6	98.3	--
Pilot F/A = 0.003	12.45	57	38.6	94.8	--
Pilot F/A = 0.0019	10.5	65.5	75.4	90.9	--
II-15					
Pilot F/A = 0.006, P_{T3} = 9.53 atm	13.4	37.7	7.7	98.4	2
Pilot F/A = 0.004, P_{T3} = 9.53 atm	16.62	19.5	1.9	99.3	1
Pilot F/A = 0.004, P_{T3} = 4.76 atm	16.0	46.5	10.0	97.1	1
Pilot F/A = 0.004, P_{T3} = 3.06 atm	15.85	55.8	22.5	96.4	--
Pilot F/A = 0.006, P_{T3} = 9.53 atm	27.2	9.0	1.8	99.6	2
Pilot F/A = 0.006, P_{T3} = 4.76 atm	22.7	20.2	0.2	99.5	2
Pilot F/A = 0.006, P_{T3} = 3.06 atm	24.2	37.0	3.4	98.8	1
III-2 P_{T3} = 4.76 atm					
Pilot F/A = 0.003	16.0	16.7	1.4	99.5	--
Pilot F/A = 0.004	17.8	11.4	0.6	99.7	--
Pilot F/A = 0.005	20.7	6.6	0.3	99.8	2

Note: * For Models II-6,7 and II-10, rig data were not obtained at the hot day takeoff conditions. The NO_x engine data presented above were extrapolated from rig climbout data.

Table XXXVII. Standard Day Cruise Emissions Data, Radial/Axial Staged CF6-50 Combustors.

Engine Test Conditions:	P_{T3}	T_{T3}	V_{ref}	Fuel-Air Ratio
	14.4 atm	733° K	24.4 m/s	0.0210

Rig Testing at Reduced Pressure Up to 9.6 atm. Other Conditions Duplicated.

	Oxides of Nitrogen g/kg Fuel	Carbon Monoxide g/kg Fuel	Unburned Hydrocarbons g/kg Fuel	Combustion Efficiency %	Smoke Number SAE No.
Program Goals	----	----	----	99+	--
CF6-50 Combustor Rig Data (At P_{T3} = 9.53 atm)	17.6	0.9	0.3	99.9	7
Radial/Axial Combustor Configurations:					
II-6,7 P_{T3} = 4.76 atm					
Pilot Only Fueled	14.6	6.9	-0-	99.8	2
Alternate Secondary Chutes Fueled					
Pilot F/A = 0.016	14.6	41.0	7.4	98.3	1
Pilot F/A = 0.012	18.17	44.3	6.4	98.4	0
Pilot F/A = 0.008	13.14	65.5	11.5	97.3	0
II-10 P_{T3} = 4.76 atm					
Pilot F/A = 0.007	8.09	78.8	34	94.8	--
Pilot F/A = 0.005	3.84	98	128	84.9	--
II-12 P_{T3} = 3.39 atm*					
Pilot Only Fueled	12.7	----	----	----	--
II-14 P_{T3} = 6.8 atm#					
Pilot F/A = 0.005	7.57	----	----	----	--
Pilot F/A = 0.003	3.46	----	----	----	--
II-15 P_{T3} = 9.53 atm					
Alternate Secondary Chutes Fueled					
Pilot F/A = 0.007	13.06	31	1.5	99.1	4
All Secondary Chutes Fueled					
Pilot F/A = 0.0057	8.06	72.3	14.3	96.9	3
Pilot F/A = 0.0038	3.97	95	78.1	90.0	2
III-2 P_{T3} = 4.76 atm					
Pilot Only Fueled	12.2	6.1	0.2	99.8	16
Alternate Secondary Chutes Fueled					
Pilot F/A = 0.014	12.2	18.6	1.1	99.4	--
Pilot F/A = 0.010	15.23	27.7	1.8	99.2	--
Pilot F/A = 0.006	14.04	51.1	6.4	98.2	--

Notes * For Model II-12, rig data were not obtained at the CTOL cruise condition. The NO_x engine data presented above were extrapolated from rig hot day approach data.

\# For Model II-14 rig data were not obtained at the CTOL cruise condition. The NO_x engine data presented above were extrapolated from rig hot day climbout data.

II-12 airflow splits, was designated Configuration II-15 and tested over a broad range of inlet conditions and fueling modes. As is shown in Figure 55, the NO_x levels were essentially independent of overall fuel-air ratio but highly dependent upon pilot stage fuel-air ratio. Combustion efficiency levels were also highly dependent upon overall fuel-air ratio, as is shown in Figure 56. The measured combustion efficiency values of the Radial/Axial Staged Combustor configurations were extrapolated to true engine operating conditions using the relationships shown in Figure 56.

Figures 57 and 58 show the effect of pilot-to-total fuel flow split at the hot day takeoff operating conditions for each of the configurations tested. For any common fuel flow split, the combustion efficiency levels improved when the pilot swirler airflow was decreased (Configurations II-12, II-14 and II-15). The combination of reduced swirler airflow and the addition of chute turning vanes (Configuration III-2) provided a significant improvement in combustion efficiency. The NO_x emission levels of all configurations also showed a strong dependency on fuel flow split, but configuration effects were less apparent. The lowest levels were obtained with Configurations II-12, II-14 and II-15 with low pilot fuel flows. Configuration III-2 produced significantly higher NO_x emissions levels at these low pilot fuel flows, showing that there are trade offs between combustion efficiency and NO_x emission levels which complicate any direct comparison of configurations. Figure 59 is a cross plot of Figures 57 and 58 showing these trade offs. Except for Configuration III-2, the data fall into a fairly tight band. Configurations II-6, II-7 and II-14 tend to define the lowest performance levels of this band; II-10 tends to be intermediate; and II-12 and II-15 tend to define the best performance levels. For an extrapolated combustion efficiency level of 99.8 percent, NO_x emissions levels ranged from about 13 to 20. The data suggest that had the pilot fuel flow split been further reduced on each configuration to the point where the objective NO_x emission index was obtained, the extrapolated combustion efficiency levels would have ranged from about 98.8 to 99.7 percent.

Configuration II-12 was rebuilt since it produced, overall, the lowest emissions levels and was retested as Configuration II-15. The first part of this test was a sea level ignition test. The measured lean blowout fuel flow rates were virtually the same as those of the CF6-50 production engine combustor at all airflow rates. At the highest airflow rate, the full propagation fuel flow rate was also virtually the same. At lower airflow rates, higher fuel flow rates were required for full propagation. These results were highly encouraging and suggest that, as is, the combustor would probably meet most of the CF6-50 engine altitude relight requirements. Altitude relight testing was planned, but abandoned when it was found that the electrical ignitors were faulty. They failed to fire when wet with fuel.

The typical exit temperature profile characteristics at high power conditions were very flat and the peak profiles tended to be double lobed. One good feature of this design approach was that profiles were relatively insensitive to operating mode. Overall, the results suggest that acceptable exit temperature profile characteristics can be achieved with this design approach.

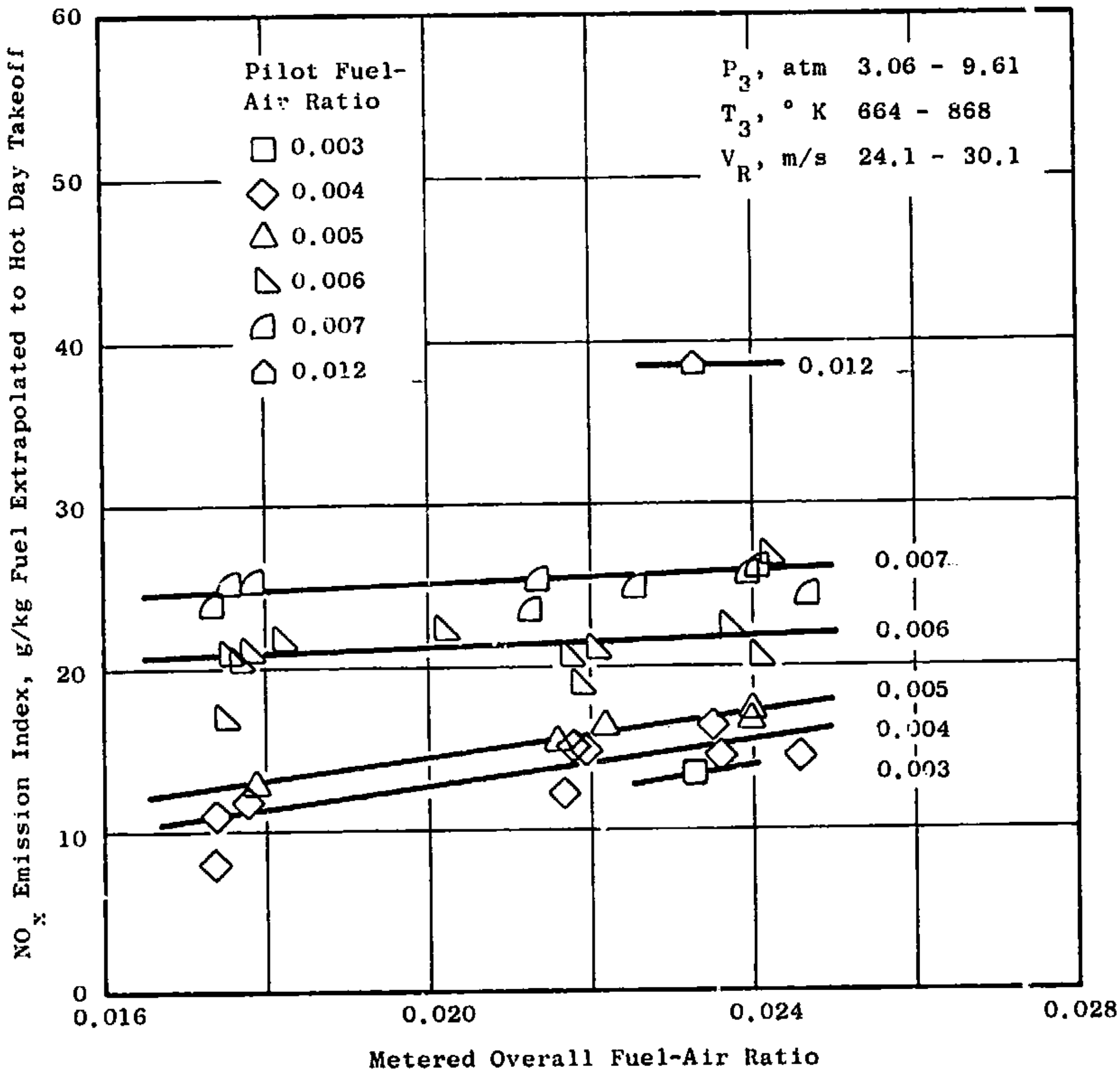


Figure 55. NO_x Emissions Levels, Radial/Axial Staged Combustor, Configurations II-12 and 15.

$$(100-\eta)_{SLTO} = (100-\eta)_{meas} \left(\frac{26.5}{V_R}\right)\left(\frac{P_3}{29.1}\right)^{1.13} \left[\exp\left(\frac{T_3-858}{76.1}\right)\right], \%, \text{ m/s, atm, }^\circ\text{K}$$

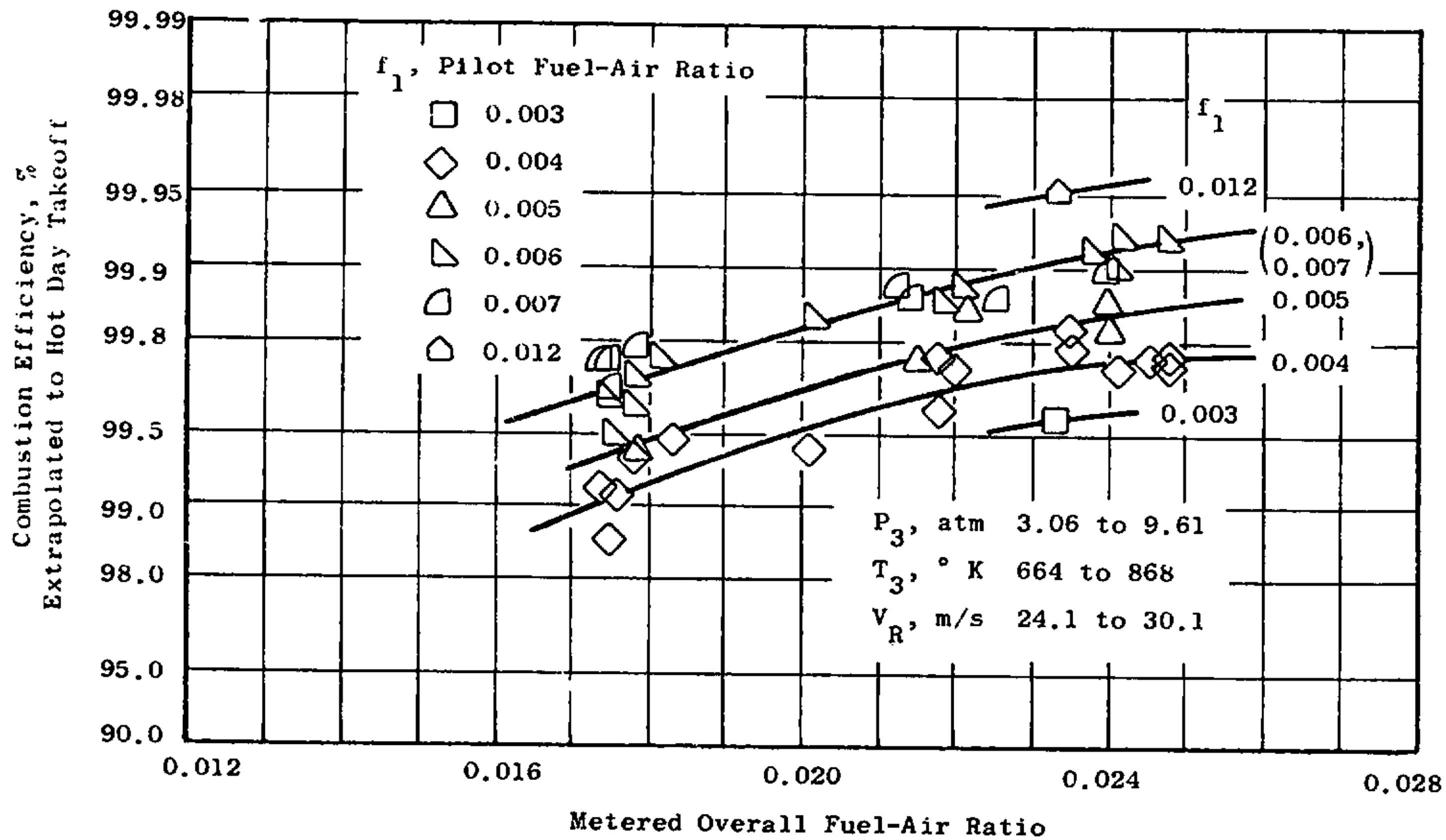


Figure 56. Combustion Efficiency Levels, Radial/Axial Staged Combustor, Configurations II-12 and 15.

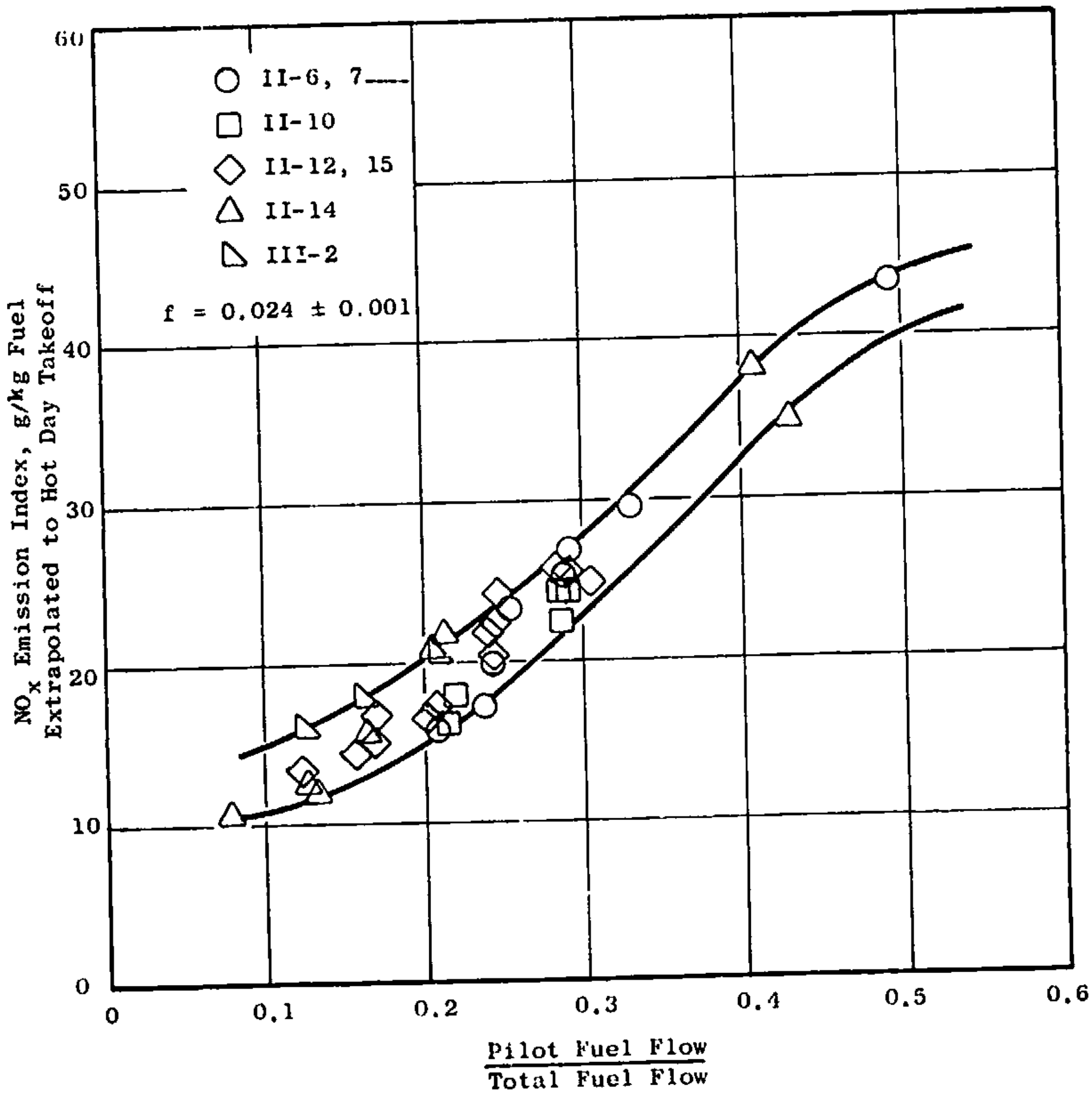


Figure 57. Effect of Fuel Flow Split on NO_x Emissions Levels, Radial/Axial Staged Combustor.

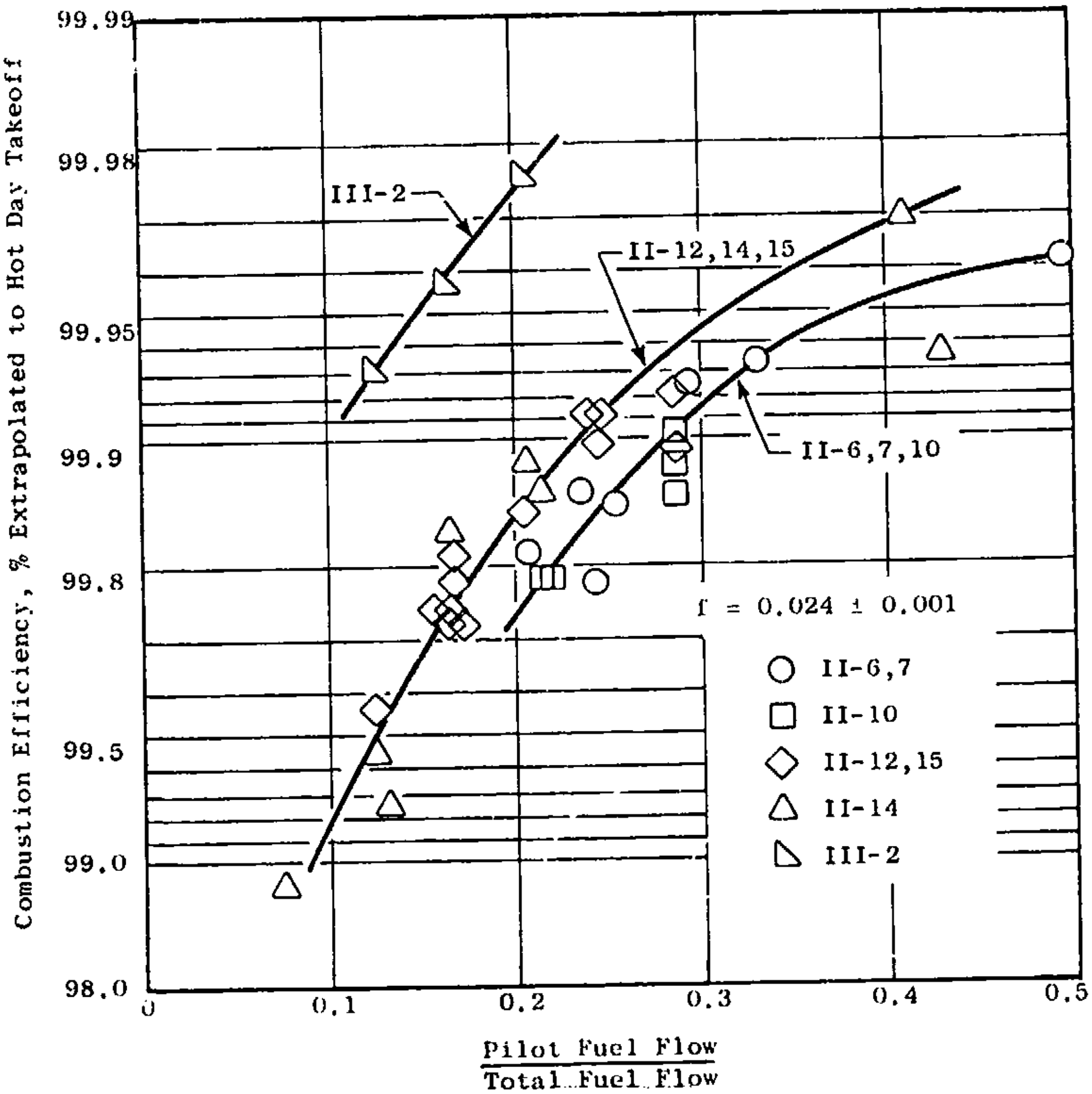


Figure 58. Effect of Fuel Flow Split on Combustion Efficiency, Radial/Axial Staged Combustor.

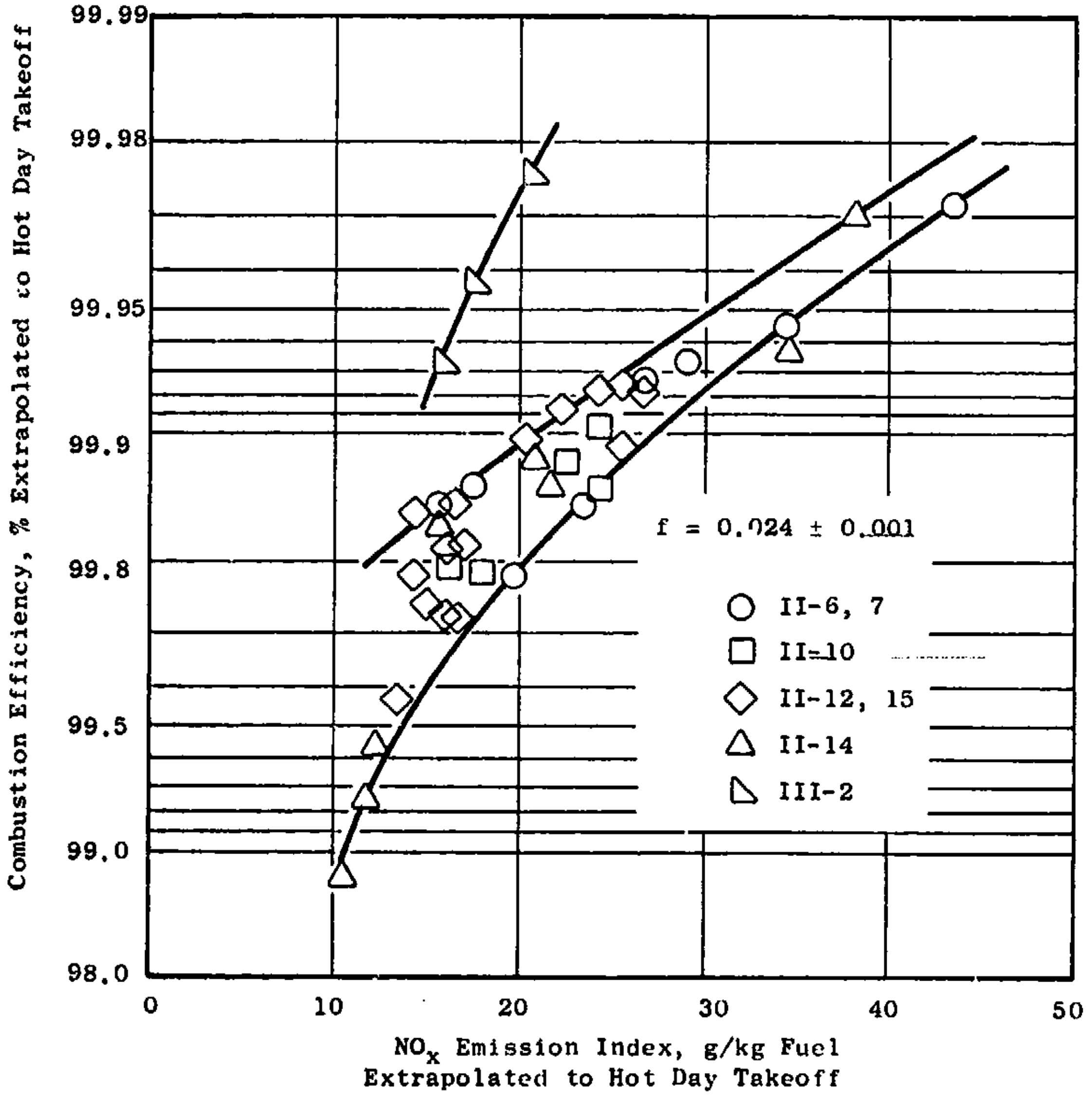


Figure 59. Tradeoff Between Combustion Efficiency and NO_x Emissions Level, Radial/Axial Staged Combustor.

The isothermal pressure loss levels were close to those of the production engine combustor, as intended. All of the configurations, however, had three to four times as much heat addition loss as the production engine combustor, since at high power conditions the major portion of the fuel was burned in high velocity regions. Augmentor designers have, of course, always recognized this characteristic, but main combustor designers have not generally needed to be concerned with it.

The mechanical and cooling characteristics of the Radial/Axial Staged Combustor configurations were very satisfactory. Over 115 hours of combustor operation were accrued in this series and the hardware was still in good condition, especially in the main stage flameholder and outer liner regions which were of concern in the design phase. Some distress in the aft cooling slot overhangs of the inner liner indicated that, for long term durability, additional and/or more effective cooling in this region may be required. As in the case of the Double Annular Combustor, the pilot stage dome hardware was in excellent condition, and some reductions in dome flameshield impingement cooling airflows may be possible for reapportionment to the aft inner liner. Light carbon-accumulation on the pilot stage dome and its fuel injectors was observed. But it is anticipated that by applying simple design features which have been developed in other current programs, this problem could be readily eliminated.

ASSESSMENTS OF RESULTS

NO_x Emissions Comparisons

The NO_x emissions characteristics of each of the basic design approaches investigated in this program are compared in Figure 60. At low fuel-air ratios, each of the design approaches produced significant reductions in NO_x emissions levels when compared to those of the production CF6-50 engine combustor. However, at the hot day takeoff operating conditions, the Double Annular and Radial/Axial Staged Combustor design approaches were found to be the most promising. A key ingredient of all of the designs was lean combustion regions (on a bulk basis) and advanced fuel-air mixing devices. The failure to achieve any significant reduction in NO_x emissions levels with the Lean Dome Single Annular approach is an indication that the combustion processes are very rapid compared to fuel-air mixing processes. With this design approach, much of the combustion must have occurred in near-stoichiometric regions. This result was not totally unexpected since the combustor had only 30 direct fuel injection points (no premixing). All of the other design approaches investigated, therefore, incorporated increased numbers of fuel injection points and, except for the Lean Dome Double Annular Combustor design approach, some degree of premixing. The NASA Swirl-Can-Modular Combustors incorporated both of these ingredients. The failure to achieve any sizeable NO_x emissions reductions with this combustor design approach is attributed to a combination of the following factors:

- Relatively coarse fuel atomization.
- Relatively low swirler airflow quantities.

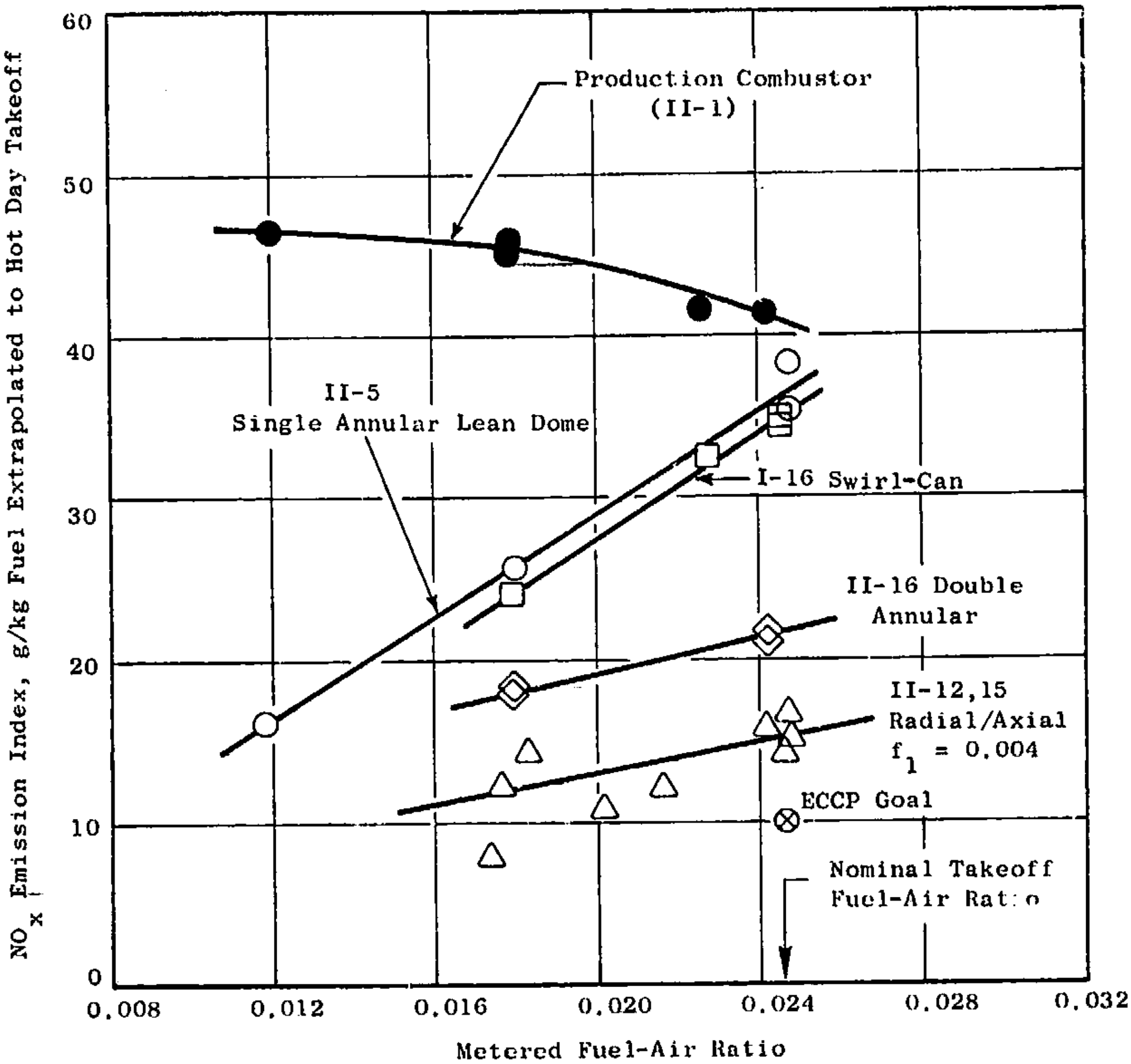


Figure 60. NO_x Emissions Levels, Best Configuration of Each Major Design Approach.

- Relatively slow mixing between the swirl-can flow and the other dome airflow (around/through the flameholders).

Some improvement was obtained with the last two configurations tested (Configurations III-1 and I-16) by grossly adjusting these parameters.

The first Double Annular Combustor configuration (Configuration II-4) had two of the ingredients thought to be important, good fuel atomization and high swirler airflows. However, at takeoff, its NO_x levels were only moderately reduced. This finding was attributed to relatively slow mixing of the primary and secondary swirler airflows, which was confirmed by flow visualization tests. In this design, fuel injector/primary swirler devices developed for a smaller engine were utilized in conjunction with new, higher flow, secondary swirlers. Good fuel atomization was still obtained, but mixing was compromised. Ideally, the primary swirler would also have been scaled up to the CF6-50 combustor-size flows, but cost, timing and dome size limitations were overriding factors in the selection. The later tests showed, however, that at least for the outer annulus, the selection was well chosen. The second test configuration (Configuration II-8) incorporated reduced secondary swirler airflow (to about the CF6-50 production engine combustor level) which visually provided improved mixing and resulting in a swirl cup fuel-air ratio at takeoff operating conditions of 0.066. Its NO_x emissions level was about 25 percent higher than that of the CF6-50 production engine combustor. Much-improved idle emissions levels were, however, obtained. The approach followed in the next configurations was, therefore, to bias the dome airflows. Steady progress was made thereafter by incorporating more rapid inner dome fuel-air mixing features. Based on these results, the next step appears to be to improve the effectiveness and/or airflow level of the inner annulus air swirlers and/or move the inner liner air dilution holes closer to the dome. Dilution air introduction into the inner annulus from the centerbody might also be effective.

As anticipated, the Radial/Axial Staged Combustor design approach produced the lowest NO_x emissions levels. The key features of this design approach that resulted in low NO_x levels were its very lean main stage and the use of fuel-air premixing in the main stage. Even though the fuel split was highly biased to the main stage at takeoff and the pilot was also lean, the major portions of the NO_x emissions were generated in the pilot stage. This effect was so strong that NO_x emissions levels were more dependent upon fuel flow split than any of the configuration changes which were made. Combustion efficiency levels were also very sensitive to fuel flow split, but configuration effects were observed, particularly with the last configuration (Configuration III-2). The results suggest that further significant progress may be obtained by a combination of:

- Airflow split adjustments.
- Main stage length adjustments.
- Added main stage air introduction features (such as turning vanes).
- Improved main stage fuel injection techniques.

Idle Emissions Comparisons

Figure 61 compares the idle emissions characteristics of each of the major design approaches investigated in this program. Fuel staging at idle was a significant factor in all of the design approaches. The HC emissions goal was achieved and the CO goal was approached with the CF6-50 production engine combustor using sector burning. Significant reductions, which correlated well with previous engine test experience, were also achieved with compressor bleed air extraction as shown in Figure 62. Therefore, it appears that the idle emissions goals might be achieved with the CF6-50 production engine combustor, using some combination of: (1) sector burning; (2) compressor bleed air extraction; and, (3) further improved fuel atomization. To some extent, these approaches are applicable to any other combustor.

The lowest idle emissions levels were achieved with the Radial/Axial Staged Combustor, which was also anticipated since the pilot stage was designed specifically for idle operation. The HC emissions goal was achieved, with margin, and the CO goal closely approached with the first test configuration. With compressor bleed air extraction, the CO goal was more nearly approached. It is anticipated that further progress could be made by pilot air swirler and/or dome cooling air adjustments.

The Double Annular Combustor, with outer annulus burning, provided the second lowest idle emissions levels in this program. These reductions are attributed to two features which are common to the Radial/Axial Combustor: fuel staging and improved fuel atomization. The difference in idle emissions levels of the two combustors is attributed to the degree to which the pilot stage is isolated from the main stage. The data strongly suggest that further significant reductions in the idle emissions levels of the Double Annular Combustor could be obtained by lengthening the centerbody (perhaps from the current one dome height to two dome heights).

The failure to achieve significant reductions in idle emissions levels with the NASA Swirl-Can-Modular Combustors is attributed primarily to its relatively coarse fuel atomization. A second important feature is its high dome airflows, with no biasing or isolation between dome annuli.

Intermediate Power Considerations

The primary focus in this program was upon NO_x emissions levels at the hot day takeoff conditions and HC and CO emissions levels at the standard day idle conditions. However, significant NO_x emissions level reductions, with high combustion efficiency levels, were obtained with several of the NASA Swirl-Can-Modular Combustor configurations at the intermediate power conditions. The results show that fuel staging was a key needed ingredient in each design approach. With the Double Annular and Radial/Axial Staged Combustor design approaches, obtaining acceptable combustion efficiency performance at these intermediate power operating conditions generally required the use of optimum fuel flow splits to the two combustor stages. With these combustor design approaches, therefore, further development efforts must be addressed to

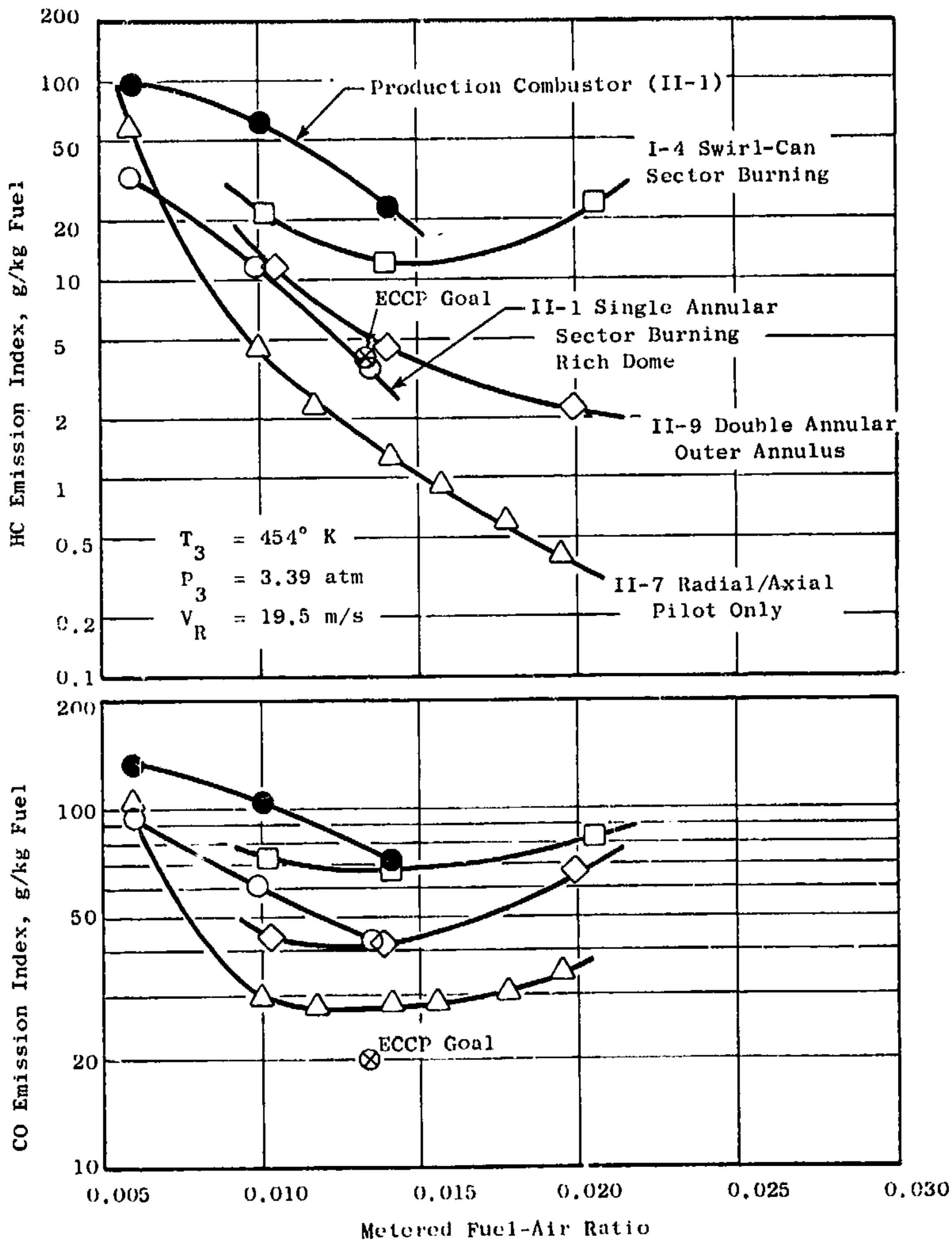


Figure 61. Idle Emissions Levels, Best Configuration of Each Major Design Approach.

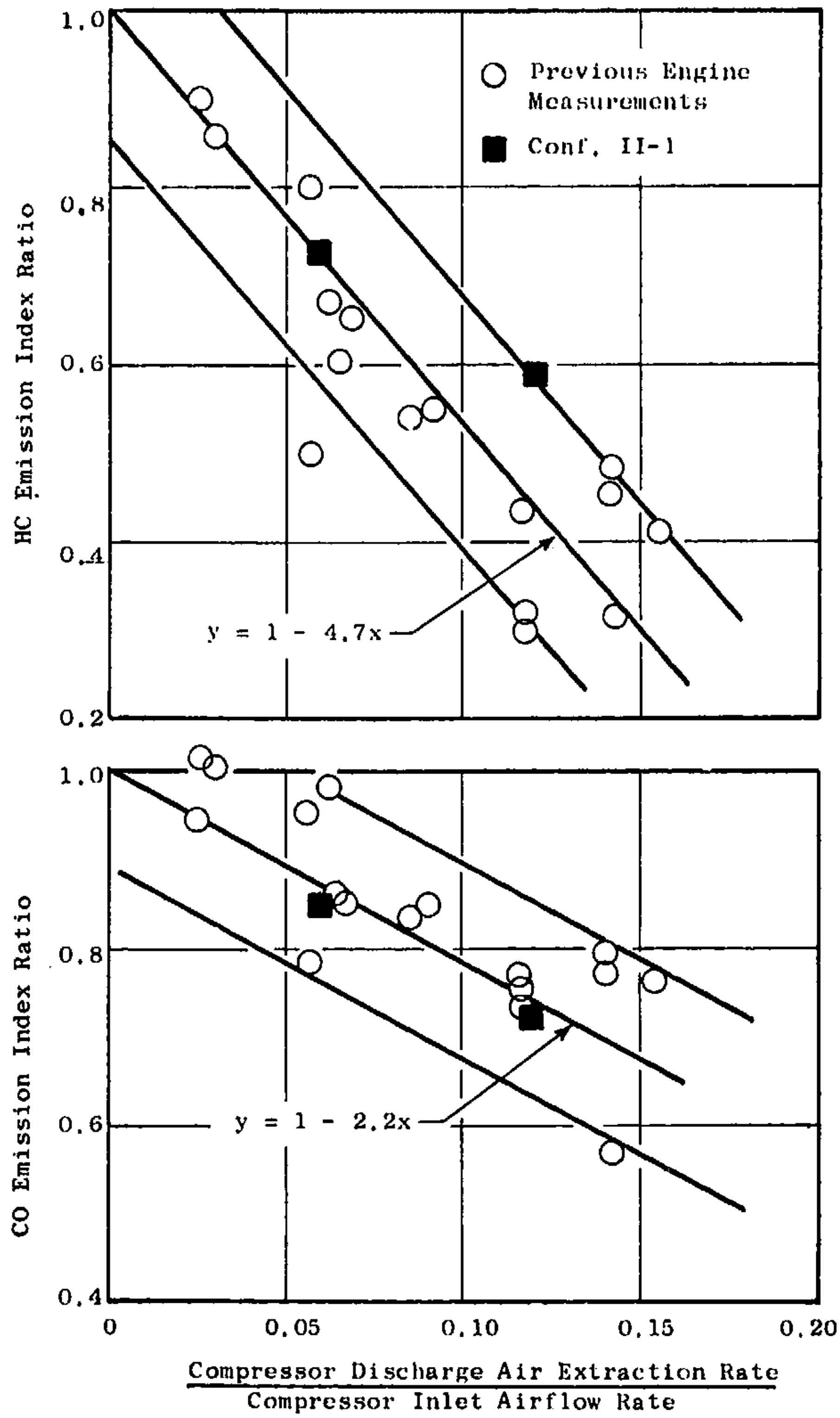


Figure 62. Effect of Compressor Bleed Air Extraction on Idle Emissions Levels.

determining where and how to schedule these changes in fueling mode. The combustor design must be integrated with the fuel delivery and engine control designs. This design problem is not really new. Main combustor designers have long dealt with dual-orifice fuel nozzles and the associated relative size/cut-in point considerations. The production CF6-50 engine combustor has three distinct fueling modes: (1) alternate nozzles - primary only; (2) alternate nozzles - primary and secondary; and, (3) all nozzles - primary and secondary. Augmentor designers have similarly incorporated three or more fueling modes including spatial staging; i.e., local, fill and fan air carburetion. Engine fuel delivery and control designers have then scheduled and integrated these designs to respond to throttle setting. Low emissions main combustors must now utilize and extend these technologies. The Radial/Axial Staged Combustor design approach perhaps presents the greatest challenge in this respect since emissions levels and combustion efficiency levels have been found to be highly sensitive to both inlet conditions and fueling mode.

Advanced commercial CTOL aircraft engines, such as the CF6-50 engine, are designed to have very low specific fuel consumption rates at the design cruise condition (generally 10.6 km, 0.85 M_p). To achieve low specific fuel consumption rates, the combustion efficiency levels must be very high (at least 99.8 percent or possibly 99.9 percent). From a fuel utilization standpoint slightly lower combustion efficiency levels (98.0 to 99.0 percent) could probably be tolerated in the idle, takeoff and approach modes. Such lower combustion efficiency levels would, however, make it virtually impossible to meet the EPA-defined emissions standards for HC and CO emissions, particularly with respect to CO emissions. Therefore, the fueling mode must be selected to obtain very high combustion efficiency levels not only at cruise, but throughout the EPA-defined landing and takeoff mission cycle.

The highest Radial/Axial Staged Combustor efficiency levels were obtained with the last configuration tested (Configuration III-2). The effects of fuel flow split at high power were investigated in detail. At the CF6-50 cruise condition (10.6 km, 0.85 M_p, standard day), combustion efficiency levels increased with increasing pilot fuel flow and/or circumferential staging of the main fuel flow. Sixty percent or more of the fuel in the pilot was required to reach the 99.8 percent combustion efficiency level. With all of the fuel introduced into the pilot, a combustion efficiency level of over 99.9 percent was obtained. The NO_x emissions levels peaked with about 40 percent of the fuel in the pilot. With all of the fuel in the pilot, a NO_x emissions level about 35 percent lower than that of the production CF6-50 engine combustor resulted. Thus, both from a combustion efficiency and NO_x emissions standpoint, the best way to operate this combustor at CTOL cruise appears, at this time, to be with only the pilot stage fueled.

The combustion efficiency levels of the Double Annular Combustors were found to be far less sensitive to inlet conditions and fuel split, thus fuel scheduling could be based upon exhaust emissions considerations only.

Similar studies, but in less detail, have been made at the approach (30 percent power) and climbout (85 percent power) conditions. At approach, the inlet pressure level is about the same as at cruise, but the inlet temperature is lower (661 versus 731° K) and the fuel-air ratio is much lower (0.014 versus 0.021). In order to meet the CO emissions standards, pilot-only operation seems to be needed at this engine operating mode with both the Radial/Axial Staged and Double Annular Combustors. At climbout, the combustor inlet pressure, inlet temperature, and fuel-air ratio are much closer to the takeoff conditions than to the cruise conditions. Thus, to meet the NO_x emissions standards, two-stage operation with the fuel highly biased to the main stage seems to be the optimum mode. If used in this way, the overall flight operational mode with these two staged combustor design approaches would be to idle and taxi out on pilot only, turn on the main stage for takeoff and climbout, then shut it down for the remainder of the flight (cruise, approach, taxi in and idle). In this scheme, the main stage is used much the same as an afterburner is used in military aircraft except that the main stage is never relighted in flight.

DEVELOPMENT STATUS OF BEST DESIGN APPROACHES

Pollutant Emissions Characteristics Status

The pollutant emissions goals of the basic Phase I Program were most closely approached with the Radial/Axial Staged and Double Annular Combustors. Table XXXVIII compares the emissions status of the best configurations to the program goals and the CF6-50 production engine combustor. In the case of the Radial/Axial Staged Combustor design, the NO_x emissions levels have been defined at the fuel flow split which provides an extrapolated combustion efficiency level of 99.85 percent. NO_x emissions levels at both the hot and standard day takeoff conditions are shown since: (1) the program goals were specified at the hot day condition; (2) the EPA-defined regulations are specified at the standard day condition; and, (3) the change in NO_x emissions levels at the two conditions varies with combustors. The CF6-50 engine operating conditions for the two ambient temperature levels are compared in Table XXXIX.

At standard day operating conditions, the combustor inlet temperature is significantly lower. Reference velocity and fuel-air ratio are also somewhat lower. In the case of the Radial/Axial Staged Combustor, this lower fuel-air ratio tends to offset the NO_x emissions level reductions associated with the lower inlet air temperature, since the pilot stage fuel flow percentage must be increased to maintain the same combustion efficiency. At a constant fuel-air ratio, the NO_x emissions levels would nominally be 19 percent lower at the standard day conditions. This degree of reduction is projected for the Double Annular Combustor since the effect of fuel-air ratio on its NO_x emissions levels is very slight. The NO_x emissions levels of the CF6-50 production engine combustor are expected to be only 16 percent lower at the standard day conditions, since the NO_x level increases with decreasing fuel-air ratio. Thus, at the hot day operating conditions, the Radial/Axial Staged Combustor is far superior, but the margin between it and the Double Annular Combustor diminishes somewhat at the standard day conditions.

Table XXXVIII. Summary of Exhaust Emissions Status.

	Emission Indices, g/kg Fuel			
	Radial/Axial Staged	Double Annular	Program Goal	Current Production Engine
HC at Standard Day Idle	2	6	4	27
CO at Standard Day Idle	28	34	20	67
NO_x at Hot Day Takeoff	~14(1)	21(2)	10	44
NO_x at Standard Day Takeoff	~14(1)	17(2)	--	35
	Smoke Index, SAE, SN			
Peak Smoke	<15	<15	15	12

(1) Extrapolated to true engine P_3 level with fuel flow splits which result in a projected combustion efficiency level of 99.85%

(2) Extrapolated to true engine P_3 level

Table XXXIX. Comparison of CF6-50 Combustor Operating Conditions at Takeoff.

Day	Hot	Standard
T_0, ° K	303	288
T_3, ° K	858	819
P_3, atm	29.1	29.1
V_R, m/s	26.5	25.9
f	.0245	.0225

NO Severity Ratio (standard day to hot day)

$$= \left(\frac{26.5}{25.9}\right) \left(\frac{29.1}{29.1}\right)^{\frac{1}{2}} \left[\exp\left(\frac{819-858}{169}\right)\right]$$

$= 0.810$

at constant fuel-air ratio

Overall Performance Status

The overall performance status of the two combustor design approaches is assessed in Table XL with respect to the degree of further development required for engine installation. In most respects, both combustors are classified as "essentially already meets requirements" or "expected to meet requirements with normal development."

Exit temperature distribution of both combustors is classified as "significant further development needed to meet requirements," although the test results were quite encouraging. In previous combustor developments, small changes to improve other aspects of performance, such as altitude relight and liner life, often have made large effects on exit temperature profile and pattern factor characteristics. Traditionally, exit temperature profiles have then been adjusted by altering the axial and circumferential locations of the dilution air holes. This tool is not available in these low emissions combustors, so adjustments to the exit temperatures are expected to be more difficult. Further, since gross changes in fuel staging are mandatory, the exit profiles must be considered at each operating mode.

Combustion efficiency at part-power and cruise of the Radial/Axial Staged Combustor is classified as "significant further development needed to meet requirements" for reasons discussed in the preceding sections of this chapter.

Flashback in the Radial/Axial Staged Combustor is also classified as "significant further development needed to meet requirements" for reasons common to any system incorporating fuel-air premixing. No problems were encountered in this program, but testing was: (1) limited to 9.5 atm; and, (2) no severe transients were attempted (such as an engine throttle chop). Much further development testing is required to prove the reliability of this aspect of the combustor design.

Overall Applications Status

Table XLI summarizes the key applications considerations associated with the Radial/Axial Staged and Double Annular Combustors. Their impacts on an intended engine application appear greatest in three areas:

- Modified turbine operating/performance capabilities may be required for application of either combustor, particularly the Double Annular Combustor. It is probable that the exit temperature profiles will deteriorate somewhat at one or more engine operating conditions because of the fuel staging that is required.

- The fuel delivery system will be more complex in a CF6-50 engine application:

  - 60 or 90 fuel injectors, flow dividers and pigtails are required versus 30 in the current configuration.

Table XL. Summary of Overall Performance Status.

Key Performance Aspect	Double Annular Status (1) 1	2	3	Radial/Axial Staged Status (1) 1	2	3
Other Emissions						
Smoke	x			x		
White Smoke (subidle)		x			x	
Ignition						
Ground Start	x			x		
Altitude Relight		x			x	
Pressure Drop	x			x———		
Combustion Efficiency						
at idle		x		x		
at SLS high power	x				x	
at part-power (approach)	x					x
at cruise modes	x					x
Exit Temperature Distribution						
Profile Factor			x			x
Pattern Factor			x			x
Flashback		x				x
Carboning		x			x	
Liner Life		x (2)			x (2)	

(1) Status Classification

Status 1: Essentially already meets requirements

Status 2: Expected to meet requirements with normal development

Status 3: Significant further development needed to meet requirements

(2) At least equivalent to current production combustor

Table XLI. Key Applications Considerations.

Combustor	Characteristic	Impact
Radial/Axial Staged	Combustion Efficiency Very Sensitive to T_3, P_3, & Fuel Flow Split Between Stages.	Only Pilot Stage Operation Can be Used at Cruise & Approach.
		Dual Fuel Manifolds & Added Fuel Control Sophistication May be Required.
	Involves Use of Two Axial Fuel Injection Locations.	Requires Much Added Complexity in Fuel Supply System.
Double Annular	Combustion Efficiency Sensitive to Fuel Flow Split Between Stages.	Dual Fuel Manifolds & Added Fuel Control Sophistication May be Required.
	Possible Abrupt Transition From Outer Dome Only Burning to Full Burning.	Abrupt Thrust Increase, May Require Special Fuel Control Features.
	Exit Temperature Profiles May Vary Widely Over Engine Operating Modes.	Modified Turbine Operating/Performance Capabilities May be Required.
	Involves Use of Twice as Many Fuel Injection Points.	Requires Some Added Complexity in Fuel Supply Systems.

- Possibly two fuel manifolds are required versus one in the current configuration.

- Two axial fuel injection locations are required, in the case of the Radial/Axial Staged Combustor, versus one in the current configuration.

- The fuel control system may be more complex (scheduling of fuel flow split is required, in addition to overall flow rate).

Limited studies have indicated that satisfactory means of handling these applications aspects can be attained, but significant design and development efforts will be involved.

MISCELLANEOUS DATA CORRELATIONS

Idle Emissions Correlations

In this program, 34 combustor configurations were tested. A broad range of combustor airflow splits was encompassed with these configurations. In addition, three major types of fuel injection methods were employed (conventional pressure atomizers, air blast devices and NASA Swirl-Can-Modular devices). Many of the configurations were tested with different fueling modes at idle (outer annulus, inner annulus, both annuli and alternate or sector burning). A total of 69 data points were obtained at the nominal idle test condition (P_3 = 3.39 atm, T_3 = 454° K, V_R = 19.5 m/s, f = 0.014). The CO, HC and NO_x emissions results are compared in Figures 63 and 64. These various configuration/fueling mode changes resulted in CO emissions indices ranging from about 25 to 150. The HC and NO_x indices seem to be uniquely related to the CO index; i.e., any configurational change which reduced CO emission levels, simultaneously reduced HC levels, but increased NO_x levels. The correlations suggest that a configuration which achieves the CO emission goal of 20 g/kg fuel would have an HC index of about 0.4 (an order of magnitude below the goal) and a NO_x index of about 3.7 at idle (50 percent increase from the CF6-50 production engine combustor). In the CF6-50 production engine combustor the quantity of NO_x emissions generated in the idle operating mode is a small fraction of NO_x emissions summed over the EPA-prescribed takeoff and landing cycle. However, if the takeoff NO_x emissions goal is achieved, the idle NO_x emissions will become a significant portion of the total NO_x emissions produced on the overall mission cycle.

Pressure Loss - NO_x Relationship

All combustors investigated in this program were designed to have about the same pressure loss as the CF6-50 production engine combustor. At one time in the program, it appeared that the NO_x emissions levels of the NASA Swirl-Can-Modular Combustors might be related to pressure drop, so two configurations with increased pressure loss were evaluated (Configurations I-10 and I-11). No improvement was noted. Late in the program, the two AST configurations (III-1 and III-2) were designed to have lower pressure drop and again no direct

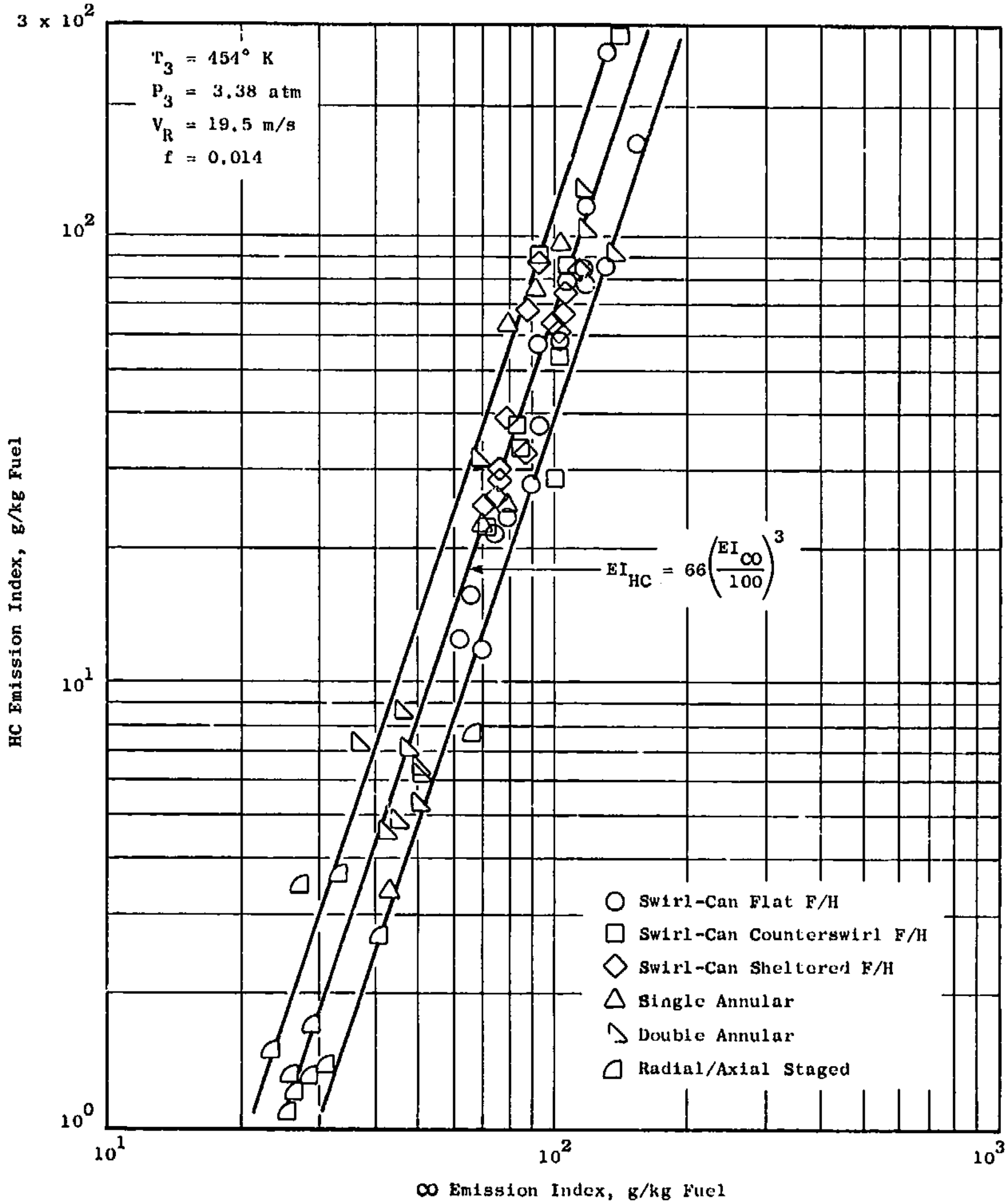


Figure 63. Correlation of HC and CO Emissions Levels at Idle, Configurations and Fueling Modes.

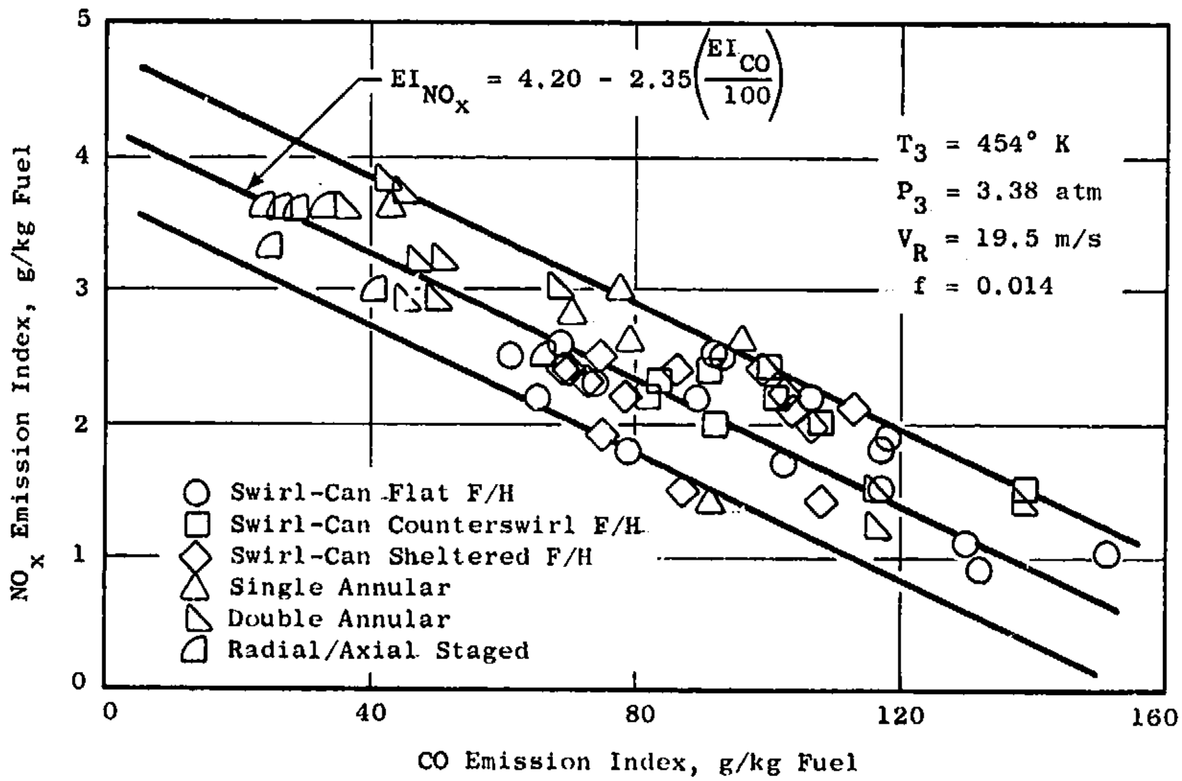


Figure 64. Correlation of NO_x and CO Emissions Levels at Idle, All ECCP Configurations and Fueling Modes at One Operating Condition.

effect was observed. The overall conclusion is that isothermal pressure drop alone is not a strong influence on emissions characteristics. However, all of the configurations which produced significant NO_x reductions had increased heat addition pressure loss. This was particularly noticeable in the tests of Double Annular Combustor configurations. NO_x emissions reductions were achieved when the dome airflow was increased and the airflow was biased to the inner annulus. Both of these features increased dome velocity and, hence, heat addition pressure loss. The Radial/Axial Staged Combustor was, of course, always designed to have high velocities in the main stage heat addition region. These trends suggest low NO_x emissions combustor designs must incorporate high velocity in the heat addition regions (to reduce residence time) in addition to lean mixtures.

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CHAPTER IV. AST ADDENDUM

INTRODUCTION

The efforts of the basic Phase I Program were concerned with the reductions of the pollutant emissions levels of high pressure ratio CTOL engines at engine operating conditions that primarily occur in and around airports: taxi and idle, takeoff, climbout and approach. In this addendum to the basic program, combustor design and development efforts were directed toward reducing the NO_x emissions levels of combustors at AST engine cruise operating conditions. This program addendum consisted of three tasks:

Task 1 - AST Screening Tests

Task 2 - AST Cruise Designs

Task 3 - AST Engine-Concept Designs

The screening tests consisted of selecting several of the most promising Program Element I and II combustor configurations of the basic program and evaluating them at a selected set of combustor operating conditions that would nominally be associated with an AST engine at supersonic operating conditions. Based on the measured NO_x emissions data, two modified Element I and two modified Element II configurations were then to be defined in Task 2. One of each design type was then to be selected, fabricated and tested as a part of Task 2. Task 3 consisted of selecting a realistic AST engine cycle and defining two combustor concept designs sized for this selected engine cycle, utilizing the best of the NO_x emissions reduction technology developed in the program.

The following are the combustor operating conditions, pollutant emissions levels and combustor performance levels specified for these AST Addendum design and development efforts:

AST Cruise Operating Conditions

P_{T_3}	6.8 atm
T_{T_3}	833° K
$T_{T_{3.9}}$	1589° K
$f_{3.9}$	0.023

AST Cruise Emissions Levels

NO_x	5 g/kg Fuel
HC	1 g/kg Fuel
CO	5 g/kg Fuel
Smoke	$\leq$ 15 (SAE Smoke Number)

AST Cruise Performance Levels

η_0	$\geq$ 99.8%
$\Delta P_T/P_{T3}$	$\leq$ 6.0%
Pattern Factor	$\leq$ 0.25

TASK 1 - AST SCREENING TESTS

Thirteen of the most promising Element I and Element II combustor test configurations of the basic program were selected and evaluated at the defined set of AST operating conditions. These AST Addendum evaluations were conducted as piggybacked tests to the basic Phase I Program tests. The 13 selected configurations are identified in Table XLII. Four Program Element I and nine Program Element II configurations were selected for these tests. The selection of Program Element I configurations was somewhat limited because some of these NASA Swirl-Can-Modular CF6-50 Combustors had excessive flame stabilizer metal temperatures and, therefore, could not be operated at the AST operating condition. The Element I configurations consisted of 3 90-swirl-can configurations and 1 72-swirl-can configuration. The Element II configurations included one Lean Dome Single Annular, four Double Annular and four Radial/Axial Staged Combustor configurations.

Summaries of the data obtained in the tests of these 13 configurations are presented in Table XLIII. Since these combustors were sized for the CF6-50 engine and, therefore, had a design reference velocity of 26.5 m/s, the AST cruise evaluations were run at or near this design reference velocity. However, AST engine combustors are more typically sized for reference velocities of approximately 32 m/s. Therefore, Table XLIII also includes emissions and performance values that have been corrected to the 32 m/s reference velocity. As is shown in this summary of results, the Double Annular and the Radial/Axial Staged Combustor configurations provided the lowest NO_x emissions levels of the configurations that were evaluated.

With the Program Element I NASA-Swirl-Can-Modular Combustor configurations, the NO_x levels varied between 14.6 and 17.4 g/kg fuel at the design fuel-air ratio. Only relatively small changes in NO_x levels were obtained with large variations in design configuration parameters, such as: the number of swirl cans utilized, the amount of airflow through the swirlers or the combustor pressure drop. The extrapolated NO_x emissions level for the production CF6-50 engine combustor at the AST operating conditions is approximately 17.2 g/kg fuel. All of these test configurations had combustion efficiencies of 99.7 percent or higher at the AST cruise operating point.

The NO_x emissions level of the Lean Dome Single Annular Combustor configuration was about 16 g/kg fuel at the AST cruise operating point. This represents a very small improvement over the production CF6-50 engine combustor operating at these conditions, even though the overall dome fuel-air ratio was markedly decreased and the combustor pressure drop substantially increased. It was thus concluded that the local dome fuel-air ratios were not being sufficiently

Table XLII. Summary Of Combustor Configurations Tested In Task 1 Of AST Addendum.

CF6-50 Combustor Configuration	Modification Description
Program Element I (NASA Swirl-Can-Modular)	
I-8	90-Swirl-Can, Sheltered Flameholders - High Swirl-Can Flow (24.8% W_c); No Dilution
I-10	90-Swirl-Can, Sheltered Flameholders - High Pressure Drop ($\Delta P_T/P_T$ = 4.69%); No Dilution
I-12	90-Swirl-Can, Sheltered Flameholders - Outer Liner Dilution (6.9% W_c)
I-16	72-Swirl-Can, Counterswirl Flameholders - Increased Flameholder Wetted Perimeter
Program Element II	
II-2	Lean Dome Single Annular
II-9	Lean Dome Double Annular - High Airflow Inner Annulus (W_{swirl} = 32.9% W_c)
II-11	Lean Dome Double Annular - Second Inner Panel Dilution (W_{dil} = 13.8% W_c)
II-13	Lean Dome Double Annular - First Inner Panel Dilution (W_{dil} = 13.8% W_c)
II-16	Lean Dome Double Annular - Modified Inner Annulus Dilution Air Entry
II-7	Radial/Axial Staged - Baseline (W_{swirl} = 12.7% W_c)
II-10	Radial/Axial Staged - Splash Plates Added to Main Stage Fuel Injectors
II-12	Radial/Axial Staged - Pilot Airflow Reduced (W_{swirl} = 10.9% W_c)
II-14	Radial/Axial Staged - Pilot Airflow Further Reduced (W_{swirl} = 8.1% W_c)

Table XLIII. Summary of AST Addendum Test Results.

Configuration	Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel/g air Metered Values		Gas Sample Combustion Efficiency %	Total Pressure Loss %	Emission Index g/kg Fuel Measured Values NO_x	Reference Velocity 26.5 m/s NO_x Emission Index at AST	Reference Velocity 32.0 m/s NO_x Emission Index at AST
						Overall	Outer Annulus or Pilot					
I-8	322	6.82	829	2.2	26.9	0.0179	0.0089	99.8	4.08	16.3	15.7	13.0
	323	6.82	837	2.2	26.7	0.0231	0.0114	99.8	4.06	17.7	16.5	13.7
	324	6.82	829	2.4	29.2	0.0231	0.0114	99.8	5.11	15.7	16.5	13.7
I-10	434	6.80	829	2.5	26.8	0.0120	0.0060	99.6	4.94	13.4	12.9	10.7
	435	6.77	834	2.5	26.8	0.0180	0.0090	99.9	4.95	16.2	15.2	12.6
	436	6.79	834	2.5	27.1	0.0227	0.0113	99.9	4.94	17.5	16.6	13.8
	437	6.78	833	2.5	26.9	0.0242	0.0120	99.9	4.85	17.9	17.0	14.1
	438	6.79	831	2.6	29.4	0.0178	0.0089	99.8	6.04	14.9	15.7	13.0
	439	6.83	830	2.6	29.3	0.0228	0.0114	99.8	6.03	16.3	17.0	14.1
	440	6.84	831	2.6	29.3	0.0243	0.0121	99.8	6.08	16.6	17.2	14.3
I-12	534	6.82	832	3.4	27.0	0.0117	0.0059	99.6	4.41	14.3	13.9	11.5
	535	6.80	833	3.4	26.9	0.0176	0.0088	99.8	4.57	16.4	15.9	13.2
	536	6.82	834	3.4	27.0	0.0227	0.0113	99.8	4.31	17.7	16.9	14.0
	537	6.81	834	3.4	27.0	0.0224	0.0118	99.8	4.38	17.3	16.7	13.8
	538	6.82	833	3.4	27.0	0.0224	0.0128	99.8	4.36	17.2	16.5	13.7
	539	6.82	831	3.4	26.9	0.0224	0.0134	99.8	4.33	16.9	16.4	13.6
	540	6.81	833	3.4	26.8	0.0242	0.0121	99.8	4.33	18.1	17.3	14.3
	541	6.82	828	3.7	29.3	0.0225	0.0112	99.8	5.38	15.7	17.1	14.2
I-16	804	4.72	828	6.3	26.3	0.0179	0.0090	98.6	4.16	8.2	10.1	8.4
	805	4.73	825	6.3	26.2	0.0227	0.0113	99.7	4.02	10.9	13.6	11.3
	806	4.72	828	6.4	26.1	0.0245	0.0122	99.7	4.09	11.9	14.4	11.9
II-2	111	7.69	828	2.3	27.6	0.0235	-	99.7	6.93	17.2	16.1	13.3
	112	6.73	830	2.9	26.4	0.0236	-	99.7	6.09	17.4	16.7	13.8
	113	6.82	826	2.9	28.8	0.0165	-	98.3	7.41	11.5	12.2	10.1
	114	6.76	829	2.9	26.3	0.0177	-	99.3	6.02	14.4	13.8	11.4
	115	6.82	830	2.7	26.1	0.0240	-	99.7	5.99	18.3	17.2	14.3
	116	6.73	831	3.2	27.0	0.0230	-	99.6	6.46	16.6	16.3	13.5
	117	6.72	828	3.8	26.8	0.0181	-	99.3	6.41	13.5	13.6	11.3
II-9	383	6.76	835	5.1	26.6	0.0181	0.0050	99.8	4.56	12.4	12.1	10.0
	384	6.78	833	5.0	27.1	0.0225	0.0049	99.9	4.93	12.7	12.7	10.5
	385	7.15	831	5.6	2[illegible].8	0.0227	0.0040	99.7	5.09	11.9	13.0	10.8
II-11	470	6.80	835	3.4	26.7	0.0177	0.0059	99.9	4.95	10.9	10.3	8.5
	471	6.81	833	3.4	27.0	0.0174	0.0039	99.8	5.02	10.5	10.1	8.4
	472	6.80	833	3.3	26.6	0.0243	0.0040	99.9	4.97	12.5	11.8	9.8
	473	6.80	834	3.3	26.9	0.0240	0.0059	100.0	5.15	12.0	11.5	9.5
II-13	580	6.74	835	3.9	26.7	0.0177	0.0050	99.8	5.79	9.9	9.5	7.9
	581	6.75	836	4.0	26.8	0.0177	0.0030	99.8	5.86	9.2	8.8	7.3
	582	6.73	838	4.0	27.1	0.0239	0.0049	99.9	6.00	10.5	10.0	8.3
	583	6.74	837	4.0	26.9	0.0242	0.0040	99.9	5.93	10.6	10.2	8.5
	584	6.74	837	4.0	26.9	0.0239	0.0030	99.9	6.01	10.8	10.3	8.5
	585	7.34	834	4.3	29.0	0.0225	0.0050	99.9	7.02	9.6	9.7	8.0
	586	7.34	835	4.3	28.8	0.0227	0.0040	99.9	7.00	9.4	9.3	7.7

Table XLIII. Summary of AST Addendum Test Results (Concluded).

Configuration	Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Inlet Air Humidity g/Kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel/g air Metered Values Overall	Fuel-Air Ratio Metered Values Outer Annulus or Pilot	Gas Sample Combustion Efficiency %	Total Pressure Loss %	Emission Index g/kg fuel Measured Values NO_x	Reference Velocity 26.5 m/s NO_x Emission Index at AST	Reference Velocity 32.0 m/s NO_x Emission Index at AST
II-7	274	6.82	830	3.4	26.9	0.0049	0.0049	99.7	4.78	12.8	12.5	10.4
	275	6.80	830	3.4	26.6	0.0059	0.0059	100.0	4.81	18.1	17.6	14.6
	276	6.76	830	3.4	27.0	0.0068	0.0068	100.0	4.79	24.7	24.7	20.5
	277	6.80	831	3.6	26.6	0.0227	0.0049	96.9	5.11	7.2	6.9	5.7
	278	6.86	831	3.4	29.2	0.0231	0.0061	97.9	4.90	8.9	8.5	7.0
	279	6.86	831	3.6	29.4	0.0221	0.0047	96.0	6.24	5.8	6.2	5.1
	280	6.87	832	3.6	29.5	0.0220	0.0057	97.3	6.33	7.1	7.5	6.2
II-10	410	6.86	834	2.6	29.0	0.0176	0.0049	92.6	4.82	5.07	4.8	4.0
	411	6.84	834	2.7	26.6	0.0181	0.0070	97.0	4.74	10.64	9.8	8.1
	412	6.88	836	2.7	26.5	0.0220	0.0071	98.9	4.84	11.05	10.1	8.4
	413	6.82	836	2.7	26.7	0.0220	0.0050	96.7	4.88	6.52	6.1	5.1
	414	6.84	834	2.7	26.5	0.0246	0.0054	98.5	4.90	8.10	7.5	6.2
	415	6.94	836	2.7	26.6	0.0240	0.0069	99.1	4.90	11.08	10.1	8.4
II-12	517	6.80	840	5.6	26.8	0.0179	0.0050	95.9	5.26	5.5	5.3	4.4
	518	6.82	843	5.6	27.1	0.0176	0.0069	97.8	5.28	11.0	10.5	8.7
	519	6.79	840	5.4	27.1	0.0216	0.0049	98.3	5.47	6.6	6.4	5.3
	520	6.80	840	5.1	27.1	0.0214	0.0069	99.1	5.50	11.1	10.6	8.8
	521	6.77	843	5.1	27.4	0.0240	0.0050	98.8	5.74	7.4	7.1	5.9
	522	6.82	843	5.1	27.2	0.0240	0.0069	99.3	5.63	11.3	10.7	8.9
	523	7.07	832	5.0	30.1	0.0226	0.0069	99.0	6.88	9.8	10.4	8.6
II-14	610	7.29	830	3.1	29.3	0.0228	0.0030	93.0	6.85	4.6	4.7	3.9
	611	6.74	833	3.1	26.9	0.0227	0.0030	94.5	5.55	5.2	5.0	4.1
	612	6.76	830	3.1	26.5	0.0228	0.0049	99.0	5.50	9.4	9.1	7.5
	613	5.85	831	3.0	26.0	0.0178	0.0030	83.5	5.05	2.9	2.7	2.2
	614	6.80	830	3.1	26.2	0.0177	0.0050	97.0	5.35	8.5	8.1	6.7
II-16	740	6.80	840	6.0	27.1	0.0173	0.0047	9[illegible].7	-	7.4	7.8	6.5
	741	6.82	848	6.0	26.6	0.0180	0.0030	99.8	-	7.8	7.6	6.3
	742	6.80	855	6.3	26.9	0.0242	0.0049	100.0	-	8.9	9.0	7.5
	743	6.82	853	6.3	26.9	0.0242	0.0030	99.9	6.22	9.0	8.9	7.4
	744	6.81	857	6.3	29.1	0.0243	0.0049	100.0	7.60	8.5	9.0	7.5
	745	6.82	853	6.3	25.3	0.0238	0.0048	100.0	5.10	10.5	9.2	7.6
III-1	785	6.78	845	4.3	27.6	0.0117	0.0058	99.7	3.66	11.8	11.0	9.1
	786	6.79	844	4.3	27.4	0.0176	0.0088	99.9	3.60	14.4	18.5	11.2
	787	6.72	844	4.3	27.2	0.0228	0.0113	99.9	3.48	16.2	15.2	12.6
	788	6.78	839	4.3	26.9	0.0244	0.0121	99.8	3.26	16.3	15.3	12.7
	789	6.73	843	4.3	29.4	0.0180	0.0090	99.9	3.94	13.5	14.2	11.8
	790	6.73	843	4.3	29.6	0.0229	0.0114	99.8	4.01	14.9	15.2	12.6
	791	6.76	858	4.3	30.1	0.0245	0.0121	99.8	4.00	15.1	14.8	12.3
III-2	818	6.82	826	6.0	29.2	0.0227	0.0050	99.6	5.24	9.3	10.6	8.8
	819	6.82	827	4.3	29.4	0.0225	0.0030	97.9	5.25	5.7	6.3	5.2
	820	6.88	830	4.3	26.8	0.0175	0.0048	97.7	3.96	8.5	8.3	6.9
	821	6.78	828	5.3	27.0	0.0223	0.0078	99.7	4.26	15.8	16.4	13.6
	822	6.80	828	5.7	27.0	0.0222	0.0058	99.7	4.24	12.7	13.2	10.9
	823	6.80	826	5.7	27.0	0.0223	0.0049	99.6	4.24	9.8	10.2	8.5
	824	6.78	826	5.7	26.8	0.0226	0.0040	99.4	4.11	7.8	8.1	6.7
	825	6.78	828	6.0	26.6	0.0227	0.0030	98.7	4.19	6.3	6.5	5.4
	826	6.85	827	6.0	26.3	0.0221	0.0079	99.8	3.97	17.9	18.4	15.2
	827	6.78	827	6.0	26.7	0.0187	0.0059	99.3	4.11	15.1	15.7	13.0
	828	6.82	827	6.0	26.5	0.0178	0.0049	98.8	4.03	11.8	12.2	10.1

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reduced and that the mixture residence times at these high fuel-air ratios were too long. Furthermore, it was also concluded that variable airflow geometries would be necessary to meet idle and relight performance requirements.

In the tests of the four Double Annular Combustor configurations, the major geometry parameter varied was inner liner dilution air location and dilution airflow hole design. The NO_x emissions level was reduced when the dilution airflow was moved upstream towards the dome. Also, the NO_x emissions level was further reduced when the dilution hole geometry was modified to obtain greater dilution air penetration into the dome region. A maximum reduction in NO_x emissions level of about 41 percent was obtained at the AST cruise operating point. At the AST cruise operating point, the combustion efficiencies of all test configurations were 99.8 percent or higher.

The results obtained with the Radial/Axial Staged Combustor configurations illustrate the same relationships between combustion efficiency and NO_x emissions levels at the AST cruise conditions as were obtained with these same configurations at the CTOL operating conditions. The NO_x emission levels varied from about 6.5 to 9.2 g/kg fuel over the range of configuration modifications tested at the AST cruise conditions. A maximum NO_x reduction of about 62 percent from the level of the production CF6-50 engine combustor at AST conditions was achieved, but with a combustion efficiency of only about 97 percent. To obtain the target combustion efficiency (99.8 percent) with this design concept, higher pilot stage fuel-air ratios were required and, as the pilot stage fuel-air ratios were increased, the NO_x levels were also increased. Therefore, further design modifications that would improve main stage combustion efficiency without a requirement for increased pilot stage fuel-air ratios would be required to more closely approach the AST cruise emissions and performance goals.

Accordingly, the Double Annular Combustor configurations were found to provide the best combination of low NO_x emissions levels and high combustion efficiency performance, at the specified AST cruise operating conditions.

TASK 2 - AST CRUISE DESIGNS

Based on these screening test results, two Program Element I-type and two Program Element II-type combustor designs were defined as candidate approaches for further development evaluations to approach the AST Addendum pollutant emissions and performance goals. A description of each design is presented in the following sections of this chapter.

Design Number 1 - Fuel Atomizer/High Flow 72-Swirl-Can Combustor Configuration

The principle design technique used in this Program Element I-type configuration was to provide a lean homogeneous fuel-air mixture in the dome region with no local fuel-air equivalence ratios above 0.76. A sketch of this design is presented in Figure 65. The combustor design consisted of the 72-swirl-can dome, with counterswirl outside swirlers. In this design the

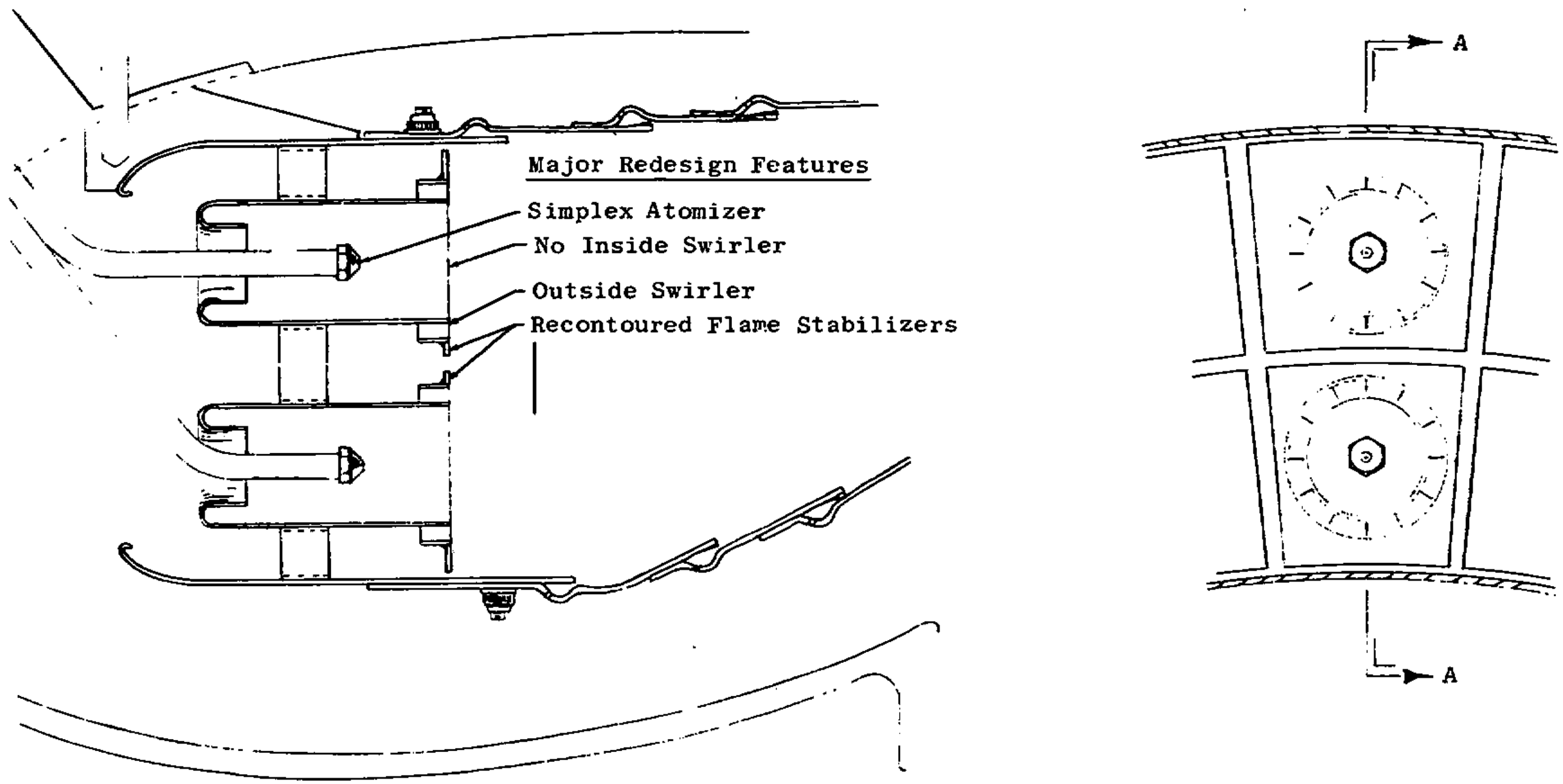

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Figure 65. AST Cruise Design No.1, Fuel-Atomizer/High Flow 72-Swirl-Can Combustor, Configuration I-16.

fuel was injected into each swirl can through small simplex pressure-atomizing spray nozzles attached to the existing fuel injector tubes. No internal swirlers were utilized in the swirl cans in order to obtain the highest swirl-can airflow possible with the existing hardware. The flat plate flameholders were designed to reduce the airflow around the flameholders and direct a greater airflow through the swirl cans. In this manner, 30 percent of the combustor airflow was directed through the swirl cans. Thus, a 50 percent increase in swirl-can airflow over the previously tested swirl-can configurations was achieved. The outside swirlers handled an additional 14 percent of the airflow, resulting in a total of 44 percent of the combustor airflow through or immediately surrounding the swirl cans. With this airflow level through the 72 cans and swirlers, an average fuel-air mixture equivalence ratio of 0.76 at the swirl-can exit plane would result at the AST cruise point fuel-air ratio of 0.023. The possibility of atomized fuel droplets migrating upstream of the combustor dome in the wakes of fuel injector tubes was eliminated in this design by placing the fuel spray nozzle tip downstream of the swirl-can air metering area cross section. Therefore, with a dome design pressure drop of approximately three percent, it was considered unlikely that upstream migration of fuel through this area would occur.

Design Number 2 - Extended Perimeter 60-Swirl-Can Combustor Configuration

The basic Phase I Program Swirl-Can-Modular Combustors were designed such that the overall dome fuel-air equivalence ratios in the order of 0.43 resulted at the AST cruise point conditions, with the assumption of homogeneous mixing. However, the basic Phase I Program test results showed that some of the dome airflow passing around the flame stabilizers was not mixing homogeneously with the fuel and swirl-can air mixtures. In AST Cruise Design Number 1, lean homogeneous dome mixtures were created by employing pressure-atomized fuel and greatly increased airflow through the swirl cans. In this second Program Element I-type design (AST Cruise Design Number 2), lean homogeneous mixtures were created by significantly increasing the wetted perimeter of the flat plate flame stabilizers of the standard 60-swirl-can combustor. A sketch of this design is presented in Figure 66.

The basic flat plate flame stabilizer for the swirl-can configurations was trapezoidal in shape with the overall blockage being selected to control dome pressure drop. The flat flameholder design was modified for this design to redistribute the dome open area by adding a series of radial slot openings in each flameholder. In this manner, the wetted perimeter was increased to approximately three times that of previous configurations with the same overall blockage. This design feature was intended to redistribute the flameholder bypass airflow more effectively, relative to the swirl-can exit fuel-air mixture flow, and thus create a more uniform lean dome fuel-air ratio mixture. The 60-swirl-can dome array was used in this design because it provided the largest wetted perimeter. In this design, the wetted perimeter was increased approximately 50 percent, for the same blockage pressure loss, over those of the previously tested swirl-can combustor configurations.

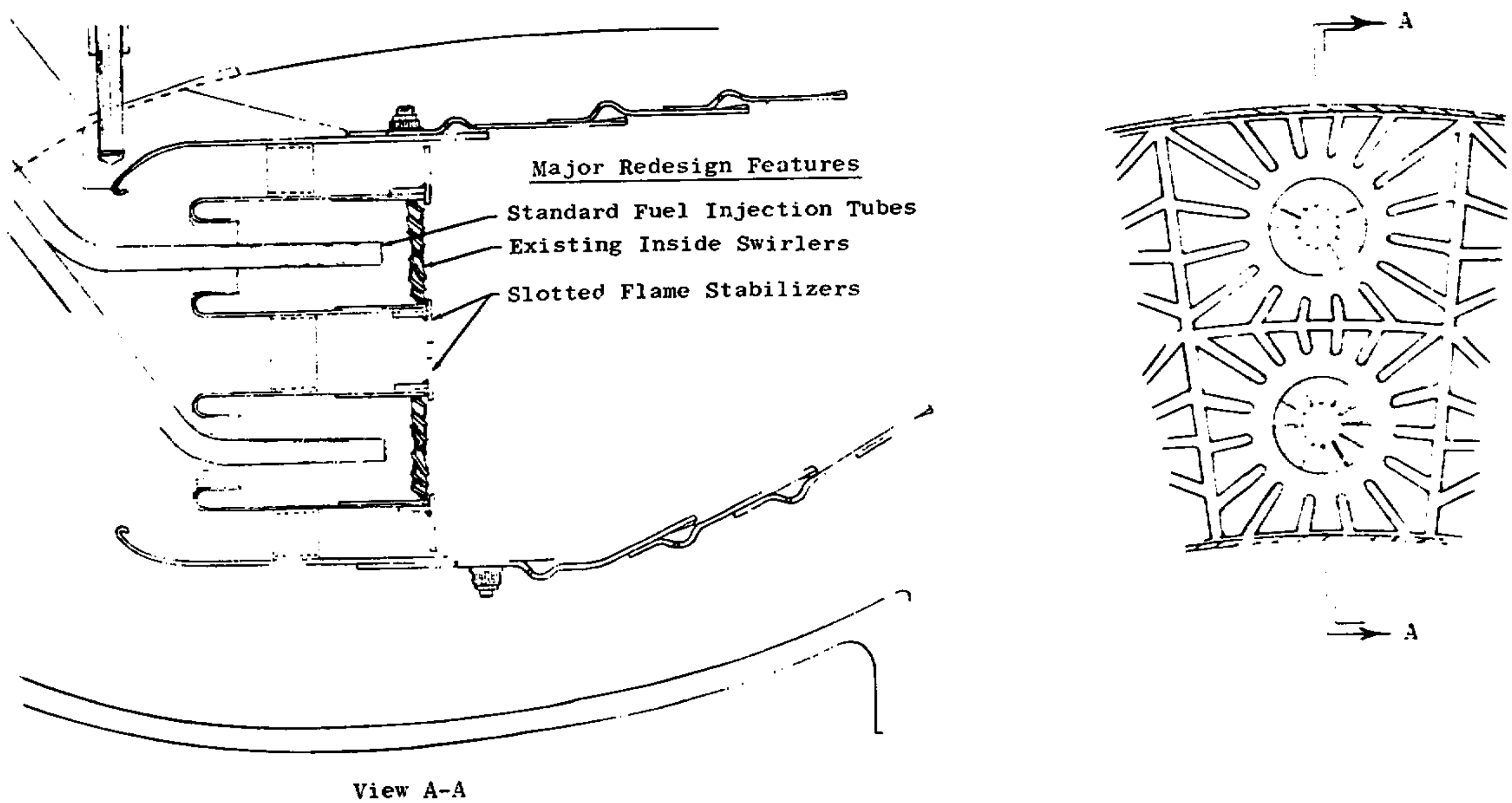


Figure 66. AST Cruise Design No.2, Extended Perimeter 60-Swirl-Can Combustor, Configuration III-1.

Design Number 3 - Double Annular Combustor Configuration

The Double Annular Combustor configuration screening test results showed that biasing both the fuel and the air flows to the inner annulus, such that lean dome fuel-air ratios were obtained in both annuli and such that short reaction residence times were obtained in the inner annulus dome, produced reduced NO_x emissions levels. Therefore, the AST Cruise Design Number 3 was designed to further reduce the residence time in the inner annulus. This was accomplished by further biasing the airflow towards the inner annulus and modifying the dilution air entry array of the inner annulus. A sketch of this Program Element II-type design is presented in Figure 67. Dilution holes in the centerbody in combination with thimbled dilution holes in the first inner liner panel were employed. The centerbody dilution holes were intended to further increase early air penetration and to provide more rapid fuel and air mixing.

Design Number 4 - Radial/Axial Staged Combustor Configuration

The Radial/Axial Staged Combustor configuration screening results showed that the airflow split between the pilot and main stages affected both the NO_x emissions levels and the overall combustion efficiency performance levels. These results also showed that increases in the pilot stage fuel-air ratio improved combustion efficiency but that, to obtain low NO_x levels, the pilot stage had to be operated very lean and/or that most of the total fuel flow had to be introduced into the main stage. The AST Cruise Design Number 4 was defined using correlations of these data as guidelines. A sketch of this second Program Element II-type combustor design is presented in Figure 68. The two key design features of this configuration were: 1) a further decrease in pilot airflow rate, to permit a reduction in the amount of fuel introduced into this stage; and, 2) the addition of turning vanes in the main stage air chutes. The pilot airflow was reduced to approximately eight percent of the total combustor airflow, which was considered to be a limiting value without major new hardware fabrication efforts. The turning vanes were added to reduce stratification between the pilot stage gases and the main stage flow. The design intent was to achieve an earlier ignition of the main stage fuel-air mixtures by turning the flow inward to mix with the higher temperature pilot stage combustion gases. Since the main stage combustion efficiency was found to be highly dependent on the pilot stage fuel-air ratio, or temperature level, this dependence was interpreted to be due to a main stage mixture ignition delay effect. Therefore, it was expected that the turning vanes would improve main stage combustion efficiency without increasing NO_x emissions.

Test Results

From these four designs, one Program Element I-type design and one Program Element II-type design were subsequently selected for fabrication and test. Assessments of these designs suggested that Design 2 of Element I-types and Design 4 of the Element II-types offered the greatest potential for providing possible significant further reductions in NO_x emissions levels at the AST cruise operating conditions. These two designs were incorporated into

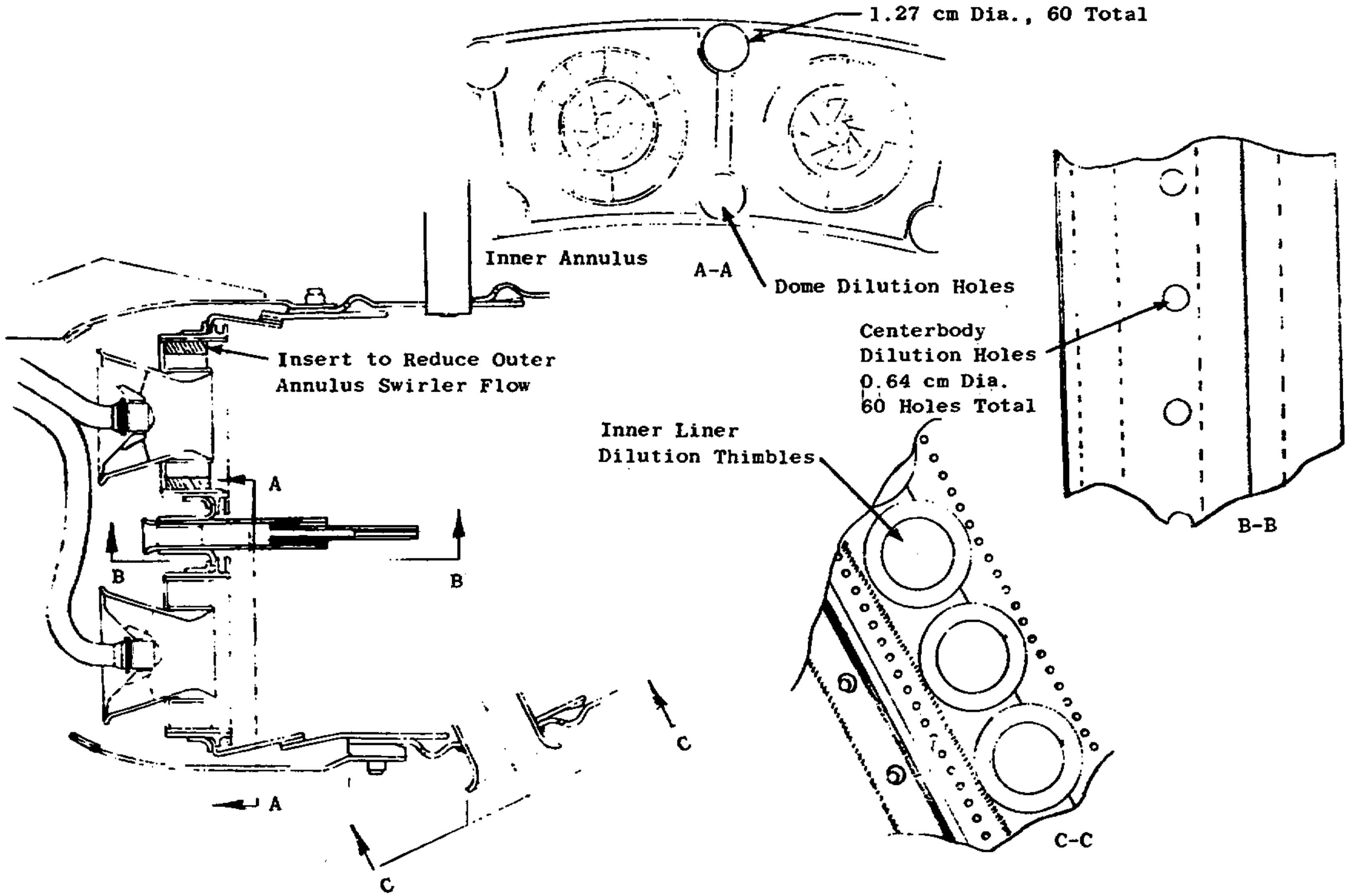


Figure 67. AST Cruise Design No.3, Double-Annular Combustor, Configuration II-16.

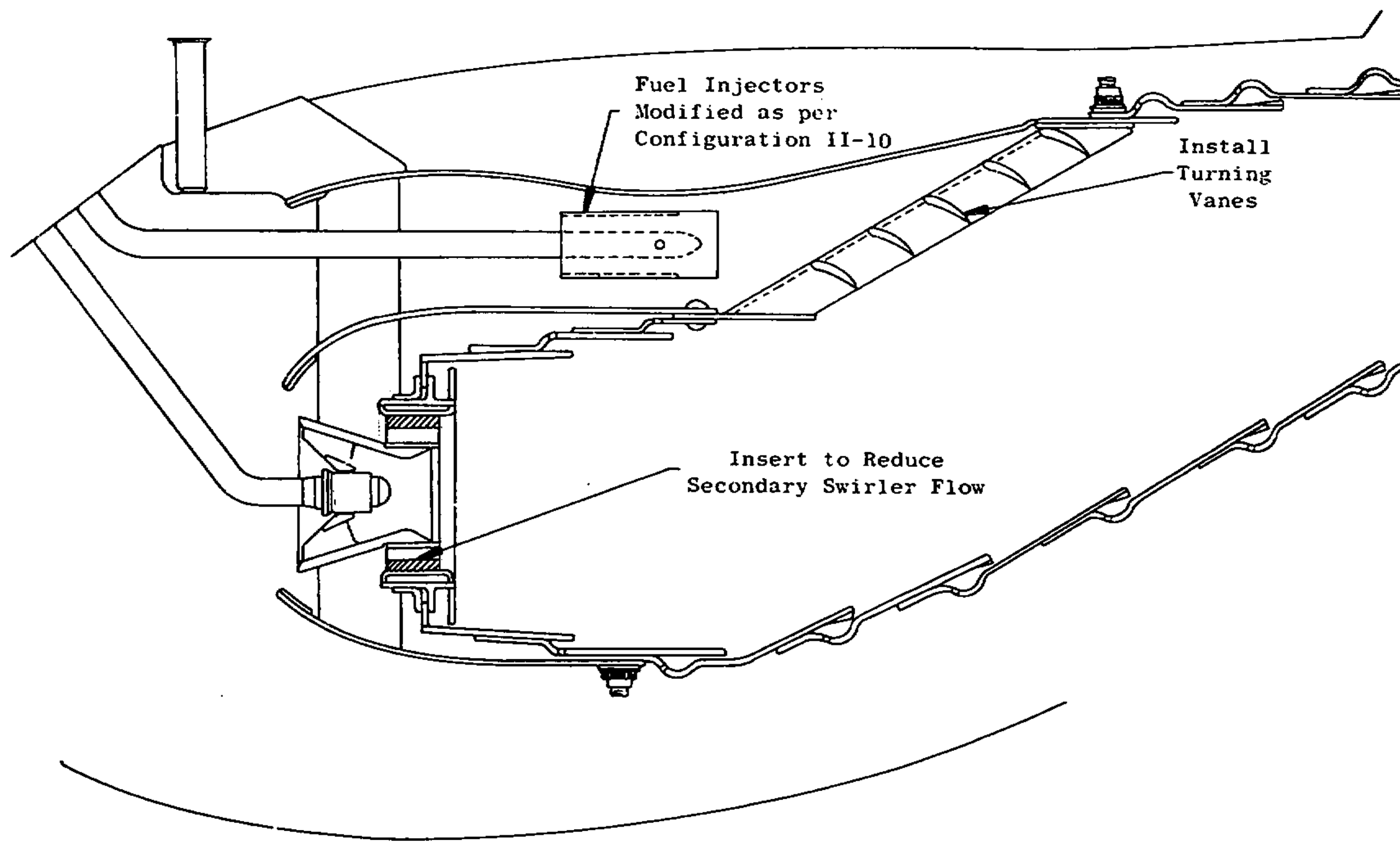


Figure 68. AST Cruise Design No. 4, Radial/Axial Staged Combustor (Configuration III-2).

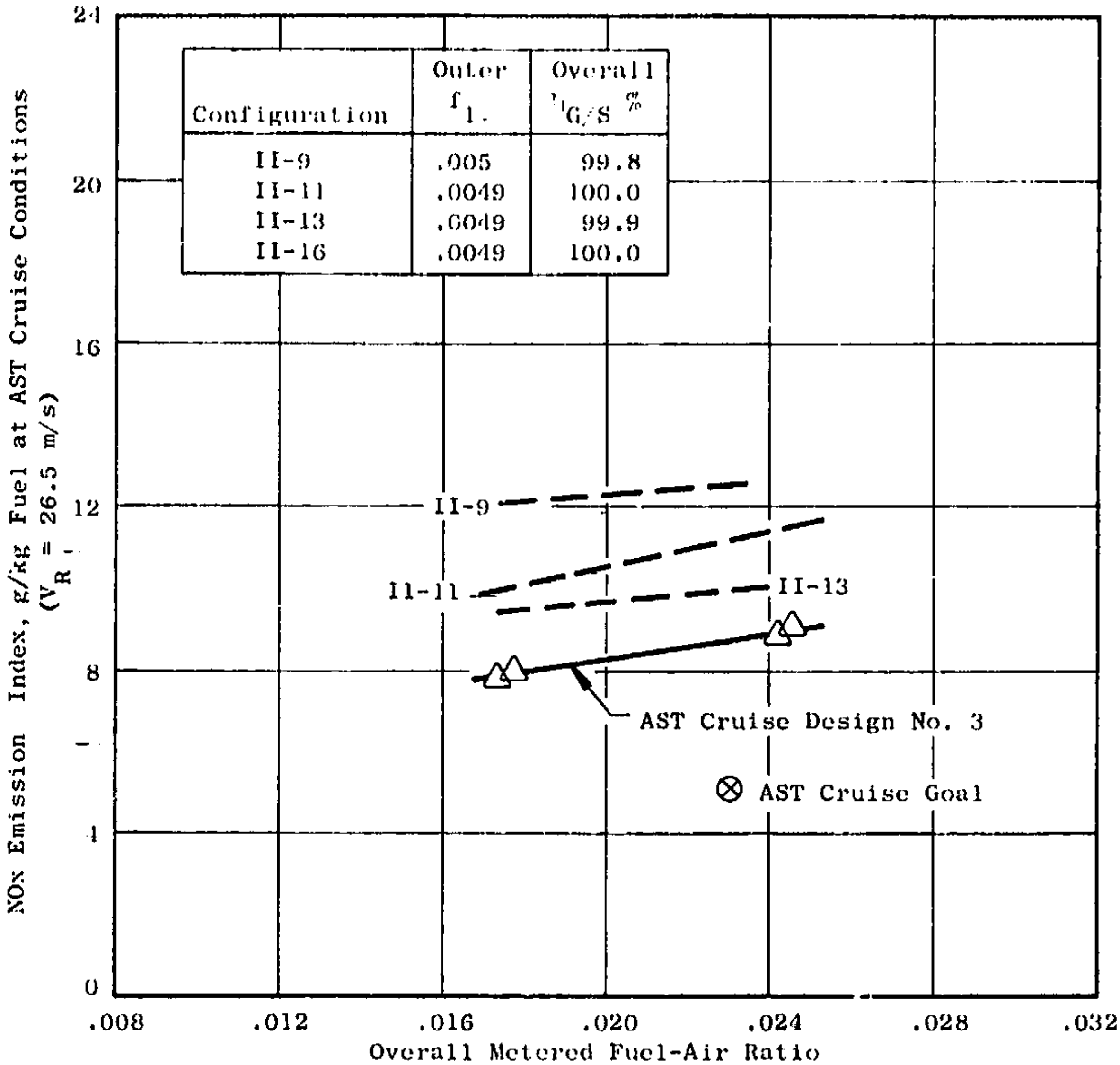
the existing basic Phase I Program hardware. Tests of these two configurations (Configuration III-1 and III-2) were then conducted both at the specified AST cruise conditions and at the CF6-50 combustor operating conditions. The results of the AST tests are included in Table XLIII. In addition, Designs 2 and 3 were also pursued as candidate designs in the basic program. In the basic Phase I Program, both of these designs were built and tested as Configurations I-16 and II-16. As a part of these latter tests, piggybacked evaluations at the AST cruise operating conditions were included. Thus, tests of these two configurations were conducted as a part of the Task 1 screening tests, in which 13 configurations were evaluated, in piggybacked tests, at the specified AST cruise conditions. The AST cruise data obtained with these two test configurations are also included in Table XLIII.

Comparisons of the Task 1 and 2 test results showed that Design Number 1 (Configuration I-16) produced a NO_x emissions level reduction of about 21 percent, relative to that of the production CF6-50 engine combustor. AST Cruise Design Number 2 (Configuration III-1) produced a reduction of about 12 percent. Thus, Design Number 1, utilizing pressure-atomizing fuel spray nozzles, produced the lowest NO_x emissions of all the Swirl-Can-Modular configurations tested at the specified AST operating conditions.

The design intent of the AST Cruise Design Number 3 (Configuration II-16) was to further bias the airflow split and to increase dome mixing in the inner annulus. The results obtained with this design are presented in Figure 69. A 49 percent reduction in NO_x emissions level was obtained relative to that of the production CF6-50 engine combustor. Each configuration modification to this combustor concept did result in progressively lower NO_x emissions levels, with no decrease in combustion efficiency. Thus, the Double Annular combustor design approach was found to provide the best overall emissions and performance characteristics at the specified AST operating conditions.

The AST Cruise Design Number 4 (Configuration III-1) was a modified Radial/Axial Staged Combustor configuration. The intent of this design was to improve the main stage combustion efficiency by increasing the degree of mixing between the pilot exhaust gases and the main stage mixture. With this design, the overall combustion efficiency was significantly improved. However, its NO_x levels were not significantly different from those of the previously tested configurations. The resulting improved trade off between combustion efficiency and NO_x levels is illustrated in Figure 70. It is clear from these data that for a given NO_x level, a higher combustion efficiency was achieved with the AST Cruise Design Number 4. However, at the target combustion efficiency level, the NO_x emissions level of this configuration was about the same as that of the current production CF6-50 engine combustor.

Based on these results, it appears that further improvement is feasible with this combustor concept. Since the data show that combustion performance is sensitive to the mixing interrelation between the pilot stage and main stage gases, configuration development would logically include pilot stage resizing studies and the incorporation of improved mixing devices in the main stage.



Configuration	Outer f_1.	Overall $\eta_{G/S}$ %
II-9	.005	99.8
II-11	.0049	100.0
II-13	.0049	99.9
II-16	.0049	100.0

Figure 69. NO_x Emission Levels, AST Cruise Combustor Design No. 3 (Double Annular Combustor Concept).

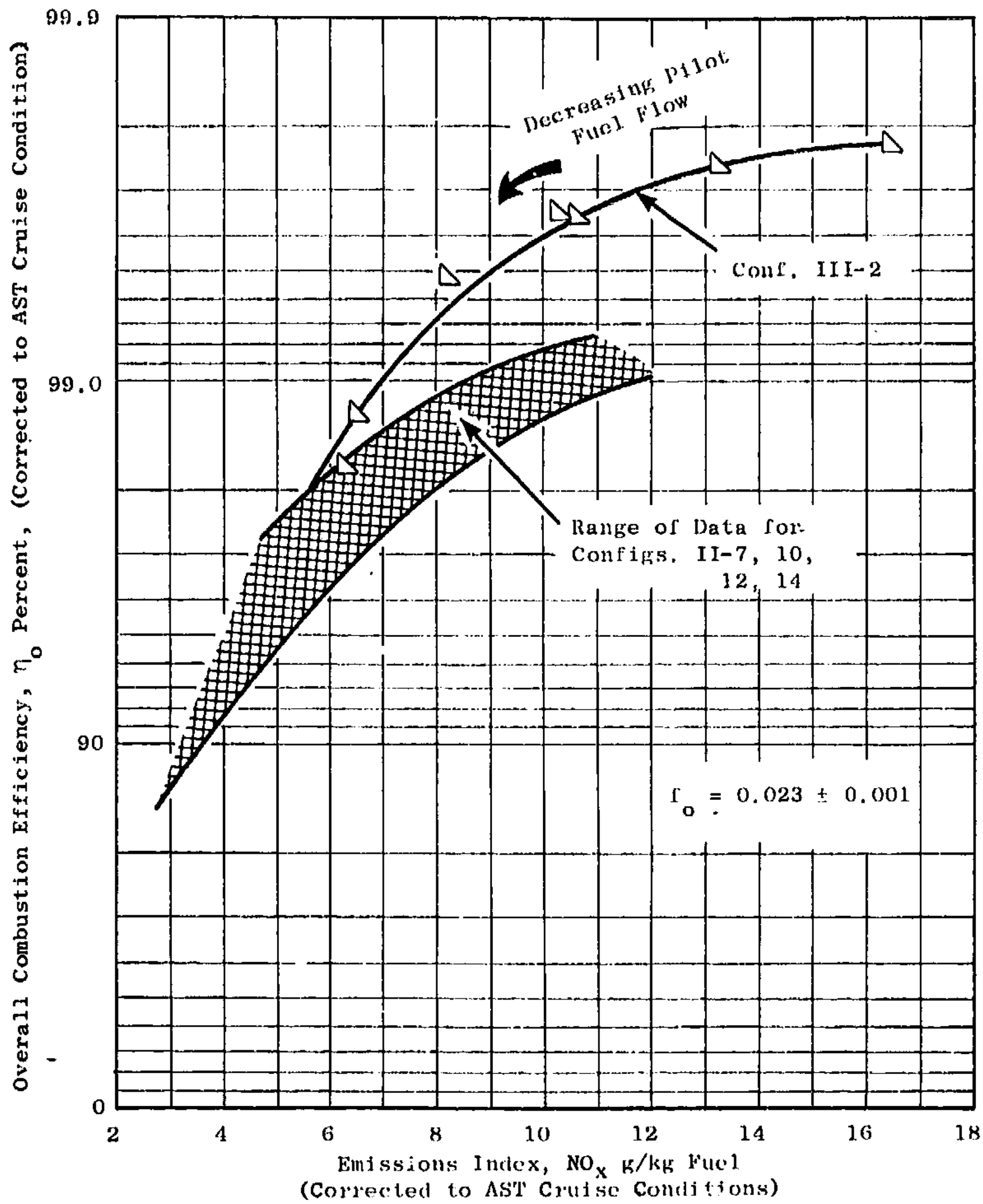


Figure 70. Relationship Between Overall Efficiency and NO_x Emission, AST Cruise Combustor Design No. 4.

TASK 3 - AST ENGINE CONCEPT DESIGNS

Numerous engine designs have been studied at General Electric for future AST application, including both augmented and nonaugmented turbojet and turbofan engines. For use in conducting these Task 3 design studies, a dual-rotor turbojet engine, which had been previously defined as a part of the General Electric "Advanced Supersonic Propulsion System Technology Study" (Contract NAS3-16950), was selected as the reference engine. The combustor operating conditions of this engine cycle closely approximated the nominal values specified by NASA for use in conducting these design studies. The key combustor operating parameters for this selected engine cycle are summarized in Table XLIV.

Based on the results of the Task 1 and 2 design and development efforts, two advanced combustor design approaches, the Double Annular and the Radial/Axial Staged Combustor concepts, were selected for the Task 3 design studies. A configuration of each kind, sized to fit within the selected dual-rotor turbojet engine combustor flowpath, was defined. The combustors were aerodynamically sized for sea level static takeoff engine operating conditions consistent with normal engine design practice. However, the inclusion of key geometrical features for controlling the fuel-air mixing process in the manner required to reduce NO_x emissions at the AST cruise conditions was the primary consideration in these design efforts.

Radial/Axial Staged Combustor Design Concept

The previously designed and tested Radial/Axial Staged Combustors of this program were design-constrained by the existing envelope of the CF6-50 engine. Thus, no changes to the existing engine diffuser design were made. However, for the AST engine design applications, the diffuser and combustor were treated as an integral design problem. Accordingly, a more optimum diffuser/combustor combination was designed to fit within the combustor flowpath boundaries.

The diffuser/combustor flowpath layout for the Radial/Axial Staged Combustor installed in the AST dual-rotor turbojet engine configuration is presented in Figure 71. This integrated design concept results in a short length combustion system with very low diffuser pressure losses. This feature provides the potential advantage of converting the pressure gained for additional fuel-air mixing which may be required during combustor development to achieve the low pollutant emission and performance goals.

The diffuser design consists of two separate parallel diffuser systems. Immediately downstream of the compressor exit station, the flow is divided into two streams; the large main stage stream and the smaller pilot stage stream. The inner diffuser flowpath and pilot stage combustor dome configurations are similar to the CF6-50 engine step diffuser and combustor dome designs. The inner passage prediffuser area ratio is 2.0 and the passage length-to-inlet height ratio is 6.6 which places this design below the curve of no appreciable stall on the Stanford diffuser correlations.

C.3

Table XLIV. Summary of AST Engine Cycle Conditions.

Engine Selected for Combustor Concept Study:
Dual-Rotor Dry Turbojet (GE21/J3 Study A2(P1); Case 2)

Flight Mode Cycle Parameter	Supersonic Cruise	SLS Takeoff
Altitude	18,288 m	0 m
Mach Number	2.2	0
Thrust	72,533 N	276,417 N
SFC	1.29	0.884
W_2	157.8 kg/s	358.8 kg/s
P_{AMB}	.07 atm	1.0 atm
T_{AMB}	294° K	288° K
P_3	6.6 atm	16.6 atm
T_3	846° K	710° K
T_4	1644.9° K	1535.3° K
W_3	119.7 kg/s	311.6 kg/s
W_C	106.1 kg/s	284.4 kg/s
f_o	0.024	0.024

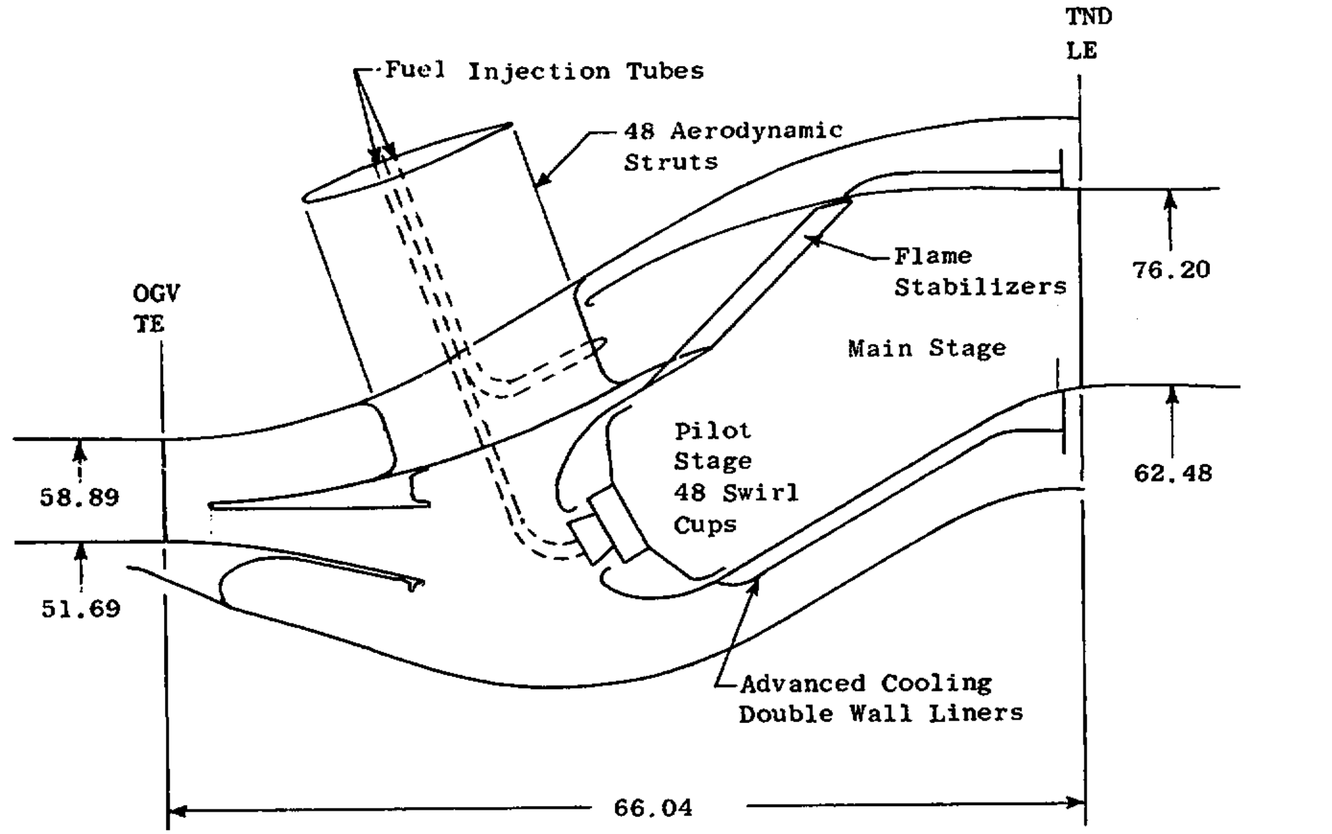


Figure 71. Diffuser-Combustor Flowpath Layout, Radial/Axial Staged Combustor Concept Installed in the Dual-Rotor Turbojet.

The outer passage curves outward into the premixing duct of the main (or second) stage. An area ratio of 2.0 in this passage reduces the flow velocity to 91 m/s at the plane of fuel injection. The velocity level was selected to prevent flashback or carbon formation without causing excessive pressure losses. This diffuser design also falls below the curve of no appreciable stall on the Stanford diffuser correlations. The fuel injector tubes were designed into 48 large aspect ratio hollow radial struts which pass through the outer passage near the downstream end of the outer diffuser. These struts, which enclose both the pilot stage and second stage fuel tubes, have a maximum thickness of 9.2 percent of the chord length and have a total passage blockage ratio of 18.4 percent.

The outer diffuser flow passage was designed to have very low pressure losses, since the wall contours are continuous with no dumping losses and the drag losses are minimized. This flow is accelerated across the main stage flame stabilizers into the combustor with the absolute velocity vector almost straight downstream.

More rapid mixing of the pilot stage and main stage flow streams would be expected with appropriately designed flow turning vanes incorporated into the flame stabilizer design. The turning vanes are not included in the conceptual design presented since the extent of interstage mixing must first be determined experimentally for the basic design. Accordingly, the addition of turning vanes, if required, would be considered a development refinement.

The key design parameters of this combustor are summarized in Table XLV. The selection of design velocities is important for this concept. The conventional reference velocity term is included in the table; however, for a staged burner concept the pilot dome velocity and the main stage duct velocity are more critical design velocity terms. Low pilot stage dome velocities have been employed to ensure high pilot stage efficiencies over the entire engine operating cycle. The main stage flow velocities were selected consistent with current afterburner design practice. Accordingly, achievement of high performance in the main stage is critically dependent on the pilot stage operating characteristics.

The procedure used for predicting the NO_x emissions index for this Radial/Axial Staged Combustor was based on the data correlations for both the pilot stage and main stage burners obtained from previous testing in this program. The calculated NO_x emissions levels of this design are presented in Figure 72. The NO_x levels are shown as a trade off with overall combustion efficiency. As is shown, the target NO_x levels are predicted, but not with the target efficiency level of 99.8 percent. However, the attainment of the target NO_x level with a 99.8 percent efficiency is considered to be attainable with a Radial/Axial Staged Combustor concept of this kind with further improvements in fuel-air mixing, relative to those of the configurations previously tested.

Table XLV. AST Engine Radial/Axial Staged Combustor Concept, Combustor Design Parameters.

Geometric	
Mean Radius at Compressor OGV, cm	53.98
Annulus Height at Compressor OGV, cm	7.29
Mean Radius at Turbine Nozzle Diaphragm, cm	69.34
Annulus Height at Turbine Nozzle Diaphragm, cm	13.72
Overall Combustion System Length, cm	66.0
Combustor Length, cm	38.1
Ratio of Combustor Length to Dome Height, (Pilot)	2.73
Ratio of Combustor Length to Fuel Injector Spacing, (Pilot)	5.56 (1)
Velocities	
Reference Velocity @ SLS, m/s	37.8
Reference Velocity @ Cruise, m/s	43.3
Pilot Dome Velocity @ SLS, m/s	9.4
Main Stage Duct Velocity @ SLS (at Plane of Fuel Injector), m/s	86.0
Other Performance Parameters	
Space Rate @ SLS (J/hr atm m^3)	2.9 x 1011
Fuel Loading Parameter (Fuel Flow per Cup per atm - Pilot, kg/hr/cup/atm)	6.49 (2)

(1) 48 injectors

(2) with 22 percent of the fuel in the pilot stage

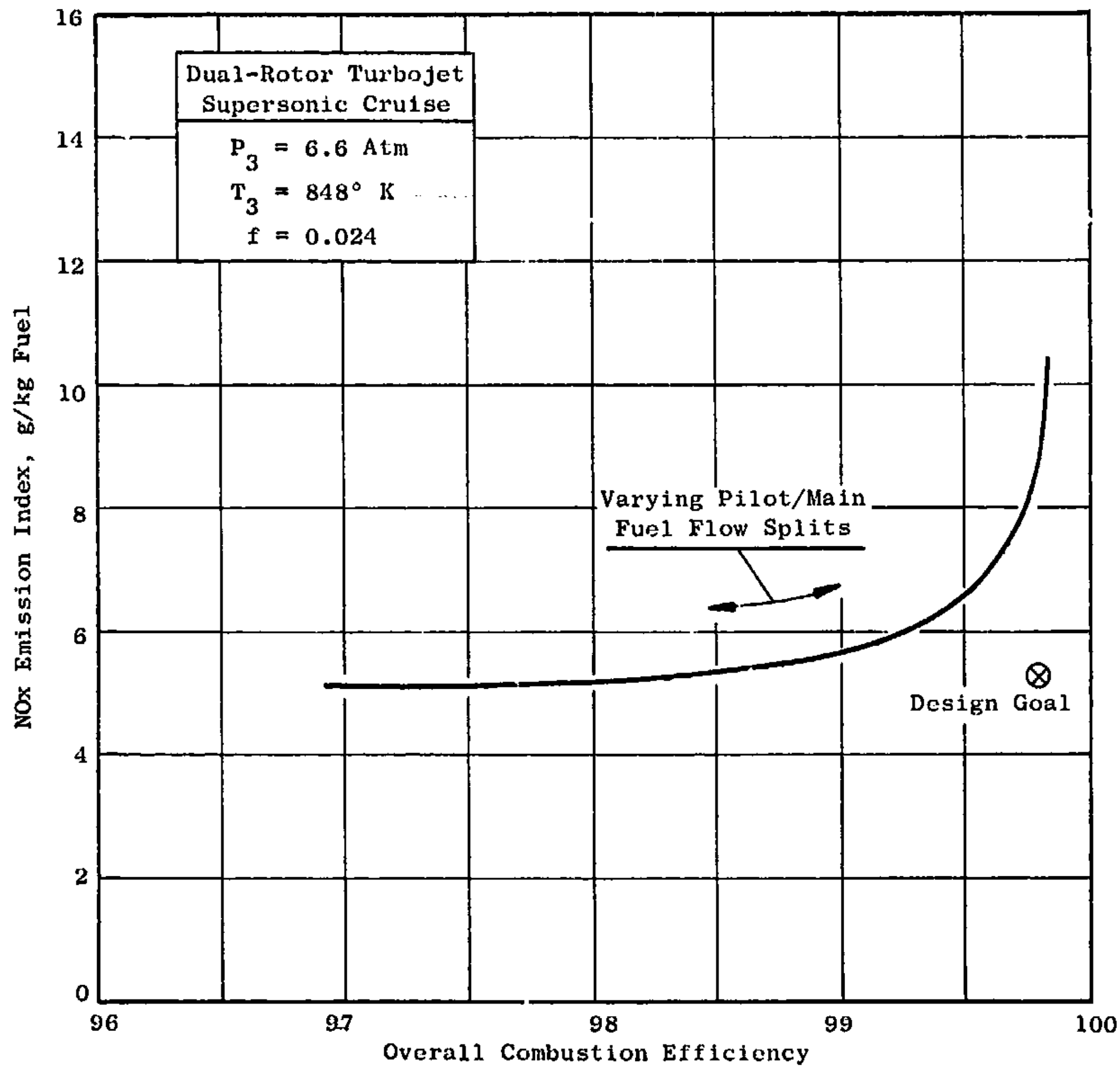


Figure 72. Estimated NO_x Emission Levels, Radial/Axial Staged Combustor, AST Engine Concept Design.

Double Annular Combustor Design Concept

The key design parameters of this combustor are summarized in Table XLVI. The outer annulus was designed with a low dome velocity to ensure high combustion efficiency and, thus, low CO and HC emissions at idle power operation. The combustor was designed to react approximately 87 percent of the total fuel injected into the combustor in the inner annulus during high power operation. Therefore, the NO_x emissions levels of this combustor design would be controlled by the design features of the inner annulus.

The diffuser design selected for this combustor is a short length step diffuser configuration with a central annular splitter vane. The splitter vane divides the flow into two passages with the outer passage flow directed to the outer annulus combustor dome and the inner passage flow directed to the inner annulus combustor dome. With this configuration, each combustor dome recovers a large proportion of the prediffuser exit velocity head. A flowpath design layout for this Double Annular Combustor configuration installed in the AST dual-rotor turbojet engine is presented in Figure 73.

For a given prediffuser passage length-to-inlet height ratio, which is the basis of the Stanford diffuser correlations, the diffuser splitter vane shown reduces the length of the prediffuser. The area ratio of each passage was set at 2.0, and the passage length-to-inlet height was selected to place each passage below the curve of no appreciable stall on the Stanford diffuser correlations.

The estimated NO_x emissions levels and combustion efficiency levels of this Double Annular Combustor concept were based on performance measurements obtained with the Double Annular Combustor configurations previously tested in this program. The Double Annular Combustor configurations consistently produced high values of combustion efficiency. The efficiency remained high for either annulus operated separately or combined. Furthermore, significant reductions in NO_x emissions were achieved when dilution airflow was moved upstream in the inner annulus. It was concluded from those test results that reduced residence times in the inner annulus is a key parameter for reducing NO_x emission levels. Accordingly, this Double Annular Combustor was designed with a moderately high inner annulus dome velocity. Its estimated NO_x emission levels were specifically calculated by using the emissions level data obtained at the AST cruise condition with Configuration II-13. The estimated NO_x level at the selected AST cruise design point is 6.5 g/kg fuel. However, if the inner annulus liner dilution air entry station can be successfully moved further upstream, the estimated NO_x emissions achievable would be lowered to 5.0 g/kg fuel. The final relationship between dilution air entry design, combustion efficiencyand NO_x emissions level would of necessity be defined during the development testing of the combustor. However, it is reasonable to expect that this combustor concept potentially could be developed with NO_x emissions levels approaching 5.0 g/kg fuel at the AST cruise operating conditions, as defined in Table XLIV.

Table XLVI. AST Engine Double Annular Combustor Concept, Combustor Design Parameters.

Geometric

Mean Radius at Compressor OGV, cm	53.98
Annulus Height at Compressor OGV, cm	7.29
Mean Radius at Turbine Nozzle Diaphragm, cm	69.34
Annulus Height at Turbine Nozzle Diaphragm, cm	13.72
Overall Combustion System Length, cm	68.33
Combustor Length, cm	35.56
Centerbody Length, cm	10.67
Ratio of Combustion System Length to Dome Height	
Outer	2.73 (H=14.0 cm)
Inner	2.38 (H=16.0 cm)
Ratio of Combustor Length to Fuel Injector Spacing(1)	
Outer	5.6
Inner	5.35

Velocities

Reference Velocity @ SLS, m/s	27.4
Reference Velocity @ Cruise, m/s	31.4
Pilot Dome Velocity @ SLS, m/s	10.4(2)
Main Stage Dome Velocity @ SLS, m/s	33.8(2)

Other Performance Parameters

Space Rate @ SLS (J/hr atm m^3)	1.9 x 1011
Fuel Loading Parameter(3) (Fuel Flow per Cup per atm kg/hr/cup/atm)	
Outer Annulus	14.0
Inner Annulus	95.8

(1) 60 injectors

(2) Based on swirler plus dome cooling flow

(3) With 22 percent of the fuel in the outer annulus and 60 injectors in each annulus

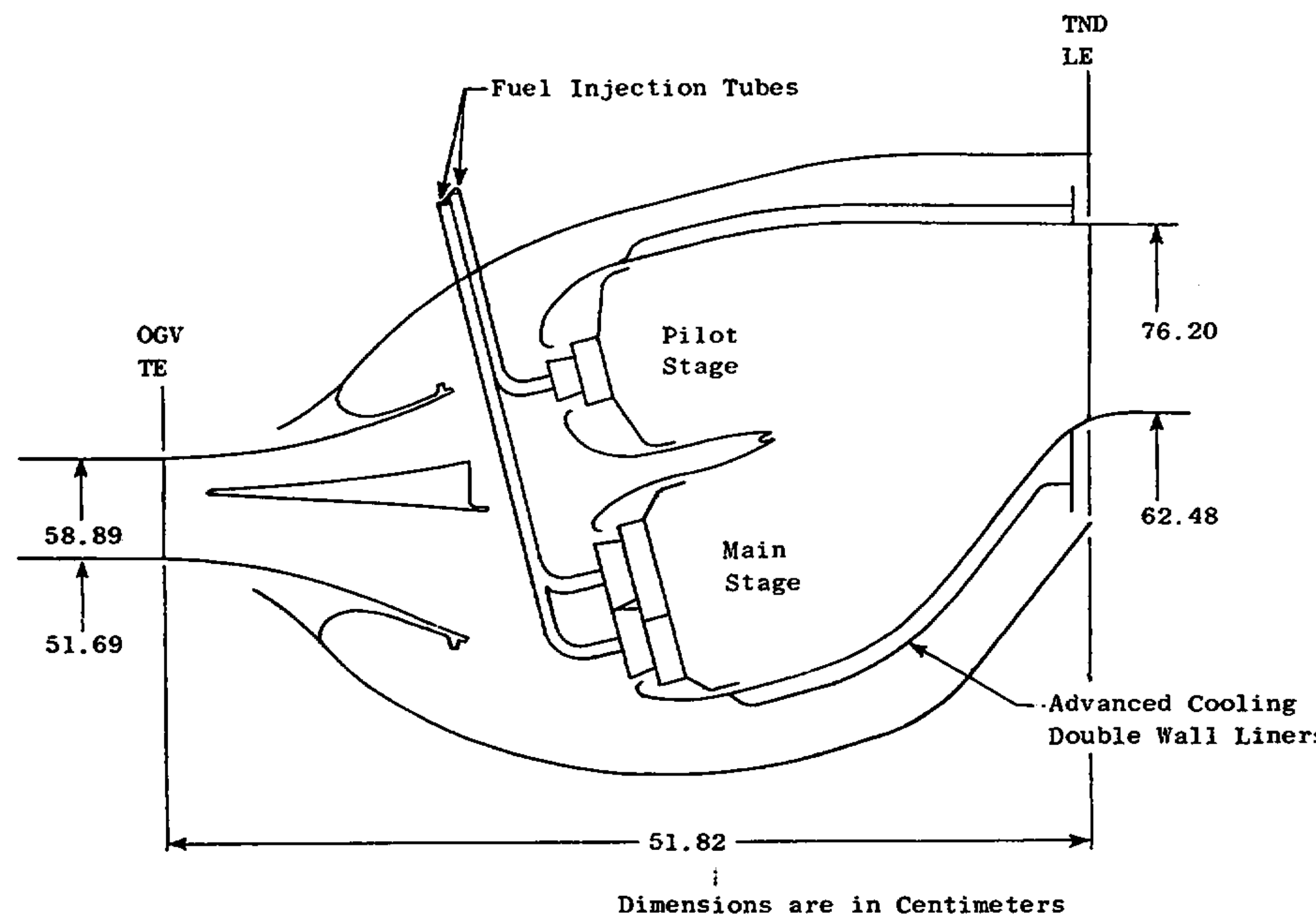


Figure 73. Diffuser-Combustor Flow Path Layout, Double Annular Combustor Concept Installed in the Dual-Rotor Turbojet Engine.

APPENDIX A

DESCRIPTION OF CF6-50 COMBUSTOR

This appendix contains additional information concerning the design of the current production CF6-50 engine combustor and the designs of the fuel control and supply systems used with this combustor. This material is intended as a supplement to the related descriptive material presented in Chapter II.

The current production CF6-50 combustor is an annular design and contains 30 fuel nozzles. An axial swirler cup is used with each fuel nozzle. A cross-sectional drawing of this combustor, as installed in the engine, is presented in Figure 3 and a photograph is presented in Figure 4. The combustor consists of four major sections which are riveted together into one unit and spot-welded to prevent rivet loss: the cowl assembly, the dome assembly and the inner and outer liner skirts. The combustor is mounted at the cowl assembly by 30 equally-spaced radial mounting pins. Mounting the combustor at the cowl assembly provides accurate control of diffuser dimensions and eliminates changes in the diffuser flow pattern due to axial thermal growth. The inner and outer skirts each consist of a series of circumferentially stacked rings which are joined by resistance welded and brazed joints. The liners are film cooled by air which enters each ring through closely spaced circumferential holes. Three axial planes of dilution holes on the outer skirt and five planes on the inner skirt are employed to promote additional mixing and to lower the exit temperatures at the turbine inlet.

At the engine compressor discharge plane, the Mach number is 0.27 (with a discharge coefficient of 0.90). This high velocity flow is diffused through an area ratio of 2.0 in a relatively long, area-rule prediffuser. Ten large frame struts pass through the diffuser near the aft end of the prediffuser passage. The prediffuser walls are contoured to area-rule the passage around these airfoil shaped strut sections. This area ruling minimizes strut wakes and strut-wall interference effects. The passage area is then held constant for a distance of about 5.1 cm downstream of the strut trailing edges to mix out any remaining strut wakes. This design approach has proved to be very successful. Test results show that the strut wakes cannot be detected in the inner and outer passage airflows or in the temperature distributions at the combustor exit plane.

At the exit end of the prediffuser passage, the flow is dumped into the combustion chamber at a low Mach number and with low pressure losses. The flow is then divided into three streams. The inner and outer streams are accelerated smoothly around the combustor cowling contours into the inner and outer liner passages. The center stream enters the cowling and, in turn, flows into the combustor primary zone. The cowling opening is oversized to provide free stream diffusion of the dome flow, which increases the static pressure recovery ahead of the dome. This feature results in high pressure recoveries in this center stream and, therefore, in higher pressure drops and higher velocities through the swirl cups and other dome flow openings.

A schematic of the CF6-50 engine fuel system is shown in Figure 74. The main engine control is a hydromechanical unit which meters combustor fuel flow to maintain the desired engine speed selected by the throttle. The response of the control to power demand inputs is continuously biased by compressor inlet temperature, compressor discharge pressure, and core engine rotor speed. Metered fuel from the control flows through the fuel manifold into 30 fuel nozzles. The fuel nozzles are the dual-orifice type with an integral flow divider. A diagram of the fuel nozzle assembly is shown in Figure 75. The dual-orifice nozzle system provides primary and secondary flows for proper fuel atomization during all phases of engine operation. The 30 fuel nozzles are individually installed through pads in the compressor rear frame.

The fuel manifold is a single-tube unit which distributes the metered fuel to the 30 fuel nozzles. A schematic of the CF6-50 fuel manifold is shown in Figure 76. The assembly, including the 30 feeder tubes, is shrouded for protection against fire and high pressure leaks. It is divided into right and left halves, each of which supplies 15 feeder tubes. The manifold is supplied by a single tube which enters the core engine compartment from the fan accessory compartment through a sealed junction trap.

The inner and outer combustor liner shells join the dome structure at the forward end of the shells. These liner shells are film cooled with a "stacked ring" structure. The film cooling features of this design maintain the average peak metal temperatures in the various cooling rings at or below 1088° K. The outer shell has three bands of dilution holes and the inner shell has four bands of dilution holes. These holes are carefully sized and placed to provide the required turbine inlet temperature profile and the lowest possible pattern factor. The mechanical and structural features of these liners are designed to meet extended cyclic life requirements. The total life requirements of this design are as follows:

Operating Hours	18,000
Thermal Cycles*	30,000
Normal Maintenance & Repair Hours	6,000
Normal Maintenance & Repair Thermal Hours	12,000

* Two Thermal Cycles per Flight Cycle

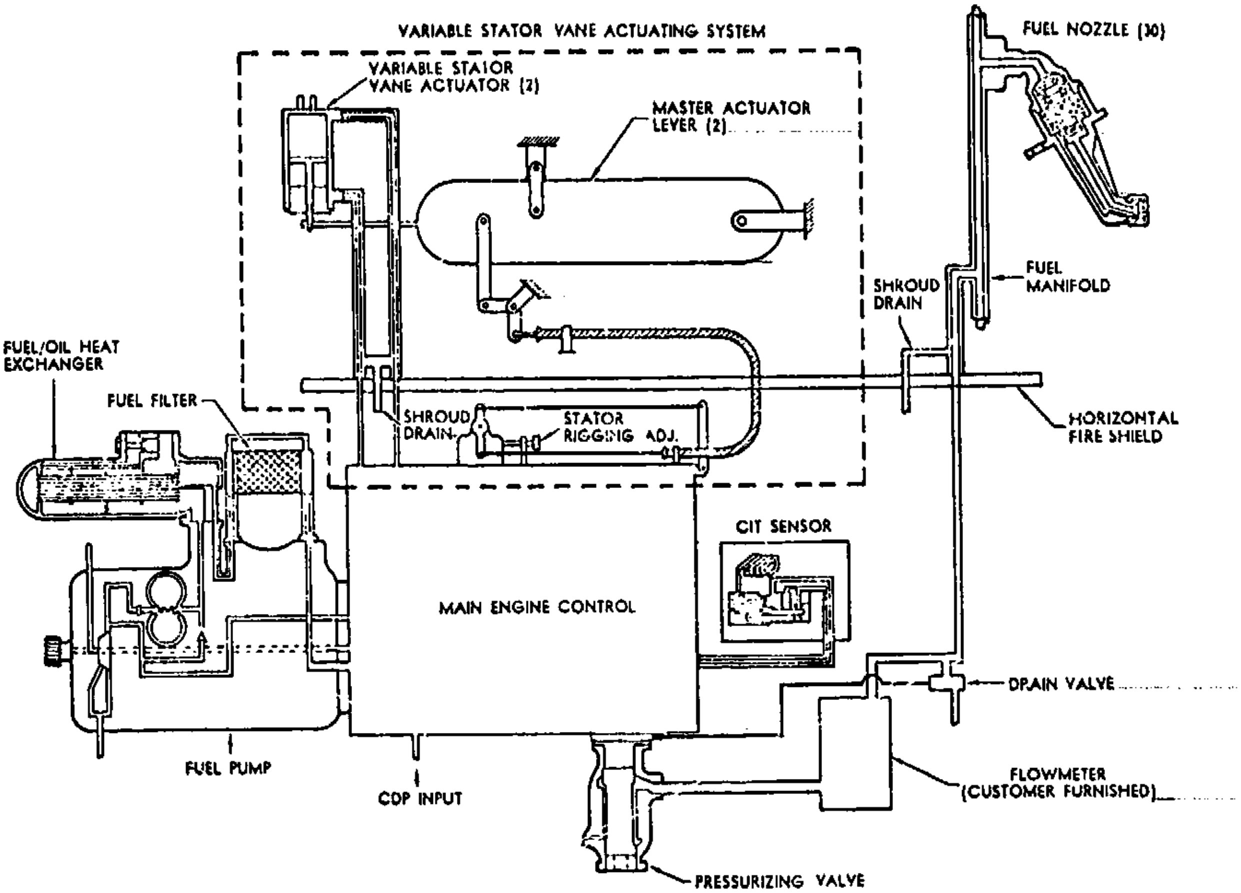


Figure 74. CF6-50 Engine Fuel System.

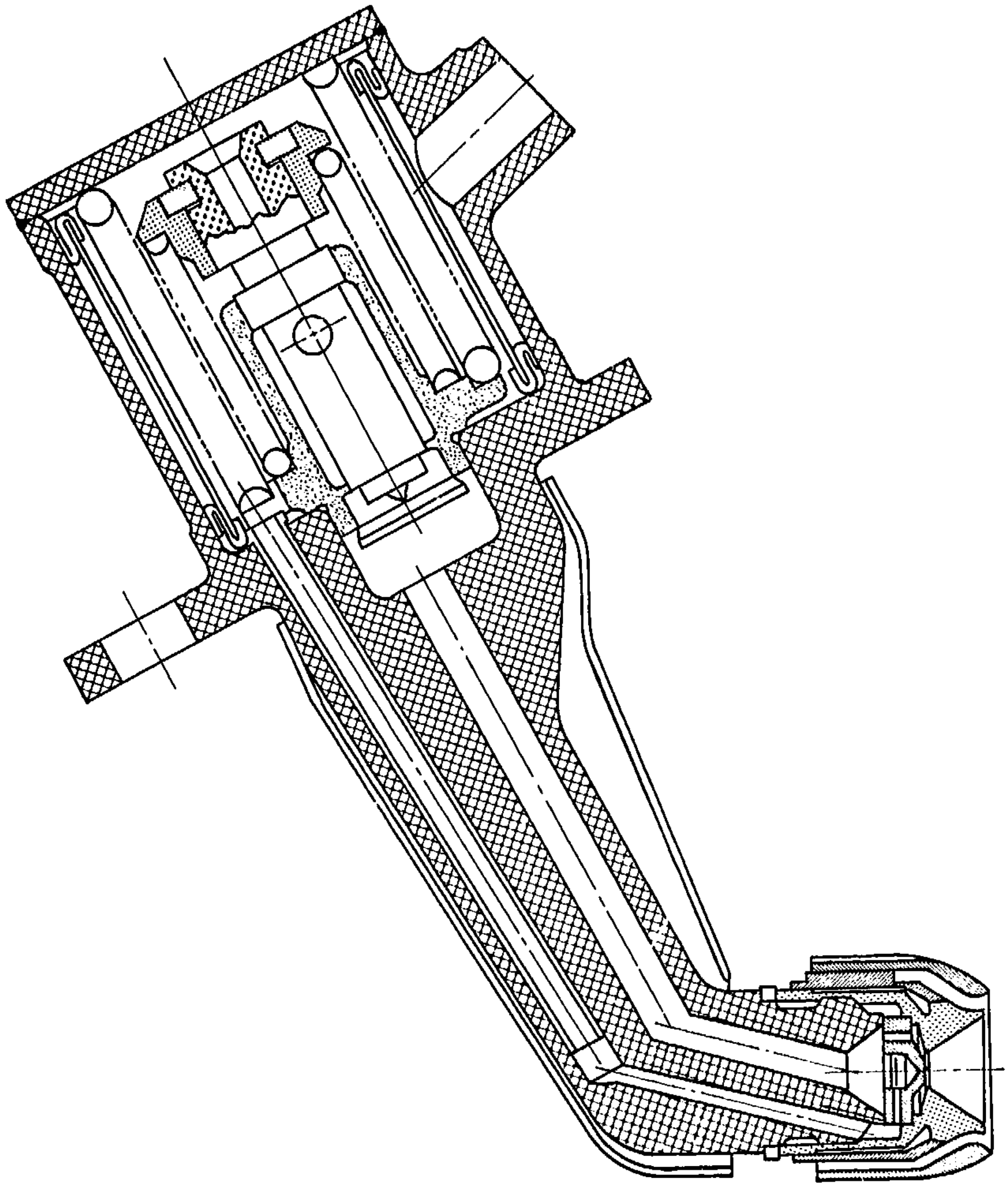


Figure 75. CF6 Fuel Nozzle Cross Section.

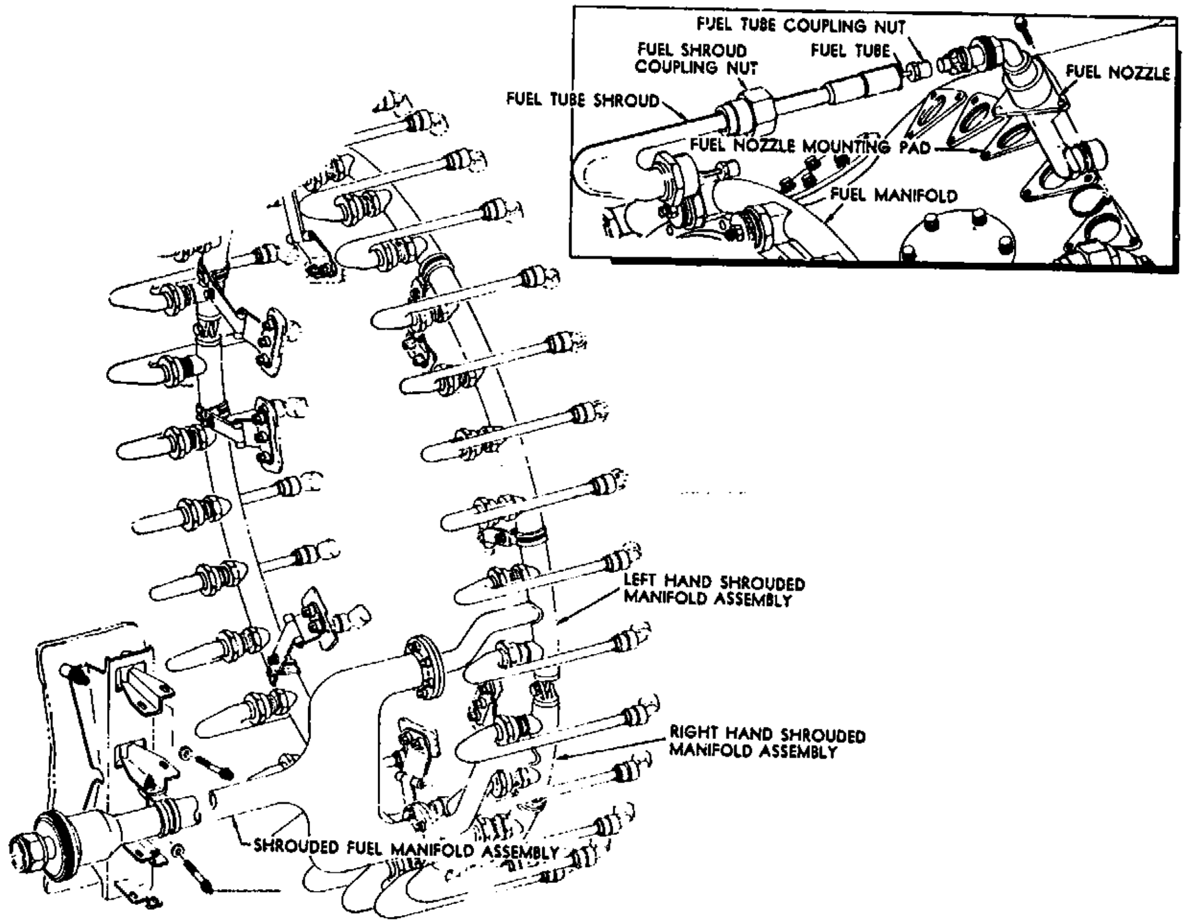


Figure 76. CF6-50 Engine Fuel Manifold Assembly.

APPENDIX B

POLLUTANT EMISSIONS SAMPLING/ANALYSIS SYSTEM AND ASSOCIATED TESTING PROCEDURES

This appendix contains additional information concerning the equipment and procedures used to measure the pollutant emissions characteristics of the various combustor test configurations. This information is intended as a supplement to the related descriptive material presented in Chapter II.

EXHAUST GAS ANALYSIS EQUIPMENT

The pollutant emissions data were obtained in this program with an on-line gas analysis system. With this system, exhaust gas sample streams were continuously processed and the CO_2, CO, HC, smoke, NO and NO_2 concentrations were continuously determined. A flow diagram of the system is shown in Figure 21. A photograph of the on-line gas analysis system installation used in the Phase I Program is shown in Figure 77. The five basic instruments for measuring the gaseous emissions concentrations in this on-line system are a flame ionization detector (FID) for measurements of the total HC concentrations, two nondispersive infrared (NDIR) analyzers for measurements of the CO and CO_2 concentrations and a heated chemiluminescence analyzer for measuring the NO and NO_2 concentrations.

A Beckman model 402 flame ionization detector is utilized in this system. This analyzer was designed specifically for determining the total HC concentrations in gas turbine engine exhaust gases. It consists of a heated inlet sample line, an ionization analyzer module, and an electrometer amplifier module.

The nondispersive infrared (NDIR) analyzers used in this system to measure CO and CO_2 concentrations are Beckman models 315B and 864, respectively. A water trap is installed upstream of the analyzers to provide dry samples for analysis.

The chemiluminescence analyzer used to measure NO and NO_2 concentrations is a Beckman model 951 instrument. The NO in the sample gas is measured directly with this instrument. The internal temperature of the analyzer flowpaths is controlled at about 328° K to prevent moisture condensation within the system. The measurement of the total NO_x concentration of the exhaust gas is accomplished by the use of a thermal converter. With this device, NO_2 in the gas sample is reduced to NO and oxygen as a result of heating the sample to a prescribed temperature for a given period of time. When the sample leaving the converter is passed through the NO analyzer, a reading is obtained that is equal to the NO_x concentration (the sum of the newly formed NO plus the NO present in the original stream).

None of the foregoing analyzers measures quantitatively without being calibrated. There is no electrical calibration signal that can be used to simulate an actual reading, such as millivolt simulation for temperature in the case of thermocouples. The standard General Electric analyzer calibration procedures were used throughout the program. These calibration procedures

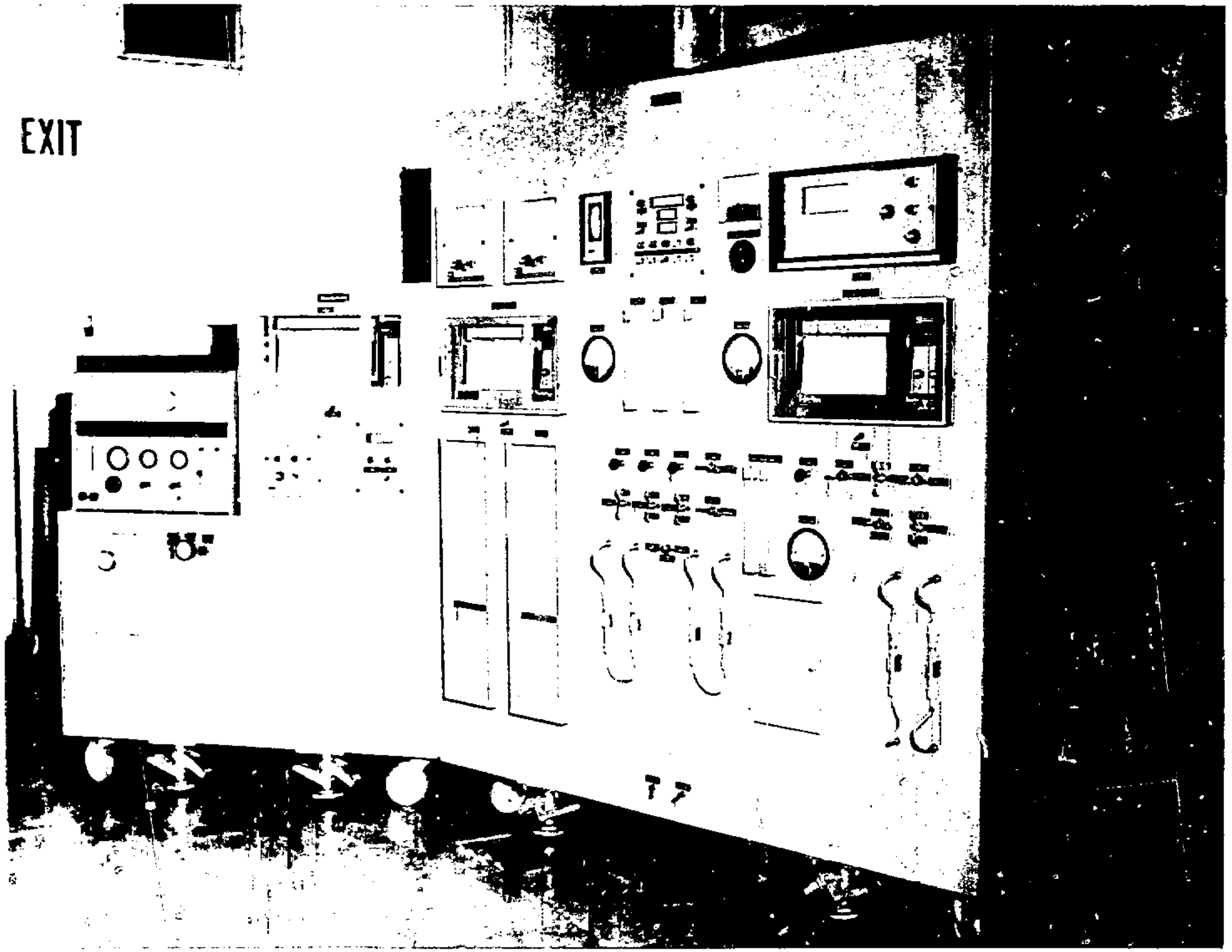


Figure 77. General Electric Emissions Measurement System.

involve the use of calibration gases having nominal concentrations of CO, NO, NO_2 and propane in nitrogen and oxygen mixtures which are obtained from an appropriate vendor. The vendor prepares the mixture of the gases by the use of partial pressures or gravimetrically and then analyzes the gas in the bottle. The precision of the calibration procedure is obtained by requiring the supplier to guarantee that all of the constituents in the bottle are within five percent of the nominal value specified and that the accuracy of the analyses meets the following criteria:

Constituent Concentration Range	Analysis Accuracy
10 - 15%	± 2% Relative
50 ppm - 10%	± 3% Relative
10 ppm - 50 ppm	± 5% Relative

In addition, helium, argon, and other impurities must be held to a minimum and be listed in the chemical analyses if over 10 ppm.

The zero on each NDIR instrument is set by using dry nitrogen, which has been checked for the absence of H_2, CO, CO_2, and NO. All of the NDIR dual cell instruments have three full-scale ranges per cell which makes a total of six scale ranges available. The CO_2 analyzer is a single-cell instrument having only three scale ranges available. Range 1 is the least sensitive, the second range can be set up to three times the first range, and the third range can be set up to nine times the first range. The zero of the FID analyzer was set by using ultrapure breathing air.

The CO, CO_2, HC and NO_x analyzers were electronically integrated with the test cell digital data acquisition system. At each test condition, this digital system automatically scanned the numerous combustor operating parameters being monitored and converted the amplified DC signals of each measurement to digital form. These data were recorded on a printed paper tape and simultaneously transmitted to an on-line computer. Thus, at each traverse position, the outputs of these on-line emissions analyzers were automatically recorded and transmitted to the computer along with the normal combustor operating data.

A new emissions data reduction program was developed for use in this Phase I Program and was incorporated into the existing CF6-50 combustor performance data reduction program. This new data reduction program provided on-line calculations of the exhaust emissions concentrations, the various emissions indices, gas sample combustion efficiency values and the gas sample fuel-air ratio value at each traverse position for any given test condition. The output from this data reduction program was transmitted back to the test cell teletype, and the reduced data were, thus, available shortly after the completion of a test point. With this automatic emissions data aquisition system, a normal 12-position manifolded traverse could be completed in about 15 minutes. Within another 10 to 15 minutes, the measured emissions levels and combustor performance data were available within the test cell. An overall schematic of the emissions data acquisition system is shown in Figure 78. The gaseous emissions sampling equipment used in this program was in general conformance with the SAE ARP 1256 guidelines, except for the use of a chemiluminescent NO_x analyzer.

Smoke emissions were measured in this program using the standard General Electric filter stain method. With this method, a measured volume of sample gas is drawn through a filter paper. The smoke particulates filtered out of the sample gas leave a black stain on the white paper. The "blackness" of the spot is measured on a reflection densitometer. The densitometer is calibrated against absolute reflectance standards. Readings are converted to a sample flow flux of 0.0016 kg of exhaust gas per square cm of filter paper before computing to provide a smoke emission value in terms of the SAE Smoke Number. The entire General Electric smoke measurement system is packaged into a portable console that also contains a pump, control valves, and flow metering devices. One of the smoke measurement consoles is shown in Figure 79 and a flow diagram is shown in Figure 80. This General Electric smoke measurement technique is in conformance with SAE ARP 1179.

EXHAUST GAS SAMPLING EQUIPMENT

The gas sample rakes used in this program contained multielement, quick-quenching probes which utilized both water cooling of the probe body and steam heating of the sample lines within the probe. Each rake contained five individual probes, or elements, and each element was led out of the rake separately. There was no common manifolding of these sample lines within the sampling rake. The tips of each of these sampling elements, shown in Figure 81, were designed to quench the chemical reactions of the extracted gas sample as soon as the sample entered the rake. This quenching, or freezing, of the reactions was necessary to eliminate the possibility of further reactions within the sample lines. Water cooling of the rake body was required to maintain the mechanical integrity of the rakes in the high temperature, high pressure environment in which they operated. Steam heating of the sample lines within the rake, on the other hand, was needed to maintain these sample lines at a temperature high enough to prevent condensation of hydrocarbon compounds and water vapor within the sample lines. A schematic of the steam-heated/water-cooled feature of these gas sample rakes is shown in Figure 19.

With 5 sampling rakes with 5 elements each, a total of 25 gas sampling locations existed within the combustor exit plane at each angular position of the traverse assembly. Of the 25 available probe elements, however, only 15 were used for gaseous emissions sampling, with the remaining 10 elements used for combustor exit pressure measurements and smoke emission sampling. A selector valve in each of these latter ten sample lines allowed either smoke or exit pressure to be read at any selected angular position. The individual rake elements selected for the gas sampling measurements are shown in Figure 20.

During each survey of the combustor exit plane, the combustor exit pressure was determined at only the first rake position, and smoke was measured

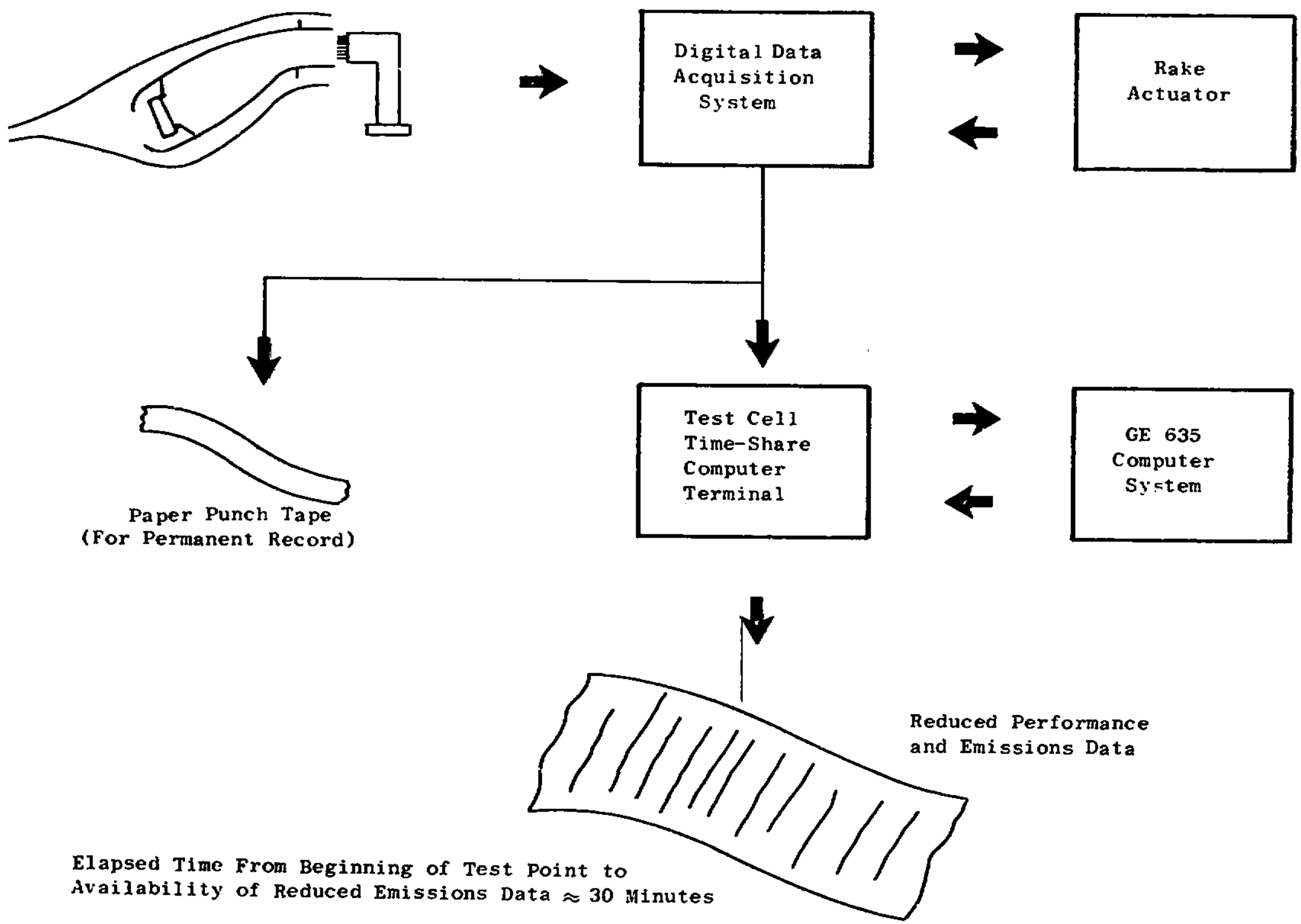


Figure 78. Data Acquisition and Processing Procedure Flow Diagram.

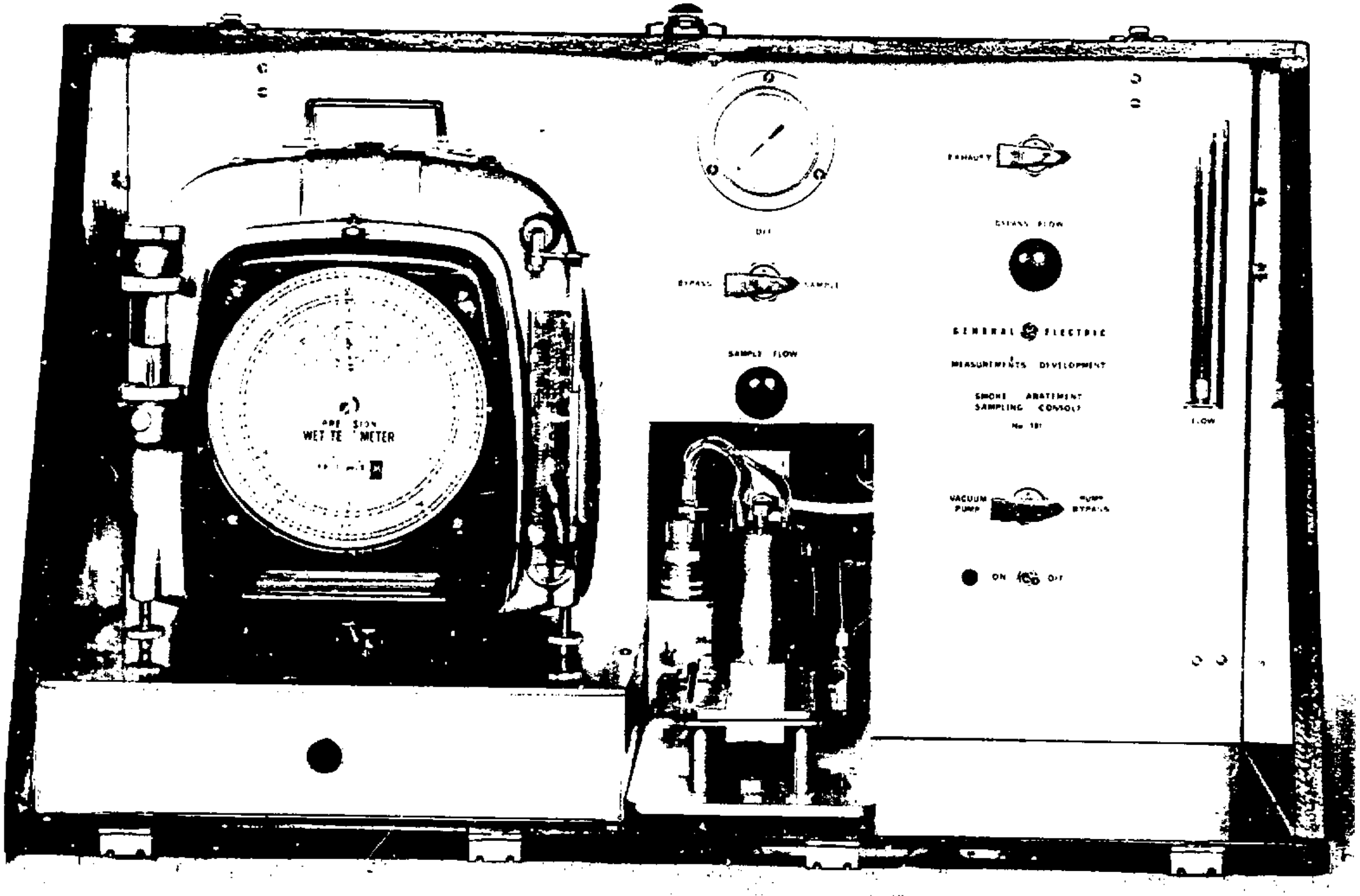


Figure 79. General Electric Smoke Measurement Console.

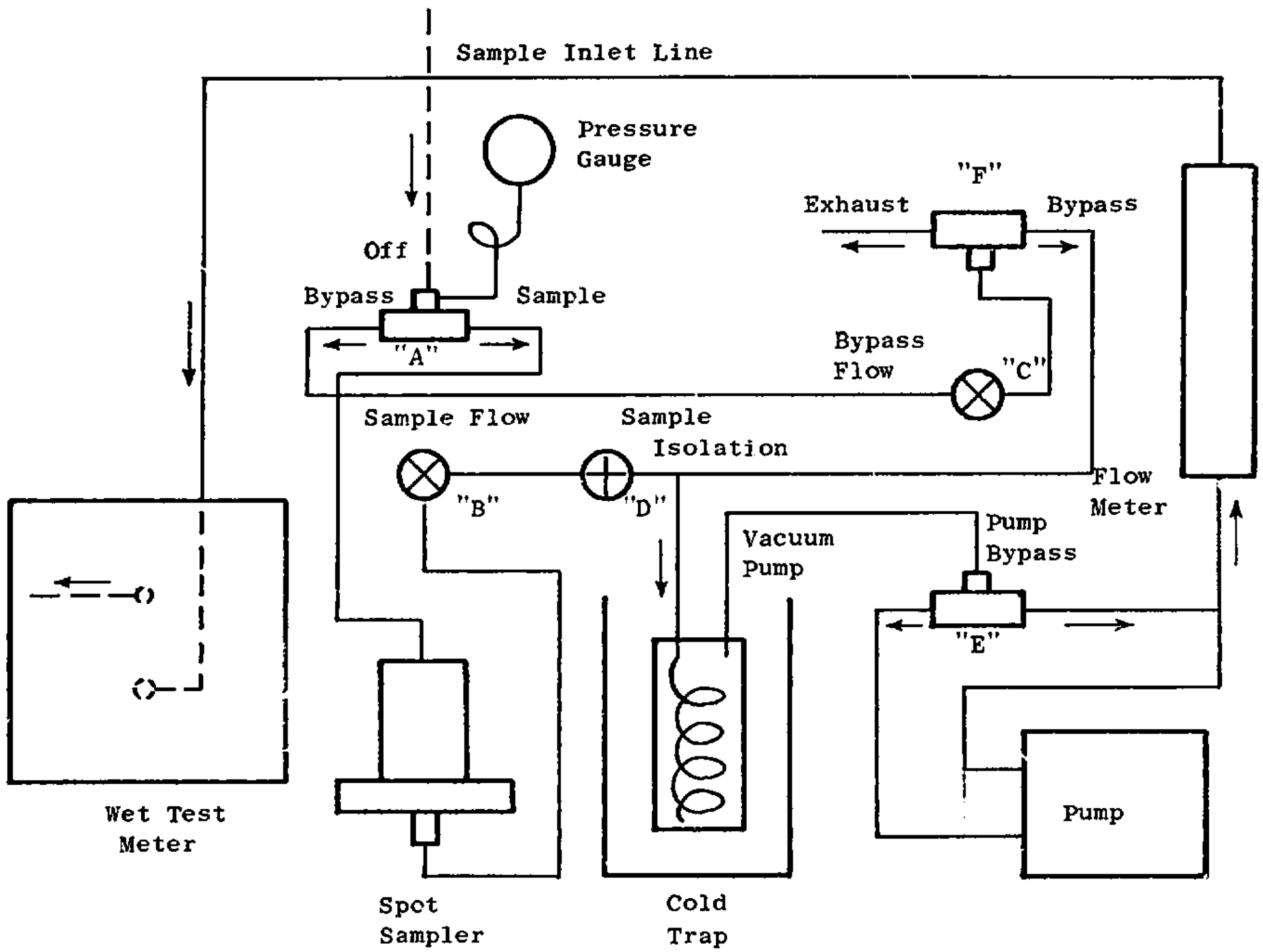


Figure 80. General Electric Smoke Measurement System Flow Diagram.

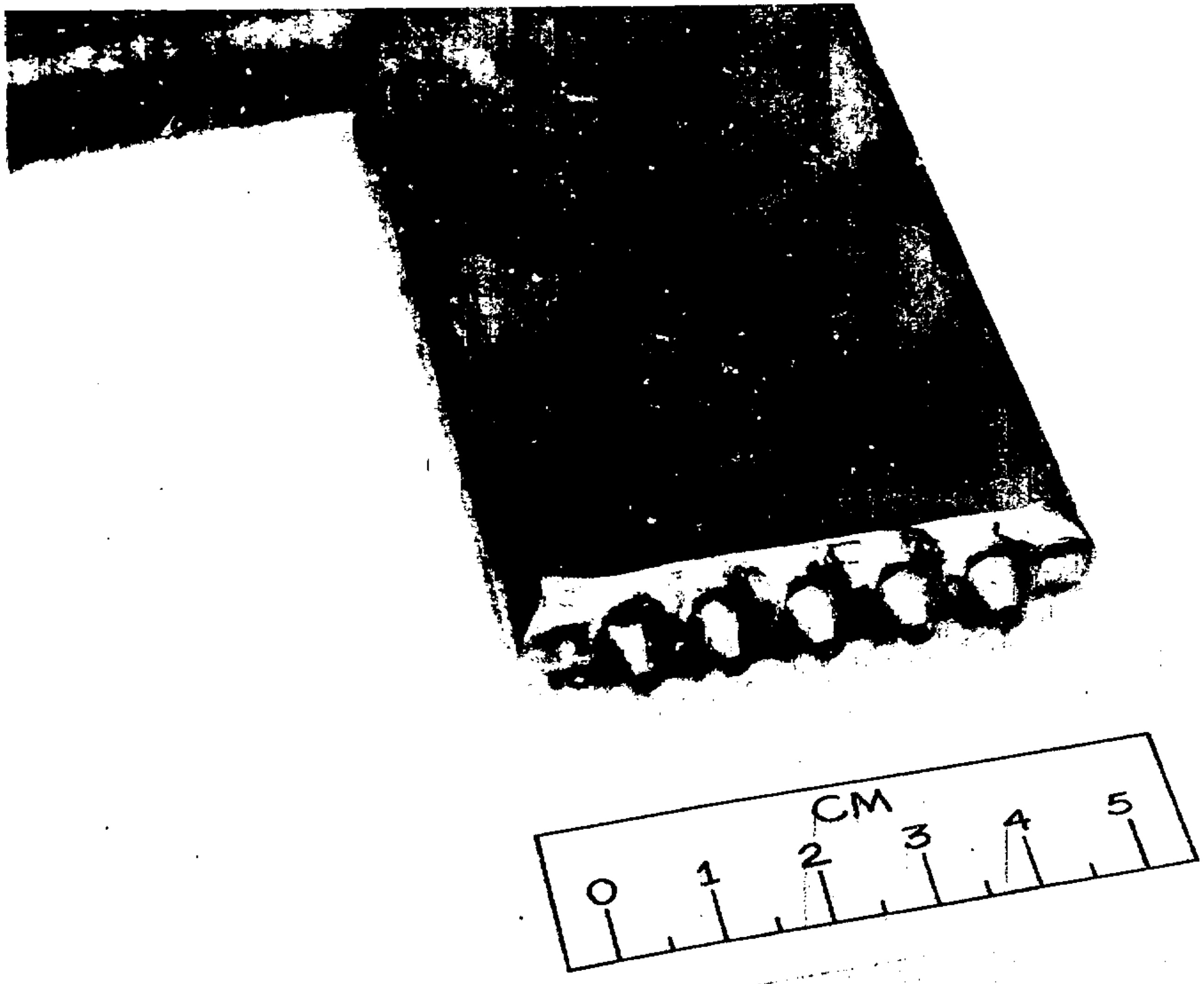


Figure 81. Gas Sample Rake Quick-Quenching Probe Tips.

during the remainder of the survey. Gaseous emissions were measured at each rake position of the survey. As a result, exit pressure, smoke, and gaseous emissions data were obtained from numerous locations with the combustor exit plane, as shown in Figures 82, 83 and 84. In this manner, a very detailed and accurate measure of the emissions levels was obtained at each test condition.

After leaving the rakes, the individual gas sample lines were led to a series of selector valves and then to the emissions analyzers located within to the test cell. These sample lines were grouped into bundles of five lines (one bundle for each gas sample rake), and each bundle was steam-traced from the probes to the analyzers, as shown in Figure 85, to maintain the sample line temperatures near 422° K. Each sample line was constructed of 0.64-cm diameter, 0.089-cm wall stainless steel tubing. Two thermocouples were installed in each tube bundle, as shown in Figure 85, to monitor the temperature of the steam used for heating the sample lines. In addition, one sample line from each bundle was instrumented to provide a measurement of the pressure within the sample line. This pressure measurement provided assurance that sufficient flow was being drawn through the sample lines to quench the reactions at the probe tips.

In the test cell control room, the 25 individual sample lines were connected to a group of 3-way selector valves, as shown in Figure 86. At this panel, the ten smoke/pressure elements were separated (by the valving arrangement) from the gaseous emissions elements. By manipulation of the appropriate valves, any individual element or any desired combination of elements could be selected for the gaseous emissions measurements. The normal procedure used was to manifold all 15 gas sample elements together at this control valve panel, thereby supplying 1 average gas sample to the emissions analyzers at each traverse position. This manifolding procedure was a very fast method of determining the average level of the various emissions at the circumferential traverse position and alleviated the need to analyze each sample individually at every traverse position of a given test condition.

EXHAUST GAS SAMPLING PROCEDURES

Because of the wide variations in fuel staging techniques which were investigated as a part of this program, various exhaust gas sample manifolding techniques were employed. The normal procedure was to manifold together only gas samples which had nearly equal sample densities, in order to provide properly weighted results. During normal fueling points (combustor fueled uniformly) all the various gas samples could be manifolded together. On points where only one annulus, or stage, was fueled, only samples from the same radial immersion were combined, due to the large radial gradients which could exist. On points where only a sector of the combustor was fueled, only samples taken from the same circumferential position were manifolded together because of the strong circumferential variations.

During these tests, one of the following sampling modes was used on every test point for determining the gaseous pollutant emissions concentrations:

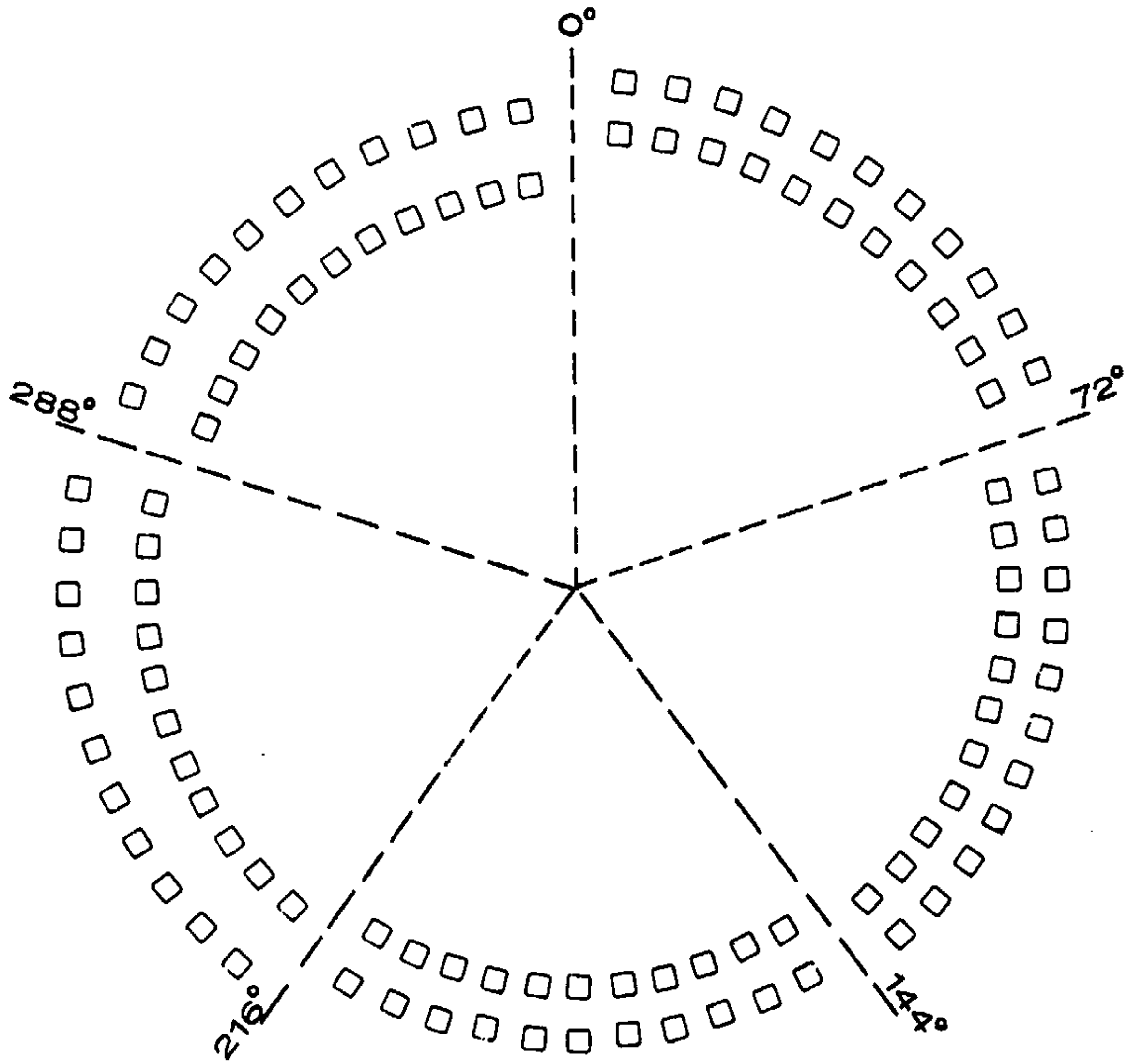


Figure 82. Smoke Sample Measurement Locations, Combustor Exit Plane, Aft Looking Forward.

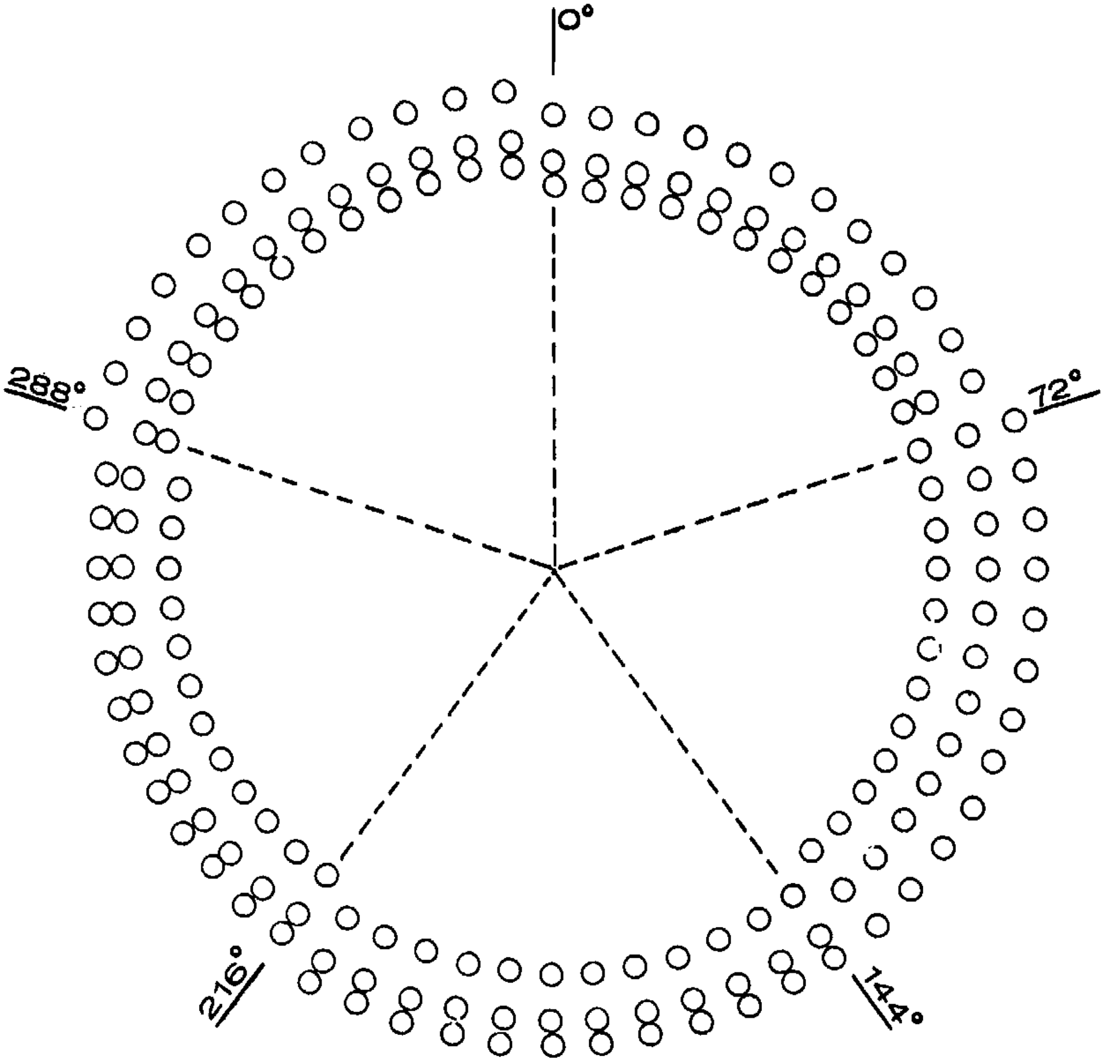


Figure 83. Gaseous Emissions Sample Measurement Locations, Combustor Exit Plane, Aft Looking Forward.

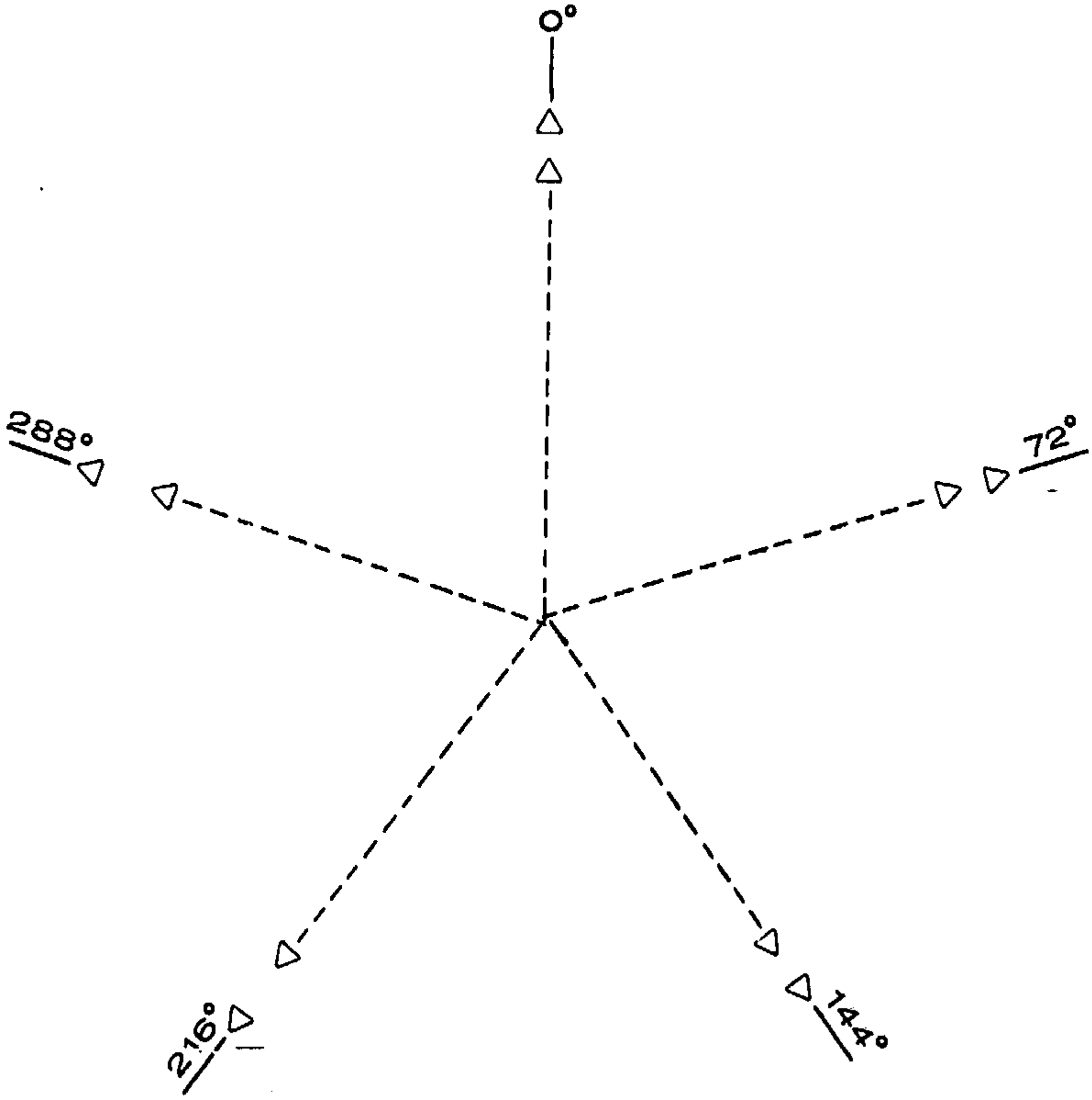


Figure 84. Pressure Measurement Locations, Combustor Exit Plane, Aft Looking Forward.

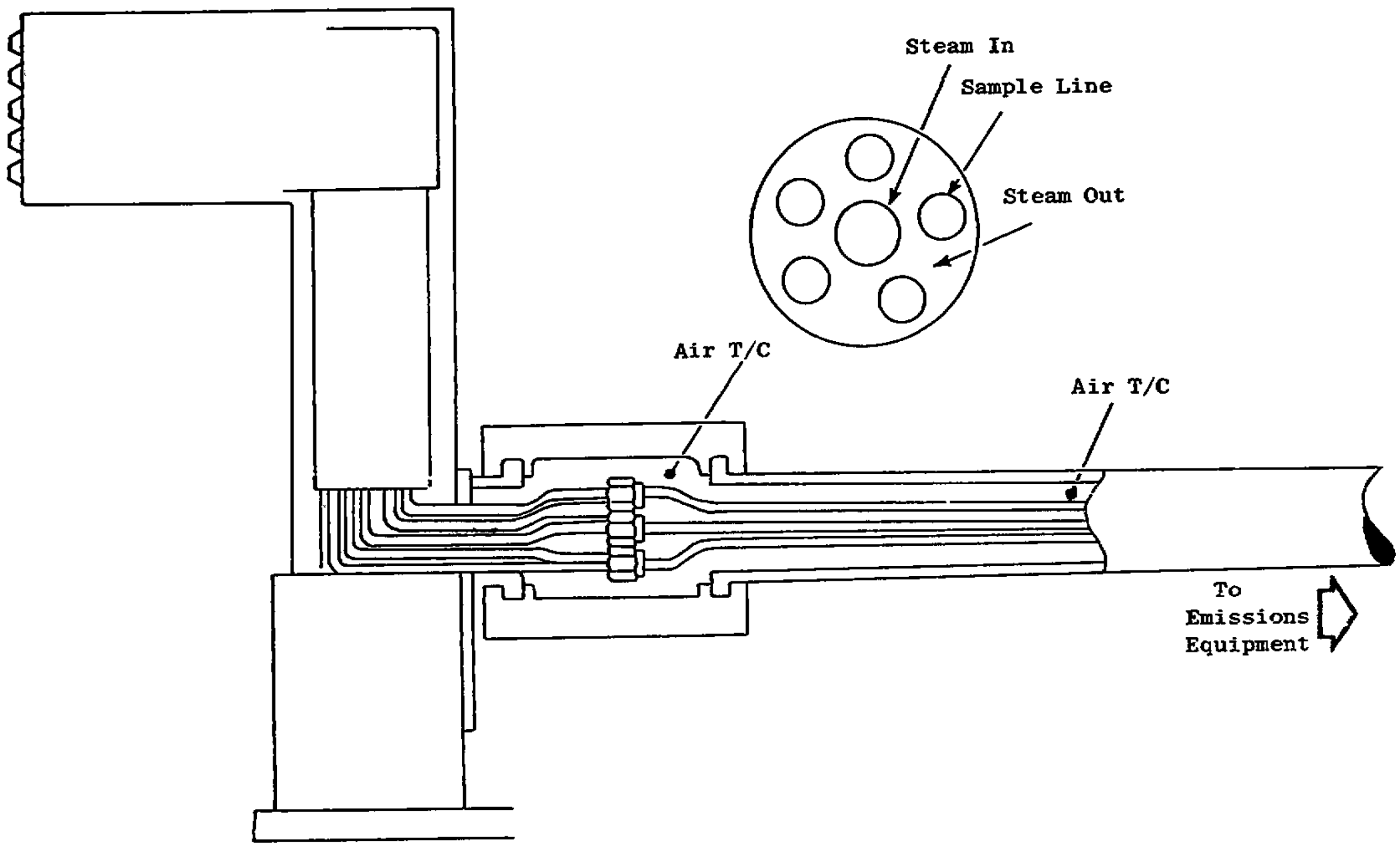


Figure 85. Steam-Heated Gas Sample Transfer Line.

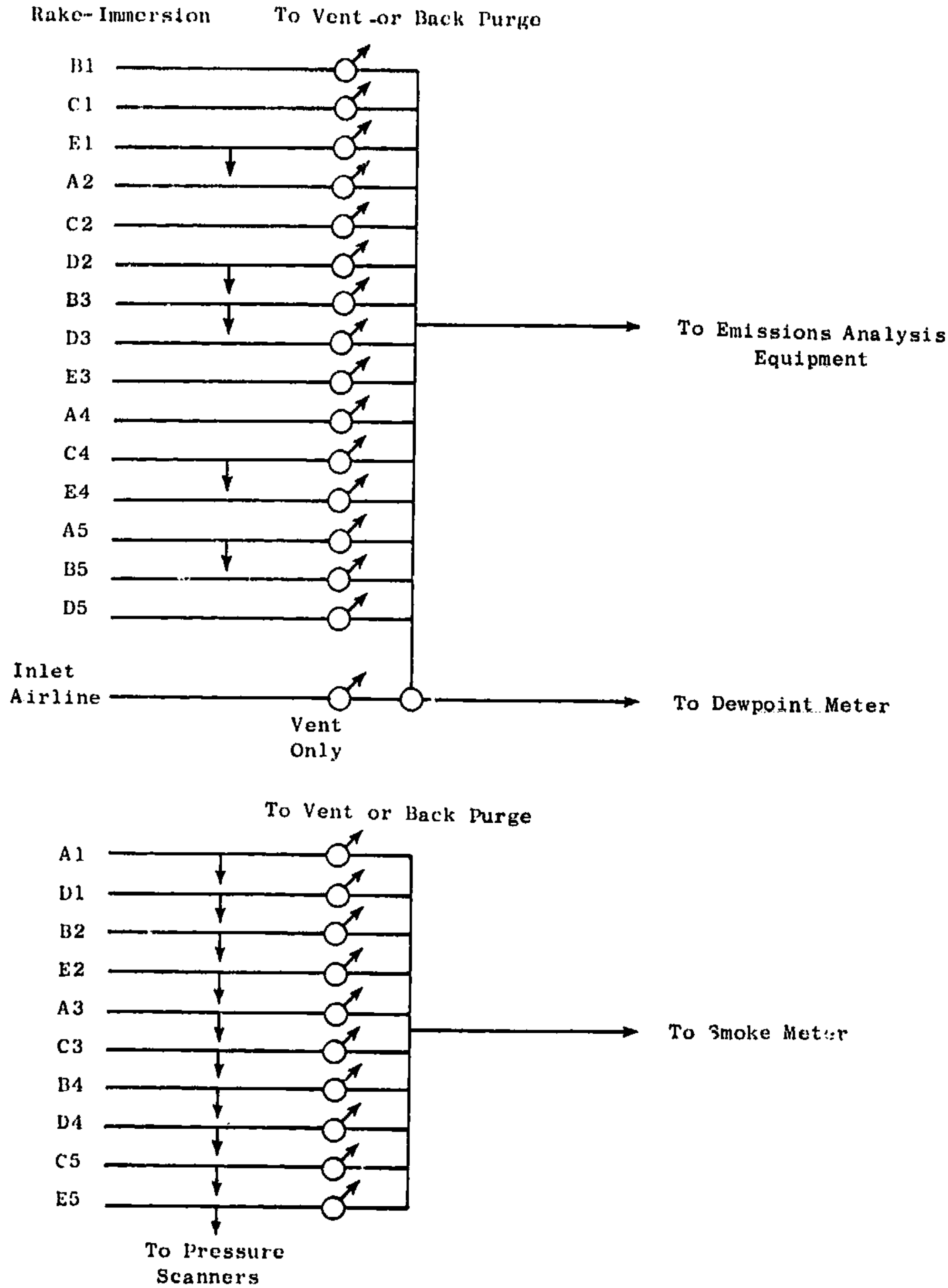


Figure 86. Gas Sample Line Manifolding Schematic.

- Normal Sampling Mode - In this mode, which was used for about 75 percent of all test points, all of the 15 available gas sample lines were manifolded together, and 1 average gas sample was supplied to the emissions analyzers at each traverse position of a test point. This technique was usually employed whenever both annuli, or stages, of the combustor were fueled and the combustor exit temperature distribution was relatively uniform.

- Radial Immersion Sampling Mode- In this mode, which was used for about 20 percent of all test points, only gas samples extracted from the same radial immersion were manifolded together. The three sample lines from the first radial immersion were manifolded together, and the exhaust plane was sampled at four rake traverse positions. The traverse was then returned to its original position, the first immersion sample lines were valved to a vent manifold, and the three sample lines from the second radial immersion were sampled together at four traverse positions. This process was repeated until all five radial immersions had been sampled at four traverse positions. This sampling mode was usually used when fuel was supplied to only one annulus or stage of the combustor. Upon occasion, this sampling mode was also employed on points where the combustors were fueled uniformly, in order to obtain detailed emission profile data from the combustor exit plane. Points which were sampled both in this manner and in the normal sampling mode showed very good agreement with respect to measured average emissions levels.

- Individual Rake Sampling Mode - In this sampling mode, used almost exclusively for sector fuel staging test points, the gas samples from only one exit gas sample rake were manifolded together and samples were taken at 12 rake positions. The traverse was then returned to its original position, and all the elements from a second rake were manifolded together and sampled over 12 rake positions. This process was then repeated until all the desired area in the exit plane had been surveyed. Usually, however, only two rakes were sampled. One rake, which began its traverse in a non-fueled region and ended its traverse in a fueled region, was sampled to define the hot/cold zone interface. Another rake, whose entire traverse was in a fueled region, was also sampled to define the emissions levels within the burning zones.

- High Density Sampling Mode - This mode, which was used infrequently, is identical to the normal sampling mode, except that the fully manifolded samples were extracted at 24 rake positions (3 degrees apart) in the combustor exit plane, instead of just 12 positions. This technique was generally used to better define the pattern and profile factors for the test condition, and to provide a denser collection of gas samples from which to determine the average emissions levels. The emissions levels determined from the normal mode and the high density mode were usually in excellent agreement.

During some of these combustor tests, smoke emissions levels were also measured at selected test points of interest. These levels were generally not measured on tests where the maximum combustor inlet pressure level was less than seven atmospheres, since the smoke levels at such low pressure levels would be too low to be accurately determined. The smoke levels of the CF6-50 production combustor are already very low and the smoke levels of the various Phase I Program configurations were expected to be even lower. Thus, smoke emissions characteristics were generally not considered to be of concern. On those conditions where smoke data were acquired, samples were extracted from the combustor exit plane with ten elements, as shown in Figure 20. These ten elements were manifolded together to provide one average sample to the smoke measurement console. At least three smoke spots were taken at each test condition and the average SAE Smoke Number for this operating point was determined from the average of these three spots.

The normal General Electric procedure for measuring smoke levels is to extract several 0.0057 cubic meter samples, but due to the low smoke levels of most of the combustor configurations of this program, larger samples of 0.0198 cubic meters were used. With this size sample, more accurate reflectance measurements could be obtained because the spots were darker. This is also about the largest size spot which could be used to obtain three smoke spots in the time required for a normal traverse of the combustor exit plane.

APPENDIX C

SUMMARY OF TEST RESULTS

This appendix contains summaries of the operating conditions, combustor performance data and exhaust emissions data of each test conducted during this entire program, including the tests conducted as a part of the AST Addendum. These tables are ordered according to Program Element and configuration number within each element. Descriptions of each of the various test configurations and the key results obtained with these configurations are presented in Chapters III and IV.

The sequence in which the tests were conducted is presented in Table XLVII. All of the data obtained in these tests are summarized in this appendix. All of the NO_x data are presented in two forms, as measured and adjusted to the hot day SLS takeoff operating conditions of the CF6-50 engine. All of the data in these tables, except in the two tables containing ignition data, are grouped according to simulated engine power setting. The nominal combustor inlet total temperature for CF6-50 standard day idle, CF6-50 hot day approach, CF6-50 hot day climbout, CF6-50 standard day takeoff, CF6-50 hot day takeoff, CF6-50 standard day cruise and AST cruise are 454, 661, 825, 810, 858, 733 and 833° K, respectively. With the use of these nominal tempe ature values, the intended combustor operating condition may be ascertained for the various test points contained in the data summary tables. Additional information on the operating conditions used in conducting the elevated pressure tests is presented in Table VI of Chapter II.

The actual measured total pressure loss values are presented in the data tables. In the assessments of these data, which are presented in Chapters III and IV, these measured pressure loss data were adjusted using conventional corrections to the proper combustor reference Mach number and temperature rise ratio whenever the test conditions did not duplicate the CF6-50 engine combustor operating conditions.

In the data tables, only the measured combustor airflows are shown for the sake of brevity. In conducting the tests, the total airflow and the bleed airflows were actually measured and the combustor airflow was obtained as the difference between these two measured values. Nominally, the combustor airflow was 84 percent of the total inlet airflow.

Table XLVII. Experimental Clean Combustor Program Test Sequence.

Run No.	Test Date	Configuration Number	AST Cruise Test Points	Noise Measurements	Final Reading Number	Maximum Test Conditions Attained T_3 °K	P_3 atm
1	10/15/73	II-1			11	462	3.4
2	10/16	II-1			16	459	3.4
3	10/17	II-1			27	773	9.5
4	10/18	II-1			45	860	9.6
5	10/22	I-1			61	673	7.3 (1)
6	11/1	I-2			70	825	9.5 (1)
7	11/24	I-3			83	661	7.2 (1)
8	11/26	I-4			97	456	3.4
9	11/29	II-2	Yes		126	860	9.6
10	12/10	I-5			146	864	4.8
11	1/17/74	II-3			162	859	4.8
12	1/22	I-6			176	856	4.8
13	1/26	II-4			195	859	4.8
14	1/29	I-7			209	823	4.8
15	1/31	II-5			218	855	11.5
16	2/5	II-6			237	734	4.8
17a	3/1	II-7			242	455	3.4
17b	3/4	II-7	Yes		286	832	6.9
18	3/7	II-8			303	739	4.8 (1)
19	3/22	I-8	Yes	Yes	335	856	6.8
20	3/27	I-9			358	861	4.8
21	4/1	II-9	Yes	Yes	386	863	7.2
22	4/4	II-10	Yes		415	836	6.9
23	4/9	I-10	Yes		449	860	4.8
24	4/17	II-11	Yes	Yes	478	857	6.8
25	4/22	I-11			496	716	4.8 (1)
26	4/26	II-12		Yes	516	868	4.8
27	4/29	II-12	Yes	Yes	526	859	7.1
28	5/1	I-12	Yes	Yes	539	860	6.8
29	5/3	II-13	Yes		586	865	6.7
30	5/7	II-14	Yes		614	858	7.3
31	5/10	I-13			634	826	4.8 (1)
32	5/14	II-15			4	301	1.0 (2)
33	5/15	II-15			668	857	9.5
34	5/17	II-15			682	851	9.6
35	5/22	I-14		Yes	708	788	4.8 (1)
36	5/24	II-16			711	298	1.0 (2)
37	5/28	II-16	Yes		746	859	4.8
38	6/5	I-15			4	294	1.0 (2)
39	6/5	I-15			766	868	3.4
40	6/10	I-15			768	885	6.7 (3)
41	6/13	III-1	Yes	Yes	793	865	6.8
42	6/18	I-16	Yes	Yes	806	828	4.8 (3)
43	6/27	III-2	Yes		837	863	6.9

(1) Maximum test conditions limited by combustor metal temperatures.
(2) Ignition test.
(3) Maximum test conditions limited by upstream burning.

Table XLVIII. Summary of Test Results, Configuration I-1.

CONFIGURATION DESCRIPTION 72-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air: Metered Outer Annulus	Metered Inner Annulus	Metered Over-All	Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
51	1.09	474	3.6	0	4.9	13.2	0	0	0	-	-	-	-	-	-	—	1.46	474	—	—	
52	3.84	450	16.7	611	4.9	17.6	.0102	0	.0102	.0103	93.5	76.6	47.0	3.2	63.8	—	2.77	828	—	—	1
55	3.39	440	16.3	809	5.0	19.7	.0138	0	.0138	.0144	92.0	93.3	58.4	2.5	55.9	—	3.82	957	—	—	1
57	3.38	434	16.3	819	5.3	19.4	.0070	.0069	.0139	.0151	88.8	116.5	84.8	1.8	41.4	—	4.13	931	—	—	
59	3.39	586	16.5	814	5.7	24.8	.0069	.0068	.0137	.0156	96.5	78.6	17.0	3.0	40.7	—	4.69	1096	—	—	
60	6.87	655	31.4	1944	5.7	26.2	.0086	.0086	.0172	.0194	99.4	19.3	1.6	6.2	41.4	—	4.76	1277	—	—	
61	7.28	673	30.9	2469	5.7	25.2	.0110	.0112	.0222	.0250	99.7	9.0	0.6	7.3	41.2	—	4.55	1467	—	—	

NOTES:

1. Radial Immersion Sampling Mode

Table XLIX. Summary of Test Results, Configuration I-2.

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air: Metered Outer Annulus	Metered Inner Annulus	Metered Over-All	Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
62	3.37	500	16.7	0	3.3	21.8	0	0	0	-	-	-	-	-	-	-	4.80	500	-	-	
63	3.28	450	16.6	597	3.3	20.1	.0100	0	.0100	.0107	90.4	121.8	67.5	2.2	51.1	-	4.79	810	-	-	
64	3.40	450	16.8	810	3.9	19.7	.0134	0	.0134	.0149	94.0	92.1	38.5	2.5	57.9	-	4.71	941	-	-	1
65	3.31	453	16.4	811	2.7	19.8	.0069	.0069	.0138	.0128	70.7	131.6	262.2	0.9	20.9	1	4.63	829	-	-	
66	6.76	668	30.5	1534	1.7	26.4	.0070	.0070	.0140	.0160	99.0	32.3	2.9	5.0	29.2	-	5.80	1176	-	-	
67	7.06	657	30.4	1977	3.0	25.0	.0090	.0090	.0180	.0209	99.6	12.5	0.7	6.1	36.0	4	5.26	1301	-	-	
68	9.43	734	34.7	1989	2.1	24.1	.0080	.0080	.0160	.0181	99.9	5.6	0	8.9	27.3	-	4.32	1306	-	-	
69	9.51	733	34.8	2629	2.3	24.0	.0205	.0105	.0210	.0244	99.9	2.3	0	11.0	33.7	7	4.20	1459	-	-	
70	9.53	825	33.4	2390	2.1	25.9	.0100	.0099	.0199	.0216	99.9	1.1	0	14.3	27.5	-	4.25	1502	-	-	

NOTES:

1. Radial Immersion Sampling Mode

Table L. Summary of Test Results, Configuration I-3.

CONFIGURATION DESCRIPTION 60-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
71	3.40	458	16.1	0	-	19.2	0	0	0	-	-	-	-	-	-	-	3.75	458	-	-	
72	3.42	456	16.2	573	8.3	19.1	.0098	0	.0098	.0100	88.1	119.0	91.0	2.7	63.7	-	4.12	802	-	-	1
73	3.41	457	16.2	797	8.3	19.3	.0098	0	.0136	.0142	89.6	106.0	79.4	2.2	52.1	-	4.25	941	-	-	1
74	3.45	456	16.4	1114	8.3	19.3	.0188	0	.0188	.0204	91.0	104.0	65.5	2.4	56.7	-	4.24	1113	-	-	1
75	3.37	456	15.8	798	8.3	19.0	0	.0140	.0140	.0154	97.3	61.0	12.6	2.5	59.1	-	4.27	994	-	-	1
76	3.38	456	16.0	804	6.9	19.2	.0069	.0071	.0140	.0152	89.3	117.0	79.6	1.5	34.7	6	4.34	944	-	-	
77	3.36	594	12.7	454	3.7	20.2	.0050	.0051	.0101	.0110	93.6	86.5	43.5	3.0	30.7	-	3.25	974	-	-	
78	6.82	665	31.0	1510	2.6	26.4	.0068	.0067	.0135	.0153	99.2	25.4	1.6	5.6	33.7	-	5.59	1164	-	-	
79	6.80	661	30.5	1948	2.1	26.0	.0089	.0088	.0177	.0197	99.6	13.4	0.6	6.3	36.7	6	5.61	1296	-	-	
80	7.22	666	30.5	2616	2.1	25.1	.0120	.0118	.0238	.0271	99.7	10.5	0.3	7.3	40.3	6	5.12	1492	-	-	
81	3.44	661	15.3	757	3.7	25.8	.0069	.0068	.0137	.0150	98.6	47.0	3.1	3.5	30.4	2	5.65	1164	-	-	
82	3.62	656	15.6	962	4.6	24.8	.0087	.0085	.0172	.0193	99.3	24.5	1.0	4.2	35.7	-	5.23	1273	-	-	
83	3.84	656	15.2	1304	4.6	23.3	.0119	.0119	.0238	.0263	99.5	19.7	0.4	5.3	41.0	-	4.73	1483	-	-	

NOTES:

1. Radial Immersion Sampling Mode

Table LI. Summary of Test Results, Configuration I-4.

CONFIGURATION DESCRIPTION 60-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
84	3.38	459	16.8	0	3.7	20.2	0	0	0	-	-	-	-	-	-	-	3.94	459	-	-	
85	3.40	455	16.5	807	3.7	19.6	.0090	.0046	.0136	.0145	85.7	118.0	116.0	1.9	42.5	-	4.38	915	-	-	
86	3.40	456	16.4	770	3.7	19.5	.0065	.0065	.0130	.0167	92.5	87.8	54.3	1.9	42.2	-	4.55	939	-	-	
89	3.39	456	15.8	1168	3.7	19.0	.0137	.0068	.0205	.0262	95.7	82.5	23.9	2.8	60.4	-	4.35	1195	-	-	1
92	3.38	456	16.1	809	3.7	19.2	.0095	.0045	.0140	.0204	96.5	69.2	11.8	2.6	56.8	-	4.32	985	-	-	2
95	3.38	456	16.3	598	3.7	19.4	.0068	.0034	.0102	.0136	96.1	73.1	21.8	2.5	55.4	-	4.37	852	-	-	2

NOTES:

1. Fueled in Two Opposing 120° Sectors
2. Fueled in Two Opposing 90° Sectors

Table LII. Summary of Test Results, Configuration I-5.

CONFIGURATION DESCRIPTION 72-SWIRL-CAN/COUNTERSWIRL FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
127	3.45	454	16.1	0	-	18.7	0	0	0	-	-	-	-	-	-	-	3.55	454	-	-	
128	3.38	453	16.0	593	1.9	19.0	.0103	0	.0103	.0119	84.4	123.0	127.0	2.6	56.4	-	3.61	797	-	-	1
129	3.40	452	16.1	824	2.1	19.0	.0142	0	.0142	.0169	88.7	108.0	87.3	2.0	41.8	-	4.02	936	-	-	1
130	3.38	455	16.0	809	2.3	19.1	0	.0140	.0140	.0177	94.8	100.0	29.0	2.4	50.7	-	3.76	969	-	-	1
131	3.38	451	16.1	593	2.5	19.0	0	.0101	.0101	.0126	90.8	107.0	66.7	2.1	46.7	-	3.83	812	-	-	1
132	3.36	454	16.0	820	2.3	19.1	.0093	.0050	.0143	.0139	68.7	139.0	280.0	1.5	31.6	1	3.91	831	-	-	
133	3.38	453	16.5	1165	2.3	19.6	.0096	.0098	.0196	.0226	88.9	102.0	87.0	1.6	34.7	-	4.46	1092	-	-	
134	3.35	599	12.8	644	2.3	20.6	.0070	.0070	.0140	.0159	94.6	98.0	39.8	3.1	30.0	-	3.35	1090	-	-	
135	3.41	666	15.4	777	1.8	26.3	.0071	.0069	.0140	.0164	96.9	80.8	12.1	3.8	31.5	1	5.02	1166	-	-	
136	3.43	668	15.4	1016	1.8	26.3	.0091	.0092	.0183	.0217	98.4	49.2	4.1	4.6	38.0	-	5.00	1309	-	-	
137	4.78	728	17.6	910	1.7	23.8	.0071	.0072	.0143	.0167	99.2	27.0	1.3	7.5	33.0	-	3.67	1245	-	-	
138	4.76	733	17.6	1330	1.8	24.0	.0105	.0105	.0210	.0248	99.6	16.7	0.1	9.4	40.6	9	3.67	1459	-	-	
139	4.79	831	16.9	1112	1.8	26.0	.0091	.0091	.0182	.0214	99.9	5.8	0	12.6	32.8	-	3.71	1463	-	-	
140	4.79	833	17.0	1392	1.9	26.1	.0114	.0114	.0228	.0260	99.0	10.2	0	14.3	37.3	8	3.94	1599	-	-	
141	4.76	861	16.5	718	2.4	26.6	.0060	.0061	.0121	.0132	99.7	12.0	0	11.9	27.0	2	3.78	1292	-	-	
142	4.76	864	16.2	1061	1.8	26.5	.0091	.0089	.0180	.0207	99.9	4.4	0	14.5	31.6	19	3.74	1486	-	-	
143	4.77	863	16.4	1425	2.1	26.4	.0122	.0119	.0241	.0278	99.7	11.3	0	17.1	37.8	25	3.85	1657	-	-	
144	4.76	863	16.3	1437	2.1	26.4	.0123	.0122	.0245	.0301	99.7	13.2	0	16.8	37.2	-	3.88	1674	-	-	
145	4.78	864	18.6	1628	1.7	29.5	.0120	.0120	.0240	.0280	99.7	11.4	0	15.[illegible]	38.4	-	5.16	1659	-	-	
146	4.78	866	15.0	1307	2.3	24.5	.0122	.0120	.0242	.0277	99.8	9.9	0	18.2	36.7	-	3.17	1671	-	-	

NOTES:

1. Radial Immersion Sampling Mode

Table LIII. Summary of Test Results, Configuration I-6 (1).

CONFIGURATION DESCRIPTION 72-SWIRL-CAN/COUNTERSWIRL FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature ° K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature ° K	Profile Factor	Pattern Factor	Notes
163	3.44	455	16.6	0	-	19.4	0	0	0	-	-	-	-	-	-	-	4.23	455	-	-	
164	3.38	451	16.5	596	4.3	19.5	0	.0101	.0101	.0159	94.9	84.7	31.7	2.5	57.9	-	4.75	816	-	-	
165	3.38	453	16.5	814	4.6	19.5	0	.0137	.0137	.0222	94.0	91.0	38.9	2.4	54.8	-	4.68	956	-	-	
166	3.38	453	16.5	593	4.3	19.6	.0100	0	.0100	.0098	89.3	112.2	81.0	2.1	49.3	-	4.85	802	-	-	
167	3.42	451	16.4	801	4.5	19.3	.0136	0	.0136	.0137	92.2	100.8	54.3	2.2	50.9	-	4.68	912	-	-	
168	4.82	735	17.7	880	4.3	24.3	.0069	.0069	.0138	.0167	98.8	28.8	4.9	7.4	33.1	2	3.98	1227	-	-	
169	4.82	738	17.9	1311	4.4	24.6	.0101	.0102	.0203	.0250	99.5	17.9	1.4	8.8	39.5	3	4.48	1446	-	-	
170	4.84	856	16.7	698	3.9	26.5	.0058	.0058	.0116	.0138	99.5	13.9	1.6	11.4	26.9	1	4.25	1250	-	-	
171	4.82	855	16.8	1049	3.9	26.7	.0087	.0087	.0174	.0210	99.8	6.2	0.7	13.7	32.9	-	4.40	1436	-	-	
172	4.82	851	16.7	1054	3.9	26.4	.0097	.0078	.0175	.0204	99.8	5.5	0.7	13.5	32.9	-	4.42	1430	-	-	
173	4.78	854	16.8	1055	3.9	26.9	.0079	.0095	.0174	.0214	99.8	8.1	0.6	13.8	33.6	-	4.53	1435	-	-	
174	4.80	854	16.7	1424	4.3	26.7	.0118	.0119	.0237	.0285	99.7	11.8	0.4	15.1	36.8	6	4.41	1657	-	-	
175	4.78	856	16.8	1055	4.3	26.8	.0101	.0074	.0175	.0202	99.8	6.1	0.5	13.0	31.5	-	4.44	1438	-	-	
176	4.81	855	16.7	1050	4.3	26.6	.0070	.0104	.0174	.0225	99.7	10.5	0.5	14.3	34.5	-	4.37	1436	-	-	

NOTES:

1. All Data Taken at Only One Rake Position, Radial Immersion Sampling Mode

Table LIV. Summary of Test Results, Configuration I-7.

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
196	3.35	459	16.0	0	4.1	18.7	0	0	0	-	-	-	-	-	-	-	2.59	459	-	-	-
197	3.37	458	16.0	588	4.1	21.3	.0102	0	.0102	.0109	78.7	117.0	185.0	1.6	36.7	-	2.71	779	-	-	1
198	3.36	465	16.0	811	4.1	18.9	.0141	0	.0141	.0151	89.1	107.1	83.7	2.0	41.5	-	2.97	953	-	-	1
199	3.35	455	16.2	587	3.8	19.6	0	.0101	.0101	.0117	89.3	111.4	81.1	2.0	45.1	-	2.91	814	-	-	1
200	3.35	455	16.3	807	3.8	19.6	0	.0137	.0137	.0156	91.5	102.8	61.5	2.2	49.7	-	2.92	942	-	-	1
201	3.42	459	18.2	894	4.3	21.3	0	.0137	.0137	.0157	91.6	104.2	59.7	2.2	52.6	-	3.49	946	-	-	1
202	3.39	456	18.0	632	3.5	21.2	0	.0098	.0098	.0107	88.4	120.6	87.7	1.9	45.6	-	3.46	803	-	-	1
203	3.41	668	15.6	763	3.5	26.7	.0069	.0066	.0135	.0141	94.9	88.0	30.4	4.1	35.6	1	4.00	1142	1.09	.40	-
204	3.48	669	15.4	965	3.6	26.0	.0088	.0084	.0172	.0184	97.0	58.4	16.1	4.9	40.4	-	3.72	1271	1.09	.36	-
205	4.80	726	17.9	884	3.5	24.3	.0069	.0068	.0137	.0144	97.7	41.9	13.4	8.3	38.9	-	2.76	1212	1.09	.33	-
206	4.77	730	18.1	1315	3.5	24.8	.0102	.0100	.0202	.0219	99.0	19.6	5.2	8.8	41.0	3	2.66	1431	1.08	.36	-
207	4.77	819	17.6	1090	3.8	26.6	.0086	.0085	.0171	.0182	99.4	12.3	3.5	12.0	35.6	-	3.08	1409	1.10	.34	-
208	4.76	823	17.4	1489	3.5	26.6	.0120	.0117	.0237	.0253	99.6	8.3	2.1	13.1	35.0	3	3.03	1613	1.10	.38	-
209	4.84	816	17.1	719	4.1	25.9	.0059	.0058	.0117	.0116	98.7	27.5	7.1	12.7	37.5	3	2.84	1224	1.11	.35	-

Notes:

1. Radial Immersion Sampling Mode

Table LV. Summary of Test Results, Configuration I-8 (1).

CONFIGURATION DESCRIPTION: 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air: Metered Outer Annulus	Metered Inner Annulus	Metered Over-All	Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
304	3.34	454	16.2	0	3.4	19.5	0	0	0	-	-	-	-	-	-	-	3.78	454	-	-	-
305	3.40	454	16.1	0	3.4	19.1	0	0	0	-	-	-	-	-	-	-	3.66	454	-	-	-
333	3.42	450	16.1	596	3.4	19.0	.0103	0	.0103	.0104	83.8	126.6	132.2	2.0	45.0	-	3.73	788	-	-	2
334	3.40	451	16.1	811	3.2	19.0	.0140	0	.0140	.0145	88.8	112.9	84.9	2.1	46.0	-	3.92	929	-	-	2
330	3.42	450	16.2	591	3.0	19.0	0	.0102	.0102	.0094	80.5	124.7	165.8	2.0	43.3	-	3.72	770	-	-	2
331	3.41	450	16.2	819	3.0	19.0	.0140	0	.0140	.0147	91.3	99.5	64.2	2.4	52.1	-	3.94	941	-	-	2
332	3.41	450	16.4	1168	3.3	19.1	0	.0198	.0198	.0205	91.8	102.9	58.1	2.3	51.9	-	4.30	1125	-	-	2
329	2.74	453	13.1	661	3.1	19.1	0	.0140	.0140	.0133	91.5	106.6	60.4	3.0	73.9	-	3.99	947	-	-	2
326	4.10	450	19.4	979	2.2	19.0	.0140	0	.0140	.0143	92.2	92.7	55.6	3.5	69.2	-	3.79	945	-	-	2
327	4.79	449	22.8	813	2.3	19.0	.0099	0	.0099	.0093	85.8	112.8	115.5	3.5	64.6	-	3.72	790	-	-	2
328	4.78	453	22.6	1137	2.3	19.1	0	.0140	.0140	.0143	92.8	90.1	51.4	3.5	63.1	-	3.86	951	-	-	2
325	3.40	592	12.4	624	2.6	19.6	.0140	0	.0140	.0145	97.7	47.9	12.3	5.9	57.5	-	2.77	1101	-	-	2
335	3.40	366	19.9	999	3.3	18.7	0	.0140	.0140	.0136	79.5	134.9	173.4	0.8	28.0	-	5.00	802	-	-	2
307	3.44	660	16.8	0	3.4	25.8	0	0	0	-	-	-	-	-	-	-	4.66	660	-	-	-
314	3.41	658	15.2	434	2.9	25.7	.0040	.0039	.0079	.0065	58.0	115.5	393.1	2.4	20.8	-	5.04	836	-	-	-
313	3.43	658	15.3	602	2.9	25.7	.0055	.0054	.0109	.0115	91.6	116.9	57.1	3.8	32.7	-	5.05	1033	1.12	.85	-
308	3.45	661	15.3	765	3.4	25.7	.0069	.0070	.0139	.0151	95.8	82.1	22.6	3.7	31.7	-	4.96	1150	1.10	.72	-
309	3.42	661	15.2	997	2.7	25.7	.0091	.0091	.0182	.0198	97.6	55.1	11.0	4.7	40.1	-	5.02	1296	1.08	.65	-
310	3.52	662	15.1	1154	2.7	24.9	.0105	.0107	.0212	.0231	98.3	44.1	6.6	5.2	41.8	-	4.86	1397	1.06	.60	-
311	3.54	659	15.2	1345	2.6	25.0	.0122	.0123	.0245	.0266	98.7	40.2	4.1	5.6	45.8	-	4.98	1499	1.06	.57	-
312	3.53	658	15.2	1342	2.7	24.9	.0121	.0124	.0245	.0258	98.6	42.0	4.6	5.6	46.2	-	5.02	1487	-	-	2
315	4.79	734	17.7	891	3.1	24.3	.0070	.0070	.0140	.0152	93.3	33.1	9.8	8.2	36.1	-	3.81	1240	1.13	.69	-
316	4.79	731	17.9	1334	3.4	24.4	.0103	.0104	.0207	.0225	99.3	19.1	3.0	8.8	40.3	-	3.98	1440	1.10	.66	-
317	4.80	822	17.2	1111	3.4	26.3	.0090	.0089	.0179	.0191	99.7	10.1	1.1	12.6	36.1	-	3.93	1439	1.16	.75	-
318	4.78	823	17.4	1293	3.3	26.6	.0103	.0104	.0207	.0220	99.7	9.2	0.8	13.2	37.9	-	4.03	1523	1.14	.75	-
306	4.78	856	15.3	0	3.4	26.9	0	0	0	-	-	-	-	-	-	-	3.75	856	-	-	-
319	4.78	856	16.5	721	3.3	26.5	.0061	.0060	.0121	.0130	99.6	12.7	1.1	14.5	34.1	-	3.76	1284	1.17	.72	-
320	4.73	855	16.6	1062	3.1	26.6	.0089	.0089	.0178	.0193	99.8	7.3	0.5	15.5	36.6	-	3.79	1447	1.18	.75	-
321	4.78	858	16.7	1454	3.3	26.7	.0121	.0121	.0242	.0262	99.8	8.7	0.3	16.8	39.4	-	3.94	1664	1.09	.77	-
322	6.82	829	24.8	1603	2.2	26.9	.0089	.0090	.0179	.0195	99.8	6.6	0.6	16.3	37.5	-	4.08	1442	1.14	.69	-
323	6.82	832	24.5	2043	2.2	2[illegible].7	.0114	.0117	.0231	.0248	99.8	5.7	0.4	17.7	39.6	-	4.06	1606	1.25	.73	-
324	6.82	829	27.4	2273	2.4	29.2	.0114	.0117	.0231	.0249	99.8	7.0	0.5	15.7	39.5	-	5.11	1600	1.13	.77	-

Notes:

1. Acoustic Probe Installed, 150° of Exit Plane Surveyed
2. Radial Immersion Sampling Mode

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Table LVI. Summary of Test Results, Configuration I-9.

CONFIGURATION DESCRIPTION 72-SWIRL-CAN/COUNTERSWIRL FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm.	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
336	[illegible]	[illegible]	16.0	0	3.4	18.7	0	0	0	0	-	-	-	-	-	-	3.01	456	-	-	
337	1.44	[illegible]	[illegible]	595	3.4	19.2	0	.0102	.0102	.0121	90.0	113.9	73.5	2.0	41.9	-	4.17	862	-	-	1
[illegible]	[illegible]	[illegible]	[illegible]	800	3.7	19.1	0	.0139	.0139	.0153	94.7	83.5	33.8	2.3	49.7	-	4.33	968	-	-	1
[illegible]	1.43	[illegible]	16.0	1167	4.0	18.8	0	.0202	.0202	.0254	95.0	91.7	28.5	2.5	53.7	-	4.21	1166	-	-	1
[illegible]	[illegible]	[illegible]	15.9	[illegible]	4.2	18.6	0	.0141	.0141	.0170	94.3	82.4	37.9	2.2	50.1	-	4.23	957	-	-	1
[illegible]	[illegible]	[illegible]	15.9	1150	4.4	19.0	.0068	.0133	.0201	.0231	88.6	106.3	89.0	1.4	29.5	-	4.28	1115	1.09	.53	
[illegible]	[illegible]	[illegible]	16.0	1609	4.4	18.7	.0140	.0140	.0280	.0333	96.1	70.0	22.4	2.1	44.7	-	4.32	1412	[illegible]	.45	
[illegible]	[illegible]	643	15.4	596	4.5	25.8	.0054	.0054	.0108	.0101	65.8	173.7	301.0	1.1	4.5	-	5.30	928	[illegible]	.98	
[illegible]	1.45	649	15.3	758	4.8	26.0	.0069	.0068	.0137	.0159	92.5	114.5	48.3	2.4	20.6	-	5.40	1144	[illegible]	.56	
[illegible]	[illegible]	[illegible]	15.0	974	5.0	25.7	.0090	.0091	.0181	.0210	97.3	61.8	13.1	3.1	27.1	-	5.62	1301	1.06	[illegible]	
346	[illegible]	[illegible]	[illegible]	1137	5.0	25.5	.0102	.0107	.0209	.0245	98.5	40.1	5.4	3.6	31.8	-	5.56	1379	1.07	.44	
347	[illegible]	662	[illegible]	1345	5.1	24.5	.0123	.0129	.0252	.0289	99.1	26.0	2.9	4.7	38.3	-	5.01	1523	1.07	.46	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.8	24.7	.0119	.0123	.0242	.0273	99.0	26.2	3.4	4.7	37.8	-	5.03	1494	-	-	1
[illegible]	[illegible]	661	15.2	1526	4.4	23.7	.0137	[illegible]	.0279	.0329	99.3	24.6	1.8	5.6	42.6	-	4.56	1600	1.06	.46	
[illegible]	[illegible]	725	16.7	[illegible]	4.6	23.1	.0096	.0096	.0192	.0224	99.6	15.4	0.9	6.7	30.8	-	3.74	1392	[illegible]	.47	
[illegible]	[illegible]	[illegible]	16.6	[illegible]	4.2	23.2	.0115	.0076	.0191	.0217	99.4	19.7	1.2	6.7	30.4	-	3.74	1394	1.13	.52	
[illegible]	[illegible]	[illegible]	[illegible]	1153	4.2	23.4	.0076	.0115	.0191	.0224	99.5	16.1	1.0	7.0	31.9	-	3.75	1398	[illegible]	.56	
[illegible]	[illegible]	[illegible]	16.5	1472	4.2	23.0	.0124	.0124	.0248	.0286	99.7	9.8	0.4	8.3	37.3	-	3.71	1565	[illegible]	.44	
[illegible]	4.71	726	16.8	1481	4.2	23.3	.0120	.0122	.0242	.0272	99.7	10.5	0.7	7.9	36.0	-	3.88	1546	-	-	1
[illegible]	[illegible]	824	16.6	1049	4.6	26.2	.0087	.0088	.0175	.0202	99.8	5.0	0.6	9.1	26.4	-	4.30	1426	1.05	.49	
[illegible]	4.77	861	16.8	[illegible]	5.1	27.0	.0058	.0059	.0117	.0133	99.2	22.2	2.6	8.8	21.3	-	4.40	1234	[illegible]	.56	
[illegible]	[illegible]	[illegible]	16.7	[illegible]	4.8	27.2	.0087	.0090	.0177	.0205	99.8	3.2	0.9	10.3	25.7	-	4.62	1444	1.09	.53	
[illegible]	[illegible]	[illegible]	16.6	1050	4.8	27.0	.0079	.0096	.0175	.0205	99.8	3.4	0.9	10.4	25.8	-	4.35	1457	1.07	.52	

NOTES:

1. Radial Immersion Sampling Mode

Table LVII. Summary of Test Results, Configuration I-10.

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
449	3.39	458	16.3	0	3.7	19.5	0	0	0	-	-	-	-	-	-	-	4.52	458	-	-	-
448	3.40	456	16.3	592	3.7	19.4	.0101	0	.0101	.0093	87.9	118.8	93.8	2.1	46.5	-	4.72	807	-	-	1
447	3.38	455	16.3	816	3.9	19.5	.0139	0	.0139	.0135	90.5	104.3	66.9	2.2	49.9	-	4.84	942	-	-	1
446	3.39	456	16.3	1158	3.9	19.5	.0197	0	.0197	.0294	92.0	101.9	56.2	2.3	48.1	-	4.72	1135	-	-	1
445	3.40	456	16.2	583	3.9	19.4	0	.0100	.0100	.0115	80.4	118.3	168.9	1.6	35.0	-	4.65	775	-	-	1
444	3.38	457	16.3	825	3.7	19.5	0	.0140	.0140	.0148	89.0	91.9	88.6	2.0	44.0	-	4.80	937	-	-	1
443	3.39	452	16.1	1170	3.6	18.2	0	.0203	.0203	.0213	93.3	89.3	45.7	2.2	47.4	-	4.67	1148	-	-	1
441	3.39	450	15.6	1160	3.6	18.5	.0103	.0104	.0207	.0221	91.1	85.9	68.6	2.0	44.3	-	4.45	1148	1.18	.72	-
442	3.53	457	15.9	1615	3.4	17.5	.0141	.0142	.0283	.0308	95.3	75.0	30.0	2.5	48.8	-	4.38	1417	1.15	.58	-
416	3.42	656	15.6	0	2.8	26.1	0	0	0	-	-	-	-	-	-	-	6.24	656	-	-	-
417	3.41	662	15.4	776	2.8	26.0	.0069	.0071	.0140	.0149	96.6	76.9	16.4	4.0	33.9	-	6.29	1172	1.10	.67	-
418	3.40	663	15.2	992	2.9	25.9	.0090	.0091	.0181	.0194	98.1	48.0	7.6	4.8	41.5	-	6.34	1313	1.09	.76	-
419	3.48	663	15.2	1145	2.9	25.4	.0104	.0105	.0209	.0229	98.7	36.8	4.3	5.5	45.6	-	5.95	1412	1.04	.78	-
420	3.58	663	15.2	1337	2.9	24.7	.0122	.0122	.0244	.0262	99.0	31.3	2.5	6.1	47.8	-	5.71	1518	1.13	.69	-
421	3.58	660	15.0	1341	2.8	24.4	.0124	.0124	.0248	.0274	99.1	30.0	1.7	6.3	49.6	-	5.62	1518	-	-	1
422	3.71	661	15.0	1526	3.0	23.7	.0141	.0141	.0282	.0303	99.1	32.2	1.6	6.6	50.0	-	5.22	1606	1.03	.60	-
423	3.39	660	15.1	609	3.0	25.8	.0056	.0055	.0111	.0111	91.3	117.8	59.7	3.1	26.6	-	5.87	1003	1.09	1.09	-
424	4.73	734	17.5	884	3.3	24.4	.0070	.0070	.0140	.0147	98.9	31.5	4.0	7.8	35.1	-	4.54	1233	1.14	.80	-
425	4.73	732	17.6	1330	3.3	24.4	.0105	.0104	.0209	.0224	99.5	15.0	1.2	8.2	37.3	-	4.72	1449	1.14	.76	-
426	4.74	733	17.7	1550	3.3	24.4	.0122	.0121	.0243	.0259	99.6	14.4	0.8	9.1	41.0	-	4.79	1554	1.14	.68	-
427	4.74	827	17.3	1039	3.1	26.8	.0088	.0089	.0177	.0187	99.8	9.3	0.4	12.7	36.1	-	5.02	1456	1.14	.73	-
428	4.74	824	17.3	1277	3.1	26.8	.0103	.0102	.0205	.0218	99.8	7.5	0.2	13.3	38.2	-	4.97	1516	1.14	.76	-
429	4.74	824	17.0	1496	3.1	26.3	.0123	.0122	.0245	.0258	99.8	8.2	0.1	14.2	40.4	-	4.87	1640	1.13	.65	-
430	4.74	860	16.4	707	3.1	26.6	.0060	.0060	.0120	.0122	99.6	13.8	0.7	12.2	28.3	-	4.75	1281	1.16	.82	-
431	4.74	860	16.5	1061	3.1	26.8	.0089	.0090	.0179	.0183	99.9	5.7	0.2	14.9	34.6	-	4.74	1479	1.14	.74	-
432	4.75	859	16.4	1235	3.3	26.5	.0105	.0105	.0210	.0222	99.9	4.7	0	16.1	37.4	-	4.62	1572	1.13	.74	-
433	4.75	858	16.4	1439	3.3	26.5	.0122	.0122	.0244	.0257	99.9	5.9	0	16.9	39.7	-	4.66	1665	1.12	.65	-
434	6.80	829	24.5	1061	2.5	26.7	.0060	.0060	.0120	.0124	99.6	12.9	0.7	13.4	30.8	-	4.94	1252	1.13	.72	-
435	6.77	834	24.4	1582	2.5	26.8	.0090	.0090	.0180	.0180	99.9	5.4	0.3	16.2	36.5	-	4.95	1460	1.09	.73	-
436	6.79	834	24.8	2033	2.5	27.1	.0113	.0114	.0227	.0242	99.9	4.8	0.2	17.5	39.7	-	4.94	1593	1.08	.77	-
437	6.78	833	24.6	2146	2.5	26.9	.0120	.0122	.0242	.0261	99.9	4.8	0.2	17.9	40.8	-	4.85	1641	1.07	.66	-
438	6.79	831	27.5	1762	2.6	29.4	.0089	.0089	.0178	.0191	99.8	7.2	0.6	14.9	37.6	-	6.04	1446	1.18	.71	-
439	6.83	830	27.4	2252	2.6	29.3	.0114	.0114	.0228	.0245	99.8	5.6	0.3	16.2	40.8	-	6.03	1594	1.16	.74	-
440	6.84	831	27.5	2411	2.6	29.3	.0121	.0122	.0243	.0261	99.8	5.6	0.3	16.6	41.3	-	6.08	1637	1.16	.65	-

Notes:

1. Radial Immersion Sampling Mode

Table LVIII. Summary of Test Results, Configuration I-11.

CONFIGURATION DESCRIPTION 60-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
479	3.66	456	16.3	0	6.3	18.3	0	0	0	-	-	-	-	-	-	-	4.48	456	-	-	
480	3.40	454	16.5	816	6.3	19.5	.0067	.0070	.0137	.0151	88.4	129.6	86.1	1.6	38.5	-	5.62	926	1.11	.36	
481	3.41	455	16.4	1166	6.3	19.4	.0100	.0097	.0197	.0221	93.9	90.6	39.6	1.8	42.9	-	5.56	1142	1.11	.38	
491	3.38	444	16.1	608	7.3	18.8	.0027	.0078	.0105	.0116	90.4	115.1	69.3	1.7	42.6	-	5.35	799	-	-	1
492	3.40	446	16.1	815	7.1	18.8	.0035	.0106	.0141	.0163	94.2	86.4	37.8	1.9	45.9	-	5.46	932	-	-	1
493	3.42	446	16.1	1157	6.3	18.7	.0050	.0150	.0200	.0223	96.5	75.3	17.8	2.3	54.1	-	5.49	1164	-	-	1
494	3.39	454	15.9	604	6.1	18.9	.0051	.0055	.0106	.0124	95.2	80.4	29.2	2.2	51.1	-	5.22	849	-	-	2
495	3.41	454	15.8	819	6.3	18.7	.0049	.0095	.0144	.0161	96.8	71.4	15.5	2.5	55.8	-	5.00	990	-	-	2
482	3.42	589	12.4	626	5.4	19.4	.0070	.0070	.0140	.0154	97.7	61.6	8.6	3.2	33.1	-	4.10	1101	1.11	.31	
484	3.42	656	15.3	762	6.3	25.7	.0069	.0069	.0138	.0154	98.0	62.8	5.6	3.2	29.9	-	7.09	1161	1.10	.31	
485	3.48	656	15.4	984	6.3	25.3	.0089	.0089	.0178	.0197	98.9	37.8	2.2	3.6	33.1	-	6.90	1279	1.11	.36	
486	3.47	658	15.2	1138	6.3	25.1	.0104	.0103	.0207	.0231	99.2	27.9	1.2	3.9	35.2	-	6.86	1382	1.10	.31	
487	3.58	660	15.1	1333	6.1	24.3	.0123	.0123	.0246	.0271	99.4	22.6	0.6	4.8	40.6	-	6.38	1505	1.11	.33	
488	3.58	659	15.0	1327	5.8	24.2	.0123	.0123	.0246	.0271	99.5	20.3	0.5	5.1	42.5	-	6.65	1503	-	-	3
489	3.77	661	15.1	1522	5.6	23.1	.0141	.0139	.0280	.0303	99.4	23.6	0.6	5.7	43.4	-	5.94	1606	1.12	.32	
490	3.44	660	15.0	596	5.6	25.3	.0055	.0055	.0110	.0118	96.5	90.4	13.8	3.5	30.5	-	6.85	1056	1.11	.33	
483	4.81	716	16.1	607	6.7	23.8	.0071	.0069	.0140	.0157	99.5	19.6	1.0	5.7	29.2	-	5.30	1224	1.10	.27	

NOTES:

1. Fueled in One 240° Sector
2. Fueled in One 180° Sector
3. Radial Immersion Sampling Mode

Table LIX. Summary of Test Results, Configuration I-12 (1).

CONFIGURATION DESCRIPTION: 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
527	3.36	452	16.1	0	6.3	19.1	0	0	0	-	-	-	-	-	-	-	3.68	452	-	-	-
528	3.38	455	16.1	597	6.3	19.2	0	.0103	.0103	.0104	89.6	103.5	80.3	1.9	44.9	-	4.06	814	-	-	-
529	3.37	456	16.1	811	6.5	19.4	0	.0140	.0140	.0144	94.7	86.4	33.2	2.4	54.9	-	4.35	967	-	-	2
530	3.38	457	16.1	1158	5.6	19.3	0	.0200	.0200	.0213	93.3	93.5	44.7	2.0	44.3	-	4.57	1152	-	-	2
531	3.33	454	16.2	1156	5.2	19.4	.0099	.0099	.0198	.0217	91.4	88.8	65.4	1.6	36.2	-	4.20	1121	1.07	.60	2
532	3.55	455	16.2	1620	5.1	18.6	.0139	.0138	.0277	.0311	96.1	72.8	21.6	2.3	49.3	-	3.88	1406	1.06	.45	-
558	3.40	663	15.5	0	3.0	26.2	0	0	0	-	-	-	-	-	-	-	5.29	663	-	-	-
533	3.40	668	15.5	764	4.7	26.6	.0069	.0058	.0137	.0143	96.8	75.7	13.9	3.7	32.9	-	5.48	1156	1.07	.38	-
549	3.40	653	15.1	969	2.3	25.3	.0089	.0089	.0178	.0194	97.9	51.2	8.7	4.7	40.7	-	5.11	1280	1.09	.53	-
550	3.48	655	14.9	1244	2.4	24.6	.0107	.0106	.0213	.0232	98.5	40.1	5.2	5.5	45.4	-	4.82	1389	1.09	.52	-
551	3.61	659	15.1	1321	2.6	24.2	.0122	.0121	.0243	.0262	98.8	35.8	3.2	6.0	46.7	-	4.67	1483	-	-	2
552	3.61	662	15.1	1313	2.5	24.2	.0122	.0120	.0242	.0258	98.9	35.6	3.1	6.3	48.7	-	4.70	1490	1.09	.51	-
553	3.65	664	15.2	1343	2.7	24.3	.0130	.0115	.0245	.0258	98.8	36.3	3.4	6.1	46.7	-	4.75	1501	1.09	.54	-
554	3.64	665	15.2	1328	2.7	24.4	.0138	.0105	.0243	.0258	98.8	37.0	3.3	6.0	45.4	-	4.78	1496	1.10	.58	-
555	3.63	665	15.1	1329	2.7	24.3	.0146	.0098	.0244	.0257	98.8	38.9	3.4	5.9	44.9	-	4.74	1496	1.09	.60	-
556	3.63	662	15.1	1331	2.7	24.2	.0154	.0091	.0245	.0258	98.7	40.6	3.7	5.8	44.7	-	4.71	1496	1.10	.65	-
557	3.76	662	15.3	1518	3.0	23.7	.0138	.0138	.0276	.0291	98.9	36.2	2.1	6.5	48.1	-	4.54	1589	1.10	.48	-
[illegible]	4.80	850	16.3	0	3.0	26.0	0	0	0	-	-	-	-	-	-	-	3.53	850	-	-	-
542	4.75	860	16.7	834	3.9	26.9	.0069	.0070	.0139	.0144	99.7	11.3	0.8	14.7	35.0	-	3.93	1350	1.09	.43	-
543	4.74	853	16.6	1050	3.7	26.6	.0088	.0088	.0176	.0186	99.8	8.5	0.5	15.5	37.9	-	3.97	1451	1.09	.46	-
544	4.75	855	16.6	1235	3.6	26.7	.0103	.0104	.0207	.0244	99.8	6.9	0.4	14.9	36.0	-	4.22	1556	1.08	.49	-
545	4.76	855	16.6	1427	3.6	26.6	.0119	.0120	.0239	.0276	99.8	7.6	0.3	16.2	38.8	-	4.21	1650	1.09	.50	-
546	4.77	855	16.5	1435	3.6	26.5	.0127	.0114	.0241	.0271	99.8	7.9	0.3	16.1	38.5	-	4.17	1651	1.08	.49	-
547	4.73	856	16.6	1436	3.6	26.7	.0136	.0104	.0240	.0268	99.8	8.4	0.3	16.1	38.8	-	4.23	1652	1.08	.50	-
548	4.73	856	16.6	1437	3.6	26.7	.0144	.0097	.0241	.0266	99.8	9.1	0.3	16.0	38.5	-	4.20	1652	1.08	.52	-
534	6.82	832	24.9	1047	3.4	27.0	.0059	.0058	.0117	.0122	99.6	11.2	1.1	14.3	33.2	-	4.41	1248	1.09	.44	-
535	6.80	833	24.7	1569	3.4	26.9	.0088	.0088	.0176	.0189	99.8	5.9	0.8	16.4	38.0	-	4.57	1441	1.08	.48	-
536	6.82	834	24.8	2021	3.4	27.0	.0113	.0114	.0227	.0242	99.8	5.0	0.4	17.7	40.5	-	4.31	1593	1.08	.47	-
537	6.81	834	24.9	2004	3.4	27.0	.0118	.0106	.0224	.0241	99.8	5.4	0.5	17.3	39.9	-	4.38	1585	1.10	.52	-
538	6.82	833	24.9	2013	3.4	27.0	.0128	.0096	.0224	.0240	99.8	6.0	0.3	17.2	39.6	-	4.36	1583	1.10	.56	-
539	6.82	831	24.9	2003	3.4	26.9	.0134	.0090	.0224	.0238	99.8	6.6	0.4	16.9	39.3	-	4.33	1581	1.10	.58	-
540	6.81	833	24.6	2139	3.4	26.8	.0121	.0121	.0242	.0257	99.8	6.4	0.4	18.1	41.4	-	4.33	1633	1.08	.48	-
541	6.82	828	27.6	2233	3.7	29.3	.0112	.0113	.0225	.0240	99.8	8.0	0.4	15.7	40.9	-	5.38	1581	1.09	.44	-

Notes:

1. Acoustic Probe Installed, 150° of Exit Plane Surveyed
2. Radial Immersion Sampling Mode

Table LX. Summary of Test Results, Configuration I-13.

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
615	3.39	454	16.9	0	4.6	20.0	0	0	0	-	-	-	-	-	-	-	3.82	454	-	-	-
616	3.36	454	15.9	1172	4.6	19.1	.0103	.0102	.0205	.0228	87.4	91.1	104.6	1.6	35.0	-	3.86	1117	1.06	.85	-
617	3.40	454	15.6	1637	4.2	18.2	.0147	.0146	.0293	.0329	95.7	74.4	26.1	2.4	50.0	-	3.73	1448	1.06	.49	-
618	3.35	454	16.0	824	3.9	19.3	.0072	.0071	.0143	.0152	91.1	86.7	69.1	1.5	34.1	-	4.10	958	-	-	1
619	3.34	456	16.1	1168	4.1	19.5	.0101	.0101	.0202	.0219	94.9	71.3	34.9	2.2	48.6	-	4.27	1167	-	-	1
620	3.35	455	15.8	1170	4.2	17.1	.0103	.0102	.0205	.0206	94.9	74.2	33.7	2.2	48.0	-	4.18	1178	-	-	2
621	3.32	455	16.0	812	3.9	19.4	.0071	.0070	.0141	.0157	95.8	69.9	25.3	2.4	52.8	-	4.08	974	-	-	2
622	3.33	455	15.9	600	4.1	19.3	.0053	.0052	.0105	.0118	93.1	81.9	50.2	1.9	41.6	-	3.95	842	-	-	2
623	3.32	456	15.9	597	4.1	19.4	.0052	.0052	.0104	.0113	95.1	75.7	31.8	2.3	51.3	-	4.08	844	-	-	3
624	3.32	447	16.1	919	4.1	19.2	.0071	.0070	.0141	.0141	94.3	78.8	39.0	2.2	50.6	-	4.00	961	-	-	3
625	3.37	658	15.0	777	4.2	25.7	.0072	.0072	.0144	.0159	96.7	77.7	14.9	3.5	31.0	-	5.38	1172	1.07	.49	-
626	3.38	666	14.8	1051	4.2	25.7	.0099	.0098	.0197	.0217	98.7	43.1	2.5	4.8	40.6	-	5.16	1355	1.09	.48	-
627	3.55	666	14.9	1343	4.2	24.6	.0126	.0125	.0251	.0285	99.3	29.0	0.1	6.1	47.9	-	4.75	1523	1.09	.49	-
628	3.55	665	15.0	1339	4.0	24.7	.0124	.0124	.0248	.0290	99.3	29.2	0.5	5.8	45.9	-	4.97	1516	-	-	4
629	3.71	663	14.9	1533	4.0	23.7	.0143	.0142	.0285	.0320	99.1	31.4	1.5	6.6	49.9	-	4.73	1621	1.10	.43	-
630	4.75	731	17.7	896	5.1	24.4	.0070	.0070	.0140	.0156	99.0	30.9	3.2	7.9	36.9	-	4.21	1235	1.08	.40	-
631	4.74	733	17.6	1335	5.0	24.1	.0106	.0105	.0211	.0241	99.6	13.3	1.0	9.6	43.8	-	4.04	1473	1.09	.43	-
634	4.76	726	17.9	1562	5.0	24.3	.0122	.0121	.0243	.0282	99.6	11.9	0.6	9.8	47.3	-	4.04	1561	1.10	.48	-
632	4.72	824	17.3	860	5.0	26.5	.0070	.0070	.0140	.0154	99.6	12.0	0.8	11.4	33.5	-	4.31	1318	1.09	.42	-
633	4.71	826	17.1	1106	5.0	26.6	.0090	.0090	.0180	.0201	99.8	6.5	0.5	13.0	38.3	-	4.26	1447	1.09	.42	-

Notes:

1. Fueled in One 240° Sector
2. Fueled in One 176° Sector
3. Fueled in One 120° Sector
4. Radial Immersion Sampling Mode

Table LXI. Summary of Test Results, Configuration I-14 (1).

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/FLAT FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air: Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
683	3.50	461	15.9	0	-	18.7	0	0	0	-	-	-	-	-	-	-	3.51	461	-	-	
699	3.65	452	16.3	1630	8.2	18.1	.0140	.0137	.0277	.0325	96.9	64.9	15.9	2.2	49.5	-	3.68	1410	1.13	.47	
700	3.38	455	16.1	1171	8.2	19.3	.0102	.0100	.0202	.0233	93.4	84.6	46.8	1.7	41.3	-	4.20	1156	1.14	.60	
701	3.39	455	16.1	1183	8.2	19.2	0	.0203	.0203	.0234	96.1	80.5	20.4	2.5	60.7	-	4.14	1178	-	-	2
702	3.38	456	16.2	828	8.2	19.4	0	.0142	.0142	.0162	95.1	73.5	31.8	2.3	55.3	-	4.08	976	-	-	2
703	3.38	455	16.1	604	8.2	19.3	0	.0104	.0104	.0110	90.7	103.5	68.8	1.4	33.8	-	3.99	828	-	-	2
704	3.38	454	16.1	1170	8.2	19.2	.0202	0	.0202	.0235	93.2	96.4	45.8	1.7	42.0	-	4.34	1153	-	-	2
705	3.38	458	16.1	828	8.2	19.4	.0143	0	.0143	.0173	95.1	88.7	28.3	2.2	53.2	-	4.13	980	-	-	2
706	3.39	454	16.2	594	8.2	19.2	.0102	0	.0102	.0118	93.2	92.8	46.1	1.9	44.7	-	3.99	831	-	-	2
684	3.42	664	15.3	0	-	26.1	0	0	0	-	-	-	-	-	-	-	4.90	664	-	-	
685	3.38	666	15.2	765	6.3	26.1	.0070	.0070	.0140	.0159	97.9	60.0	6.8	3.0	27.0	-	5.57	1172	1.10	.40	
686	3.43	665	15.1	964	7.9	25.7	.0089	.0088	.0177	.0202	99.0	32.1	2.4	3.6	33.3	-	5.41	1297	1.11	.43	
687	3.57	662	15.2	1142	7.9	24.9	.0104	.0104	.0208	.0240	99.4	21.2	1.2	4.5	39.1	-	5.10	1390	1.12	.42	
688	3.66	663	15.0	1346	8.2	24.0	.0125	.0124	.0249	.0284	99.5	19.6	0.7	5.2	43.9	-	4.53	1518	1.12	.44	
689	3.69	662	15.1	1335	8.2	24.0	.0124	.0122	.0246	.0297	99.4	22.5	0.5	5.0	42.3	-	4.72	1509	-	-	2
690	3.81	663	15.1	1530	8.2	23.4	.0142	.0139	.0281	.0323	99.3	26.2	0.6	5.9	47.2	-	4.50	1611	1.17	.44	
707	4.80	734	17.9	0	-	24.5	0	0	0	-	-	-	-	-	-	-	3.61	734	-	-	
691	4.76	734	16.9	1543	8.9	23.4	.0127	.0126	.0253	.0253	99.8	8.4	0.1	7.8	37.3	-	4.01	1592	1.14	.43	
692	4.74	734	17.1	1335	8.9	23.7	.0110	.0107	.0217	.0248	99.8	4.5	0.1	7.2	35.0	-	4.12	1475	1.14	.43	
693	4.78	732	17.1	1151	8.9	23.4	.0095	.0093	.0188	.0213	99.8	7.6	0.3	6.7	32.3	-	3.87	1391	1.13	.41	
694	4.76	733	17.1	902	8.9	23.6	.0074	.0073	.0147	.0164	99.5	16.0	0.9	5.6	26.9	-	3.88	1261	1.13	.43	
708	4.75	788	18.0	0	-	27.2	0	0	0	-	-	-	-	-	-	-	4.38	788	-	-	
695	4.76	788	18.0	1577	8.9	26.3	.0123	.0121	.0244	.0283	99.9	6.2	0.1	9.8	38.0	-	4.85	1608	1.14	.43	
696	4.76	786	18.0	1354	8.9	26.3	.0105	.0104	.0209	.0240	99.9	4.3	0.0	8.5	33.6	-	4.72	1501	1.14	.46	
697	4.78	786	18.1	1160	8.9	26.3	.0090	.0089	.0179	.0206	99.9	5.1	0.1	7.6	29.9	-	4.67	1407	1.13	.44	
698	4.77	785	18.1	906	8.9	26.4	.0070	.0069	.0139	.0158	99.7	12.5	0.6	6.5	25.9	-	4.73	1280	1.12	.42	

NOTES:

1. Acoustic Probe Installed, 150° of Exit Plane Surveyed
2. Radial Immersion Sampling Mode

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Table LXII. Summary of Test Results, Configuration I-15.

CONFIGURATION DESCRIPTION 90 SWIRL CAN/SHELTERED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
748	2.72	368	16.1	0	-	20.0	0	0	0	-	-	-	-	-	-	-	5.32	368	-	-	-
749	2.73	366	16.1	806	8.9	15.8	.0139	0	.0139	.0137	80.0	147.2	165.7	0.7	29.0	-	5.73	809	1.25	1.13	-
750	3.38	366	19.5	1009	9.9	18.5	.0144	0	.0144	.0151	82.1	129.5	148.4	0.8	31.5	-	5.37	842	1.27	1.10	-
751	3.39	448	16.3	602	8.2	19.1	.0103	0	.0103	.0110	87.8	120.1	94.2	1.3	31.4	-	4.31	815	-	-	1
752	3.38	457	16.2	817	8.2	19.4	.0140	0	.0140	.0146	90.0	107.9	75.1	1.4	34.4	-	4.56	951	1.23	1.01	2
753	3.38	455	16.2	816	8.2	19.4	.0140	0	.0140	.0160	90.9	103.5	66.9	1.5	36.0	-	4.39	955	-	-	1
754	3.40	458	16.3	1158	8.2	19.5	.0197	0	.0197	.0219	92.6	101.8	49.9	1.8	43.0	-	4.66	1154	-	-	1
755	3.40	458	16.3	1163	8.2	19.4	.0099	.0099	.0198	.0216	90.7	98.5	70.4	1.3	31.5	-	4.47	1140	1.08	.78	-
756	3.39	456	16.3	1393	8.2	19.4	.0118	.0119	.0237	.0263	93.5	83.4	45.6	1.6	37.8	-	4.79	1263	1.07	.68	-
757	3.48	454	16.2	1616	8.2	18.6	.0138	.0140	.0278	.0306	95.5	74.5	27.2	1.9	43.1	-	4.48	1398	1.06	.60	-
758	3.61	455	16.1	1805	8.2	18.2	.0157	.0155	.0312	.0342	96.4	73.0	18.9	2.1	45.8	-	4.26	1511	1.07	.49	-
759	3.59	454	20.1	1005	9.1	22.1	.0139	0	.0139	.0142	88.1	118.6	91.8	2.3	63.1	-	6.30	935	1.23	1.06	-
760	3.42	453	12.1	608	9.1	14.7	.0140	0	.0140	.0147	91.9	90.9	60.1	2.6	48.7	-	2.40	956	1.25	.87	-
761	4.14	456	19.5	975	8.6	18.6	.0139	0	.0139	.0147	90.9	97.7	68.1	2.5	52.2	-	4.47	953	1.22	.97	-
762	3.41	584	12.6	626	5.0	19.1	.0138	0	.0138	.0147	96.5	65.4	20.2	4.3	44.9	-	3.37	1075	1.20	.79	-
763	3.22	861	10.7	469	4.6	26.5	.0061	.0061	.0122	.0122	98.9	26.2	4.7	10.3	29.9	-	4.44	1292	1.07	.46	-
764	3.10	867	10.8	681	4.2	26.4	.0088	.0087	.0175	.0196	99.8	6.9	0.6	12.2	34.4	-	4.57	1465	1.08	.53	-
765	3.59	869	10.6	922	4.2	26.6	.0123	.0120	.0243	.0265	99.7	9.2	0.4	-	-	-	4.46	1684	1.08	.47	2
766	3.39	864	10.5	921	4.2	26.3	.0122	.0122	.0244	.0269	99.7	9.8	0.5	-	-	-	4.35	1676	-	-	1

Notes:

1. Radial Immersion Sampling Mode
2. High Density Sampling Mode

Table LXIII. Summary of Sea Level Ignition Test Results, Configuration I-15.

CONFIGURATION DESCRIPTION 90-SWIRL-CAN/SHELTERED FLAMEHOLDER

Point Number	Inlet Total Pressure Atm	Inlet Total Temperature ° K	Combustor Airflow kg/s	Type Ignitor	Required Fuel Flow (kg/hr)					
					Lightoff	50% Propagation	100% Propagation	One Cup Out	50% Cups Out	Lean Blowout
1	1.027	294	5.44	Torch	387	403	435	-	338	292
				Torch	399	410	446	-	314	241
				Spark	628	628	723	-	454	-
				Spark	571	571	650	-	-	517
				Spark	572	572	691	-	604	499
2	1.016	292	4.58	Torch	325	-	438	-	336	293
				Torch	315	408	439	-	331	290
				Torch	295	410	439	-	314	244
				Spark	570	-	570	-	-	-
3	1.006	292	3.67	Torch	243	369	408	-	304	193
				Torch	266	372	410	-	290	193
				Torch	241	371	412	-	309	197
				Spark	558	-	557	-	-	-
4	0.998	292	2.77	Torch	315	423	430	-	273	-
				Torch	317	410	416	-	-	-

Notes:

a) JP5 fuel at 293° K for all points.

b) Barometric Pressure = .987 - .988 atmospheres

Table LXIV. Summary of Test Results, Configuration I-16 (1).

CONFIGURATION DESCRIPTION 72-SWIRL-CAN/COUNTERSWIRL FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g Air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
[illegible]	[illegible]	451	16.0	0	-	18.6	0	0	0	-	-	-	-	-	-	-	3.71	451	-	-	
[illegible]	[illegible]	[illegible]	16.1	800	6.1	18.8	0	.0138	.0138	.0181	88.8	92.1	90.5	2.0	43.3	-	3.94	934	-	-	2
[illegible]	[illegible]	[illegible]	16.0	1606	6.1	18.1	.0139	.0140	.0279	.0325	93.5	74.1	47.4	2.0	40.5	-	3.81	1400	1.12	.35	
[illegible]	[illegible]	458	16.1	1300	6.1	19.2	.0112	.0113	.0225	.0237	82.9	100.7	147.7	1.2	26.9	-	4.22	1154	1.13	.53	
[illegible]	[illegible]	666	15.2	806	5.6	25.9	.0073	.0074	.0147	.0141	73.0	126.2	240.1	1.2	10.7	-	5.28	1056	1.18	.89	
[illegible]	[illegible]	667	15.2	972	5.6	25.7	.0090	.0089	.0177	.0198	85.3	92.8	125.1	2.1	17.8	-	5.38	1207	1.14	.54	
[illegible]	[illegible]	668	15.1	1341	5.6	24.9	.0123	.0124	.0247	.0284	97.2	45.2	17.5	4.3	34.9	-	4.94	1496	1.11	.34	
[illegible]	[illegible]	733	17.6	873	6.3	23.9	.0069	.0069	.0138	.0140	74.4	126.3	186.5	2.2	10.[illegible]	-	3.96	1122	1.15	.70	
[illegible]	[illegible]	732	17.7	1124	6.1	24.0	.0088	.0088	.0176	.0199	94.2	62.4	43.2	4.7	22.4	-	3.97	1325	1.11	.39	
[illegible]	[illegible]	[illegible]	17.[illegible]	1539	6.3	23.7	.0122	.0123	.0245	.0278	99.1	20.6	4.2	7.3	35.0	-	3.92	1567	1.11	.34	
[illegible]	[illegible]	[illegible]	17.1	1105	6.3	26.3	.0090	.0089	.0179	.0203	98.6	24.8	8.5	8.2	24.2	-	4.16	1442	1.11	.34	
[illegible]	[illegible]	[illegible]	17.[illegible]	1408	6.3	26.2	.0113	.0114	.0227	.0259	99.7	9.6	1.1	10.9	32.5	-	4.02	1592	1.11	.34	
[illegible]	[illegible]	[illegible]	17.[illegible]	1498	6.4	26.1	.0122	.0123	.0245	.0281	99.7	10.5	0.9	11.9	34.6	-	4.09	1656	-	-	

Notes:

1. [illegible] Probe Installed, 150° of Exit Plane Surveyed
2. Radial Traverse Sampling Mode

Table LXV. Summary of Test Results, Configuration II-1.

CONFIGURATION DESCRIPTION: CF6-50 PRODUCTION COMBUSTOR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered Over-All	Fuel-Air Ratio g fuel / g air, Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	Emission Indices g/kg fuel, HC	Emission Indices g/kg fuel, NOx	Emission Indices g/kg fuel, NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
1	1.01	292	2.7	-	-	6.0	-	-	-	-	-	-	-	-	0.66	292	-	-	
22	3.41	453	16.1	356	2.7	19.0	.0061	.0061	87.6	133.7	92.4	2.61	56.0	-	4.07	677	-	-	1
21	3.37	445	16.1	587	2.2	18.9	.0101	.0105	91.5	103.5	60.0	2.7	59.2	6	4.29	813	-	-	1
23	3.39	454	16.2	819	5.5	19.1	.0141	.0156	96.1	69.6	22.6	2.8	60.3	3	4.39	983	-	-	1
24	3.37	453	15.3	631	5.8	18.4	.0115	.0127	93.5	87.3	44.4	2.7	57.1	-	3.80	871	-	-	1
25	3.35	456	13.9	670	5.8	17.1	.0134	.0150	94.7	75.6	35.7	2.8	54.9	-	3.22	947	-	-	1
20	3.44	449	16.1	1172	5.1	18.7	.0202	.0220	98.0	53.0	7.6	3.2	68.4	-	4.63	1195	-	-	
14	3.37	457	16.8	348	2.2	20.1	.0057	.0055	79.3	209.8	158.3	1.8	41.1	-	5.20	653	-	-	
12	3.38	458	16.9	591	2.2	20.2	.0097	.0102	91.3	123.9	57.9	2.0	58.2	-	5.40	803	-	-	
16	3.36	449	16.7	821	2.2	19.7	.0136	.0145	95.6	78.6	25.3	2.6	60.1	-	5.57	948	-	-	
43	3.39	454	16.2	353	3.6	19.6	.0060	.0067	94.6	94.2	31.7	3.8	97.4	-	4.46	680	-	-	2
40	3.37	448	16.8	598	7.6	19.7	.0099	.0116	97.4	60.7	11.8	3.5	84.5	-	4.55	829	-	-	2
37	3.41	442	16.8	816	5.9	19.4	.0135	.0147	98.7	42.8	3.4	3.6	90.8	-	4.76	958	-	-	2
35	6.84	652	29.9	1536	3.2	25.3	.0143	.0143	99.8	7.3	0.3	8.6	54.3	-	5.12	1176	-	-	
34	6.90	663	30.5	1975	4.2	25.8	.0180	.0196	99.9	2.6	-	8.8	53.7	1	4.69	1311	-	-	
18	9.50	735	35.5	3192	4.4	24.5	.0250	.0270	100.0	0.7	0.2	14.2	45.7	7	4.36	1595	-	-	
17	9.54	730	36.0	1787	4.8	24.7	.0138	.0153	99.9	1.4	0.5	15.9	53.4	11	4.18	1224	-	-	
28	9.53	833	34.3	2214	2.2	26.7	.0179	.0197	100.0	0.4	0.3	22.9	43.2	1	4.48	1454	-	-	
29	9.51	827	33.8	2750	2.7	26.3	.0226	.0245	100.0	0.3	0.1	21.6	41.6	2	4.53	1594	-	-	
30	9.51	858	33.0	1422	2.4	26.6	.0120	.0129	100.0	0.7	-	28.5	46.5	2	6.01	1292	-	-	
31	9.50	857	33.0	2129	2.4	26.6	.0179	.0193	100.0	0.1	0.0	27.7	45.4	1	4.46	1478	-	-	
32	9.52	857	33.4	2910	2.5	26.8	.0242	.0264	100.0	0.4	0.0	25.0	41.4	1	4.42	1668	-	-	

NOTES:

1. Alternate Nozzles Fueled
2. Fueled in Two 90° Sectors

Table LXVI. Summary of Test Results, Configuration II-2.

CONFIGURATION DESCRIPTION SINGLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air Metered Over-All	Fuel-Air Ratio Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
[illegible]	[illegible]	[illegible]	16.2	0	-	19.8	0	-	-	-	-	-	-	-	6.24	468	-	-	
[illegible]	3.42	451	16.4	1174	6.6	19.4	.0199	.0198	84.9	110.0	126.0	1.5	34.5	-	6.21	1082	-	-	
[illegible]	3.34	450	16.2	1137	8.7	19.0	.0199	.0205	91.8	83.6	62.6	2.6	64.8	-	6.02	1130	-	-	1
[illegible]	[illegible]	451	16.2	819	8.7	18.8	.0141	.0143	87.6	96.2	101.3	2.6	62.7	-	5.95	923	-	-	1
[illegible]	3.37	452	15.9	1035	9.1	18.8	.0180	.0205	91.6	97.0	61.0	3.0	73.1	-	5.84	1073	-	-	2
[illegible]	3.37	450	15.9	810	9.6	18.6	.0142	.0185	91.8	77.6	64.0	3.0	72.0	-	5.77	950	-	-	2
[illegible]	3.39	[illegible]	15.9	605	5.1	18.6	.0106	.0126	87.[illegible]	107.0	101.0	2.8	62.9	-	5.68	917	-	-	2
[illegible]	[illegible]	[illegible]	15.7	[illegible]	7.0	18.6	.0144	.0172	91.6	103.0	60.0	3.7	89.9	-	5.80	962	-	-	3
[illegible]	[illegible]	[illegible]	[illegible]	1541	2.0	25.7	[illegible]	.0157	94.6	102.0	29.7	4.6	28.6	-	7.46	1142	-	-	
[illegible]	[illegible]	[illegible]	30.0	1995	1.9	25.7	.0185	.0205	97.0	64.8	15.0	4.5	26.4	-	7.56	1305	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	1762	2.2	24.2	[illegible]	.0158	97.6	63.5	9.2	7.6	23.6	5	5.84	1228	-	-	
[illegible]	9.57	729	15.3	2692	2.1	24.1	.0212	.0240	99.2	23.2	2.4	11.2	35.2	-	5.71	1459	-	-	
[illegible]	[illegible]	826	14.8	2225	2.1	26.9	.0178	.0204	99.5	16.3	1.2	15.2	27.7	-	6.21	1437	-	-	
[illegible]	9.55	826	[illegible]	2795	2.2	26.5	.0227	.0256	99.7	9.0	0.8	19.1	37.2	-	6.09	1587	-	-	
[illegible]	[illegible]	857	32.9	1419	2.0	26.6	.0119	.0132	97.9	50.4	9.7	11.8	19.2	-	5.86	1271	-	-	
[illegible]	[illegible]	[illegible]	33.0	2145	2.3	26.6	.0180	.0202	99.6	12.1	0.9	17.8	29.1	-	5.91	1473	-	-	
[illegible]	[illegible]	[illegible]	33.2	2912	2.1	26.6	.0244	.0267	99.8	6.2	0.4	24.7	40.1	2	5.99	1668	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	939	8.9	27.1	.0239	.0260	99.4	22.8	0.7	12.4	40.2	1	6.61	1645	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	611	8.9	27.0	.0157	.0176	98.5	34.9	6.9	6.8	22.5	-	6.41	1397	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	1596	2.9	28.8	.0165	.0186	98.3	35.7	8.6	11.5	29.2	5	7.41	1390	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	1594	3.5	26.8	.0181	.0202	99.3	22.8	1.6	13.5	32.5	2	6.41	1446	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	1528	2.9	26.3	.0177	.0198	99.3	22.9	1.5	14.4	33.0	2	6.02	1435	-	-	
[illegible]	[illegible]	[illegible]	[illegible]	2053	2.9	26.4	.0236	.0255	99.7	12.2	0.7	17.4	39.9	2	6.09	1617	-	-	
[illegible]	[illegible]	[illegible]	24.7	2348	3.2	27.0	.0230	.0258	99.6	13.0	0.8	16.6	39.0	2	6.46	1596		-	
[illegible]	[illegible]	[illegible]	[illegible]	2075	2.7	26.1	.0240	.0269	99.7	11.5	0.6	18.3	41.1	2	5.99	1628	-	-	
[illegible]	[illegible]	[illegible]	28.7	2429	2.1	27.6	.0235	.0256	99.7	11.4	0.8	17.2	38.5	2	6.93	1613	-	-	

NOTES:

1. Fueled in Two Opposing 120° Sectors
2. Fueled in Two Opposing 90° Sectors
3. Fueled in Two Opposing 60° Sectors

Table LXVII. Summary of Test Results, Configurations II-3, 5 (1).

CONFIGURATION DESCRIPTION SINGLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature ° K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air Metered Over-All	Fuel-Air Ratio g fuel / g air Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature ° K	Profile Factor	Pattern Factor	Notes
148	3.55	411	16.0	0	-	16.8	0	-	-	-	-	-	-	-	3.86	411	-	-	
149	3.42	446	15.8	1163	7.2	18.5	.0205	.0210	82.0	110.0	154.1	1.0	20.5	-	4.52	1035	-	-	
150	3.31	454	15.8	770	7.1	19.3	.0135	.0183	90.2	91.2	76.8	1.4	33.5	-	4.85	924	-	-	2
152	3.40	453	15.8	1079	7.1	18.8	.0190	.0229	91.5	94.7	63.0	1.7	39.6	-	4.75	1105	-	-	2
154	3.37	453	15.2	560	6.6	18.9	.0098	.0125	84.6	119.1	127.0	1.0	23.0	-	4.71	780	-	-	2
210	2.85	405	11.4	0	-	14.9	0	-	-	-	-	-	-	-	3.23	405	-	-	
211	11.59	733	35.2	3098	1.0	20.4	.0244	.0251	99.4	16.6	1.9	16.3	37.9	16	3.27	1561	-	-	
212	9.60	729	35.9	2690	1.0	24.4	.0208	.0218	99.0	31.8	3.1	10.5	32.4	10	4.84	1443	-	-	
213	9.57	727	35.9	1787	1.0	24.4	.0138	.0142	96.4	81.5	17.2	6.9	21.2	26	4.81	1207	-	-	
214	9.57	729	36.4	2815	.6	24.8	.0239	.0249	99.3	22.8	2.1	12.0	38.0	7	4.93	1545	-	-	
215	9.56	853	33.3	1413	.8	26.6	.0118	.0121	97.6	60.8	9.8	9.9	16.0	17	4.80	1262	-	-	
216	9.57	854	33.2	2156	.8	26.5	.0180	.0196	99.4	14.1	2.5	16.5	25.8	9	4.78	1469	-	-	
217	9.57	855	32.7	2911	.6	26.2	.0248	.0255	99.7	6.8	1.6	24.3	38.3	5	4.79	1676	-	-	
218	9.58	853	32.7	2915	.6	26.2	.0248	.0252	99.7	6.1	1.7	22.3	35.5	12	4.91	1672	-	-	3

NOTES:

1. Configuration II-3 Reading 148 154, Configuration II-5 Reading 210-218
2. Fueled in Two Opposing 90° Sectors
3. Radial Immersion Sampling Mode

Table LXVIII. Summary of Test Results, Configuration II-4.

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
[illegible]	[illegible]	[illegible]	16.3	0	-	20.2	0	0	0	-	-	-	-	-	-	-	5.54	470	-	-	
[illegible]	[illegible]	451	16.3	864	3.4	19.1	.0147	0	.0147	.0101	55.9	158.0	397.5	0.3	7.7	-	4.59	770	1.25	[illegible]	
[illegible]	[illegible]	[illegible]	16.6	1165	4.4	18.8	.0095	.0100	.0195	.0214	83.9	129.5	131.2	0.9	21.2	-	5.09	1062	1.16	.49	
[illegible]	1.38	454	16.4	596	3.7	19.6	.0099	0	.0099	.0101	78.9	148.2	171.5	1.7	37.2	-	4.85	762	-	-	1
[illegible]	1.39	456	16.4	911	3.9	19.5	.0138	0	.0138	.0152	86.8	116.7	104.6	1.5	32.9	-	4.89	920	-	-	1
[illegible]	[illegible]	454	16.2	582	3.4	19.2	0	.0099	.0099	.0089	73.9	175.9	220.3	0.7	14.5	-	[illegible]	743	-	-	1
[illegible]	[illegible]	[illegible]	16.5	909	3.9	19.2	0	.0136	.0136	.0135	84.5	116.2	127.5	1.2	27.5	-	4.99	593	-	-	1
[illegible]	1.34	655	15.2	765	2.9	25.8	.0069	.0070	.0139	.0154	91.4	151.9	50.2	2.1	19.1	4	6.27	1107	1.11	.40	
[illegible]	[illegible]	659	15.2	994	2.9	25.9	.0090	.0089	.0179	.0203	94.9	92.1	30.0	2.7	24.0	2	4.56	1263	-	-	1
[illegible]	1.36	658	15.3	989	3.7	26.2	.0089	.0089	.0178	.0204	95.8	89.8	21.1	2.8	25.4	-	6.44	1263	1.11	.35	
[illegible]	[illegible]	731	[illegible]	975	3.4	24.1	.0063	.0070	.0133	.0154	94.6	92.5	12.2	4.4	19.8	4	4.58	1206	1.11	.31	
[illegible]	[illegible]	731	17.4	1324	3.7	24.0	.0101	.0110	.0211	.0237	99.0	25.5	3.8	6.7	30.5	4	4.77	1462	1.10	.33	
[illegible]	[illegible]	859	[illegible]	791	3.9	26.5	.0059	.0060	.0119	.0133	98.0	34.2	11.9	7.8	18.3	3	4.71	1271	1.13	.32	
[illegible]	[illegible]	[illegible]	16.3	[illegible]	4.1	26.6	.0090	.0089	.0179	.0198	98.6	14.1	10.5	11.2	26.7	3	4.78	1463	1.12	[illegible]	
[illegible]	[illegible]	859	16.4	[illegible]	4.3	26.6	.0090	.0089	.0179	.0190	97.2	14.7	24.0	11.1	26.6	2	4.71	1455	-	-	1
[illegible]	[illegible]	[illegible]	16.5	1441	4.4	26.4	.0120	.0123	.0243	.0273	99.3	8.2	5.0	13.9	34.2	1	4.72	1654	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	1055	4.3	26.5	.0109	.0070	.0178	.0190	97.7	18.3	19.1	10.8	25.9	2	4.78	1454	-	-	1
[illegible]	4.73	[illegible]	16.4	1032	4.4	26.5	.0078	.0100	.0178	.0189	97.5	20.5	20.5	10.0	24.3	1	4.76	1452	-	-	1

NOTES:

1. Radial Immersion Sampling Mode

Table LXIX. Summary of Test Results, Configuration II-6.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Main Stage	Metered, Pilot Stage	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
219	3.31	398	15.8	0	2.3	17.2	0	0	0	-	-	-	-	-	-	-	3.82	398	-	-	
220	3.34	453	16.2	349	2.4	19.8	0	.0060	.0060	.0059	91.7	101.8	59.3	2.0	42.8	-	4.90	678	1.15	.40	
221	3.38	458	16.7	587	2.6	20.0	0	.0098	.0098	.0106	98.1	39.3	10.1	3.9	85.7	2	5.12	843	1.13	.40	
222	3.37	455	16.2	811	2.6	19.6	0	.0139	.0139	.0147	93.9	32.7	3.7	3.6	78.7	1	5.14	987	1.12	.39	
223	3.43	453	15.8	1162	2.6	18.8	0	.0204	.0204	.0227	99.1	32.7	1.5	3.0	63.5	-	4.70	1214	1.10	.42	
224	4.72	729	17.5	499	2.6	24.2	0	.0080	.0080	.0083	99.8	3.1	1.6	14.6	66.0	-	4.34	1035	1.14	.44	
225	4.74	733	17.5	763	2.6	24.2	0	.0121	.0121	.0139	99.8	4.1	0.9	16.7	74.1	1	4.52	1173	-	-	1
226	4.73	734	17.4	1021	2.6	24.2	0	.0163	.0163	.0181	99.8	5.0	0.6	11.1	49.1	2	4.65	1307	1.11	.58	
227	4.71	734	17.5	1019	2.6	24.3	.0084	.0078	.0162	.0164	95.0	89.5	29.4	8.2	36.6	1	4.64	1277	1.08	.38	2
228	4.70	734	17.3	1481	2.6	24.2	.0163	.0082	.0245	.0246	98.3	50.3	4.9	8.1	35.5	1	4.84	1556	1.07	.49	2
229	4.71	733	17.5	1135	2.6	24.4	.0061	.0119	.0180	.0188	97.3	62.9	12.8	11.6	51.8	1	4.87	1349	1.09	.40	2
230	4.73	731	17.5	1514	2.6	24.3	.0122	.0118	.0240	.0239	99.2	26.6	1.6	10.7	48.2	0	4.85	1564	-	-	1, 2
231	4.74	729	17.5	1516	2.6	24.1	.0122	.0119	.0241	.0252	99.0	32.3	2.3	10.4	46.7	-	5.02	1553	1.07	.45	2, 3
232	4.77	731	17.5	1275	2.3	24.1	.0043	.0159	.0202	.0219	98.1	45.4	8.8	9.1	40.5	0	4.75	1433	1.11	.37	2
233	4.78	731	17.5	1531	2.3	24.0	.0084	.0160	.0244	.0259	99.2	24.5	2.1	8.8	38.8	0	4.73	1564	1.25	.41	2
234	4.78	731	17.6	1525	2.6	24.2	.0160	.0080	.0240	.0250	97.5	64.6	9.7	6.6	29.5	0	5.06	1535	1.07	.26	
235	4.78	732	17.6	1529	2.6	24.2	.0121	.0119	.0240	.0258	98.6	39.2	4.7	9.9	43.5	0	4.86	1552	-	-	1
236	4.76	730	17.5	1533	2.6	24.0	.0083	.0160	.0243	.0258	97.9	50.4	9.4	7.7	34.4	1	4.97	1548	1.10	.24	
237	4.77	730	17.5	1549	2.6	26.0	.0188	.0058	.0246	.0246	95.0	82.1	30.7	3.9	17.2	0	4.92	1526	1.09	.32	

NOTES:

1. Radial Immersion Sampling Mode
2. Alternate Chutes Pooled
3. High Density Sampling Mode

Table LXX. Summary of Test Results, Configuration II-7.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Main Stage	Metered: Pilot Stage	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
238	3.42	369	20.4	0	2.4	19.2	0	0	0	-	-	-	-	-	-	-	5.64	369	-	-	
239	3.49	366	20.2	712	2.4	18.6	0	.0099	.0099	.0098	93.4	64.9	50.5	1.9	67.2	-	5.73	739	1.17	.67	
240	3.49	366	20.0	1008	2.1	18.4	0	.0140	.0140	.0148	95.8	53.1	30.0	1.8	61.5	-	5.88	900	1.19	.73	
241	3.39	366	20.2	1146	2.0	18.1	0	.0158	.0158	.0166	97.9	49.9	9.5	2.1	69.4	-	5.72	985	1.15	1.69	
242	3.42	455	16.0	574	2.1	18.9	0	.0100	.0100	.0113	99.0	27.2	3.5	4.3	86.8	-	4.54	851	-	-	1
243	3.46	369	26.2	0	-	15.2	0	0	0	-	-	-	-	-	-	-	3.39	369	-	-	
244	3.42	458	24.2	582	5.0	19.5	0	.0100	.0100	.0109	98.9	29.7	4.4	4.2	93.9	-	4.90	861	1.14	.52	2
245	3.37	460	16.7	697	5.0	20.0	0	.0118	.0118	.0125	99.1	28.0	2.2	3.9	87.8	-	5.06	916	1.13	.60	
246	3.37	456	16.2	823	4.4	19.5	0	.0141	.0141	.0157	99.2	28.5	1.3	3.3	73.6	-	5.15	994	1.10	.55	2
247	3.40	457	16.3	920	4.0	19.5	0	.0157	.0157	.0169	99.1	28.4	0.9	2.8	61.8	-	5.01	1051	1.08	.62	
248	3.37	456	16.2	1035	4.0	19.5	0	.0174	.0178	.0188	99.2	31.2	0.6	2.5	54.2	-	5.25	1120	1.09	.63	
249	3.38	459	16.4	1153	3.7	20.0	0	.0195	.0195	.0203	99.1	35.4	0.4	2.5	55.9	-	5.39	1178	1.10	.69	
250	3.40	456	15.4	536	3.7	18.4	0	.0097	.0097	.0107	98.8	30.7	4.3	4.3	90.1	-	4.29	834	1.14	.54	
251	3.39	450	15.3	758	3.6	18.2	0	.0138	.0138	.0144	99.3	25.5	1.1	3.3	70.6	-	4.35	990	1.11	.44	
252	3.39	450	15.3	1082	2.7	18.4	0	.0195	.0195	.0203	99.2	33.1	0.5	2.8	59.4	-	4.57	1179	1.11	.68	
253	3.38	450	14.5	503	2.7	17.4	0	.0096	.0096	.0102	98.7	29.9	5.6	4.2	85.3	-	3.88	837	1.14	.53	
254	3.38	451	14.4	708	2.7	17.4	0	.0136	.0136	.0148	99.3	23.7	1.5	3.6	73.0	-	3.77	993	1.10	.59	
255	3.38	451	14.2	1025	2.7	17.2	0	.0198	.0198	.0206	99.2	29.8	0.9	3.0	58.7	-	3.82	1177	1.09	.65	
256	3.39	592	13.0	445	2.4	20.4	0	.0095	.0095	.0105	99.8	8.5	0.2	8.2	83.3	-	3.92	965	1.11	.41	
257	3.39	591	12.8	622	2.3	20.2	0	.0135	.0135	.0149	99.8	10.1	0	6.5	65.7	-	3.98	1099	1.13	.58	
258	3.39	591	12.7	891	2.1	20.0	0	.0195	.0195	.0218	99.6	15.4	0	5.0	49.2	-	3.94	1294	1.10	.52	
259	4.72	731	17.7	372	2.1	24.5	0	.0058	.0058	.0058	99.9	3.1	0.2	9.0	40.6	-	4.39	958	1.12	.44	
260	[illegible]	731	18.0	492	2.2	24.4	0	.0076	.0076	.0080	100.0	1.3	0.1	14.7	65.2	-	4.56	1026	1.11	.43	2
261	4.76	731	17.6	623	2.4	24.1	0	.0098	.0098	.0104	99.9	2.2	0.1	18.5	82.4	-	4.66	1097	1.12	.48	
262	4.79	730	17.7	765	2.0	24.4	0	.0116	.0116	.0127	99.9	2.9	0.1	16.5	74.2	-	4.78	1153	1.12	.52	
263	4.74	731	17.8	978	2.0	24.4	0	.0153	.0153	.0183	99.9	3.4	0	10.5	49.1	-	4.77	1279	-	-	1
264	4.75	731	17.8	1233	1.9	24.4	0	.0193	.0193	.0218	99.9	5.8	0	9.3	43.0	-	4.82	1411	1.14	.51	
266	4.72	730	17.6	1001	4.2	24.2	0	.0159	.0159	.0190	99.9	4.7	0.1	10.4	48.4	-	4.71	1299	1.13	.54	2
267	4.78	923	17.2	303	5.1	26.4	0	.0049	.0049	.0049	99.9	2.9	0.2	10.1	30.0	-	4.79	1022	1.13	.39	
268	4.79	[illegible]	17.5	495	5.4	26.7	0	.0058	.0058	.0060	99.9	1.3	0.1	11.9	42.6	-	4.67	1055	1.12	.38	

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Table LXX. Summary of Test Results, Configuration II-7 (Concluded).

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
269	4.74	822	17.1	485	5.3	26.4	0	.0079	.0079	.0085	100.0	1.4	0.1	24.5	73.6	-	4.81	1107	1.13	.40	
270	4.74	822	17.1	973	5.3	26.5	0	.0158	.0158	.0182	99.9	3.1	0	15.3	45.8	-	5.01	1373	1.15	.55	
271	4.78	823	16.9	1211	5.0	26.0	0	.0199	.0199	.0228	99.9	4.3	0	13.3	38.6	-	4.88	1506	1.13	.46	
273	4.78	823	16.8	1486	5.3	25.9	0	.0245	.0245	.0268	99.8	8.4	0	12.3	35.9	-	4.94	1654	1.13	.53	
274	6.82	830	24.9	436	3.4	26.9	0	.0049	.0049	.0047	99.9	2.2	0.2	12.8	30.0	-	4.78	1013	1.11	.39	
275	6.80	830	23.5	523	3.4	26.6	0	.0059	.0059	0060	100.0	1.0	0.1	18.1	42.1	-	4.81	1046	1.11	.38	
276	6.76	830	24.7	586	3.4	27.0	0	.0068	.0068	.0071	100.0	1.0	0.2	24.7	59.1	-	4.99	1079	1.13	.40	
277	6.80	831	24.5	2002	3.6	26.6	.0178	.0049	.0227	.0256	96.9	85.4	11.0	7.2	16.5	-	5.11	1579	-	-	
278	6.86	831	24.3	1937	3.4	25.2	.0170	.0061	.0231	.0258	97.9	73.6	3.8	8.9	20.3	-	4.90	1612	-	-	
279	6.86	831	27.6	2199	3.6	29.4	.0174	.0047	.0221	.0265	96.0	92.9	18.0	5.8	14.8	-	6.24	1562	-	-	
280	6.87	832	27.9	2115	3.6	29.5	.0163	.0057	.0220	.0246	97.3	82.1	8.0	7.1	17.9	-	6.33	1564	-	-	

NOTES:

1. Radial Immersion Sampling Mode
2. High Density Sampling Mode

Table LXXI. Summary of Test Results, Configuration II-8.

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
287	1.64	379	9.4	0	—	18.8	0	0	0	-	-	-	-	-	-	-	5.92	57?	-	-	
288	3.36	458	16.1	558	6.3	19.5	.0101	0	.0101	.0117	95.7	81.1	24.5	2.6	59.4	-	4.88	843	-	-	2
289	3.42	451	16.2	805	6.7	19.0	.0138	0	.0138	.0166	98.1	45.5	8.6	2.9	67.4	-	4.72	974	-	-	2
290	3.39	452	16.0	552	7.3	19.0	0	.0101	.0101	.0110	95.1	85.9	28.6	2.4	57.3	-	4.73	832	-	-	1
291	3.35	452	16.1	804	6.3	19.2	0	.0139	.0139	.0155	98.3	49.9	5.4	2.9	68.8	-	4.84	979	-	-	1
302	3.40	452	16.1	474	7.1	19.0	.0080	0	.0080	.0187	99.1	29.3	2.3	2.9	69.6	-	4.56	776	-	-	2
303	3.41	451	16.2	611	7.3	18.9	.0105	0	.0105	.0238	98.7	46.7	2.4	2.9	68.5	-	4.69	875	-	-	2
292	3.38	453	16.3	797	5.7	19.4	.0069	.0067	.0136	.0148	87.7	137.6	91.0	1.4	32.9	-	4.80	920	-	-	1
293	3.37	453	16.3	791	6.0	19.4	.0068	.0068	.0136	.0148	87.3	136.8	95.5	1.4	32.3	-	4.88	915	1.10	.35	3
294	3.19	452	15.0	1144	7.3	19.0	.0099	.0099	.0198	.0222	96.9	67.3	15.2	2.1	50.1	-	4.83	1207	1.09	.30	
295	3.43	668	15.2	805	7.3	25.7	.0074	.0074	.0148	.0164	99.3	24.8	1.4	4.0	35.4	-	6.00	1209	1.09	.32	
296	3.43	665	15.0	971	9.4	25.5	.0090	.0090	.0180	.0200	99.7	10.3	0.5	4.9	44.4	-	6.10	1543	1.08	.31	
301	3.69	663	15.2	1335	5.3	24.1	.0122	.0122	.0244	.0268	99.9	3.6	0	6.1	49.8	-	5.33	1518	1.09	.24	
297	4.79	719	17.7	869	5.1	24.4	.0068	.0068	.0136	.0154	99.8	8.2	0.5	7.0	31.7	-	4.59	1242	1.09	.32	
298	4.77	[illegible]	17.7	1301	5.3	24.3	.0102	.0102	.0204	.0229	100.0	1.7	0.2	10.0	46.8	-	4.59	1453	1.09	.25	
299	4.78	[illegible]	17.6	1540	5.3	24.2	.0122	.0122	.0244	.0269	100.0	1.3	0.1	10.8	49.7	-	4.59	1580	1.10	.23	3
300	4.77	[illegible]	17.4	1539	6.4	24.1	.0123	.0122	.0245	.0269	99.9	1.3	0.1	10.7	49.3	-	4.58	1582	-	-	1

NOTES:

1. Radial Immersion Sampling Mode
2. Fueled in one 168° Sector
3. High Density Sampling Mode

Table LXXII. Summary of Test Results, Configuration II-9 (1).

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
359	3.39	454	16.0	-	-	19.1	0	0	0	-	-	-	-	-	-	-	4.17	454	-	-	
360	3.38	459	15.9	601	4.4	19.3	.0105	0	.0105	.0116	97.8	42.2	11.3	3.1	67.6	-	4.44	872	-	-	2
361	3.38	458	16.3	817	4.7	19.6	.0139	0	.0139	.0175	98.5	41.7	4.6	3.8	80.3	-	4.50	989	-	-	2
362	3.35	453	16.1	1153	5.1	19.2	.0199	0	.0199	.0255	98.2	66.5	2.3	3.3	76.7	-	4.56	1173	-	-	2
386	3.45	448	16.0	639	5.1	18.6	.0111	0	.0111	.0169	98.5	34.3	6.1	3.7	83.9	-	3.98	874	-	-	2
363	3.40	659	15.2	542	4.4	25.8	.0099	0	.0099	.0115	99.7	8.7	0.4	7.1	63.5	-	5.60	1028	-	-	
364	3.36	658	15.2	985	4.2	26.0	.0180	0	.0180	.0219	98.9	44.4	0.1	7.2	65.2	-	5.82	1290	-	-	2
365	3.64	659	15.3	1320	4.4	24.4	.0098	.0142	.0240	.0267	99.1	29.8	1.5	5.4	44.2	-	5.01	1496	1.15	.39	
366	4.75	732	17.5	391	5.7	24.1	.0062	0	.0062	.0070	99.8	5.3	0.5	7.3	34.2	-	4.10	972	-	-	
367	4.79	735	17.1	507	6.0	23.7	.0082	0	.0082	.0098	99.9	1.7	0.2	10.7	48.1	-	3.82	1051	-	-	
368	4.78	734	17.0	656	6.2	23.7	.0107	0	.0107	.0115	99.9	2.1	0.3	12.6	57.7	-	4.02	1138	-	-	
369	4.74	729	17.7	1152	7.0	23.6	.0061	.0120	.0181	.0199	98.9	32.0	3.6	6.3	29.9	-	4.26	1371	1.12	.31	
370	4.76	728	17.7	897	6.4	23.6	.0061	.0080	.0141	.0149	97.5	70.6	8.8	5.6	26.4	-	4.13	1230	1.18	.45	
371	4.76	826	17.1	1086	6.7	25.4	.0100	.0077	.0177	.0179	99.3	24.7	1.0	12.1	35.9	-	4.54	1446	1.31	.70	
372	4.74	823	17.0	1097	6.7	25.9	.0060	.0119	.0179	.0193	99.7	10.3	0.3	9.1	27.3	-	4.38	1440	1.14	.32	
373	4.74	825	17.2	1395	7.0	26.1	.0098	.0128	.0226	.0241	99.8	5.7	0.3	12.1	36.5	-	4.45	1592	1.20	.43	
374	4.74	825	17.1	1396	7.0	25.9	.0059	.0168	.0227	.0250	99.9	3.3	0.2	10.2	30.3	-	4.64	1592	1.13	.32	
375	4.70	859	17.2	410	6.7	26.7	.0066	0	.0066	.0076	100.0	0.6	0.1	12.0	30.2	-	4.68	1134	-	-	2
376	4.68	854	17.6	1072	7.0	26.3	.0100	.0083	.0183	.0185	99.8	15.4	0.4	14.5	37.2	-	4.48	1495	1.27	.60	
377	4.67	853	16.7	1065	6.7	26.8	.0080	.0098	.0178	.0185	99.7	10.8	0.3	11.5	30.1	-	4.67	1459	1.22	.40	
378	4.73	861	16.4	1443	7.0	26.4	.0050	.0195	.0245	.0267	99.9	4.7	0.1	12.0	29.5	-	4.44	1679	1.12	.30	
379	4.75	863	16.4	1446	7.2	26.4	.0050	.0195	.0245	.0269	99.9	4.5	0.0	11.8	28.9	-	4.53	1683	-	-	2
380	4.77	859	16.4	1437	8.4	26.0	.0099	.0145	.0244	.0254	99.9	3.6	0.1	15.0	37.1	-	4.35	1675	1.20	.38	
381	4.77	858	15.8	1437	7.2	26.0	.0080	.0163	.0243	.0257	99.9	3.1	0.1	13.0	32.1	-	4.38	1665	1.15	.29	
382	4.75	859	16.3	1435	8.4	25.9	.0060	.0185	.0245	.0263	99.9	3.8	0.0	12.3	30.2	-	4.31	1675	1.14	.31	
383	6.76	835	24.3	1575	5.1	26.6	.0050	.0131	.0181	.0193	99.8	6.1	0.2	12.4	29.0	-	4.56	1470	1.15	.32	
384	6.78	833	24.9	2017	5.0	27.1	.0049	.01'6	.0225	.0243	99.9	3.5	0.1	12.7	30.4	-	4.93	1591	1.11	.27	
385	7.15	831	29.5	2401	5.6	29.8	.0040	.0187	.0227	.0252	99.7	6.6	1.3	11.9	31.2	-	5.09	1596	1.13	.33	

NOTES:

1. Acoustic Probe Installed, 150° of Exit Plane Surveyed
2. Radial Immersion Sampling Mode

Table LXXIII. Summary of Test Results, Configuration II-10.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Main Stage	Metered: Pilot Stage	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
187	2.94	371	14.4	0	-	16.5	0	0	0	-	-	-	-	-	-	-	3.80	373	-	-	
188	2.74	358	14.2	714	5.1	16.6	0	.0143	.0143	.0145	96.4	64.5	20.5	2.4	92.4	-	4.69	906	-	-	1
189	3.45	360	17.8	911	5.1	16.6	0	.0142	.0142	.0139	97.6	51.1	12.2	2.6	86.8	-	4.33	911	-	-	1
190	3.46	459	15.9	816	4.6	18.8	0	.0143	.0143	.0144	99.3	25.9	1.3	3.6	77.1	-	4.29	1010	-	-	1
191	4.14	457	19.2	974	5.1	18.2	0	.0141	.0141	.0141	99.4	20.2	0.9	1.7	71.4	-	4.27	996	-	-	1
192	4.14	511	17.8	906	4.7	20.1	0	.0141	.0141	.0142	99.7	12.7	0.3	5.0	66.7	-	4.27	1066	-	-	1
193	3.62	662	13.6	682	4.6	21.5	0	.0139	.0139	.0146	99.8	9.1	0.2	6.5	67.3	-	4.30	1185	-	-	1
194	4.94	722	17.6	847	4.7	24.1	0	.0140	.0140	.0148	99.9	4.0	0.2	13.5	60.8	-	4.18	1246	-	-	1
198	4.92	731	17.6	884	4.7	21.8	.0069	.0070	.0139	.0142	88.2	91.8	96.7	6.0	27.4	-	4.41	1170	-	-	1,2
199	4.79	732	17.6	1131	4.7	24.1	.0109	.0069	.0178	.0188	94.2	82.4	39.2	5.8	22.2	-	4.46	1376	-	-	1,2
397	4.92	733	17.6	1139	4.7	21.9	.0120	.0060	.0180	.0184	83.0	116.0	143.2	3.2	14.5	-	4.37	1297	1.08	.55	
400	4.93	711	17.6	1384	4.7	24.0	.0148	.0070	.0218	.0230	94.2	83.1	38.7	4.9	22.2	-	4.52	1455	1.09	.50	
401	4.81	730	17.6	1383	4.6	21.9	.0168	.0050	.0218	.0228	86.5	94.5	112.6	2.5	11.3	-	4.43	1394	1.09	.51	
402	4.80	731	17.6	1554	4.6	21.9	.0175	.0070	.0245	.0259	95.7	71.7	26.4	4.9	22.5	-	4.63	1542	1.08	.49	
403	4.79	731	17.4	1545	4.6	21.7	.0197	.0050	.0247	.0261	91.1	82.1	69.7	3.1	13.9	-	4.47	1513	1.05	.44	
404	4.79	927	16.8	1095	4.3	25.9	.0131	.0050	.0181	.0191	89.7	104.9	78.5	3.6	9.9	-	4.53	1398	1.08	.42	
405	4.81	824	17.0	1106	4.0	25.8	.0110	.0070	.0180	.0190	95.1	90.9	27.9	7.5	21.2	-	4.49	1417	1.11	.41	
406	4.90	922	17.0	1155	4.0	25.9	.0152	.0070	.0222	.0236	98.3	50.6	5.2	8.1	22.8	-	4.67	1564	1.11	.42	
407	4.81	822	17.0	1154	4.0	25.8	.0171	.0050	.0221	.0238	95.5	71.9	28.0	4.8	13.6	-	4.69	1537	1.12	.48	
408	4.83	924	16.9	1509	4.0	25.8	.0195	.0053	.0248	.0266	97.4	56.6	12.8	5.8	16.2	-	4.64	1623	1.08	.44	
409	4.82	823	16.8	1507	4.4	25.6	.0178	.0071	.0249	.0263	98.8	37.9	2.9	8.6	24.3	-	4.60	1646	1.13	.43	
410	6.96	834	25.2	1592	2.6	27.0	.0127	.0049	.0176	.0188	92.6	100.4	5.1	5.1	11.4	-	4.82	1401	1.09	.39	
411	6.94	834	24.5	1599	2.7	26.6	.0111	.0070	.0181	.0192	97.0	76.4	12.5	10.5	23.4	-	4.74	1451	1.12	.42	
412	6.99	836	24.5	1940	2.7	26.5	.0150	.0070	.0220	.0237	98.9	38.6	2.1	11.1	24.1	-	4.84	1580	1.10	.39	
413	6.97	836	24.5	1962	2.7	26.7	.0170	.0050	.0220	.0237	96.6	63.2	18.8	6.5	14.5	-	4.88	1563	1.09	.43	
414	6.96	[illegible]	24.4	2161	2.7	26.5	.0192	.0054	.0246	.0262	98.5	43.2	5.0	8.1	18.0	-	4.90	1643	1.05	.39	
415	6.91	836	24.8	2161	2.7	26.6	.0171	.0069	.0240	.0256	99.1	30.9	1.9	11.0	24.2	-	4.90	1639	1.08	.36	

NOTES:

1. Radial Immersion Sampling Mode
2. Alternate Chutes Fueled

Table LXXIV. Summary of Test Results, Configuration II-11 (1).

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
450	3.68	454	16.5	-	-	18.2	0	0	0	-	-	-	-	-	-	-	3.92	454	-	-	
451	3.40	458	16.4	599	3.7	19.6	0	.0101	.0101	.0115	96.8	56.1	18.6	2.4	53.6	-	4.54	852	-	-	2
452	3.41	455	16.3	701	3.7	19.4	0	.0119	.0119	.0132	97.9	41.8	11.6	3.1	67.3	-	4.57	910	-	-	2
453	3.50	455	16.2	808	3.7	18.8	0	.0139	.0139	.0167	98.4	36.3	7.3	3.6	75.1	-	4.21	992	-	-	2
454	3.50	455	16.1	931	3.7	18.7	0	.0161	.0161	.0186	98.4	43.5	6.2	4.0	85.1	-	4.20	1041	-	-	2
455	3.55	665	15.5	230	3.6	25.5	0	.0048	.0048	.0051	95.3	128.0	17.2	3.2	26.5	-	5.65	851	-	-	2
456	3.53	665	15.4	389	3.7	25.5	0	.0070	.0070	.0079	99.1	27.4	2.5	4.6	38.1	-	5.66	938	-	-	2
457	3.55	665	15.3	504	3.6	25.2	0	.0091	.0091	.0109	99.6	10.7	1.0	6.3	51.1	-	5.45	1011	-	-	2
458	3.40	664	15.4	344	3.3	26.2	0	.0062	.0062	.0073	98.5	45.4	4.5	4.0	34.6	-	6.12	903	-	-	2
459	3.55	664	15.3	946	3.6	24.6	.0116	.0059	.0175	.0194	97.3	74.4	9.3	3.4	27.4	-	5.60	1282	1.13	.28	
460	3.55	663	15.2	968	2.9	24.5	.0136	.0040	.0176	.0192	97.1	84.1	9.7	3.4	26.8	-	5.61	1280	1.12	.37	
461	3.85	664	15.5	1328	3.3	23.1	.0180	.0058	.0238	.0262	99.4	22.9	1.1	4.5	31.9	-	4.92	1501	1.12	.35	
462	3.85	666	15.6	1329	3.4	23.3	.0198	.0039	.0237	.0262	99.0	34.9	1.9	4.6	32.6	-	4.96	1499	1.15	.38	
478	3.86	677	15.7	-	-	23.9	0	0	0	-	-	-	-	-	-	-	4.81	677	-	-	
463	4.77	852	16.5	725	3.4	25.8	.0066	.0052	.0118	.0124	98.8	44.3	1.8	8.9	21.0	-	4.60	1362	1.15	.49	
464	4.76	853	16.7	1061	2.9	25.9	.0125	.0052	.0177	.0196	99.8	5.0	0.3	9.9	23.1	-	4.69	1573	1.14	.30	
465	4.79	856	16.6	1055	2.9	25.8	.0136	.0039	.0177	.0195	99.8	5.5	0.4	10.0	22.8	-	4.67	1579	1.13	.35	
466	4.79	856	16.7	1059	3.0	25.9	.0143	.0030	.0177	.0192	99.8	7.8	0.3	10.3	23.5	-	4.72	1578	1.13	.37	
467	4.80	857	16.5	1432	2.9	25.8	.0182	.0059	.0241	.0262	99.9	2.5	0.2	11.8	26.7	-	4.77	1762	1.14	.33	
468	4.80	857	16.6	1420	2.9	25.9	.0199	.0039	.0238	.0256	99.9	4.2	0.2	11.9	26.9	-	4.95	1771	1.14	.37	
469	4.79	857	16.5	1436	2.7	25.8	.0213	.0029	.0242	.0258	99.8	6.8	0.2	12.3	27.7	-	4.93	1771	1.13	.59	
477	4.72	855	17.0	-	-	26.8	0	0	0	-	-	-	-	-	-	-	4.63	855	-	-	
470	6.80	835	24.4	1560	3.4	26.7	.0119	.0059	.0177	.0196	99.8	6.2	0.1	10.9	24.6	-	4.95	1550	1.13	.27	
471	6.81	833	24.9	1560	3.4	27.0	.0135	.0039	.0174	.0193	99.8	6.7	0.1	10.5	24.3	-	5.02	1582	1.13	.37	
472	6.80	833	24.4	2130	3.3	26.6	.0203	.0040	.0243	.0268	99.9	2.8	0.1	12.5	28.4	-	4.97	1582	1.13	.37	
473	6.80	834	24.7	2133	3.3	26.9	.0181	.0059	.0240	.0265	100.0	1.5	0.1	12.0	27.5	-	5.15	1582	1.13	.32	
474	4.78	852	16.5	1438	3.3	26.7	0	.0242	.0242	.0222	99.8	6.7	0.2	13.5	31.5	-	4.74	1780	-	-	2
475	4.76	850	16.5	991	3.3	25.8	0	.0167	.0167	.0152	99.9	4.6	0.3	12.0	28.5	-	4.72	1531	-	-	2
476	4.78	854	16.1	682	3.3	25.9	0	.0114	.0114	.0101	99.5	19.0	0.5	11.6	27.0	-	4.64	1438	-	-	2

NOTES:

1. Acoustic Probe Installed 150° Exit Plane Surveyed
2. Radial Immersion Sampling Mode

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Table LXXV. Summary of Test Results, Configuration II-12.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Main Stage	Metered, Pilot Stage	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
497	3	449	16.2	0	-	18.9	0	0	0	-	-	-	-	-	-	-	4.35	449	-	-	
498	3.42	455	16.1	595	4.0	18.9	0	.0103	.0103	.0104	98.9	28.4	4.4	4.4	94.6	-	4.64	865	-	-	2
499	3.42	453	15.9	698	3.9	18.7	0	.0122	.0122	.0127	99.1	27.4	2.5	4.2	90.3	-	4.59	920	-	-	2
500	3.40	450	16.3	808	4.0	19.0	0	.0137	.0137	.0149	99.2	29.0	1.7	3.6	81.4	-	4.96	986	-	-	2
501	3.43	454	16.3	929	4.0	19.0	0	.0158	.0158	.0176	99.2	30.3	1.2	3.3	71.4	-	5.06	1058	-	-	2
502	3.44	671	15.4	231	3.9	26.3	0	.0042	.0042	.0037	97.7	62.1	9.0	3.2	26.5	-	6.82	832	-	-	2
503	3.45	671	15.4	443	4.0	26.3	0	.0080	.0080	.0077	99.8	5.5	0.3	9.1	76.0	-	6.32	973	-	-	2
504	3.47	672	15.3	334	4.4	25.9	0	.0061	.0061	.0056	99.8	8.9	0.3	5.7	47.0	-	6.04	914	-	-	2
505	3.46	669	15.5	765	4.4	26.1	0	.0137	.0137	.0145	99.7	13.0	0	7.5	63.7	-	6.46	1171	-	-	2
506	3.57	668	15.4	1293	4.4	25.3	.0117	.0116	.0233	.0246	93.6	88.8	43.4	4.7	38.5	-	6.52	1430	1.11	.47	
526	3.36	631	15.3	0	-	25.2	0	0	0	-	-	-	-	-	-	-	5.81	631	-	-	
507	4.95	865	16.7	1046	4.6	26.7	.0107	.0067	.0174	.0189	98.1	66.2	3.7	10.3	23.6	-	5.00	1453	1.12	.40	
508	4.86	869	16.9	1056	4.4	26.8	.0117	.0058	.0175	.0191	97.5	76.8	6.8	7.4	16.6	-	5.02	1450	1.14	.41	
509	4.47	867	16.7	1047	4.4	26.7	.0135	.0039	.0174	.0186	89.6	112.4	77.8	3.4	7.7	-	4.94	1405	1.14	.46	
510	4.36	868	16.7	1278	4.6	26.6	.0145	.0068	.0213	.0211	99.2	31.5	1.1	10.3	23.2	-	5.23	1588	1.12	.44	
511	4.77	865	16.3	1284	5.1	26.5	.0159	.0060	.0219	.0238	99.0	37.0	1.3	8.0	18.6	-	5.07	1592	1.11	.37	
512	4.77	855	16.4	1281	5.1	26.3	.0177	.0040	.0217	.0237	96.8	66.4	16.0	4.9	12.1	-	5.12	1556	1.08	.41	
513	4.78	851	16.5	1430	5.1	26.3	.0172	.0069	.0241	.0257	99.4	25.8	0.5	10.3	25.7	-	5.16	1642	1.11	.39	
514	4.79	855	15.5	1427	5.0	26.3	.0182	.0059	.0241	.0259	99.2	30.7	1.0	8.5	20.2	-	5.20	1650	1.10	.37	
515	4.80	856	16.4	1451	5.1	26.1	.0207	.0039	.0246	.0264	98.1	52.1	7.3	6.0	14.4	-	5.13	1652	1.06	.34	
516	4.40	859	16.5	1428	5.1	26.4	.0192	.0049	.0240	.0258	98.9	39.7	2.1	6.9	16.5	-	5.17	1647	1.08	.37	
524	4.73	851	16.3	1049	4.9	26.2	.0110	.0069	.0179	.0196	98.1	63.4	4.1	10.3	25.4	-	4.78	1106	1.15	.55	
525	4.75	859	16.2	0	-	26.2	0	0	0	-	-	-	-	-	-	-	4.32	859	-	-	
517	6.93	849	24.1	1567	5.6	26.8	.0129	.0050	.0179	.0199	95.9	85.1	20.9	5.5	12.6	-	5.26	1428	1.10	.43	
518	6.92	843	24.7	1564	5.6	27.1	.0107	.0069	.0176	.0194	97.8	67.8	6.0	11.0	25.0	-	5.28	1433	1.11	.47	
519	6.79	840	24.7	1921	5.4	27.1	.0167	.0049	.0216	.0240	98.3	50.9	5.4	6.6	15.3	-	5.47	1562	1.08	.41	
520	6.86	840	24.7	1908	5.1	27.1	.0145	.0069	.0214	.0237	99.1	33.0	1.7	11.1	25.4	-	5.50	1562	1.13	.48	
521	6.77	843	24.9	2137	5.2	27.4	.0190	.0050	.0240	.0267	98.8	39.2	3.2	7.4	17.0	-	5.74	1635	1.10	.45	
522	6.92	841	24.7	2137	5.1	27.2	.0171	.0069	.0240	.0264	99.3	24.6	1.2	11.3	25.6	-	5.63	1635	1.14	.53	
523	7.07	912	29.1	2371	5.0	30.1	.0157	.0069	.0226	.0251	99.0	37.3	1.8	9.8	24.9	-	6.88	1572	1.17	.56	

NOTES:

1. Acoustic Probe Installed, 150° of Exit Plane Surveyed
2. Radial Immersion Sampling Mode

Table LXXVI. Summary of Test Results, Configuration II-13.

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Outer Annulus	Metered, Inner Annulus	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
560	3.40	450	16.0	0	-	18.7	0	0	0	-	-	-	-	-	-	-	4.70	450	-	-	
561	3.44	455	16.2	584	6.0	19.1	.0100	0	.0100	.0116	91.9	88.6	59.8	2.4	55.1	-	5.09	833	-	-	1
562	3.42	456	16.5	688	5.6	19.5	.0116	0	.0116	.0142	94.0	74.6	42.5	2.8	64.1	-	5.34	885	-	-	1
563	3.42	458	16.3	796	5.6	19.3	.0136	0	.0136	.0173	95.2	67.9	32.2	3.0	66.2	-	5.36	966	-	-	1
564	3.42	458	16.3	909	5.4	19.3	.0155	0	.0155	.0199	95.7	69.9	26.7	3.0	67.0	-	5.40	1040	-	-	1
565	4.76	728	17.4	251	5.1	22.9	.0040	0	.0040	.0046	96.4	90.9	15.0	5.5	26.1	-	4.78	888	-	-	1
566	4.76	728	17.3	322	5.1	23.8	.0052	0	.0052	.0059	98.1	49.6	7.0	7.4	34.5	-	4.74	944	-	-	1
567	4.73	732	17.7	376	5.4	24.1	.0059	0	.0059	.0070	98.8	32.1	4.4	9.6	40.1	-	5.01	966	-	-	1
568	4.74	733	17.5	1129	5.4	23.8	.0050	.0129	.0179	.0205	98.7	34.1	6.8	4.7	21.8	-	5.13	1371	1.08	.28	
569	4.78	732	17.9	1530	6.0	24.0	.0050	.0188	.0238	.0270	99.6	9.5	1.8	5.4	25.2	-	5.40	1559	1.11	.27	
570	4.23	861	16.5	698	5.6	26.2	.0050	.0067	.0117	.0130	98.6	49.4	2.8	8.8	21.0	-	5.22	1274	1.17	.56	
571	4.73	863	16.6	1042	5.4	26.2	.0049	.0126	.0175	.0197	99.8	4.7	1.0	8.5	20.0	-	5.45	1476	1.11	.30	
572	4.73	865	16.5	1058	5.1	26.2	.0040	.0138	.0178	.0198	99.8	5.0	0.8	8.1	18.9	-	5.44	1479	1.10	.32	
573	4.73	861	16.7	1036	5.1	26.4	.0029	.0144	.0173	.0195	99.7	7.7	0.8	7.9	19.0	-	5.51	1444	1.10	.35	
574	4.73	862	16.7	1423	5.4	26.6	.0049	.0187	.0236	.0264	99.9	2.3	0.5	9.5	22.9	-	5.64	1653	1.11	.33	
575	4.74	860	16.3	1422	5.1	26.0	.0040	.0202	.0242	.0271	99.9	3.2	0.5	9.8	22.8	-	5.32	1677	1.10	.33	2
576	4.74	860	16.4	1397	5.4	26.2	.0030	.0206	.0236	.0265	99.9	4.9	0.3	9.8	23.3	-	5.46	1652	1.12	.32	
577	4.71	860	16.3	1424	5.4	26.2	0	.0243	.0243	.0270	99.8	5.7	0.3	11.7	27.8	-	5.49	1651	1.11	.30	
578	4.74	860	16.4	1047	5.4	26.1	0	.0177	.0177	.0197	99.9	3.0	0.2	9.3	21.9	-	5.21	1471	1.11	.35	
579	4.72	861	16.1	703	5.4	25.9	0	.0121	.0121	.0133	99.6	13.0	0.6	8.7	20.4	-	5.05	1292	1.10	.34	
580	6.74	835	24.4	1554	5.9	26.7	.0050	.0127	.0177	.0198	99.8	5.5	0.2	9.9	22.7	-	5.79	1451	1.13	.36	
581	6.75	836	24.4	1559	4.0	26.8	.0030	.0147	.0177	.0200	99.8	8.9	0.3	9.2	21.0	-	5.86	1430	1.12	.67	
582	6.73	838	24.5	2112	4.0	27.1	.0049	.0190	.0239	.0268	99.9	1.9	0.1	10.5	24.1	-	6.00	1651	1.12	.48	
583	6.74	837	24.4	2125	4.0	26.9	.0040	.0202	.0242	.0270	99.9	2.8	0.1	10.6	24.3	-	5.93	1657	1.09	.47	
584	6.74	837	24.4	2107	4.0	26.9	.0030	.0209	.0239	.0269	99.9	4.4	0.1	10.8	24.7	-	6.01	1641	1.12	.45	
585	7.34	834	29.2	2368	4.3	29.0	.0050	.0175	.0225	.0254	99.9	2.0	0.1	9.6	23.3	-	7.02	1610	1.13	.52	
586	7.34	835	28.9	2359	4.3	28.8	.0040	.0187	.0227	.0252	99.9	3.1	0.2	9.4	22.3	-	7.00	1612	1.13	.48	

NOTES:
1. Radial Immersion Sampling Mode
2. High Density Sampling Mode

Table LXXVII. Summary of Test Results, Configuration II-14.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED COMBUSTOR

Reading Number	Inlet Total Pressure atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Main Stage	Metered: Pilot Stage	Metered: Over-All	Sample Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
[illegible]	[illegible]	455	15.8	0	—	19.5	0	0	0	-	-	-	-	-	-	-	4.35	455	-	-	
[illegible]	[illegible]	453	16.2	477	3.3	19.4	0	.0083	.0083	.0088	98.3	37.4	8.3	4.1	89.1	-	4.53	788	-	-	1
[illegible]	[illegible]	456	16.2	615	3.1	19.3	0	.0106	.0105	.0117	98.5	39.9	5.5	3.5	77.2	-	4.79	862	-	-	1
[illegible]	[illegible]	457	15.3	706	3.4	19.4	0	.0121	.0121	.0139	98.7	40.2	3.8	3.3	71.5	-	4.89	909	-	-	1
[illegible]	[illegible]	457	15.4	825	4.4	19.5	0	.0140	.0140	.0164	98.8	40.4	2.7	3.0	67.9	-	4.97	996	-	-	1
[illegible]	3.34	[illegible]	16.2	936	4.4	19.5	0	.0160	.0160	.0182	98.8	43.0	2.1	3.0	66.3	-	4.97	1060	-	-	1
[illegible]	[illegible]	733	17.7	263	4.4	24.4	0	.0041	.0041	.0038	99.8	2.6	1.6	8.5	39.3	-	4.72	909	-	-	1
[illegible]	[illegible]	734	17.7	329	4.0	24.4	0	.0052	.0052	.0050	99.9	1.4	1.0	13.8	62.6	-	4.62	1064	-	-	1
[illegible]	[illegible]	733	17.7	374	4.0	24.4	0	.0061	.0061	.0061	99.9	1.8	0.9	18.9	86.2	-	4.61	1136	-	-	1
[illegible]	[illegible]	733	17.8	1539	[illegible]	24.4	.0142	.0098	.0240	.0262	98.9	36.4	2.8	8.3	38.1	-	5.23	1554	1.11	.41	
[illegible]	[illegible]	[illegible]	[illegible]	1262	4.0	26.9	.0129	.0049	.0177	.0189	96.7	77.8	14.6	7.0	16.6	-	5.37	1453	1.19	1.07	
[illegible]	[illegible]	858	16.6	1326	[illegible]	26.7	.0138	.0044	.0192	.0187	94.7	93.9	30.9	4.8	11.4	-	5.20	1459	1.27	.86	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26.8	.0146	.0031	.0177	.0178	84.0	113.0	134.0	2.5	5.9	-	4.98	1371	1.25	1.37	
[illegible]	[illegible]	457	16.4	1442	3.7	26.4	.0194	.0050	.0244	.0250	99.1	23.7	3.4	8.9	20.9	-	5.28	1663	1.09	.37	
[illegible]	[illegible]	457	16.4	1437	4.0	26.4	.0203	.0040	.0243	.0257	98.7	38.5	4.3	6.7	15.8	-	5.24	1654	1.08	.34	
[illegible]	[illegible]	[illegible]	16.4	1442	4.4	26.5	.0213	.0031	.0244	.0255	95.7	57.2	29.4	5.2	12.4	-	5.26	1647	1.07	.36	
[illegible]	[illegible]	[illegible]	16.4	1442	4.7	26.5	.0225	.0019	.0244	[illegible]	90.9	65.5	75.4	4.6	10.5	-	5.12	1596	1.07	.46	
805	[illegible]	456	16.4	1442	4.4	26.5	.0139	.0105	.0244	.0262	99.5	9.8	2.6	14.4	34.7	-	5.21	1661	1.13	.35	
[illegible]	[illegible]	[illegible]	16.6	1294	4.0	26.6	.0138	.0079	.0217	.0231	99.5	18.2	0.6	16.5	39.2	-	5.19	1587	1.36	.46	
[illegible]	[illegible]	[illegible]	16.6	1299	[illegible]	26.6	.0168	.0050	.0218	.0234	99.0	34.6	1.8	8.3	19.8	-	5.31	1585	1.20	.49	
[illegible]	[illegible]	456	16.3	1293	4.1	26.5	.0179	.0041	.0220	.0233	97.9	30.7	8.8	6.1	14.2	-	5.02	1592	1.14	.52	
[illegible]	[illegible]	454	16.4	1300	4.2	26.4	.0159	.0031	.0220	.0230	94.1	66.8	43.0	4.6	11.0	-	5.10	1570	1.07	.54	
[illegible]	[illegible]	[illegible]	29.4	[illegible]	3.1	29.3	.0198	.0030	.0228	.0239	93.0	74.8	52.9	4.6	11.2	-	6.85	1544	1.06	.42	
[illegible]	[illegible]	[illegible]	[illegible]	2029	3.1	28.9	.0197	.0030	.0227	.0252	94.5	66.5	39.4	5.2	11.9	-	5.55	1558	1.06	.37	
[illegible]	[illegible]	[illegible]	24.5	2035	3.1	28.5	.0179	.0049	.0228	.0243	99.0	31.8	2.5	9.4	21.7	-	5.50	1585	1.12	.37	
[illegible]	[illegible]	831	24.7	1581	3.0	28.0	.0148	.0030	.0178	.0176	83.5	114.9	138.0	2.9	6.4	-	5.05	1346	1.12	.77	
[illegible]	[illegible]	[illegible]	24.9	[illegible]	3.2	28.2	.0127	.0050	.0177	.0190	97.0	71.2	13.4	8.5	39.4	-	5.35	1428	1.14	.41	

NOTES:
1. Radial Immersion Sampling Mode

Table LXXVIII. Summary of Test Results, Configuration II-15.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered, Main Stage	Metered, Pilot Stage	Metered, Over-All	Sample, Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel, CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
635	3.35	356	19.0	0	-	18.3	0	0	0	-	-	-	-	-	-	-	5.42	356	-	-	
636	3.45	348	20.1	1008	5.1	18.4	0	.0139	.0139	.0147	98.1	50.3	7.1	2.4	84.9	-	5.72	905	1.17	.67	
664	2.96	425	13.8	452	6.4	18.3	0	.0091	.0091	.0102	97.8	42.8	11.9	3.3	93.5	1	4.36	782	1.18	.65	
665	2.96	424	13.5	616	6.9	17.8	0	.0127	.0127	.0149	98.7	34.7	4.6	3.2	90.4	0	4.55	916	-	-	1
666	2.89	424	13.4	615	7.0	17.6	0	.0128	.0128	.0145	98.6	39.4	5.4	3.3	91.4	-	4.50	920	1.14	.66	
667	2.88	424	13.8	750	7.0	18.1	0	.0151	.0151	.0172	98.7	39.9	3.6	2.8	79.3	1	4.64	996	1.16	.62	
668	2.74	418	13.0	655	7.0	17.7	0	.0140	.0140	.0139	98.6	40.8	4.9	2.9	85.6	-	4.71	953	1.15	.64	
663	3.03	433	14.5	583	7.1	18.4	0	.0112	.0112	.0130	98.7	[illegible]	5.0	3.4	91.8	-	4.86	870	1.16	.60	
656	3.38	455	16.1	357	7.9	19.2	0	.0062	.0062	.0063	94.9	73.5	34.1	2.8	67.6	-	4.72	696	1.17	.61	
657	3.38	448	16.1	576	7.9	19.0	0	.0103	.0103	.0118	99.0	26.5	3.6	4.3	104.7	2	4.42	851	1.11	.51	
658	3.40	460	16.0	815	8.1	19.0	0	.0142	.0142	.0166	99.2	27.1	3.5	3.5	82.9	1	4.83	1040	1.15	.63	
659	3.35	453	16.0	817	8.1	19.2	0	.0142	.0142	.0163	99.3	26.2	1.2	3.4	82.1	-	4.86	997	-	-	1
660	3.39	451	16.0	1166	8.6	18.9	0	.0203	.0203	.0239	99.0	41.1	0.9	2.8	69.6	-	4.98	1209	1.17	.59	
661	3.47	450	18.3	936	9.6	20.6	0	.0142	.0142	.0164	99.1	31.4	1.4	2.8	75.3	-	6.00	995	1.16	.52	
662	3.40	452	11.0	542	5.4	13.9	0	.0142	.0142	.0172	98.9	25.6	4.8	4.4	73.1	-	2.10	990	1.15	.79	
655	3.35	586	12.2	466	4.4	19.4	0	.0106	.0106	.0117	99.7	10.9	0.9	7.8	84.0	-	3.67	990	1.15	.51	
637	6.81	665	30.4	1525	4.9	26.0	0	.0140	.0140	.0149	99.8	5.7	0.6	9.0	55.6	-	6.95	1177	1.13	.57	
638	6.84	666	30.4	2263	4.9	26.0	0	.0207	.0207	.0221	99.8	8.0	0.5	6.9	42.3	-	6.98	1392	1.19	.57	
639	6.79	667	30.4	1519	5.1	26.2	.0069	.0070	.0139	.0154	90.9	92.3	69.7	5.9	36.6	-	6.55	1127	1.11	.82	4
640	6.79	664	30.0	1952	5.1	25.7	.0110	.0071	.0181	.0197	95.2	71.4	31.8	6.1	37.7	1	6.70	1282	1.13	.70	2, 4
641	9.49	735	35.7	1759	5.1	24.6	.0068	.0069	.0137	.0158	95.9	77.8	23.4	11.8	38.8	-	4.86	1223	1.15	.70	4
642	9.49	733	34.9	2258	6.1	24.1	.0110	.0070	.0180	.0198	98.3	45.5	6.7	11.5	38.1	4	4.87	1356	1.15	.70	2, 4
643	9.55	732	36.0	2264	6.1	24.5	.0107	.0068	.0175	.0201	95.6	90.9	22.9	9.3	35.9	5	5.11	1325	1.14	.51	2
644	9.53	730	36.1	2631	6.3	24.7	.0145	.0057	.0202	.0237	96.9	72.3	14.3	6.4	22.1	3	5.28	1409	1.08	.49	
645	9.53	732	36.0	2624	6.3	24.7	.0164	.0038	.0202	.0225	90.0	95.0	78.1	3.2	10.9	2	5.51	1362	1.08	.59	
670	9.56	826	34.4	2177	10.7	26.5	.0117	.0059	.0176	.0209	97.2	54.0	15.9	8.9	20.6	-	5.22	1421	1.07	.32	
671	9.56	824	33.1	2260	10.7	26.4	.0136	.0038	.0174	.0200	95.3	86.8	27.3	4.7	10.9	-	5.17	1401	1.07	.45	
672	9.56	827	34.5	2731	10.7	26.5	.0182	.0038	.0220	.0259	98.5	41.1	5.1	6.5	14.9	1	5.31	1563	1.05	.34	
673	9.57	821	34.2	2726	10.7	26.2	.0173	.0049	.0222	.0261	99.1	28.3	2.9	7.1	16.4	1	5.20	1407	1.07	.33	
674	9.53	822	34.1	2717	10.7	26.2	.0163	.0058	.0221	.0262	99.3	21.3	2.0	9.6	21.0	1	5.28	1570	1.09	.36	

Table LXXVIII. Summary of Test Results, Configuration II-15 (Concluded).

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature ° K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Main Stage	Metered: Pilot Stage	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature ° K	Profile Factor	Pattern Factor	Notes
646	4.78	855	16.7	1059	5.0	26.6	.0137	.0039	.0176	.0198	92.5	81.3	55.8	5.0	12.4	-	4.86	1419	1.09	.59	
647	4.78	853	16.6	1056	5.0	26.5	.0118	.0059	.0177	.0204	97.5	56.8	11.8	8.2	20.3	-	5.14	770	1.11	.49	
648	4.78	855	16.6	1444	5.0	26.6	.0202	.0040	.0242	.0238	97.8	47.9	11.2	6.4	15.8	1	5.47	1419	1.05	.40	2
649	4.75	857	16.7	1424	5.1	26.8	.0179	.0058	.0237	.0271	99.3	25.2	1.0	9.1	22.4	2	5.51	1628	1.07	.46	
650	3.06	853	10.3	676	5.1	25.9	.0120	.0062	.0182	.0207	96.6	63.7	19.0	7.1	21.6	-	4.71	1459	1.10	.59	
651	3.08	850	10.4	685	5.0	25.8	.0140	.0043	.0183	.0205	92.3	80.5	58.5	4.7	14.3	-	4.62	1428	1.06	.60	
652	3.05	844	10.4	924	5.0	25.8	.0186	.0061	.0247	.0280	98.8	36.2	3.1	7.6	24.3	1	5.00	1654	1.07	.46	
653	3.06	856	10.5	934	5.3	26.2	.0205	.0042	.0247	.0267	96.4	55.3	22.8	5.6	16.9	0	5.10	1644	1.06	.48	2
654	3.04	857	10.5	934	5.3	26.4	.0204	.0041	.0247	.0286	96.7	55.2	20.6	4.9	15.0	-	—	1672	-	-	1
675	9.53	850	31.4	2137	10.7	25.4	.0139	.0039	.0178	.0211	77.6	65.7	99.2	6.3	11.8	-	4.71	1445	1.07	.27	
676	9.53	851	32.5	2079	10.7	25.3	.0119	.0059	.0178	.0209	98.9	37.0	2.2	11.0	20.7	-	4.74	1455	1.04	.26	
677	9.57	850	32.8	2755	11.0	25.4	.0204	.0629	.0233	.0272	98.4	37.7	7.7	7.0	13.4	2	4.89	1615	1.05	.33	
678	9.56	851	33.2	2799	11.0	25.5	.0197	.0038	.0235	.0268	99.3	21.9	2.2	8.4	16.1	1	4.98	1625	1.04	.32	2
679	9.60	851	31.6	2801	11.0	25.3	.0198	.0038	.0236	.0285	99.2	22.1	2.8	7.6	14.2	-	4.94	1634	-	-	1
680	9.34	848	32.6	2836	11.0	25.3	.0184	.0058	.0242	.0282	99.7	9.5	1.7	13.3	26.7	2	4.94	1645	1.08	.33	
681	9.57	850	32.5	2549	11.0	25.3	.0179	.0039	.0218	.0255	99.1	28.3	2.7	7.9	15.0	-	4.94	1573	1.07	.34	
682	9.55	850	32.3	2546	11.0	25.2	.0159	.0059	.0218	.0240	99.6	13.7	1.2	10.9	20.5	-	4.93	1581	-	-	3

NOTES:

1. Radial Immersion Sampling Mode
2. High Density Sampling Mode
3. 70° of Exit Plane Surveyed
4. Alternate Chutes Fueled

Table LXXIX. Summary of Sea Level Ignition Test Results, Configuration II-15.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Point Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Type Ignitor	Required Fuel Flow (kg/hr) Lightoff	50% Propagation	100% Propagation	One Cup Out	50% Cups Out	Lean Blowout
60	0.985	299	2.72	Torch	125	-	-	-	-	-
				Torch	95	256	-	-	-	45
				Torch	109	-	-	-	-	-
				Torch	109	270	325	218	144	45
				Torch	131	253	320	246	194	45
80	0.992	298	3.63	Torch	181	254	308	270	200	64
				Torch	200	263	313	268	200	61
				Torch	195	259	297	274	200	62
120	1.015	295	5.44	Torch	200	209	218	218	172	54
				Torch	191	209	218	210	172	54
				Torch	191	195	213	204	177	60

Notes:

a) JP5 Fuel at 299°K for all points

b) Barometric Pressure = .972 - .981 atmospheres

Table LXXX. Summary of Test Results, Configuration II-16.

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature ° K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature ° K	Profile Factor	Pattern Factor	Notes
712	2.71	364	16.1	0	—	18.8	0	0	0	-	-	-	-	-	-	-	6.22	5c-	-	-	
713	2.94	369	15.9	806	9.1	17.4	.0141	0	.0141	.0170	96.1	77.9	21.0	2.1	83.0	-	5.82	893	1.44	1.09	
714	3.30	372	29.3	997	8.9	17.4	.0143	0	.0143	.0177	96.6	70.4	17.9	2.0	72.3	-	6.04	883	1.42	1.13	
715	3.33	451	15.9	357	8.9	18.5	.0063	0	.0063	.0063	90.4	126.5	66.1	1.5	37.1	-	5.36		1.35	1.49	
716	3.33	456	15.7	579	8.9	18.9	.0102	0	.0102	.0116	98.1	37.9	10.2	3.1	73.5	3	5.46		1.38	1.27	
717	3.30	460	15.8	804	9.1	19.3	.0141	0	.0141	.0164	98.2	50.5	6.3	3.2	77.1	4	5.73		1.42	1.18	1
718	3.34	460	15.9	804	8.9	19.2	.0141	0	.0141	.0133	98.2	47.0	7.1	3.2	75.3	–	5.60		-	-	2
719	3.33	458	15.9	806	8.9	19.1	.0142	0	.0242	.0155	98.2	50.4	6.4	3.2	76.7	-	5.60	994	1.42	1.17	1
720	3.33	456	15.7	1030	8.9	18.9	.0182	0	.0182	.0202	97.6	79.9	5.8	2.7	64.7	–	5.66	1126	1.41	0.95	
721	3.37	456	14.1	713	7.6	17.1	.0140	0	.0140	.0154	98.5	45.2	4.9	3.7	77.4	3	4.34	990	1.44	1.17	
722	4.09	456	15.5	757	8.6	15.5	.0136	0	.0136	.0151	98.9	31.3	3.8	4.2	73.4	4	3.47	985	1.43	1.19	
723	4.04	455	19.6	970	9.1	18.7	.0137	0	.0137	.0153	98.6	41.1	4.2	3.3	72.2	2	5.82	983	1.40	1.25	
746	2.65	399	16.[illegible]	0	—	20.7	-	0	0	-	—	-	-	-	-	-	-	596	-	-	
724	4.76	735	17.9	263	8.9	24.5	.0041	0	.0041	.0037	99.0	30.4	2.9	5.0	25.0	1	5.43	904	1.36	1.06	
725	4.76	739	17.7	322	8.4	24.6	.0050	0	.0050	.0048	99.7	8.5	0.8	6.6	32.2	–	5.52	937	1.36	1.01	
726	4.79	739	17.6	382	9.1	24.1	.0060	0	.0040	.0058	99.9	2.3	0.3	8.9	44.1	-	5.26	982	1.42	1.13	
727	4.76	739	17.5	2133	10.1	24.0	.0049	.0131	.0180	.0201	98.3	43.0	7.0	4.1	21.0	0	5.61	1380	1.12	.27	
728	4.78	738	17.6	1541	9.9	24.1	.0049	.0193	.0242	.0274	99.8	5.3	1.2	4.7	23.6	-	5.62	1587	1.09	.25	
729	4.74	859	16.5	1048	9.9	26.6	.0049	.0128	.0177	.0195	99.8	5.3	0.7	7.1	19.0	-	5.93	1563	1.10	.28	
730	4.76	859	16.4	1063	8.4	26.5	.0041	.0139	.0180	.0197	99.9	3.9	0.6	7.0	17.9	-	5.75	1579	1.08	.26	
731	4.76	855	16.5	1057	8.4	26.5	.0031	.0147	.0178	.0196	99.8	4.4	0.6	7.4	19.2	-	5.97	1569	1.07	.26	
732	4.76	856	16.3	1437	8.4	26.2	.0051	.0194	.0245	.0267	99.9	1.3	0.4	8.5	21.9	-	6.01	1786	1.08	.27	
733	4.74	857	16.3	1420	8.4	26.4	.0041	.0201	.0242	.0267	99.9	1.6	0.3	8.4	21.7	0	5.87	1789	1.08	.29	1
734	4.77	857	16.3	1448	8.4	26.2	.0031	.0215	.0246	.0272	99.9	2.4	0.3	8.7	22.3	1	5.89	1789	1.09	.27	1
735	4.7[illegible]	856	16.3	727	8.4	26.3	.0122	0	.0122	.0102	99.7	5.6	1.6	25.6	66.2	-	5.46	1341	-	-	2
742	4.76	827	16.2	1427	8.1	26.2	.0123	.0121	.0244	.0265	99.8	7.8	0.0	17.1	44.1	-	5.80		1.07	.24	
[illegible]	4.77	836	16.3	1361	8.1	26.1	0	.0231	.0231	.0263	99.9	3.3	0.0	8.7	22.6	-	5.86		1.08	.26	
[illegible]	4.75	934	16.3	1061	8.1	26.2	0	.0181	.0181	.0212	99.9	2.8	0.4	7.8	20.5	-	5.71	1605	1.09	.24	
[illegible]	4.77	838	16.2	721	8.1	25.8	0	.0124	.0124	.0137	99.4	22.5	0.6	7.4	19.2	-	5.61	1380	1.10	.29	
[illegible]	6.42	847	25.2	1570	6.0	27.1	.0047	.0126	.0173	.0192	99.7	9.6	0.4	7.4	18.8	-	—	1536	1.09	.24	
[illegible]	6.82	848	24.4	1581	6.0	26.6	.0030	.0150	.0180	.0198	99.6	5.8	0.2	7.8	18.2	-	-	1586	1.09	.24	
[illegible]	6.92	855	24.7	1215	6.3	26.9	.0049	.0193	.0242	.0268	100.0	1.0	0.1	8.9	21.5	-	-	1760	1.20	.53	
[illegible]	6.82	851	24.7	2151	6.3	26.9	.0030	.0212	.0242	.0269	99.9	2.0	0.1	9.0	21.3	1	6.22	1761	-	-	2
[illegible]	6.41	457	24.4	2349	6.3	29.1	.0049	.0193	.0243	.0269	100.0	1.0	0.1	8.5	21.6	-	7.60	1772	-	-	2
[illegible]	6.42	851	22.6	2336	6.3	25.3	.0049	.0190	.0238	.0262	100.0	0.7	0.1	10.5	22.0	-	5.10	1770	-	-	2

NOTES:

1. High Density Sampling Mode
2. Radial Immersion Sampling Mode

Table LXXXI. Summary of Sea Level Ignition Test Results, Configuration II-16.

CONFIGURATION DESCRIPTION DOUBLE ANNULAR

Point Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Type Ignitor	Required Fuel Flow (kg/hr) Lightoff	50% Propagation	100% Propagation	One Cup Out	50% Cups Out	Lean Blowout
60	0.999	296	2.72	Torch	289	360	-	-	-	-
				Torch	363	-	-	-	-	225
				Torch	363	-	-	-	-	277
				Torch	367	-	-	-	-	273
				Spark	No Lite	-	-	-	-	-
80	1.008	296	3.63	Torch	298	320	322	295	254	179
				Torch	312	312	356	283	246	191
				Spark	243	332	344	236	260	183
				Spark	283	332	358	325	264	197
				Spark	312	319	344	282	255	178
				Spark	258	-	-	-	-	-
				Spark	251	-	-	-	-	-
81	1.025	296	4.85	Spark	253	299	-	316	252	176
				Spark	220	255	327	-	-	117
120	1.035	297	5.44	Spark	208	242	281	238	191	122
				Spark	195	225	273	209	173	125
				Spark	186	228	271	214	176	199
				Spark	192	228	291	235	187	122

Notes:

a) JP5 Fuel at 294°K for all points

b) Barometric Pressure = .976 atmospheres

Table LXXXII. Summary of Test Results, Configuration III-1.

CONFIGURATION DESCRIPTION AST 60-SWIRL-CAN/SLOTTED FLAMEHOLDER

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Outer Annulus	Metered: Inner Annulus	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
769	3.30	448	15.5	0	-	18.7	0	0	0	-	-	-	-	-	-	-	3.74	448	-	-	
770	3.37	453	16.0	589	6.3	19.1	0	.0102	.0102	.0103	84.7	135.7	121.4	1.1	24.7	-	4.15	754	1.25	1.00	
771	3.38	453	16.1	816	6.3	19.2	0	.0141	.0141	.0154	91.7	102.0	59.4	1.7	40.6	2	4.35	969	1.28	.95	
772	3.40	454	15.9	1161	6.3	19.0	0	.0202	.0202	.0222	93.2	118.9	40.7	1.9	43.6	-	4.38	1180	1.29	.80	
773	3.39	454	16.1	804	6.1	19.2	.0069	.0069	.0138	.0144	80.2	151.1	163.2	1.0	22.8	2	4.31	886	1.10	.50	
774	3.38	455	16.1	1153	6.1	19.2	.0099	.0100	.0199	.0224	89.3	102.1	83.4	1.4	32.5	-	4.35	1119	1.11	.43	
775	3.69	453	16.3	1610	6.4	18.0	.0137	.0138	.0275	.0319	94.8	78.8	33.5	1.8	38.7	-	3.93	1386	1.12	.38	
792	3.35	664	14.9	0	-	25.8	0	0	0	-	-	-	-	-	-	-	3.34	664	-	-	
776	3.39	655	15.7	663	6.0	26.4	.0058	.0059	.0117	.0129	94.9	110.2	24.9	2.9	28.4	-	5.77	1068	1.07	.32	
777	3.53	664	15.2	973	6.6	25.1	.0089	.0089	.0178	.0204	98.2	49.7	6.4	4.3	37.2	1	5.30	1288	1.08	.36	
778	3.76	664	15.2	1333	6.6	23.8	.0122	.0122	.0244	.0256	98.9	38.7	2.4	5.6	44.0	8	4.79	1501	1.08	.53	
779	4.72	735	17.4	757	6.6	24.2	.0060	.0061	.0121	.0134	98.8	37.4	3.5	5.8	27.1	-	4.17	1169	1.07	.39	
780	4.72	733	17.6	1136	6.6	24.4	.0090	.0090	.0180	.0208	99.5	16.5	.9	8.0	38.1	1	4.06	1363	1.08	.45	
781	4.74	734	17.4	1538	6.6	24.1	.0123	.0123	.0246	.0291	99.5	20.8	.5	9.3	43.4	22	3.87	1563	1.09	.42	
793	4.74	859	16.9	0	-	27.2	0	0	0	-	-	-	-	-	-	-	2.54	859	-	-	
782	4.76	864	16.7	706	6.6	27.0	.0059	.0059	.0118	.0133	99.7	11.6	.5	10.6	25.7	-	3.72	1279	1.07	.35	
783	4.75	865	16.6	1053	6.6	27.0	.0088	.0088	.0176	.0204	99.9	4.4	.1	13.2	31.7	-	3.72	1471	1.09	.40	
784	4.74	863	16.6	1434	6.6	27.0	.0119	.0120	.0239	.0276	99.8	8.5	.1	15.5	38.0	2	3.90	1657	1.10	.43	
785	4.79	845	24.9	1030	4.3	27.6	.0058	.0059	.0117	.0137	99.7	10.0	.5	11.8	26.4	2	3.66	1259	1.09	.38	
786	4.78	844	24.9	1576	4.3	27.4	.0088	.0088	.0176	.0206	99.9	3.9	.2	14.4	32.5	2	3.60	1452	1.09	.46	
787	4.72	844	24.5	2013	4.3	27.2	.0113	.0115	.0228	.0266	99.9	5.8	.1	16.2	36.5	7	3.48	1604	1.09	.47	
788	4.78	839	24.4	2147	4.3	26.9	.0121	.0123	.0244	.0280	99.8	8.4	.1	16.3	36.8	6	3.26	1653	1.09	.49	
789	4.75	838	27.1	1752	4.3	29.4	.0090	.0090	.0180	.0206	99.9	5.0	.1	13.5	34.0	2	3.94	1455	1.09	.44	
790	4.73	843	27.0	2231	4.3	29.6	.0114	.0115	.0229	.0264	99.8	7.5	.1	14.9	36.5	5	4.01	1610	1.09	.42	
[illegible]	4.76	858	27.0	2393	4.3	30.1	.0121	.0124	.0245	.0281	99.8	10.0	.1	15.1	35.4	6	4.00	1673	1.09	.45	

Table LXXXIII. Summary of Test Results, Configuration III-2.

CONFIGURATION DESCRIPTION RADIAL/AXIAL STAGED

Reading Number	Inlet Total Pressure Atm	Inlet Total Temperature °K	Combustor Airflow kg/s	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/s	Fuel-Air Ratio g fuel / g air, Metered: Main Stage	Metered: Pilot Stage	Metered: Over-All	Sample: Over-All	Gas Sample Combustion Efficiency %	Emission Indices g/kg fuel: CO	HC	NOx	NOx SLTO	SAE Smoke Number	Total Pressure Loss %	Average Exit Temperature °K	Profile Factor	Pattern Factor	Notes
[illegible]	3.40	454	16.1	0	-	19.2	0	0	0	-	-	-	-	-	-	-	3.51	454	-	-	
[illegible]8	3.38	452	16.3	342	11.0	19.3	0	.0058	.0058	.0065	92.1	94.4	57.3	3.0	78.3	-	3.80	669	1.16	.58	
811	3.44	459	16.5	491	7.6	19.5	0	.0083	.0083	.0084	94.9	82.0	32.3	3.4	79.2	-	4.08	780	1.14	.52	
812	3.47	451	16.4	573	7.6	19.0	0	.0097	.0097	.0106	96.0	77.3	21.9	3.3	76.9	-	3.86	798	1.13	.43	
813	3.38	454	16.5	806	7.6	19.6	0	.0136	.0136	.0154	97.6	66.2	8.6	2.5	61.0	12	4.07	940	1.11	.38	
814	3.40	455	16.3	1036	7.6	19.4	0	.0176	.0176	.0201	98.4	51.5	3.9	2.4	56.5	-	4.29	1119	1.12	.43	
833	3.45	664	15.0	772	4.6	25.5	.0064	.0079	.0143	.0146	89.0	106.0	85.7	5.4	45.7	-	5.03	1242	1.18	.58	2
834	3.38	663	15.2	772	4.6	26.1	0	.0141	.0141	.0159	99.3	3.1	2.1	5.1	45.6	2	5.34	1200	1.15	.56	
835	3.39	665	15.2	434	4.6	26.1	0	.0079	.0079	.0085	99.2	6.2	1.6	9.8	85.8	-	5.25	978	1.21	.64	
836	3.39	664	15.3	335	4.6	26.1	0	.0061	.0061	.0064	99.3	19.8	2.0	9.5	83.7	-	5.19	916	1.24	.74	
837	3.41	661	15.1	183	4.6	25.6	0	.0034	.0034	.0030	96.1	83.1	19.2	3.8	33.2	-	4.98	806	1.25	.55	
829	4.72	724	17.3	1333	4.6	23.8	.0153	.0061	.0214	.0231	90.2	51.1	6.4	8.1	38.5	-	3.93	1499	1.14	.72	2
830	4.74	723	17.5	1344	4.6	23.9	.0113	.0101	.0214	.0239	99.2	27.7	1.8	8.7	41.8	-	3.83	1504	1.17	.64	2
831	4.74	722	17.3	1349	4.6	23.7	.0073	.0143	.0216	.0241	99.4	19.6	1.1	7.0	33.4	-	3.83	1509	1.17	.59	2
832	4.72	721	17.3	1343	4.6	23.7	0	.0215	.0215	.0242	99.8	6.1	0.2	6.9	33.4	16	3.93	1507	1.17	.61	
815	4.76	863	16.6	1437	7.3	26.9	.0190	.0050	.0240	.0264	99.8	6.6	0.3	8.4	20.7	2	4.01	1666	1.09	.39	1
816	4.75	863	16.5	1423	7.3	26.8	.0200	.0039	.0239	.0262	99.7	11.4	0.6	7.2	17.8	-	4.06	1666	1.08	.38	
817	4.76	860	16.6	1435	7.0	26.8	.0211	.0030	.0241	.0267	99.5	16.7	1.4	6.4	16.0	-	4.02	1660	1.07	.36	
818	6.82	826	27.5	2249	6.0	29.2	.0177	.0050	.0227	.0249	99.6	16.0	0.6	9.3	25.5	-	5.24	1602	1.09	.39	
819	6.82	827	27.6	2232	4.3	29.4	.0195	.0030	.0225	.0245	97.9	48.1	9.9	5.7	15.1	-	5.25	1588	1.09	.37	
820	6.79	830	24.9	1565	4.3	26.8	.0127	.0040	.0175	.0192	97.7	9.2	6.8	8.5	20.0	-	3.96	1428	1.11	.32	
821	6.78	828	24.9	1999	5.3	27.0	.0145	.0078	.0223	.0246	99.7	9.7	0.3	15.8	39.2	1	4.26	1598	1.12	.36	
822	6.80	828	25.0	2004	5.7	27.0	.0164	.0058	.0222	.0247	99.7	11.0	0.3	12.7	31.6	1	4.24	1598	1.12	.33	
823	6.80	826	24.9	2006	5.7	27.0	.0174	.0049	.0223	.0247	99.6	14.7	0.5	9.8	24.4	1	4.24	1594	1.10	.32	
824	6.78	826	24.7	2009	5.7	26.8	.0186	.0040	.0226	.0251	99.4	20.0	1.1	7.8	19.4	1	4.11	1594	1.12	.34	
825	6.78	828	24.5	2007	6.0	26.6	.0197	.0030	.0227	.0250	98.7	35.8	5.2	6.3	15.5	1	4.19	1590	1.08	.35	
826	6.85	827	24.4	1943	6.0	26.3	.0142	.0079	.0221	.0240	99.8	9.4	0.3	17.9	44.0	1	3.97	1596	1.14	.53	2
827	6.72	827	24.7	1658	6.0	26.7	.0128	.0059	.0187	.0205	99.3	25.6	1.2	15.1	37.7	-	4.11	1472	1.16	.43	2
828	6.82	827	24.6	1577	6.0	26.5	.0129	.0049	.0178	.0194	98.8	39.7	2.9	11.8	29.2	-	4.03	1464	1.17	.42	2

NOTES:

1. High Density Sampling Mode
2. Alternate Chutes Fueled

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