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# POLLUTION REDUCTION TECHNOLOGY PROGRAM
# SMALL JET AIRCRAFT ENGINES

## PHASE I - FINAL REPORT

by: T. W. Bruce, F. G. Davis
T. E. Kuhn and H. C. Mongia

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
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T.W. Bruce, F.G. Davis, T.E. Kuhn, and H.C. Mongia

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Project Manager, James S. Fear, Airbreathing Engines Division, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

A series of combustor pressure rig screening tests was conducted on three combustor concepts applied to the AiResearch TFE731-2 turbofan engine combustion system for the purpose of evaluating their relative emissions reduction potential consistent with prescribed performance, durability, and envelope constraints. The three concepts and their modifications represented increasing potential for reducing emission levels with the penalty of increased hardware complexity and operational risk. Concept 1, representing the least risk and the smallest potential for emissions reductions, entailed advanced modifications to the present production TFE731-2 combustion system. Concept 2, involving an intermediate amount of risk and moderate emissions reduction potential was based on the incorporation of an axial air-assisted airblast fuel injection system. Concept 3, entailing the greatest development and operational risk, along with the greatest potential for reduced emissions, was a staged premix/prevaporizing combustion system. Significant emissions reductions were achieved in all three concepts, consistent with acceptable combustion system performance. As a result of this screening effort, Concepts 2 and 3 were identified as having the greatest achievable emissions reduction potential, and were selected to undergo refinement in Phase II to prepare for ultimate incorporation within an engine.

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# FOREWORD

This document is the final report for work performed by AiResearch Manufacturing Company of Arizona, a division of The Garrett Corporation, under NASA Contract NAS3-18560. This program, under the joint sponsorship and direction of the National Aeronautics and Space Administration (NASA) Lewis Research Center and the AiResearch Manufacturing Company of Arizona, accomplished Phase I of the Pollution Reduction Technology Program for Small Jet Aircraft Engines (EPA Class T1).

The authors wish to acknowledge the assistance and guidance rendered by Mr. James S. Fear of the NASA Lewis Research Center who was the Project Manager for the Program.

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# SUMMARY

The objectives of the Pollution Reduction Technology Program for Small Jet Aircraft Engines are to identify technological approaches that will significantly reduce exhaust emissions of current small gas turbine aircraft engines, and to demonstrate this improved technology through combustor rig testing and full-scale engine testing. The emission goals for this program are the 1979 emission standards specified for Class T1 aircraft propulsion engines (turbojet and turbofan engines of less than 35.6 kN thrust) by the Environmental Protection Agency (EPA) (Ref. 1).

The program is being conducted in three phases. This report covers the results of the 19-month Phase I program, which employed the combustion system of the AiResearch Model TFE731-2 civil turbofan engine as the baseline design. Six builds each of three advanced combustor concepts, designed for the TFE731-2 engine, were evaluated in screening tests to identify those configurations with the greatest potential for reducing carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen ($NO_X$), and smoke to levels that are equal to or lower than the program goals.

Phase II, which was awarded to AiResearch in June, 1976, is directed toward the refinement of the two best combustor concepts evolved from Phase I to ensure attainment of combustion system performance consistent with overall program goals and engine mechanical and functional compatibility.

Phase III will include full-scale engine tests of one or both of the refined combustor concepts evolved from the Phase II effort to demonstrate the emissions reduction merits of the selected design, and the compatibility of the engine-combustor system interfaces.

The 1979 EPA standards for exhaust emissions, which serve as goals for this program, represent ambitious reductions below levels that exist in current engines. In order for the TFE731-2 engine to meet these standards, the approximate emission indices [grams of pollutant per kilogram of fuel burned (g/kg fuel)] required for CO and HC at the taxi-idle engine operating condition are 30 and 6, respectively. At the sea-level takeoff thrust condition, the emission index goal for $NO_X$ is approximately 10 g/kg fuel, and the smoke number goal is 40.

The Phase I combustion rig screening testing reported herein involved three combustor concepts:

Concept 1 - Advanced modifications to the existing TFE731-2 combustion system

Concept 2 - Air-assisted airblast fuel injection system

Concept 3 - Premixing/prevaporizing combustion system.

The full annular high-pressure test rig was designed to simulate the combustor operation in the TFE731-2 engine. The combustor inlet conditions were identical with the engine conditions, except for the combustor inlet pressure, which was set to 414 kPa at the high-power operating conditions to compensate for facility airflow limitations. Airflow was adjusted accordingly to maintain an equivalent inlet Mach number. The initial screening tests were conducted primarily at taxi-idle and simulated takeoff engine power conditions. The two most promising concepts, identified as Concept 2 and Concept 3, were selected from the screening evaluation and subjected to refinement testing. These tests included operation at all the simulated EPA landing/takeoff (LTO) cycle points, operation at simulated altitude conditions to evaluate relight capability and stability, and operation at off-design points.

Concept 1 demonstrated control techniques that produced significant reductions in taxi-idle emission levels below the TFE731-2 production baseline values. The most promising of the Concept 1 configurations tested employed compressor bleed and air-assisted fuel atomization. A combination of these techniques produced emission indices of 0.6 and 30.0 g/kg fuel for HC and CO, respectively. At takeoff, the only Concept 1 configuration that met the $NO_x$ goal utilized water-methanol injection into the combustor primary zone. An $NO_x$ emission index of 7.0 was attained with a water/methanol-to-fuel injection rate ratio of 0.62.

Concept 2, which incorporated 20 air-assisted airblast fuel injectors inserted axially through the combustor dome, also produced significant reductions in gaseous emissions below the baseline levels as well as in the smoke number. The Concept 2 configurations, which simultaneously produced the greatest reduction in emissions, employed techniques that simulated variable-geometry air swirlers for the purpose of controlling the primary zone equivalence ratio over the combustor operating envelope. At the taxi-idle conditions, emission index values of 1.6 and 32.1 g/kg fuel were measured for HC and CO, respectively. At takeoff, $NO_x$ was measured to be 6.5 g/kg fuel, and the smoke number was zero.

The Concept 3 combustion system employed a piloted premixing/prevaporizing fuel injection system. The pilot zone, fueled by 20 pilot nozzles, was located at the dome of the combustor. The main combustion region was located downstream of the pilot zone. The fuel for the main combustion region was introduced upstream of the combustor through 40 pressure atomizers and was premixed with compressor discharge air prior to being introduced into the burning region. The hot gases exiting the pilot zone acted as the ignition source for the main mixture. The pilot zone was continuously operated at all power settings. The Concept 3 configuration demonstrated the lowest $NO_x$ value (3.5 g/kg fuel) of any configuration tested, and the premix system experienced no difficulties with flashback or auto-ignition. At the taxi-idle conditions, emission indices for HC and CO were 3.2 and 25.7 g/kg fuel, respectively. The smoke number measured on the rig was zero.

Concepts 2 and 3, as evaluated during Phase I, were selected for additional refinement tests and evaluation during Phase II. Both of these concepts demonstrated a potential for achieving the characteristics.

# INTRODUCTION

The Pollution Reduction Technology Program for Small Jet Aircraft Engines was initiated by NASA in December 1974. The purpose of this program is to evolve and demonstrate the advanced combustor technology required for the development of EPA Class T1 engines (less than 35.6 kN thrust) to meet aircraft emissions standards (Ref. 1). Accordingly, the primary goals of the program involve significant reductions in emissions of carbon monoxide (CO), total unburned hydrocarbons (HC), and total oxides of nitrogen ($NO_x$). Reductions in exhaust smoke are also sought while other combustion performance parameters such as pressure loss, exit temperature pattern factor, and relight capability are to be maintained at acceptable levels.

The underlying motivation for this program emanates from public concern for the mounting dangers of air pollution as expressed by Congress in the Clean Air Act Amendments of 1970. In compliance with this legislation, the EPA published standards for control of air pollution from aircraft engines on July 17, 1973 (Ref. 1) that would require significant reductions in exhaust emissions from Class T1 engines by January 1, 1979. Concerted efforts on the part of the general aviation industry and various government agencies have shown the current standards to be unachievable by means of design modifications to existing engine components (Ref. 2). Instead, the attainment of emission levels as required by the EPA standards are considered to depend on the successful development of advanced combustor design concepts such as those resulting from the NASA Pollution Reduction Technology Program.

The Pollution Reduction Technology Program for Small Jet Aircraft Engines is planned to be conducted in three phases: I - Combustor Concept Screening, II - Combustor Compatibility Testing, and III - Combustor Engine Testing. The program is based on the use of the AiResearch Model TFE731-2 turbofan combustion system, which is an annular reverse-flow type common to several current production engines in the EPA Class T1 category. This report describes the Phase I activities, which consisted of combustor component rig tests on three basic emission control concepts: (1) advanced modifications to the existing configuration, (2) the application of airblast atomizers, and (3) a premixing/prevaporizing staged fuel injection system.

The Phase I test program was primarily directed toward determination of HC and CO emissions reductions at taxi-idle, and $NO_x$ at takeoff conditions, with only a preliminary evaluation of other performance factors such as combustor exit pattern factor or ignition capability. More extensive development tests were performed during the refinement testing portion of the test task.

All three combustor concepts were developed through a series of design modifications to achieve reductions in HC emissions well below the EPA requirements and CO levels that are marginally close. Only the airblast and the premixing/prevaporizing combustors demonstrated the capability to meet the $NO_x$ emission standard without the use of water injection. Descriptions of the three combustor concepts and the design modifications for each configuration employed in the program, test procedures, and the test results are presented in this report.

# CHAPTER I

# POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR SMALL JET AIRCRAFT ENGINES - PROGRAM DESCRIPTION

## General Description

The Pollution Reduction Technology Program for Small Jet Aircraft Engines (EPA Class T1 turbojet and turbofan engines of less than 35.6 kN thrust) is a multi-year effort initiated in 1974 and scheduled for completion by late 1978. The overall program objectives are to:

- Identify technology capable of attaining the emissions reduction goals consistent with performance constraints.
- Screen and develop configurations employing the technological advancements through full-scale rig testing.
- Demonstrate the most promising approaches in full-scale engine testing.

The AiResearch Model TFE731-2 turbofan engine combustion system was selected for the T1 Class development effort. It is expected that the emission control technology derived from this program will be applicable to other engines within the T1 class, and possibly to gas turbine engines in other classes as well. It is also anticipated that the results of this program may suggest additional designs or techniques that might merit further evaluation for other specific engine applications or under other research programs.

## Program Goals

The program goals for emission levels are consistent with the Environmental Protection Agency 1979 Standards for T1 Class engines. The required reductions of HC, CO, and $NO_x$ were of sufficient magnitude to necessitate advancements in the state-of-the-art. The smoke and performance goals for the program were approximately the same levels as those attained on current TFE731-2 engines. The emission goals were to be achieved without compromise to combustor performance factors, durability, or existing envelope constraints.

Emission goals. - The emission goals for this program are consistent with the EPA Class T1 gas turbine engine requirements currently specified by the EPA for new aircraft gas turbine engines manufactured after January 1, 1979. The goals for the individual emission constituents and average levels measured on production engines are listed in Table I. The goals listed in Table I are based on the simulated landing-takeoff (LTO) cycle shown in Table II.

TABLE I. - EMISSION COMPARISON - PROGRAM GOALS VS TFE731-2 ENGINE CHARACTERISTICS

| Pollutant | Program Goals<br>Gaseous Emissions, lb/1000 lb Thrust-hr/LTO cycle[a] | TFE731-2 Engine Characteristics<br>Gaseous Emissions, lb/1000 lb Thrust-hr/LTO cycle[a,b] | Percent Reduction Needed to Meet Goals |
|---|---|---|---|
| Total unburned hydrocarbons (HC) | 1.6 | 6.6 | 76 |
| Carbon monoxide (CO) | 9.4 | 17.5 | 46 |
| Oxides of nitrogen ($NO_x$) | 3.7 | 5.0 | 26 |
| Smoke No. | 40 | 36 | 0 |

[a] LTO (landing-takeoff) cycle as defined in Table II.

[b] Average of six engines measured prior to start of program.

TABLE II. - EPA SPECIFIED LANDING-TAKEOFF CYCLE FOR CLASS T1 ENGINES

| Mode | Duration of mode (Minutes) | Engine power setting, (percent of rated power) |
|---|---|---|
| Taxi-idle (out) | 19.0 | 5.7[a] |
| Takeoff | 0.5 | 100 |
| Climbout | 2.5 | 90 |
| Approach | 4.5 | 30 |
| Taxi-idle (in) | 7.0 | 5.7[a] |

[a] Recommended power setting of 0.89 kN thrust for taxi-idle operation of the AiResearch TFE731-2 turbofan in accordance with applicable Federal Aviation Administration Regulations.

Emission indices, expressed as grams of pollutant per kilogram of fuel burned, that approximately correspond to the EPA gaseous emission standards for Class T1 engines at specific operating conditions are:

| Pollutant | Operating condition | Emission index, g/kg fuel |
|---|---|---|
| HC | Taxi-idle | 6 |
| CO | Taxi-idle | 30 |
| $NO_x$ | Takeoff | 10 |

Combustor performance, life, and envelope goals - The following combustor performance, life, and envelope goals have been established to ensure that the final selected combustor system is compatible with the engine cycle and configuration:

| | |
|---|---|
| Combustion efficiency | $\geq$ 99 percent at all engine operating conditions |
| Combustor exit temperature pattern factor[a] | $\leq$ 0.19 at takeoff conditions |
| Combustor life | Commensurate with the current TFE731-2 |
| Engine relight capability | Commensurate with the current TFE731-2 relight envelope |
| Combustor size and shape | Compatible with TFE731-2 engine installation |
| Fuel | ASTM D1655-75 Type Jet A (or equivalent) |

[a] Pattern factor (PF) = $\frac{T_{t4max} - T_{t4avg}}{T_{t4avg} - T_{t3avg}}$

## Program Plan

The Pollution Reduction Technology Program for Small Jet Aircraft Engines is a three-phase effort with each phase independently funded. The three phases are:

- Phase I - Combustor screening tests of low emission concepts
- Phase II - Combustor refinement and optimization tests
- Phase III - Engine testing with selected combustor concept(s)

Phase I program. - The 19-month Phase I effort involved the design, rig testing, and data analysis on a number of candidate approaches for reducing HC, CO, $NO_x$, and smoke emissions. The objective of this phase was to identify and develop emission control technology concepts. A detailed description of the Phase I Program and the results are presented in the following chapters of this report.

Phase II program. - During Phase II, the two most promising combustor configurations identified in Phase I will undergo more extensive testing in the component rig to develop systems that optimize emissions reductions consistent with acceptable combustion system performance required in an engine application. Therefore, the testing involved in Phase II will entail development in the areas of off-design-point operation, lean stability and altitude relight capability, and exit temperature profile and pattern factor. In addition to the rig tests, a provision has been made in Phase II to conduct limited engine tests using test rig adaptive hardware, with the intention of obtaining a correlation between the emission levels measured on the engine and rig. These tests will be confined to brief correlation checks, and no refinement or development work scheduled for Phase III will be conducted in Phase II.

Phase III program. - The most promising combustion system or systems developed and refined through Phases I and II will be assembled on a TFE731-2 engine,and undergo a series of tests to demonstrate the actual performance and emissions characteristics in an engine environment.

## Program Schedule

The program schedule for the Pollution Reduction Technology Program for Small Jet Aircraft Engines is shown in Figure 1. Phase I was a 19-month technical effort which has been completed. Phase II, which was awarded in June, 1976, is a 14-month program. Phase III is anticipated to be a 15-month effort with a completion date prior to 1979.

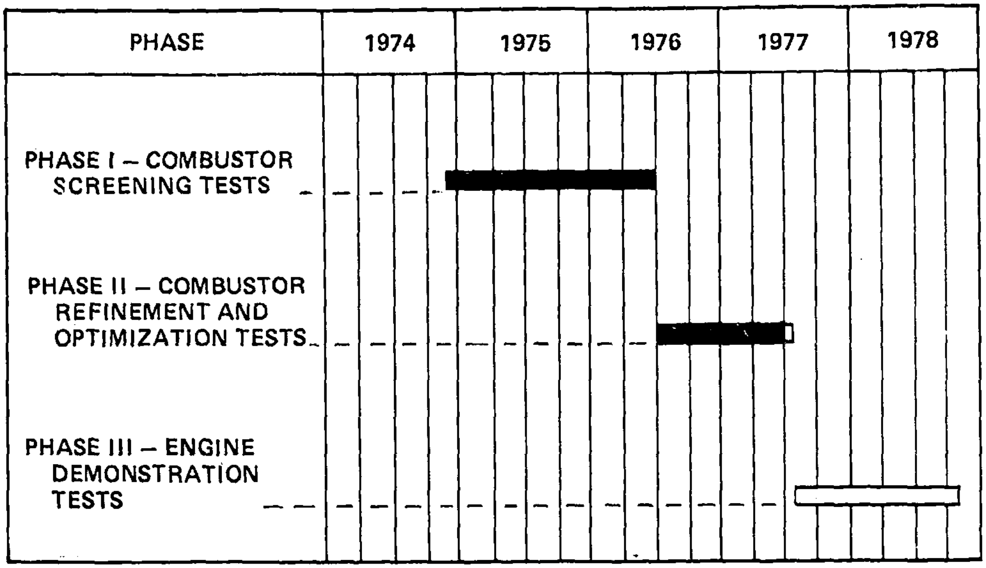

Figure 1. Program Schedule for the Pollution Reduction Technology Program for Small Jet Aircraft Engines

# CHAPTER II

# PHASE I PROGRAM - EQUIPMENT AND PROCEDURES

## Introduction

This chapter contains a description of the AiResearch TFE731-2 Engine and its combustion system. The TFE731-2 was selected as being representative of current technology turbofan engines of EPA Class T1, and to serve as the baseline for comparison for the program results. In addition, the test facilities and equipment, including the emissions sampling and analysis instrumentation, test procedures, and data analysis procedures and methods, are described.

## Baseline Test Items Description and Performance

TFE731 turbofan engines - general description. - The AiResearch TFE731-2 Engine is a 15.6 kN thrust engine, which is the lower power version of the two TFE731 Engine models currently in production. The other version, designated TFE731-3, is rated at 16.5 kN thrust. Both engines are of a two-spool, geared front fan design with a bypass ratio (BPR) of 2.67. The fan is coupled through a planetary gearbox to the low-pressure spool, which consists of a four-stage axial compressor and a three-stage axial turbine. The high-pressure spool consists of a single-stage centrifugal compressor and a single-stage axial turbine. The production combustion system utilizes a reverse-flow annular combustor with 12 dual-orifice pressure atomizing fuel injectors installed radially through the outer wall. A photograph of the engine is shown in Figure 2. Overall engine dimensions and weight are included in Figure 3. Details regarding the combustor design are shown in Figure 4.

Performance characteristics for the TFE731-2 Engine are listed in Table III. A plot of the TFE731-2 operating and starting envelope is presented in Figure 5.

TABLE III. TFE731-2 ENGINE PERFORMANCE

| | |
|---|---|
| Thrust, kN: | |
| Sea-level takeoff (maximum thrust) | 15.6 |
| Maximum cruise (12,192 m, 0.8 Mach No.) | 3.36 |
| Thrust specific fuel consumption, kg/N-hr: | |
| Sea-level takeoff (maximum thrust) | 0.048 |
| Maximum cruise (12,192 m, 0.8 Mach No.) | 0.082 |
| Noise level, EPNdB: | |
| Sea-level takeoff | 82.6 |

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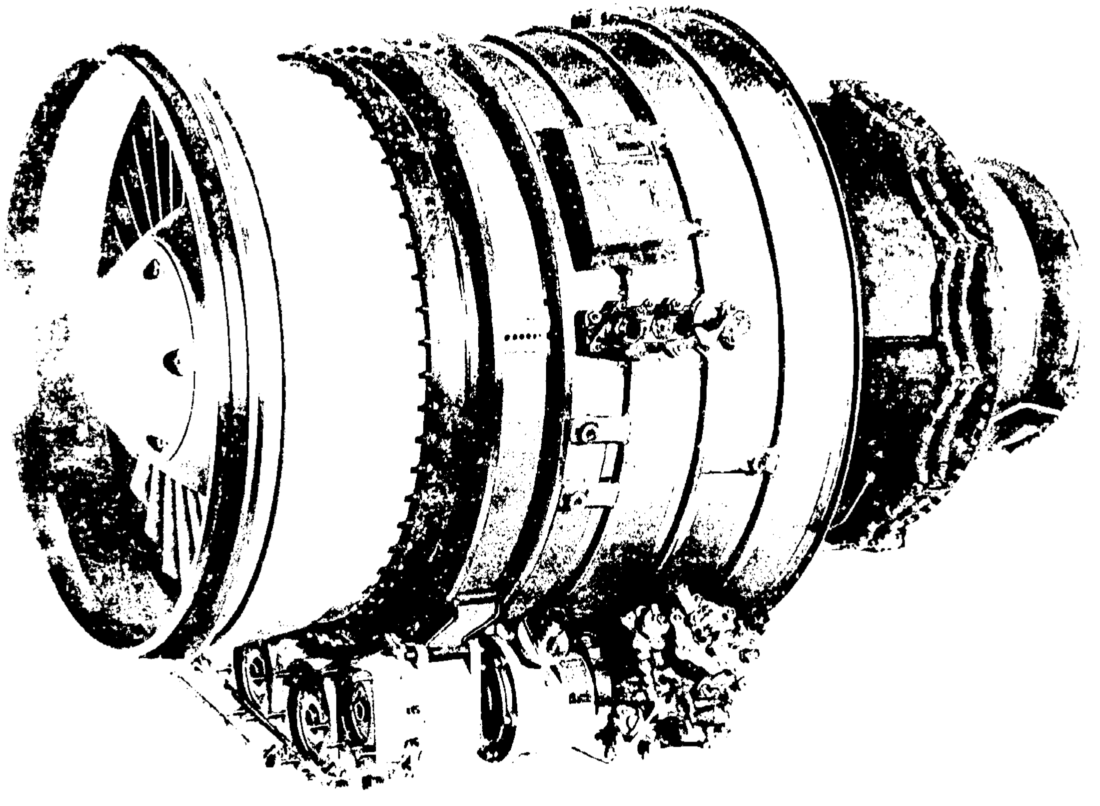

Figure 2. Model TFE731 Turbofan Engine

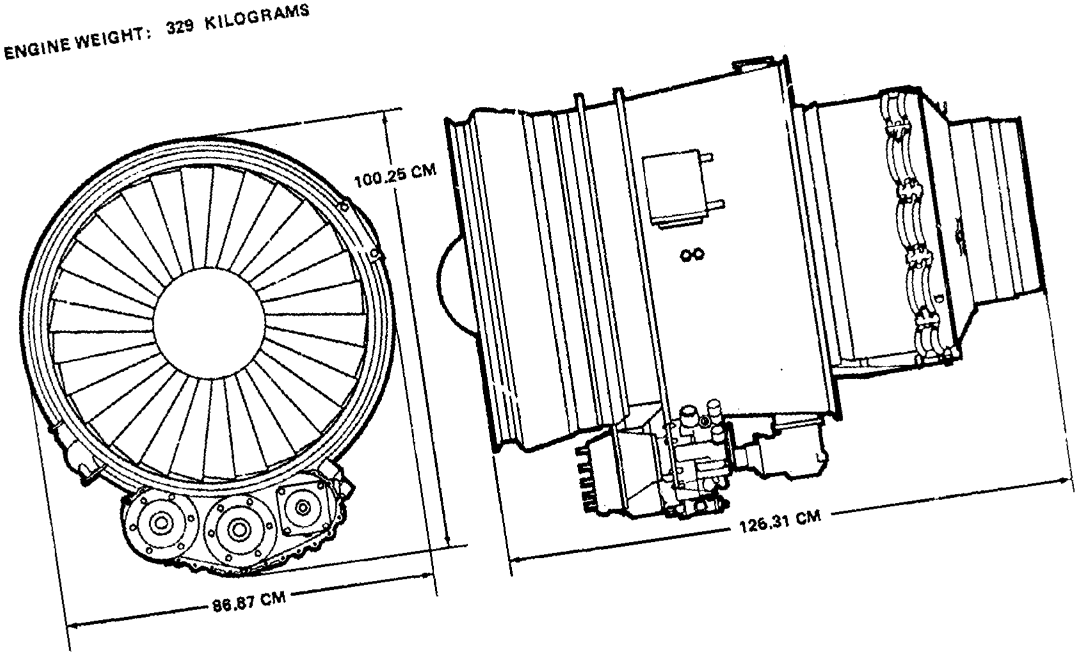

Figure 3. TFE731 Engine Envelope

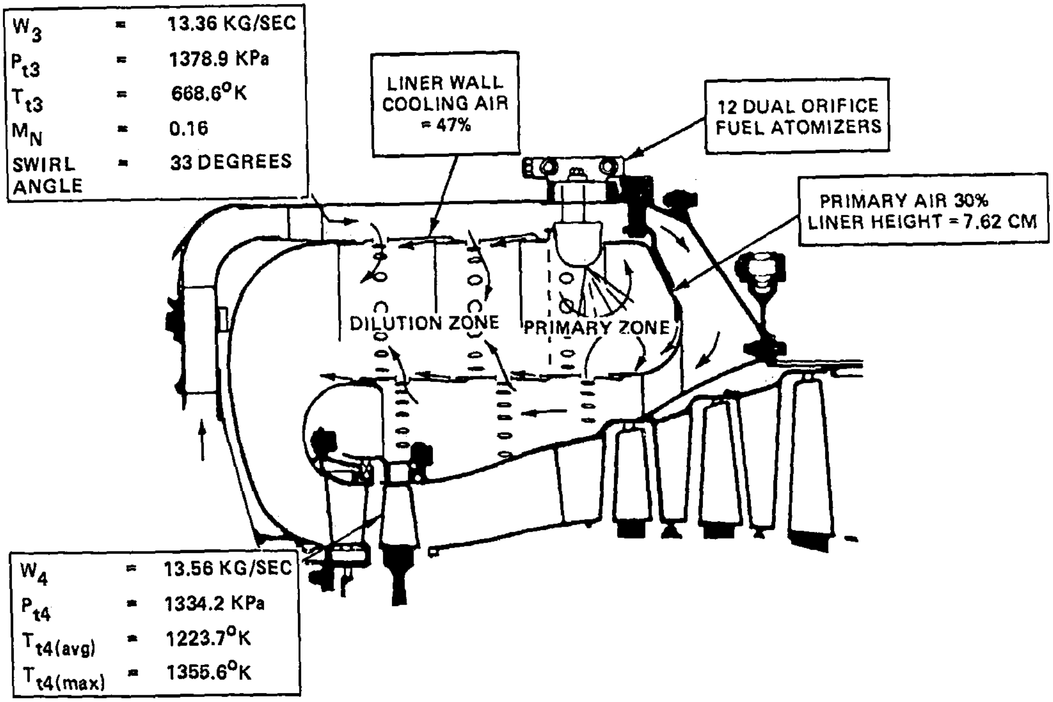

Figure 4. TFE731-2 Turbofan Reverse-Flow Annular Combustor System, Sea-Level Standard Day Static Conditions

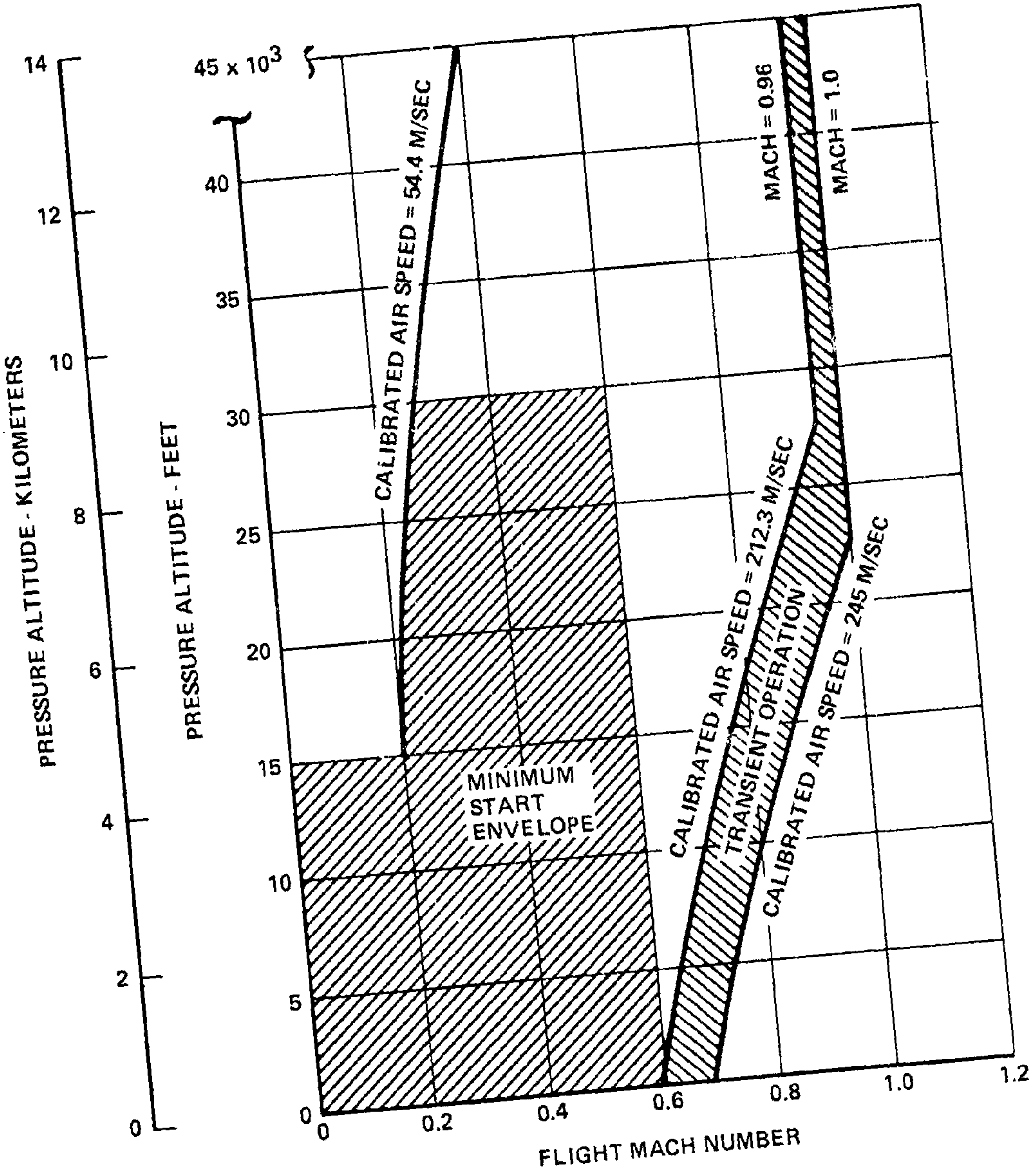

Figure 5. TFE731 Engine Flight Envelope

TFE731-2 combustion system description.. - The TFE 731-2 combustor is a reverse-flow annular design. The combustor liner consists of an inner and an outer panel connected by a dome. Cooling bands (two on the outer and three on the inner) are brazed to these panels. Fuel is injected into the combustor through twelve dual-orifice fuel nozzles inserted radially through the liner outer panel near the dome. The fuel spray cone is angled 35 degrees toward the dome, and injects nearly tangentially around the combustor annulus in the direction of the inlet air swirl. A single fuel flow divider valve is used to regulate the fuel flow between the primary and secondary flow circuits. Ignition and engine acceleration is performed on primary fuel only, with the secondary fuel being phased in slightly before the taxi-idle power setting is reached. The ignition system consists of two air-gap igniters connected to a capacitance discharge ignition unit. The igniters are located in the bottom quadrant of the combustor and align axially with the fuel nozzles. The key combustor operating parameters at the taxi-idle and takeoff power settings are listed in Table IV.

TABLE IV. - KEY OPERATING PARAMETERS OF THE TFE731-2 COMBUSTOR

| Parameter | Taxi-Idle | Takeoff |
|---|---|---|
| Combustor airflow, kg/sec | 2.31 | 13.36 |
| Compressor discharge total pressure, kPa | 197.6 | 1379.0 |
| Combustor pressure loss, percent | 3.0 | 4.5 |
| Compressor discharge temperature, $^{\circ}K$ | 365.8 | 668.6 |
| Combustor discharge temperature, $^{\circ}K$ | 722.9 | 1223.7 |
| Combustor discharge pattern factor | 0.35 | 0.19 |
| Combustor fuel flow, kg/hr | 80.4 | 752.3 |

Baseline pollution levels. - At the onset of the test phase, rig testing was performed on current production combustion system hardware to establish baseline emission values. This data, together with the program goals, are shown in Table V for the taxi-idle and simulated takeoff points.

TABLE V. - TEST RIG BASELINE EMISSION VALUES

| | Taxi-idle emissions | | Takeoff emissions | |
|---|---|---|---|---|
| | HC, g/kg fuel | CO, g/kg fuel | $NO_x$, g/kg fuel | Smoke |
| Current production[a] | 20.6 | 58.8 | 11.5 | 16 |
| Goals (compensated for rig conditions) | 6.0 | 30.0 | 7.0 | 12 |
| Required reduction, percent | 70.9 | 49 | 39.4 | 25 |

[a] As measured at test rig conditions.

## Test Rig and Facilities

Pressure rig and instrumentation. - The pressure rig used for testing was originally designed for use in the development of the present combustion system for the TFE731 turbofan engine. Only minor modifications and the refurbishment of hot-end components were required for its use on the NASA T1 emission reduction program. A cross-section layout of the rig is shown in Figure 6. The compressor diffuser, deswirl vanes, and inner and outer transition liners were all reworked engine components to ensure that the combustion system aerodynamics simulated engine conditions as nearly as possible. A traversing instrumentation drum was located at the axial plane of the turbine stator inlet. This drum contained the combustor exit instrumentation. The inlet instrumentation was mounted on the combustor plenum at the discharge of the compressor deswirl vanes. The following paragraphs contain a detailed description of the instrumentation that is listed in Table VI.

Combustor inlet instrumentation. - Figure 7 shows the circumferential location of the combustor inlet instrumentation. There were four four-element total-pressure rakes located 90-degrees apart around the plenum. The angle of the probes,with respect to axial position was adjustable, and the probes were set to correspond to the maximum total pressure value facing the direction of air swirl at the inlet to the combustor. A static-pressure wall tap immediately upstream of each total-pressure rake was used for measurement of combustor inlet static pressure. Four inlet total-temperature thermocouples were located at the same axial plane as the total-pressure rakes,and circumferentially spaced halfway (45 degrees) between the rakes. The thermocouples were iron-constantan with a closed bead. The bead was immersed halfway into the inlet channel.

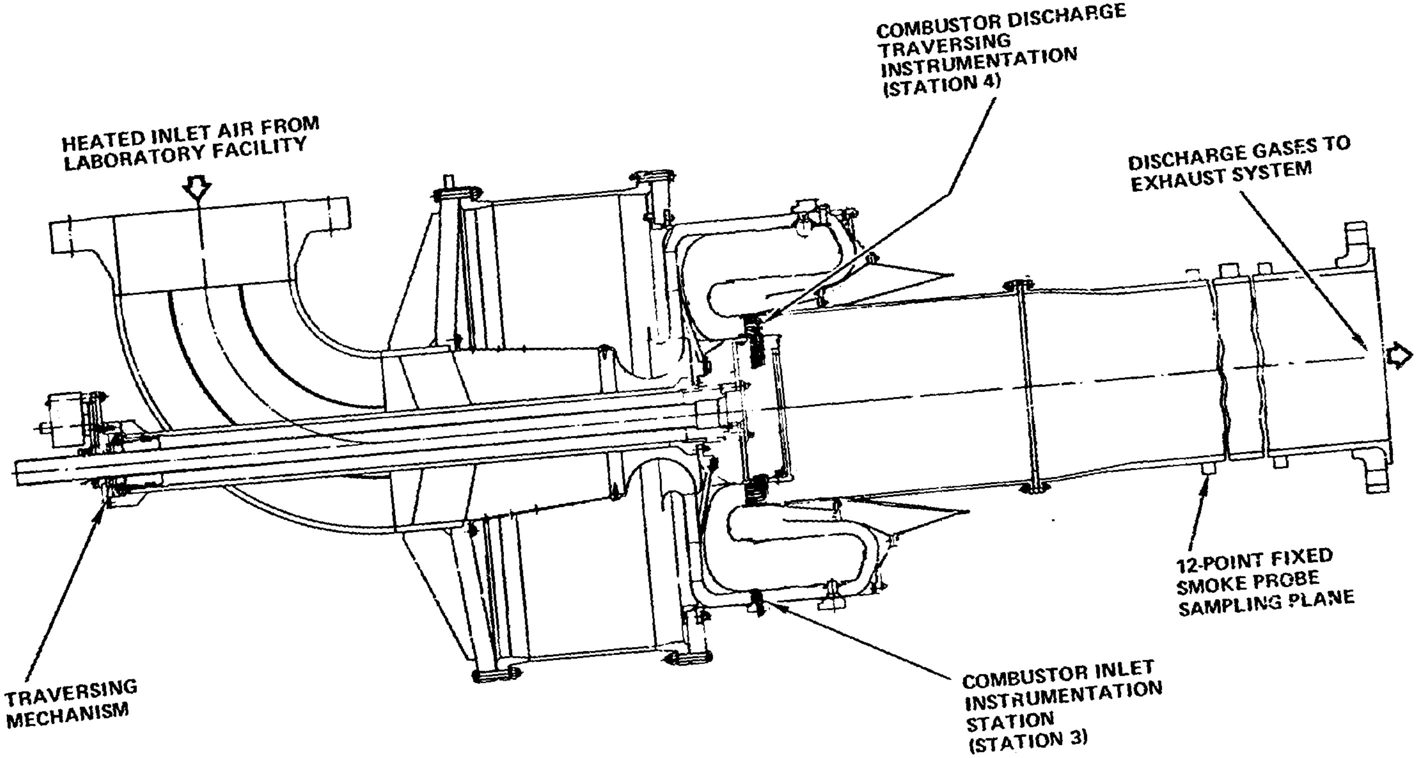

Figure 6. Full-Scale Reverse-Flow Annular Combustor Test Rig

## TABLE VI. - COMBUSTOR PRESSURE RIG INSTRUMENTATION LIST

| Parameter | Symbol | Angular Position, Degrees | Immersion, cm | Sensor Type (Dimensions in cm) |
|---|---|---|---|---|
| Combustor Inlet Static Pressure | $P_{S31}$ | 345 | 0 | 0.140 Dia. Tap |
| Combustor Inlet Static Pressure | $P_{S32}$ | 75 | 0 | 0.140 Dia. Tap |
| Combustor Inlet Static Pressure | $P_{S33}$ | 165 | 0 | 0.140 Dia. Tap |
| Combustor Inlet Static Pressure | $P_{S34}$ | 255 | 0 | 0.140 Dia. Tap |
| Combustor Inlet Total Pressure | $P_{T311}$ | 345 | 0.413 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T312}$ | 345 | 0.730 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T313}$ | 345 | 1.048 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T314}$ | 345 | 1.365 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T321}$ | 75 | 0.413 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T322}$ | 75 | 0.730 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T323}$ | 75 | 1.048 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T324}$ | 75 | 1.365 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T331}$ | 165 | 0.413 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T332}$ | 165 | 0.730 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T333}$ | 165 | 1.048 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T334}$ | 165 | 1.365 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T341}$ | 255 | 0.413 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T342}$ | 255 | 0.730 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T343}$ | 255 | 1.048 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Pressure | $P_{T344}$ | 255 | 1.365 | 0.317 Dia. Pitot Tubes |
| Combustor Inlet Total Temperature | $T_{T31}$ | 30 | 0.889 | CA Thermocouples bead-type half-shielded (all $T_{T3}$ locations) |
| Combustor Inlet Total Temperature | $T_{T32}$ | 120 | 0.889 | |
| Combustor Inlet Total Temperature | $T_{T33}$ | 210 | 0.889 | |
| Combustor Inlet Total Temperature | $T_{T34}$ | 300 | 0.889 | |
| Combustor Discharge Static Pressure | $P_{S41}$ | Rotating Rake | 0 | 0.175 Dia. Tap |
| Combustor Discharge Total Pressure | $P_{T41}$ | | 0.343 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Pressure | $P_{T42}$ | | 0.775 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Pressure | $P_{T43}$ | | 1.283 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Pressure | $P_{T44}$ | | 1.816 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Pressure | $P_{T45}$ | | 2.324 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Pressure | $P_{T46}$ | | 2.857 | 0.317 Dia. Pitot Tubes |
| Combustor Discharge Total Temp. | $T_{T41}$ | | 0.349 | Pt/Pt and 10% Rh Thermocouples shielded (all $T_{T4}$ locations) |
| Combustor Discharge Total Temp. | $T_{T42}$ | | 0.768 | |
| Combustor Discharge Total Temp. | $T_{T43}$ | | 1.289 | |
| Combustor Discharge Total Temp. | $T_{T44}$ | | 1.810 | |
| Combustor Discharge Total Temp. | $T_{T45}$ | | 2.330 | |
| Combustor Discharge Total Temp. | $T_{T46}$ | | 2.850 | |
| Sample Gas Temperature | $T_{SG1}$ | - | - | CA Thermocouples shielded |
| Sample Gas Temperature | $T_{SG2}$ | - | - | CA Thermocouples shielded |

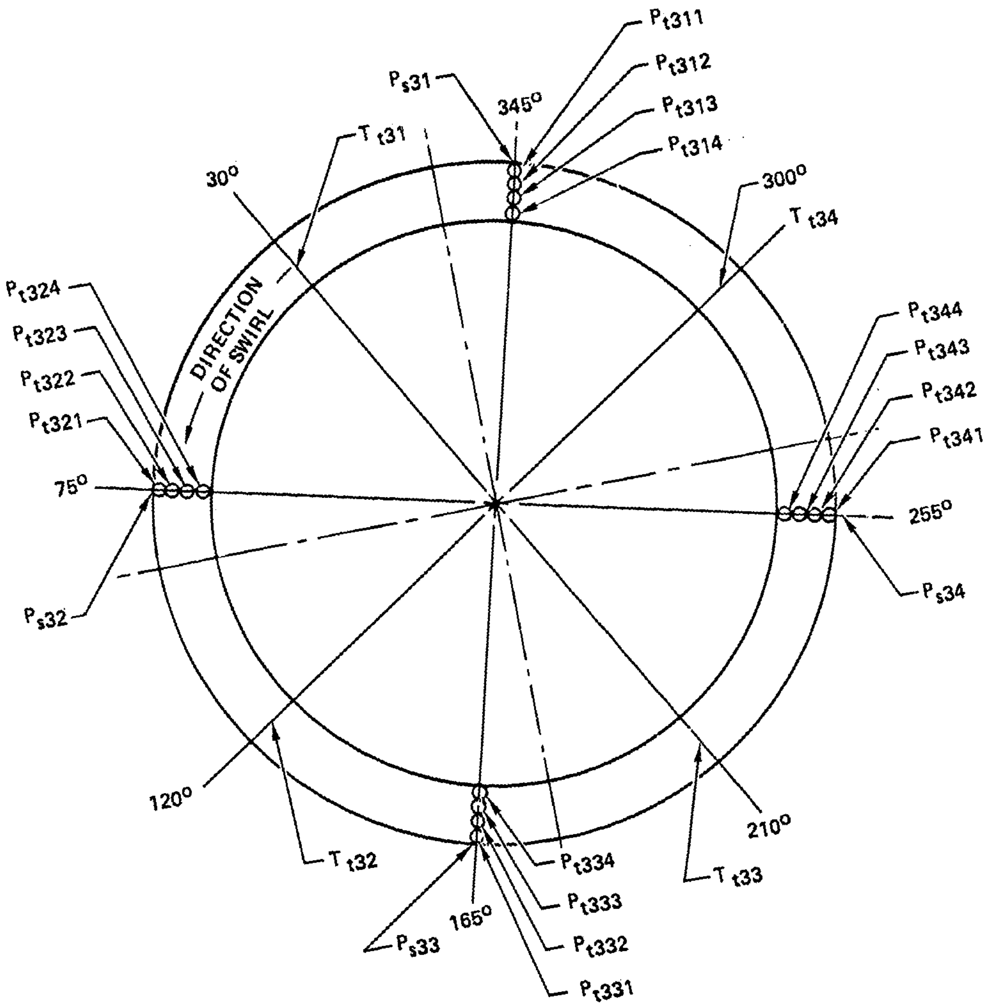

Figure 7. Circumferential Location of Inlet Instrumentation - Combustor Test Rig - View Looking Into Combustion Chamber Liner Discharge

Combustor discharge instrumentation. - The combustor discharge instrumentation was located in the plane of the turbine stator inlet. The drum was connected to a stepping motor, which indexed the drum in 10-degree increments. The rakes were canted at a 20-degree angle to compensate for combustor swirl. These rakes were:

- A six-element platinum/platinum-10-percent rhodium thermocouple rake
- A six-element total-pressure rake with one static-pressure tap
- A four-point, water-cooled emissions rake.

The lines from these rakes were inserted into the traversing drum where they entered the instrumentation shaft through gas-tight compression fittings. The cooling water lines for the emission probe also entered the shaft through compression fittings. At the end of the shaft, these rig instrumentation lines were terminated and connected to facility lines. The emissions rake consisted of four 0.317 cm diameter stainless steel probes that were connected to a common 0.635 cm diameter stainless steel tube. The tips of the four probes were located in the combustor exhaust gas stream, and the sample gases passed through them and into the common collector. Surrounding the collector was a water jacket that contained inlet and exit ports for water cooling. The cooling water was supplied through a closed-circuit system connected to the facility cooling tower. Thermocouples were located in the emission sample gas stream, (one near the probe and the other at the exit of the instrumentation shaft) to monitor the sample temperature. The cooling water flow rate was adjusted to maintain the desired 422°K to 811°K sample temperature.

In addition to the emission probe on the instrumentation drum, a fixed-position smoke sampling rake was located in the tailpipe downstream of the exhaust gas mixing basket. This rake consisted of four 0.317 cm stainless steel probes externally manifolded and inserted through the rig tailpipe. Each tube had three 0.08 cm orifices drilled through the wall and spaced on centers of equal areas for the tailpipe.

Emission sampling and analysis facilities and equipment. - The AiResearch exhaust-gas emissions sampling and analysis equipment that was used in the program consisted of two basic types: that used for sampling gaseous emissions of $NO_x$, HC, CO, and $CO_2$; and that used to obtain the smoke number of insoluble particulates in the exhaust gas. The analyzers, together with all required calibration gases and other support equipment, were installed in the mobile units shown in Figures 8 and 9. All equipment, including plumbing and materials, conforms to EPA recommendations on exhaust emission analysis, as specified in Section 87.82 of the 1979 aircraft emission standards (Ref. 1). A schematic of the gas analyzer flow system is shown in Figure 10. A schematic of the particulate analyzer flow system is shown in Figure 11. This equipment is described in the following paragraphs.

Gaseous emissions analysis equipment. - This equipment consisted of the following analyzers, along with the refrigeration, gasifier, filtration, and pumping devices required for obtaining and processing the samples:

- A Thermo Electron chemiluminescent analyzer for determinating the presence of oxides of nitrogen over a range from 0 to 10,000 ppm
- A Beckman Model 402 hot flame-ionization-detection hydrocarbon analyzer capable of discriminating unburned hydrocarbons in the sample over a range of 5 ppm to 10 percent
- A Beckman Model 315B carbon monoxide analyzer. This analyzer has three discrete sensitivity ranges corresponding to 0 to 100 ppm, 0 to 500 ppm, and 0 to 2500 ppm
- A Beckman Model 315B carbon dioxide analyzer. The sensitivity ranges of this analyzer correspond to 0 to 2 percent, 0 to 5 percent, and 0 to 15 percent. (The measurement of carbon dioxide is not specifically required for the determination of pollutant emission rates. However, AiResearch conducts analyses of carbon dioxide in engine exhaust gases to provide a carbon balance with the fuel consumed as a means of checking the validity of test data).

All instruments, zero gases, and span gases are kept at a constant temperature to avoid drift. The equipment is capable of continuous monitoring of oxides of nitrogen, unburned hydrocarbons, carbon monoxide, and carbon dioxide in exhaust gases. Test results are recorded automatically when required. The zero and span gases used to calibrate the instruments are given in Table VII.

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| GAS MEASURED | INSTRUMENT |
|---|---|
| OXIDES OF NITROGEN | CHEMILUMINESCENT ANALYZER |
| HYDROCARBONS | FLAME IONIZATION DETECTOR |
| CARBON MONOXIDE<br>CARBON DIOXIDE | NON-DISPERSIVE INFRARED ANALYZER |

Figure 8. Gaseous Exhaust Emissions Measurement Instrumentation

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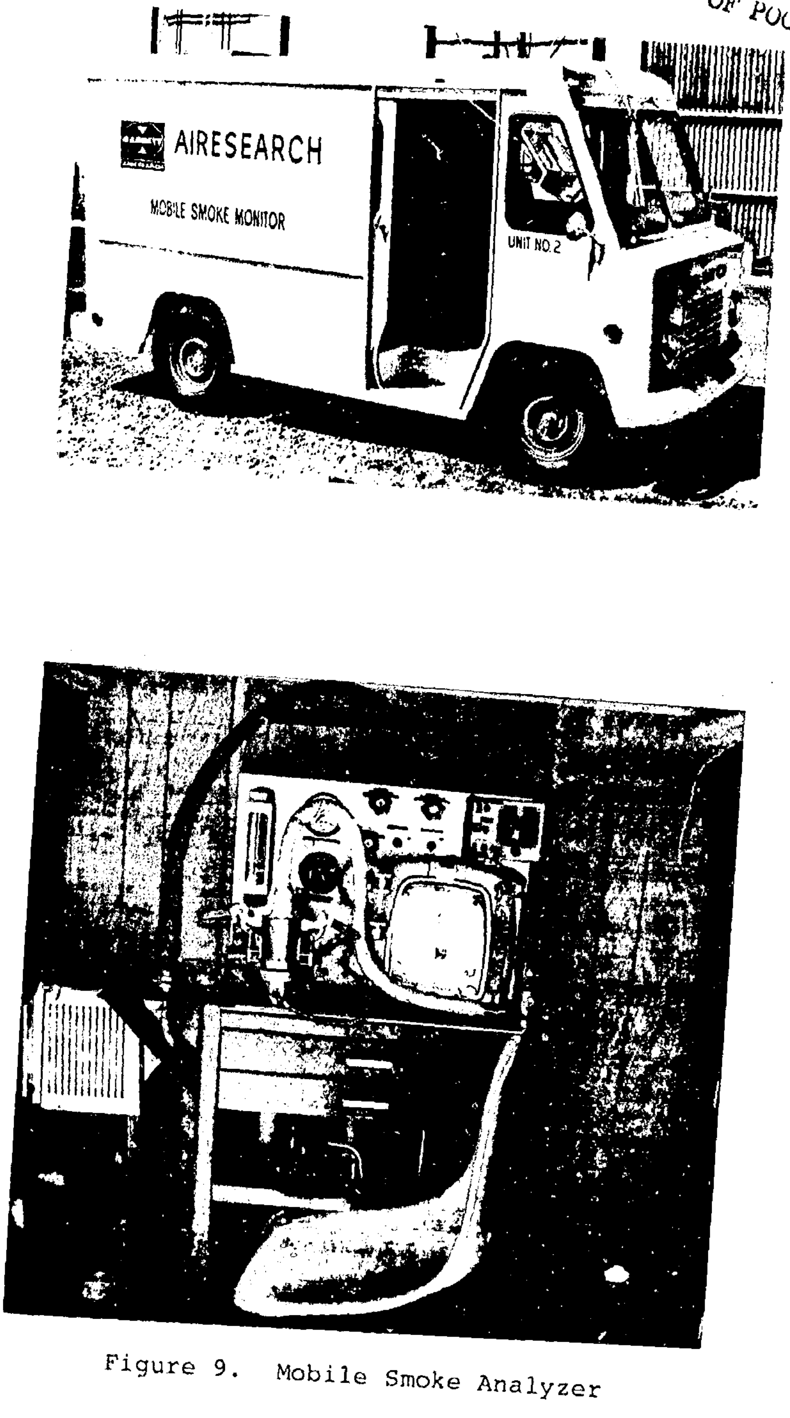

MP-43861

Figure 9. Mobile Smoke Analyzer

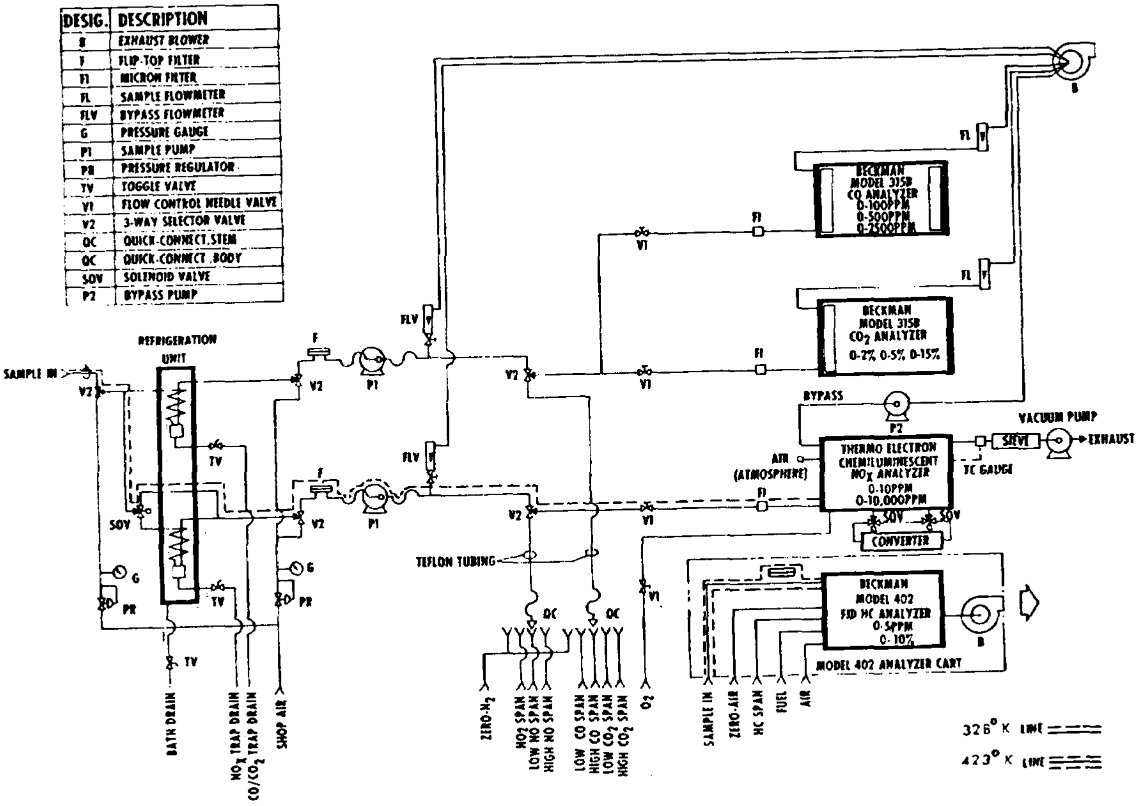

Figure 10. Exhaust Gas Analyzer Flow System

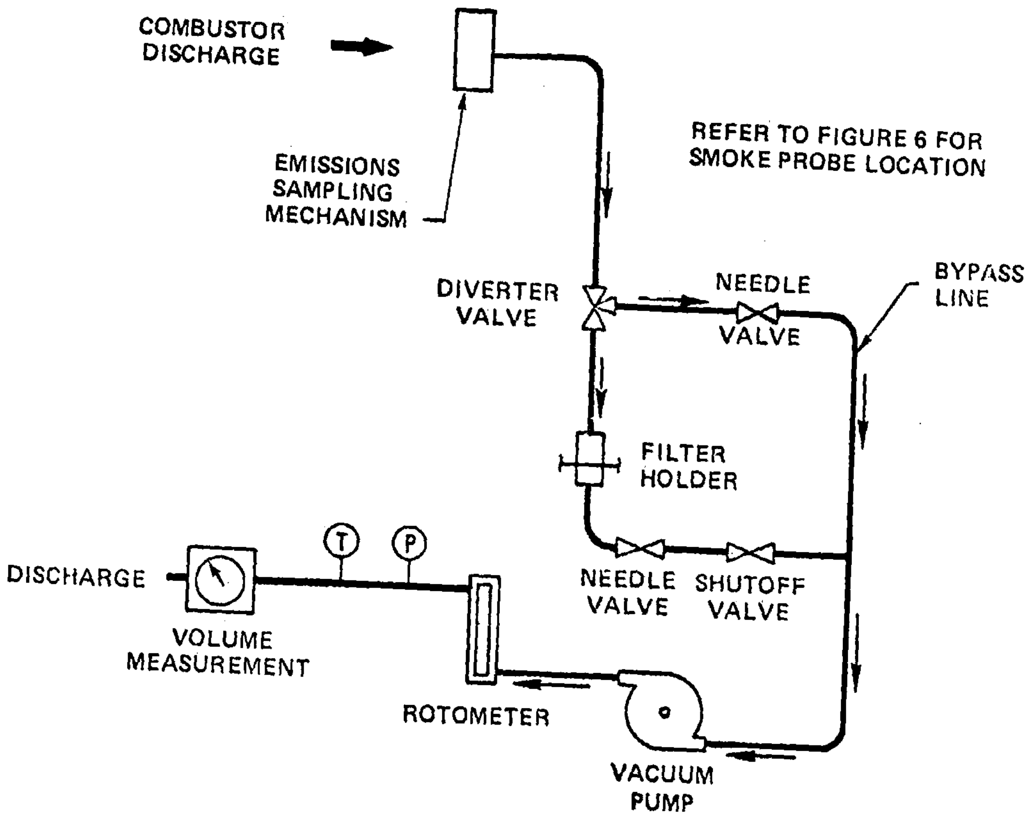

Figure 11. Particulate Analyzer Flow System

TABLE VII. - ZERO AND SPAN GASES

| Gas | Concentration | Manufacturer |
|---|---|---|
| Zero Air and $N_2$ | HC $\leq$ 1.0 ppm | Air Products |
| $C_3H_8$ in Air | 6.3 ppm<br>52.0 ppm<br>105.0 ppm | Air Products |
| NO in $N_2$ | 16.9 ppm<br>46.5 ppm<br>109.0 ppm | Scott Research Labs |
| CO in $N_2$ | 65.0 ppm<br>250.0 ppm<br>440.0 ppm | Air Products<br>Matheson<br>Air Products |
| $CO_2$ in $N_2$ | 1.05%<br>1.97%<br>3.05% | Scott Research Labs |

Particulate emissions sampling and analysis equipment. - Sample size measurements were made with a Precision Scientific Wet Test Meter accurate to within ±0.005 standard cubic meter. Wet test pressure and temperature were measured within ±68 Pa and 0.50°K respectively. Sample flow measurements were conducted with a Brooks Rotometer, Model 110, accurate to within ±0.017 cubic meter per minute. A Duo-Seal Model 1405 vacuum pump, with a free flow capacity of 0.0057 cubic meters/minute and no-flow vacuum capability of one micron, was used. Reflectance measurements were conducted with a Welch Densichron Model 3837 photometer.

Data acquisition. - For rig tests, all pressure readings were read from pressure gauges, manometers, and a pressure transducer readout display and manually recorded on the data sheets. Inlet temperature values were read on a temperature display and manually recorded on the data sheets. Combustor discharge temperatures were read by a low-speed digital system and recorded on paper tape. This tape was converted to computer cards at the conclusion of each test for input into the exhaust temperature survey computer program. Fuel- and water-flow rates were read on rotometers and recorded manually on the data sheets.

Gaseous emission data was recorded on a moving strip chart and manually transferred to the computer input sheets for data reduction. Late in the test phase, this system was modified to acquire the emission values on a digital system with a punched tape as output. This tape was used to punch computer cards for input into the data reduction program, thus reducing the time-consuming step of manually reading and averaging the emission values. This strip chart data was still taken and used as a check of the new system. Smoke emissions were sampled, and the smoke number determined.

Combustion component test facility. - The combustion facility has the capability of supplying up to 4.08 kg/sec of unvitiated air at a pressure and temperature of 690 kPa and 700°K, respectively. Higher airflow rates are possible with corresponding decreases in pressure. The facility is instrumented to measure pertinent air and fuel flow rates, temperatures, and pressures necessary to determine performance factors such as efficiency, discharge temperature pattern factor, combustor total pressure drop, ignition, and emissions. Pressures from 0 to 1015 kPa can be measured with the use of pressure gauges. These gauges were used to measure those parameters necessary to the determination of airflow rate. Rig pressures were measured with a transducer connected to a switching valve. Temperatures were measured as follows:

- Combustor inlet - iron-constantan thermocouples (200 to 810°K)
- Combustor discharge - platinum/platinum-10-percent rhodium thermocouples (255 to 1922°K).

Inlet air humidity was measured at the start of each test with a Beckman Electrolytic Hygrometer. Liquid fuel flow was measured with five rotometers that have a total range of 2 to 450 kg/hr. Airflow was measured in accordance with standard ASME orifice metering practice. Data was recorded both manually and by means of a digital recorder.

## Test Conditions

The combustor rig tests were conducted in two phases. The first was conducted over a nine-month period and involved the screening of 18 different combustion system configurations for their emission reduction potential. The majority of this testing was performed at the taxi-idle and simulated takeoff power settings. However, for configurations that appeared promising, a limited amount of data was also taken at the approach and climb points. Pattern factor, pressure loss, and wall temperature data was also measured at the takeoff power settings on most of the configurations. Generally, parametric evaluation was limited on Concepts 1 and 2. The most common parametric testing involved investigating the effect of variation in overall fuel/air ratio on $NO_x$ formation at the takeoff power setting. At taxi-idle, a series of simulated compressor bleed points were tested on many of the configurations to evaluate the effect on HC and CO. Concept 3, on the other hand, underwent extensive parametric evaluation of fuel splits between the pilot and main combustion zones.

The second phase of the rig testing was used to refine the two concepts that showed the most promise in simultaneously meeting all three LTO standards with a minimum compromise to the combustor operating characteristics. Concepts 2 and 3 were selected to undergo refinement testing, and two configurations of each concept were evaluated. During these tests, gaseous emissions were measured at all four LTO cycle points. On the configurations where smoke was measured, the sample was taken at the takeoff point. Combustor performance data was taken at each power setting tested, and included pattern factor, pressure loss, and combustion efficiency. Wall temperatures were measured at only the takeoff power setting, using temperature-sensitive paint.

In addition to these tests, the combustors underwent ignition (including altitude relight) and stability tests. Test points were established based on existing rig data from ignition and stability tests performed on the present production TFE731-2 combustor, and the starting and operating envelope of the engine.

The rig test conditions for the four LTO power settings are shown in Table VIII, together with the TFE731-2 engine conditions for comparison. The rig and engine conditions for the taxi-idle and approach points were identical. However, at takeoff and climbout, the combustor inlet pressure was restricted to 414 kPa as a result of facility airflow limitations. Consequently, the airflow and fuel flow rates were reduced to produce the same volumetric airflow rate and fuel/air ratio.

## Emission Data and Calculation Procedure

Emission data processing procedure. - The voltage output of the gaseous analysis equipment was recorded on a moving strip chart as ppm concentrations and, for most of the program, manually transferred to cards for computer processing. The equations used to calculate emission indices, carbon balance, fuel/air ratios, and combustion efficiency are equivalent to those in SAE ARP 1256 (Ref. 3).

EPAP adjustment procedure and calculations. - No attempt was made to correct the test data for small variations from the design-point pressure, fuel/air ratio, inlet temperature, or reference velocity. It was not possible to simulate standard humidity or the actual engine combustor inlet pressure at the takeoff and climbout conditions in the combustor rig. However,

TABLE VIII. - RIG TEST CONDITIONS

| Mode[a] | $P_{t3}$ kPa | $T_{t3}$ °K | $W_a$ kg/sec | $W_f$ kg/hr | Fuel/air ratio | Engine thrust, percent rated |
|---|---|---|---|---|---|---|
| Idle | | | | | | |
| Engine | 198 | 366 | 2.31 | 80.4 | 0.0097 | 5.7 |
| Rig | 198 | 366 | 2.31 | 80.4 | 0.0097 | - |
| Approach | | | | | | |
| Engine | 527 | 500 | 5.75 | 244 | 0.0118 | 30 |
| Rig | 527 | 500 | 5.75 | 244 | 0.0118 | - |
| Climb | | | | | | |
| Engine | 1265 | 652 | 12.45 | 671 | 0.0150 | 90 |
| Rig | 414 | 652 | 4.06 | 220 | 0.0150 | - |
| Takeoff | | | | | | |
| Engine | 1379 | 669 | 13.36 | 752 | 0.0156 | 100 |
| Rig | 414 | 669 | 4.02 | 225 | 0.0156 | - |

[a] Engine conditions stated for reference only.

the emission indices that appear in this report are not corrected for these effects with the exception of humidity. All reported $NO_x$ emission indices have been corrected to standard-day humidity conditions. Pressure corrections have been made to the emission indices only in the calculation of the EPA parameters (EPAP).

The Environmental Protection Agency emission standards are expressed in terms of a parameter (EPAP) that integrates the emission rates at the engine idle, approach, climbout, and takeoff operating modes over a specific landing and takeoff cycle. The equation used to calculate the EPAP is exactly that specified in the EPA emission standards (Ref. 1) for Class T1 engines.

The TFE731-2 design engine data used to calculate the EPAP is given in Table IX.

TABLE IX. - TFE731-2 DESIGN ENGINE DATA, SEA-LEVEL STATIC STANDARD DAY

| Engine mode | Net thrust, kN | Fuel flow, kg/hr |
|---|---|---|
| Taxi-idle | 0.9 | 80.4 |
| Approach | 4.7 | 243.7 |
| Climbout | 14.0 | 670.8 |
| Takeoff | 15.6 | 752.3 |

Using the EPAP equation given in the EPA emissions standards cited above, the following expression for the EPA parameter for HC, CO, and $NO_x$ was obtained in terms of the emission indices (EI, uncorrected) at each mode by the following expression:

$$\begin{aligned} EPAP = {} & 0.23554\ EI_{taxi\text{-}idle} + 0.12348\ EI_{approach} \\ & + 0.11835\ EI_{climbout} + 0.04236\ EI_{takeoff} \end{aligned}$$

The CO and HC emission indices at the takeoff and climbout conditions for use in the EPAP calculation were corrected as follows for the effects of inlet pressure:

$$EI_{engine} = EI_{rig}\left(\frac{P_{t3\ rig}}{P_{t3\ engine}}\right)$$

where:

$EI$ = Emission index of carbon monoxide or unburned hydrocarbons for use in EPAP calculations

$P_{t3}$ = Inlet total pressure, kPa

= 414 kPa for takeoff and climbout rig conditions

= 1379 kPa for takeoff engine condition

= 1265 kPa for climbout engine condition

The $NO_x$ emission indices for use in the EPAP calculation were corrected as follows for the effects of inlet pressure at the takeoff and climbout conditions and for the effects of humidity at all conditions. The humidity correction produces approximately 12-percent reduction in the $NO_x$ index. Typical rig inlet air humidity measurements were 0.00035 to 0.0005 g $H_2O$/g air.

$$EI_{engine} = EI_{rig}\left(\frac{P_{t3\ engine}}{P_{t3\ rig}}\right)^{n}\left(e^{19\ (H_{rig} - H_{std})}\right)$$

where:

$EI$ = Emission index of oxides of nitrogen for use in EPAP calculation

$P_{t3}$ = Inlet total pressure, kPa

$H$ = Inlet specific humidity, g $H_2O$/g air

$H_{std}$ = 0.00634 g $H_2O$/g air for standard engine humidity

$n$ = $NO_x$ pressure correction exponent

The $NO_x$ pressure correction exponent, n, was determined during engine-rig correlation tests, and was calculated to be 0.35 for the takeoff power setting. This value is not in good agreement with the 0.5 value more commonly used throughout the industry. Data from the General Electric Clean Combustor Program (Ref. 4) suggests that an "n" term lower than 0.5 results from testing a combustor designed to operate with a near-stoichiometric primary zone, but that n approaches 0.5 as the primary zone is leaned out. The TFE731-2 engine-rig correlation tests were run with a production combustion system that was designed to operate with a near-stoichiometric primary zone, which could explain the low n value. Therefore, $NO_x$ EPAP values for Concepts 2 and 3 configurations, which have lean primary zones, were calculated with both n = 0.35 and n = 0.5. For comparative purposes, the rig value for $NO_x$, which corresponds to an emission index of 10 g/kg for the engine at the takeoff setting, ranges from 5.5 to 6.6 g/kg fuel, depending on the value of the pressure correction exponent used ($0.5 \geq n \geq 0.35$).

## Combustor Performance Data Calculation Procedure

All the combustor performance data given in Appendix B was either measured directly or calculated from measured data, as shown in Table X.

TABLE X. - COMBUSTOR PERFORMANCE PARAMETERS

| Parameter | Units | Measured | Calculated |
|---|---|---|---|
| Total airflow | kg/sec | | x |
| Combustor airflow | kg/sec | | x |
| Air assist airflow | kg/sec | | x |
| Bleed airflow | kg/sec | | x |
| Fuel flow (primary or secondary) | kg/hr | x | |
| Inlet total temperature | $^{\circ}$K | x | |
| Inlet total pressure | kPa | x | |
| Reference velocity | m/sec | | x |
| Inlet air humidity | g $H_2O$/g air | x | |
| Fuel/air ratio (metered) | | | x |
| Fuel/air ratio (carbon balance) | | | x |
| Combustion efficiency | | | x |

# CHAPTER III

# RESULTS AND DISCUSSION

## Combustion Configurations Tested

During Phase I of the Pollution Reduction Technology Program for Small Jet Aircraft Engines, three distinct combustor configurations and subsequent modifications were designed, fabricated, and tested. The first configuration, Concept 1, entailed advanced modifications to the production TFE731-2 combustion system. Concept 2 utilized 20 air-assisted airblast fuel injectors inserted through the dome of a newly-designed combustor. In Concept 3, two combustion zones were axially staged, consisting of a pilot zone that was fueled by 20 pressure atomizers, and a secondary or main combustion zone having a premixing/prevaporizing (PM/PV) region that was fueled by 40 simplex pressure atomizers. These three combustion system concepts are shown in Figures 12, 13, and 14.

Concept 1 demonstrated that HC and CO values could be reduced to below the program goals with the use of air assist and compressor bleed. With water-methanol injection (70/30 mixture by volume) at the takeoff condition, $NO_x$ levels were also reduced below the program goals. Smoke levels measured on the rig were slightly above the program goals.

Concept 2 configurations produced $NO_x$ levels of 6.5 g/kg fuel without the use of water injection. At taxi-idle, these configurations demonstrated HC levels lower than the required emission index, and CO was also significantly reduced. Smoke emissions were virtually eliminated as measured on the test rig.

The Concept 3 PM/PV combustion system produced the lowest $NO_x$ value of the three concepts. An $NO_x$ emission index of 3.5 g/kg fuel was measured on a Concept 3 configuration with a premixing region compatible with the engine geometry. Taxi-idle HC and CO values were reduced to 3.2 and 25.7 g/kg fuel, respectively, on the same configuration. The premix system operated successfully in all the Concept 3 configurations and there was no evidence of flashback or autoignition in this region during any of the tests. Smoke levels measured on the rig were zero.

The configuration that produced the best emission results is tabulated below for each concept. The program goals are also shown for comparison.

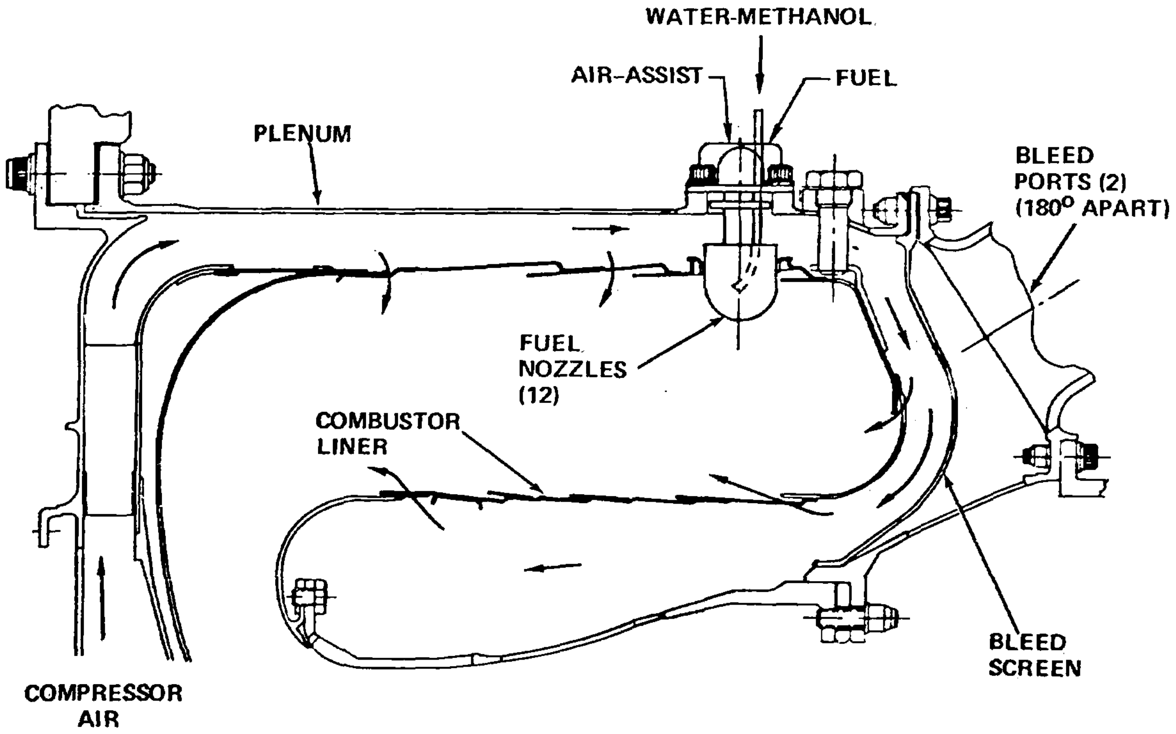

Figure 12. Concept 1 Combustion System

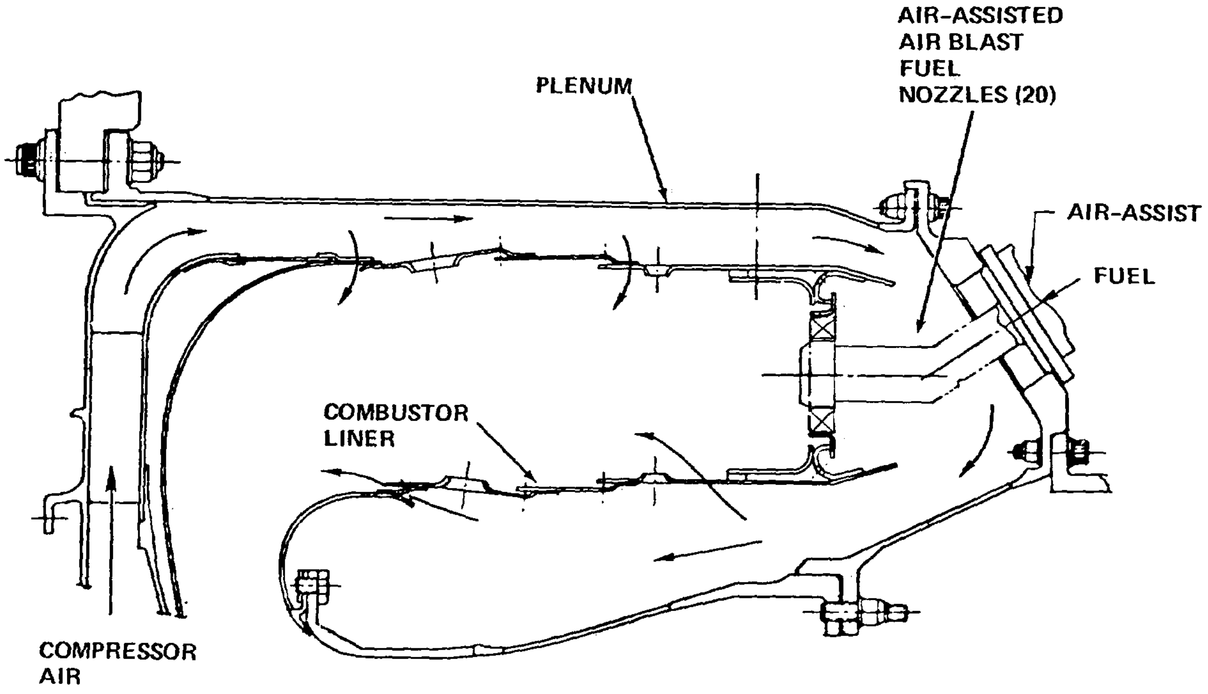

Figure 13. Concept 2 Combustion System

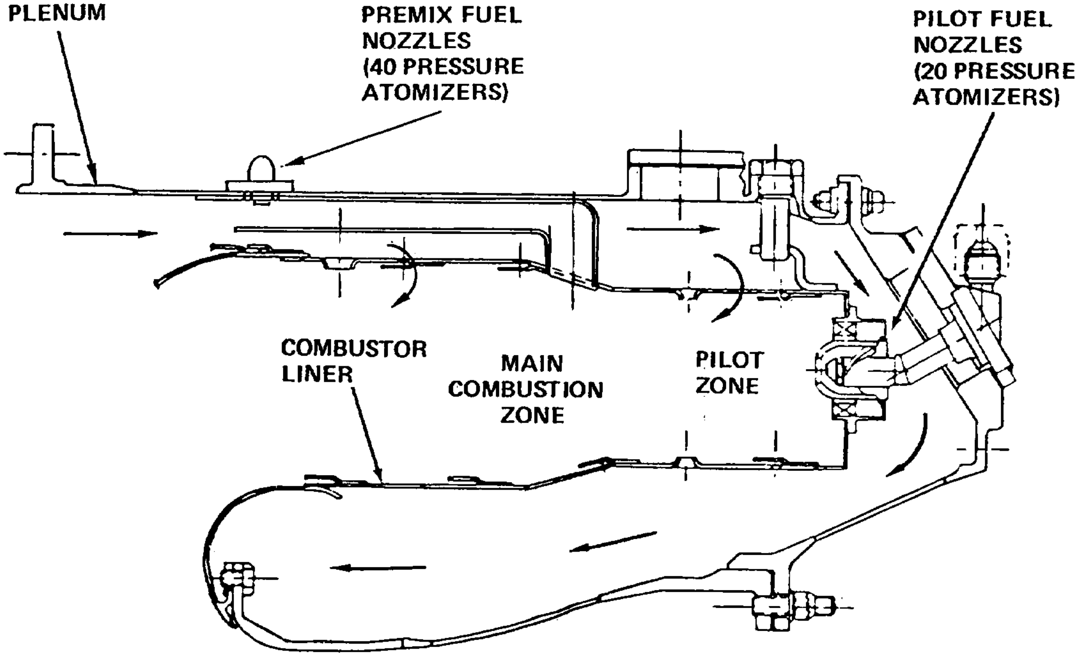

Figure 14. Concept 3 Combustion System

| Concept | Taxi HC g/kg fuel | Taxi CO g/kg fuel | Takeoff $NO_x$ g/kg fuel | Takeoff Smoke No. |
|---|---|---|---|---|
| Concept 1 | 0.6 | 30.0 | 6.6* | 16 |
| Concept 2 | 1.5 | 31.7 | 6.5 | 0 |
| Concept 3 | 3.2 | 25.7 | 3.5 | 0 |
| Program Goals | 6.0 | 30.0 | 5.5-6.6** | 12 |

*With water-methanol injection

**The 5.5 g/kg goal assumes a rig-to-engine pressure exponent (n) of 0.50 at takeoff. The 6.6 goal assumes n = 0.35.

## Experimental Emission Results

The rig testing of the program was directed into two phases. The first phase, designated as combustor screening tests, was of nine months duration and involved the testing of six configurations of each concept. The majority of these tests were only run at the takeoff and the taxi-idle power points, with parametric evaluation limited to determining the optimum emission reduction potential of a configuration. The second phase of testing, refinement tests, was of two months duration and involved a more detailed evaluation of two configuration each of the two most promising concepts. Most of these configurations were tested over the four LTO cycle power settings, and limited ignition and stability tests were run.

### Screening tests. -

1. Concept 1. - This approach to the reduction of emissions was based on advanced modifications to the production TFE731-2 combustion system. The production system consists of a reverse-flow annular combustor with a manifold of 12 dual orifice pressure atomizers inserted radially through the combustor liner outer wall. During this test segment, a basic combustion system and five modifications were evaluated. The test configurations are listed in Table XI, and the best results of each configuration are summarized in Figure 15. The most significant reduction in taxi-idle pollutants was attained with the use of air-assist and compressor bleed, and is compared with program goals in Table XII.

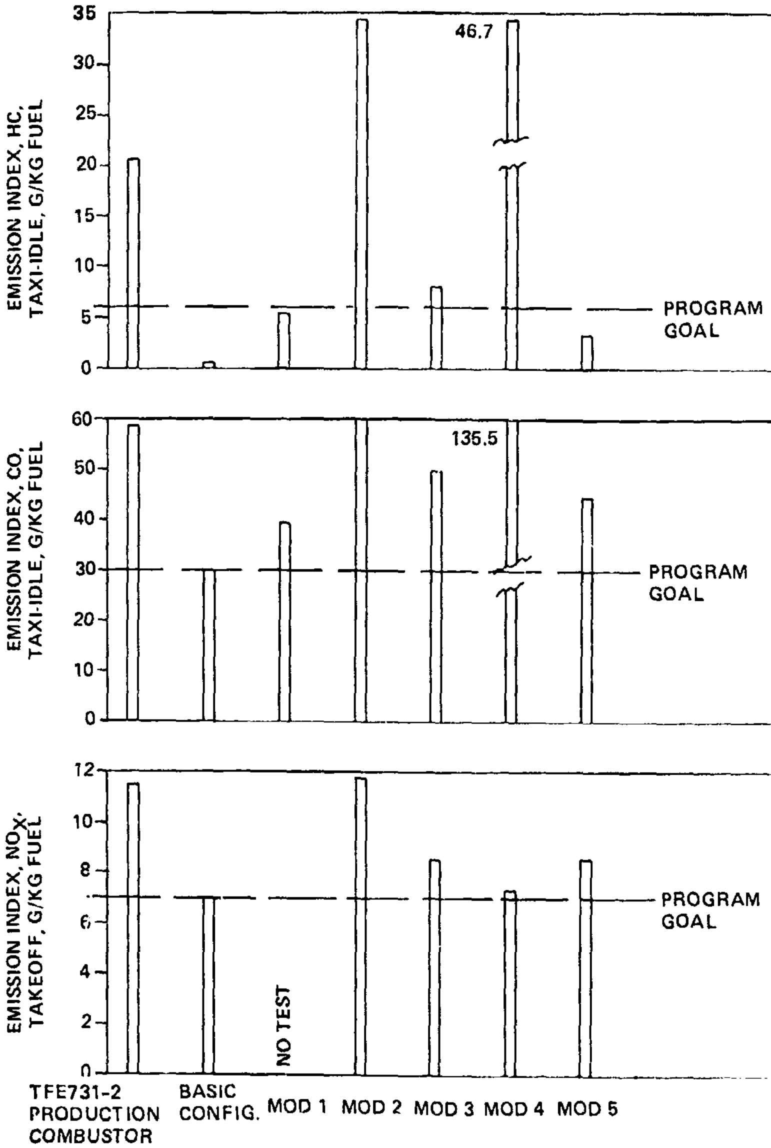

Figure 15. Summary of Emission Tests, Concept 1

TABLE XI. - CONCEPT 1 TEST CONFIGURATIONS

| Configuration | Modification |
|---|---|
| Basic configuration | Water injection at takeoff<br>Air-assist at taxi-idle<br>Compressor bleed at taxi-idle |
| Modification 1 | Quadrant fuel staging |
| Modification 2 | Increased airflow passage of fuel nozzle air swirler |
| Modification 3 | Airblast nozzles |
| Modification 4 | Combustor orifice change to produce a leaner primary zone with continued use of airblast nozzles |
| Modification 5 | Combustor dome modification |

TABLE XII. - COMPARISON - CONCEPT 1 TEST RESULTS VS PROGRAM GOALS

| | Pollutant Levels, g/kg fuel | | Rig Test Conditions |
|---|---|---|---|
| | HC | CO | |
| Production | 20.6 | 58.8 | |
| Air-assist and bleed (Concept I) | 0.6 | 30.0 | Air-assist flow rate = 0.006 kg/sec<br>Air-assist pressure = 544 kPa<br>Bleed rate = 11.5% |
| Program goals | 6 | 30 | |

The $NO_x$ level at takeoff was reduced below the program goal of 6.6 g/kg fuel (at rig pressure) with the use of water-methanol injection (0.68 kg of water-methanol per kg of fuel) into the combustor primary zone. An aircraft utilizing this technique would require approximately 27 kg of water-methanol solution per engine for each takeoff and climb cycle.

A brief description of each of the six Concept 1 configurations is presented in the following paragraphs.

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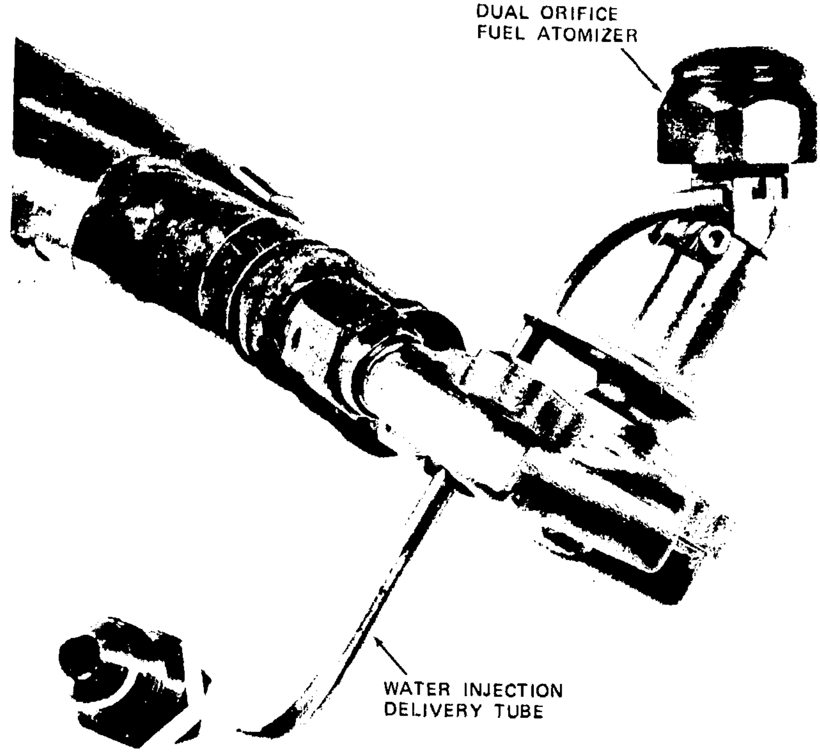


Figure 16. Concept 1 Water Injection Fuel Nozzle, Shroud Removed for Clarity.

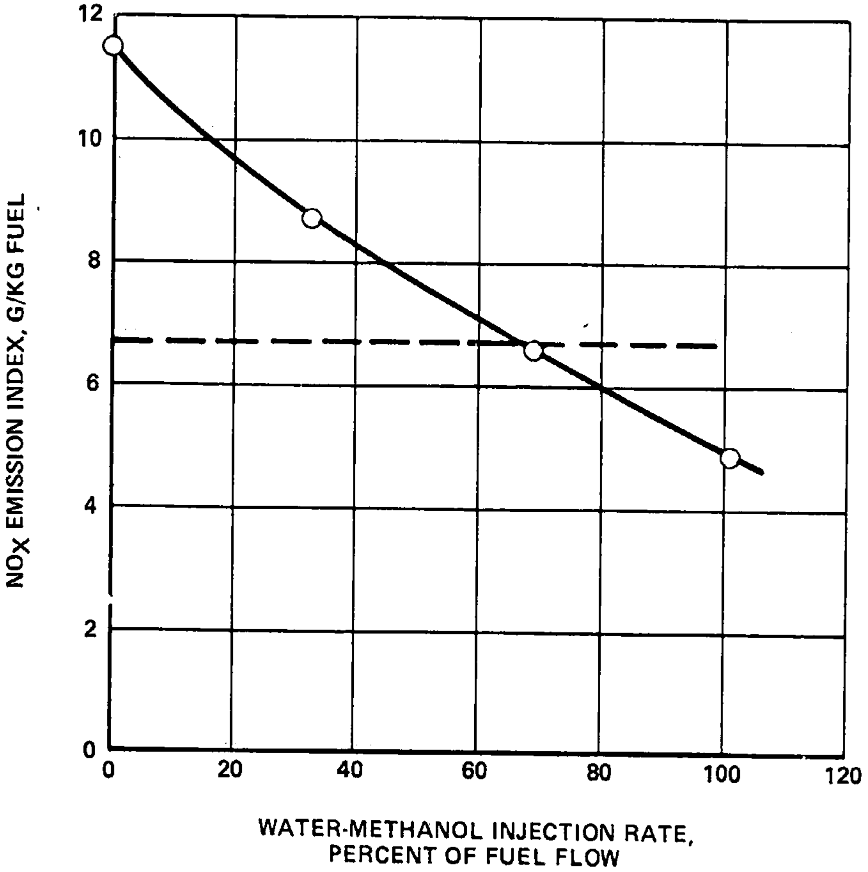


Figure 17. Effect of Water-Methanol Injection on $NO_x$ Emissions, Concept 1, Basic Configuration

a. Concept 1, Basic Configuration. - This combustion system utilized the production TFE731-2 combustor and fuel manifold. Individual fuel nozzles were modified with the addition of a 0.32-cm diameter water-methanol injection tube brazed to each nozzle body as shown in Figure 16. These tubes were used to inject a water-methanol solution in the combustor primary zone at the simulated takeoff thrust setting as a means of reducing $NO_x$. A series of increasing water-methanol flow rates was evaluated with the results shown in Figure 17. With the use of Figure 17, it can be calculated that a water-methanol flow rate of 467 kg/hr is required to meet the 1979 EPA emission standards.

Air-assist and combustor inlet air bleed were evaluated at the taxi-idle condition (separately and in combination) as a means of controlling HC and CO. In the air-assist mode, air at pressures above compressor discharge pressure was injected through the secondary fuel circuit of the dual-orifice fuel injectors, while all of the fuel was introduced through the primary circuit. The purpose of the air-assist was to improve fuel atomization, thereby increasing combustion efficiency. A range of air-assist pressures was evaluated, and the effect of this technique on HC and CO formation is shown in Figures 18 and 19. In the bleed mode, a portion of the combustor inlet air was bled from the system through a baffle located at the dome of the combustor. In order to maintain the required taxi-idle power, it was necessary to increase the fuel flow which in-turn resulted in improved atomization. A series of bleed flow rates up to 23 percent of the combustor inlet airflow was evaluated. The results are shown in Figures 20 and 21. Combinations of air-assist and bleed were also evaluated, and these results are also shown in Figures 20 and 21.

The configuration that was not compatible with the production combustion system utilized a bleed of 11.5 percent and an air-assist flow rate of 0.006 kg/sec at 544 kPa nozzle differential air pressure. This resulted in HC and CO levels of 0.6 and 30.0 g/kg, respectively.

b. Concept 1, Modification 1. - In this configuration, the 12 standard fuel nozzles were manifolded in groups of three to form quadrants. Rig testing was limited to taxi-idle conditions with only the primary circuit of the top and bottom nozzle quadrants flowing, while the left and right quadrants were turned off. Flow through the six functioning nozzles was thereby doubled, which required an increase in the differential pressure across the fuel nozzles by a factor of approximately four. This resulted in finer atomization of the fuel, more rapid evaporation, and a consequent reduction in HC and CO levels. As can be seen in Figure 15, HC and CO were reduced to 5.6 and 39.7 g/kg fuel, respectively.

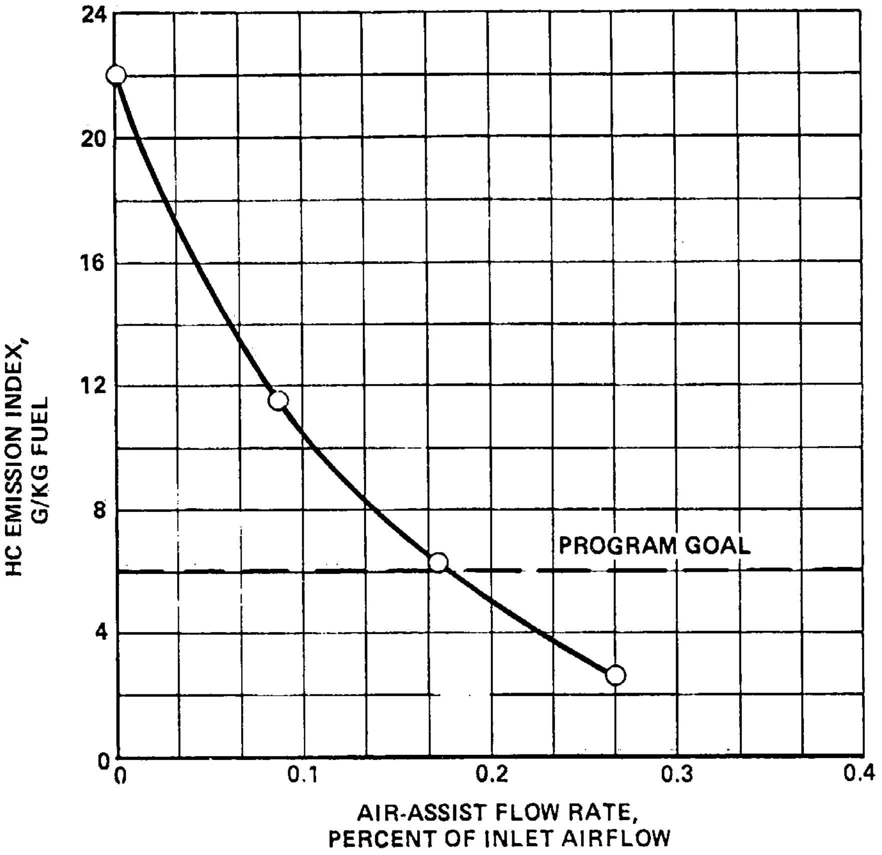


Figure 18. Effect of Air-Assist on HC, Concept 1, Basic Configuration

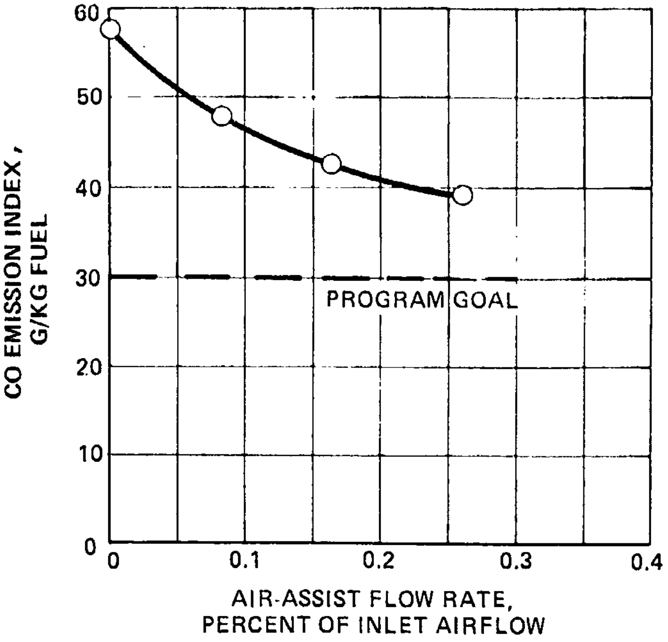


Figure 19. Effect of Air-Assist on CO, Concept 1, Basic Configuration

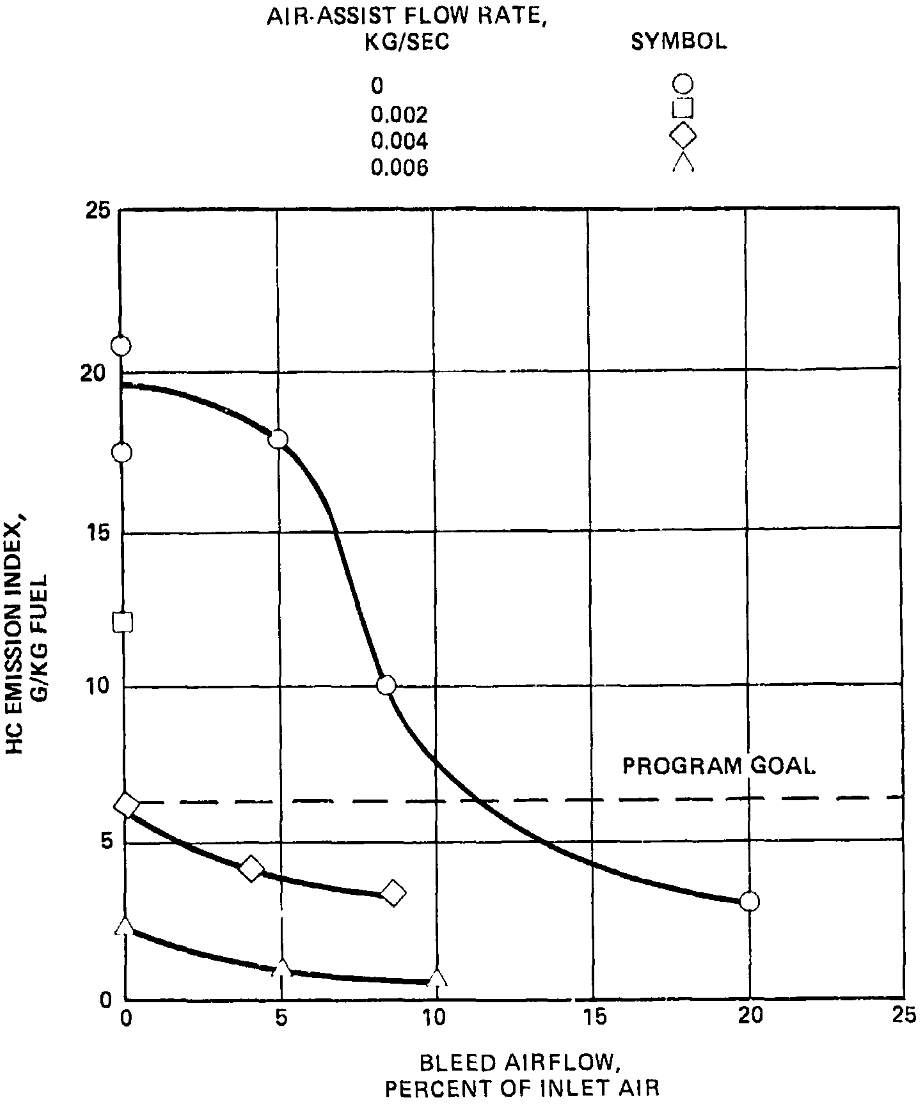


Figure 20. Effect of Bleed and Air-Assist on HC Emissions, Concept 1, Basic Configuration

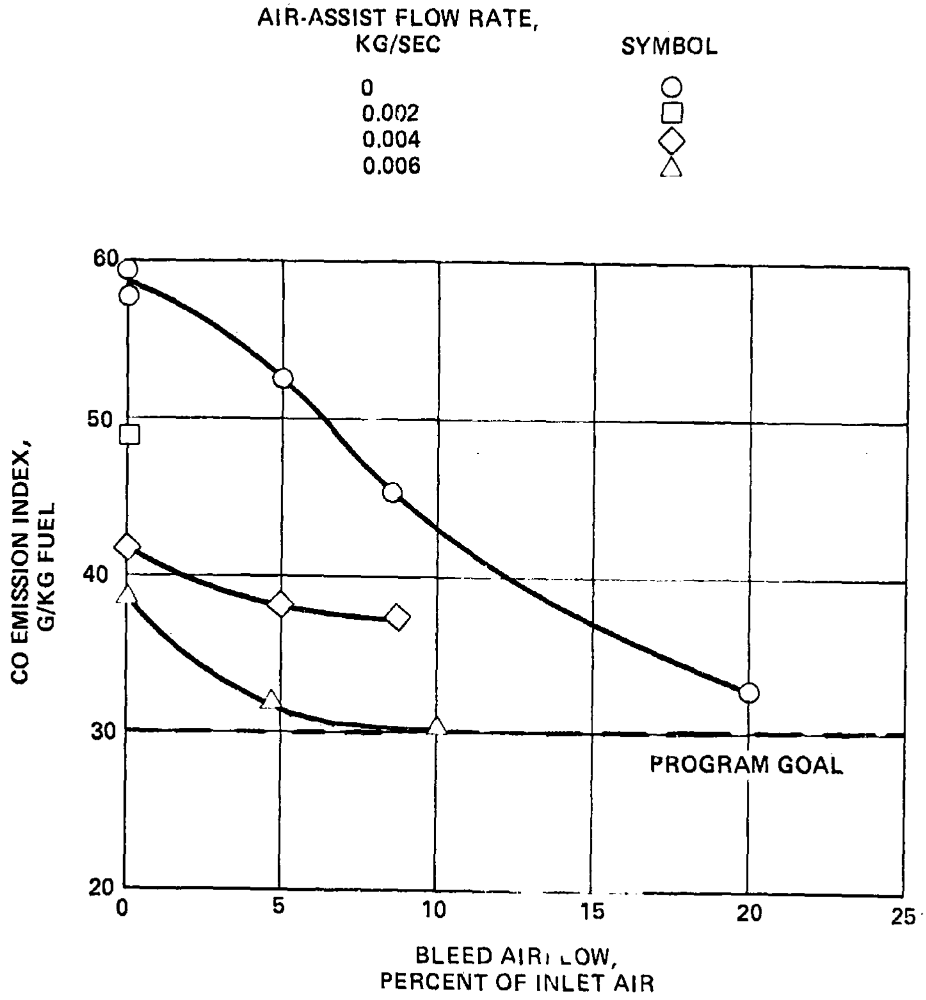


Figure 21. Effect of Bleed and Air-Assist on CO Emissions, Concept 1, Basic Configuration

c. Concept 1, Modification 2. - The second modification to the Concept 1 combustion system entailed an increase in the area of the airflow passage of the fuel nozzle air swirlers. In the production configuration, a small amount of air is ducted around the face of each fuel nozzle to prevent carbon buildup on the nozzle tip, and to aid in fuel atomization. This airflow rate was increased for Modification 2 by a factor of approximately two. The intent of the modification was to improve atomization at the taxi-idle power setting, thereby reducing HC and CO. The results summarized in Figure 15 show that at taxi-idle HC increased to 34.4 g/kg fuel with virtually no effect on CO and $NO_x$ emissions as compared to the production combustor. However, smoke emissions were reduced by 20 percent at takeoff. The test results indicated that the increased airflow in the vicinity of the fuel nozzle discharge caused the spray cone to collapse, and thereby actually reduced the atomization and degree of mixing.

d. Concept 1, Modification 3. - In this modification, the production TFE731-2 combustor was tested using piloted airblast fuel nozzles. Fuel nozzle sets supplied by two vendors (Delavan and Parker Hannifin) were evaluated. The designs of both manifolds incorporated a simplex pressure atomizer as a pilot nozzle, and an airblast secondary fuel circuit in which the fuel is sheared by counterrotating air from two swirlers, and accelerated by the pressure drop across the combustor outer liner. During taxi-idle operation, the pilot nozzle was air-assisted by injecting air through the secondary fuel passages to improve fuel atomization. The greatest reductions in emissions occurred at the highest available facility air-assist pressure (1,689 kPa differential) and were similar for both manifolds. HC was reduced to 8.0 g/kg fuel, while the reduction in CO was to 49.6 g/kg fuel. These reductions are not sufficient to meet the 1979 EPA emissions requirements. At air-assist pressure levels compatible with engine operation, the taxi-idle emission values were even higher, and it was concluded that improvement in the atomization of pilot flow was required to produce acceptable HC and CO levels. At the simulated takeoff settings, both manifolds produced significant reductions in $NO_x$ when operated only on airblast secondaries. The Delavan design showed a 16-percent reduction and the Parker Hannifin design a 26-percent reduction. These results were encouraging in light of the fact that the basic production combustor was used. No significant change in smoke number was observed.

e. Concept 1, Modification 4. - In an attempt to further reduce $NO_x$ at high-power conditions, a new combustor design was fabricated which was used in conjunction with the Parker Hannifin piloted airblast nozzles. The new design consisted essentially of a primary zone orifice change, and is shown in Figure 22. The production combustor is included in Figure 22 for comparison. As can be seen, the primary orifice pattern was changed to introduce

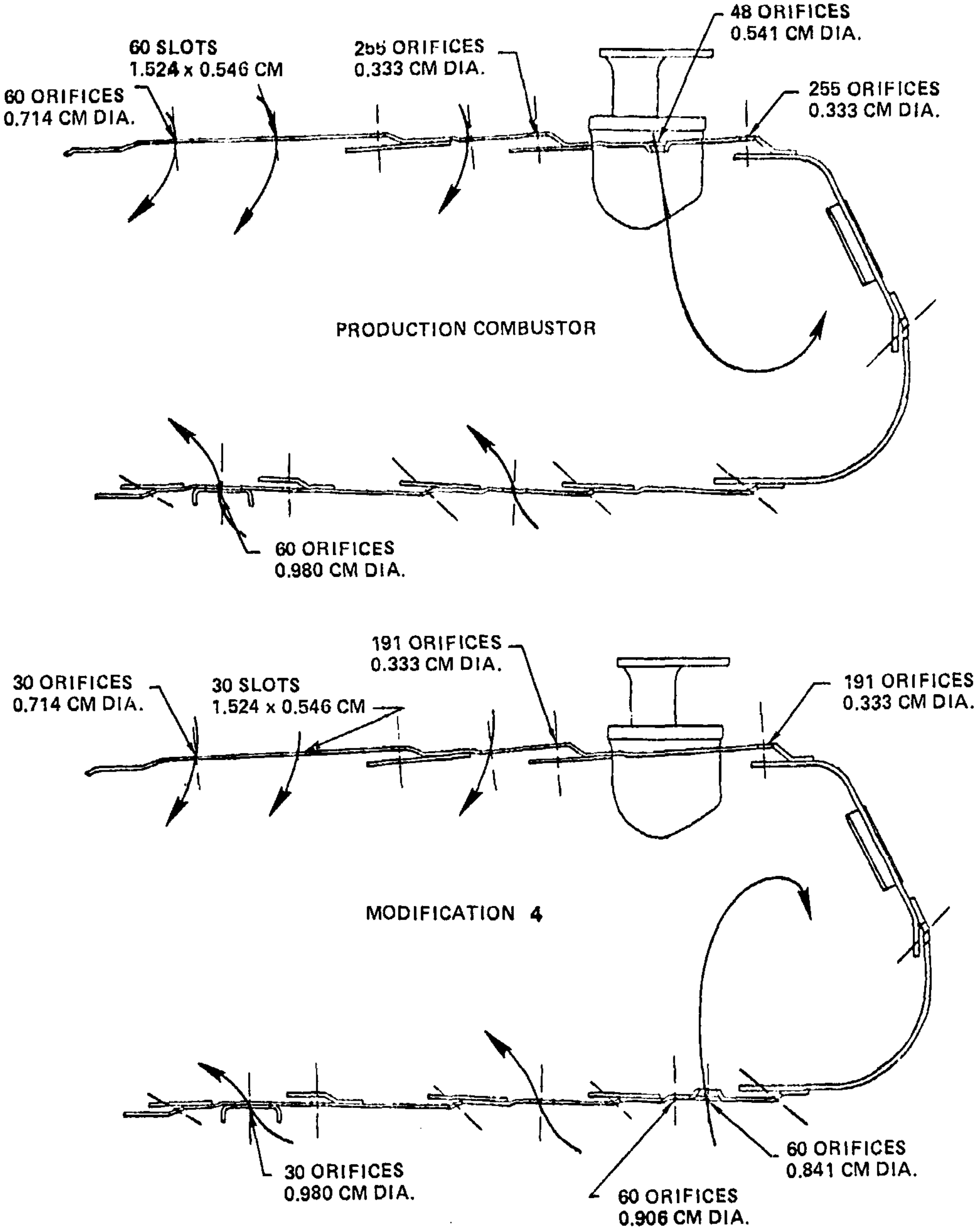


Figure 22. Combustor Configuration for Concept 1, Basic Configuration and Modification 4

all of the primary air from the inside panel through two rows of orifices and reduce the primary zone calculated equivalence ratio to approximately 0.5. This modification produced a 36-percent reduction in $NO_x$ at the simulated takeoff point. With the production dual-orifice pressure atomizer, $NO_x$ was reduced by 28 percent from the baseline. However, when operating with the same injectors at taxi-idle, CO and HC more than doubled. This orifice pattern change resulted in an overly lean recirculation zone and a shortened residence time at the taxi-idle condition, which quenched the combustion process. The smoke emissions increased significantly apparently due to the quenching effect.

f. Concept 1, Modification 5. - The intent of Modification 5 was to apply technology demonstrated on Concept 2 in order to reduce $NO_x$ at takeoff. The dome of the production combustor was replaced with a flat baseplate that was tested both with and without dome swirlers. This was to evaluate the effect of variable-area swirlers, and to determine the change in emission levels as a function of calculated primary zone equivalence ratio. The primary zone orifice pattern was changed to a row of rectangular slots on both the inner and outer primary panels. The purpose of the slots was to introduce air in an almost continuous band to more effectively terminate the recirculation zone, and to quench $NO_x$ being formed near the combustor wall during takeoff. Concept 1, Modification 5 is shown in Figure 23.

The combustor was tested in two configurations, with and without dome swirlers, and with three different fuel manifolds:

- Delavan piloted airblast
- Pressure atomizers injecting nearly radially (77 degrees from axial)
- Present production pressure atomizers (57 degrees from axial).

At the taxi-idle point, tests were performed with quadrant-staged fuel nozzles, simulated air bleed, and with air-assisted primary nozzles. Takeoff points were run with the normal primary-secondary fuel splits. At taxi-idle, all configurations required simulated air bleed to attain CO levels below the production baseline value. HC levels were below the program goal of 6 g/kg fuel for many of the configurations. The lowest taxi-idle CO value was 44.3 g/kg fuel, which is a 25-percent reduction from the production baseline, and was obtained using dome swirlers with the Delavan piloted airblast injectors operating in a quadrant-stage mode. The Delavan airblast nozzles, in conjunction with dome swirlers, also produced the lowest $NO_x$ value. The $NO_x$ index of 8.6 g/kg fuel was a 25-percent reduction from the production baseline, but was not as low as the $NO_x$ value attained with Modification 4. The swirler configuration produced a significant reduction in the smoke number at

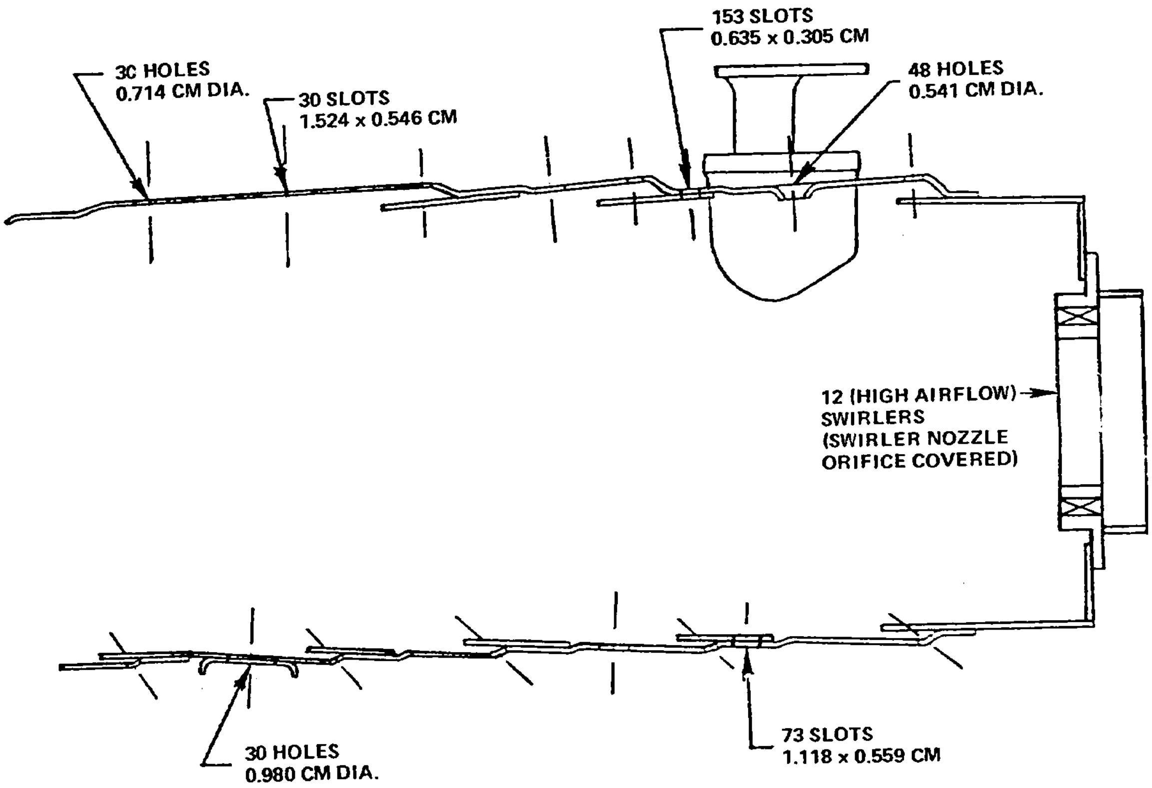


Figure 23. Combustor Configuration for Concept 1, Modification 5

the simulated takeoff condition with the Delavan piloted airblast nozzles and the 77-degree down angle pressure atomizing nozzles. The 77-degree down angle nozzles produced a smoke number of 7 compared to the production rig baseline of 16 at the test rig conditions. Taxi-idle test data indicated that without the dome swirlers, the reaction zone was over-rich; and with the swirlers, the reaction zone was too lean to meet the CO goals. An improved CO level could possibly have been achieved with a reduced airflow swirler. At takeoff, $NO_x$ reduction was hindered by inadequate mixing as evidenced by a 0.417 pattern factor.

2. Concept 2. - The Concept 2 combustion system design was based on the use of air-assisted, airblast fuel nozzles that were inserted axially through the combustor dome. A schematic of this nozzle is shown in Figure 24. The nozzles were designed such that the fuel was filmed in a swirl chamber, and then sheared on the outer surface of the film by assist-air or airblast air. The assist-air was supplied from an external source at pressures above combustor plenum levels, and was directed through a swirler. This air-assist swirler was located inside the airblast swirler, which was fed by the pressure drop across the combustor dome. Nozzle spacing was selected at a conventional value equivalent to the channel height of the combustor primary zone, which resulted in 20 nozzles being utilized. The nozzles were located in the combustor air swirlers that were interchanged during different operating modes. At taxi-idle power settings, the swirlers were blocked (no flow), and at takeoff, the swirlers operated at full airflow. The intent of varying the airflow through the swirlers was to produce a primary zone that was stoichiometric at taxi-idle, and lean at takeoff. However, in most of the modifications tested, both the taxi-idle and takeoff power settings were evaluated with full-flow and blocked swirlers to assess the possible need for variable geometry.

During Phase I, eight Concept 2 configurations were tested. The results of these tests indicate that the level of HC emissions can be reduced below the program goals with the use of blocked swirlers and air-assist at the taxi-idle power setting. The configuration that produced the greatest $NO_x$ reduction attained a value of 6.5 g/kg fuel measured at the simulated takeoff conditions with full airflow through the swirlers. This same configuration produced a CO value of 32.1 g/kg fuel at taxi-idle using air-assist and simulated compressor bleed.

The configurations of each of the modifications tested in the screening evaluation of Concept 2 are shown in Table XIII, and the emission levels attained are summarized in Figure 25. A brief description of the six screening test configurations is presented in the following paragraphs. The two refinement test configurations are described on Page 86.

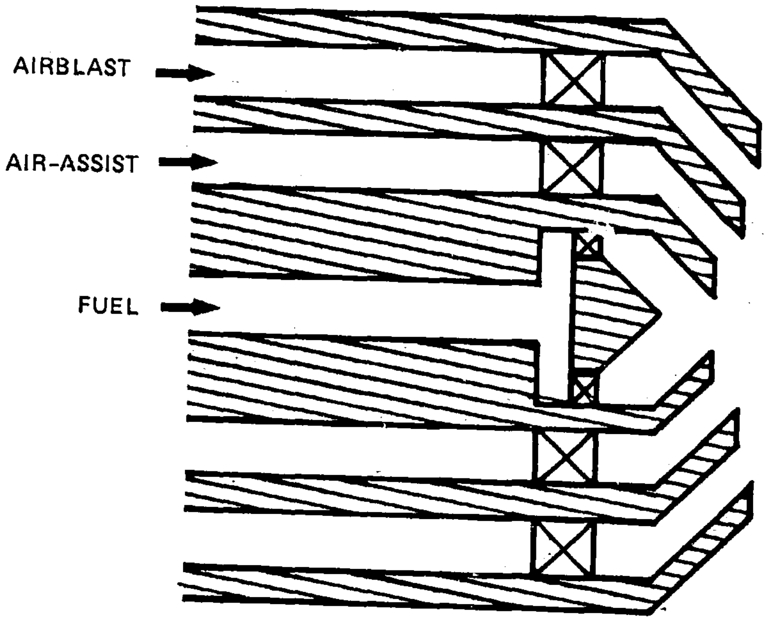


Figure 24. Air-Assisted, Airblast Fuel Nozzle, Used in Concept 2

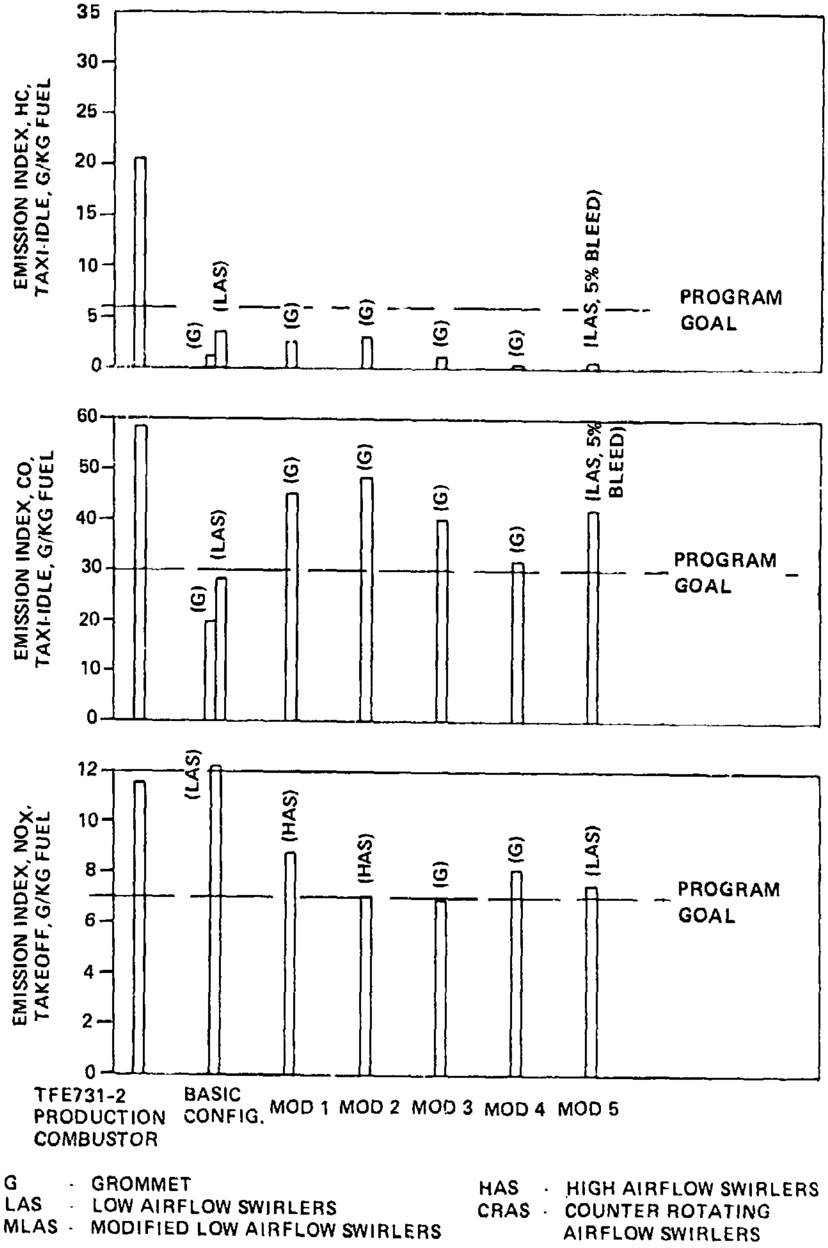


Figure 25. Summary of Emission Tests, Concept 2.

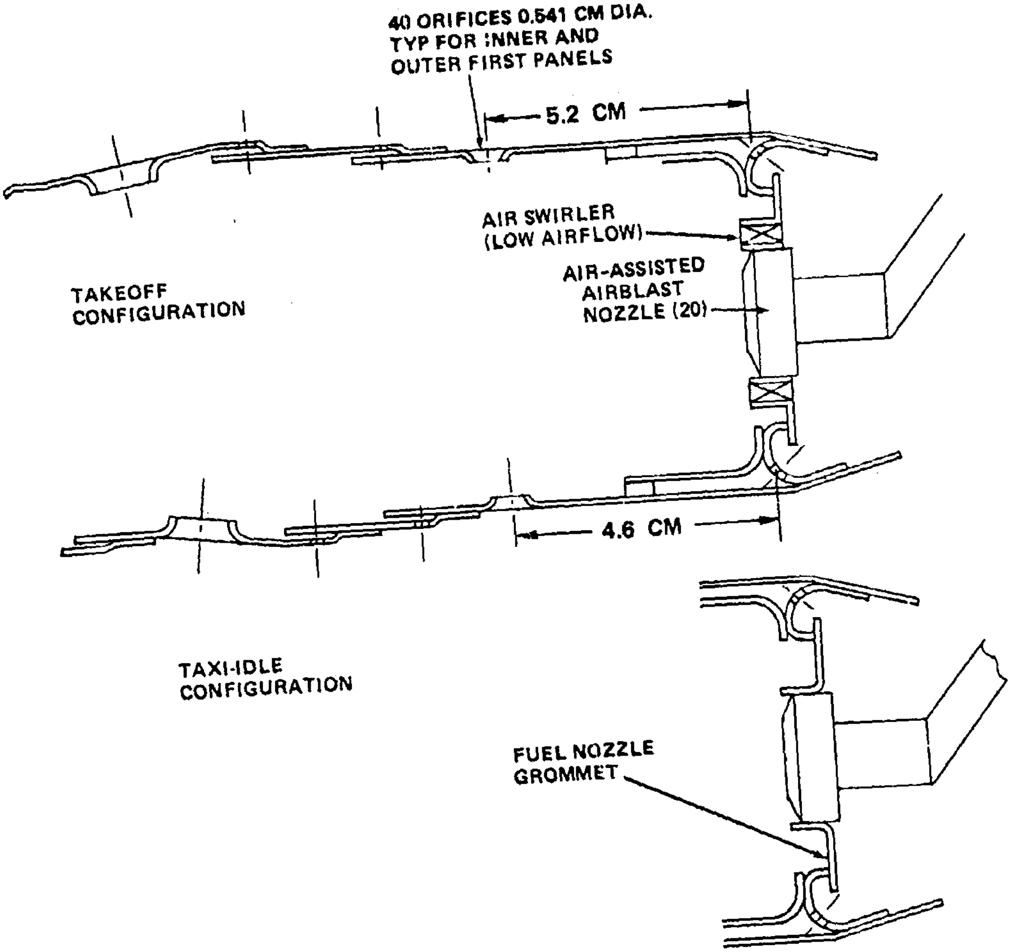


Figure 26. Combustor Configuration for Concept 2, Basic Configuration

a. Concept 2, Basic Configuration. - This configuration is shown in Figure 26. When operated with the blocked swirlers (grommets) and 68.9 kPa air-assist at the taxi-idle power condition (no compressor bleed), this configuration achieved the lowest HC and CO values (1.4 and 19.6 g/kg fuel, respectively) of any of the Concept 2 configurations tested. These values are well below the program goals of 6.0 and 30.0 g/kg fuel for HC and CO, respectively. The system also produced low HC and CO levels (3.6 and 28.2 g/kg fuel, respectively) with the full airflow swirlers and air-assist at taxi-idle. However, the $NO_x$ at the simulated takeoff point (12.2 g/kg fuel) was slightly higher than the production baseline. This was attributed to inadequate airflow into the reaction region resulting in an overly rich primary zone. The measured smoke number was zero at the rig simulated takeoff condition.

TABLE XIII. CONCEPT 2 TEST CONFIGURATIONS.

| Configuration | Modification |
|---|---|
| Basic configuration | Air-assist airblast fuel nozzles |
| Modification 1 | Primary orifice changed to reduce primary fuel/air ratio and produce early quench<br>Increased swirler area by factor of 1.5 |
| Modification 2 | Added primary orifice row for $NO_x$ control |
| Modification 3 | Relocated primary orifices downstream for control of taxi-idle emissions<br>Reduced jet penetration of outer primary orifices for $NO_x$ control |
| Modification 4 | Relocated and increased diameter of outer primary orifices to increase jet penetration<br>Low airflow swirlers |
| Modification 5 | Relocated and modified outer primary orifices to produce leaner primary zone |

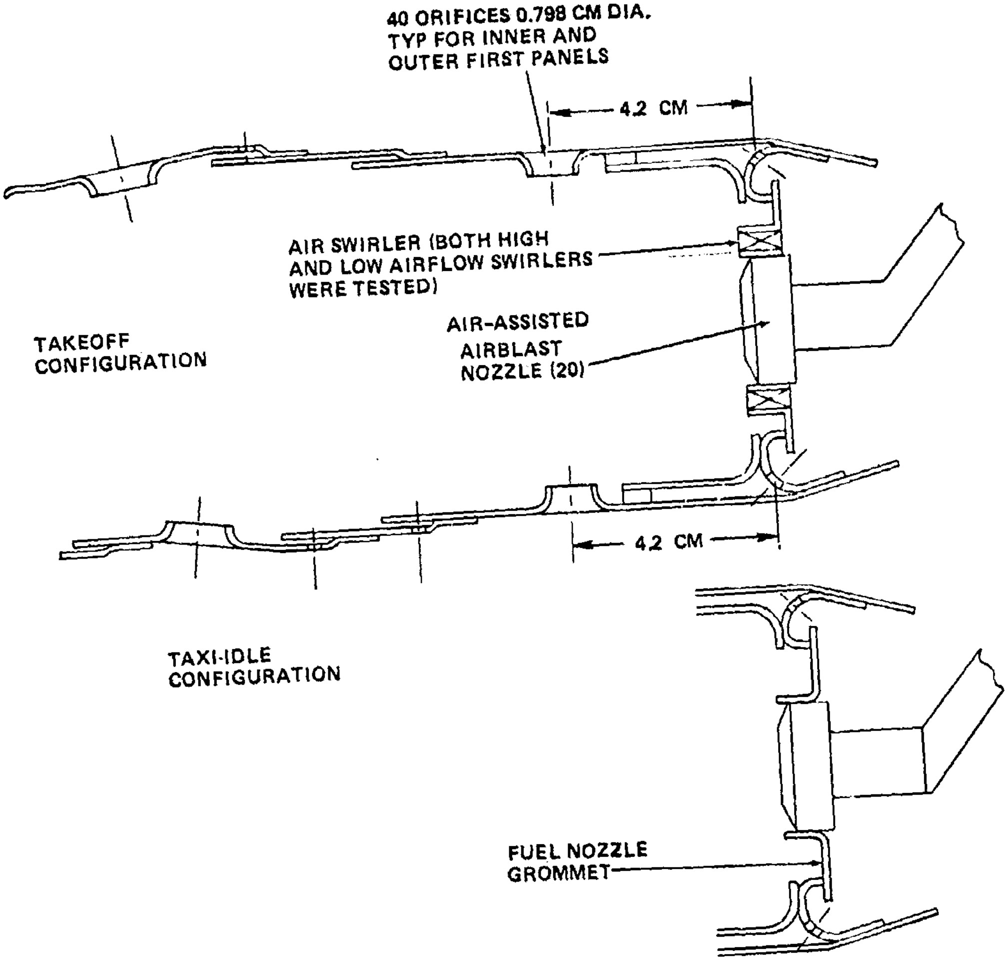


Figure 27. Combustor Configuration for Concept 2, Modification 1

b. Concept 2, Modification 1. - A sketch of the first Concept 2 modification is presented in Figure 27. This modification consisted of increasing the diameter of the primary orifices on both the inner and outer wall panels to reduce the fuel/air ratio in the primary zone, and relocating these orifices closer to the dome to produce an early quench effect. Swirlers with an effective area of 1.5 times the original design (high airflow swirlers) were evaluated as well as the standard design, and produced a takeoff $NO_x$ value of 8.4 g/kg fuel. Analysis of these test rig data indicated that a significant portion of this $NO_x$ was being formed close to the combustor outer wall. HC emissions at taxi-idle without swirler air increased slightly, but still met the program goals. The CO value increased from the previous configuration to a value of 43.1 g/kg fuel. The smoke number at takeoff remained at zero.

c. Concept 2, Modification 2. - Modification 2 is shown in Figure 28. To reduce the $NO_x$ formed near the combustor outer wall, a row of small orifices was added between and 1.04-cm downstream of the outer panel primary orifices. The size and location of these orifices were designed to reduce $NO_x$ formed near the wall during takeoff without significantly penetrating the taxi-idle reaction zone. In addition, the increased airflow swirlers were utilized. This configuration produced further $NO_x$ reductions to a value of 7.1 g/kg fuel. The modification had little effect on taxi-idle emissions, which indicated that the taxi-idle reaction zone.

d. Concept 2, Modification 3. - The third modification of Concept 2 is shown in Figure 29. In this configuration, the large primary orifices were relocated downstream to further reduce the HC and CO products produced at taxi-idle. The large orifices in the Modification 2 location had produced jets that penetrated into the combustor reaction zone during taxi-idle operation, which resulted in some quenching of HC and CO prior to completion of the reaction. In an attempt to further reduce $NO_x$, the 0.541-cm diameter orifices were eliminated, and a row of small orifices was added to the outer primary panel closer to the combustor dome. These orifices were smaller in diameter, but greater in number than in the Modification 2 configuration to reduce jet penetration, and to more uniformly distribute the air in the region near the outer wall.

In the taxi-idle configuration (with grommets), the HC value was below the program goal, and CO was reduced to 40.1 g/kg fuel--a 17-percent reduction from the previous configuration. When operated at takeoff, this grommeted configuration produced the lowest $NO_x$ values attained at that time of any Concept 2 configuration (6.9 g/kg fuel). This was contrary to the anticipated results as the calculated primary zone equivalence ratio was much higher than Modification 2 with the swirlers. Zone burning was considered as a possible explanation. In this situation, the

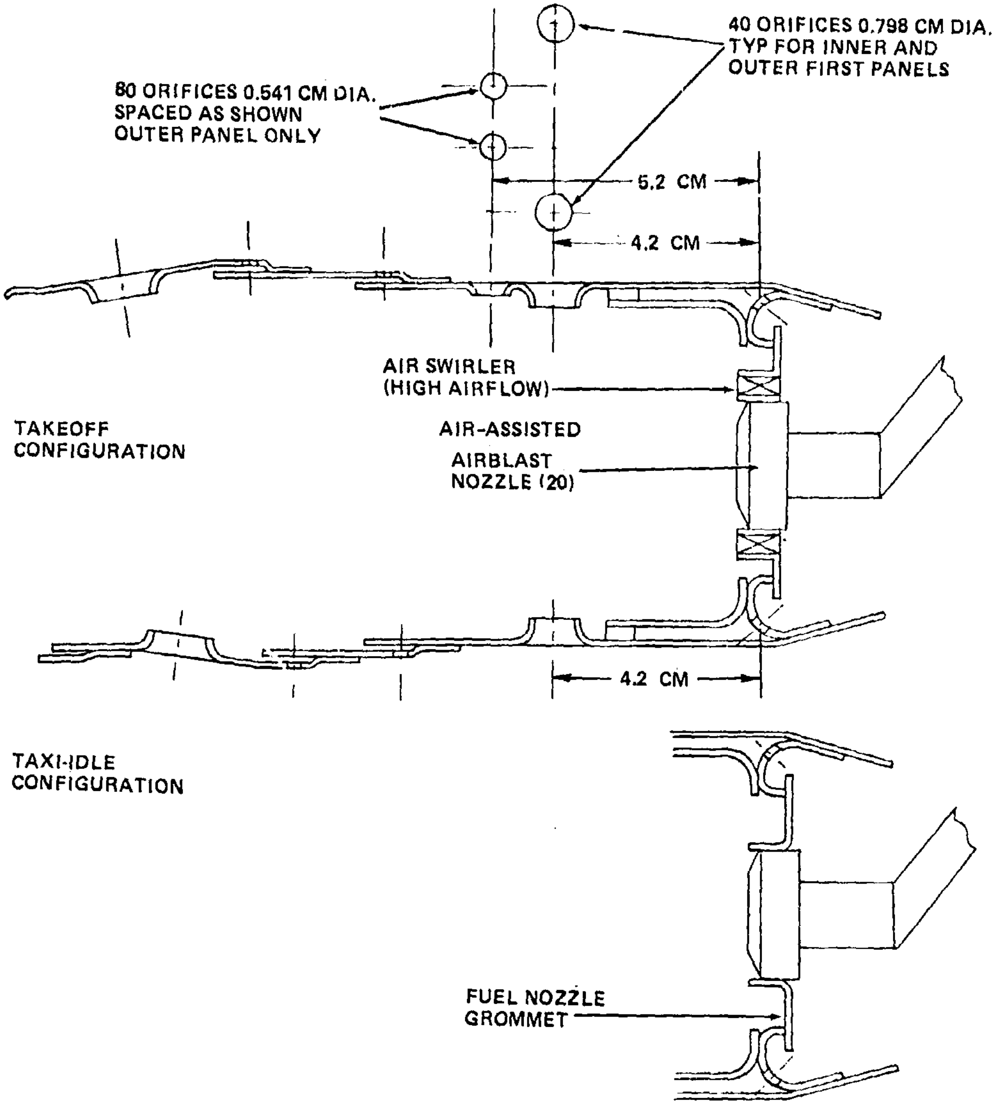


Figure 28. Combustor Configuration for Concept 2, Modification 2

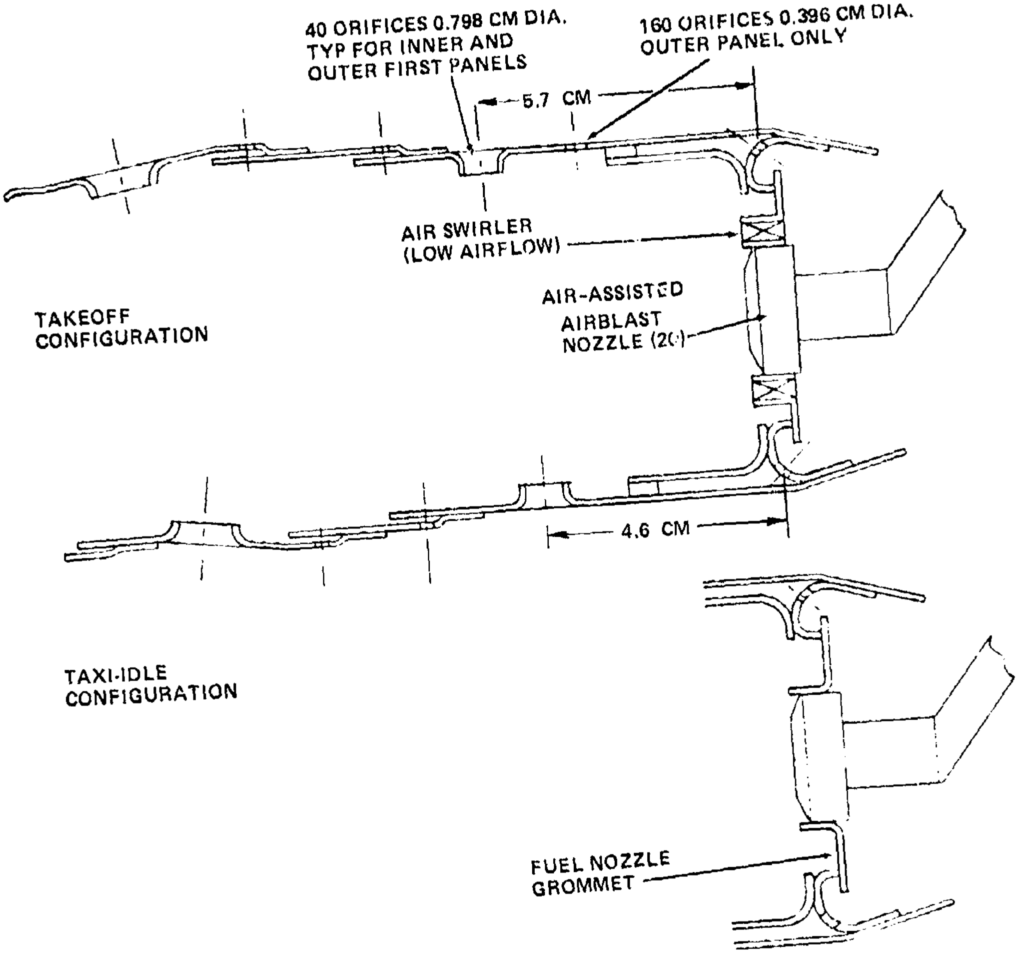


Figure 29. Combustor Configuration for Concept 2, Modification 3

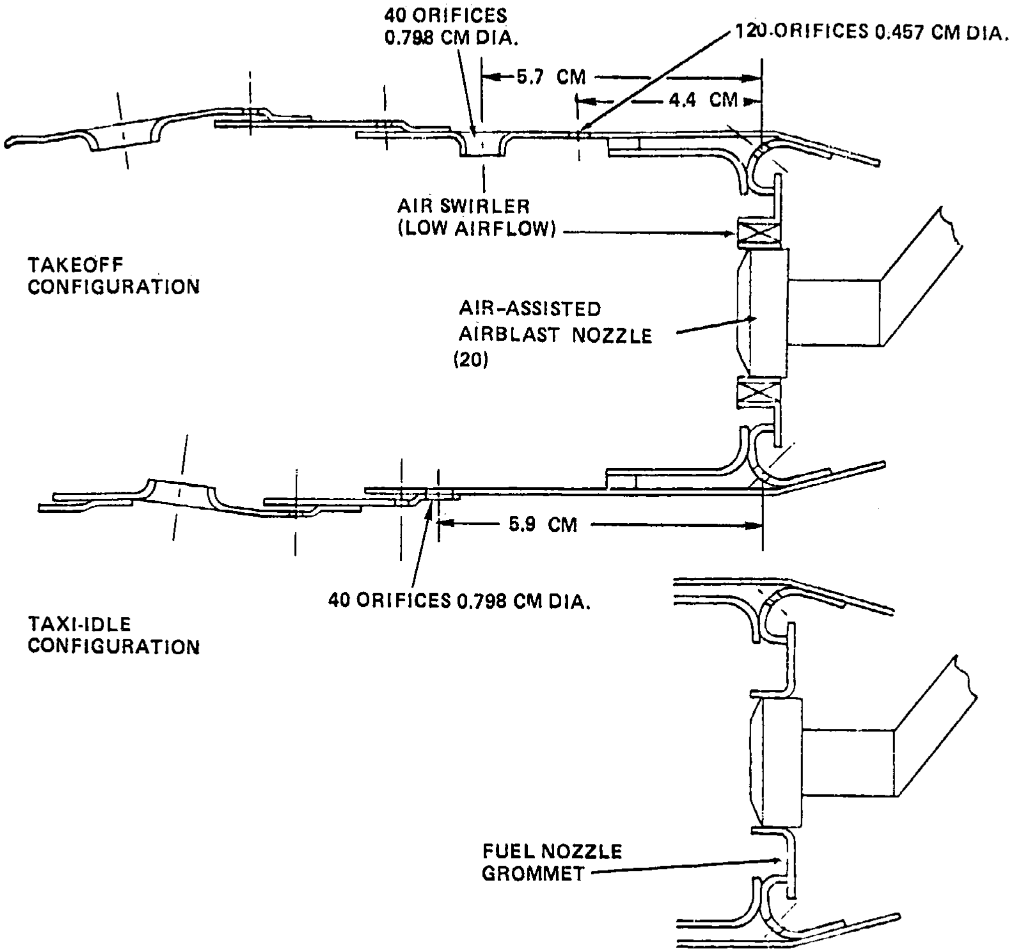


Figure 30. Combustor Configuration for Concept 2, Modification 4

fuel/air ratio in the vicinity of the fuel injectors is considered to be richer than stoichiometric, which results in a low flame temperature, and therefore, low $NO_x$ levels. However, HC and CO values in this region are high due to insufficient oxygen. Immediately downstream of this fuel-rich region, additional air was injected through the 0.396-diameter orifices in sufficient quantities to quench the $NO_x$ formation, and to react with the HC and CO, thereby lowering their values to acceptable levels.

e. Concept 2, Modification 4. - This modification is shown in Figure 30. To increase the penetration of the small orifices on the outer wall over those in Modification 3, the diameter of the orifices was increased, and the number of orifices were reduced to produce the same open area. Also, to further increase penetration, the location of this row of orifices was moved slightly downstream from the discharge of the first panel cooling flow, and this cooling flow was reduced by one-third. The low-airflow swirler was used.

At taxi-idle, in the grommet configuration, a CO value of 31.8 g/kg fuel was attained, which is only slightly above the program goal of 30.0 g/kg fuel. Unburned hydrocarbons were well below the program goal with a value of 0.3 g/kg fuel. The $NO_x$ levels at takeoff in this configuration increased over the previous value, but were still less than Modification 4 with the swirler.

An additional takeoff test was performed on a slightly modified version of this configuration. The primary panel cooling air was returned to the original value, and a small amount of additional air was introduced into the outer primary panel by adding a row of 160 orifices of 0.396-cm diameter, as in Modification 3. This configuration produced the lowest measured $NO_x$ for Concept 2 during Phase I testing--6.4 g/kg fuel. However, examination of the combustor upon teardown revealed that the burner had large deposits of carbon adhering to the dome and dome cooling panels. The high levels of HC and CO produced in this region were reduced when additional air was introduced, and reacted downstream of the fuel-rich zone. This additional airflow quenched the $NO_x$ formation, but the exiting gas temperature was of sufficient magnitude to facilitate the further reaction of the HC and CO. This test confirmed that two-zone burning was taking place as hypothesized for the previous modification. The large amounts of carbon build-up were considered unacceptable, and this approach was abandoned.

In the swirler configuration at takeoff, the $NO_x$ level was essentially unchanged from Modification 3. It appeared that the jets from the small orifices were still unable to sufficiently penetrate into the reaction region.

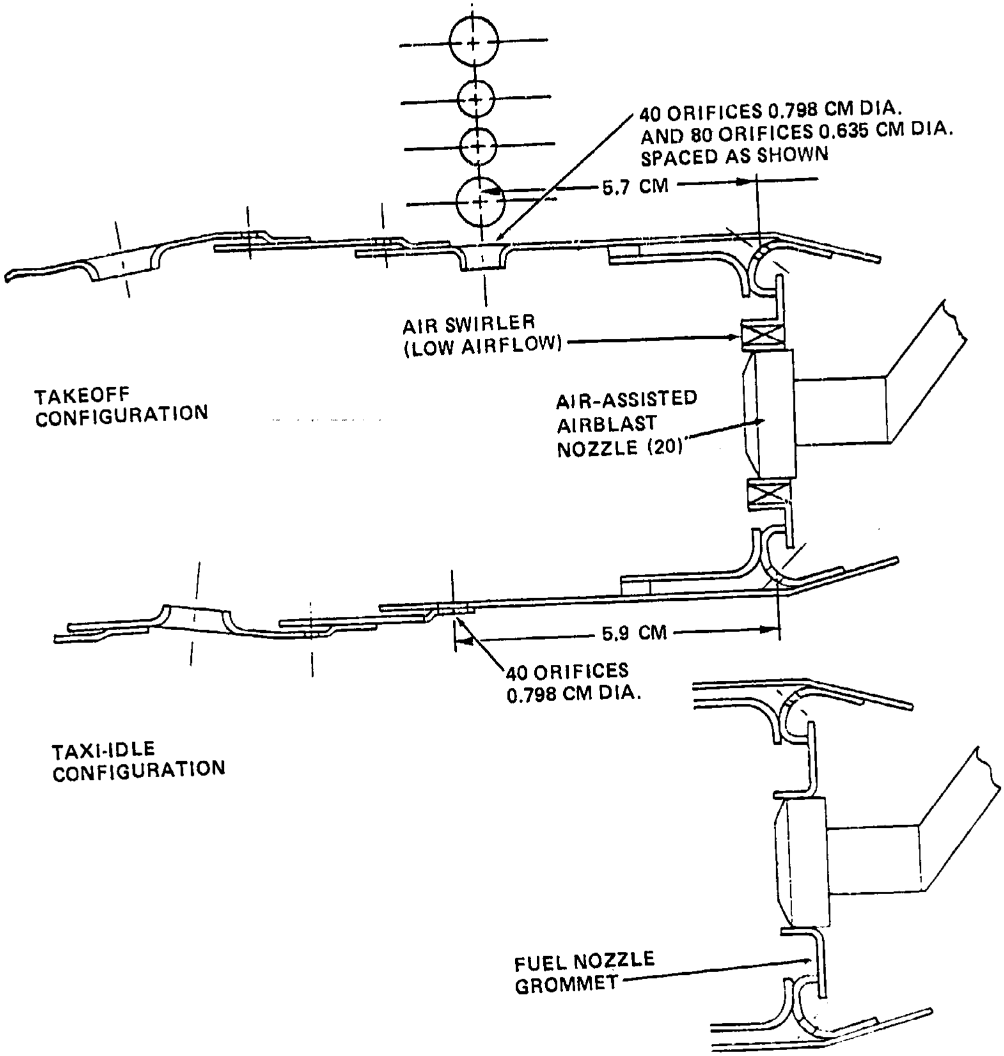


Figure 21. Combustor Configuration for Concept 2,
Modification 5

f. Concept 2, Modification 5. - Based on the test results of Modification 4, it was decided to review the results of Modification 2, which produced the greatest $NO_x$ reduction while utilizing swirlers. Modification 5 was designed to be an extension of Modification 2, with the taxi-idle results of Modifications 3 and 4 also considered in the design. A sketch of the configuration is shown in Figure 31.

As can be seen in the sketch, the large primary orifices remained unchanged from Modification 4. The position of these orifices was considered to aid in the CO reduction attained with that configuration. The additional row of small orifices in the outer primary panel was moved downstream to align axially with the large primary orifices. The orifice size was increased, and the number of orifices was reduced to 80. These orifices were also plunged. The primary zone cooling orifices were restored to their originally designed open area. The overall effect of the modification was to produce a calculated primary zone equivalence ratio at takeoff that was slightly leaner than that of Modification 2.

At taxi-idle in the grommet configuration, there was a significant increase in CO. The measured value was 83.5 g/kg fuel--42.2-percent greater than that produced by the production baseline configuration. This was even higher than the value measured with the swirlers, which was almost equivalent to the production baseline. The apparent cause for the high CO level was that the primary orifices were located too far downstream, and that very little of this orifice air recirculated and entered into the reaction. In the grommet configuration, the fuel nozzle swirlers did not produce a large enough low-pressure region in the reaction zone to entrain the primary orifice airflow. This was borne out by examination of the combustor upon teardown. Heavy carbon buildup in the primary zone gave evidence of an excessively fuel-rich burning process.

At takeoff, in the swirler configuration, the $NO_x$ level was slightly higher than Modification 2. With Modification 5, less of the primary orifice air reacted than with Modification 2. The location of the primary orifices were too far downstream to have a sufficient amount of the orifice airflow entrained by the swirler flow, and although the overall primary zone was leaner, there was apparently less air involved in the reaction zone as compared to Modification 2.

3. Concept 3 - Of the three combustion concepts that were evaluated during the first phase of the Pollution Reduction Technology Program for Small Jet Aircraft Engines, Concept 3 was considered to present the highest technical risk, but offer the greatest potential for meeting the program emission goals. The design employed axially-staged fuel injection with a pilot zone located at the dome end of the combustor, and a main combustion region immediately downstream of the pilot.

The pilot zone used 20 fuel nozzles inserted through the combustor dome. For most of the configurations tested, these fuel nozzles were of the simplex pressure atomizing type. However, air-assisted, airblast injectors were evaluated in the last configuration. The pilot zone was continuously operated at all power settings, and the development of this region was directed to ensure minimum HC and CO at taxi-idle. It would also serve as an efficient ignition source for the main combustion zone at the higher power settings without producing excessive $NO_x$.

The main combustion zone was adjacent to, and downstream of the pilot. Fuel was staged into this zone only at operating modes above the simulated taxi-idle power setting. In the staging operation, fuel was injected into a mixing region upstream of the combustor by means of simplex atomizing nozzles. This fuel was premixed with air, and the mixture injected into the main burning zone. An extensive portion of the development testing of this configuration was used in optimizing the fuel/air ratios of the main combustion zone mixture and the fuel flow split between this region and the pilot zone. Ideally, in a premix configuration, most of the fuel is introduced into the main combustion zone. This fuel is premixed with a sufficient amount of air to produce a very lean reaction zone, thereby minimizing the $NO_x$ formation. The fuel flow to the pilot region is maintained as low as possible to minimize the $NO_x$ formation, but high enough to produce a hot-gas ignition source for the main combustion zone. This will result in acceptable HC and CO levels. Several parameters were evaluated to ensure thorough mixing of the fuel and air, and to prevent flashback or autoignition of the mixture. These parameters included: fuel injection length, premix residence time, premix fuel/air ratio, and velocity in the premix tubes.

The first four combustion system configurations tested utilized 40 tubes external to the combustor plenum as premix chambers. The tubes were connected to an external air supply that provided air at the same temperature as the main combustor inlet air. This allowed the examination of the effects of fuel/air ratio and premix velocity on emission formation. Premix velocity was evaluated with the use of premix tube sets that had different inside diameters. This made it possible to vary pilot-main zone splits and tube velocity independently. Each tube had five fuel injection points spaced at 7.6-cm intervals along its length to determine the optimum premix length for minimum emission levels. Initially, gaseous propane was used as the premix fuel to eliminate vaporization of the fuel as a variable. Later tests used liquid Jet A fuel.

Based on test results attained with the external premix system, an internal system was designed that was compatible with the existing engine envelope. An annular passage next to the plenum wall was utilized as the premix region. This annulus was connected to 40 combustor chutes that injected the fuel/air mixture into the main combustion zone. Two fuel injection points (premix lengths) were evaluated.

During screening and refinement testing, eight configurations of this concept were evaluated on the combustion rig. The test results indicate that it is possible to reduce the takeoff $NO_x$ emission values well below the program goal while maintaining high combustion efficiency. At low-power operation, HC values were also well below the program goal. CO levels, although slightly above the program goal, were considered to be within range of the objective with further development reeffort.

The test configurations are listed in Table XIV, and the emission levels attained for each of the Concept 3 configurations tested are summarized in Figure 32. A brief description of each of the six screening configurations is presented in the following paragraphs. The two refinement configurations are described on Page 89.

a. Concept 3. - Basic Configuration. - This configuration is shown in Figure 33. The combustor was divided into two burning regions. A pilot zone, at the dome of the combustor, was fueled by 20 simplex pressure atomizing nozzles inserted axially through the liner baseplate. The main burning region was downstream of the piloted zone, and was fueled by 40 PM/PV tubes that were inserted radially through the combustor outer wall. For purposes of parametric evaluation, the meterable air supply of the PM/PV system was separated from the main combustor air source. Design optimization tests were conducted involving such variables as PM/PV tube air velocity, fuel/air ratio, and pilot/main combustion zone air splits. The first series of tests of the PM/PV system utilized gaseous propane. The flame temperature of propane is similar to that of vaporized Jet A fuel, and $NO_x$ data obtained with gaseous propane was expected to indicate the maximum $NO_x$ reduction potential of perfectly vaporized Jet A fuel.

Rig testing demonstrated a dramatic decrease in HC with increasing fuel/air ratio in the pilot zone at the taxi-idle inlet pressure and temperature levels, as can be seen in Figure 34. At the taxi-idle point, the system produced an HC emission index of 4.9 g/kg fuel with 25 percent of the combustor airflow admitted through the premix tubes. This value meets the program goal. The CO emission index at taxi-idle also decreased with increasing fuel/air ratio, as shown in Figure 35. The emission index of 36.7 g/kg fuel with 25-percent premix air compared to 25 g/kg fuel

TABLE XIV. CONCEPT 3 TEST CONFIGURATIONS

| Configuration | Modification |
|---|---|
| Basic configuration | External premix tubes |
| Modification 1 | Pilot OD primary orifices increased to isolate pilot from main combustion zone<br>Main combustion zone cooling air decreased |
| Modification 2 | Added coarse pore cooling to ID inclined wall<br>Used both Jet A and propane premix fuel |
| Modification 3 | Added premix chutes to impart 45-degrees swirl to flow<br>Dilution orifice location and angle changed to increase main combustor residence time<br>Added impingement film cooling band to ID inclined wall<br>Added film cooling band to pilot OD wall |
| Modification 4 | Converted premix tubes to internal annulus |
| Modification 5 | Pilot swirler airflow reduced 50 percent |

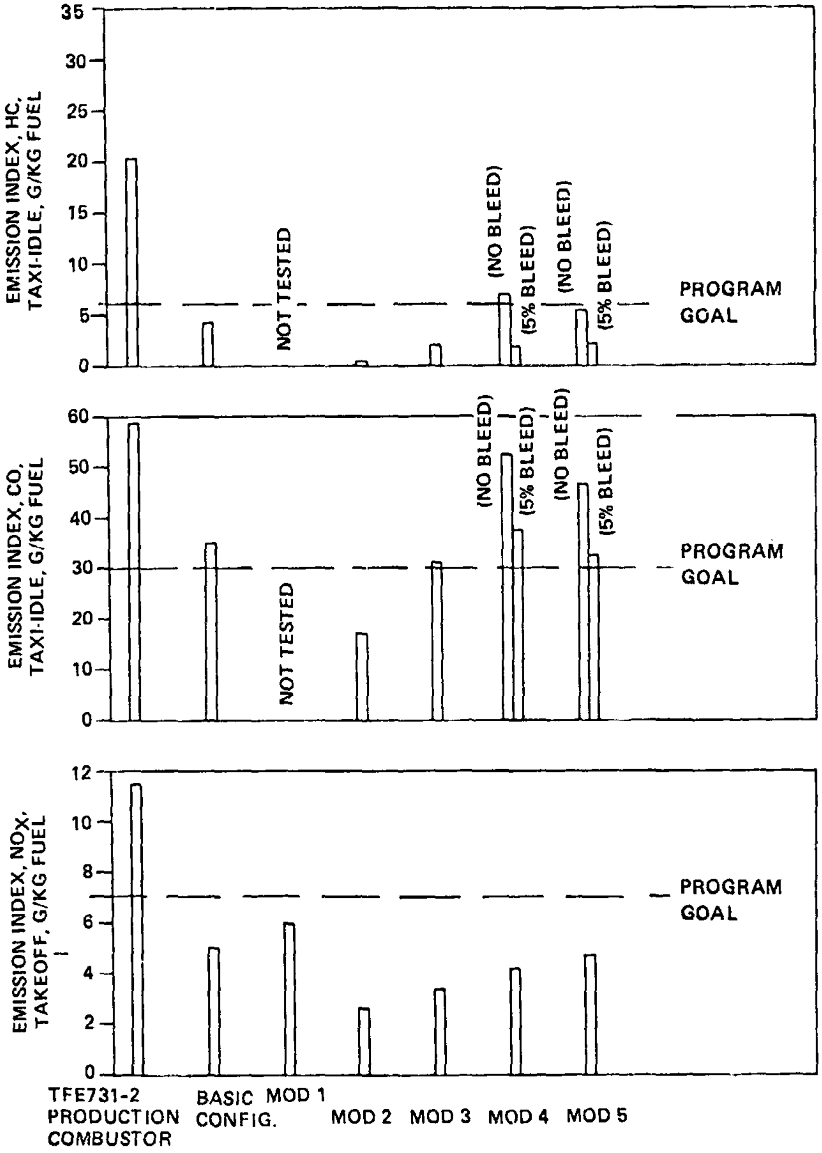


Figure 32. Summary of Emission Tests, Concept 3

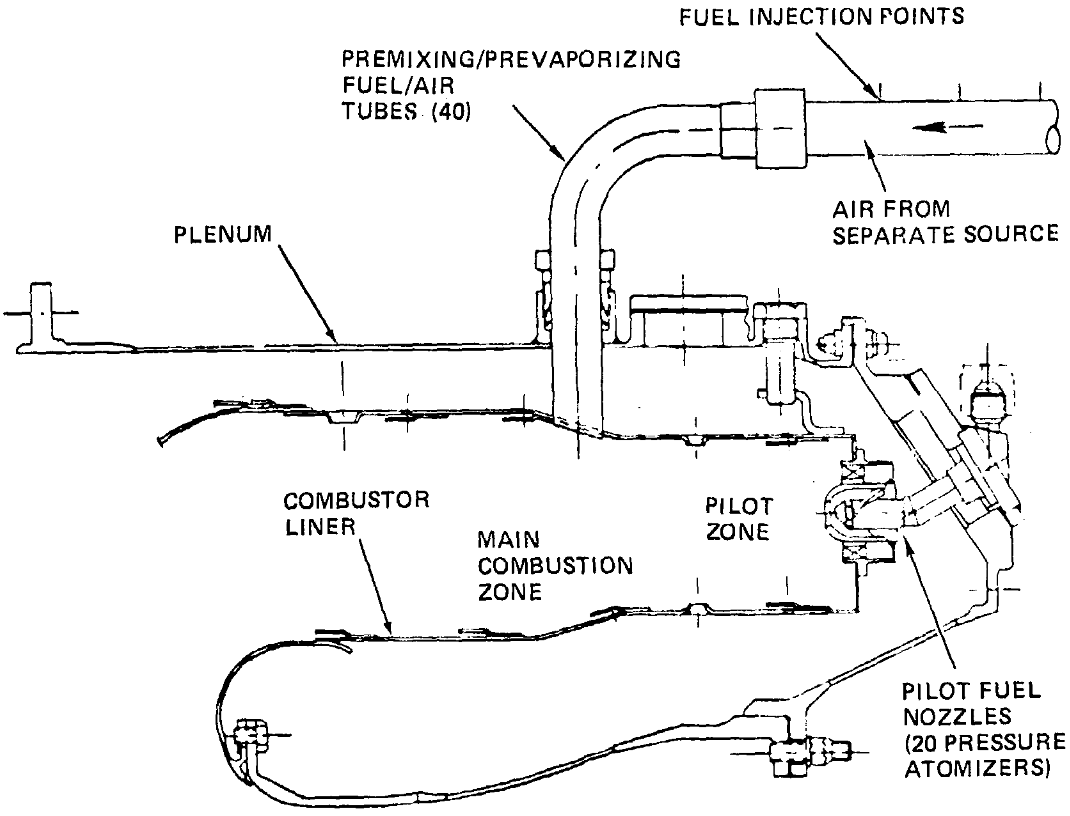
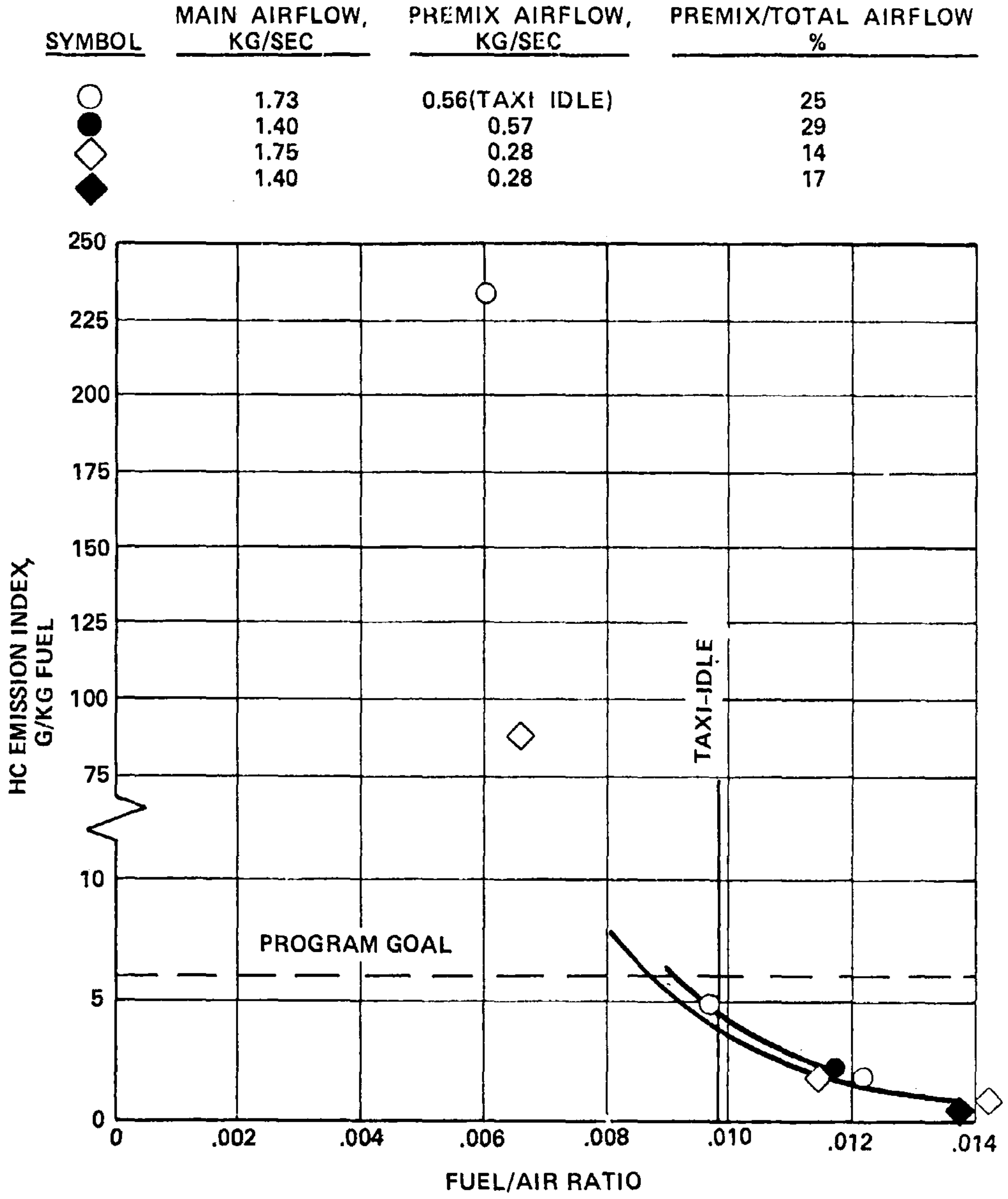


Figure 33. Combustion System, Concept 3
Basic Configuration



| SYMBOL | MAIN AIRFLOW, KG/SEC | PREMIX AIRFLOW, KG/SEC | PREMIX/TOTAL AIRFLOW % |
|---|---|---|---|
| ○ | 1.73 | 0.56(TAXI IDLE) | 25 |
| ● | 1.40 | 0.57 | 29 |
| ◇ | 1.75 | 0.28 | 14 |
| ◆ | 1.40 | 0.28 | 17 |

Figure 34. HC Emissions, Concept 3, Basic Configuration Taxi-Idle

| SYMBOL | MAIN AIRFLOW, KG/SEC | PREMIX AIRFLOW, KG/SEC | PREMIX/TOTAL AIRFLOW % |
|---|---|---|---|
| ○ | 1.73 | 0.56 (TAXI IDLE) | 25 |
| ● | 1.40 | 0.57 | 29 |
| ◇ | 1.75 | 0.28 | 14 |
| ◆ | 1.40 | 0.28 | 17 |

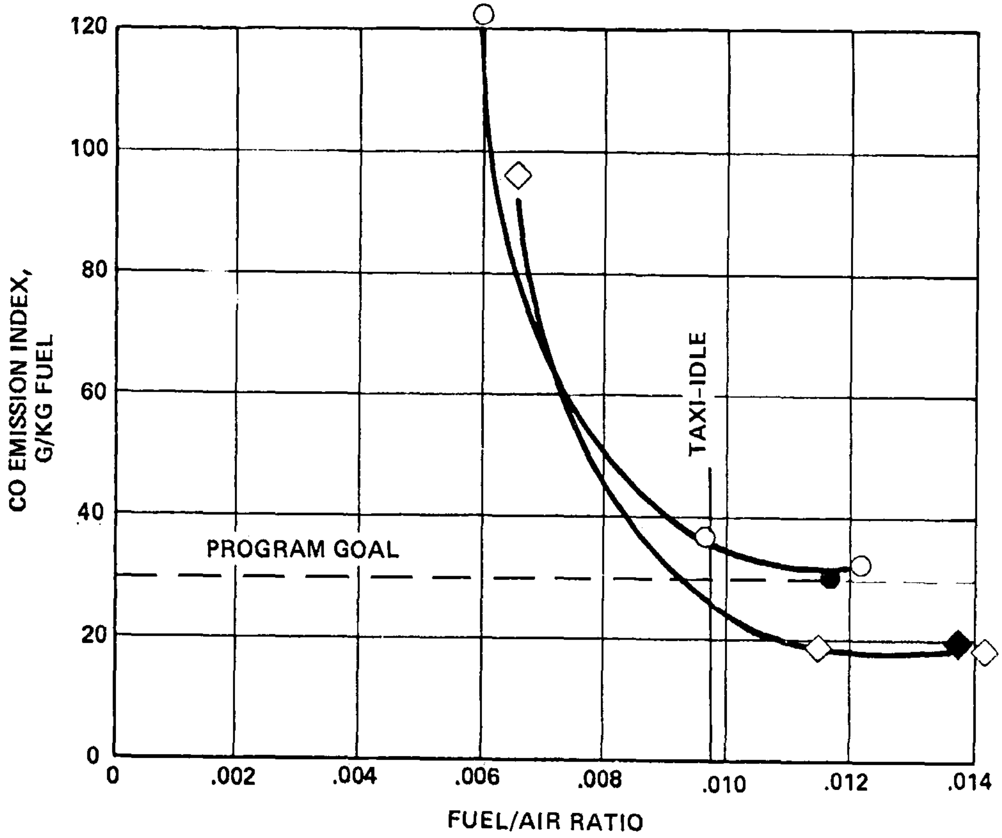


Figure 35. CO Emissions, Concept 3, Basic Configuration, Taxi-Idle

with 14-percent premix air. Although a CO emission index of 36.7 g/kg fuel is above the program goal, this value represents a reduction of approximately 40 percent from the present production system.

At simulated takeoff inlet conditions, a series of parametric tests were run to minimize the $NO_x$ value. The first of these tests was to determine the effect of pilot zone fuel/air ratio on the $NO_x$ levels exiting that region (no premix fuel flow). The test data showed a marked increase in $NO_x$ with increasing fuel/air ratio, as can be seen in Figure 36, and indicated a need to maintain the pilot zone fuel/air ratio as low as possible.

Following the pilot-only test, a series of tests was performed with both the pilot and main combustion zones fueled. These tests evaluated the effect of premix tube fuel/air ratio, and the fuel flow split between the pilot and the main combustion zones. Figure 37 shows $NO_x$ versus overall fuel/air ratio for two premix tube fuel/air ratios. Figures 38 and 39 show HC and CO for the same parameters. These curves show that $NO_x$ increases with increasing overall fuel/air ratio and decreasing premix tube fuel/air ratio, and that HC and CO are extremely sensitive to small changes in overall fuel/air ratio.

The fuel flow split that gave the lowest $NO_x$ emission index moved approximately one-third of the fuel through the pilot system. This produced 5.0 g/kg fuel of $NO_x$, which results in a reduction beyond the level required to meet the program goal. The corresponding emission indices for HC and CO were approximately 5.0 and 17, respectively, which resulted in a combustion efficiency of approximately 99.0 percent at the simulated takeoff condition.

The Concept 3 Basic Configuration was tested with gaseous propane in the PM/PV system, and liquid Jet A fuel in the pilot.

b. Concept 3 - Modification 1. - The first modification to Concept 3 consisted of an increase in the number of OD panel primary orifices from 30 to 120 to promote mixing and to quench $NO_x$ being formed near the outer wall of the pilot zone. This was similar to the Concept 2 Modification 2 design. In addition, the primary cooling airflow rate was reduced by 25 percent on the OD panel and 33 percent on the ID panel to reduce wall quenching effects.

The combustor was coated with temperature sensitive paint to determine the liner temperature characteristics at the simulated takeoff point. The combustor temperature levels downstream of the primary orifices on the OD panel were high, but could have been reduced to an acceptable level by the incorporation of additional

| SYMBOL | MAIN AIRFLOW KG/SEC | PREMIX AIRFLOW KG/SEC | PREMIX/TOTAL AIRFLOW % |
|---|---|---|---|
| ○ | 3.05 | 0.99(SIM. TAKEOFF) | 24 |
| ◐ | 3.70 | 0.99 | 21 |
| ◑ | 2.48 | 0.99 | 28 |
| ◇ | 3.05 | 0.49 | 14 |

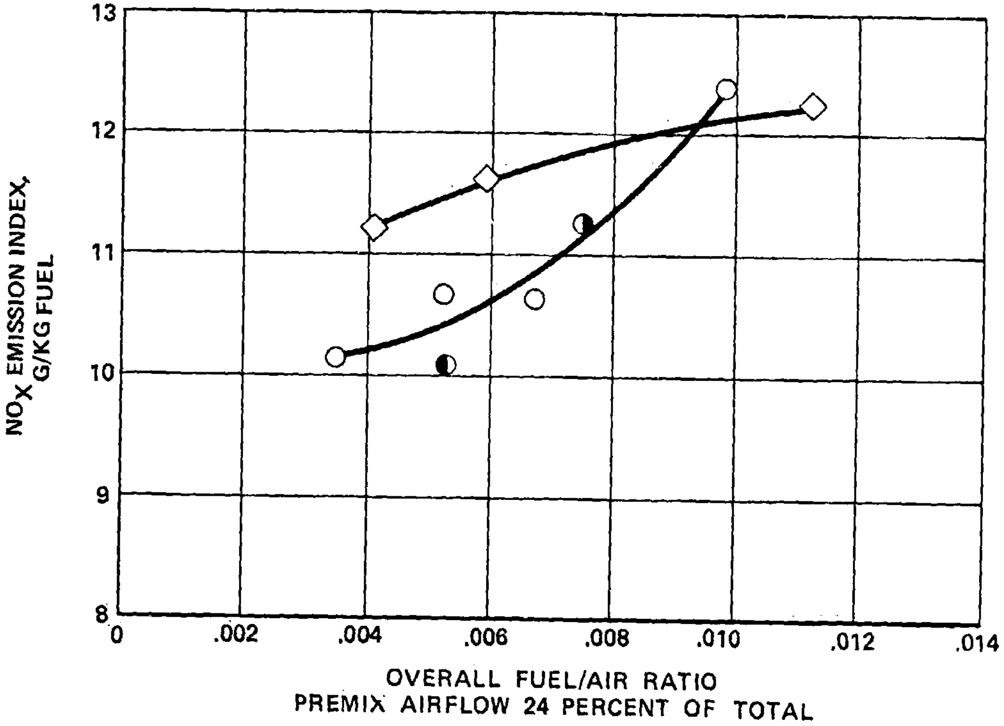


Figure 36. $NO_x$ Emissions, Concept 3, Modification 1, Takeoff Condition, Pilot Only, Basic Configuration

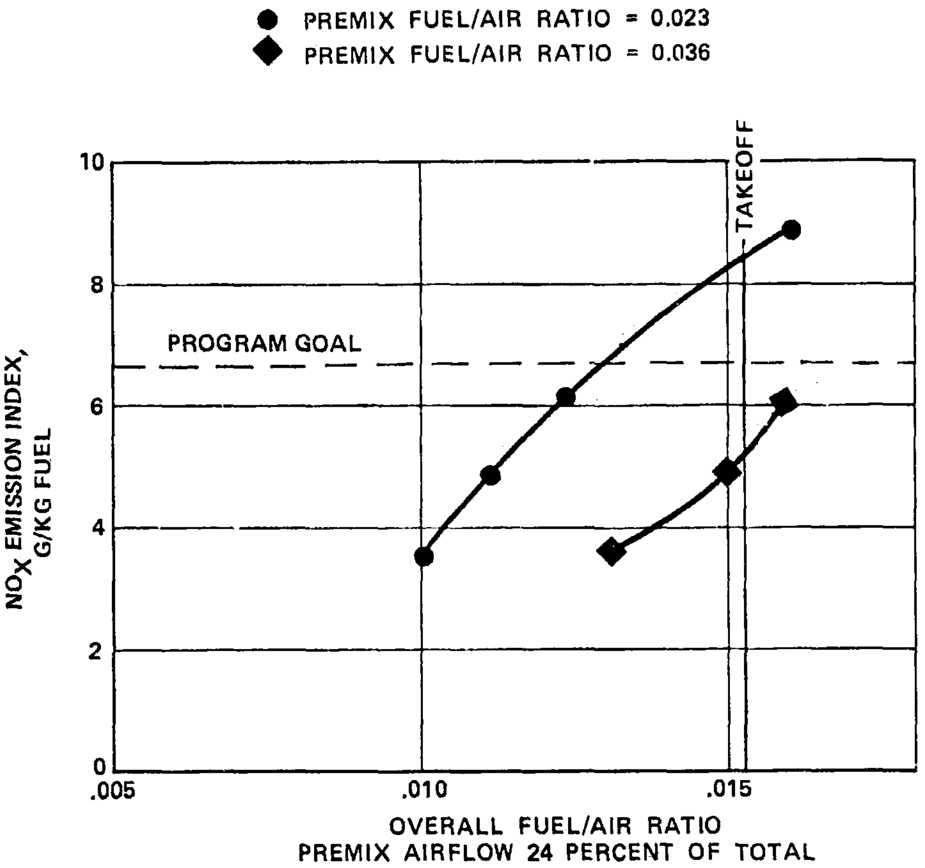


Figure 37. Effect of Fuel/Air Ratio on $NO_x$ Emissions, Concept 3, Basic Configuration

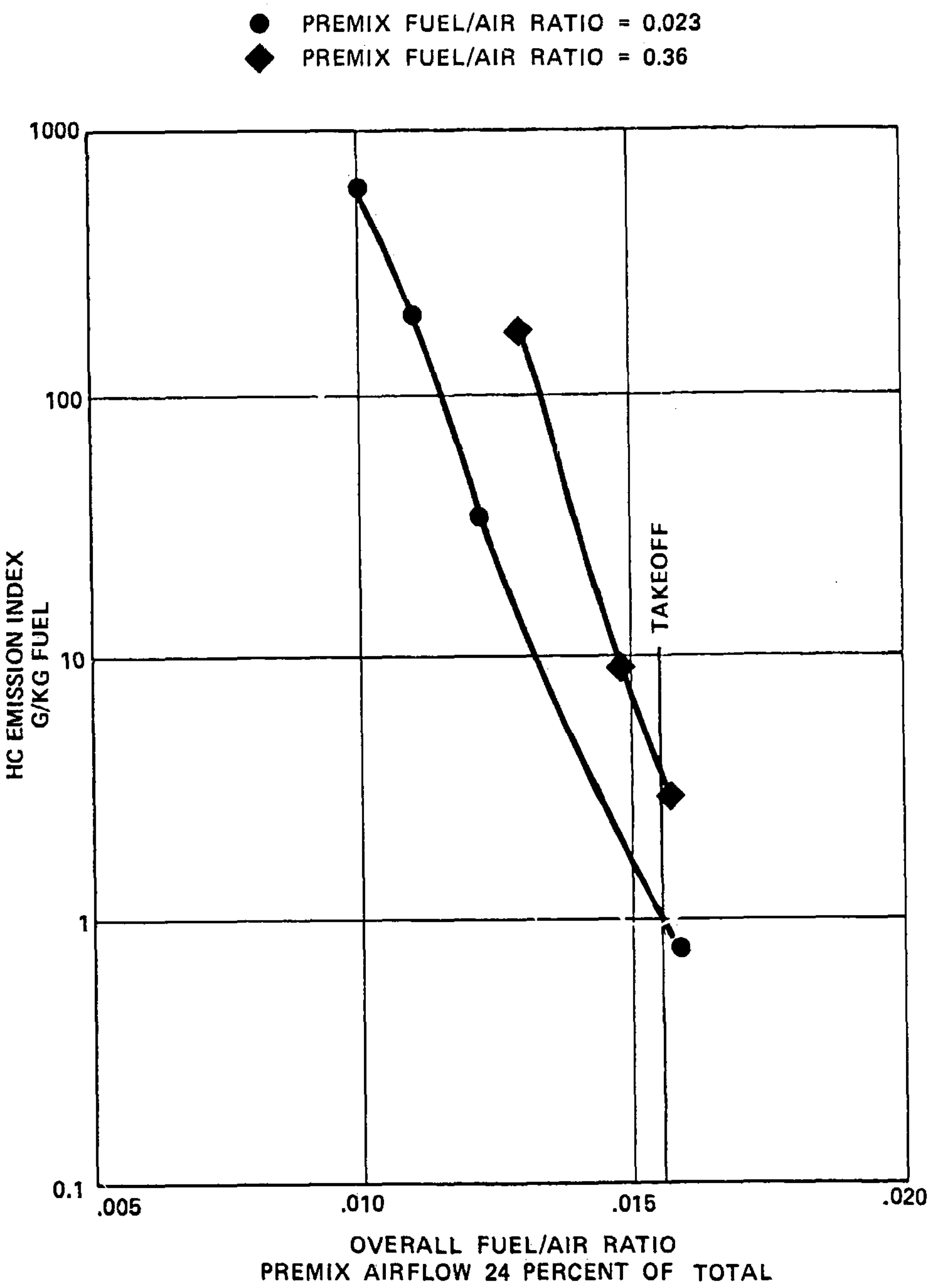


Figure 38. Effect of Fuel/Air Ratio on HC Emissions, Concept 3, Basic Configuration

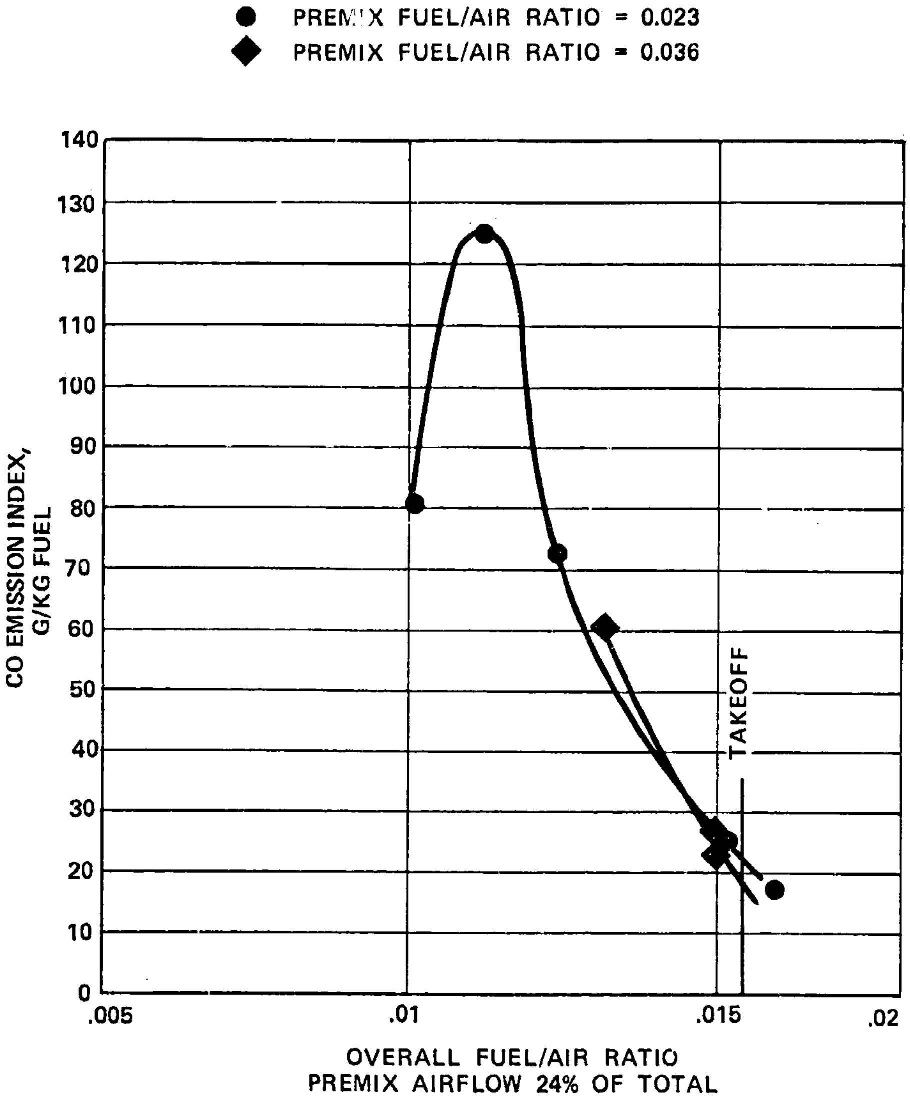


Figure 39. Effect of Fuel/Air Ratio on CO Emissions, Concept 3, Basic Configuration

cooling film air in this location. In the main burning region, the temperature of the inner inclined wall just opposite the PM/PV jets was high, and was attributed to the impinging premix jets.

This configuration was tested only at the simulated takeoff point, and the fuel flow split was approximately 30 percent to the pilot. The PM/PV zone was again fueled with propane. The measured $NO_x$ level in this test was 6.0 g/kg fuel, which was higher than that of the basic configuration. However, HC and CO values were 0.05 and 5.1 g/kg fuel, respectively, which were less than half the values of the basic configuration. Combustion efficiency at this point was 99.9 percent.

c. <u>Concept 3 - Modification 2.</u> - Based on the results of the liner wall temperature test of the previous configuration, 120 holes in each of four rows 0.25-cm diameter simulating coarse transpiration cooling were drilled in the liner OD wall across from the discharge of the PM/PV tubes.

This configuration was evaluated over an extensive matrix of test points using both propane and liquid Jet A fuel in the PM/PV system. Data was taken at taxi-idle, simulated approach, and simulated takeoff power settings to evaluate the effects of the following variables on emission formation and combustion characteristics:

- Premix-to-pilot zone air and fuel flow splits
- Premixing length
- Pilot nozzle flow number
- Comparison of $NO_x$ levels with propane and liquid Jet A as premix fuels.

The configuration that produced the lowest $NO_x$ value while maintaining an acceptable efficiency level utilized Jet A as the PM/PV fuel, with the injection point 35.6 cm from the combustor. The pilot nozzles in this configuration had a flow number* of 0.63. The previous two configurations had used 0.9 flow number nozzles.

---

$$*\text{Flow number} = \frac{\text{Fuel flow, lb/hr}}{(\text{Fuel pressure drop, psid})^{0.5}}$$

At taxi-idle, the combustor produced HC and CO levels of 0.50 and 17.3 g/kg fuel, respectively. These values were well below the program goals. At takeoff, the measured $NO_x$ level was 2.6 g/kg fuel, which was also below the program goal. The combustion efficiency at the takeoff point was 98.2 percent. The inefficiency was attributed to:

- Variation of the fuel/air ratio between the individual PM/PV tubes
- Partially clogged pilot nozzles, discovered after the test was concluded. This resulted in a highly stratified temperature profile of the pilot zone gas that acted as the ignition source for the main combustion zone
- Insufficient residence time in the main combustion zone.

In addition, the wall temperature of the inner panel opposite the PM/PV tube discharges, while lower than the previous configuration, was still considered unacceptably high with a value of 1172°K, as compared to a design objective of 1090°K.

Figure 40 presents a plot of the results for the takeoff points and shows $NO_x$ as a function of the premix tube fuel/air ratio for a series of pilot zone fuel flow rates and fuel injection lengths. The curves show, as would be expected, that increased premix length and lean premix fuel/air ratios produce the lowest $NO_x$ levels. Also, the pilot zone fuel flow rate of 68 kg/hr resulted in the lowest $NO_x$ values plotted. Lower pilot zone fuel flow rates did produce lower $NO_x$ readings. However, the HC and CO values increased rapidly for pilot fuel flow rates of less than 68 kg/hr, and the attendant decrease in combustion efficiency was considered unacceptable. At actual engine conditions, where the combustor is operating at full pressure, it is reasonable to assume that, with lower pilot zone fuel flow rates and leaner premix fuel/air ratios, lower $NO_x$ values could be achieved without a decrease in combustion efficiency.

Included in Figure 40 are the results of the test points where propane was used as the premix fuel. The Jet A liquid fuel and the propane curves follow the same trend as a function of premix fuel/air ratio, but the propane data shows higher $NO_x$ levels at corresponding points. During the series of tests shown in Figure 40, the differential injection pressure of the propane gas at the simulated takeoff point was quite low (34.5 kPa), and it is questionable whether the propane and the premix air were well mixed before entering the combustion zone. Subsequent modifications in the premix fuel manifold to produce a higher injection differential pressure (138 kPa) resulted in a 20-percent decrease in $NO_x$. Further increases in the propane pressure would have resulted in the gas changing to a liquid state. In contrast,

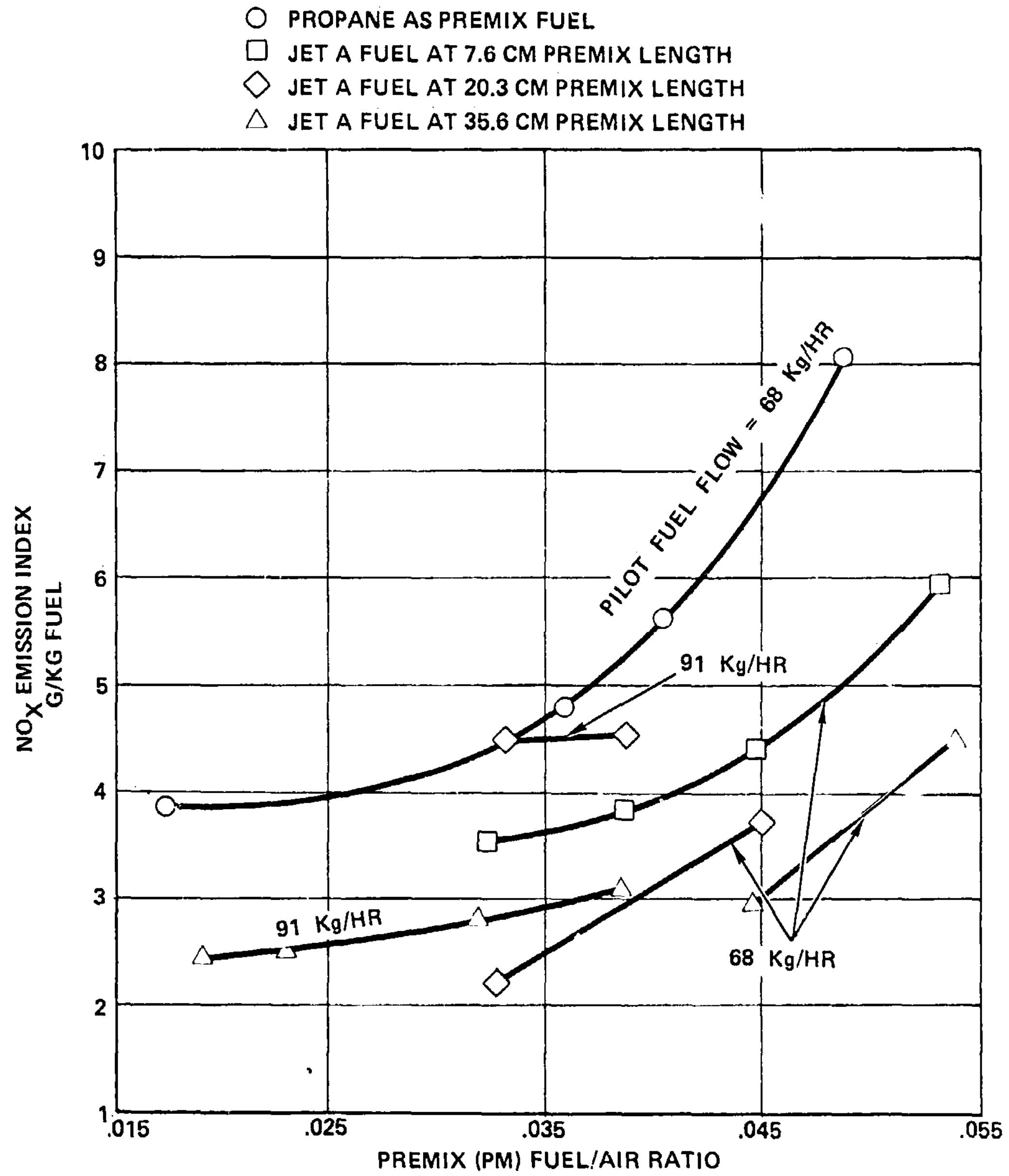


Figure 40. $NO_x$ Emissions, Concept 3, Modification 2

during tests where Jet A was used as the premix fuel, the fuel pressure was of sufficient magnitude to produce extremely small droplets. In all probability, some of the droplets moved across the premix tubes and filmed on the wall. The mixture entering the combustor consisted of liquid and partially vaporized fuel and air. The time required to vaporize the liquid fuel reduced the time available for reaction in the main combustion region, which resulted in slightly lower efficiencies and $NO_x$ values. The conclusions reached from this data is that the degree of fuel vaporization is less important than such factors as degree of fuel/air mixing and residence time of the reacting flow.

d. Concept 3 - Modification 3. - To increase the residence time in the main combustion zone, the exits of the PM/PV tubes were inclined 45 degrees in the direction of the combustor swirl. This modification also prevented the premix flow from impinging on the liner inner wall. This impingement was considered responsible for the high metal temperatures in this region in earlier tests. An additional feature incorporated to increase residence time was the use of inclined tubes in the dilution orifices that directed the air downstream, thereby increasing the reaction volume. To improve the wall cooling, additional cooling bands were added in the primary zone, as well as one band on the inner liner panel opposite the PM/PV tube discharge. Modification 3 is shown in Figure 41.

The combustion system was tested using 0.90 flow number pressure atomizing fuel nozzles as the pilot zone injectors. The PM/PV system was tested with Jet A fuel only. A single injection length of 20.3 cm was evaluated. The combustion system was tested over the LTO cycle with gaseous emissions being taken at all four points, and smoke sampled at takeoff only. A limited amount of parametric evaluation was performed to determine the effects of fuel flow splits and PM/PV tube velocities. At the simulated takeoff point, these fuel flow splits were evaluated together with two premix airflow rates to establish their relationship to $NO_x$ formation. The results of the test are shown in Figure 42.

At taxi-idle, the test results from the configurations that produced the best overall emission results for the LTO cycle had HD and CO levels of 2.1 and 30.7 g/kg fuel, respectively, with a premix airflow rate of 24 percent of the total. The HC value was well below the program goal, and the CO level was only slightly above the goal of 30.0 g/kg fuel. At the simulated takeoff point with the pilot fuel flow equal to 30 percent of the total, and the PM/PV airflow equal to 24 percent of the total, the measured $NO_x$ level was 3.4 g/kg fuel. The measured smoke number was zero, and the combustion efficiency at this point was calculated from emissions to be 99.94 percent. Other takeoff combustor performance parameters such as pattern factor (0.146) and pressure loss (4.43

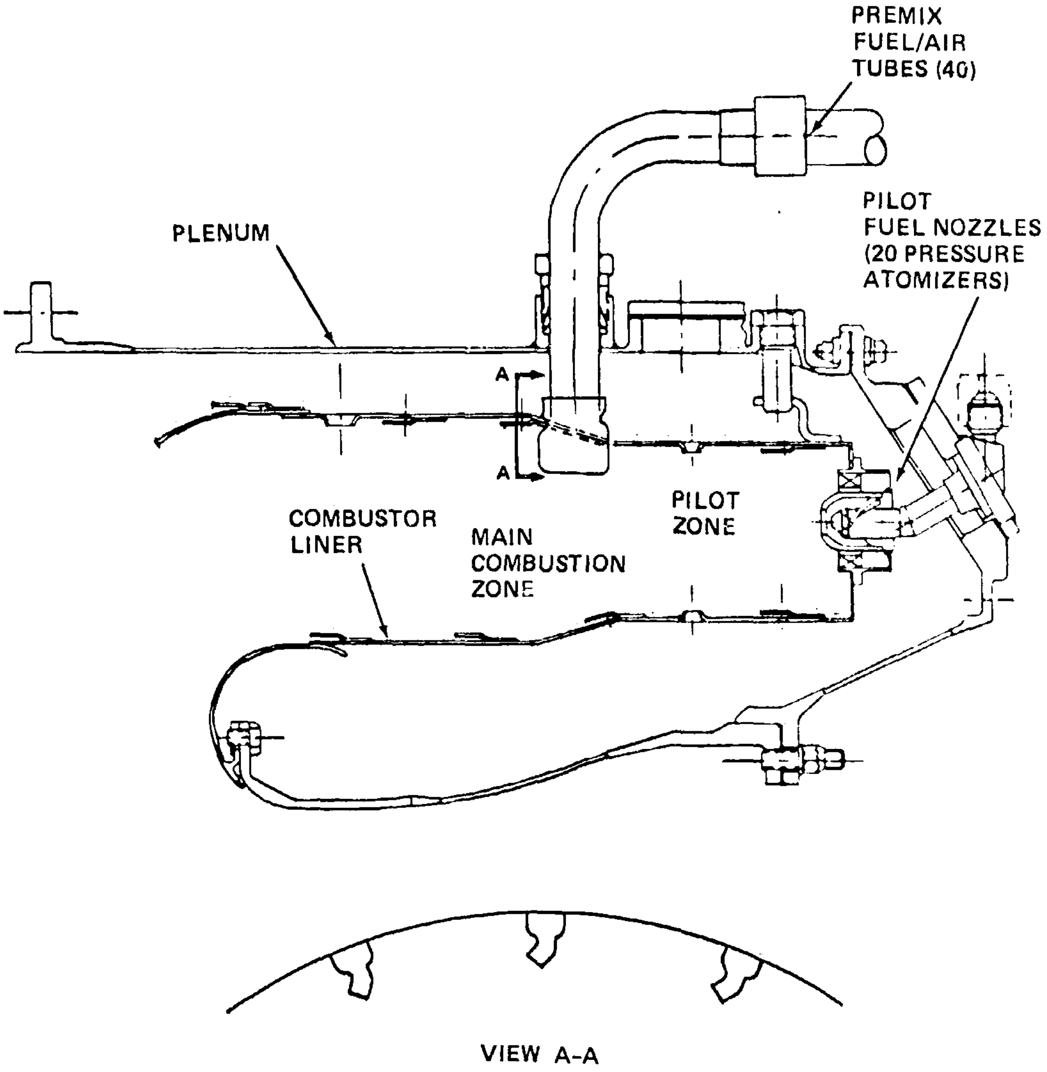


Figure 41. Combustion System Concept 3, Modification 3

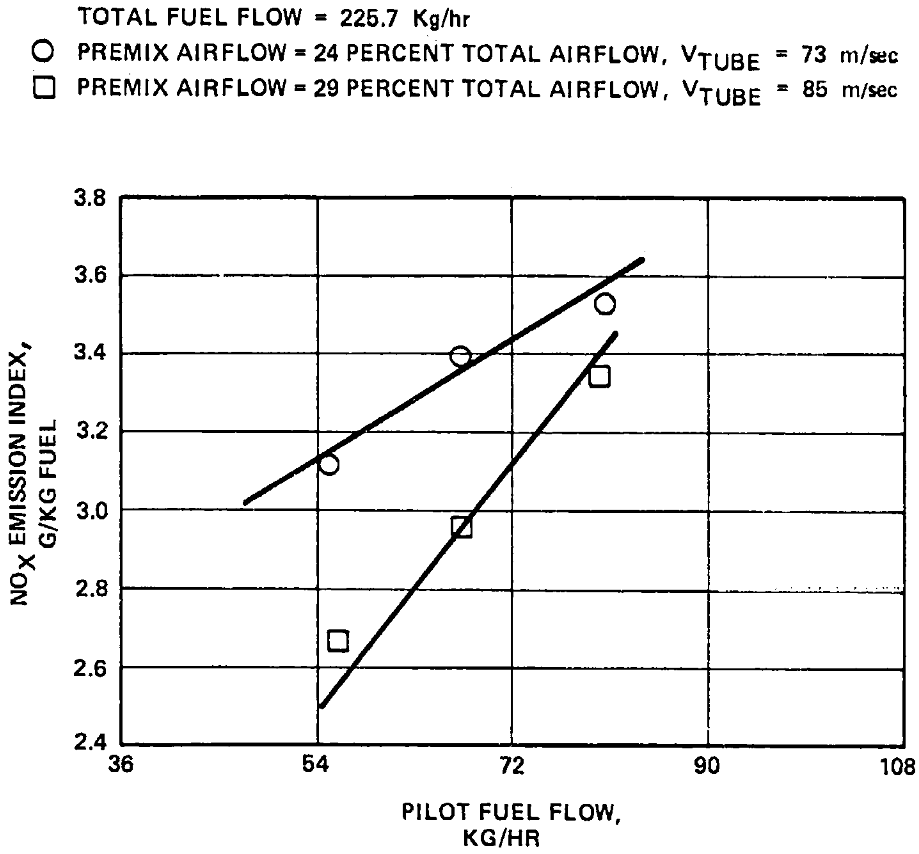


Figure 42. Effect of Fuel Flow Splits at Constant Premix Airflow Rate on $NO_x$, Concept 3, Modification 3

percent) were within engine requirements. The combustor wall temperatures were much improved over the previous configuration, and the hot areas in the PM/PV region were eliminated.

LTO cycle points calculated from the test data are shown below:

| | LTO Cycle Points, lb/1000-lb thrust hr/cycle<br>Program Goals | Concept 3 Mod. 3 |
|---|---|---|
| HC | 1.6 | 0.6 |
| CO | 9.4 | 8.8 |
| $NO_x$ | 3.7 | 2.7 |

These factors were calculated from rig data with all $NO_x$ emission indices corrected to standard humidity, and the climbout and takeoff $NO_x$ indices corrected for pressure differences between rig and engine test points. A pressure exponent of 0.5 was used. The remaining rig values were uncorrected.

e. Concept 3 - Modification 4. - As a result of the successful performance of the preceding configuration, a combustion system was designed with an internal PM/PV system intended to simulate realistic engine hardware. As can be seen in Figure 43, the PM/PV system consisted of an annulus surrounding the outer wall of the combustor, and extended from the diffuser deswirl vanes to the axial mid-point of the burner. At this point the PM/PV annulus was divided into 40 chutes that ducted the fuel-air mixture into the combustor. The combustor, including the 40 PM/PV inlet tubes, remained unchanged from the Modification 3 configuration. In order to maximize the premix length, the PM/PV annulus was extended to the diffuser discharge, thereby necessitating the removal of the outer portion of the deswirl vanes. The swirl angle in the PM/PV annulus remained at essentially the compressor exit swirl angle of 55 degrees, as compared to 35 degrees downstream of the deswirl vanes in the inner airflow passage. The inner and outer walls of the PM/PV annulus were connected by five equally spaced ribs, each in the form of a 55 degree helix aligned in the direction of the swirl angle. Premix fuel was introduced through 40 equally spaced pressure atomizing fuel nozzles. Two premix lengths were investigated--7.6 and 20.3 cm. Both 0.68 and 0.90 flow number pressure atomizing nozzles were evaluated as pilot nozzles.

The system was tested at all four LTO cycle points. At the taxi-idle condition, tests were made both with and without simulated compressor bleed. At the higher power settings, parametric tests were run to evaluate the effect of fuel flow splits on emissions. Prior to commencing combustion testing, tests were performed on the internal PM/PV system to determine the airflow distribution as compared to the external PM/PV system of the

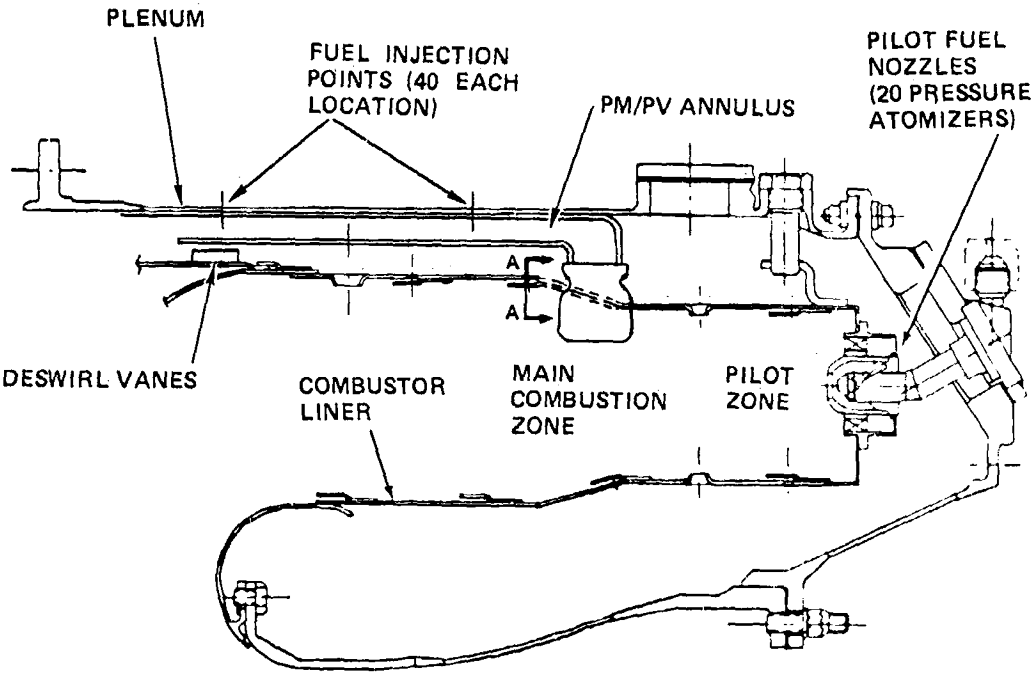


Figure 43. Combustion System, Concept 3, Modification 4

previous configuration. Measurements were accomplished by placing total pressure probes in the premix annulus. These pressure measurements, together with the known effective area of the discharge tubes and the combustor discharge pressure, allowed an iterative calculation to determine the annulus airflow rate. The test data indicated that the PM/PV airflow rate had been reduced 21 percent (from 24 to 19 percent of the total airflow) from Modification 3. Additionally, the PM/PV system exhibited non-uniform air distribution within the annulus. The hardware was reworked to reduce the non-uniformity through improved control of the tolerances; but the flow variations were still significant, and the airflow rate through the PM/PV tubes was unaffected.

At taxi-idle, the emission values were slightly higher than those of the external PM/PV configuration. This could be accounted for by the airflow distribution differences. The reduced airflow in the internal PM/PV annulus resulted in an increase in the pilot zone flow, thus producing a leaner primary zone. At taxi-idle, the emission values for HC and CO were 7.1 and 52.7 g/kg fuel, respectively. To attain further reductions in these pollutants, the system was tested with 5-percent simulated compressor bleed, and produced HC and CO indices of 1.9 and 37.6 g/kg fuel, respectively.

At the simulated takeoff condition, the minimum measured $NO_x$ value was 4.2 g/kg fuel as compared to 3.4 g/kg fuel for the external PM/PV combustor. The minimum $NO_x$ value was attained with the pilot fuel flow equal to 33 percent of the total. Combustion efficiency was measured to be 99.3 percent. The premix length at this point was 20.3 cm.

f. Concept 3 - Modification 5. - This modification was designed primarily to reduce taxi-idle emissions. This modification, and subsequent changes, may not have been required if the airflow splits and distribution had been as they were in Modification 3. The modification consisted of blocking every other vane of the existing combustor swirlers. This increased the pilot zone equivalance ratio and residence time. The PM/PV airflow rate was increased only slightly from 19.1 to 19.5 percent as a result of the change. The 0.68 flow number pressure atomizing nozzles were used in the pilot injectors for all test points. The premix fuel injection length was 20.3 cm.

The combustor was tested at taxi-idle both with and without simulated compressor bleed, and at simulated approach and takeoff points. At taxi-idle, the lowest emission levels were attained with simulated 5-percent compressor bleed. At this point, the HC and CO emission levels were 2.2 and 32.6 g/kg fuel, respectively. Without bleed, the HC and CO values were 5.6 and 46.5 g/kg fuel, respectively. At simulated approach, the measured emission levels for HC, CO, and $NO_x$ were 1.4, 8.4, and 4.6 g/kg fuel, respectively.

At the simulated takeoff point the minimum measured $NO_x$ level was 4.7 g/kg fuel. The pilot zone flow at this point was 30 percent of the total. This represents an increase in $NO_x$ over the previous modification, which can be attributed, in part, to an increase in the $NO_x$ produced in the pilot zone as a result of the increased residence time.

Refinement Tests. - At the completion of the screening tests, Concepts 2 and 3 were selected to proceed into refinement testing. These two concepts were chosen as having the best potential for simultaneously meeting the program emission goals while maintaining acceptable combustor performance.

The testing during the refinement phase of the test task was more extensive than the previous combustor screening testing. Emission and performance measurements were taken at the four LTO cycle points (taxi-idle, approach, climbout, and takeoff). Smoke and combustor wall temperature measurements were obtained at the simulated takeoff power setting. In addition, ignition (including altitude relight) and stability tests were performed, and the results compared to those of the present production combustion system.

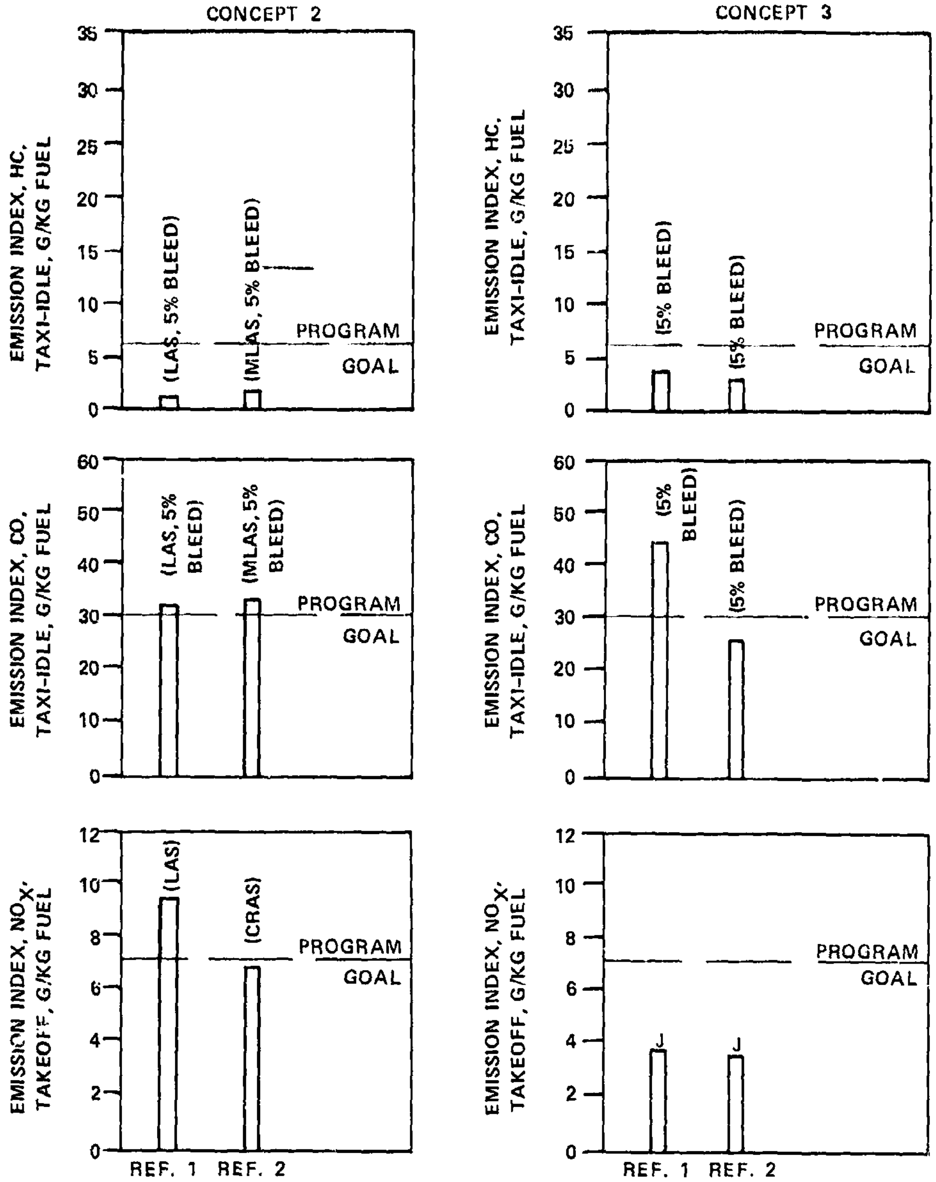
The test configurations and the emissions results for the two refinement tests of Concept 2 are shown in Table XV and Figure 44, respectively. Similarily, the configurations and results for the Concept 3 refinement tests are shown in Table XVI and Figure 44, respectively.

TABLE XV. - CONCEPT 2 REFINEMENT TEST CONFIGURATIONS

| | |
|---|---|
| Refinement 1 | Relocated inner and outer primary orifices to produce same airflow as basic configuration and added row of outer primary orifices for $NO_x$ control<br>Low- and high-airflow swirlers evaluated |
| Refinement 2 | Modified primary orifices to increase airflow and obtain a primary zone equivalence ratio of 0.5 at takeoff<br>Modified high-airflow swirlers |

TABLE XVI. - CONCEPT 3 REFINEMENT TEST CONFIGURATIONS

| | |
|---|---|
| Refinement 1 | Pilot primary air orifices removed<br>Pilot cooling air decreased 50 percent<br>Used half and full area pilot swirlers |
| Refinement 2 | Airblast pilot nozzles |



LAS - LOW AIRFLOW SWIRLERS
MLAS - MODIFIED LOW AIRFLOW SWIRLERS
CRAS - COUNTER ROTATING AIRFLOW SWIRLERS
J = JET A FUEL (PREMIX SECTION)

Figure 44. Summary of Refinement Tests

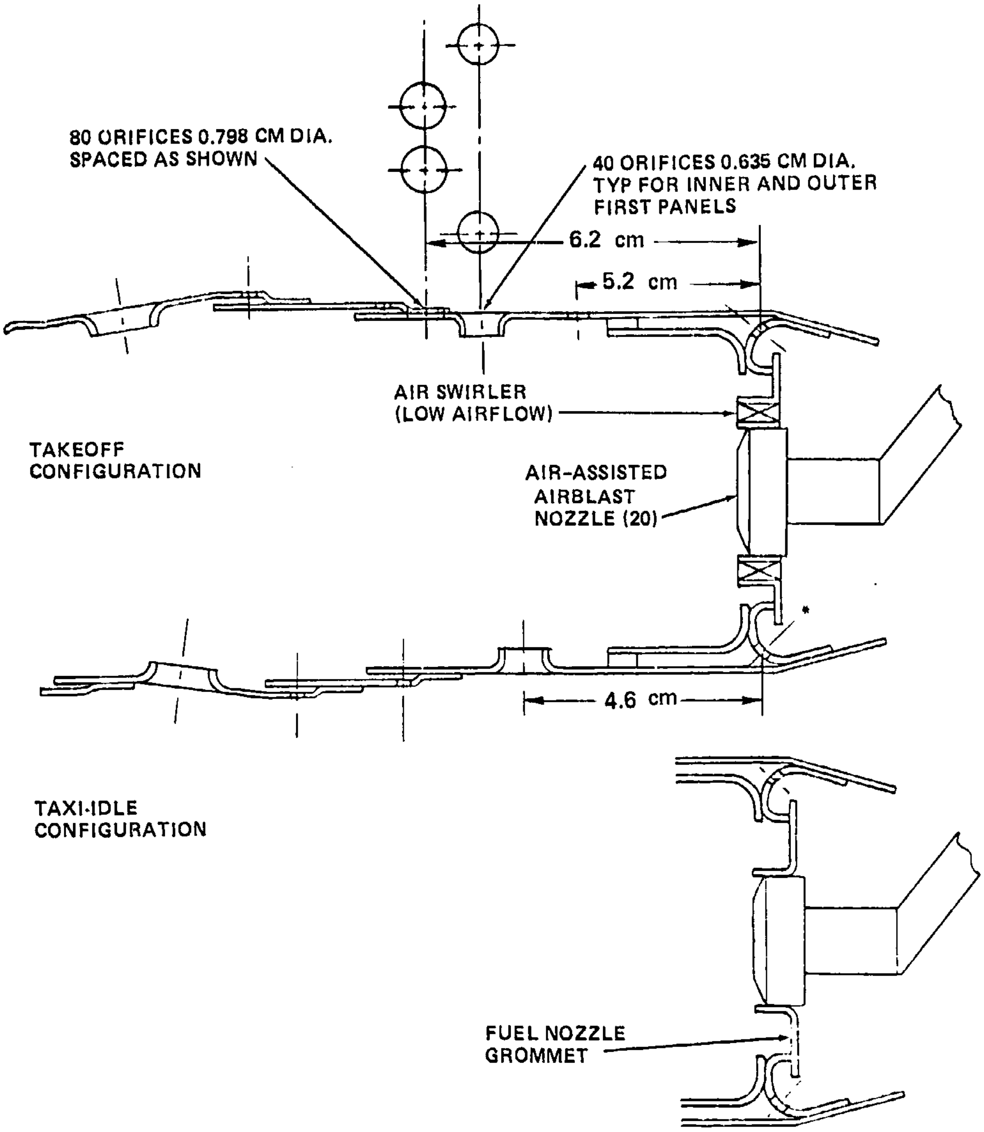
### 1. Concept 2. -

a. Concept 2, Refinement Test 1. - From the test results of Modification 5, it was determined that in the fuel nozzle grommet configuration, the primary zone orifices were located too far downstream for the air entering through these orifices to take part in the combustion reaction during low-power operation. This resulted in an over-rich primary zone, as evidenced by the high HC and CO values, and the heavy buildup of carbon in the combustor primary zone. On the other hand, the air entering through the primary orifices was effective in leaning out the reaction zone at the simulated takeoff setting in the Modification 5 swirler configuration. Based on those considerations, the Concept 2 combustor for the first refinement test was designed with the primary orifice was effective in leaning out the reaction zone at the simulated takeoff setting in the Modification 5 swirler configuration. Based on those considerations, the Concept 2 combustor for the first refinement test was designed with the primary orifice pattern, as shown in Figure 45. The first row of orifices on both the inner and outer primary panels was sized to produce approximately the same airflow as in the Concept 2 basic configuration. The axial location of these orifices was identical to the basic configuration, which produced the lowest taxi-idle emission levels of the Concept 2 configurations. A second row of primary orifices on the outer panel was positioned downstream of the first row such that the airflow through these holes would not significantly affect taxi-idle operation. However, it would substantially reduce $NO_x$ at takeoff. These orifices were sized to produce a primary zone equivalence ratio at takeoff that was less than the Modification 2 and Modification 5 designs.

The first refinement test combustor was evaluated in three configurations:

- With low airflow swirlers
- With high airflow swirlers
- With fuel nozzle grommets

The first series of tests was conducted on the combustor utilizing the low airflow swirlers. This configuration was evaluated at taxi-idle (both with and without simulated compressor bleed), approach, climbout, and takeoff. At the simulated takeoff inlet conditions, parametric tests were conducted to determine $NO_x$ as a function of fuel/air ratio. In addition, the combustor was painted with temperature sensitive paint (Thermindex OG-6), and a wall temperature evaluation was obtained at the takeoff point. A smoke measurement was also taken at this power setting. Following these performance tests, ignition and stability limit tests were performed.



* INNER AND OUTER PRIMARY COOLING AIR REDUCED BY ONE-THIRD FROM MODIFICATION 5

Figure 45. Combustor Configuration for Concept 2, Refinement Test 1

C-2

At the completion of these tests, the combustor was removed, and the low airflow swirlers were replaced with the high airflow version. This assembly was tested only at the simulated climbout and takeoff inlet conditions with variations in fuel/air ratio.

For testing at the taxi-idle conditions, the combustor was modified by replacing the swirlers with grommets, and was tested both with and without simulated compressor bleed. Ignition tests were also conducted in this configuration.

The tests at taxi-idle indicated that in the grommet configuration, the reaction zone was too rich, at least locally near the dome, as evidenced by carbon buildup in this region. Subsequent tests with the low airflow swirler configuration produced CO slightly lower, even though the calculated primary zone equivalence ratio was leaner. With simulated 5-percent compressor bleed, the low airflow swirler configuration met the CO goal.

At the simulated takeoff point, there was no appreciable variation in $NO_x$ between the two swirler sizes. Figure 46 shows a plot of $NO_x$ as a function of fuel/air ratio for both swirler configured burners, and it can be seen that the curves are almost identical. Assuming that the swirlers were flowing at the design rates, it was concluded that the $NO_x$ formation rate was relatively unaffected by the degree of change in the calculated primary zone equivalence ratio (from $\phi = 1.03$ to $\phi = 0.86$), and that a more significant change in equivalence ratio was required to produce lower $NO_x$ values.

The measured smoke number on the low airflow swirler configuration was essentially zero, and wall temperatures were 1005°K or less for most of the combustor surface, with no excessive temperature gradients. One small isolated area had a maximum temperature of 1144°K; however, overall wall temperatures were considered satisfactory for this stage of development. The combustor stability test showed that both swirler configurations had combustion stability better than the present production combustor. Ignition tests did not produce satisfactory ignition performance, and indicated that the igniter is not located at the optimum position for the Concept 2 liners.

b. Concept 2 Refinement Test 2. - The second refinement test combustor is shown in Figure 47. Extensive orifice pattern modifications were made as well as changes to the fuel nozzle swirlers.

The intent of the modification was to produce a calculated primary zone equivalence ratio of 0.5 at the takeoff condition as an extension of Refinement Test 1. Most of the increased airflow was introduced through the dome with the intent of producing thorough fuel/air mixing near the fuel injection point. The high

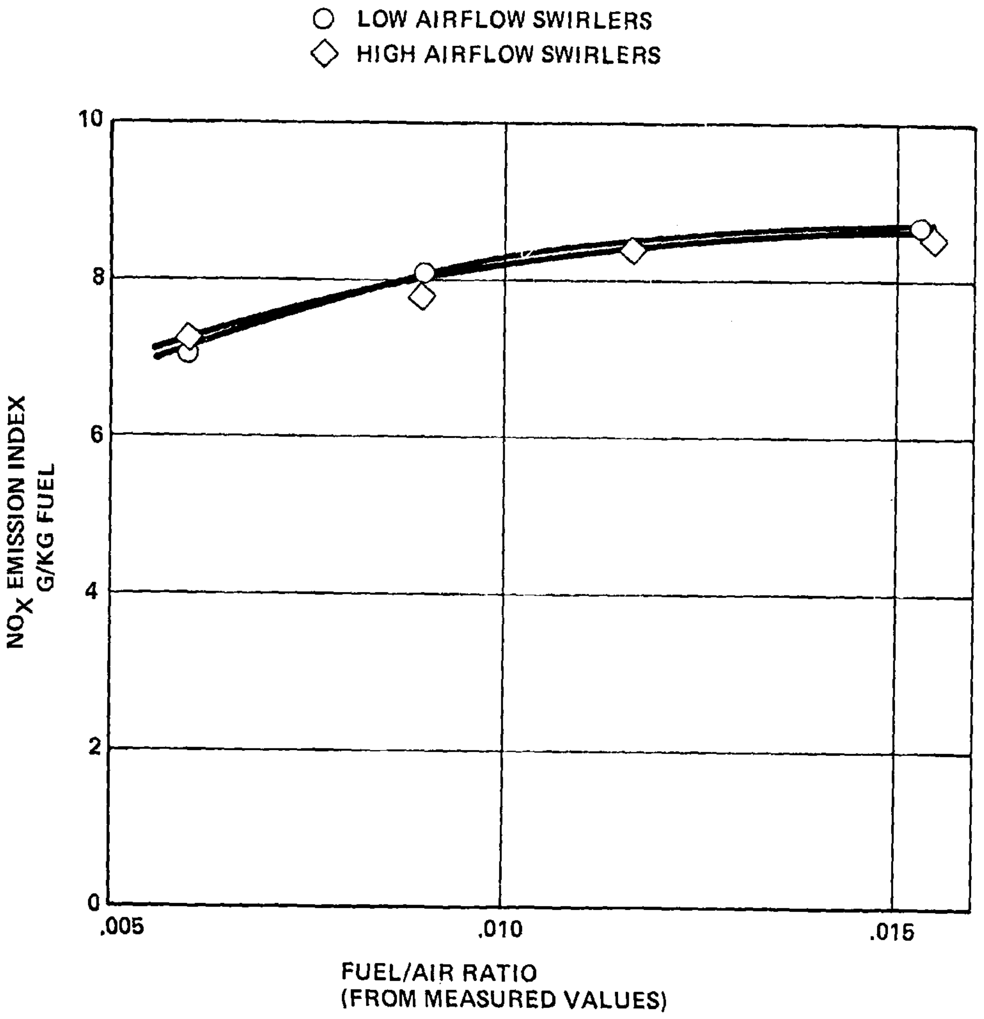
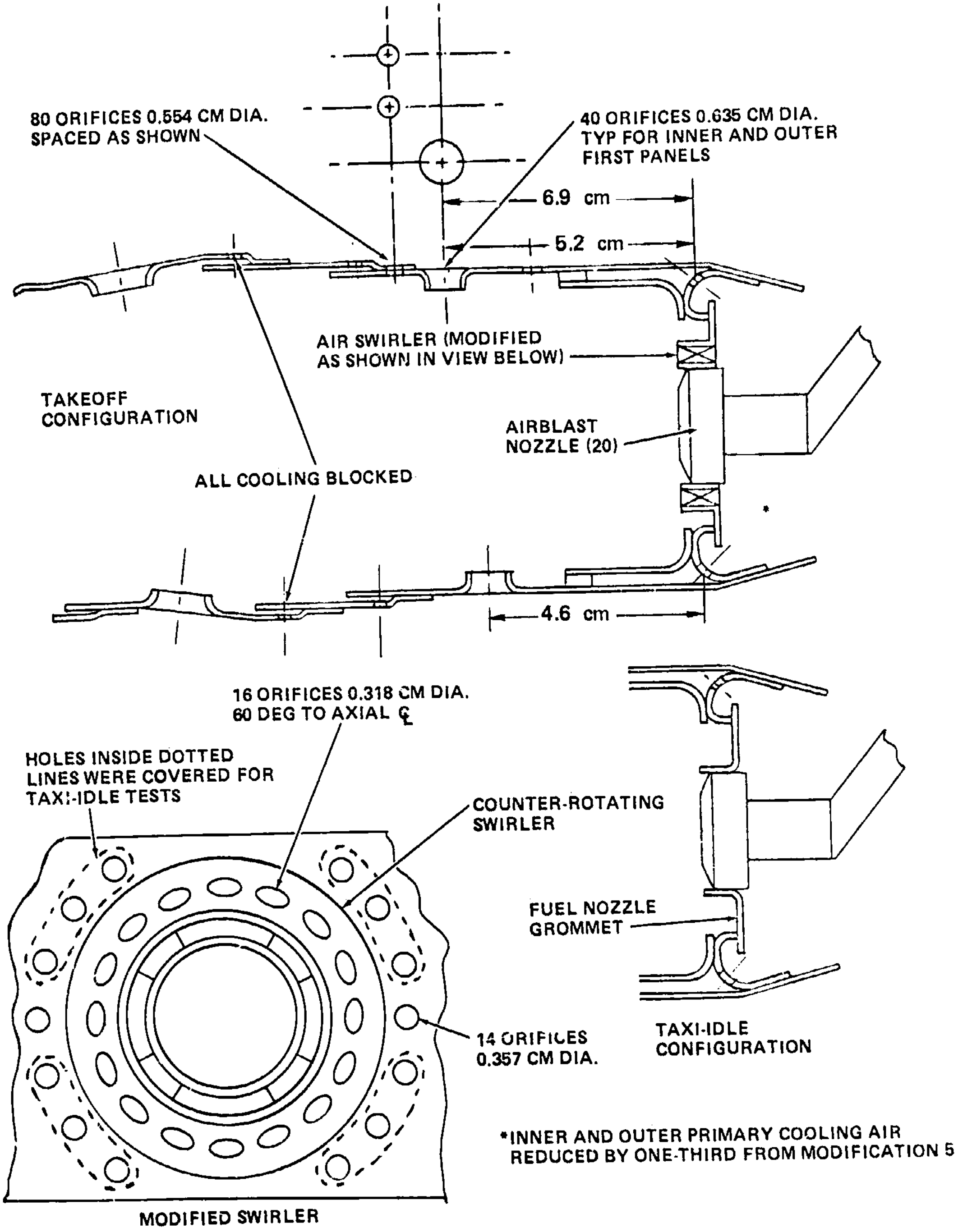


Figure 46. $NO_x$ Emissions, Concept 2, Refinement 1, Takeoff Condition



*INNER AND OUTER PRIMARY COOLING AIR REDUCED BY ONE-THIRD FROM MODIFICATION 5

Figure 47. Combustor Configuration for Concept 2, Refinement 2

airflow swirlers were modified by the addition of a ring of eloxed orifices surrounding the swirler inlet. The orifices were eloxed at a 60-degree angle to the axial centerline and in the opposite direction to the main swirler, thus producing a counter rotation of the inlet air. The counter-rotating airstreams were selected to produce a short reaction zone with improved fuel-air distribution as a means of $NO_x$ reduction. The overall combustor effective open area was maintained at 0.017 $m^2$ to provide sufficient combustor pressure drop for adequate mixing. These required reductions in cooling airflow rates were considered acceptable, based on liner wall temperatures from the first refinement test.

At the low-power points, modified low airflow swirlers were utilized in place of the grommets. In the last two previous grommeted configurations tested at taxi-idle, carbon formation was noted in the dome, and the CO levels were actually higher than when the same combustors were tested with the low airflow swirlers. Therefore, these swirlers were modified around the outer portion of the swirler to reduce the open area by approximately 50 percent. This small amount of air was intended to prevent carbon formation and not produce an overly overly-lean condition in the dome.

The measured takeoff $NO_x$ level of 6.5 g/kg fuel was the lowest attained to date with the Concept 2 configurations that utilized swirlers. This low $NO_x$ level was attained with a minimum of air assist (required to prevent the coking of the nozzle air-assist passages). Three emission scans were made with decreasing air-assist flow rates to determine the effect on $NO_x$ formation. The tests showed that $NO_x$ decreased linearly with decreasing air-assist pressure.

The stability of the combustor was determined to be superior to the first refinement combustor, which in turn offered improved stability as compared to the present production system.

The taxi-idle conditions were run both with and without simulated compressor bleed. The HC values met the program goal without compressor bleed. However, the CO values exceeded the program goal of 30 g/kg fuel with a level of 31.7 g/kg fuel with 5-percent bleed.

At the first taxi-idle point, a single isolated spike in the HC circumferential transverse plot indicated that an abnormality existed in the test hardware. A significant rise in the CO value was also noted at the same location. In an attempt to correct this condition, the individual fuel nozzle metering devices were removed and flow checked, as were two of the fuel nozzles. Four of the metering devices were replaced with new hardware, as were both of the fuel injectors. The taxi-idle points were rerun with a significant reduction in the HC spike (30-percent reduction of spike amplitude). The spike, however, was not eliminated, nor were the CO values appreciably changed within the available test period.

2. Concept 3. -

a. Concept 3, Refinement Test 1. - The first refinement modification was designed as a means of reducing takeoff $NO_x$. The modification consisted of eliminating the airflow through the OD and ID primary orifices by covering two rows of holes with shimstock bands. This increased the airflow in the PM/PV annulus to approximately 22 percent at takeoff, 2-percent less than the optimum external PM/PV configuration. Testing was performed with two swirler configurations:

- The swirlers from Modification 5 with half the normal flow area

- Full open area swirlers

The combustor with the reduced area swirlers was tested with 0.68 flow number pilot nozzles only. The configuration with full area swirlers was tested with both the 0.68 and 0.90 flow number pressure atomizers. The PM/PV injection length was 7.6 cm for all test points.

The combustor was tested at taxi-idle, simulated approach, and simulated takeoff power settings. At taxi-idle, tests were performed both with and without simulated compressor bleed. At takeoff, various pilot PM/PV fuel flow splits were evaluated.

At taxi-idle, HC and CO increased dramatically from the previous configuration. Even though the calculated primary zone equivalence ratio was less than in the previous configuration, the lowest HC and CO levels were 4.0 and 44.7 g/kg fuel, respectively, with the reduced area swirlers, 5-percent bleed, and 0.68 flow number pilot nozzles. With the full-area swirlers in the same configuration, the values were 5.3 and 52.9 g/kg fuel. Without the primary zone orifices to terminate the pilot reaction zone, very little of the reacting flow recirculated, and the residence time in the burning zone was significantly reduced.

At the simulated approach point with the half-area swirlers, the HC, CO, and $NO_x$ values were 0.3, 16.7, and 4.1 g/kg fuel, respectively. With the full-area swirlers, these values were 0, 16.5, and 4.5 g/kg fuel. Both configurations were tested only with the pilot fuel nozzles.

At the simulated takeoff point, an $NO_x$ emission index of 3.7 g/kg fuel was the lowest value measured with the reduced area swirlers. Pilot fuel flow was only 20 percent of the total. Combustion efficiency at this point was 99.8 percent. This represents the lowest $NO_x$ value measured for the internal PM/PV system with a 7.6 cm injection point. With the full-open swirler, $NO_x$ was 4.1 g/kg fuel.

b. Concept 3 - Refinement Test 2. -- In this configuration, the pressure atomizing pilot fuel nozzles were replaced with the air-assisted airblast injectors of Concept 2. The combustor swirlers were also replaced with the Concept 2 hardware. Tests were run with the low airflow swirlers, the fuel nozzle grommets (zero airflow), and with modified low airflow swirlers that had the flow area reduced by one half. The tests with the full-open swirlers were run with the primary orifices blocked. All subsequent tests had these orifices open. The PM/PV fuel injection length was 7.6 cm for all test points.

The combustor was run at taxi-idle, approach, and simulated takeoff. At the taxi-idle setting, the combustor was run in various combinations of compressor bleed and air-assist flow rates to the airblast injectors. At the simulated takeoff setting, various pilot PM/PV fuel flow splits were evaluated.

The tests at taxi-idle reaffirmed the conclusion that the primary orifices were required to terminate the pilot reaction zone. Similarly, it was determined in the test with the zero airflow grommets that without the swirlers, little of the primary orifice air recirculated upstream into the reaction zone, as evidenced by high HC and CO levels (65.5 and 100 g/kg fuel, respectively) and carbon buildup in the liner dome. The configuration that produced the lowest taxi-idle emissions used the half-area swirlers and open primary orifices. The HC and CO values were 3.2 and 25.7 g/kg fuel, respectively. This was measured at 5-percent bleed with 195.6 kPa differential air-assist pressure.

Takeoff performance was not as good as in previous configurations. With the full-area swirlers and the primary orifices blocked, an $NO_x$ level of 2.5 g/kg fuel was measured; however, the combustion efficiency was only 97.8 percent. With the half-area swirlers and the open primary orifices, an $NO_x$ value of 3.5 g/kg fuel was measured at a combustion efficiency of 98.9 percent.

### Combustor Performance

In addition to the gaseous emission and smoke measurements performed on the various combustor configurations, performance data was also taken. Pattern factor and pressure loss data was recorded for nearly all configurations at the simulated takeoff and taxi-idle power settings. These results are tabulated in Table XVII. Most of this data was recorded at the same test point as the emissions data discussed in previous sections of this report. However, at some points where pressure drop and/or pattern factor data was not taken, values have been recorded for the same configuration, but with a slightly different set of test data (e.g., a different fuel flow split between the pilot and main combustion zones on Concept 3). Wall temperature tests were performed at the simulated takeoff condition whenever a design modification resulted in a major change to the cooling characteristics of the combustor. Ignition, altitude relight, and stability characteristics were evaluated on the refinement configurations only.

Pressure loss. - The present production combustion system has a pressure loss of 4.5 percent at the takeoff power setting, and the design criterion for all three concepts was to maintain this value as closely as possible in all configurations. As shown in Table XVII, all but two of the configurations tested were within ±1 percent of the design goal. Although intermediate modifications were above the goal, the final (Refinement 2) configuration met the goal.

Exit temperature pattern factor. - The NASA Class T1 program goal calls for a pattern factor of less than 0.19. Table XVII indicates that all of the Concept 2 configurations produced pattern factors of less than 0.18. The second refinement test configuration of this concept, which the Phase II design will be based on, had a pattern factor of 0.12--well below the engine requirement and program goal.

The 0.30 pattern factor of the Concept 3 second refinement configuration ran higher than the program goal of 0.19. This is attributed to the nonuniformities in the premix annulus, which resulted in a variation in the fuel/air ratio of the mixture. The pattern factor can be reduced to acceptable levels by maintaining close tolerances in fabrication.

Combustor durability. - The potential durability of the combustor designs was assessed primarily by wall temperature tests utilizing temperature sensitive paint that covered the entire surface of the liner. In Concept 1, where the changes from the production design were minimal, the wall temperature levels were considered acceptable. For Concept 2, the wall cooling airflow rates were progressively decreased during development with little significant effect on wall temperatures. The one exception to this was the combustor dome, which was attached to the inner and outer side panels of the liner by wiggle strips. Differential expansion of the dome and side panels tended to distort the wiggle strips and crack the welds, which resulted in a distortion of the cooling airflow to the primary zone panels. In some instances,

TABLE XVII - SUMMARY, PRESSURE LOSS AND PATTERN FACTOR DATA

| | Taxi-idle | | Takeoff | |
|---|---|---|---|---|
| | Pressure loss, ΔP/P | Temperature spread factor | Pressure loss, ΔP/P | Temperature spread factor |
| Concept 1 | | | | |
| Basic Configuration | 3.6 | 0.17 | 4.3 | 0.06 |
| Modification 1 | 3.7 | 0.71 | - | - |
| Modification 2 | 3.8 | - | 4.4 | 0.10 |
| Modification 3 | 3.9 | 0.14 | 4.0 | 0.14 |
| Modification 4 | 3.7 | - | 3.8 | - |
| Modification 5 | 4.2 | 0.28 | 4.2 | 0.42 |
| Concept 2 | | | | |
| Basic Configuration | 6.5 | 0.18 | 7.0 | 0.18 |
| Modification 1 | 4.9 | 0.17 | 5.7 | 0.16 |
| Modification 2 | 4.2 | 0.22 | 4.6 | 0.09 |
| Modification 3 | 4.8 | 0.19 | 5.0 | 0.18 |
| Modification 4 | 4.3 | 0.22 | 5.3 | 0.12 |
| Modification 5 | 4.3 | 0.16 | 5.1 | 0.15 |
| Refinement 1 | 4.7 | 0.07 | 5.0 | 0.08 |
| Refinement 2 | 3.9 | 0.11 | 4.1 | 0.12 |
| Concept 3 | | | | |
| Basic Configuration | 3.2 | 0.18 | 3.7 | 0.19 |
| Modification 1 | - | - | 4.9 | 0.12 |
| Modification 2 | 4.2 | 0.44 | - | 0.17 |
| Modification 3 | 2.9 | 0.16 | 4.4 | 0.15 |
| Modification 4 | 3.1 | 0.17 | 3.8 | 0.19 |
| Modification 5 | 3.6 | - | 4.5 | 0.23 |
| Refinement 1 | 4.2 | 0.19 | 4.1 | 0.32 |
| Refinement 2 | - | - | - | 0.30 |
| Production | 3.0 | 0.33 | 4.5 | 0.19 |

the cooling gap was completely closed. The Phase II design will be modified to incorporate a conventional film cooling geometry in this region.

Durability problems with the Concept 3 configurations centered on the impingement of the PM/PV fuel-air mixture on the combustor inner wall. This was resolved by the addition of a film cooling panel at this location, and by inclining the PM/PV tubes in the direction of the inlet air swirl.

Ignition, altitude relight, and stability. - Ignition, altitude relight, and combustion stability tests were performed during the refinement testing portion of the program. The test points were selected to match existing data points from tests performed on the production combustion system, and to evaluate the extreme corners of the starting and operating envelopes.

Figure 48 shows the results of the lean stability limit tests for Concept 2. Data from both refinement configuration combustors is presented. The results indicate that the stability of both these configurations represents an improvement over the production system.

Figure 49 presents ignition and altitude relight data for the first refinement configuration of Concept 2. Test data indicated that the ignition and altitude relight capability was not as good as the present production system. However, based on the stability results, it was assumed that satisfactory ignition and altitude relight could be achieved with proper placement of the igniter. No ignition tests were performed on the second refinement configuration.

Ignition, altitude relight, and combustion stability were tested on the first refinement combustor of Concept 3. Figure 50 is a plot of these results. The results of these tests indicated that the lean stability limits were superior to the present production system, and that ignition and altitude relight capabilities were marginal. Results were sufficiently close to the program goals to indicate that satisfactory performance could be achieved with normal development efforts.

## Assessment of Emission Results

From the data accumulated during the test phase of the program, it can be concluded that several design approaches have been demonstrated that have shown significant reductions in combustion emission levels. Most of these reductions were attained without major sacrifices to combustor performance, but involved varying degrees of added complexity. An assessment of the emission results of each concept is discussed below.

PARAMETERS:

$V_R$ = REFERENCE VELOCITY, M/SEC

$\theta_3$ = INLET TEMPERATURE, °K/288°K

$\delta_3$ = INLET PRESSURE, KPa/101.4 KPa

○ CONCEPT 2, REFINEMENT 1 (LOW AIRFLOW SWIRLERS)

☐ CONCEPT 2, REFINEMENT 2 (MODIFIED LOW AIRFLOW SWIRLERS)

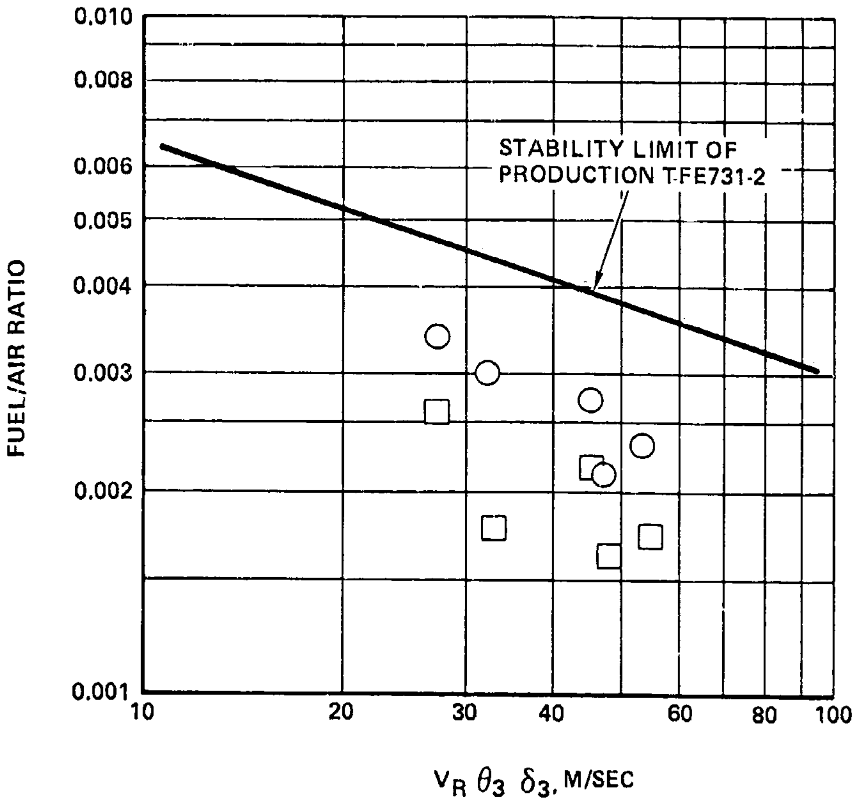


Figure 48. Concept 2 Lean Stability Limits

PARAMETERS:

$V_R$ = REFERENCE VELOCITY, M/SEC
$\theta_3$ = INLET TEMPERATURE, °K/288°K
$\delta_3$ = INLET PRESSURE, KPa/101.4 KPa

○ CONCEPT 2, REFINEMENT 1
(LOW AIRFLOW SWIRLERS)

☐ CONCEPT 2, REFINEMENT 2
(MODIFIED LOW AIRFLOW SWIRLERS)

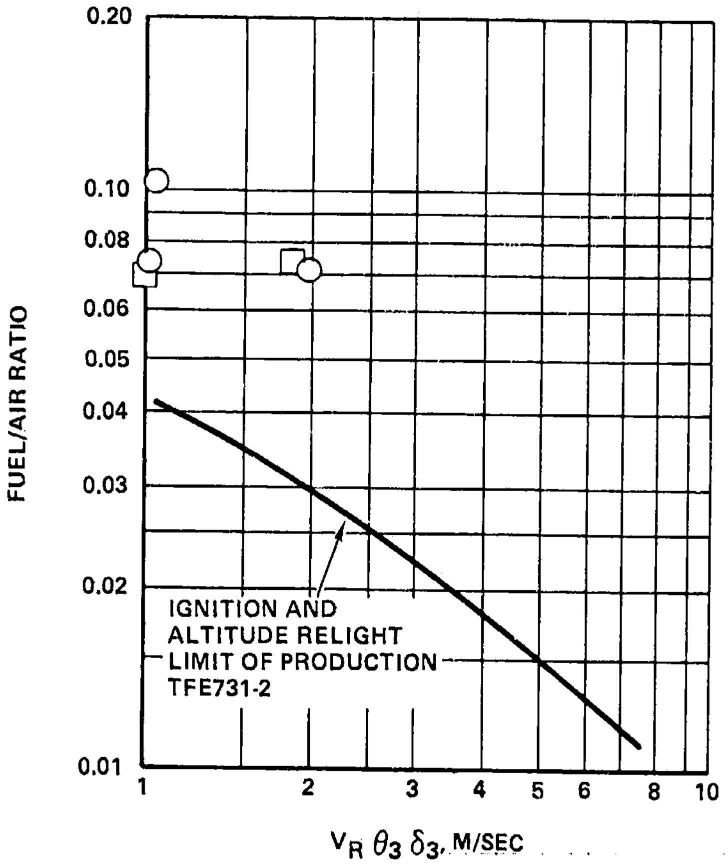


Figure 49. Concept 2 Ignition and Altitude Relight Tests

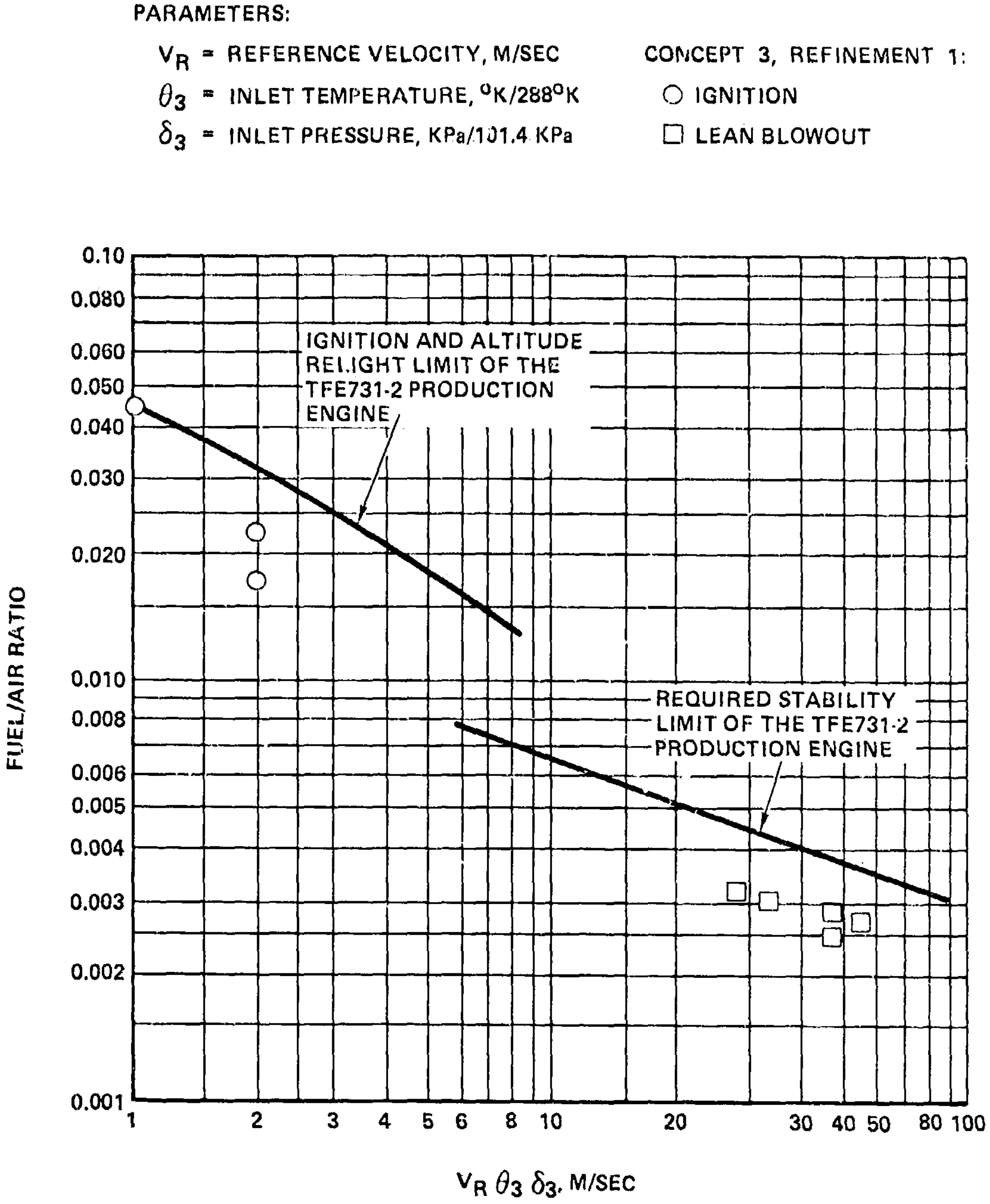


Figure 50. Concept 3 Stability Limits

Concept 1. - Two configurations of Concept 1 demonstrated low taxi-idle emission levels for HC and CO. Both of these systems utilized modifications of the present production combustor and fuel injection system.

The basic configuration of Concept 1 produced HC and CO levels of 0.6 and 30.0 g/kg fuel, respectively. These values were attained with the use of air-assist, wherein air was injected through the secondary fuel circuit of the production duplex fuel nozzles, while fuel flow was maintained through the primary circuit only. In conjunction with air-assist, the system was operated at a 11.5-percent compressor bleed condition. In order to maintain the same power level with the reduced airflow, it was necessary to increase the fuel flow from 359 to 423 kg/hr, an increase of 28.6 kg fuel used during the 26-minute taxi-idle portion of the LTO cycle. These two changes produced:

- Improved fuel atomization as a result of the air-assist, and increased pressure drop across the pressure atomizer
- A richer primary reaction zone.

The combined effect of the two factors was sufficient to reduce the HC and CO levels below the program goals.

Modification 1 also utilized improved atomization and a locally fuel-rich primary zone as a means of reducing the emission levels at taxi-idle. In this configuration, the fuel nozzles were operated in quadrants of three nozzles each. The top and bottom quadrants flowed fuel while the left and right quadrants were shut off with the total fuel flow unchanged. Therefore, the fuel flow per nozzle was doubled, and the atomization was improved as a result of increased pressure drop across the nozzles. The local fuel/air ratio in the two fuel quadrants was also increased with the overall effect of reducing HC and CO levels to 5.6 and 39.7 g/kg fuel, respectively. It should be pointed out that the pattern factor for this configuration was 0.7, which is a factor of three higher than the normal taxi-idle pattern factor; but the peak temperature was still well below the maximum allowable engine stator inlet temperature. However, before this approach could be implemented, the impact of the high-temperature gradient of the discharge gases on the turbine stators would need to be determined.

At the takeoff power setting, the only configuration that met the program goal for $NO_x$ reduction employed water-methanol injection into the combustor primary zone. While this approach did produce low $NO_x$ levels, the associated logistic and aircraft weight penalties that would be present with this technique make it an impractical solution from an application standpoint. The only other approach that offered potential was the use of piloted-airblast injectors, which when used in conjunction with the present production combustor, produced a 25-percent reduction in $NO_x$--approximately half of the required reduction.

Concept 2. - The second refinement test combustor of Concept 2 produced the best overall emission performance of that concept. LTO cycle calculations made for that configuration are presented below together with the program goals.

The LTO cycle EPAP values were calculated by two methods. In the first, HC and CO emission indices were uncorrected for all the LTO power settings. $NO_x$ values were corrected to standard-day humidity conditions, and the climbout and takeoff $NO_x$ levels used a 0.5 pressure exponent to correct measured rig values to engine conditions.

The second method is similar to the first with the following two exceptions:

- HC and CO emission indices at the climbout and takeoff point were corrected as an inverse function of the engine-to-rig combustor inlet pressure ratio
- The climbout and takeoff $NO_x$ values used a 0.29 and 0.35 pressure exponent, respectively, to correct measured rig values to engine conditions.

These pressure exponents were established from rig-to-engine correlation tests on the production TFE731-2 combustion system, which operates with a near-stoichiometric primary zone. Recent data derived from the Clean Combustor Program (Ref. 4), as published by General Electric, indicates that a pressure exponent of 0.35 is realistic for combustors with near-stoichiometric primary zones, but for lean primary zone burners the exponent is closer to 0.5. These two methods of calculation bracket the LTO cycle EPAP values that may be anticipated from the Concept 2 combustion system.

EPAP values for Concept 2, Refinement Test 2 for both methods of correction are compared below.

EPAP, lb/1000 lb thrust-hr/cycle

| Pollutant | Concept 2 Refinement 2 Correction Method 1 | Concept 2 Refinement 2 Correction Method 2 | Program Goals |
|---|---|---|---|
| HC | 0.5 | 0.4 | 1.6 |
| CO | 11.5 | 10.0 | 9.4 |
| $NO_x$ | 3.9 | 3.5 | 3.7 |

This data shows that the configuration produced:

- HC below the program goal
- The $NO_x$ level may be below the program goal depending on the applicable pressure correction exponent
- CO value is slightly above the program goal.

In reference to the CO term, it should be pointed out that engine rig correlation tests performed on production combustion systems consistently produced taxi-idle rig values of CO approximately 1.25 times the measured engine data. In view of the fact that the rig and engine flow conditions at taxi-idle conditions were identical, and the same combustor system hardware was used for both tests, no plausible explanation could be given for the difference, and therefore, the correlation term was not applied. However, the difference was consistent for three engine-rig correlation tests. If the correction term had been applied to the taxi-idle CO term in the LTO calculation, the CO EPAP value would be 8.3, well below the required goal.

The above LTO values were based on the use of changes in swirler goemetry. Test data from all the configurations in Phase I of this concept have demonstrated the need to vary the swirler airflow so as to maintain the reaction zone equivalence ratio for minimum emission levels of both taxi-idle HC and CO, and climbout and takeoff $NO_x$.

Concept 3. - The potential for low emission levels with an axially-staged fuel injection system utilizing premix/prevaporizing (PM/PV) fuel injection was demonstrated with Modification 3, which employed an external PM/PV system. Emissions increased somewhat when the premix system was incorporated within the simulated engine envelope. However, it is expected that with improved fabrication control, the Modification 3 emission levels can be attained with an engine compatible design.

Modification 3 produced LTO cycle EPAP values as shown below. This data is presented in both corrected and uncorrected form similar to the previous presentation of Concept 2 data.

EPAP, lb/1000 lb thrust-hr/cycle

| Pollutant | Concept 3 Modification 3 Correction Method 1 | Concept 3 Modification 3 Correction Method 2 | Program Goals |
|---|---|---|---|
| HC | 0.6 | 0.5 | 1.6 |
| CO | 8.8 | 8.3 | 9.4 |
| $NO_x$ | 2.7 | 2.5 | 3.7 |

This data shows that Modification 3 with the external PM/PV system was well below the program goals for all three pollutants, even when using the first correction method.

For comparative purposes, the LTO cycle EPAP values from the Refinement Test 2 combustor with the internal PM/PV system are shown below. The data for the climbout point was approximated, as this configuration was not tested at the climbout condition.

EPAP, lb/1000 lb thrust-hr/cycle

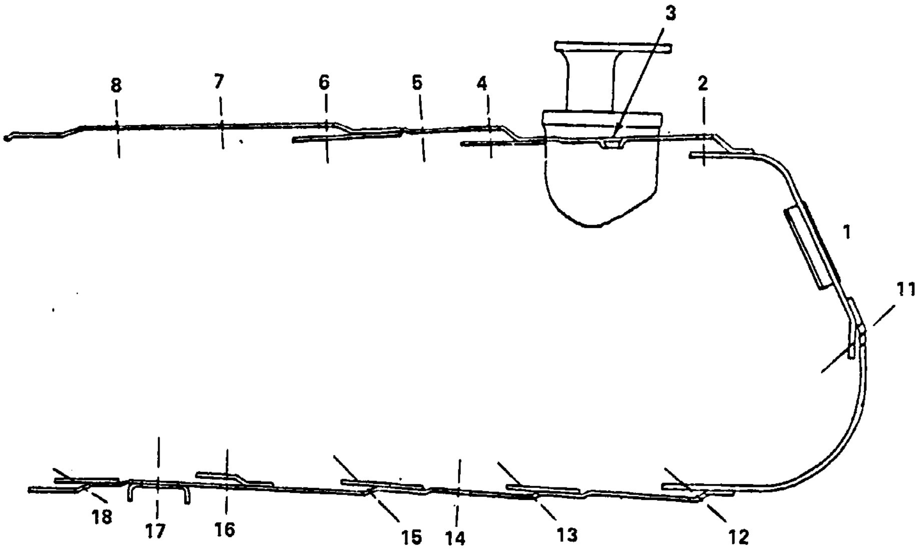
| Pollutant | Concept 3 Refinement 2 Correction Method 1 | Concept 3 Refinement 2 Correction Method 2 | Program Goals |
|---|---|---|---|
| HC | 1.6 | 1.0 | 1.6 |
| CO | 18.0 | 10.9 | 9.4 |
| $NO_x$ | 2.6 | 2.3 | 3.7 |

This data shows that while this configuration meets the HC and $NO_x$ program goals, the CO value is high. This was caused by abnormally high levels of CO produced at the takeoff condition, because of an improper airflow split between the pilot and main combustion region.

The program schedule precluded corrective reworking of the PM/PV annulus. However, the demonstrated emission performance of the Modification 3 combustor is considered to be attainable with a properly fabricated internal PM/PV system. The required emphasis will be placed on the fabrication of this hardware during Phase II of the program to ensure that the PM/PV hardware achieves the desired conformity and size.

# APPENDIX A

# COMBUSTOR HOLE PATTERN



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | 48 louvers | 336 | .279 | 20.60 | 8.9 |
| 2 | Cooling | 255 | .330 | 22.17 | 8.9 |
| 3 | Plunged | 48 | .540 | 11.03 | 4.6 |
| 4 | Cooling | 255 | .330 | 22.17 | 8.0 |
| 5 | Flush | 60 | .710 | 24.01 | 6.1 |
| 6 | Cooling | 376 | .226 | 15.09 | 4.6 |
| 7 | Flush slots | 60 | .989 | 46.10 | 11.2 |
| 8 | Flush | 60 | .710 | 24.01 | 5.3 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .370 | 12.78 | 5.4 |
| 12 | Cooling | 262 | .230 | 11.24 | 3.3 |
| 13 | Cooling | 262 | .230 | 11.24 | 3.5 |
| 14 | Flush | 60 | .530 | 13.41 | 3.1 |
| 15 | Cooling | 262 | .230 | 11.24 | 3.6 |
| 16 | Cooling | 262 | .230 | 11.24 | 3.7 |
| 17 | Flush | 60 | .990 | 45.10 | 12.4 |
| 18 | Cooling | 120 | .307 | 8.90 | 3.4 |

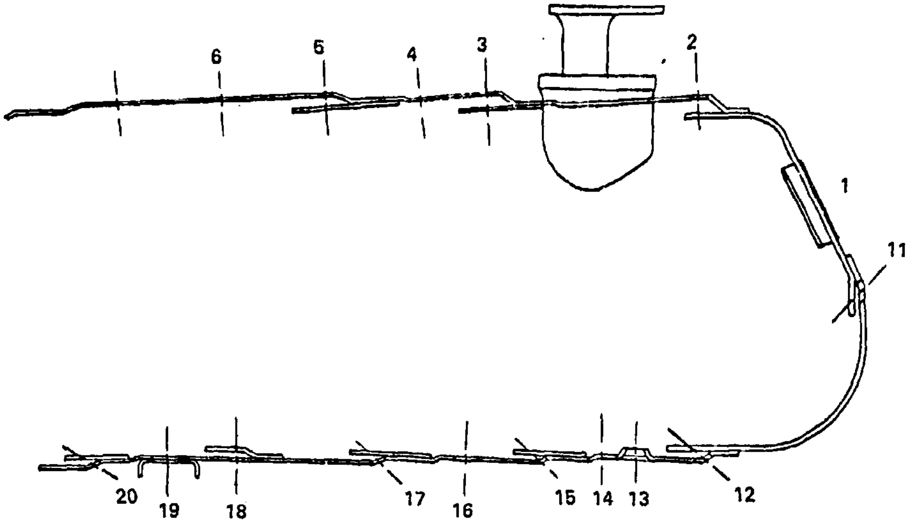
Fuel Nozzles

Basic Configuration and Modification 1: Production pressure atomizing nozzle; air flow = 2.55%.

Modification 2: Pressure atomizing nozzle with nozzle swirler airflow increased 122%. Airflow = 5.3%.

Modification 3: Airblast nozzles. Delavan nozzles airflow = 5.07%. Parker-Hannifin nozzles airflow = [illegible].55%

Figure A-1. Combustor Orifice Pattern, Concept 1, Basic Configuration and Modifications 1, 2, and 3.



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | 48 louvers | 336 | .279 | 20.60 | 8.0 |
| 2 | Cooling | 191 | .333 | 16.61 | 6.4 |
| 3 | Cooling | 191 | .330 | 16.61 | 6.1 |
| 4 | Flush | 60 | .710 | 24.01 | 6.3 |
| 5 | Cooling | 376 | .226 | 15.09 | 4.8 |
| 6 | Flush slots | 30 | .990 | 46.10 | 6.0 |
| 7 | Flush | 30 | .710 | 24.01 | 3.0 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .370 | 12.78 | 5.6 |
| 12 | Cooling | 262 | .230 | 11.24 | 3.0 |
| 13 | Plunged | 60 | .840 | 33.31 | 11.0 |
| 14 | Flush | 60 | .907 | 38.75 | 9.6 |
| 15 | Cooling | 262 | .230 | 11.24 | 3.9 |
| 16 | Flush | 60 | .530 | 13.41 | 3.4 |
| 17 | Cooling | 262 | .230 | 11.24 | 4.0 |
| 18 | Cooling | 262 | .230 | 11.24 | 4.1 |
| 19 | Flush | 30 | .990 | 45.10 | 6.4 |
| 20 | Cooling | 120 | .307 | 8.90 | 3.6 |

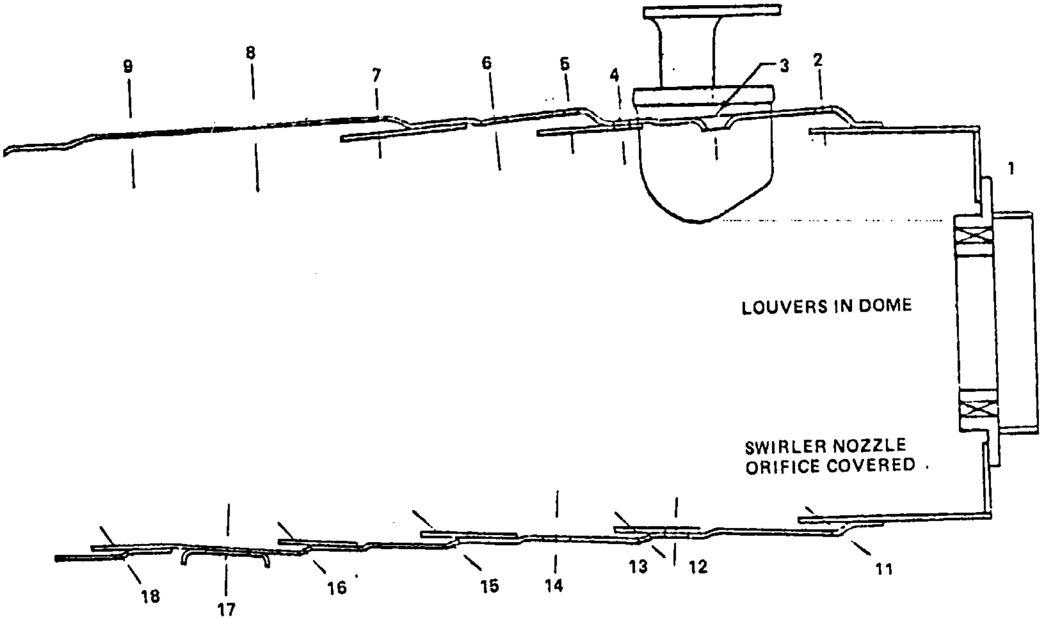
Fuel Nozzles

Production pressure atomizing nozzle: Airflow = 2.5%.
Parker-Hannifin nozzles: Airflow = 2.5%

Modifications: (Refer to Figure A-1).

1. Outer primary orifices removed
2. Outer primary cooling reduced 25%.
3. Two rows of inner primary orifices added.
4. Inner and outer dilution orifices reduced by 50%.

Figure A-2. Combustor Orifice Pattern, Concept 1, Modification 4



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 1 | 12 louvers | 96 | .413 | 12.85 | 6.2 | 5.4 |
| 2 | Cooling | 127 | .333 | 11.04 | 5.2 | 4.5 |
| 3 | Plunged | 48 | .540 | 11.03 | 5.7 | 4.9 |
| 4 | Flush slots | 153 | .518 | 32.26 | 11.8 | 10.2 |
| 5 | Cooling | 191 | .333 | 16.61 | 5.8 | 5.0 |
| 6 | Flush | 60 | .714 | 24.01 | 7.1 | 6.2 |
| 7 | Cooling | 376 | .226 | 15.09 | 5.3 | 4.6 |
| 8 | Flush slots | 30 | .990 | 46.10 | 6.7 | 5.8 |
| 9 | Flush | 30 | .710 | 24.01 | 3.3 | 2.9 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 11 | Cooling | 120 | .370 | 12.78 | 2.7 | 2.3 |
| 12 | Flush slots | 73 | .843 | 40.77 | 11.8 | 10.2 |
| 13 | Cooling | 262 | .234 | 11.24 | 3.6 | 3.1 |
| 14 | Flush | 60 | .530 | 13.41 | 3.1 | 2.7 |
| 15 | Cooling | 262 | .230 | 11.24 | 3.7 | 3.2 |
| 16 | Cooling | 262 | .230 | 11.24 | 3.8 | 3.3 |
| 17 | Flush | 30 | .990 | 45.10 | 6.0 | 5.2 |
| 18 | Cooling | 120 | .307 | 8.90 | 3.4 | 2.9 |

(a) Grommet - Grommet Configuration has no swirler airflow.

(b) Swirler - 12 swirlers: area = 2.48 $cm^2$; airflow = 13.4%

Fuel Nozzles

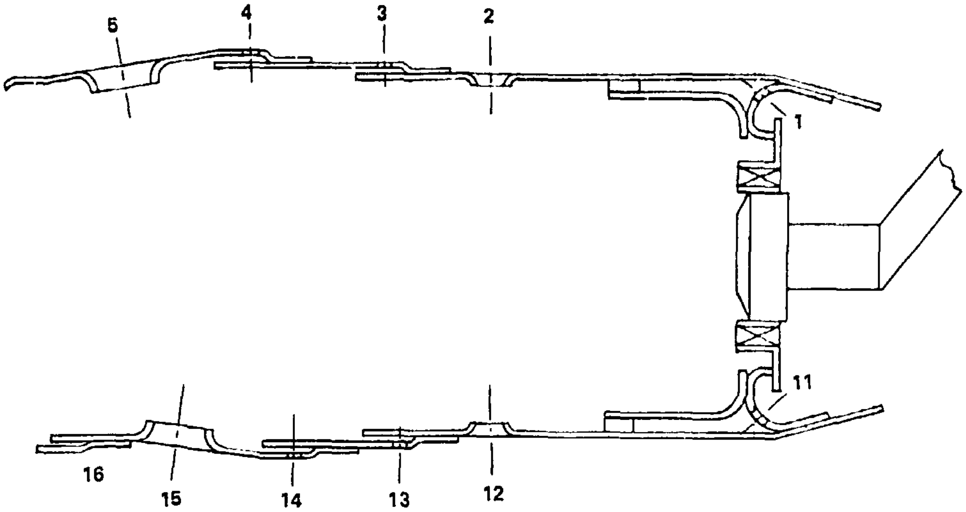
Pressure atomizing nozzles: 57° and 77° down angle; airflow = 3.1% Grommet Configuration, 2.7% Swirler Configuration

Delavan airblast nozzles: Airflow = 5.9% Grommet Configuration, 5.1% Swirler Configuration

Modifications: (Refer to Figure A-1).

1. 12 swirlers added to dome and dome louvers reduced in airflow.
2. Outer primary cooling reduced 50%; outer secondary cooling reduced 25%
3. Slots added to outer and inner primary panels.
4. Outer and inner dilution orifices reduced 50%.

Figure A-3. Combustor Orifice Pattern, Concept 1, Modification 5



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 180 | .445 | 27.93 | 14.6 | 12.8 | 11 | Cooling | 120 | .445 | 18.62 | 9.8 | 8.6 |
| 2 | Plunged | 40 | .540 | 9.19 | 4.8 | 4.2 | 12 | Plunged | 40 | .540 | 9.19 | 4.8 | 4.2 |
| 3 | Cooling | 180 | .290 | 12.06 | 6.3 | 5.5 | 13 | Cooling | 120 | .267 | 6.7 | 3.5 | 3.1 |
| 4 | Cooling | 180 | .240 | 8.23 | 4.3 | 3.8 | 14 | Cooling | 120 | .267 | 6.7 | 3.5 | 3.1 |
| 5 | Plunged | 40 | 1.060 | 35.41 | 18.6 | 16.3 | 15 | Plunged | 40 | 1.060 | 35.41 | 18.6 | 16.3 |
| | | | | | | | 16 | Cooling | 120 | .267 | 6.7 | 3.5 | 3.1 |

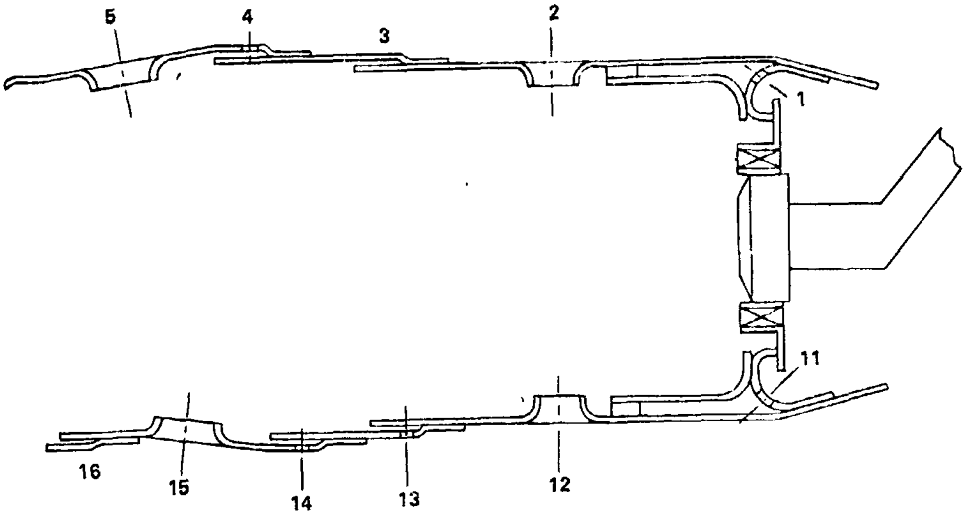
(a) Grommet - Grommet Configuration has no swirler airflow.

(b) Swirler - 20 swirlers: area = 33.55 $cm^2$, percentage airflow = 12.4

Fuel Nozzles

20 air-assisted, airblast nozzles: airflow = 7.7%
Grommet Configuration; 6.7% Swirler Configuration

Figure A-4. Combustor Orifice Pattern, Concept 2, Basic Configuration



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 1 | Cooling | 180 | .445 | 27.93 | 13.2 | 11.7 |
| 2 | Plunged | 40 | .800 | 19.98 | 9.4 | 8.4 |
| 3 | Cooling | 180 | .290 | 12.06 | 5.7 | 5.C |
| 4 | Cooling | 180 | .240 | 8.23 | 3.9 | 3.4 |
| 5 | Plunged | 40 | 1.060 | 35.41 | 16.7 | 14.8 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 11 | Cooling | 120 | .445 | 18.62 | 8.8 | 7.8 |
| 12 | Plunged | 40 | .800 | 19.99 | 9.4 | 8.4 |
| 13 | Cooling | 120 | .267 | 6.7 | 3.2 | 2.8 |
| 14 | Cooling | 120 | .267 | 6.7 | 3.2 | 2.8 |
| 15 | Plunged | 40 | 1.060 | 35.41 | 16.7 | 14.8 |
| 16 | Cooling | 120 | .267 | 6.7 | 3.2 | 2.8 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: Area = 33.55 $cm^2$; percentage airflow = 11.3

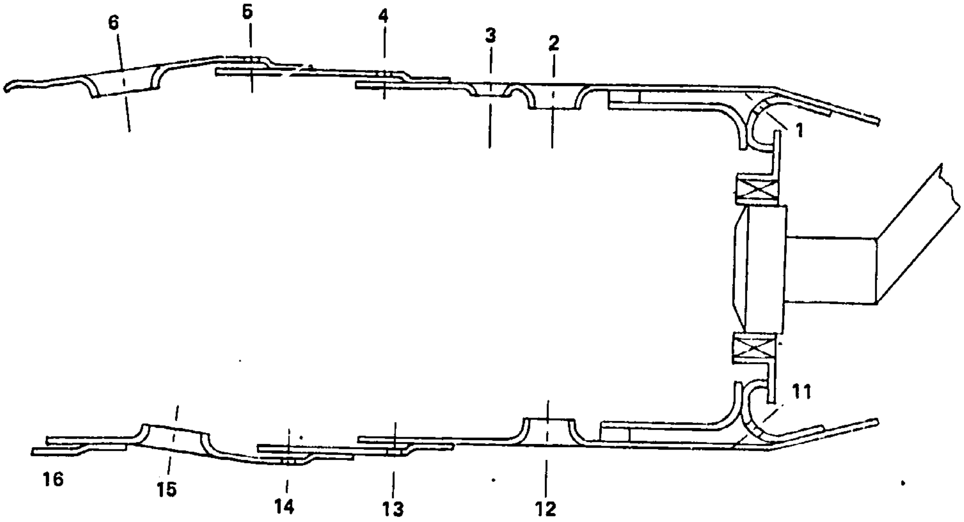
Modifications: (Refer to Figure A-4)

1. Area of O.D. primary holes increased by 54%
2. O.D. primary holes relocated closer to dome at 4.17 cm from dome

Fuel Nozzles

20 air-assisted, airblast nozzles: airflow = 6.9% Grommet Configuration, 6.1% Swirler Configuration

Figure A-5. Combustor Orifice Pattern, Concept 2, Modification 1



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 180 | .445 | 27.93 | 12.1 | 10.3 | 11 | Cooling | 120 | .445 | 18.62 | 8.1 | 6.8 |
| 2 | Plunged | 40 | .800 | 19.98 | 8.7 | 7.3 | 12 | Plunged | 40 | .800 | 19.98 | 8.7 | 7.3 |
| 3 | Plunged | 80 | .540 | 18.32 | 7.9 | 6.7 | 13 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.5 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.2 | 4.4 | 14 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.5 |
| 5 | Cooling | 180 | .240 | 8.23 | 3.6 | 3.0 | 15 | Plunged | 40 | 1.060 | 35.41 | 15.3 | 13.0 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 15.3 | 13.0 | 16 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.5 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: area = 52.0 $cm^2$; percentage airflow = 15.3

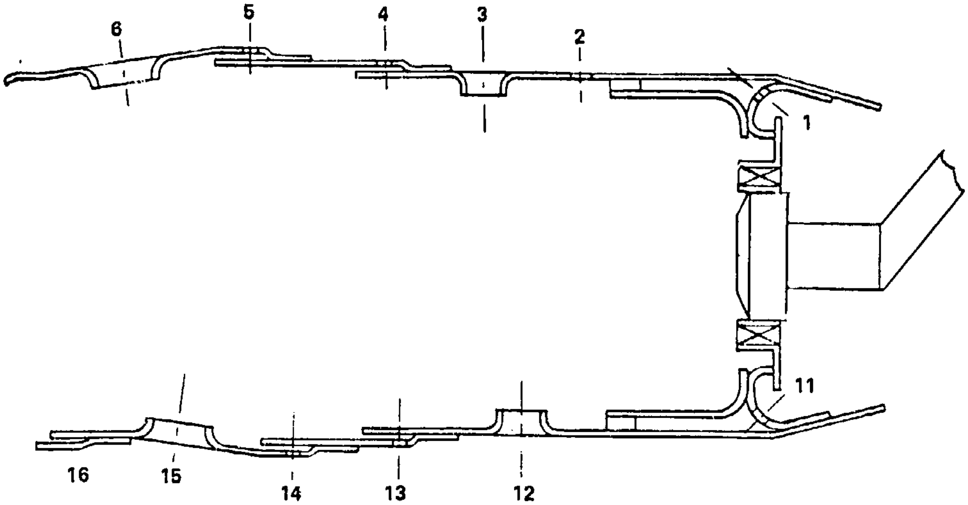
Fuel Nozzle

Percentage airflow with grommets - 6.4
Percentage airflow with swirlers - 5.4

Modifications: (Refer to Modification 1, Figure A-5).

1. 80 O.D. primary orifices added
2. Area of swirlers increased by 50%

Figure A-6. Combustor Orifice Pattern, Concept 2, Modification 2



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 180 | .445 | 27.93 | 12.0 | 10.8 | 11 | Cooling | 120 | .445 | 18.62 | 8.0 | 7.2 |
| 2 | Flush | 160 | .396 | 19.73 | 8.5 | 7.6 | 12 | Plunged | 40 | .800 | 19.98 | 8.6 | 7.7 |
| 3 | Plunged | 40 | .800 | 19.98 | 8.6 | 7.7 | 13 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.2 | 4.7 | 14 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |
| 5 | Cooling | 180 | .240 | 8.23 | 3.5 | 3.2 | 15 | Plunged | 40 | 1.060 | 35.41 | 15.3 | 13.7 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 15.3 | 13.7 | 16 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: area = 33.55 $cm^2$; percentage airflow = 10.4

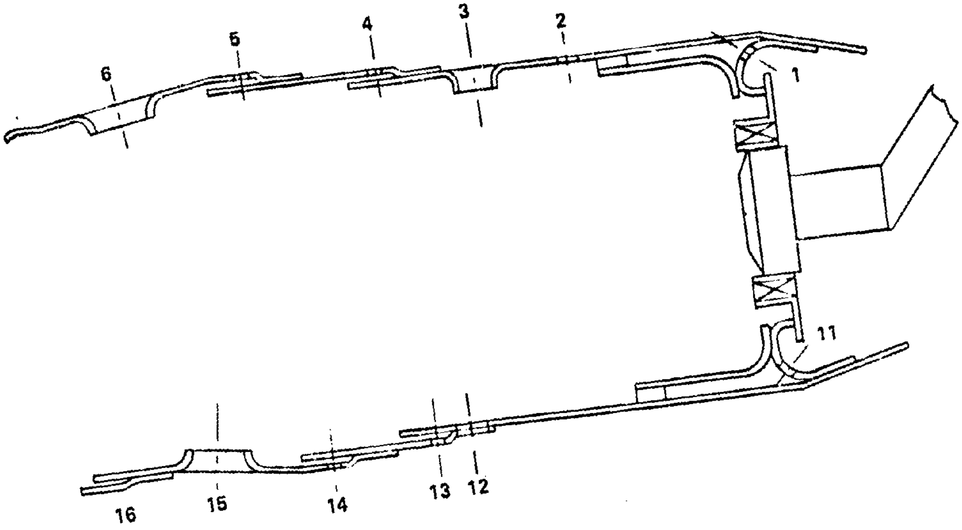
Fuel nozzles

20 air-assisted, airblast nozzles: Airflow =
6.4% Grommet Configuration;
5.7% Swirler Configuration

Modifications (Refer to Modification 2, Figure A-6)

1. O.D.: .798 cm diameter primary orifices relocated away from dome at 5.7 cm from done
2. I.D.: .798 cm diameter orifices relocated away from dome at 4.65 cm from done
3. Row of flush orifices added to O.D. primary

Figure A-7. Combustor Orifice Pattern, Concept 2, Modification 3



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 120 | .445 | 18.62 | 8.6 | 7.6 | 11 | Cooling | 80 | .445 | 12.41 | 5.7 | 5.1 |
| 2 | Flush | 120 | .457 | 19.70 | 9.1 | 8.1 | 12 | Flush | 40 | .800 | 19.98 | 9.2 | 8.2 |
| 3 | Plunged | 40 | .800 | 19.98 | 9.2 | 8.2 | 13 | Cooling | 120 | .267 | 6.7 | 3.1 | 2.7 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.6 | 5.0 | 14 | Cooling | 120 | .267 | 6.7 | 3.1 | 2.7 |
| 5 | Cooling | 180 | .240 | 8.23 | 3.8 | 3.4 | 15 | Plunged | 40 | 1.060 | 35.41 | 16.4 | 14.5 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 16.4 | 14.5 | 16 | Cooling | 120 | .267 | 6.7 | 3.1 | 2.7 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirlers - 20 swirlers Area = 33.55 cm$^2$;
Percentage a.rflow = 11.2

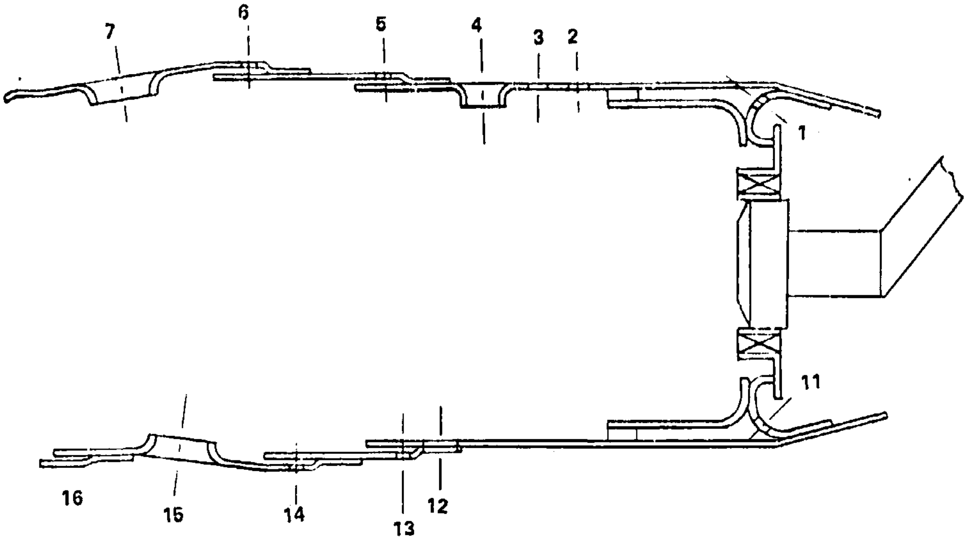
Fuel nozzles

20 air-assisted, airblast nozzles: Airflow = 6.9% Grommet Configuration; 6.1% Swirler Configuration

Modifications: (Refer to Modification 3, Figure A-7)

1. Inner and outer primary cooling reduced by 33%.
2. Flush O.D. primary orifices increased in diameter and relocated closer to dome at 4.4 cm from dome

Figure A-8. Combustor Orifice Pattern, Concept 2, Modification 4 (Reduced Cooling Version)



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 180 | .445 | 27.93 | 11.1 | - | 11 | Cooling | 120 | .445 | 18.62 | 7.4 | - |
| 2 | Flush | 160 | .396 | 19.73 | 7.8 | - | 12 | Flush | 40 | .800 | 19.98 | 7.9 | - |
| 3 | Flush | 120 | .457 | 19.70 | 7.8 | - | 13 | Cooling | 120 | .267 | 6.70 | 2.7 | - |
| 4 | Plunged | 40 | .800 | 19.98 | 7.9 | - | 14 | Cooling | 120 | .267 | 6.70 | 2.7 | - |
| 5 | Cooling | 180 | .290 | 12.06 | 4.8 | - | 15 | Plunged | 40 | 1.060 | 35.41 | 14.1 | - |
| 6 | Cooling | 180 | .240 | 8.23 | 3.3 | - | 16 | Cooling | 120 | .267 | 6.70 | 2.7 | - |
| 7 | Plunged | 40 | 1.060 | 35.41 | 14.1 | - | | | | | | | |

(a) Grommet - Tested only in Grommet Configuration

(b) Swirler - Not applicable

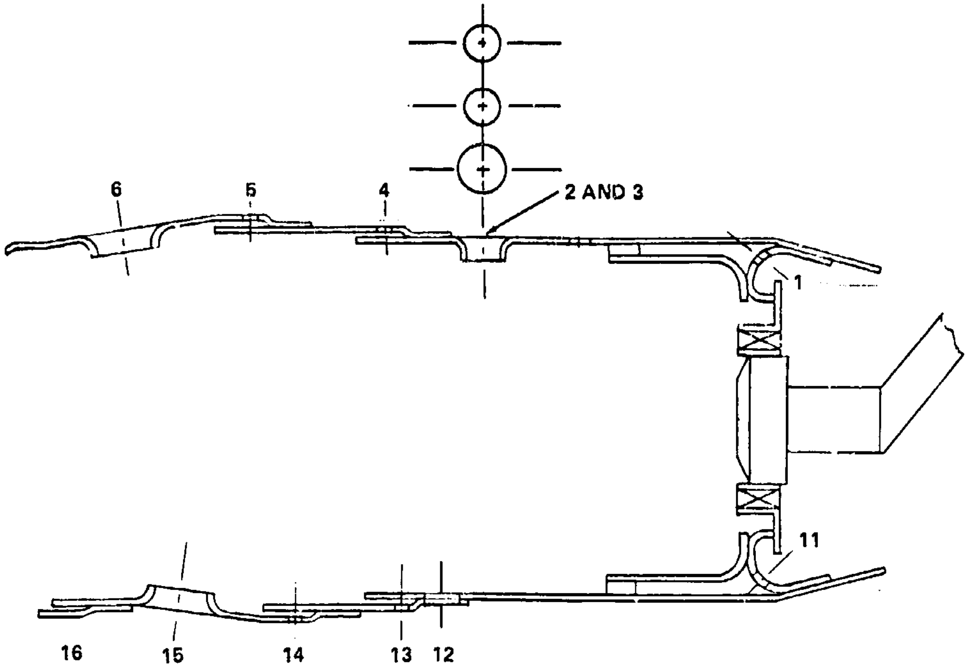
Fuel nozzles

20 air-assisted, airblast nozzles: airflow = 5.8% Grommet Configuration

Modifications: (Refer to Modification 4, Figure A-8)

1. 160 - .396 cm diameter flush orifices added to outer primary panel
2. Inner and outer primary cooling increased 50%

Figure A-9. Combustor Orifice Pattern of Concept 2, Modification 4, (Increased cooling version)



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 180 | .445 | 27.93 | 11.7 | 10.0 | 11 | Cooling | 120 | .445 | 18.62 | 7.8 | 6.7 |
| 2 | Plunged | 40 | .800 | 19.98 | 8.4 | 7.1 | 12 | Flush | 40 | .800 | 19.98 | 8.4 | 7.1 |
| 3 | Plunged | 80 | .635 | 25.34 | 10.7 | 9.1 | 13 | Cooling | 120 | .267 | 6.7 | 2.8 | 2.4 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.1 | 4.3 | 14 | Cooling | 120 | .267 | 6.7 | 2.8 | 2.4 |
| 5 | Cooling | 180 | .240 | 8.23 | 3.5 | 2.9 | 15 | Plunged | 40 | 1.060 | 35.41 | 14.9 | 12.7 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 14.9 | 12.7 | 16 | Cooling | 120 | .267 | 6.7 | 2.8 | 2.4 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: area - 52.4 $cm^2$; percentage airflow = 15.0

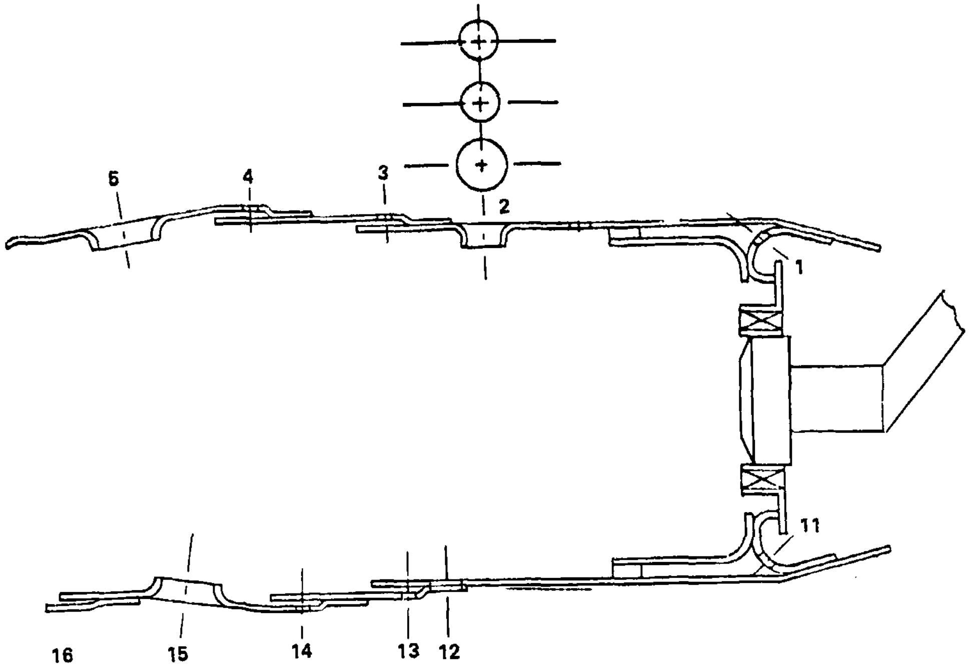
Modifications: (Refer to Modification 4, Figure A-9)

1. Primary orifices all moved to same axial location and 80 - .635 cm orifices added.

Fuel nozzle

20 air-assisted, airblast nozzles: airflow = 6.2% Grommet Configuration; 5.2% Swirler Configuration

Figure A-10. Combustor Orifice Pattern, Concept 2, Modification 5



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 120 | .445 | 18.62 | 8.4 | 7.5 | 11 | Cooling | 80 | .445 | 12.41 | 5.6 | 5.0 |
| 2 | Plunged | 40 | .800 | 19.98 | 9.0 | 8.0 | 12 | Flush | 40 | .800 | 19.98 | 9.0 | 8.0 |
| 3 | Plunged | 80 | .635 | 25.34 | 11.4 | 10.2 | 13 | Cooling | 120 | .267 | 6.70 | 3.0 | 2.7 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.4 | 4.3 | 14 | Cooling | 120 | .267 | 6.70 | 3.0 | 2.7 |
| 5 | Cooling | 180 | .240 | 8.23 | 3.7 | 3.3 | 15 | Plunged | 40 | 1.060 | 35.41 | 15.9 | 14.2 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 15.9 | 14.2 | 16 | Cooling | 120 | .267 | 6.70 | 3.0 | 2.7 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: area = 33.55 $cm^2$, percentage airflow = 10.8

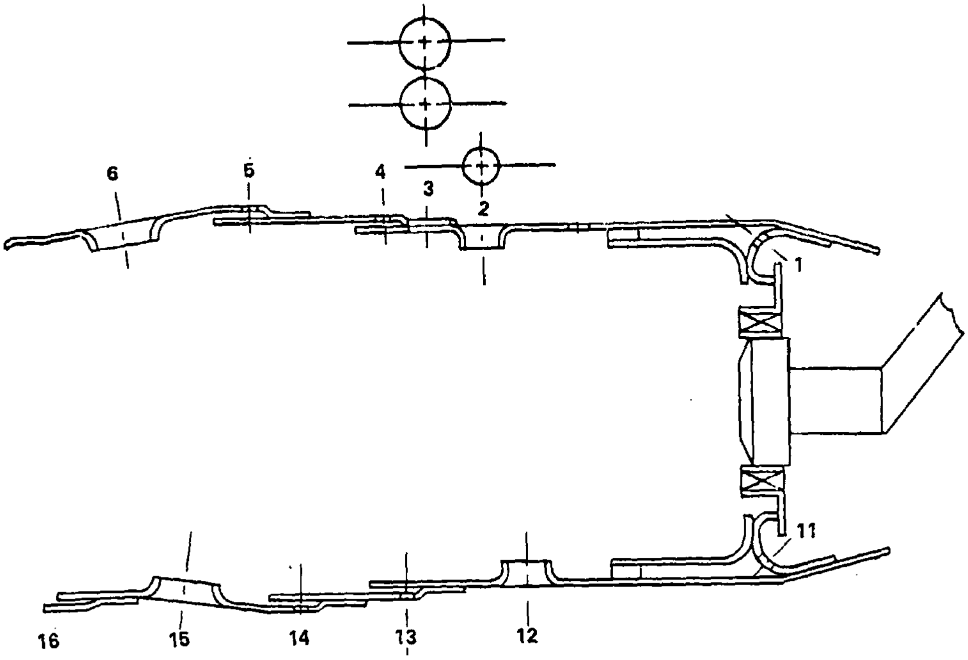
Modifications. (Refer to Modification 5, Figure A-10 (2))

1. Primary inner and outer cooling reduced by 33%

Fuel nozzles

20 air-assisted, airblast nozzles: airflow = 6.6 Grommet Configuration; 5.9% Swirler Configuration

Figure A-11. Combustor Orifice Pattern, Concept 2, Modification 5 (With Reduced Primary Cooling)



| Outside diameter | | | | | | | Inside diameter | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total | Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
| 1 | Cooling | 120 | .445 | 18.62 | 8.1 | 7.3 | 11 | Cooling | 80 | .445 | 12.41 | 5.4 | 4.8 |
| 2 | Plunged | 40 | .635 | 12.67 | 5.5 | 4.9 | 12 | Plunged | 40 | .800 | 19.98 | 8.7 | 7.8 |
| 3 | Flush | 80 | .800 | 39.97 | 17.4 | 15.6 | 13 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |
| 4 | Cooling | 180 | .290 | 12.06 | 5.3 | 4.7 | 14 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |
| 5 | Cooling | 180 | .241 | 8.23 | 3.6 | 3.2 | 15 | Plunged | 40 | 1.060 | 35.41 | 15.4 | 3.8 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 15.4 | 13.8 | 16 | Cooling | 120 | .267 | 6.70 | 2.9 | 2.6 |

(a) Grommet - Grommet Configuration has no swirler airflow

(b) Swirler - 20 swirlers: area = 33.55 $cm^2$, percentage airflow = 10.5

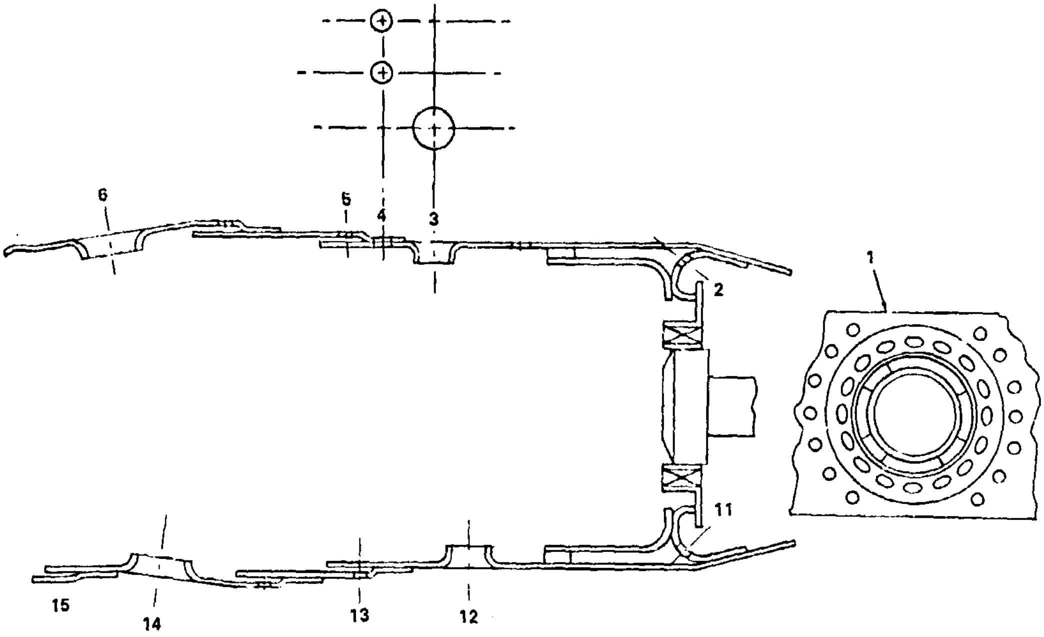
Modifications: (Refer to Modification 5, Figure A-10(b))

1. Primary orifices moved further from dome and made flush
2. Primary inner and outer cooling reduced by 33%

Fuel nozzles

20 air-assisted, airblast nozzles: airflow = 6.4% Grommet Configuration; 5.7% Swirler Configuration

Figure A-12. Combustor Orifice Pattern, Concept 2, Refinement Test 1



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Takeoff air-flow, % total | Taxi-idle air-flow, % total |
|---|---|---|---|---|---|---|
| 1 | Flush | 280 | .357 | 28.05 | 10.1 | - |
| 2 | Cooling | 120 | .445 | 18.62 | 6.7 | 9.3 |
| 3 | Plunged | 40 | .635 | 12.67 | 4.6 | 6.3 |
| 4 | Flush | 80 | .554 | 19.26 | 6.9 | 9.6 |
| 5 | Cooling | 120 | .290 | 8.04 | 2.9 | 4.0 |
| 6 | Plunged | 40 | 1.060 | 35.41 | 12.7 | 17.6 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Takeoff air-flow, % total | Taxi-idle air-flow, % total |
|---|---|---|---|---|---|---|
| 11 | Cooling | 80 | .445 | 12.41 | 4.5 | 6.2 |
| 12 | Plunged | 40 | .800 | 19.98 | 7.2 | 9.9 |
| 13 | Cooling | 80 | .267 | 4.47 | 1.6 | 2.2 |
| 14 | Plunged | 40 | 1.060 | 35.41 | 12.7 | 17.6 |
| 15 | Cooling | 120 | .267 | 6.70 | 2.4 | 3.3 |

(a) Taxi-idle - 20 Concept II Refinement 1 swirlers modified by reducing swirler area by 50%; area = 16.78, percentage airflow = 6.7

(b) Takeoff - 20 Concept II Modification 3 swirlers modified by adding 10 - .318 cm diameter counter-rotating orifices to each swirler: area = 77.74 $cm^2$; percentage airflow = 6.7

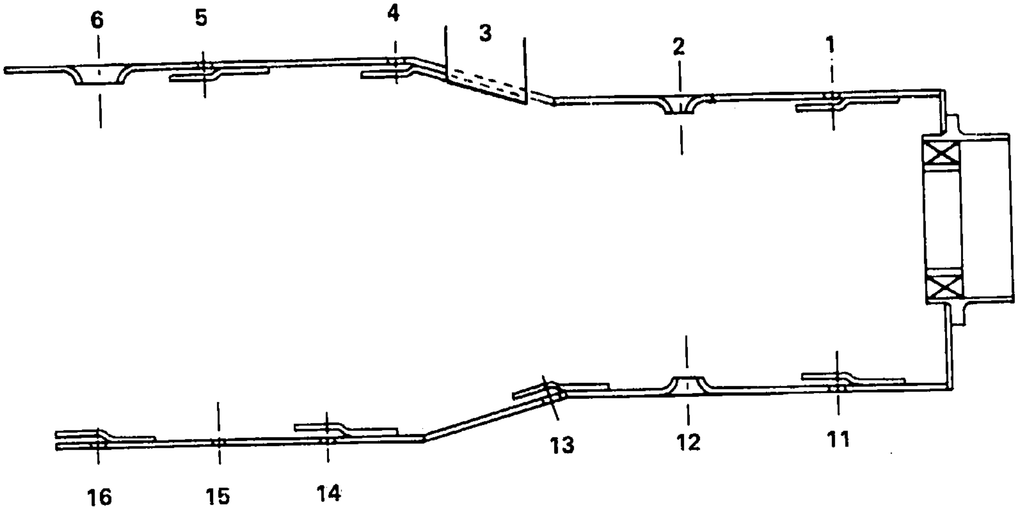
Modifications: (Refer to Refinement Test 1, Figure A-12)

1. 280 orifices added to dome only for takeoff configuration
2. 80 primary flush orifices reduced in diameter
3. Secondary cooling reduced by 33%; Dilution cooling completely blocked

Fuel nozzles

20 air-assisted, airblast nozzles: airflow = 5.3% for takeoff condition; 7.3% for taxi-idle condition

Figure A-13. Combustor Orifice Pattern, Concept 2 Refinement Test 2



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .280 | 11.4 | 3.0 |
| 2 | Plunged | 40 | .376 | 4.4 | 2.1 |
| 3 | Premix air | | | | 24.0 |
| 4 | Cooling | 180 | .284 | 11.4 | 5.5 |
| 5 | Cooling | 180 | .287 | 11.6 | 5.5 |
| 6 | Plunged | 80 | .740 | 34.3 | 16.1 |

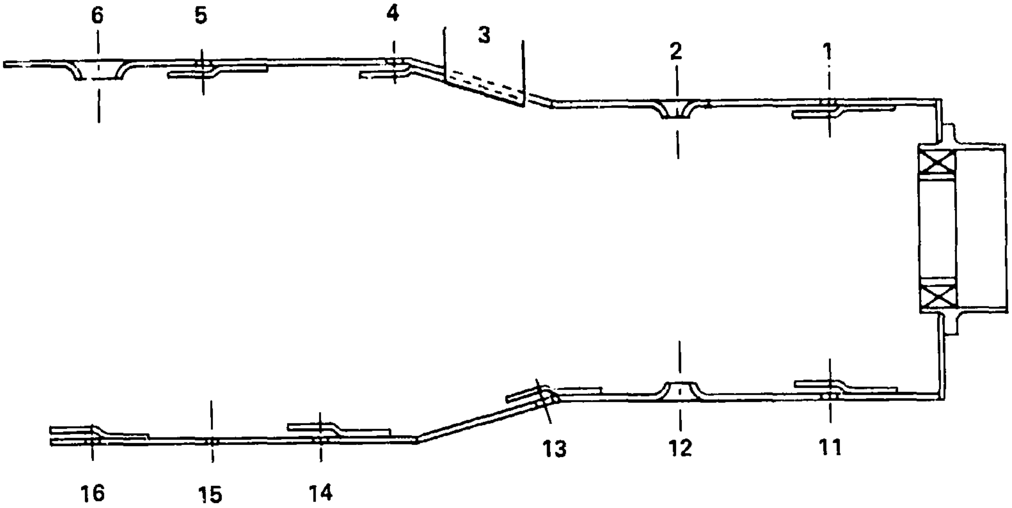
Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .378 | 13.50 | 2.0 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.2 |
| 13 | Cooling | 120 | .360 | 12.40 | 3.2 |
| 14 | Cooling | 120 | .371 | 12.95 | 4.5 |
| 15 | Flush | 80 | .955 | 57.30 | 16.3 |
| 16 | Cooling | 120 | .297 | 8.30 | 3.3 |

Swirlers - 20 swirlers: area = 32.3 $cm^2$; airflow = 6.55%

Pressure atomizing pilot fuel nozzles: Shroud airflow - 3.8%

Figure A-14. Combustor Orifice Pattern, Concept 3, Basic Configuration



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .248 | 8.7 | 3.7 |
| 2 | Plunged | 120 | .376 | 13.3 | 5.9 |
| 3 | Premix air | | | | 24.0 |
| 4 | Cooling | 180 | .284 | 11.4 | 5.0 |
| 5 | Cooling | 180 | .287 | 11.6 | 5.0 |
| 6 | Plunged | 80 | .740 | 34.3 | 14.9 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .309 | 9.00 | 2.7 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.1 |
| 13 | Cooling | 120 | .360 | 12.40 | 2.9 |
| 14 | Cooling | 120 | .370 | 12.95 | 4.2 |
| 15 | Flush | 80 | .955 | 57.30 | [illegible] |
| 16 | Cooling | 120 | .297 | [illegible] | 3.0 |

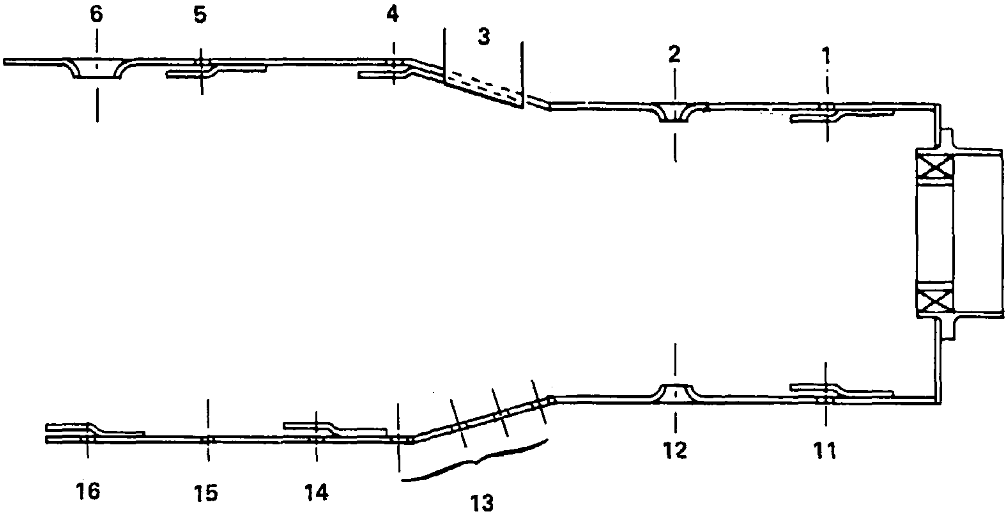
Swirlers - 20 swirlers: area - 32.3 $cm^2$; airflow - 6.05%

Pressure atomizing pilot fuel nozzles: Shroud airflow - 3.5%

Modifications: (Refer to Basic Configuration, Figure A-14)

1. Outer primary cooling reduced 25%, inner primary cooling by 33%
2. Outer primary orifices increased from 40 to 120

Figure A-15. Combustor Orifice Pattern, Concept 3, Modification 1



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .248 | 8.70 | 3.6 |
| 2 | Plunged | 120 | .376 | 13.30 | 5.7 |
| 3 | Premix air | | | | 24.0 |
| 4 | Cooling | 180 | .284 | 11.40 | 4.9 |
| 5 | Cooling | 180 | .287 | 11.60 | 4.9 |
| 6 | Plunged | 80 | .740 | 34.30 | 14.5 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .309 | 9.00 | 2.7 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.1 |
| 13 | Cooling | 480 | .253 | 24.05 | 5.4 |
| 14 | Cooling | 120 | .370 | 12.95 | 4.1 |
| 15 | Flush | 80 | .955 | 57.30 | 14.7 |
| 16 | Cooling | 120 | .297 | 8.30 | 3.0 |

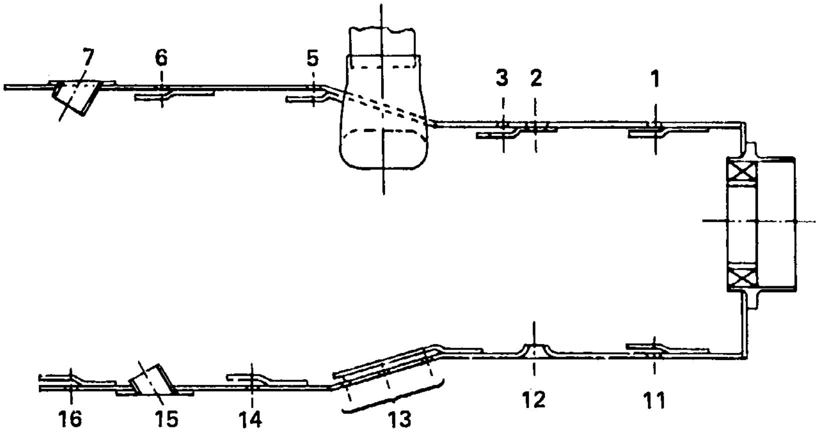
Swirlers - 20 swirlers: area = 32.3 cm$^2$; airflow = 5.9%

Pressure atomizing pilot fuel nozzles: Shroud airflow = 3.4%

Modifications: (Refer to Modification 1, Figure A-15)

1. No. 2 inner cooling skirt removed and three additional rows of cooling added to inner secondary panel

Figure A-16. Combustor Orifice Pattern, Concept 3, Modification 2



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .248 | 8.70 | 3.6 |
| 2 | Plunged | 80 | .376 | 8.90 | 3.8 |
| 3 | Cooling | 180 | .200 | 5.70 | 2.2 |
| 4 | Premix air | | | | 24.0 |
| 5 | Cooling | 180 | .284 | 11.40 | 4.8 |
| 6 | Cooling | 180 | .287 | 11.60 | 4.8 |
| 7 | Tubes | 80 | .762 | 36.50 | 15.3 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .309 | 9.00 | 2.7 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.0 |
| 13 | Cooling | 360 | .253 | 18.05 | 5.7 |
| 14 | Cooling | 120 | .370 | 12.95 | 4.1 |
| 15 | Tubes | 80 | .762 | 36.50 | 13.7 |
| 16 | Cooling | 120 | .297 | 8.30 | 2.9 |

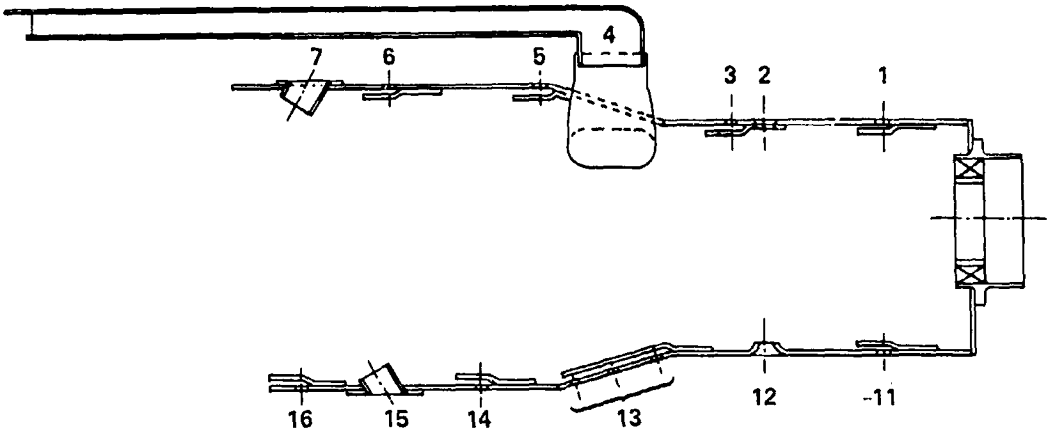
Swirlers - 20 swirlers: area = 32.3 cm$^2$; airflow = 5.85%

Pressure atomizing pilot fuel nozzles: Shroud airflow = 3.35%

Modifications: (Refer to Modification 2, Figure A-16)

1. End of premix tubes is 45° from vertical
2. Outer and inner dilution orifices replaced by tubes
3. Impingement cooled skirt added to inner secondary panel
4. Outer primary orifices reduced to 80
5. Cooling skirt added to outer primary panel

Figure A-17. Combustor Orifice Pattern, Concept 3, Modification 3



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .248 | 8.70 | 4.1 |
| 2 | Plunged | 80 | .376 | 8.90 | 4.4 |
| 3 | Cooling | 180 | .200 | 5.70 | 2.6 |
| 4 | Premix air | | | 73.70 | 19.1 |
| 5 | Cooling | 180 | .284 | 11.40 | 4.7 |
| 6 | Cooling | 180 | .287 | 11.60 | 4.7 |
| 7 | Tubes | 80 | .762 | 36.50 | 14.7 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .309 | 9.00 | 2.9 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.2 |
| 13 | Cooling | 360 | .253 | 18.05 | 6.0 |
| 14 | Cooling | 120 | .370 | 12.95 | 4.3 |
| 15 | Tubes | 80 | .762 | 36.50 | 14.9 |
| 16 | Cooling | 120 | .297 | 8.30 | 3.2 |

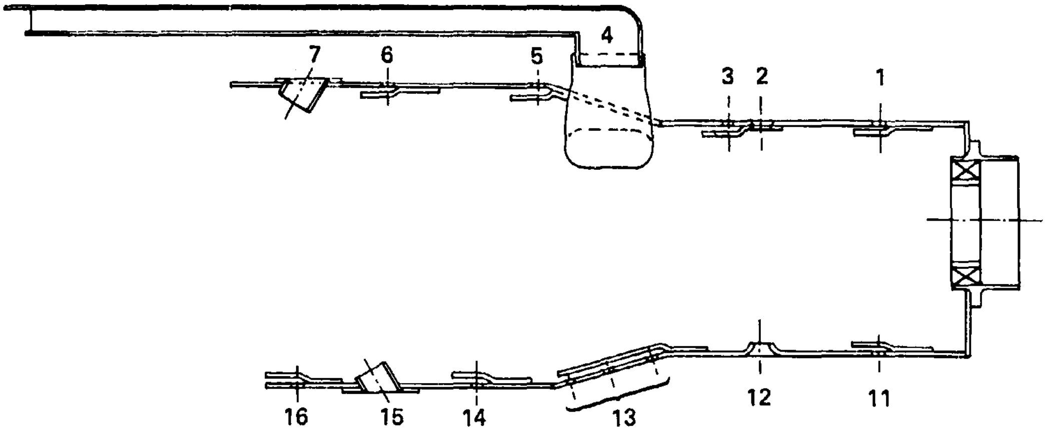
Swirlers - 20 swirlers: area = 32.3 $cm^2$; airflow = 6.8%

Pressure atomizing pilot fuel nozzles: Shroud airflow = 3.9%

Modifications: (Refer to Modification 3, Figure A-17)

1. Internal premix annulus added

Figure A-18. Combustor Orifice Pattern, Concept 3, Modification 4



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Airflow, % |
|---|---|---|---|---|---|
| 1 | Cooling | 180 | .248 | 8.70 | 4.2 |
| 2 | Plunged | 80 | .376 | 8.90 | 4.5 |
| 3 | Cooling | 180 | .200 | 5.70 | 2.7 |
| 4 | Premix air | | | 23.70 | 10.5 |
| 5 | Cooling | 180 | .284 | 11.40 | 4.9 |
| 6 | Cooling | 180 | .287 | 11.60 | 4.9 |
| 7 | Tubes | 80 | .762 | 36.50 | 15.3 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm² | Airflow, % |
|---|---|---|---|---|---|
| 11 | Cooling | 120 | .309 | 9.03 | 3.7 |
| 12 | Plunged | 40 | .440 | 6.10 | [illegible] |
| 13 | Cooling | 360 | .253 | 18.05 | [illegible] |
| 14 | Cooling | 120 | .370 | 12.95 | 4.5 |
| 15 | Tubes | 80 | .762 | 36.50 | 15.3 |
| 16 | Cooling | 120 | .297 | 8.30 | [illegible] |

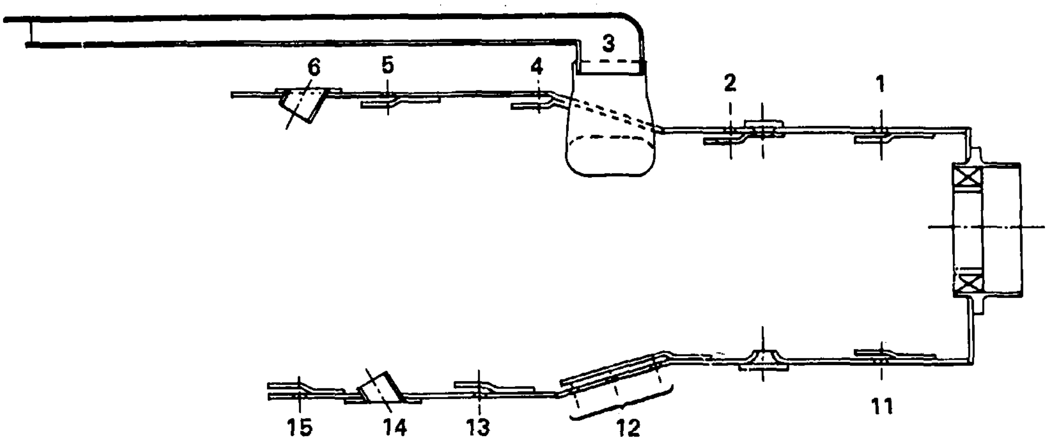
Swirlers - 20 swirlers: Basic configuration with flow area reduced 50%; area 16.1 cm²; airflow [illegible]

Pressure atomizing pilot fuel nozzles: Shroud airflow - 4.0%

Modifications: (Refer to Modification 4, Figure A-16)

1. Swirler area decreased 50%

Figure A-19. Combustor Orifice Pattern, Concept 3, Modification 5



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 90 | .248 | 4.30 | 2.5 |
| 2 | Cooling | 180 | .200 | 5.70 | 3.3 |
| 3 | Premix air | | | 73.70 | 22.7 |
| 4 | Cooling | 180 | .284 | 11.40 | 6.3 |
| 5 | Cooling | 180 | .287 | 11.60 | 6.3 |
| 6 | Tubes | 80 | .762 | 36.50 | 19.9 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 60 | .309 | 4.50 | 2.1 |
| 12 | Cooling | 240 | .253 | 12.05 | 5.8 |
| 13 | Cooling | 120 | .370 | 12.95 | 6.4 |
| 14 | Tubes | 40 | .762 | 18.25 | 9.9 |
| 15 | Cooling | 120 | .297 | 8.30 | 4.4 |

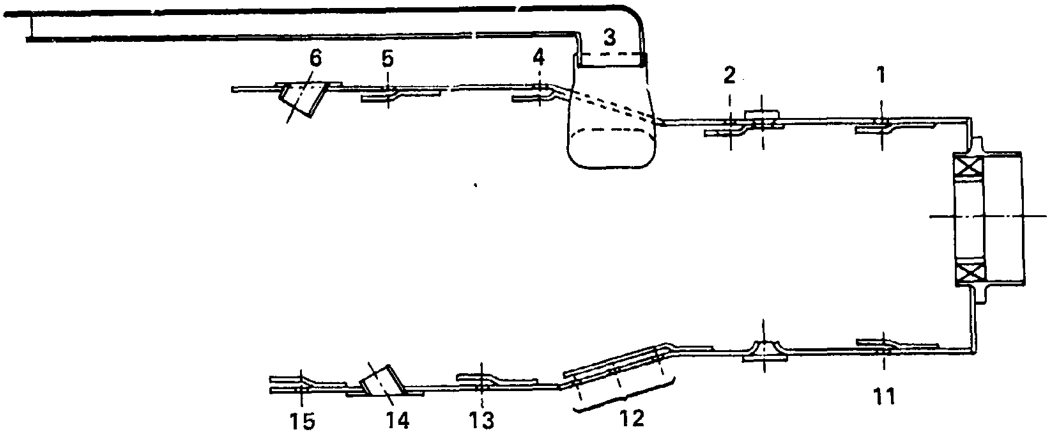
Swirlers - 20 swirlers: Basic Configuration with flow area reduced by 50%; area = 16.1 cm$^2$; airflow 4.1%

Pressure atomizing pilot fuel nozzles: Shroud airflow = 4.7%

Modifications: (Refer to Midification 5, Figure A-19)

1. Outer and inner primary orifices removed
2. Outer and inner primary cooling reduced 50%
3. Inner dilution orifices reduced 50%
4. Middle row of impingement cooled skirt removed

Figure A-20. Combustor Orifice Pattern, Concept 3, Refinement Test 1 (50% swirler area)



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 90 | .248 | 4.30 | 2.5 |
| 2 | Cooling | 180 | .200 | 5.70 | 3.2 |
| 3 | Premix air | | | 73.70 | 22.0 |
| 4 | Cooling | 180 | .284 | 11.40 | 6.0 |
| 5 | Cooling | 180 | .287 | 11.60 | 6.0 |
| 6 | Tubes | 80 | .762 | 36.50 | 19.0 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 60 | .309 | 4.50 | 2.0 |
| 12 | Cooling | 240 | .253 | 12.05 | 5.5 |
| 13 | Cooling | 120 | .370 | 12.95 | 6.1 |
| 14 | Tubes | 40 | .762 | 18.25 | 9.5 |
| 15 | Cooling | 120 | .297 | 8.30 | 4.2 |

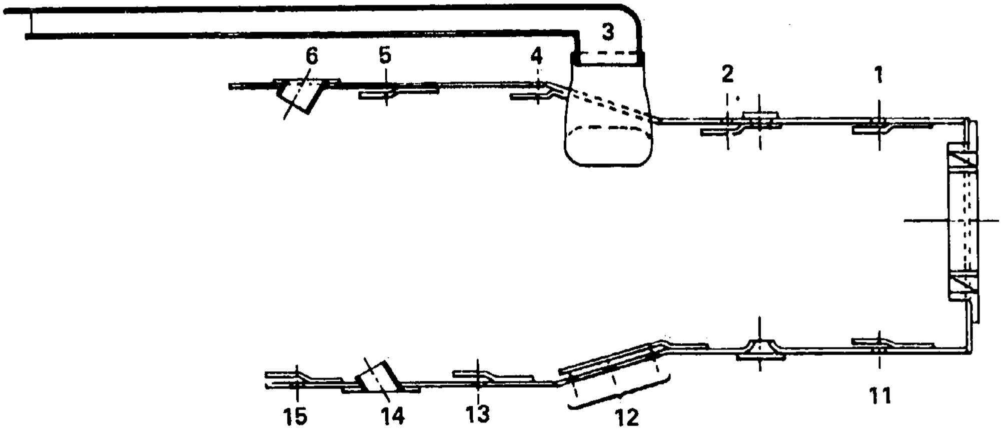
Swirlers - 20 swirlers: area = 32.3 cm$^2$; airflow = 8.0%

Pressure atomizing pilot fuel nozzles: Shroud airflow = 4.6%

Modifications: (Refer to Refinement Test 1, Figure A-20)

1. Swirler restored to full flow area

Figure A-21. Combustor Orifice Pattern, Concept 3, Refinement Test 1 (Full swirler area)



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 1 | Cooling | 90 | .248 | 4.30 | 2.5 |
| 2 | Cooling | 180 | .200 | 5.70 | 3.2 |
| 3 | Premix air | | | 73.70 | 22.1 |
| 4 | Cooling | 180 | .284 | 11.40 | 6.0 |
| 5 | Cooling | 180 | .287 | 11.60 | 6.0 |
| 6 | Cooling | 80 | .762 | 36.50 | 19.1 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, cm$^2$ | Airflow, % total |
|---|---|---|---|---|---|
| 11 | Cooling | 60 | .309 | 4.50 | 2.0 |
| 12 | Cooling | 240 | .253 | 12.05 | 5.6 |
| 13 | Cooling | 120 | .370 | 12.95 | 6.1 |
| 14 | Tubes | 40 | .762 | 18.25 | 9.6 |
| 15 | Cooling | 120 | .297 | 8.3 | 4.2 |

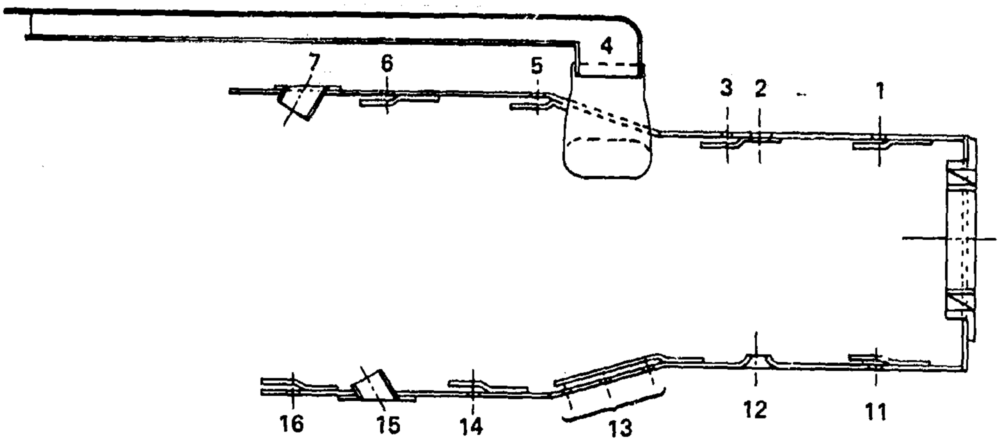
Swirlers = 20 swirlers: Basic Configuration with area reduced 50%; area = 27.7 cm$^2$; airflow = 5.7%.

Delavan airblast pilot fuel nozzles: Shroud airflow = 6.5%.

Modifications: (Refer to Refinement Test 1, Figure A-19)

1. Swirler airflow increased and pilot nozzles replaced by airblast nozzles.

Figure A-22. Combustor Orifice Pattern, Concept 3, Refinement Test 2 (50% swirler area)



Outside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 1 | Cooling | 90 | .248 | 4.30 | 2.4 | 2.3 |
| 2 | Plunged | 80 | .376 | 8.90 | 5.3 | 5.0 |
| 3 | Cooling | 180 | .200 | 5.70 | 3.1 | 3.0 |
| 4 | Premix air | | | 73.70 | 21.7 | 20.9 |
| 5 | Cooling | 180 | .284 | 11.40 | 5.9 | 5.5 |
| 6 | Cooling | 180 | .287 | 11.60 | 5.9 | 5.5 |
| 7 | Cooling | 80 | .762 | 36.50 | 18.5 | 17.3 |

Inside diameter

| Row number | Type of orifice | Number of orifices | Diameter, cm | Total area, $cm^2$ | Grommet air-flow, % total | Swirler air-flow, % total |
|---|---|---|---|---|---|---|
| 11 | Cooling | 60 | .309 | 4.50 | 2.0 | 1.8 |
| 12 | Plunged | 40 | .440 | 6.10 | 2.9 | 2.7 |
| 13 | Cooling | 240 | .253 | 12.05 | 5.4 | 5.0 |
| 14 | Cooling | 120 | .370 | 12.95 | 5.9 | 5.5 |
| 15 | Tubes | 40 | .762 | 18.25 | 9.3 | 8.7 |
| 16 | Cooling | 120 | .297 | 8.30 | 4.1 | 3.8 |

(a) Grommet - Grommet Configuration has no swirler airflow.

(b) Swirler - 20 swirlers: Basic Configuration with area reduced 50%; area = 27.7 $cm^2$; airflow = 5.4%

Modification: (Refer to Refinement Test 2, Figure A-..)

1. Outer and inner primary orifices added

Fuel nozzles

Delavan airblast pilot fuel nozzles: airflow, 6.4% Grommet Configuration; 6.1% Swirler Configuration

Figure A-23. Combustor Orifice Pattern, Concept 3, Refinement Test 2

# APPENDIX B

# EXPERIMENTAL TEST RESULTS

# TEST RESULTS FOR CONCEPT 1

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Simulated bleed airflow, kg/sec | Water flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | BASIC CONFIGURATION | | | | | | | | | | | |
| A-1 | 2 | 2.327 | - | - | - | .02220 | 367.06 | 1.95 | 7.796 | .422 | .61 | .00950 | .0114 | 2.24 | 57.88 | 17.31 | 2.79 | 97.12 | - | No Bleed | Taxi-Idle |
| | 3 | 2.191 | - | .1342 | - | .02472 | 366.72 | 1.98 | 7.306 | .322 | .61 | .01128 | .0118 | 2.32 | 51.98 | 18.17 | 2.69 | 97.18 | - | 5% Bleed | |
| | 4 | 2.082 | - | .2430 | - | .02645 | 366.17 | 1.97 | 6.940 | .284 | .61 | .01270 | .0133 | 2.64 | 45.10 | 15.12 | 2.91 | 98.05 | - | 10% Bleed | |
| | 6 | 1.792 | - | .5337 | - | .03110 | 367.28 | 1.97 | 6.011 | .188 | .61 | .01736 | .0187 | 3.74 | 31.32 | 4.17 | 3.26 | 98.96 | - | 20% Bleed | |
| | 2 | 2.313 | - | - | - | .02206 | 366.50 | 1.98 | 7.685 | .285 | .52 | .00954 | .0100 | 1.95 | 59.62 | 23.87 | 2.20 | 96.50 | - | | Taxi-Idle |
| | 12 | 2.321 | .00201 | - | - | .02206 | 366.50 | 1.97 | 7.748 | .117 | .52 | .00951 | .0100 | 2.00 | 48.48 | 11.58 | 2.83 | 97.84 | - | 110 kPa AA | |
| | 13 | 2.328 | .00396 | - | - | .02206 | 365.40 | 1.98 | 7.724 | .124 | .52 | .00940 | .0100 | 2.00 | 42.23 | 5.12 | [illegible] | 98.56 | - | [illegible] kPa AA | |
| | 15 | 2.200 | .00392 | .1265 | - | .02206 | 365.40 | 1.98 | 7.315 | .151 | .52 | .01000 | .0105 | 2.11 | 38.28 | 4.32 | 3.09 | 98.72 | - | 5% Bleed | |
| | 14 | 2.311 | .00606 | - | - | .02200 | 370.06 | 1.96 | 7.842 | .221 | .50 | .00955 | .0099 | 1.98 | 39.65 | 2.67 | 3.55 | 98.83 | - | 544 kPa AA | |
| | 16 | 2.191 | .00604 | .1285 | - | .02470 | 368.17 | 1.97 | 7.370 | .254 | .50 | .01128 | .0116 | 2.34 | 31.09 | 1.43 | 3.51 | 98.14 | - | 5% Bleed, 544 kPa AA | |
| | 17 | 2.085 | .00396 | .2394 | - | .02206 | 366.50 | 1.98 | 6.940 | .162 | .52 | .01068 | .0112 | 2.25 | 36.35 | 3.34 | 3.27 | 98.85 | - | 236 kPa AA, 10% Bleed | |
| | 18 | 2.057 | .00600 | .2658 | - | .02640 | 368.19 | 1.96 | 6.952 | .171 | .50 | .01286 | .0133 | 2.68 | 29.77 | 0.62 | 3.67 | 98.24 | - | 11% Bleed, 544 kPa AA | |
| | 7 | 4.061 | - | - | 0 | .06260 | 665.22 | 4.18 | 11.674 | .077 | .61 | .01540 | .0155 | 3.17 | 4.51 | 0.16 | 11.56 | 98.88 | 14 | No $H_2O$ injection | Takeoff |
| | 8 | 4.048 | - | - | .0211 | .06350 | 671.33 | 4.18 | 11.765 | .087 | .61 | .01568 | .0175 | 3.56 | 7.76 | 0.14 | 8.77 | 98.80 | - | 33% $H_2O$ injection | |
| | 9 | 4.067 | - | - | .0444 | .06440 | 666.33 | 4.18 | 11.735 | .076 | .61 | .01583 | .0176 | 3.57 | 11.97 | 0.27 | 6.71 | 98.68 | 15 | 67% $H_2O$ injection | |
| | 10 | 4.059 | - | - | .0661 | .06520 | 666.33 | 4.18 | 11.674 | .062 | .52 | .01606 | .0187 | 3.78 | 13.67 | 0.40 | 4.93 | 98.70 | 16 | 100% $H_2O$ injection | |
| | | | | | | | | | | | Modification 1 | | | | | | | | | | |
| A-1 | 2 | 2.325 | - | - | - | .02207 | 365.61 | 1.97 | 9.680 | .708 | .70 | .00950 | .0097 | 1.95 | 39.66 | 5.59 | 3.26 | 98.58 | - | Taxi-Idle | |
| | | | | | | | | | | | Modification 2 | | | | | | | | | | |
| A-1 | 4 | 2.311 | - | - | - | .02207 | 365.94 | 1.96 | 11.485 | - | .70 | .00960 | .0095 | 1.84 | 60.11 | 34.35 | 2.67 | 95.57 | - | Taxi-Idle | |
| | 5 | 4.056 | - | - | - | .06256 | 668.33 | 4.18 | [illegible] | .097 | .70 | .01540 | .0165 | 3.35 | 11.22 | .05 | 11.89 | 99.73 | 13 | Takeoff | |

# TEST RESULTS FOR CONCEPT 1 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Simulated bleed airflow, kg/sec | Water flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Modification 3<br>Delavan airblast nozzles | | | | | | | | | |
| A-1 | 2 | 2.309 | - | - | - | .02233 | 365.78 | 1.99 | 7.632 | .333 | .34 | .00956 | [illegible] | 1.40 | [illegible] | [illegible] | 2.81 | 95.11 | - | Primary + secondary fuel | Taxi-idle |
| | 2 | 2.312 | - | - | - | .02233 | 366.83 | 1.97 | [illegible] | [illegible] | .47 | .00960 | [illegible] | [illegible] | 54.31 | [illegible] | 3.06 | 96.95 | - | Primary fuel only | |
| | 3 | 2.317 | .01349 | - | - | .02233 | 365.22 | 1.99 | 7.718 | .384 | .47 | .00960 | [illegible] | [illegible] | [illegible] | 15.93 | [illegible] | 97.41 | - | [illegible] | |
| | 3 | 2.314 | .01733 | - | - | .02233 | [illegible] | 1.98 | 7.765 | .362 | .47 | .00960 | .00983 | [illegible] | [illegible] | 14.37 | 2.74 | [illegible] | - | [illegible] kPa AA 3[illegible] K | |
| | 3 | 2.324 | .02372 | - | - | .02233 | 367.44 | 1.97 | 7.765 | .344 | .47 | .00960 | .00960 | 1.91 | 46.37 | 13.37 | [illegible] | [illegible] | - | [illegible] kPa AA 394 K | |
| | 12 | 4.049 | - | - | - | .04763 | 663.00 | 4.17 | 11.625 | - | .34 | .01180 | [illegible] | 2.57 | 4.87 | 4 | 10.75 | [illegible] | - | f/a = .012 | Takeoff - reduced $W_f$ |
| | | 4.549 | - | - | - | .05556 | 663.00 | 4.17 | 11.625 | - | .36 | .01375 | .01453 | 2.95 | 4.77 | [illegible] | 10.46 | 99.89 | - | f/a = .014 | |
| | 13 | 4.049 | - | - | - | .06237 | 663.00 | 4.17 | 11.625 | - | .34 | .01540 | [illegible] | [illegible] | 3.77 | [illegible] | 10.37 | 99.91 | 16 | Takeoff | |
| | 10 | 4.033 | - | - | - | .02391 | 660.22 | 4.17 | [illegible] | - | .47 | [illegible] | .00650 | 1.36 | 6.56 | [illegible] | 9.29 | 99.75 | - | [illegible] | Takeoff - reduced $W_f$ |
| | 11 | 4.036 | - | - | - | .03576 | [illegible] | 4.19 | 11.543 | - | .47 | [illegible] | [illegible] | 1.92 | 4.89 | [illegible] | 11.41 | 99.97 | - | [illegible] | |
| | 12 | 4.039 | - | - | - | .04827 | [illegible] | 4.19 | 11.543 | - | .47 | [illegible] | .01250 | 2.56 | 4.74 | [illegible] | [illegible] | 99.99 | - | f/a = .012 | |
| | 13 | 4.044 | - | - | - | .06275 | 662.20 | 4.19 | 11.565 | - | .47 | [illegible] | [illegible] | 3.32 | [illegible] | [illegible] | [illegible] | 99.90 | - | Primary + secondary fuel | Takeoff |
| | 13 | 4.051 | - | - | - | .06275 | 661.92 | 4.19 | 11.592 | .136 | .47 | .01550 | [illegible] | 3.44 | [illegible] | [illegible] | 9.69 | 99.88 | - | Secondary fuel only | |
| | | | | | | | | | | | | Modification 3<br>Parker-Hannifin airblast nozzles | | | | | | | | | |
| A-1 | 10 | [illegible] | 0 | 0 | 0 | [illegible] | [illegible] | [illegible] | [illegible] | - | .40 | [illegible] | [illegible] | 1.35 | 11.14 | [illegible] | [illegible] | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | 11 | 4.044 | 0 | 0 | 0 | [illegible] | [illegible] | 4.17 | 11.567 | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | 12 | 4.047 | 0 | 0 | 0 | [illegible] | [illegible] | 4.17 | 11.576 | - | [illegible] | [illegible] | [illegible] | [illegible] | 5.91 | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | 14 | 4.359 | 0 | 0 | 0 | [illegible] | [illegible] | 4.14 | 11.832 | [illegible] | [illegible] | [illegible] | [illegible] | 1.33 | 4.55 | [illegible] | [illegible] | 99.87 | 21 | | Takeoff |
| | 15 | [illegible] | .00155 | - | 0 | .06265 | [illegible] | 4.14 | [illegible] | [illegible] | [illegible] | .01540 | [illegible] | 3.34 | 4.67 | [illegible] | 5.61 | [illegible] | 16.5 | All fuel through secondaries, 7.3 kPa AA through primaries | |
| | 5 | 2.313 | 0 | 0 | 0 | .02234 | [illegible] | 1.97 | 7.727 | .423 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 96.15 | - | | Taxi-idle |
| | 6 | 2.313 | 0 | 0 | 0 | .02234 | [illegible] | 1.97 | 7.727 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 97.34 | - | Primary only | |
| | 7 | 2.322 | .00990 | 0 | 0 | .02234 | 365.4[illegible] | 1.97 | 7.754 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA [illegible] K | |
| | 8 | [illegible] | [illegible] | 0 | 0 | [illegible] | [illegible] | 1.97 | 7.779 | [illegible] | [illegible] | [illegible] | [illegible] | 1.95 | [illegible] | [illegible] | 3.06 | 98.13 | - | [illegible] kPa AA [illegible] K | |
| | 9 | 2.319 | [illegible] | 0 | 0 | .02234 | 365.4[illegible] | 1.97 | 7.733 | .346 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 14.76 | [illegible] | [illegible] | - | [illegible] kPa AA [illegible] K | |

# TEST RESULTS FOR CONCEPT 1 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Simulated bleed airflow, kg/sec | Water flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Modification 4<br>Pressure atomizing nozzles | | | | | | | | | | |
| A-2 | 2 | 2.717 | - | - | - | .02180 | 368.17 | 2.06 | 8.714 | - | .45 | .00800 | .00970 | 1.78 | 135.47 | 46.72 | 1.94 | 92.71 | - | Taxi-Idle | |
| | 4 | 4.080 | - | - | - | .06260 | 665.20 | 4.29 | 11.299 | - | .45 | .01530 | .01700 | 3.45 | 11.49 | .16 | 8.32 | [illegible] | - | Takeoff | |
| | | | | | | | | | | | Modification 4<br>Parker-Hannifin airblast nozzles | | | | | | | | | | |
| A-2 | 13 | 4.048 | - | - | - | .06242 | 669.40 | 4.30 | 11.308 | - | .45 | .01540 | .01680 | 3.42 | 8.39 | .05 | 7.39 | 99.80 | - | Takeoff | |
| | 14 | 4.049 | .00308 | - | - | .06268 | 669.40 | 4.30 | 11.308 | .136 | .45 | .01550 | .01650 | 3.35 | 9.07 | .01 | 7.39 | 99.79 | 43 | Takeoff, 1595 kPa AA through primaries | |
| | | | | | | | | | | | Modification 5<br>Delavan airblast nozzles and swirlers | | | | | | | | | | |
| A-3 | 1 | 2.288 | - | - | - | .02234 | 367.40 | 1.96 | 7.864 | .503 | .50 | .00976 | .00999 | 1.77 | 122.29 | 79.28 | 1.69 | 90.17 | - | | Taxi-Idle |
| | 2 | 2.307 | - | - | - | .02234 | 366.90 | 1.96 | 7.833 | - | .50 | .00968 | .00970 | 1.74 | 123.79 | 67.44 | 2.15 | 91.17 | - | Primaries only | |
| | 3 | 2.299 | .00932 | - | - | .02234 | 365.20 | 1.96 | 7.894 | - | .50 | .00972 | .00960 | 1.81 | 75.29 | 37.22 | 2.14 | 94.96 | - | 873 kPa AA | |
| | 4 | 2.312 | .01631 | - | - | .02221 | 373.30 | 1.96 | 7.864 | - | .50 | .00960 | .00970 | 1.89 | 66.93 | 21.81 | 2.13 | 96.51 | - | 1625 kPa AA | |
| | 5A | 2.060 | - | - | - | .02650 | 367.70 | 1.90 | 7.132 | - | .50 | .01286 | .01310 | 2.55 | 62.18 | 19.22 | 2.77 | 96.85 | - | 10% Bleed | |
| | 5B | 2.076 | .01609 | - | - | .02650 | 366.30 | 1.91 | 7.132 | - | .50 | .01276 | .01280 | 2.56 | 48.89 | 4.32 | 2.90 | 98.47 | - | 10% Bleed, 1630 kPa AA | Taxi-Idle, quad-rant staging |
| | 6A | 2.312 | .01592 | - | - | .02221 | 365.80 | 1.96 | 7.864 | - | .50 | [illegible] | .00870 | 1.74 | 47.22 | 2.99 | 2.58 | 98.63 | - | 1572 kPa AA | |
| | 6B | 2.304 | - | - | - | .02221 | 364.40 | 1.96 | 7.894 | - | .50 | .00964 | .00930 | 1.86 | 44.29 | 3.43 | 2.62 | 98.66 | - | | |
| | 7 | 4.046 | - | - | - | .02394 | 668.00 | 4.16 | 11.735 | - | .50 | .00592 | .00620 | 1.23 | 45.78 | 9.23 | 5.85 | [illegible] | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 8 | 4.046 | - | - | - | .03597 | 668.00 | 4.16 | 11.796 | - | .50 | [illegible] | .00940 | [illegible] | [illegible] | 1.02 | 7.53 | 99.43 | - | f/a = [illegible] | |
| | 9 | 4.069 | - | - | - | .04827 | 668.00 | 4.16 | 11.765 | - | .50 | .01186 | .01240 | 2.57 | 11.72 | [illegible] | 8.83 | 99.72 | - | f/a = .012 | |
| | 10 | 4.070 | - | - | - | [illegible] | 668.00 | 4.16 | 11.857 | .417 | .50 | .01537 | .01590 | [illegible] | [illegible] | [illegible] | 8.64 | 99.65 | - | Takeoff | |

# TEST RESULTS FOR CONCEPT 1 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Simulated bleed airflow, kg/sec | Water flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Modification 5<br>21-degree down angle pressure atomizing nozzles and swirlers | | | | | | | | | | | |
| A-3 | 1 | [illegible] | - | - | - | [illegible] | 366.3[illegible] | 1.92 | 7.864 | .41[illegible] | .50 | [illegible] | [illegible] | 1.71 | [illegible] | 41.1[illegible] | [illegible] | 83.62 | - | | Taxi-idle |
| | 2 | 2.318 | - | - | - | .02221 | 366.[illegible] | 1.92 | 7.833 | - | .5[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.75 | [illegible] | - | Primary only | |
| | 3 | 2.321 | .00319 | - | - | .02221 | 366.[illegible] | [illegible] | 7.894 | - | .5[illegible] | .00956 | [illegible] | 1.74 | 87.15 | 43.7[illegible] | 1.6[illegible] | 94.11 | - | [illegible] kPa AA | |
| | 4 | 2.319 | .00591 | - | - | .02234 | 365.80 | 1.92 | 7.864 | - | .5[illegible] | .0096[illegible] | .00912 | 1.7 | 1[illegible]4.4[illegible] | 44.84 | [illegible] | 93.1[illegible] | - | [illegible] kPa AA | |
| | 5A | 2.070 | .00587 | - | - | .02650 | 365.80 | 2.92 | 7.132 | - | .5[illegible] | .0126[illegible] | [illegible] | 2.5[illegible] | 57.83 | 3.57 | 2.6[illegible] | 97.8[illegible] | - | 12% Bleed, 5[illegible] kPa AA | |
| | 5B | 2.066 | - | - | - | .02650 | 366.9[illegible] | 1.90 | 7.132 | - | .5[illegible] | .0126[illegible] | .01283 | 2.4[illegible] | 63.71 | 14.43 | 2.6[illegible] | 94.88 | - | 2[illegible]% Bleed | |
| | 6A | 2.317 | .00598 | - | - | .02220 | 366.90 | 1.90 | 7.864 | - | .5[illegible] | .0095[illegible] | .00917 | 1.82 | 45.13 | [illegible] | 1.74 | 95.7[illegible] | - | [illegible] kPa AA, Quad.Staging | |
| | 6B | 2.323 | - | - | - | .02220 | 366.90 | 1.90 | 7.894 | - | .5[illegible] | .0095[illegible] | .0087[illegible] | 1.74 | 47.92 | 2.89 | 2.82 | 98.62 | - | | |
| | 7 | 4.[illegible]69 | - | - | - | .02394 | [illegible] | 4.15 | 11.715 | - | .5[illegible] | .03568 | [illegible] | [illegible] | [illegible] | 6.[illegible] | 5.4[illegible] | 98.4[illegible] | - | f/a = .00[illegible] | Takeoff - reduced [illegible] |
| | 8 | 4.095 | - | - | - | [illegible] | [illegible] | 4.15 | 11.814 | - | .5[illegible] | .00979 | [illegible] | 1.84 | 25.40 | [illegible] | 6.4[illegible] | 99.2[illegible] | - | [illegible] | |
| | 9 | 4.074 | - | - | - | .04814 | [illegible] | 4.15 | 11.765 | - | .5[illegible] | .01182 | .011[illegible] | 2.42 | [illegible] | [illegible].69 | 7.36 | 99.55 | - | f/a = .01[illegible] | |
| | 10 | 4.095 | - | - | - | [illegible] | 668.00 | 4.15 | 11.857 | .280 | .50 | [illegible] | .0155[illegible] | 3.1[illegible] | 9.7[illegible] | [illegible] | 4.34 | 99.7[illegible] | - | Takeoff | |
| | | | | | | | | | | Modification 5<br>Delavan airblast nozzles and grommets | | | | | | | | | | | |
| A-3 | 1 | 2.343 | - | - | - | .02214 | 356.3 | 1.98 | 7.711 | - | .48 | [illegible] | [illegible] | [illegible] | 91.[illegible] | 27.15 | 2.3[illegible] | 96.48 | - | | Taxi-idle |
| | 2 | 2.318 | - | - | - | .02221 | 366.9 | 1.98 | 7.681 | - | .48 | [illegible] | [illegible] | 1.86 | 47.11 | 2.33 | 2.31 | 97.74 | - | Primary only | |
| | 5A | [illegible] | - | 14.719 | - | .02653 | 366.1 | 1.90 | 7.163 | - | .48 | .012[illegible] | .0126[illegible] | 2.51 | 53.73 | 6.41 | 2.34 | 98.17 | - | 12% Bleed | |
| | 5B | 2.[illegible]87 | [illegible] | 14.841 | - | [illegible] | 366.[illegible] | 1.91 | 7.193 | - | .48 | [illegible] | .0125[illegible] | 2.4[illegible] | 49.21 | 4.[illegible] | 2.43 | 98.4[illegible] | - | 12% Bleed, 1[illegible] kPa AA | |

## TEST RESULTS FOR CONCEPT 1 (Concluded)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Simulated bleed airflow, kg/sec | Water flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Modification 5<br>Pressure atomizing nozzles and grommets | | | | | | | | | | |
| A-3 | 1 | 2.319 | - | - | - | .02221 | 365.9 | 1.91 | 7.681 | .285 | .48 | .00958 | .00980 | 1.86 | 87.20 | 15.74 | 2.26 | 94.86 | - | | Taxi-Idle |
| | 4 | 2.319 | .00550 | - | - | .02221 | 366.3 | 1.91 | 7.681 | - | .48 | .00958 | .00980 | 1.94 | 70.16 | 7.66 | 2.66 | 97.68 | - | 568 kPa AA | |
| | 5A | 2.077 | - | - | - | .02650 | 366.9 | 1.91 | 7.132 | - | .48 | .01283 | .01310 | 2.60 | 54.23 | 4.69 | 2.70 | 98.31 | - | 10% Bleed | |
| | 5B | 2.075 | .00546 | - | - | .02650 | 366.9 | 1.91 | 7.163 | - | .48 | .01277 | .01310 | 2.60 | 48.66 | 2.32 | 2.70 | 98.63 | - | 10% Bleed, 568 kPa AA | |
| | 7 | 4.066 | - | - | - | .02394 | 669.1 | 4.17 | 11.704 | - | .48 | .00589 | .00660 | 1.34 | 20.54 | 0.86 | 10.27 | 99.44 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 8 | 4.098 | - | - | - | .03599 | 668.6 | 4.18 | 11.721 | - | .46 | .00879 | .00970 | 1.98 | 10.98 | 0.26 | 9.84 | 99.72 | - | f/a = .009 | |
| | 9 | 4.078 | - | - | - | .04814 | 668.6 | 4.18 | 11.735 | - | .48 | .01181 | .01290 | 2.64 | 4.84 | 0.13 | 6.94 | 99.87 | - | f/a = .012 | |
| | 10 | 4.081 | - | - | - | .06256 | 668.6 | 4.18 | 11.735 | .094 | .48 | .01533 | .01690 | 3.44 | 2.45 | 0.10 | 8.41 | 99.93 | - | Takeoff | |

## TEST RESULTS FOR CONCEPT 2

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission Index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | BASIC CONFIGURATION | | | | | | | | | |
| A-4 (a) | 4 | 2.316 | 0 | .0221 | 367.20 | 1.98 | 7.766 | .173 | .57 | [illegible] | .0101 | 1.95 | 60.25 | 28.78 | 2.58 | 96.06 | - | No AA | Taxi-Idle |
| | 5 | 2.320 | .00625 | .0221 | 368.40 | 1.98 | 7.785 | .171 | .57 | .00954 | .0101 | 2.03 | 35.12 | 6.83 | 2.69 | 98.58 | - | .006 kg/sec AA | |
| | 6 | 2.322 | .00797 | .0221 | 368.40 | 1.96 | 7.799 | .174 | .57 | .00953 | .0101 | 2.03 | 26.15 | 3.07 | 2.85 | 98.11 | - | [illegible] kg/sec AA | |
| | 7 | 2.324 | .01038 | .0221 | 369.60 | 1.98 | 7.805 | .178 | .57 | .00952 | .0101 | 2.04 | 19.61 | 1.32 | 2.71 | 99.42 | - | [illegible] kg/sec AA | |
| A-4 (b) | 6 | 2.307 | .00814 | .0221 | 373.30 | 1.98 | 7.843 | .144 | .37 | .00960 | .0099 | 1.96 | 41.10 | 12.91 | 2.91 | 97.85 | - | .009 kg/sec AA | |
| | 7 | 2.374 | .01340 | .0221 | 373.30 | 1.98 | 7.832 | .144 | .37 | .00960 | .0101 | 2.03 | 28.22 | 3.56 | 2.79 | 99.52 | - | [illegible] kg/sec AA | |
| | 8 | 4.067 | - | .0624 | 667.20 | 4.08 | 12.043 | .184 | .37 | .01540 | .0168 | 1.42 | 1.95 | [illegible] | 12.22 | 99.93 | - | No AA | Takeoff |
| | 8A | 4.080 | .01673 | .0624 | 667.20 | 4.10 | 12.086 | .209 | .37 | .01530 | .0166 | 3.39 | 1.65 | 0.11 | 12.90 | [illegible] | - | .017 kg/sec AA | |
| | | | | | | | | | | Modification 1 | | | | | | | | | |
| A-5 (a) | 2 | 2.292 | .01321 | .0222 | 370.60 | 1.99 | 7.656 | .167 | .35 | .00970 | .0101 | 2.02 | 45.11 | 2.51 | 2.65 | 98.72 | - | .013 kg/sec AA | Taxi-Idle |
| | 2A | 2.288 | .00813 | .0222 | 370.60 | 1.98 | 7.643 | .185 | .35 | .00970 | .0100 | 2.01 | 46.03 | 2.72 | 2.71 | 98.68 | - | .008 kg/sec AA | |
| | 2B | 2.287 | .00444 | .0222 | 370.10 | 1.98 | 7.623 | .221 | .35 | .00970 | .0100 | 1.97 | 64.90 | 14.29 | 2.48 | 97.23 | - | .004 kg/sec AA | |
| | 3 | 5.846 | .00546 | .0675 | 501.20 | 5.25 | 10.132 | .223 | .35 | .01160 | .0126 | 2.58 | [illegible] | [illegible] | 5.44 | 99.89 | - | .0055 kg/sec AA | Approach |
| | 3A | 5.845 | .00319 | .0679 | 501.20 | 5.27 | 10.131 | .181 | .35 | .01160 | .0127 | 2.59 | [illegible] | 0.11 | 5.68 | 99.30 | - | [illegible] kg/sec AA | |
| | 5 | 4.054 | .00277 | .0242 | 668.00 | 4.17 | 9.292 | - | .35 | .00600 | .0066 | 1.36 | 7.35 | [illegible] | 1.63 | 99.87 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 6 | 4.054 | .00277 | .0367 | 668.00 | 4.18 | 11.730 | - | .35 | .00910 | .0096 | [illegible] | 3.38 | [illegible] | 9.30 | 99.91 | - | f/a = .009 | |
| | 7 | 4.054 | .00277 | .0491 | 668.00 | 4.18 | 11.730 | - | .35 | .01190 | .0130 | 2.66 | 1.69 | [illegible] | 10.14 | 99.95 | - | f/a = .012 | |
| | 8 | 4.054 | .00277 | .0629 | 668.00 | 4.18 | 11.730 | - | .35 | .01550 | .0164 | 3.34 | 2.11 | [illegible] | 10.12 | 99.94 | - | Takeoff | |
| A-5 (b) | 5 | [illegible] | [illegible] | .0241 | 664.4 | 4.20 | 11.640 | - | .41 | [illegible] | .0065 | [illegible] | [illegible] | [illegible] | 6.11 | 99.57 | - | f/a = .006, .020 kg/sec AA | Takeoff - reduced $W_f$ |
| | 5A | 4.055 | [illegible] | .0241 | 664.4 | 4.21 | 11.610 | - | .41 | [illegible] | [illegible] | 1.31 | [illegible] | [illegible] | 6.47 | [illegible] | - | f/a = .006, .015 kg/sec AA | |
| | 6 | [illegible] | [illegible] | .0372 | 664.4 | 4.21 | 11.610 | - | .43 | [illegible] | [illegible] | 1.97 | 4.31 | [illegible] | [illegible] | 99.87 | - | f/a = .009, .015 kg/sec AA | |
| | 6A | 4.044 | [illegible] | .0372 | 664.4 | 4.21 | 11.640 | - | .43 | [illegible] | [illegible] | [illegible] | 4.50 | [illegible] | [illegible] | 99.87 | - | f/a = .009, .020 kg/sec AA | |
| | 7 | [illegible] | .0149 | [illegible] | 664.4 | 4.21 | 11.610 | - | .43 | [illegible] | .0131 | [illegible] | [illegible] | [illegible] | [illegible] | 99.91 | - | f/a = .012, .015 kg/sec AA | |
| | 7A | [illegible] | [illegible] | .0493 | 664.4 | 4.21 | 11.640 | - | .43 | [illegible] | .0134 | 2.74 | 2.58 | [illegible] | [illegible] | [illegible] | - | f/a = .012, .024 kg/sec AA | |
| | 8 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .41 | [illegible] | [illegible] | [illegible] | 2.12 | | [illegible] | [illegible] | - | [illegible] kg/sec AA | Takeoff |
| | 8A | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11.810 | [illegible] | .41 | [illegible] | .0171 | [illegible] | [illegible] | [illegible] | [illegible] | 99.95 | - | .024 kg/sec AA | |
| | [illegible] | [illegible] | [illegible] | .0241 | [illegible] | 4.18 | [illegible] | - | .41 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 6.41 | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | [illegible] | [illegible] | [illegible] | .0241 | [illegible] | 4.18 | [illegible] | - | .41 | [illegible] | .0064 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |

# TEST RESULTS FOR CONCEPT 2 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Modification 1 (Continued) | | | | | | | | | | | | | | | | | | | |
| | 6 | 4.071 | .0304 | .0368 | 675.0 | 4.18 | 11.880 | - | .43 | .00900 | .0095 | 1.95 | [illegible] | .12 | 7.49 | 99.88 | - | f/a = .009 | Takeoff - reduced $W_f$ |
| | 7 | 4.071 | .0304 | .0481 | 675.0 | 4.18 | 11.880 | - | .43 | .01180 | .0125 | 2.56 | [illegible] | [illegible] | 8.67 | 99.94 | - | f/a = .012 | |
| | 8 | 4.091 | .0305 | .0628 | 671.1 | 4.23 | 11.780 | - | .45 | .01530 | .0163 | 3.31 | 1.95 | .01 | 9.51 | 99.95 | - | .030 kg/sec AA | Takeoff |
| | 8A | 4.118 | .0577 | .0628 | 671.1 | 4.23 | 11.860 | .163 | .43 | .01530 | .0164 | 3.15 | 1.71 | [illegible] | [illegible] | 99.95 | - | [illegible] kg/sec AA | |
| | 8B | 4.065 | .0043 | .0628 | 671.1 | 4.23 | 11.700 | - | .43 | .01530 | .0169 | 3.45 | 1.80 | [illegible] | 10.58 | 99.96 | - | .004 kg/sec AA | |
| | 5 | 4.069 | .0590 | .0238 | 666.1 | 4.17 | 11.780 | - | .47 | .00560 | .0063 | 1.27 | 11.16 | .40 | 5.74 | 99.70 | - | f/a = .006,.060 kg/sec AA | Takeoff - reduced $W_f$ |
| | 5A | 4.059 | .0218 | .0238 | 666.1 | 4.18 | 11.750 | - | .47 | .00560 | .0063 | 1.24 | 14.89 | .14 | 5.34 | 99.62 | - | f/a = .006 .020 kg/sec AA | |
| | 6 | 4.084 | .0219 | .0378 | 668.9 | 4.17 | 11.900 | - | .47 | .00930 | .0101 | 2.07 | 3.70 | .08 | 6.73 | 99.91 | - | f/a = .009 .020 kg/sec AA | |
| | 6A | 4.075 | .0590 | .0378 | 668.9 | 4.19 | 11.890 | - | .47 | .00930 | .0100 | 2.04 | 3.75 | .08 | 6.40 | 99.90 | - | f/a = .009 .060 kg/sec AA | |
| | 7 | 4.080 | .0589 | .0479 | 668.9 | 4.17 | 11.850 | - | .47 | .01180 | .0126 | 2.58 | 2.09 | .01 | 7.32 | 99.95 | - | f/a = .012 .060 kg/sec AA | |
| | 7A | 4.069 | .0219 | .0479 | 668.9 | 4.19 | 11.830 | - | .47 | .01180 | .0126 | 2.57 | 1.91 | .01 | 8.05 | 99.95 | - | f/a = .012 .020 kg/sec AA | |
| | 8 | 4.072 | .0216 | .0630 | 667.8 | 4.17 | 11.830 | - | .47 | .01550 | .0167 | 3.41 | 1.47 | .04 | 9.50 | 99.95 | - | .020 kg/sec AA | Takeoff |
| | 8A | 4.083 | .0585 | .0630 | 667.8 | 4.19 | 11.860 | .142 | .47 | .01540 | .0163 | 3.32 | 1.60 | [illegible] | 8.81 | 99.96 | - | .060 kg/sec AA | |

# TEST RESULTS FOR CONCEPT 2 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modification 2 | | | | | | | | | | |
| A-6 (a) | 2 | 2.330 | .01920 | .0222 | 360.40 | 1.95 | 7.885 | .224 | .41 | .00951 | .0099 | 1.99 | 48.61 | 3.17 | [illegible] | [illegible] | - | [illegible] | |
| | 3 | 5.845 | .02625 | .0477 | [illegible] | 5.26 | 10.212 | - | .41 | .01159 | .0120 | 2.57 | [illegible] | [illegible] | 6.14 | 99.85 | - | [illegible] | |
| | 4 | 4.143 | .02780 | .0600 | 652.73 | 4.15 | 11.845 | - | .41 | | .0158 | 3.23 | 2.57 | [illegible] | 9.47 | [illegible] | - | [illegible] | |
| | 5 | 4.063 | .02720 | .0238 | 677.40 | [illegible] | 12.009 | - | .41 | .00586 | .0066 | [illegible] | 8.66 | [illegible] | [illegible] | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | 6 | 4.063 | .02720 | .0378 | 677.40 | 4.18 | 12.009 | - | .41 | .00931 | .0102 | 2.39 | [illegible] | [illegible] | 9.53 | [illegible] | - | [illegible] | |
| | 7 | 4.063 | .02720 | [illegible] | 667.40 | 4.18 | 12.009 | - | .41 | [illegible] | .0136 | 2.78 | 2.59 | 0.02 | 11.05 | [illegible] | - | [illegible] | |
| | 8 | 4.063 | [illegible] | .0626 | 667.40 | 4.18 | 12.009 | - | .41 | .01540 | .0169 | 3.44 | [illegible] | 0.01 | [illegible] | [illegible] | - | [illegible] | |
| A-6 (b) | 4 | 4.187 | .05770 | .0659 | 651.90 | 4.21 | 11.735 | .119 | .47 | .01460 | .0154 | 3.14 | 1.66 | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | 5 | 4.129 | .05670 | .0218 | 669.60 | 4.25 | [illegible] | - | .47 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 5.83 | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | 6 | 4.133 | .05670 | .0360 | 668.60 | 4.23 | 11.796 | - | .47 | [illegible] | .0094 | [illegible] | [illegible] | 0.04 | 5.63 | [illegible] | - | [illegible] | |
| | 7 | 4.133 | .05670 | .0431 | 668.60 | 4.23 | 11.796 | - | .47 | .01165 | .0123 | 2.52 | 3.77 | 0.01 | [illegible] | [illegible] | - | [illegible] | |
| | 8 | 4.127 | .05670 | .0626 | 668.60 | 4.22 | 11.878 | [illegible] | .47 | [illegible] | .0265 | 3.36 | 1.40 | [illegible] | [illegible] | [illegible] | - | [illegible] kg sec AA | Takeoff |
| | 8A | [illegible] | [illegible] | [illegible] | 668.60 | 4.23 | 11.878 | - | .47 | .01525 | .0169 | 3.44 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kg sec AA | |
| | | | | | | | | | Modification 1 | | | | | | | | | | |
| A-7 (a) | [illegible] | [illegible] | [illegible] | [illegible] | 362.40 | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | Taxi-idle |
| | 2A | [illegible] | [illegible] | [illegible] | 362.40 | 1.96 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | 2B | [illegible] | [illegible] | [illegible] | [illegible] | 1.96 | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | 2.334 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 1.96 | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | 8A | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | Takeoff |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |

# TEST RESULTS FOR CONCEPT 2 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Modification 3 (Continued) | | | | | | | | | | | | | | | | | | | |
| A-7 (b) | 2 | 2.340 | .01540 | .0229 | 361.50 | 1.97 | 7.761 | - | .45 | .00970 | .0099 | 1.95 | 69.28 | 8.74 | 2.29 | 97.64 | - | Taxi-Idle | |
| | 2A | 2.226 | .01800 | .0257 | 361.50 | 1.97 | 7.350 | - | .45 | .01150 | .0117 | 2.33 | 54.55 | 3.51 | 2.41 | 98.41 | - | f/a = .012 | Taxi-Idle - increased $W_f$ |
| | 2B | 1.969 | .05320 | .0301 | 361.50 | 1.99 | 6.383 | - | .45 | .01530 | .0156 | 3.12 | 35.97 | 3.81 | 2.30 | 98.82 | - | f/a = .015, .050 kg/sec AA | |
| | 2C | 1.935 | .01970 | .0301 | 361.50 | 2.00 | 6.383 | - | .45 | .01560 | .0160 | 3.32 | 31.43 | 1.37 | 2.57 | 99.13 | - | f/a = .015, .020 kg/sec AA | |
| | 8 | 4.071 | .03210 | .0238 | 668.60 | 4.17 | 11.919 | - | .45 | .00585 | - | 1.31 | 8.56 | 0.52 | 6.84 | 99.75 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 8A | 4.071 | .03210 | .0378 | 668.60 | 4.17 | 11.919 | - | .45 | .00929 | - | 2.01 | 6.89 | 0.03 | 8.56 | 99.83 | - | f/a = .009 | |
| | 8B | 4.089 | .05050 | .0480 | 668.60 | 4.17 | 11.973 | - | .45 | .01168 | - | 2.59 | 5.01 | 0.13 | 8.65 | 99.97 | - | f/a = .012 | |
| | 8C | 4.106 | .05090 | .0628 | 668.60 | 4.21 | 11.801 | .177 | .45 | .01354 | - | 3.31 | 2.94 | 0.10 | 8.82 | 99.93 | - | Takeoff | |
| Modification 4 | | | | | | | | | | | | | | | | | | | |
| A-8 (a) | 2 | 2.336 | .03150 | 0.0225 | 366.90 | 1.97 | 7.852 | - | .40 | .00962 | .0101 | 2.04 | 33.05 | 0.46 | 2.73 | 99.18 | - | .033 kg/sec AA | Taxi-Idle |
| | 2A | 2.350 | .02150 | 0.0225 | 366.90 | 1.97 | 7.891 | - | .40 | .00960 | .0100 | 2.02 | 32.70 | 0.35 | 2.62 | 99.20 | - | .023 kg/sec AA | |
| | 2B | 2.341 | .00547 | 0.0225 | 366.90 | 1.98 | 7.861 | - | .40 | .00960 | .0101 | 1.97 | 75.11 | 51.36 | 2.75 | 93.72 | - | .0055 kg/sec AA | |
| | 2C | 2.332 | .01750 | 0.0225 | 366.90 | 1.98 | 7.806 | - | .40 | .00970 | .0101 | 2.03 | 34.63 | 0.68 | 2.30 | 99.13 | - | .018 kg/sec AA | |
| | 2D | 2.336 | .02580 | 0.0225 | 366.90 | 1.98 | 7.846 | - | .40 | .00960 | .0102 | 2.05 | 31.56 | 0.38 | 2.47 | 99.22 | - | .026 kg/sec AA | |
| | 2E | 2.386 | .02580 | 0.0215 | 371.30 | 1.96 | 8.099 | .220 | .40 | .00941 | .0098 | 1.94 | 31.81 | 0.26 | 2.49 | 99.23 | - | .026 kg/sec AA | |
| | 3 | 4.119 | .05140 | 1.4160 | 669.10 | 4.18 | 11.927 | - | .40 | .00591 | .0063 | 1.29 | 12.11 | 0.23 | 7.17 | 99.33 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 4 | 4.114 | .04940 | 2.1610 | 669.10 | 4.18 | 11.924 | - | .40 | .00860 | .0096 | 1.86 | 7.59 | 0.04 | 8.78 | 99.82 | - | [illegible] | |
| | 5 | 4.114 | .05120 | 2.8960 | 668.60 | 4.18 | 11.905 | - | .40 | .01170 | .0127 | 2.60 | 5.53 | 0.13 | 8.41 | 99.87 | - | f/a = .009 | |
| | 6 | 4.121 | .05070 | 1.7610 | 668.00 | 4.18 | 11.921 | - | .40 | .01520 | .0164 | 3.31 | 1.74 | 0.05 | 8.11 | 99.95 | - | Takeoff | |

# TEST RESULTS FOR CONCEPT 2 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Modification 4 (Continued) | | | | | | | | | | | | | | | | | | |
| A-8 | 2 | [illegible] | .02270 | .0223 | 121.90 | 1.97 | 7.925 | [illegible] | .67 | [illegible] | [illegible] | 1.45 | 46.99 | [illegible] | 2.51 | 94.46 | - | Taxi-idle |
| (b) | 2A | 2.217 | .02220 | .0257 | 368.[illegible] | 1.98 | 7.468 | - | [illegible] | .0115[illegible] | .0118 | 2.[illegible] | [illegible] | [illegible] | [illegible] | 94.25 | - | 10% Bleed |
| | 2B | 1.936 | .02260 | .0301 | 365.2[illegible] | 1.96 | 6.431 | - | .6[illegible] | .0156[illegible] | .0161 | 3.[illegible] | 11.1[illegible] | [illegible] | 2.63 | [illegible].73 | - | [illegible] |
| | 3 | 4.084 | .0124[illegible] | .0238 | 672.40 | 4.16 | 11.948 | - | .6[illegible] | .00580 | .0065 | 1.33 | 4.63 | [illegible].13 | 6.82 | [illegible] | - | [illegible] kg/sec AA<br>Takeoff - reduced $W_f$ |
| | 3A | 4.1[illegible] | .0484[illegible] | .0233 | 672.40 | 4.16 | 12.0[illegible]9 | - | .60 | .00580 | .0065 | 1.33 | 5.54 | [illegible].13 | 6.7[illegible] | [illegible].36 | - | [illegible] .0284 kg/sec AA |
| | 4 | 4.114 | .04780 | .0378 | 667.40 | 4.16 | 11.948 | - | .6[illegible] | .00920 | .0102 | 2.23 | 3.58 | [illegible] | [illegible].13 | [illegible] | - | f/a = [illegible] |
| | 5 | 4.110 | .04600 | .0594 | 668.60 | 4.16 | 11.948 | - | .62 | .0123[illegible] | .0137 | 2.8 | 1.46 | | [illegible].54 | [illegible].96 | - | f/a = [illegible] |
| | 6 | 4.114 | .04803 | .0626 | 668.60 | 4.14 | 11.979 | .119 | .67 | .0152[illegible] | .0166 | 3.3[illegible] | 0.92 | [illegible] | 8.73 | [illegible].98 | - | [illegible] |
| A-9 | 2 | 2.312 | .03410 | .0223 | 365.[illegible] | 1.97 | 7.824 | .140 | .45 | .00952 | .0099 | 1.74 | 71.95 | 5.36 | 2.17 | [illegible].94 | - | Taxi-idle |
| | 2A | 2.213 | .03420 | .0257 | 367.40 | 1.96 | 7.541 | - | .45 | .01141 | .0119 | 2.23 | [illegible].14 | [illegible] | 2.19 | [illegible].77 | - | [illegible] |
| | 2B | 1.965 | .03420 | .0301 | 369.10 | [illegible] | 6.5[illegible]4 | - | .45 | .0155[illegible] | .0164 | 3.27 | 33.58 | 1.12 | 2.46 | [illegible] | - | [illegible] |
| | 1 | 4.035 | .04360 | .0238 | 669.10 | 4.16 | 11.829 | - | .45 | .00584 | .0064 | 1.31 | 12.73 | [illegible].13 | 8.23 | [illegible] | - | f/a [illegible]<br>Takeoff - reduced $W_f$ |
| | 4 | 4.047 | .03810 | .0378 | 669.10 | 4.17 | 11.848 | - | .45 | .0092[illegible] | .0131 | 2.76 | 17.10 | 0.09 | 6.1[illegible] | [illegible].75 | - | [illegible] |
| | 5 | 4.050 | .03810 | .0477 | 668.00 | 4.17 | 11.826 | - | .45 | .01171 | .0126 | 2.56 | 5.82 | 0.12 | 5.94 | [illegible].86 | - | f/a [illegible] |
| | 6 | 4.0[illegible] | .038[illegible] | .0629 | 665.20 | 4.17 | 11.876 | .130 | .45 | .01533 | .0167 | 3.34 | 2.91 | 0.72 | 6.4[illegible] | [illegible].93 | - | [illegible] |
| Modification 5 | | | | | | | | | | | | | | | | | | |
| A-11 | 2 | 2.33[illegible] | .03310 | .0223 | 366.35 | 1.97 | 7.752 | .138 | .43 | .0095[illegible] | [illegible] | 2.3[illegible] | 57.42 | 2.45 | 2.5 | 98.38 | - | Taxi-idle |
| (b) | 2A | 2.22[illegible] | .03920 | .0257 | 368.63 | 1.97 | 7.475 | - | .43 | .0114[illegible] | .0117 | 2.33 | 51.45 | 2.1[illegible] | 2.[illegible] | [illegible] | - | [illegible] |
| | 2B | 1.95[illegible] | [illegible] | [illegible] | 370.80 | 1.96 | 6.540 | - | .43 | .0155 | [illegible] | 3.1[illegible] | 23.[illegible] | 0.2[illegible] | 2.34 | [illegible].42 | - | [illegible]% Bleed |
| | 3 | 5.884 | .03320 | .0238 | 497.4[illegible] | 5.27 | 10.[illegible]91 | .11[illegible] | .43 | .0145[illegible] | .0121 | [illegible] | [illegible].16 | [illegible] | [illegible] | [illegible].97 | - | [illegible] |
| | 4 | 4.194 | [illegible] | .0378 | 651.1 | 4.14 | 11.828 | .16[illegible] | .43 | .01480 | .0152 | 3.12 | 3.15 | [illegible] | [illegible] | [illegible].42 | - | [illegible] |
| | 5 | 4.597 | .05830 | .0238 | 662.6[illegible] | 4.14 | 11.772 | - | .43 | .00580 | .0064 | 1.32 | 4.2[illegible] | [illegible].16 | 8.14 | [illegible] | - | f/a [illegible]<br>Takeoff - reduced $W_f$ |
| | 6 | 4.115 | [illegible] | .0368 | 665.2[illegible] | 4.15 | 11.841 | - | .43 | .0080[illegible] | [illegible] | [illegible] | 1[illegible].3[illegible] | [illegible].19 | [illegible] | [illegible].74 | - | [illegible] |
| | 7 | 4.1[illegible] | [illegible] | .0451 | 667.40 | 4.1[illegible] | 11.82[illegible] | - | .43 | [illegible] | .0127 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | f/a [illegible] |
| | 8 | 4.1[illegible] | [illegible] | .0627 | 669.1[illegible] | 4.14 | 11.985 | .25[illegible] | .43 | [illegible] | .0164 | 3.2[illegible] | [illegible] | [illegible] | 7.16 | [illegible] | - | [illegible] |
| A-12 | 2 | 2.351 | .0413[illegible] | .0221 | 368.5[illegible] | 1.96 | 7.882 | .16[illegible] | .46 | .0096[illegible] | [illegible] | [illegible] | [illegible] | 2.32 | [illegible] | [illegible] | - | Taxi-idle |
| [illegible] | 2A | [illegible] | .0413[illegible] | .0257 | [illegible] | 1.94 | 7.474 | - | .46 | .0114 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] |
| | 2B | 1.96[illegible] | .0413[illegible] | [illegible] | 371.9[illegible] | 1.96 | 6.562 | - | .46 | .0155 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] |

# TEST RESULTS FOR CONCEPT 2 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air-assist air-flow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modification 5 (Continued) | | | | | | | | | | |
| A-11 (b) | 2 | 2.349 | .02290 | .0221 | 364.10 | 1.95 | 7.774 | .118 | .45 | .00940 | .0094 | 1.97 | 56.54 | 1.56 | 2.51 | 98.53 | - | | Taxi-Idle |
| | 2A | 2.249 | .03330 | .0257 | 368.00 | 1.95 | 7.537 | - | .45 | .01140 | .0118 | 2.37 | 47.35 | 1.47 | 2.34 | 98.76 | - | [illegible] Bleed | |
| | 2B | 2.239 | .02300 | .0257 | 368.00 | 1.96 | 7.503 | - | .45 | .01150 | .0120 | 2.41 | 41.92 | [illegible] | 2.55 | 98.96 | - | [illegible] Bleed | |
| | 2C | 1.931 | .02300 | .0293 | 368.00 | 1.97 | 6.410 | - | .45 | .01520 | .0163 | 3.29 | 19.33 | 0.33 | 2.55 | 99.52 | - | [illegible] Bleed | |
| | 3 | 5.881 | .03370 | .0677 | 504.70 | 5.22 | 10.132 | - | .45 | .01150 | .0125 | 2.54 | 9.28 | 0.13 | 5.81 | 99.77 | - | Approach | |
| | 4 | 4.195 | .05770 | .0610 | 651.90 | 4.16 | 11.762 | - | .45 | .01460 | .0159 | 3.24 | 2.39 | 0.05 | 6.98 | 99.94 | - | Climb | |
| | 5 | 4.108 | .05770 | .0249 | 671.90 | 4.01 | 11.908 | - | .45 | .00610 | [illegible] | 1.33 | 8.72 | 0.13 | 8.11 | 99.78 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 6 | 4.127 | .05770 | .0368 | 669.70 | 4.01 | 11.922 | - | .45 | .00890 | .0096 | 1.96 | 8.33 | 0 | 8.80 | 99.80 | - | f/a = .009 | |
| | 7 | 4.127 | .05770 | .0482 | 669.70 | 4.01 | 11.922 | - | .45 | .01170 | .0123 | 2.52 | 4.13 | 0 | 8.47 | 99.90 | - | f/a = .012 | |
| | 8 | 4.127 | .05800 | .0628 | 669.70 | 4.10 | 12.102 | .123 | .45 | .01520 | .0160 | 3.26 | 2.06 | .05 | 7.47 | 99.95 | - | Takeoff | |
| | | | | | | | | | Refinement Test 1 | | | | | | | | | | |
| A-12 (b) | 2 | 2.338 | .02380 | .0221 | 367.40 | 1.96 | 7.785 | .167 | 45 | .00950 | .0097 | 1.93 | 50.96 | 3.81 | 2.06 | 98.47 | - | | Taxi-Idle |
| | 2A | 2.248 | .02920 | .0257 | 366.90 | 1.96 | 7.495 | - | .45 | .01140 | .0119 | 2.40 | 30.87 | 1.06 | 2.52 | 99.19 | - | 1 % Bleed | |
| | 2B | 1.937 | .02370 | .0293 | 367.40 | 1.96 | 6.450 | - | .45 | .01510 | .0157 | 3.17 | 16.64 | 0.27 | 2.94 | 99.58 | - | 2 % Bleed | |
| | 3 | 5.898 | .03340 | .0676 | 500.20 | 5.24 | 10.089 | .117 | .45 | .01150 | .0120 | 2.44 | 6.73 | 0.14 | 5.91 | 99.83 | - | Approach | |
| | 4 | 4.179 | .05760 | .0610 | 651.30 | 4.16 | 11.707 | .126 | .45 | .01470 | .0154 | 3.14 | 1.96 | 0.07 | 7.35 | 99.95 | - | Climb | |
| | 5 | 4.097 | .05760 | .0249 | 668.60 | 4.14 | 11.831 | - | .45 | .00610 | .0063 | 1.30 | 6.31 | 0.01 | 7.75 | 99.84 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 6 | 4.105 | .05760 | .0368 | 668.60 | 4.14 | 11.853 | - | .45 | .00900 | .0093 | 1.93 | 5.92 | [illegible] | [illegible] | 99.86 | - | f/a = .009 | |
| | 7 | 4.112 | .05760 | .0482 | 668.60 | 4.14 | 11.876 | - | .45 | .01170 | .0121 | 2.51 | 3.43 | [illegible] | 8.40 | 99.92 | - | f/a = .012 | |
| | 8 | 4.127 | .05760 | .0628 | 668.60 | 4.15 | 11.895 | - | .45 | .01520 | .0161 | 3.29 | 1.77 | 0.05 | 8.65 | 99.95 | - | Takeoff | |
| | 4 | 4.191 | .05690 | .0610 | 652.40 | 4.13 | 11.897 | .083 | .45 | .01460 | .0154 | 3.14 | 2.02 | 0.05 | 8.23 | 99.94 | - | Climb | |
| | 5 | 4.110 | .05670 | .0249 | 667.40 | 4.18 | 11.736 | - | .45 | .00610 | .0065 | 1.33 | 6.94 | 0.22 | 7.16 | 99.73 | - | f/a = .006 | Takeoff - reduced $W_f$ |
| | 6 | 4.110 | .05670 | .0373 | 667.40 | 4.18 | 11.736 | - | .45 | [illegible] | [illegible] | 1.98 | 5.22 | | 7.41 | 99.82 | - | f/a = [illegible] | |
| | 7 | 4.110 | .05670 | .0492 | 667.40 | 4.18 | 11.736 | - | .45 | .01170 | .0121 | 2.51 | 3.23 | [illegible] | 8.14 | 99.89 | - | f/a = .012 | |
| | 8 | 4.116 | .05670 | .0628 | 670.80 | 4.17 | 11.862 | .077 | .45 | [illegible] | .0160 | [illegible] | 1.66 | [illegible] | [illegible] | 99.94 | - | Takeoff | |
| A-12 (a) | 2 | 2.341 | .02230 | .0221 | 367.40 | 1.94 | 7.842 | .074 | .45 | .00940 | [illegible] | [illegible] | 52.26 | 1.81 | 2.36 | [illegible] | - | | Taxi-Idle |
| | 2A | 2.248 | [illegible] | .0257 | 367.40 | 1.97 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | | |
| | 2B | 1.937 | .02180 | .0254 | 367.40 | [illegible] | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | 23.45 | [illegible] | [illegible] | [illegible] | - | | |

## TEST RESULTS FOR CONCEPT 2 (Concluded)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, combustor, kg/sec | Air assist airflow, kg/sec | Total fuel flow, kg/sec | Inlet total temperature, K | Inlet total pressure, Pa x 10 | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Fuel/air ratio, metered | Fuel/air ratio, carbon balance | [illegible] percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | [illegible] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | 1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | Takeoff - reduced $W_f$ |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.14 | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] sec AA | Takeoff |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] sec AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] sec AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | Taxi-idle |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | Approach |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | Taxi-idle |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .44 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |

# TEST RESULTS FOR CONCEPT 3

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, $^oK$ | Premix inlet total temperature, $^oK$ | Inlet total press. Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | BASIC CONFIGURATION | | | | | | | | | | | | | |
| A-14 | 1-1 | 2.296 | 1.712 | 0.564 | .0126 | .0126 | - | 370.9 | 470.2 | 1.97 | 7.681 | - | .45 | - | .00549 | .00600 | 0.91 | 122.82 | 231.26 | 1.96 | 76.65 | - | f/a = .006 | Taxi-Idle 25% premix |
| | 1-2 | 2.293 | 1.727 | 0.563 | .0234 | .0234 | - | 371.8 | 474.1 | 1.96 | 7.772 | .178 | .45 | - | [illegible] | [illegible] | 1.96 | 34.68 | 4.45 | 3.60 | 98.70 | - | f/a = [illegible] | |
| | 1-3 | 2.292 | 1.729 | 0.564 | .0278 | .0278 | - | [illegible] | 476.3 | 1.96 | 7.864 | - | .45 | - | .01213 | .01220 | 2.45 | 32.72 | 1.79 | 3.87 | 99.07 | - | f/a = .012 | |
| | 1-4 | 1.955 | 1.389 | 0.566 | .0223 | .0223 | - | 375.1 | 480.2 | 1.98 | 6.523 | - | .45 | - | .01149 | .01170 | 2.35 | 37.41 | 7.29 | 3.48 | 99.08 | - | 20% reduced $W_a$ | Taxi-Idle |
| | 2-1 | 2.031 | 1.746 | 0.285 | .0126 | .0126 | - | 366.5 | 460.8 | 1.98 | 6.696 | - | .45 | - | .00621 | .00660 | 1.19 | 96.45 | 87.09 | 2.10 | 90.10 | - | Reduced premix $W_a$, f/a = .006 | |
| | 2-2 | 2.029 | 1.745 | 0.284 | .0224 | .0224 | - | 368.4 | 471.3 | 2.00 | 6.645 | - | .45 | - | .01100 | .01150 | 2.33 | 13.91 | 2.05 | 3.51 | 99.37 | - | Reduced premix $W_a$, f/a = .011 | |
| | 2-3 | 2.033 | 1.751 | 0.282 | .0278 | .0278 | - | 369.9 | 490.8 | 2.00 | 6.706 | - | .45 | - | .01370 | .01420 | 2.87 | 18.36 | 0.89 | 4.24 | 99.49 | - | Reduced premix $W_a$, f/a = .015 | |
| | 2-4 | 1.684 | 1.401 | 0.293 | .0224 | .0224 | - | 370.6 | 484.1 | 1.97 | 5.608 | - | .45 | - | .01330 | .01380 | 2.63 | 19.7 | 0.81 | 3.95 | 99.49 | - | 20% reduced $W_a$ | |
| | 4-1 | 4.024 | 3.045 | 0.979 | .0126 | .0126 | - | 669.7 | 670.2 | 4.13 | 11.614 | - | .45 | - | .00313 | .00350 | 0.72 | 14.31 | 1.61 | 4.08 | 99.52 | - | Pilot Only | Takeoff |
| | 4-2 | 4.018 | 3.044 | 0.974 | .0189 | .0189 | - | 669.3 | 669.7 | 4.13 | 11.612 | - | .45 | - | .00470 | .00520 | 1.06 | 7.72 | 0.53 | 9.56 | 99.76 | - | 24% premix $W_a$ | |
| | 4-3 | 4.021 | 3.051 | 0.970 | .0250 | .0250 | - | 669.7 | 671.3 | 4.17 | 11.631 | .239 | .45 | - | .00622 | .00670 | 1.37 | 4.27 | 0.38 | 9.54 | 99.87 | - | 24% premix $W_a$ | |
| | 4-4 | 4.028 | 3.053 | 0.975 | .0375 | .0375 | - | 668.6 | 670.8 | 4.13 | 11.628 | - | .45 | - | .00615 | .00980 | 2.01 | [illegible] | [illegible] | 11.08 | 99.90 | - | 24% premix $W_a$ | |
| | 4-5 | 4.670 | 3.696 | 0.974 | .0226 | .0226 | - | 670.4 | 668.6 | 4.14 | 13.332 | - | .45 | - | .00434 | .00530 | 1.39 | 5.30 | 0.39 | 9.04 | 99.84 | - | Increased main $W_a$ | |
| | 4-6 | 3.458 | 2.474 | 0.984 | .0250 | .0250 | - | 658.9 | 669.7 | 4.16 | 9.702 | - | .45 | - | .00723 | .00750 | 1.54 | 4.30 | 0.22 | 10.06 | 99.88 | - | Increased main $W_a$ | |
| | 5-1 | 3.544 | [illegible] | 0.494 | .0126 | .0126 | - | 666.3 | 672.4 | 4.13 | 10.180 | - | .45 | - | .00355 | .00410 | 0.84 | 5.05 | 0.62 | 10.05 | 99.73 | - | Reduced premix $W_a$ | |
| | 5-2 | 3.542 | 3.050 | 0.442 | .0190 | .0190 | - | 668.8 | - | 4.14 | 10.199 | - | .45 | - | .00537 | .00590 | 1.22 | 3.35 | 0.28 | 10.39 | 99.90 | - | Reduced premix $W_a$ | |
| | 5-3 | 3.563 | 3.067 | 0.493 | .0250 | .0250 | - | 668.4 | - | 4.16 | 10.193 | - | .45 | - | .00703 | .00760 | 1.57 | 1.59 | .11 | 13.96 | 99.95 | - | Reduced premix $W_a$ | |
| | 7-1 P[a] | 4.070 | 3.086 | 0.994 | .0242 | .0126 | .0116 | 670.2 | - | 4.16 | 11.707 | - | .45 | .01180 | .00594 | .00680 | 0.75 | 52.61 | [illegible] | 4.45 | 56.32 | - | Increasing pilot $W_f$<br>8 In. premix injection length | Takeoff |
| | 7-2 P | 4.037 | 3.061 | 0.976 | .0297 | .0190 | .0107 | 669.7 | - | 4.17 | 11.540 | - | .45 | .01096 | .00736 | .00790 | 1.15 | [illegible] | [illegible] | 5.98 | [illegible] | - | | |
| | 7-3 P | 4.046 | 3.065 | 0.931 | .0349 | .0250 | .0099 | 668.7 | - | 4.17 | 11.570 | - | .45 | .01015 | .00864 | .00920 | 1.54 | [illegible] | 132.38 | [illegible] | 85.66 | - | | |
| | 7-4 P | 4.042 | [illegible] | [illegible] | .0473 | .0383 | [illegible] | 672.1 | - | 4.15 | 11.671 | - | .45 | [illegible] | [illegible] | [illegible] | 2.35 | [illegible] | [illegible] | 9.02 | 96.21 | - | | |

[a] The letter P following a condition number indicates use of propane premix fuel.

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration • ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, °K | Premix inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | [illegible] per cent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ba[illegible] configuration (Continued) | | | | | | | | | | | | | | | | | | | | | | | |
| [a] | 8-1 P | 4.043 | 3.055 | 0.988 | .0613 | .0380 | .0233 | 671.[illegible] | [illegible] | 4.14 | 11.76[illegible] | .1[illegible]7 | .45 | [illegible] | [illegible] | [illegible] | [illegible] | 17.3[illegible] | [illegible] | [illegible] | [illegible] | - | | |
| | 8-2 P | 4.044 | 3.052 | 0.992 | .0491 | .0250 | .0231 | 670.8 | 596.[illegible] | 4.12 | 11.643 | - | .45 | [illegible] | .0119[illegible] | .0124 | 2.31 | 72.44 | [illegible] | 5.52 | 95.3[illegible] | - | Decreasing pilot $W_f$ | Takeoff |
| | 8-3 P | 4.042 | 3.053 | 0.999 | .0419 | .0180 | .0233 | 669.1 | 600.0 | 4.16 | 11.654 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 146.38 | 4.34 | 7[illegible].36 | - | | |
| | 8-4 P | 4.039 | 3.050 | 0.989 | .0357 | .0126 | .0231 | 667.2 | 5[illegible] | 4.1[illegible] | 11.686 | - | .45 | [illegible] | [illegible] | [illegible] | 2.93 | 8[illegible] | 546.75 | 3.15 | 4[illegible] | - | | |
| | 9-1 P | 4.037 | 3.055 | 0.982 | .0495 | .0126 | .0359 | 668.0 | 565.2 | [illegible] | 11.593 | - | .45 | .0366[illegible] | [illegible] | [illegible] | 2.13 | 65.5[illegible] | 144.54 | 3.23 | 98.54 | - | | |
| | 9-2 P | 4.032 | 3.040 | 0.992 | .0561 | .0189 | .0373 | [illegible] | 583.[illegible] | 4.17 | 11.595 | - | .45 | .03765 | .0134[illegible] | [illegible] | 2.86 | 26.61 | [illegible].73 | 4.42 | 96.54 | - | Increasing pilot $W_f$ | Takeoff |
| | 9-3 P | 4.041 | 3.052 | 0.999 | .0593 | .0250 | .0343 | 670.5 | 588.6 | 4.14 | 11.706 | .186 | .45 | .03470 | .01470 | [illegible] | 3.11 | 12.[illegible] | 2.89 | 5.36 | 9[illegible].45 | - | | |
| | 10-1 P | 4.046 | 3.055 | 0.991 | .0592 | .0183 | .0402 | 672.4 | [illegible] | 4.14 | 11.756 | .195 | .45 | [illegible] | .0146[illegible] | .0146[illegible] | 3.1[illegible] | 13.56 | 4.77 | 4.88 | 99.26 | - | [illegible] in mix $W_f$ | Takeoff |
| | 10-2 P | 4.044 | 3.054 | 0.990 | .0612 | .0221 | .0391 | 671.3 | 585.8 | 4.11 | 11.796 | .252 | .45 | [illegible] | .0149[illegible] | .0155[illegible] | 3.[illegible] | 14.[illegible] | [illegible] | 4.86 | 99.41 | - | [illegible] premix $W_f$ | |
| | Modification 1 | | | | | | | | | | | | | | | | | | | | | | | |
| A-15 | 10-3 P | 4.119 | 3.037 | 0.981 | .0383 | .0186 | .0197 | 673.[illegible] | 625.8 | 4.17 | 11.552 | .119 | .45 | [illegible] | .01450 | .01720 | 3.36 | 5.07 | [illegible] | 5.03 | 99.89 | - | | |
| | 10-4 P | 4.036 | 3.054 | 0.982 | .0541 | .0187 | .0353 | 671.[illegible] | 613.6 | 4.15 | 11.65[illegible] | - | .45 | [illegible] | .0134[illegible] | .0154[illegible] | 3.13 | [illegible].94 | [illegible] | 5.26 | 99.72 | - | Decreasing premix $W_f$ | Takeoff |
| | 10-5 P | 4.034 | 3.051 | [illegible].983 | .0436 | .0189 | .0247 | 669.1 | 5[illegible].7 | 4.14 | 11.643 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | 75.19 | 265.43 | 4.37 | 75.31 | - | | |
| | 10-6 P | 4.029 | 3.055 | 0.974 | .0314 | .0189 | .0126 | 667.4 | 5[illegible] | 4.1[illegible] | 11.482 | - | .45 | [illegible] | [illegible] | [illegible] | 3.24 | 7[illegible] | [illegible] | [illegible] | [illegible] | - | | |
| | Modification 2 | | | | | | | | | | | | | | | | | | | | | | | |
| A-16 | 10-2 P | 4.043 | 3.057 | 0.986 | .0189 | .0189 | - | 667.4 | [illegible] | 4.16 | 11.[illegible]8 | .251 | .45 | [illegible] | .00467 | [illegible] | 3.04 | [illegible] | [illegible] | [illegible] | [illegible] | | Takeoff, pilot only | |
| | 10-3 P | 4.06[illegible] | 3.074 | 0.983 | .0587 | .0189 | .0398 | 669.7 | 615.9 | 4.14 | 11.689 | [illegible] | .45 | [illegible] | [illegible] | .0160[illegible] | 3.27 | [illegible] | [illegible] | [illegible] | [illegible] | - | | |
| | 10-4 P | 4.07[illegible] | 3.0[illegible] | 0.997 | .0530 | .0189 | .0341 | 668.8 | 62[illegible].4 | 4.14 | 11.65[illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | 15.27 | 4.73 | 5.44 | 99.74 | - | | |
| | 10-5 P | 4.062 | 3.076 | 0.986 | .0436 | .0189 | .0248 | 667.7 | 626.0 | 4.13 | 11.640 | - | .45 | .02510 | .0130[illegible] | .0119 | 2.9[illegible] | 176.32 | 154.74 | 4.15 | 83.42 | - | | |
| | 10-6 P | 4.046 | 3.060 | 0.986 | .032[illegible] | .0189 | .0132 | 666.3 | 645.8 | 4.14 | 11.5[illegible] | - | .45 | [illegible] | [illegible] | [illegible] | 2.19 | 113.21 | 325.68 | 5.13 | 65.25 | - | | |
| | 10-7 P | 4.046 | 3.210 | 0.836 | .0561 | .0189 | .0372 | 668.6 | 656.9 | 4.17 | 11.528 | .120 | .4 | .0446[illegible] | .01436 | [illegible] | 3.12 | 17.[illegible] | 1.67 | 6.2[illegible] | 99.62 | - | Decreasing premix $W_f$ | Takeoff |
| | 11-3 P | 4.062 | 3.077 | [illegible] | .0587 | .0189 | .0399 | 669.1 | [illegible] | 4.13 | 11.934 | .174 | .45 | .04[illegible] | .01446 | [illegible] | [illegible] | [illegible] | 2.71 | 3.7[illegible] | 99.47 | - | | |
| | 11-4 P | 4.046 | 3.063 | 0.987 | .0534 | .0139 | .0345 | 671.2 | 62[illegible].3 | 4.16 | 11.54[illegible] | - | .45 | .0351[illegible] | [illegible] | .0143[illegible] | 3.7[illegible] | 28.41 | [illegible] | 3.58 | 98.54 | - | | |
| | 11-5 P | 4.045 | 3.06[illegible] | 0.995 | .0410 | .0157 | .0251 | 676.2 | 633.6 | 4.18 | 11.479 | - | .45 | .0259[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | | |

[a] The letter P following a condition number indicates use of propane premix fuel.

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, $^{o}K$ | Premix inlet total temperature, $^{o}K$ | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modification 2 (Continued) | | | | | | | | | | | | | | | |
| A-16 | 25-1 | 2.336 | 1.739 | 0.567 | .0159 | .0159 | - | 368.8 | 465.5 | 1.96 | 7.693 | - | .45 | - | [illegible] | [illegible] | [illegible] | [illegible] | 11.45 | [illegible] | [illegible] | - | f/a = .007 | Taxi-Idle |
| | 25-2 | 2.333 | 1.739 | 0.564 | .0224 | .0224 | - | 374.3 | [illegible] | 1.96 | 7.766 | .423 | .45 | - | [illegible] | [illegible] | [illegible] | 47.5 | [illegible] | 3.55 | 98.33 | - | [illegible] premix air | |
| | 25-3 | 2.337 | 1.744 | 0.563 | .0284 | .0284 | - | 374.3 | 472.2 | 1.97 | 7.760 | - | .45 | - | .01232 | [illegible] | [illegible] | [illegible] | [illegible] | 3.68 | 98.85 | - | f/a = .012 | |
| | 26-1 | 2.329 | 1.955 | 0.474 | .0283 | .0283 | - | 369.8 | 479.4 | 1.96 | 7.734 | - | .45 | - | [illegible] | [illegible] | [illegible] | 31.47 | [illegible] | 3.76 | [illegible] | - | f/a = [illegible] premix air | |
| | 26-2 | 2.331 | 1.955 | 0.476 | .0224 | .0224 | - | 368.4 | 482.7 | 1.96 | 7.778 | .436 | .45 | - | [illegible] | [illegible] | [illegible] | [illegible] | 5.87 | 3.64 | [illegible] | - | | |
| | 27-2 | 4.062 | 3.275 | 0.787 | .0512 | .0189 | .0323 | 663.0 | 639.1 | 4.14 | 11.549 | [illegible] | .45 | .03280 | .01201 | [illegible] | [illegible] | [illegible] | [illegible] | 1.96 | [illegible] | - | f/a = .013 | Takeoff |
| | 27-2 | 4.064 | 3.082 | [illegible] | .0579 | .0252 | .0327 | 664.1 | 641.3 | 4.16 | [illegible] | - | .45 | .03310 | .01425 | .01560 | 1.16 | 19.23 | 13.31 | 3.47 | 98.45 | - | f/a = .014 | |
| | 27-3 | 4.036 | 3.053 | 0.983 | .0632 | .0187 | .0444 | 673.0 | 643.0 | 4.15 | 11.625 | .16 | .45 | .04520 | .01566 | .0154 | [illegible] | 26.77 | 18.4 | 3.31 | 98.72 | - | [illegible] premix fuel | |
| | 27-3 | 3.998 | 3.029 | 0.978 | .0633 | .0252 | .0381 | 673.0 | 644.1 | 4.16 | 11.465 | - | .45 | [illegible] | .01583 | .0157 | 3.13 | 18.34 | 14. | [illegible] | 98.34 | - | [illegible] premix fuel | |
| | 26-3 | 2.329 | 1.854 | 0.475 | .0159 | .0159 | - | 366.8 | 493.3 | 1.94 | 7.775 | - | .45 | - | .00683 | .0074 | 1.46 | [illegible] | [illegible] | 2.64 | 97.32 | - | f/a = .007 | Taxi-Idle |
| | 26-4 | 2.333 | 1.939 | 0.369 | .0223 | .0223 | - | 367.3 | 478.3 | 1.96 | 7.644 | - | .45 | - | .00967 | [illegible] | 2.12 | 24.6 | 6.15 | 3.45 | [illegible] | - | 16% premix air | |
| | 27-4 | 4.060 | 3.244 | 0.816 | .0368 | .0183 | .0181 | 668.3 | [illegible] | 4.14 | 11.629 | - | .45 | .02220 | .00911 | [illegible] | 1.37 | 135.09 | 248.24 | [illegible] | 72.66 | - | f/a = .009 | Takeoff |
| | 27-5 | 4.060 | 3.243 | 0.817 | .0506 | .0190 | .0316 | 670.9 | 636.3 | 4.16 | 11.625 | - | .45 | .03866 | .01246 | .0151 | 2.67 | 56.15 | 119.76 | 2.45 | 85.17 | - | f/a = .012 | |
| | 27-6 | 4.064 | 3.250 | 0.814 | .0633 | .0190 | .0440 | 673.9 | 633.8 | 4.14 | 11.707 | .198 | .45 | .05410 | .01552 | [illegible] | 3.34 | 26.77 | [illegible] | 3.48 | [illegible] | - | [illegible] premix air | |
| | 28-1 | 4.050 | 3.073 | 0.977 | .0377 | .0189 | .0189 | 661.4 | [illegible] | 4.17 | [illegible] | - | .45 | .01930 | .00933 | [illegible] | 1.34 | 134.53 | [illegible] | 2.18 | [illegible] | - | | Takeoff Note ① |
| | 28-2 | 4.055 | 3.074 | 0.981 | .0503 | .0189 | .0314 | 666.7 | 653.6 | 4.13 | 11.613 | - | .45 | .03210 | .01242 | .0124 | 2.17 | [illegible] | [illegible] | 2.55 | [illegible] | - | f/a = .012 | |
| | 28-3 | 4.045 | [illegible] | 0.978 | .0626 | .0188 | .0438 | 669.7 | 649.0 | 4.15 | 11.592 | .174 | .45 | [illegible] | [illegible] | .0162 | 3.22 | 25.53 | 13.74 | 2.67 | [illegible] | - | [illegible] premix fuel | |
| | 28-4 | 4.056 | 3.242 | 0.814 | .0377 | .0189 | .0189 | 667.1 | 652.4 | 4.14 | 11.582 | - | .45 | .02320 | .00931 | [illegible] | 1.34 | 147.41 | 273.95 | 2.27 | [illegible] | - | | Takeoff Note ② |
| | 28-5 | 4.056 | 3.243 | 0.813 | .0504 | .0189 | .0316 | 667.6 | 647.4 | 4.14 | 11.562 | - | .45 | .03985 | .01245 | .0126 | 2.27 | 65.68 | 115.67 | 2.77 | [illegible] | - | f/a = .012 | |
| | 28-6 | 4.058 | 3.246 | 0.812 | .0626 | .0189 | .0438 | 670.8 | 640.2 | 4.14 | 11.674 | .172 | .45 | [illegible] | .01545 | .0161 | 3.19 | 27.30 | 11.36 | 4.37 | 98.49 | - | [illegible] premix fuel | |
| | 28-7 | 4.056 | 3.241 | 0.815 | .0628 | .0263 | .0365 | 668.2 | 645.2 | 4.14 | 11.557 | .215 | .45 | .04460 | .01550 | .0164 | 3.27 | 21.47 | 11.78 | 4.67 | [illegible] | - | [illegible] premix fuel | |
| | 28-8 | 4.076 | 3.420 | 0.656 | .0464 | .0275 | .0189 | 669.8 | 649.7 | 4.15 | 11.735 | - | .45 | [illegible] | .01140 | [illegible] | 2.37 | 54.82 | 49.55 | 5.74 | [illegible] | - | 16% premix air, f/a = .012 | Takeoff |
| | 28-9 | 4.07 | 3.409 | 0.661 | .0564 | .0275 | .0289 | 670.6 | 642.4 | 4.14 | [illegible] | - | .45 | [illegible] | [illegible] | .0146 | 2.84 | [illegible] | [illegible] | [illegible] | [illegible] | - | f/a = .014 | |
| | 28-10 | [illegible] | 3.418 | [illegible] | .0629 | .0275 | [illegible] | [illegible] | 637.4 | 4.14 | 11.765 | .236 | .45 | [illegible] | .01544 | [illegible] | 3.22 | [illegible] | 6.6 | 4.52 | [illegible] | - | [illegible] premix fuel | |
| | 29-1 | 4.049 | 3.074 | [illegible] | .0377 | .0189 | .0189 | 665.9 | 615.2 | 4.15 | 11.634 | - | .45 | .01937 | [illegible] | [illegible] | 1.41 | [illegible] | 242.80 | 2.20 | [illegible] | - | | Takeoff Note ③ |
| | 29-2 | 4.048 | [illegible] | [illegible] | .0503 | .0189 | .0314 | [illegible] | 613.6 | 4.16 | 11.631 | - | .45 | [illegible] | .01244 | [illegible] | 2.34 | [illegible] | [illegible] | [illegible] | [illegible] | - | f/a = .012 | |
| | 29-3 | 4.045 | [illegible] | [illegible] | [illegible] | .0189 | .0438 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] premix fuel | |

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/se | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, °K | Premix inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | [illegible] by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Remarks | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Modification [illegible] - Continued | | | | | | | | | | | | | | |
| A-16 | 29-4 | 4.063 | 3.247 | 0.816 | .0379 | [illegible] | [illegible] | [illegible] | 663.6 | 4.16 | 11.726 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | 134.55 | [illegible] | 2.35 | [illegible] | - | | |
| | 29-5 | 4.060 | 3.246 | 0.814 | [illegible] | .0189 | .0314 | 669.4 | [illegible] | 4.16 | 11.723 | - | .45 | .03860 | .01240 | .0122 | [illegible] | [illegible] | 12.21 | 3.4 | 92.37 | - | f/a = [illegible] | |
| | 29-6 | 4.068 | 3.256 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.17 | [illegible] | .168 | .45 | .05390 | .01541 | [illegible] | [illegible] | [illegible] | 7.33 | 5.27 | [illegible] | - | [illegible] premix fuel | Takeoff Note [illegible] |
| | 29-7 | 4.061 | 3.251 | 0.810 | .0626 | .0263 | .0365 | 669.8 | 632.4 | 4.15 | 11.762 | .194 | .45 | .04511 | .01548 | .0163 | [illegible] | 17.22 | [illegible] | 5.85 | [illegible] | - | [illegible] premix fuel | |
| | 29-8 | 4.058 | 3.395 | 0.663 | .0464 | .0275 | .0189 | 673.6 | [illegible] | 4.17 | 11.784 | - | .45 | .02853 | .01144 | .01207 | 2.31 | [illegible] | [illegible] | 6.32 | 95.55 | - | | |
| | 29-9 | 4.068 | 3.411 | 0.657 | .0562 | .0274 | .0288 | 672.1 | 617.4 | 4.17 | 11.796 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 11.47 | [illegible] | [illegible] | - | f/a = [illegible] | Takeoff Note [illegible] |
| | 29-10 | 4.061 | 3.403 | 0.658 | .0623 | .0274 | .0355 | [illegible] | 624.7 | 4.17 | 11.781 | [illegible] | .45 | [illegible] | .01551 | [illegible] | [illegible] | [illegible] | 6.14 | 7.54 | [illegible] | - | [illegible] premix fuel | |
| * | 30-1 P | 4.061 | [illegible] | 0.986 | [illegible] | .0189 | .0174 | 666.1 | 641.3 | 4.14 | 11.582 | - | .45 | [illegible] | [illegible] | [illegible] | 1.4 | 111.4 | 154.7 | [illegible] | [illegible] | - | | |
| | 30-2 P | 4.05 | 3.269 | 0.981 | [illegible] | .0189 | .0297 | 671.8 | 625.8 | 4.14 | 11.674 | - | .45 | [illegible] | [illegible] | .0144 | [illegible] | 4.38 | [illegible] | 3.77 | [illegible] | - | f/a = [illegible] | Takeoff Note [illegible] |
| | 30-3 P | 4.063 | 3.078 | 0.995 | .0587 | .0194 | .0399 | 672.4 | 618.0 | 4.12 | 11.765 | [illegible] | .45 | .04343 | .01446 | [illegible] | [illegible] | 1.22 | [illegible] | 5.51 | 99.97 | - | [illegible] premix fuel | |
| | 30-4 P | 4.062 | 3.245 | 0.817 | .0377 | [illegible] | [illegible] | 666.1 | [illegible] | 4.14 | 11.613 | - | .45 | [illegible] | [illegible] | [illegible] | 1.26 | [illegible] | 114 | 3.89 | 87.38 | - | | |
| | 30-5 P | 4.051 | 3.234 | [illegible] | .0594 | [illegible] | .0315 | [illegible] | 614.7 | 4.14 | 11.704 | - | .45 | .03967 | .01244 | .0153 | [illegible] | [illegible] | [illegible] | 4.91 | 99.95 | - | f/a = .012 | Takeoff Note [illegible] |
| | 30-6 P | 4.055 | 3.242 | 0.813 | .0585 | [illegible] | .0396 | 677.7 | 609.7 | 4.13 | 11.704 | .176 | .45 | .04842 | .01444 | .0177 | 3.46 | 1.41 | [illegible] | 7.15 | 99.96 | - | 68% premix fuel | |
| | 30-7 P | 4.055 | 3.242 | 0.813 | .0597 | .0260 | .0337 | 673.2 | 616.3 | 4.15 | 11.735 | [illegible] | .45 | .0415 | .01475 | [illegible] | [illegible] | 1.27 | [illegible] | 6.62 | [illegible] | - | [illegible] premix fuel | |
| | 30-12 P | 4.063 | [illegible] | 1.127 | .0480 | .0187 | .0292 | 675.1 | 635.8 | 4.14 | 11.659 | - | .45 | .02617 | .01471 | [illegible] | [illegible] | 21.6 | 2.94 | 3.61 | 99.33 | - | | |
| | 30-11 P | 4.057 | 2.945 | 1.112 | .0598 | .0169 | .0399 | 674.9 | 625.2 | 4.14 | 11.613 | .086 | .45 | .03597 | .01444 | [illegible] | 3.46 | [illegible] | [illegible] | 4.23 | [illegible] | - | 68% premix fuel | Takeoff Note [illegible] |
| | 30-[illegible] | 4.062 | 2.943 | 1.119 | .0189 | .0189 | - | 665.5 | 679.1 | 4.16 | [illegible] | - | .45 | - | .00465 | [illegible] | [illegible] | [illegible] | [illegible] | 6.47 | [illegible] | - | Pilot only | |
| | 30-31 | 4.053 | [illegible] | [illegible] | .0199 | .0199 | - | 668.2 | 676.9 | 4.16 | 11.476 | - | .45 | - | .00469 | .00510 | [illegible] | 4.34 | [illegible] | 8.76 | 99.85 | - | Pilot only, 24% premix air | |
| | 31-14 | 2.322 | 1.755 | 0.567 | .0223 | .0223 | - | 376.3 | 364.1 | 1.96 | 7.983 | .225 | .45 | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] Note [illegible] | |
| | 31-32 | 3.242 | 2.462 | 0.789 | .0189 | .0189 | - | [illegible] | 494.7 | 2.91 | [illegible] | .492 | .45 | - | [illegible] | [illegible] | 1.27 | [illegible] | 1.34 | 4.68 | [illegible] | - | Approach. f/a = .026 | |
| | 31-33 | 3.259 | 2.472 | 0.787 | .0382 | .0382 | - | 513.6 | 498.6 | 2.95 | [illegible] | .421 | .45 | - | .01172 | .0124 | [illegible] | [illegible] | .44 | 7.37 | [illegible] | - | [illegible] | |
| | 31-33 | 4.061 | 3.072 | 0.989 | .0189 | .0189 | - | 667.2 | 670.8 | 4.14 | 11.613 | - | .45 | - | .00465 | [illegible] | [illegible] | [illegible] | 6.74 | 4.19 | [illegible] | - | | |
| | 31-2 P | 4.077 | 3.085 | 0.992 | .0477 | .0189 | .0288 | [illegible] | 625.6 | 4.16 | 11.643 | - | .45 | .02917 | .01171 | [illegible] | [illegible] | 33.46 | 144.15 | 4.64 | [illegible] | - | f/a = [illegible] | Takeoff Note [illegible] |
| | 31-3 P | 4.071 | 3.074 | 0.997 | .0586 | .0189 | [illegible] | 670.7 | 619.0 | [illegible] | 11.704 | [illegible] | .45 | [illegible] | .01441 | [illegible] | [illegible] | [illegible] | [illegible] | 4.45 | [illegible] | - | [illegible] premix fuel | |

* The letter P following a condition number indicates use of propane premix fuel.

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, °K | Premix inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | [illegible] by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency, % | SAE smoke number | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Modification 3 | | | | | | | | | | | | | |
| A-17 | 32-1 P | 4.052 | 3.067 | 0.985 | .0434 | .0250 | .0184 | 669.7 | - | 4.17 | 11.460 | - | .45 | .01866 | .01172 | .0121 | 2.13 | 54.41 | [illegible] | 4.77 | 97.93 | - | Takeoff, Note (11) |
| a | 32-1 P | 4.055 | 3.075 | 0.985 | .0372 | .0190 | .0184 | 669.2 | - | 4.13 | 11.646 | - | .45 | .01866 | .00913 | [illegible] | 1.13 | [illegible] | 74.[illegible] | 3.42 | 79.19 | - | f/a = .0[illegible] |
| | 32-2 P | 4.060 | 3.075 | 0.985 | .0475 | .0190 | .0286 | 66[illegible].3 | - | 4.16 | 11.6[illegible] | - | .45 | .02910 | .01171 | .0127 | 2.44 | [illegible] | 6.42 | 3.74 | 99.17 | - | f/a = .012 |
| | 32-3 P | 4.037 | 3.052 | 0.985 | .0159 | .0184 | - | 669.4 | - | 4.14 | 11.592 | - | .45 | - | .00469 | .0154 | [illegible] | [illegible].25 | [illegible].31 | 8.32 | 99.82 | - | Pilot only |
| | 32-3 P | 4.051 | 3.065 | 0.986 | .0584 | .0189 | .0395 | 669.4 | - | 4.15 | 11.613 | .156 | .45 | .0401 | .01144 | .01611 | 3.15 | 2.26 | [illegible] | 3.34 | 99.91 | - | 68% premix fuel |
| | 32-5 | 4.039 | 2.607 | 1.432 | .0189 | .0183 | - | 669.8 | - | 4.14 | 11.340 | - | .45 | - | .00469 | .0052 | 1.[illegible]7 | 16.44 | .44 | 8.08 | 99.73 | - | Takeoff, Note (12) |
| | 32-5 | 4.019 | 2.606 | 1.412 | .0594 | .0183 | .0405 | 670.2 | - | 4.15 | 11.430 | .106 | .45 | .02877 | .01479 | .0168 | 3.29 | 3.54 | 1.[illegible] | 3.71 | 99.93 | - | [illegible] premix fuel |
| | 32-14 | 2.307 | 1.739 | 0.568 | .0250 | .0250 | - | 371.6 | - | 1.96 | 7.766 | - | .45 | - | .01084 | .0105 | 2.11 | 37.49 | [illegible] | 3.11 | 98.86 | - | Taxi-idle, Note (13) |
| | 32-14 | 2.307 | 1.739 | 0.569 | .0222 | .0222 | - | 371.6 | - | 1.96 | 7.766 | .176 | .45 | - | [illegible] | .0096 | 1.[illegible] | 44.61 | 6.21 | 2.7[illegible] | 98.40 | - | |
| | 32-15 | 2.307 | 1.476 | 0.831 | .0222 | .0222 | - | 371.1 | - | 1.96 | 7.736 | - | .45 | - | [illegible] | [illegible] | 1.47 | 44.[illegible] | 4.1[illegible] | 3.17 | [illegible] | | 36% premix air, Taxi-idle |
| | 33-14 | 2.2[illegible] | 1.732 | 0.567 | .0222 | .0222 | - | 37[illegible].4 | - | 1.96 | [illegible] | .155 | .45 | - | [illegible] | [illegible] | [illegible] | [illegible].74 | [illegible] | 1.84 | [illegible] | | Taxi-idle, Note (14) |
| | 33-15 | 2.308 | 1.482 | 0.826 | .0222 | .0222 | - | 37[illegible] 2 | - | 1.45 | 7.733 | - | .45 | - | .0096 | [illegible] | 1.94 | 41.[illegible] | [illegible] | [illegible] | [illegible] | | Taxi-idle, 36% premix air |
| | 33-2 P | 4.059 | 3.069 | 0.989 | .0581 | .0160 | .0421 | 669.6 | - | 4.13 | 11.683 | - | .45 | .0426 | .01433 | .01637 | 3.1[illegible] | 1.4[illegible] | - | 3.67 | 99.97 | - | Takeoff, 72% premix fuel |
| | 33-3 P | 4.054 | 3.067 | 0.987 | .0553 | .0149 | .0404 | 670.7 | - | 4.13 | 11.656 | .103 | .45 | .04195 | .01464 | .0167 | [illegible] | 1.18 | [illegible].32 | 3.45 | 99.97 | - | Takeoff, 6[illegible]% premix fuel |
| | 33-12 P | 4.056 | 2.904 | 1.152 | .0507 | .0190 | .0317 | 668.6 | - | 4.15 | 11.604 | - | .45 | .02761 | .01252 | .0144 | [illegible] | 13.9[illegible] | .47 | 4.[illegible] | 99.61 | - | Takeoff, Note (15) |
| | 34-1 | 4.054 | 3.068 | 0.985 | .0482 | .0189 | .0293 | 664.1 | - | 4.12 | 11.613 | - | .45 | .02980 | .01119 | .0123 | 2.3[illegible] | 112.62 | 14.0[illegible] | 3.26 | 94.37 | - | Takeoff, Note (16) |
| | 34-2 | 4.057 | 3.070 | 0.987 | .0481 | .0221 | .0260 | 665.7 | - | 4.15 | 11.582 | - | .45 | .02637 | .01185 | .01260 | 2.48 | 61.[illegible]8 | 8.21 | 4.[illegible] | 97.92 | - | f/a = .01[illegible] |
| | 34-3 | 4.062 | 3.070 | 0.992 | .0631 | .0222 | .0409 | 668.8 | - | 4.15 | 11.643 | - | .45 | .0413 | .01555 | .0167 | 3.41 | 1.46 | 0.50 | 3.51 | 99.91 | - | 65% premix fuel |
| | 34-5 | 4.062 | 3.091 | 0.991 | .0627 | .0157 | .0470 | 665.7 | - | 4.15 | 11.674 | .145 | .45 | .04490 | .01551 | .01637 | 3.37 | [illegible] | - | [illegible].14 | 99.91 | - | 7[illegible]% premix fuel |
| | 34-4 | 4.053 | 3.063 | 0.984 | .0624 | .0165 | .0439 | 667.[illegible] | - | 4.15 | 11.613 | .146 | .45 | .0447 | .01559 | .0165 | 3.37 | .43 | - | 3.37 | 99.94 | - | 7[illegible]% premix fuel |
| | 34-6 | 4.051 | [illegible] | 1.25[illegible] | .0482 | .019[illegible] | .0292 | 666.9 | - | 4.12 | 11.674 | - | .45 | .02547 | .01191 | .0119 | 2.54 | 14[illegible].7[illegible] | 95.37 | 2.73 | 84.57 | - | |
| | 34-7 | 4.056 | 2.907 | 1.149 | .0490 | .0252 | .0229 | 665.7 | - | 4.14 | 11.613 | - | .45 | [illegible] | .01185 | [illegible] | 2.[illegible]4 | 114.64 | [illegible] | 4.51 | 95.5[illegible] | - | f/a = .012; Takeoff, Note (17) |
| | 34-8 | 4.049 | 2.90[illegible] | 1.149 | .0631 | .0222 | .04[illegible]9 | 666.7 | - | 4.14 | 11.6[illegible]3 | - | .45 | .03[illegible] | .0156 | .0167 | 3.3[illegible] | .4[illegible] | [illegible] | 3.36 | 99.94 | - | 65% premix fuel |
| | 34-9 | 4.065 | 2.907 | 1.156 | .06[illegible]8 | .0183 | .0439 | 666.5 | - | 4.13 | 11.674 | [illegible] | .45 | [illegible] | .0154 | .016[illegible] | 3.[illegible] | [illegible] | [illegible] | 2.5[illegible] | 99.91 | - | 7[illegible]% premix fuel |
| | 34-10 | 4.055 | [illegible] | 1.149 | .0624 | .015[illegible] | .047[illegible] | 667.3 | - | 4.14 | 11.626 | .141 | .45 | .041[illegible] | .015[illegible] | [illegible] | [illegible] | 5.[illegible] | [illegible] | 2.68 | 99.97 | - | 75% premix fuel |
| | 34-4 | 4.0[illegible] | 3.06[illegible] | 0.987 | .062[illegible] | [illegible] | .044[illegible] | [illegible] | - | 4.14 | 11.61[illegible] | .14[illegible] | .45 | .04[illegible] | [illegible] | .016[illegible] | [illegible] | 2.[illegible] | .44 | [illegible] | 9[illegible].9[illegible] | - | Takeoff, 7[illegible]% premix fuel |

a The letter P following a condition number indicates use of propane premix fuel

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Main combustor airflow, kg/sec | Premix airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Main inlet total temperature, °K | Premix inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Premix fuel/air ratio, metered | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Modification 3 (Continued) | | | | | | | | | | | | | | |
| A-17 | 34-33 | 5.840 | 4.437 | 1.403 | .0623 | .0327 | .0296 | 505.9 | - | 5.20 | 10.986 | - | .45 | .02110 | .01150 | .01259 | 1.83 | 157.29 | 232.22 | 1.15 | 75.5[illegible] | - | Approach, 44% premix fuel | |
| | 34-34 | 4.886 | 3.716 | 1.170 | .0567 | .0567 | - | 508.4 | - | 4.36 | 9.583 | - | .45 | - | .01161 | .01127 | 2.28 | 7.91 | 0.75 | 6.55 | 96.77 | - | Approach, pilot only | |
| | 34-23 | 4.107 | 3.112 | 0.995 | .0610 | .0214 | .0396 | 652.9 | - | 4.13 | 11.506 | - | .45 | .03980 | .01488 | .01577 | 3.14 | 3.11 | 0.24 | 3.21 | 99.92 | - | 65% premix fuel | Climb, Note (18) |
| | 34-24 | 4.121 | 3.126 | 0.995 | .0610 | .0184 | .0426 | 650.5 | - | 4.12 | 11.531 | - | .45 | .04280 | .01481 | .01563 | 3.18 | 5.01 | 0.07 | 2.96 | 99.88 | - | [illegible] premix fuel | |
| | 34-28 | 4.123 | 2.973 | 1.157 | .0610 | .0214 | .0396 | 649.9 | - | 4.14 | 11.488 | - | .45 | .03450 | .01480 | .01580 | 3.20 | 7.30 | 0.27 | 2.92 | 99.80 | - | | |
| | 34-29 | 4.112 | 2.958 | 1.154 | .0610 | .0184 | .0426 | 651.6 | | 4.12 | 11.5[illegible] | - | .45 | .03690 | .01480 | .0159[illegible] | 3.21 | 11.[illegible] | 0.57 | 2.59 | 99.67 | - | [illegible] premix fuel | |

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix F figure | Condition number | Total airflow, kg/sec | Air-assist airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modification 4 | | | | | | | | | | | | |
| A-18 | 40-42 | 2.296 | - | .0221 | .0221 | - | 372.1 | 1.96 | 7.742 | .180 | .45 | .00962 | [illegible] | 1.94 | 64.93 | 11.79 | [illegible] | 97.12 | - | Taxi-idle, Note ⑲ | |
| | 40-42 | 2.185 | - | .0246 | .0246 | - | 367.4 | 1.91 | 7.428 | - | .45 | .01130 | .01160 | 2.31 | 42.41 | 4.56 | 2.71 | 98.60 | - | Taxi-idle, 5% Bleed | |
| | 40-11 | 5.121 | - | .0596 | .0596 | - | [illegible] | 4.58 | 9.801 | .189 | .45 | .01164 | .01250 | 2.55 | 8.32 | [illegible] | [illegible] | 99.79 | - | [illegible], pilot only | |
| | 40-14 | 4.058 | - | .0629 | .0184 | .0441 | 667.2 | 4.14 | 11.691 | .196 | .45 | .01553 | .01620 | 3.29 | 11.[illegible] | [illegible] | 4.34 | [illegible] | - | Takeoff, Note [illegible] | |
| | 40-41 | 2.322 | - | .0223 | .0223 | - | 369.3 | 1.97 | 7.733 | .177 | .45 | .00963 | .01015 | 1.94 | 61.11 | 10.24 | [illegible] | 97.66 | - | | Taxi-idle |
| | 40-42 | 2.208 | - | .0247 | .0247 | - | 369.3 | 1.92 | 7.522 | - | .45 | .01122 | .01170 | 2.34 | 41.11 | [illegible] | [illegible] | 98.62 | - | 5% Bleed | |
| | 40-11 | 4.044 | - | .0157 | .0187 | - | 661.9 | 4.15 | 11.393 | .170 | .45 | .00464 | .00510 | 1.06 | 9.47 | [illegible] | [illegible] | 99.75 | - | | Takeoff, pilot only, 30 premix nozzles |
| | 40-12 | 4.019 | - | .0379 | .0189 | .0191 | 664.3 | 4.12 | 11.439 | - | .45 | [illegible] | .00920 | [illegible] | 154.34 | 76.98 | [illegible] | 89.62 | - | f/a = [illegible] | |
| | 40-13 | 4.047 | - | .0506 | .0189 | .0317 | 664.9 | 4.13 | 11.518 | - | .45 | .01251 | .01300 | 2.62 | 25.62 | 1.04 | [illegible] | 99.13 | - | f/a = .013 | |
| | 41-1 | 4.055 | - | .0161 | .0161 | - | 662.2 | 4.15 | 11.387 | - | .45 | .00397 | .00460 | 0.94 | 13.05 | 0.54 | 7.44 | 99.64 | - | | Takeoff - pilot only, all premix nozzles |
| | 41-2 | 4.052 | - | .0623 | .0161 | .0461 | 666.5 | 4.13 | [illegible] | - | .45 | .01540 | .01647 | 3.34 | 9.21 | 0.54 | 4.44 | 99.73 | - | [illegible] premix fuel | |
| | 41-4 | 4.050 | - | .0627 | .0221 | .0391 | 666.9 | 4.13 | 11.537 | .203 | .45 | .01550 | .01640 | 3.38 | 9.58 | 0.51 | 4.22 | 99.73 | - | [illegible] premix fuel | |
| | 41-4 | 4.050 | - | .0627 | .0221 | [illegible] | 666.9 | 4.13 | 11.537 | .203 | .45 | .01550 | .01640 | 3.32 | [illegible] | [illegible] | 4.25 | 99.69 | - | [illegible] premix fuel | |
| | 41-5 | 4.055 | - | .0250 | .0250 | - | 665.2 | 4.14 | 11.503 | - | .45 | .00617 | .00670 | 1.38 | [illegible] | [illegible] | 8.41 | [illegible] | - | | |
| | 41-6 | 4.479 | - | .0687 | .0207 | .0482 | 667.4 | 4.13 | 12.789 | - | .45 | .01540 | .01620 | 3.76 | [illegible] | 2.56 | [illegible] | 99.31 | - | | Takeoff - Note [illegible] |
| | 41-11 | 4.046 | - | .0189 | .0189 | - | 666.9 | 4.15 | 11.454 | - | .45 | .00467 | [illegible] | 1.17 | 8.76 | [illegible] | [illegible] | 99.77 | - | Pilot only | |
| | 41-12 | 4.047 | - | .0377 | .0189 | .0188 | 669.1 | 4.13 | 11.558 | - | .45 | .00931 | .00940 | 1.57 | [illegible] | [illegible] | [illegible] | 83.76 | - | f/a = [illegible] | |
| | 41-13 | 4.046 | - | .0501 | .0189 | .0313 | 668.1 | 4.12 | 11.585 | - | .45 | .01241 | .01360 | 2.44 | 51.77 | [illegible] | 2.74 | [illegible] | - | f/a = .012 | |
| | 41-14 | 4.049 | - | .0627 | .0189 | .0439 | 667.2 | 4.15 | 11.503 | - | .45 | .01550 | .01650 | [illegible] | [illegible] | [illegible] | 4.34 | [illegible] | - | [illegible] premix fuel | |
| | 42-11 | [illegible] | - | .0189 | .0189 | - | 667.1 | 4.13 | 11.661 | .201 | .45 | .00465 | [illegible] | 1.03 | [illegible] | [illegible] | [illegible] | [illegible] | - | | Takeoff, 8 In. injection length, pilot only |
| | 42-12 | 4.041 | - | .0377 | .0189 | .0188 | 666.7 | 4.14 | 11.509 | - | .45 | .00933 | [illegible] | 1.53 | [illegible] | [illegible] | [illegible] | [illegible] | - | f/a = .009 | |
| | 42-13 | 4.046 | - | .0503 | .0189 | .0314 | 669.4 | 4.13 | 11.585 | - | .45 | [illegible] | [illegible] | 2.66 | 25.37 | [illegible] | [illegible] | [illegible] | - | f/a = .012 | |
| | 42-14 | 4.069 | - | .0627 | .0189 | .0439 | 668.0 | 4.14 | 11.634 | [illegible] | .45 | .01542 | .01630 | 3.37 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] premix fuel | |
| | 42-21 | 4.138 | - | [illegible] | .0182 | .0427 | [illegible] | 4.14 | 11.531 | .305 | .45 | [illegible] | [illegible] | [illegible] | 13.91 | [illegible] | [illegible] | [illegible] | - | [illegible] premix fuel | |

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Air-assist airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Modification 4 (Continued) | | | | | | | | | | | | |
| | 42-1 | [illegible] | - | .0691 | .0276 | .0415 | 668.9 | 4.16 | 12.863 | - | .45 | .01535 | .01675 | 3.34 | [illegible] | [illegible] | 4.71 | [illegible] | - | Note ㉒ | |
| | 42-2 | 4.067 | - | [illegible] | .0161 | .0468 | 666.5 | 4.15 | [illegible] | - | .45 | .01549 | [illegible] | 3.33 | [illegible] | [illegible] | [illegible] | [illegible] | - | 74% premix fuel | Takeoff |
| | 42-3 | 4.068 | - | .0626 | [illegible] | [illegible] | 668.6 | 4.14 | [illegible] | .241 | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.40 | 99.85 | - | [illegible] premix fuel | |
| | 42-4 | 4.054 | - | .0627 | .0221 | .0406 | 668.9 | 4.14 | 11.598 | - | .45 | .01548 | [illegible] | 3.41 | [illegible] | [illegible] | 4.44 | 99.85 | - | [illegible] premix fuel | |
| | 42-6 | 4.773 | - | .0688 | .0207 | .0480 | 668.2 | 4.13 | 11.692 | .296 | .45 | .01442 | [illegible] | 3.30 | 4.48 | 0.61 | 4.75 | 99.72 | - | Note ㉓ | |
| | 43-41 | 2.283 | - | .0222 | .0222 | - | 369.1 | 1.97 | 7.574 | .165 | .45 | .00974 | .01020 | [illegible] | 52.66 | 7.1 | [illegible] | 98.14 | - | Taxi-Idle, Note ㉔ | |
| | 43-42 | 2.181 | - | .0246 | .0246 | - | 369.8 | 1.92 | 7.364 | - | .45 | .01130 | .01190 | 2.37 | 37.54 | [illegible] | 2.85 | 98.95 | - | 5% Bleed | Taxi-Idle |
| | 43-43 | 1.927 | - | .0292 | .0292 | - | 370.2 | [illegible] | 6.431 | - | .45 | .01516 | .01620 | 3.28 | 16.41 | [illegible] | 3.37 | 99.56 | - | 15% Bleed | |
| | 43-11 | 4.086 | - | .0189 | .0189 | - | 664.1 | 4.15 | 11.592 | - | .45 | .00462 | .00510 | 1.05 | 7.86 | [illegible] | 7.04 | 99.76 | - | Pilot only | |
| | 43-12 | 4.058 | - | .0378 | .0189 | .0189 | 668.4 | 4.14 | 11.579 | - | .45 | .00932 | .00860 | 1.52 | 245.57 | 14.59 | 3.06 | 92.94 | - | f/a = .009 | |
| | 43-13 | 4.073 | - | .0503 | .0189 | .0314 | 667.1 | 4.15 | 11.546 | .276 | .45 | .01236 | .01340 | [illegible] | 29.96 | 2.86 | 3.48 | [illegible] | - | f/a = .012 | Takeoff |
| | 43-14 | 4.061 | - | .0628 | .0189 | [illegible] | 667.6 | 4.15 | 11.558 | .199 | .45 | .01548 | [illegible] | 3.41 | [illegible] | 0.21 | 4.48 | 99.84 | - | [illegible] premix fuel | |
| | 43-3 | 4.076 | - | .0624 | .0250 | .0374 | 669.5 | 4.17 | 11.695 | .175 | .45 | .01531 | .01640 | 3.34 | 4.11 | [illegible] | 4.32 | 99.90 | - | [illegible] premix fuel | |
| | 43-6 | 4.478 | - | .0690 | .0209 | .0482 | 667.8 | 4.13 | 12.811 | .190 | .45 | .01543 | .01633 | 3.32 | [illegible] | [illegible] | 4.18 | 99.77 | - | Note ㉕ | |
| | 43-21 | 4.130 | - | .0609 | .0182 | .0427 | 659.2 | 4.14 | 11.436 | .204 | .45 | .01475 | .01580 | 3.19 | [illegible] | [illegible] | 3.82 | 99.42 | - | [illegible] premix fuel | |
| | | | | | | | | | Modification 5 | | | | | | | | | | | | |
| A-13 | 44-41 | 2.306 | - | .0222 | .0222 | - | 369.1 | 1.97 | 7.647 | .207 | .45 | .00963 | .01020 | 2.03 | 46.59 | [illegible] | [illegible] | 98.41 | - | | Taxi-Idle |
| | 44-42 | 2.232 | - | .0250 | .0250 | - | 369.1 | 1.92 | 7.501 | - | .45 | .01117 | [illegible] | 2.41 | 32.62 | 2.24 | 2.77 | 99.34 | - | 5% Bleed | |
| | 44-44 | 2.066 | - | .0266 | .0266 | - | 370.1 | [illegible] | 7.132 | - | .45 | .01289 | .01353 | 2.73 | 23.72 | [illegible] | [illegible] | [illegible] | - | 10% Bleed* | |
| | 44-31 | [illegible] | - | .0339 | .0339 | - | 499.3 | 2.60 | 9.824 | .215 | [illegible] | [illegible] | .01220 | 2.48 | 8.45 | 1.15 | 4.55 | 99.68 | - | Approach* | |
| | 44-11 | 4.064 | - | .0199 | .0189 | - | 665.8 | 4.11 | 11.552 | .221 | .45 | .00465 | [illegible] | 1.06 | [illegible] | 0.43 | 8.92 | 99.74 | - | Pilot only | Takeoff |
| | 44-14 | 4.069 | - | .0629 | [illegible] | .0440 | 666.2 | 4.13 | 11.592 | .226 | .45 | .01545 | .01663 | 3.39 | [illegible] | [illegible] | 4.84 | [illegible] | - | | |
| | | | | | | | | | Refinement Test ([illegible] swirler area) | | | | | | | | | | | | |
| A-[illegible] | 45-41 | [illegible] | - | [illegible] | .0222 | - | 369.6 | 1.97 | 7.629 | .196 | .45 | .00960 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | | Taxi-Idle |
| | 45-42 | 2.176 | - | .0246 | .0246 | | 369.1 | 1.99 | [illegible] | - | .45 | .01132 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] Bleed* | |
| | 45-31 | [illegible] | - | .0336 | .0336 | - | 500.2 | [illegible] | [illegible] | .185 | .45 | .01160 | [illegible] | 2.44 | [illegible] | [illegible] | [illegible] | [illegible] | - | Approach* | |
| | 45-11 | [illegible] | - | .0149 | [illegible] | - | 666.1 | 4.16 | 11.491 | [illegible] | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | Takeoff, pilot only | |
| | 45-1 | [illegible] | - | [illegible] | [illegible] | - | 665.4 | 4.14 | 11.552 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | Takeoff, pilot only | |

# TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Air-assist airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Refinement Test 1 (50% swirler area) (Continued) | | | | | | | | | | | | | | | | | | | | |
| | 45-5 | 4.324 | - | .0251 | .0251 | - | 667.2 | 4.14 | 11.582 | - | .45 | .00620 | [illegible] | 1.37 | [illegible] | [illegible] | [illegible] | [illegible] | - | | Takeoff, pilot only, 3 in. premix injection length |
| | 45-12 | 4.070 | - | .0378 | .0189 | .0189 | 667.1 | 4.15 | 11.552 | - | .45 | [illegible] | [illegible] | 1.7[illegible] | 141.31 | 31.[illegible] | 6.23 | [illegible] | - | f/a = .009 | |
| | 45-12 | 4.069 | - | .0383 | .0282 | .0101 | 668.[illegible] | 4.14 | 11.613 | - | .45 | .00940 | [illegible] | 1.91 | 25.[illegible] | 4.[illegible] | [illegible] | [illegible] | - | f/a = .009 | |
| | 45-13 | 4.065 | - | .0531 | .0250 | .0253 | 664.7 | 4.14 | 11.613 | - | .45 | .0124 | .0128 | [illegible] | 6.02 | [illegible] | 4.21 | [illegible] | - | f/a = .013 | |
| | 45-13 | 4.074 | - | .0506 | .0189 | .0318 | 666.1 | 4.14 | 11.582 | - | .45 | .01260 | .0127 | [illegible] | [illegible] | [illegible] | 4.41 | [illegible] | - | f/a = .013 | |
| | 45-14 | 4.065 | - | .0632 | .0189 | .0443 | 667.7 | 4.13 | 11.582 | .242 | .45 | .01560 | .01540 | [illegible] | 2.57 | - | 5.38 | [illegible] | - | 70% premix fuel | |
| | 45-2 | 4.064 | - | .0632 | .0159 | .0474 | 665.9 | 4.14 | 11.552 | .342 | .45 | .01560 | .01530 | 3.23 | 4.[illegible] | - | [illegible] | [illegible] | - | 75% premix fuel | |
| | 45-3 | 4.071 | - | .0631 | .0125 | .0506 | 665.9 | 4.14 | 11.582 | .321 | .45 | .01560 | .0157 | 3.29 | 6.74 | 0.[illegible] | 3.[illegible] | 99.83 | - | 80% premix fuel | |
| | 46-14 | 4.063 | - | .0567 | .0189 | .0378 | 667.7 | 4.11 | 11.7[illegible] | - | .45 | .0140 | .01470 | 3.[illegible] | 4.86 | [illegible] | 4.83 | 99.82 | - | f/a = .014 | Takeoff |
| | 46-14 | 4.061 | - | .0631 | .0189 | .0442 | 667.7 | 4.14 | 11.60[illegible] | .156 | .45 | .01560 | .0164 | 3.34 | 2.56 | 0.26 | 5.61 | 99.92 | - | 70% premix fuel | |
| | 46-2 | 4.066 | - | .0632 | .0158 | .0474 | 667.7 | 4.13 | 11.629 | .231 | .45 | .01560 | .0163 | 3.26 | [illegible] | [illegible] | 5.[illegible] | 99.8[illegible] | - | 75% premix fuel | |
| | 46-3 | 4.069 | - | .0633 | .0127 | .0505 | 664.9 | 4.13 | 11.576 | .224 | .45 | .01560 | .0170 | 3.45 | [illegible] | [illegible] | 4.21 | 99.93 | - | 80% premix fuel | |
| | 46-15 | 4.066 | - | .0630 | .0094 | .0536 | 665.8 | 4.12 | 11.606 | .195 | .45 | .01510 | .0161 | 3.25 | 16.16 | [illegible] | 3.96 | 99.54 | - | 85% premix fuel | |
| | Refinement Test 2 (Full swirler area) | | | | | | | | | | | | | | | | | | | | |
| A-21 | 47-41 | 2.318 | - | .0222 | .0222 | - | 367.2 | 1.94 | 7.584 | .178 | .45 | [illegible] | .00973 | 1.4[illegible] | 74.49 | .67 | 2.31 | 96.96 | - | | Taxi-Idle |
| | 47-42 | 2.176 | - | .0247 | .0247 | - | 368.5 | 1.91 | 7.343 | - | .45 | .01140 | .01140 | 2.28 | 57.97 | 5.12 | 2.54 | 98.24 | - | 5% Bleed | |
| | 47-44 | 2.059 | - | .0266 | .0266 | - | 368.2 | 1.90 | 7.026 | - | .45 | .01290 | .01290 | 2.59 | 38.[illegible] | 2.[illegible] | 2.66 | 98.[illegible] | - | 10% Bleed | |
| | 47-31 | 2.901 | - | .0337 | .0337 | - | 4[illegible] | 2.6[illegible] | 9.805 | .157 | .45 | .01160 | .01180 | [illegible] | 16.48 | - | 4.47 | 99.61 | - | Approach | |
| | 47-11 | 4.052 | - | .0189 | .0189 | - | 667.4 | 4.14 | 11.573 | .240 | .45 | .00477 | [illegible] | 1.35 | 5.32 | 1.63 | - | 99.73 | - | Pilot only | |
| | 47-14 | 4.064 | - | .0627 | .0189 | .0438 | 667.4 | 4.14 | 11.619 | .143 | .45 | .01540 | .01590 | 3.22 | 11.39 | 1.[illegible] | 4.56 | 99.46 | - | 70% premix fuel | |
| | 47-2 | 4.059 | - | .0635 | .0158 | .0477 | 668.3 | 4.13 | 11.613 | .206 | .45 | .01570 | [illegible] | 3.23 | [illegible] | 4.[illegible] | 4.13 | [illegible] | - | 75% premix fuel | Takeoff |
| | 47-3 | 4.064 | - | .0633 | .0127 | .0506 | 662.2 | 4.14 | 11.604 | .248 | .45 | .01560 | [illegible] | 3.22 | 22.[illegible] | 4.27 | 4.27 | 99.13 | - | 80% premix fuel | |
| | 47-15 | 4.058 | - | .0630 | .0094 | .0536 | 672.3 | 4.12 | 11.747 | .251 | .45 | .01560 | .0155 | [illegible] | [illegible] | [illegible] | 4.36 | 99.55 | - | 85% premix fuel | |
| | 49-41 | 2.322 | - | .0222 | .0222 | - | 367.1 | 1.93 | 7.552 | .221 | .45 | .0096 | [illegible] | 1.41 | 71.86 | [illegible] | 2.31 | [illegible] | - | | Taxi-Idle |
| | 49-42 | 2.195 | - | .0246 | .0246 | - | 367.1 | 1.89 | 7.320 | - | .45 | .01120 | .0110 | 2.29 | [illegible] | [illegible] | [illegible] | [illegible] | - | 5% Bleed | |
| | 49-44 | 2.[illegible] | - | .0266 | .0266 | - | 368.2 | 1.93 | [illegible] | - | .45 | .01290 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 98.28 | - | 10% Bleed | |
| | 49-31 | 3.159 | - | .0440 | .0440 | - | 5[illegible] | 3.4[illegible] | [illegible] | .14[illegible] | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.[illegible] | [illegible] | | Approach | |
| | 49-11 | 4.069 | - | .0189 | .0189 | - | | 4.11 | 11.584 | .165 | .45 | .00460 | .00510 | [illegible] | [illegible] | [illegible] | 4.10 | 49.[illegible] | - | Note ① | |
| | 49-12 | 4.071 | - | .0378 | .0189 | .0189 | 664.8 | 4.13 | 11.567 | - | .45 | .00930 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | f/a = .009 | |

## TEST RESULTS FOR CONCEPT 3 (Continued)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Air-assist airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $CO_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Gas sample combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Refinement Test 1 (full swirler area) (Continued) | | | | | | | | | | | | | | | | | | | | | |
| | 48-13 | 4.058 | - | .0503 | .0189 | .0314 | 667.2 | 4.15 | 11.566 | - | .45 | .01245 | [illegible] | 2.51 | 37.82 | 3.63 | 4.[illegible] | 96.74 | - | | Takeoff |
| | 48-14 | 4.055 | - | .0627 | .0189 | .0419 | 670.2 | 4.14 | 11.611 | .267 | .45 | .01550 | .01581 | 3.21 | 6.47 | [illegible] | 4.34 | 99.83 | - | 7[illegible] premix fuel, f/a = .012 | |
| | 48-2 | 4.069 | - | .0634 | .0159 | .0475 | 665.1 | 4.16 | 11.583 | .181 | .45 | .01561 | .0159 | 3.23 | [illegible] | .44 | 4.47 | 99.6[illegible] | - | [illegible] premix fuel, f/a = .012 | |
| Refinement Test 2 (Airblast nozzles, 5[illegible] swirler area) | | | | | | | | | | | | | | | | | | | | | |
| A-12 | 49-41 | 2.323 | [illegible] | .0222 | .0222 | - | 367.9 | 1.98 | 7.579 | .189 | .45 | [illegible] | [illegible] | 1.84 | [illegible] | 48.15 | [illegible] | 94.57 | - | [illegible] kPa AA | Taxi-idle |
| | 49-411 | 2.329 | .0234 | .0222 | .0222 | - | 368.7 | 1.98 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 49-412 | 2.337 | .0359 | .0222 | .0222 | - | 366.7 | 1.98 | 7.651 | - | .45 | [illegible] | [illegible] | [illegible] | 41.[illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 49-413 | 2.363 | .0494 | .0222 | .0222 | - | 368.4 | 1.98 | 7.724 | - | .45 | [illegible] | [illegible] | 1.88 | 44.[illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 49-414 | 2.383 | .0662 | .0221 | .0221 | - | 368.2 | 1.98 | 7.790 | - | .45 | .00938 | [illegible] | 1.25 | 46.93 | 14.44 | 1.64 | 97.23 | - | 5[illegible] kPa AA | |
| | 49-322 | 5.891 | .0343 | .0671 | .0671 | - | 5[illegible]5.8 | 5.22 | [illegible] | - | .45 | .01140 | .01130 | 2.3[illegible] | 1[illegible].48 | [illegible] | 5.61 | [illegible].71 | - | 137 kPa AA | Approach |
| | 49-324 | 5.915 | .0491 | .0671 | .0671 | - | 562.4 | 5.22 | [illegible] | - | .45 | .01140 | .01127 | 2.3[illegible] | 9.73 | .42 | 5.47 | 99.73 | - | 274 kPa AA | |
| | 49-326 | 5.944 | .0632 | .0671 | .0671 | - | 561.3 | 5.23 | [illegible] | - | .45 | .01130 | .0113 | 2.31 | [illegible] | .23 | 5.[illegible] | 99.79 | - | 409.5 kPa AA | |
| | 49-11 | 4.052 | .0159 | .0189 | .0189 | - | 668.7 | 4.15 | 11.595 | .160 | .45 | .00475 | .00464 | [illegible] | 31.81 | [illegible] | 5.[illegible] | [illegible] | - | 137 kPa AA, pilot only f/a = [illegible] | Takeoff |
| | 49-112 | 4.058 | .0249 | .0189 | .0189 | - | 668.[illegible] | 4.15 | 11.677 | - | .45 | .00462 | .00482 | [illegible].98 | 28.24 | [illegible] | 5.[illegible] | 96.20 | - | [illegible].7 kPa AA, pilot only f/a = [illegible] | |
| | 49-116 | 4.114 | .0575 | .0189 | .0189 | - | 667.4 | 4.15 | 11.761 | - | .45 | .00460 | .00420 | [illegible].83 | 51.63 | 14.17 | 4.41 | 97.54 | - | 41[illegible] kPa AA, pilot only f/a = .0045 | |
| | 49-012 | 4.091 | .0299 | .0159 | .0159 | - | 666.9 | 4.14 | 11.719 | - | .45 | .00393 | .00390 | .74 | 49.41 | 73.46 | 4.56 | 92.36 | - | 139 kPa AA, pilot only f/a = .004 | |
| | 49-352 | 4.059 | .0331 | .0251 | .0251 | - | 670.8 | 4.15 | 11.755 | - | .45 | .00624 | .00620 | 1.27 | 10.71 | [illegible].05 | 7.42 | 99.76 | - | 139 kPa AA, pilot only f/a = .006 | |
| | 49-052 | 4.097 | .0359 | .0378 | .0378 | - | 669.7 | 4.14 | 11.729 | - | .45 | .00924 | .00960 | 1.96 | 4.61 | .17 | 8.44 | 99.88 | - | 139 kPa AA, pilot only f/a = .009 | |
| | 49-142 | 4.109 | .0307 | .0633 | .0378 | 0.0255 | 669.1 | 4.15 | 11.681 | - | .45 | .01550 | .0154 | 3.21 | 17.11 | .56 | 5.27 | 99.55 | - | 138 kPa AA, 40% premix fuel | |
| | 49-14 | 4.093 | .0331 | .0627 | .0189 | .0439 | 668.[illegible] | 4.15 | 11.681 | .296 | .45 | [illegible] | .01562 | 3.27 | [illegible] | [illegible] | 2.46 | 97.80 | - | 13[illegible] kPa AA, [illegible] premix fuel | |
| | 49-422 | 2.233 | .0291 | .0247 | .0247 | - | 369.3 | 1.91 | 7.449 | - | .45 | [illegible] | .01110 | 2.25 | [illegible] | 1.51 | 2.14 | 99.15 | - | 5% Bleed, 137 kPa AA | Taxi-idle |
| | 49-423 | 2.226 | .0475 | .0246 | .0246 | - | 367.7 | 1.92 | 7.467 | - | .45 | .0111 | .0110 | 2.21 | 31.5[illegible] | [illegible] | 1.9[illegible] | 95.04 | - | 5% Bleed, 3[illegible] kPa AA | |
| | 49-424 | 2.[illegible] | .0643 | .0246 | .0246 | - | 366.8 | 1.92 | 7.562 | - | .45 | [illegible] | [illegible] | 2.21 | 37.[illegible] | 4.40 | [illegible] | 98.69 | - | 5% Bleed, [illegible] kPa AA | |
| | 49-442 | 2.132 | .0240 | .0268 | .0268 | - | 366.6 | 1.90 | 7.134 | - | .45 | [illegible] | .0126 | 2.56 | [illegible] | [illegible] | 2.2[illegible] | 99.41 | - | [illegible] Bleed, 1[illegible] kPa AA | |
| | 49-443 | 2.126 | .0467 | .0266 | .0266 | - | 366.3 | 1.89 | 7.220 | - | .45 | .01210 | .01263 | 2.54 | [illegible] | [illegible] | 1.9[illegible] | [illegible] | - | [illegible] Bleed, 131 kPa AA | |
| | 49-31 | 2.321 | .0159 | .0336 | .0336 | - | 497.4 | 2.61 | 6.941 | .176 | .45 | .01150 | .0116 | 2.34 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA, [illegible] engine pressure | Approach |
| | 49-314 | 2.941 | .0396 | .0336 | .0336 | - | 56[illegible].4 | 2.6[illegible] | [illegible] | - | .45 | .01140 | [illegible] | 2.37 | 15.5[illegible] | [illegible] | 4.29 | [illegible] | - | [illegible] kPa AA | |
| | 49-316 | 2.9[illegible] | [illegible] | .0337 | .0337 | - | [illegible].3 | 2.6[illegible] | [illegible] | - | .45 | .01140 | .0116 | 2.36 | 1[illegible].43 | .24 | 4.47 | [illegible] | - | 274 kPa AA | |
| | 49-32 | 5.842 | [illegible] | .0671 | .0671 | - | 535.8 | 5.2[illegible] | [illegible] | .178 | .45 | .01145 | .0116 | 2.32 | 14.3 | [illegible] | 5.7[illegible] | [illegible] | - | [illegible] kPa AA, full engine pressure | |

# TEST RESULTS FOR CONCEPT 3 (Concluded)

| Configuration - ref. Appendix A figure | Condition number | Total airflow, kg/sec | Air-assist airflow, kg/sec | Total fuel flow, kg/sec | Pilot fuel flow, kg/sec | Premix fuel flow, kg/sec | Inlet total temperature, °K | Inlet total pressure, Pa x $10^{-5}$ | Reference velocity, m/sec | Temperature spread factor | Inlet air humidity, g/kg air | Overall fuel/air ratio, metered | Overall fuel/air ratio, carbon balance | $O_2$, percent by volume | Emission index, CO | Emission index, HC | Emission index, $NO_x$, corrected for humidity | Combustion efficiency | SAE smoke number | Comments | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Refinement Test 2 (Airblast nozzles Grommet Configuration) | | | | | | | | | | | | | | | | | | | | | |
| A-23 (a) | 50-41 | 2.310 | .0117 | .0222 | .0222 | - | 366.[illegible] | 1.98 | 7.554 | - | .45 | .00965 | [illegible] | 1.68 | 117.36 | 136.32 | 1.22 | [illegible] | - | [illegible] AA | |
| | 50-411 | 2.323 | .0232 | .0221 | .0221 | - | 366.8 | 1.98 | 7.568 | - | .45 | [illegible] | [illegible] | 1.78 | 93.97 | 65.49 | 1.45 | [illegible] | - | [illegible] AA | Taxi-idle |
| | 50-412 | 2.334 | .0337 | .0221 | .0221 | - | 366.9 | 1.97 | 7.618 | - | .45 | [illegible] | [illegible] | 1.81 | 94.73 | 56.06 | 1.42 | [illegible] | - | [illegible] | |
| | 50-413 | 2.158 | .0496 | .0221 | .0221 | - | 366.9 | 1.98 | 7.683 | - | .45 | .00940 | [illegible] | 1.78 | 122.66 | [illegible] | 1.25 | [illegible] | - | [illegible] AA | |
| | 50-414 | 2.375 | .0671 | .0221 | .0221 | - | 365.2 | 1.98 | 7.705 | - | .45 | .00930 | .00980 | 1.36 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] AA | |
| | 50-422 | 2.290 | .0293 | .0246 | .0246 | - | 367.4 | 1.92 | 7.336 | - | .45 | .01110 | .01140 | 2.21 | 70.46 | 21.54 | 1.83 | [illegible] | - | [illegible] AA | |
| | 50-423 | 2.228 | .0481 | .0244 | .0244 | - | 367.4 | 1.92 | 7.465 | - | .45 | .01110 | [illegible] | 2.15 | [illegible] | 30.84 | 1.66 | [illegible] | - | [illegible] | |
| | 50-11 | [illegible] | .0159 | .0184 | .0183 | - | 663.0 | 4.17 | 11.438 | - | .45 | .00460 | [illegible] | 0.92 | 147.14 | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA, Takeoff | |
| Refinement Test 2 (Airblast nozzles, 50% swirler area, outer and inner primary orifices added) | | | | | | | | | | | | | | | | | | | | | |
| A-23 | 51-41 | 2.332 | .0111 | .0222 | .0222 | - | 366.5 | 1.98 | 7.548 | - | .45 | [illegible] | [illegible] | 1.75 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | Taxi-idle |
| | 51-411 | 2.344 | .0194 | .0222 | .0222 | - | 365.8 | 1.98 | 7.626 | - | .45 | .00950 | .00920 | 1.82 | 45.32 | [illegible] | 1.82 | [illegible] | - | [illegible] kPa AA | |
| | 51-412 | 2.350 | .0297 | .0222 | .0222 | - | 365.8 | 1.97 | 7.643 | - | .45 | [illegible] | .00950 | 1.84 | [illegible] | 12.54 | 1.88 | [illegible] | - | [illegible] kPa AA | |
| | 51-413 | 2.367 | .0479 | .0222 | .0222 | - | 366.3 | 1.98 | [illegible] | - | .45 | .00940 | [illegible] | 1.91 | 36.63 | [illegible] | 1.91 | [illegible] | - | [illegible] kPa AA | |
| | 51-414 | [illegible] | .0647 | .0221 | .0221 | - | 366.9 | 1.97 | 7.786 | - | .45 | .00930 | [illegible] | [illegible] | 48.44 | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 51-421 | [illegible] | [illegible] | .0246 | .0246 | - | 366.9 | [illegible] | [illegible] | - | .45 | .01120 | [illegible] | 2.21 | 30.55 | [illegible] | [illegible] | [illegible] | - | 124 kPa AA | |
| | 51-422 | [illegible] | .0289 | .0246 | .0246 | - | 366.9 | [illegible] | 7.360 | - | .45 | .01120 | [illegible] | [illegible] | [illegible] | [illegible] | 2.41 | [illegible] | - | 5% Bleed, 192 kPa AA | |
| | 51-423 | [illegible] | .0464 | .0246 | .0246 | - | 367.4 | [illegible] | 7.462 | - | .45 | .01110 | [illegible] | 2.24 | [illegible] | 4.39 | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 51-424 | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | [illegible] | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | 36.61 | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 51-32 | [illegible] | [illegible] | [illegible] | .0672 | - | [illegible] | 5.21 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | Approach |
| | 51-322 | [illegible] | [illegible] | [illegible] | .0672 | - | [illegible] | 5.21 | [illegible] | - | .45 | .01140 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA | |
| | 51-11 | 4.069 | [illegible] | [illegible] | [illegible] | - | [illegible] | 4.15 | 11.633 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA, pilot only [illegible] | |
| | 51-112 | [illegible] | [illegible] | [illegible] | .0189 | - | [illegible] | 4.15 | 11.658 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA, pilot only [illegible] | |
| | 51-4 | [illegible] | [illegible] | .0210 | [illegible] | - | [illegible] | 4.13 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] kPa AA, pilot only [illegible] | |
| | 51-4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.14 | [illegible] | [illegible] | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | 51-14 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | Takeoff |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.17 | [illegible] | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 4.18 | 11.751 | - | .45 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | - | [illegible] | |

# NOTES

1 14-in. injection length, 24% premix air, f/a = 0.009

2 20% premix air, f/a = 0.009

3 3-in. injection length, 24% premix air, f/a = 0.009

4 20% premix air, f/a = 0.009

5 16% premix air, f/a = 0.012

6 24% premix air, pilot nozzle F/N decrease from 0.9 to 0.7, propane premix fuel, f/a = 0.009

7 20% premix air, f/a = 0.009

8 27% premix air, f/a = 0.009

9 Pilot nozzles returned to 0.9 F/N

10 8-in. injection length, 24% premix air, pilot only

11 11-in. injection length, f/a = 0.011

12 35% premix air, pilot only

13 24.6% premix air, f/a = 0.011

14 Pilot nozzles F/N changed to 0.7, 25% premix air

15 28% premix air, f/a = 0.013

16 8-in. injection length, 24% premix air, f/a = 0.012, pilot nozzles changed to 0.9 F/N, Jet A premix fuel

17 29% premix air, f/a = 0.012

18 29% premix air, 65% premix fuel

19 Pilot nozzles changed to 0.9 F/N

20 3-in. injection length, 70% premix fuel

21 Air and fuel flows increased 10%, 70% premix fuel

22 Air and fuel flows increased 10%, 60% premix fuel

23 Air and fuel flows increased 10%, 70% premix fuel

24 Pilot nozzles changed to 0.7 F/N

NOTES (CONTD)

25 Air and fuel flows increased 10%, 70% premix fuel

26 Pilot nozzles changed to 0.9 F/N, pilot only takeoff

27 Takeoff, 65% premix fuel, 137 kPa A.A.

28 Takeoff, 70% premix fuel, 138 kPa A.A.

29 Takeoff, 60% premix fuel, 136 kPa A.A.

30 Takeoff, 60% premix fuel, 273 kPa A.A.

31 Takeoff, 60% premix fuel, 30 kPa A.A.

# APPENDIX C

# ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| AA | Air Assist |
| CO | Carbon Monoxide |
| EI | Emission index, g pollutant/kg fuel |
| EPA | U. S. Environmental Protection Agency |
| EPAP | EPA Parameter, lbm pollutant/1000 lbf thrust-hr/ LTO cycle |
| $F_n$ | Net thrust, Newtons (N) |
| HC | Unburned hydrocarbon |
| LBO | Lean blow out |
| LTO | Landing-takeoff cycle |
| $NO_x$ | Oxides of nitrogen |
| P | Pressure, Pascal (Pa) |
| PF | Pattern factor |
| $\Delta P$ | Pressure change, Pa |
| T | Temperature, $^{\circ}$K |
| $W_a$ | Airflow, kg/sec |
| $W_f$ | Fuel flow, kg/sec |
| V | Velocity, m/sec |
| $\eta_c$ | Combustor efficiency (actual/ideal) |
| $\phi$ | Equivalence ratio |
| $\theta_3$ | Combustor inlet temperature, $^{\circ}$K/288$^{\circ}$K |
| $\delta_3$ | Combustor inlet pressure, kPa/101.4 kPa |

Subscripts

| | |
|---|---|
| r | Reference |
| s | Static conditions |
| t | Total conditions |
| 3 | Combustor inlet station |
| 4 | Combustor exit station |

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