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POLLUTION REDUCTION TECHNOLOGY PROGRAM

SMALL JET AIRCRAFT ENGINES

PHASE II - FINAL REPORT

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16. Abstract

A series of iterative combustor pressure rig tests was conducted on two combustor concepts applied to the AiResearch TFE731-2 turbofan engine combustion system for the purpose of optimizing combustor performance and operating characteristics consistant with low emissions. The two concepts, which were derived from the Phase I screening program were Concept 2, an axial air-assisted airblast fuel injection configuration with variable-geometry air swirlers, and Concept 3, a staged premix/prevaporization configuration. The iterative rig testing and modification sequence on both concepts was intended to provide operational compatibility with the engine and determine one concept for further evaluation under Phase III in a TFE731-2 engine. Based on test criteria and near term technology considerations, Concept 2 was chosen for further compatibility testing in the test rig in Phase II in preparation for engine testing in Phase III. During the rig optimization tests, the Concept 2 variable-geometry system was evaluated for optimum positioning relative to performance and emissions. In addition to the rig testing, two TFE731-2 engine tests were conducted with Concept 2 rig hardware for the purpose of obtaining rig-to-engine emissions correlation. These tests were conducted with fixed-geometry simulations of the variable-geometry system. Sufficient design input was obtained from Phase II to incorporate the variable geometry into the engine for Phase III.

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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).

The program is being conducted in three phases. Phase I was a 19-month program. During that phase three distinct combustion system concepts and their subsequent modifications were tested in a combustion rig. The designs were applicable to the AiResearch Model TFE731-2 Turbofan Engine, and the rig duplicated the engine aerodynamics. Six builds of each of the three concepts 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 would meet the program goals.

In Phase II, a 24-month program, the two best concepts of Phase I underwent continued refinement testing in the combustion rig. The purpose of this testing was to ensure attainment of combustion system performance consistent with overall program goals, and engine mechanical and functional compatibility. In addition to the rig testing, two brief engine tests were conducted for correlating engine and rig emission results. This report covers the results of the Phase II program.

Phase III will include full-scale engine tests of one 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. These standards are formulated over an operating cycle that includes taxi-idle, approach, climbout, and takeoff power settings. HC, CO, and NO_x levels are measured at each of these four settings, and a time-in-mode factor is applied for each power level. These terms are then added together for each pollutant to arrive at a term referred to as the EPA parameter (EPAP). The maximum EPAP's allowable under the 1979 EPA standards for Class T1 Engines are shown below:

Pollutant	EPAP (lb/1000 lb thrust-hr/cycle)
HC	1.6
CO	9.4
NO_x	3.7

The Phase II combustion rig refinement testing involved two combustor concepts:

Concept 2 - Variable-geometry combustor with air-assisted/ airblast fuel-injection system.

Concept 3 - Axially-staged fuel injection with premixing/ prevaporizing of the main fuel supply.

The full annular high-pressure test rig used to evaluate these two concepts was designed to simulate the combustor operation in the TFE731-2 Engine. The combustor inlet conditions were identical to the engine conditions, except for 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.

Concept 2 used 20 air-assisted/airblast fuel injectors inserted axially through the combustor dome, as compared with 12 duplex pressure atomizing injectors inserted radially in the production TFE731-2 Engine combustor. The most significant design feature of the Concept 2 Combustion System was its variable-geometry mechanism, which used flow-control valves to vary the amount of air flowing through the fuel-injector swirlers, thus controlling the primary-zone equivalence ratio. For most of the testing described in this report, the fuel injector had an airblast feature used at all operating conditions, and an air-assist feature used to enhance atomization at low-power points; however, the configuration which produced the best emissions results simulated the use of a piloted airblast fuel injector. At the taxi-idle and approach points, the combustor was operated with pressure-atomizing fuel nozzles only, representing the pilot nozzle, and the airflow-control valves were completely closed. At the climbout and takeoff points, the pressure-atomizing nozzles were replaced with airblast fuel injectors, and the airflow valves were completely opened. The emissions levels of this configuration are shown below, along with the program goals. Also shown are the results of an engine test in which this combustor configuration was tested as part of a complete TFE731-2 Engine. The engine test used the same fuel-injection and airflow-control techniques described above for the rig tests. The purpose of this test was to establish correlations between emissions data taken at test rig pressures and engine pressures.

EPAP (lb/1000 lb thrust-hr/cycle)

Pollutant	Program Goals	Concept 2 Rig Test	Concept 2 Engine Test
HC	1.6	1.01	0.92
CO	9.4	12.43	6.18
NO_x	3.7	3.90	3.89
Smoke	40.0	-	16.5

The test rig results show that this Concept 2 configuration was 32 percent higher than the CO goal, was very close to meeting the NO_x goal, but met the program goal for HC. Engine test results show HC and NO_x values very close to those of the rig tests; and a CO value significantly lower than that of the rig tests, and well within the program goal. The SAE smoke number met the program goal by a significant margin.

Concept 3 used an axially-staged fuel system with a pilot zone designed to be operated alone at taxi-idle. This zone had 20 air-assisted airblast fuel nozzles inserted axially through the dome. The main combustion zone fuel entered the combustor radially, downstream of the pilot zone. Fuel was injected by 40 pressure-atomizing nozzles into a premixing passage, through which a portion of the combustor air flowed. The fuel was mixed with this air, and was partially vaporized before entering the combustor.

Through a series of refinement tests in which premixing length was reduced, finally to almost zero, it was discovered that premixing was not required for low emission levels, and that the axially-staged system without premixing met the program goals. Air-assist was required at the taxi-idle conditions with this configuration; however, tests in which pressure-atomizing fuel nozzles were used in the pilot zone indicated that a piloted airblast system would have been adequate. The EPAP's for this configuration are shown below. The EPAP values were calculated from rig-test data, and adjusted for differences in combustor inlet pressure between rig-test conditions and engine levels at climbout and takeoff.

EPAP (lb/1000 lb thrust-hr/cycle)

Pollutant	Program Goals	Concept 3
HC	1.6	0.9
CO	9.4	10.4
NO_x	3.7	2.9
Smoke	40.0	14.0*

*Measured at approach

The data indicate that the system met the program emission goals for HC and NO_x and was slightly above the goal for CO; however, additional development is required with respect to fuel staging at the approach setting, to provide adequate engine acceleration in the event that an aborted landing occurs.

Concept 2 was selected to undergo engine testing in Phase III. The decision was based on the overall performance of this concept and its engine compatibility. Although Concept 3 demonstrated lower emission levels, the system had experienced burning in the premix/prevaporizing (PM/PV) annulus in some configurations at scaled rig pressures, which were considerably less than the engine conditions. At the higher engine-pressure levels these fires would have resulted in considerable damage to the engine hot end. It is felt that the burning in the PM/PV annulus was the result of a fuel-leak initiated fire on the outer wall of annulus, which acted as an ignition source for the fuel/air mixture inside. In the configuration where the premix length was reduced to almost zero, this problem would be all but eliminated; however, in order to produce acceptable emission levels at approach, the system had to be run on pilot nozzles only. This presents a severe problem in terms of engine acceleration. The fill time on the premix fuel manifold during engine acceleration from idle to takeoff would be excessive, and would prevent the engine from complying with the 5-second acceleration requirement.

INTRODUCTION

The Pollution Reduction Technology Program for Small Jet Aircraft Engines was initiated by NASA in December 1974. The overall program objective was 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. 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 were also sought; while other combustion performance parameters such as pressure loss, exit temperature, pattern factor, and relight capability were to be maintained at acceptable levels.

The underlying motivation for this program emanated 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 were considered to depend on the successful development of advanced combustor design concepts, such as those resulting from the NASA Pollution Reduction Technology Program and the Experimental Clean Combustor Program.

The Pollution Reduction Technology Program for Small Jet Aircraft Engines is being conducted in three phases: (1) combustor concept screening, (2) combustor compatibility testing, and (3) combustor engine testing. The program is based on the use of the AiResearch Model TFE731-2 Turbofan Engine combustion system, which is an annular reverse-flow type common to several current production engines in the EPA Class T1 category.

In March of 1978, the EPA proposed revisions to its emissions standards that would remove emissions regulations for turbojet and turbofan engines with less than 27.0 kilonewtons of thrust. While the AiResearch Model TFE731-2 Engine falls within this exempt category, the need for technology gained from this Pollution Reduction Technology program using the TFE731-2 Engine as a test vehicle will be applicable and valuable to larger engines that are still regulated. This technology will particularly address the needs of engines in the 27.0 to 35.6 kilonewtons thrust class, which are within the T1 engine classification and still subject to emissions regulations.

The results of Phase II combustor compatibility testing under the NASA Pollution Reduction Technology Program for Small Jet Aircraft Engines (Class T1) are described in this report. The major portion of testing in this phase was conducted on a combustion test rig with the objective of optimizing performance of two combustor concepts identified in Phase I as having the potential to meet program emission goals. Limited engine testing was also conducted on one of the advanced combustor concepts in Phase II for the purpose of verifying engine-to-test rig emissions correlation. During Phase II one combustor concept was chosen that will undergo incorporation into a Model TFE731-2 Engine and be subjected to emissions measurement and acceleration/deceleration testing.

The total Class T1 Pollution Reduction Technology Program is described in Chapter I. The equipment and procedures used in the Phase II program are described in Chapter II. Combustor test results and pertinent discussion are presented in Chapter III. Appendices to the report list combustor configuration hole patterns, experimental test results, engine-to-rig correlation test results, and abbreviations and symbols.

CHAPTER I

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

A.- 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 multiyear effort initiated by the NASA-Lewis Research Center in 1974, and is scheduled for completion by early 1979. 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 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 other classes as well. It is also anticipated that the results of this program may suggest additional designs or techniques that will merit further evaluation for other specific engine applications or research programs.

B.- PROGRAM GOALS

The program goals for emission levels are 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 Model TFE731-2 Engines. The emission goals were to be achieved without compromise to combustor performance factors, durability, or existing envelope constraints.

1. <u>Emission Goals</u>. - The emission goals for this program are the EPA Class T1 requirements currently specified for new aircraft gas turbine engines manufactured after January 1, 1979 (Ref. 1). 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 Gaseous Emissions, lb/1000 lb Thrust-hr/LTO cycle[a]	TFE731-2 Engine Characteristics 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 (EI), 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

These EI values are referred to as "goals" throughout the remainder of the report, since meeting these levels would very likely assure that the EPAP requirements, which are the actual program goals, would be met.

2. Combustor Performance, Life, and Envelope Goals - The following combustor performance, life, and envelope goals have been established to ensure that the final selected combustion 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 Model TFE731-2
Engine relight capability:	Commensurate with the current Model TFE731-2 relight envelope
Combustor size and shape:	Compatible with Model TFE731-2 Engine installation
Fuel:	ASTM D1655-75 Type Jet A (or equivalent)

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

C.- PROGRAM PLAN

This program is a three-phase effort, with each phase independently funded:

- 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)

1. Phase I Program. - The 19-month Phase I effort involved the design, rig testing, and data analysis of 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 Ref. 3.

2. Phase II Program. - During Phase II, the two most promising combustor configurations identified in Phase I underwent more extensive testing. A component test rig was used to develop systems that optimized emissions reductions consistent with acceptable combustion-system performance required in an engine application. Therefore, Phase II testing entailed 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 was 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 were confined to brief correlation checks, and no refinement or development work scheduled for Phase III was conducted in Phase II. A description of the Phase II program activity and results are presented in Chapters II and III of this report.

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

D.- PROGRAM SCHEDULE

The program schedule is shown in Figure 1. Phase I was a 19-month technical effort that has been completed. Phase II, which was awarded in June, 1976, was completed in 18 months. Phase III, recently awarded, will be a 14-month effort with a completion date in early 1979.

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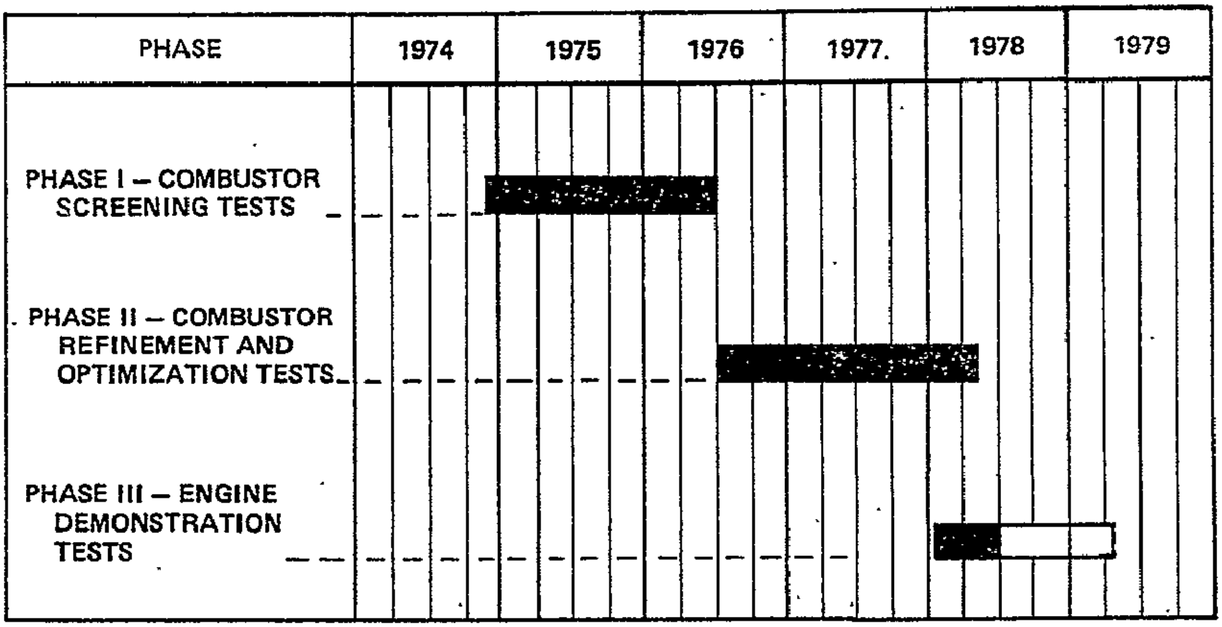

Figure 1. Program Schedule.

CHAPTER II

PHASE II PROGRAM - EQUIPMENT AND PROCEDURES

A.- INTRODUCTION

This chapter contains a description of the AiResearch Model 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, emissions sampling and analysis instrumentation, test procedures, and data-analysis procedures and methods are described.

B.- BASELINE TEST ITEMS DESCRIPTION AND PERFORMANCE

1. Model TFE731 Turbofan Engine - General Description. - The AiResearch Model 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 of 2.67. The fan is coupled through a planetary gearbox to the low-pressure (LP) spool, which consists of a four-stage axial compressor and a three-stage axial turbine. The high-pressure (HP) 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, and details regarding combustor design are shown in Figure 4.

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

TABLE III. KEY ENGINE PERFORMANCE PARAMETERS.

Thrust, kN:	
Sea-level takeoff (maximum thrust)	15.6
Maximum cruise (12,192 m, M=0.8)	3.36
Thrust specific fuel consumption, kg/N-hr:	
Sea-level takeoff (maximum thrust)	0.048
Maximum cruise (12,192 m, M=0.8)	0.082
Noise level, EPNdb:	
Sea-level takeoff	82.6

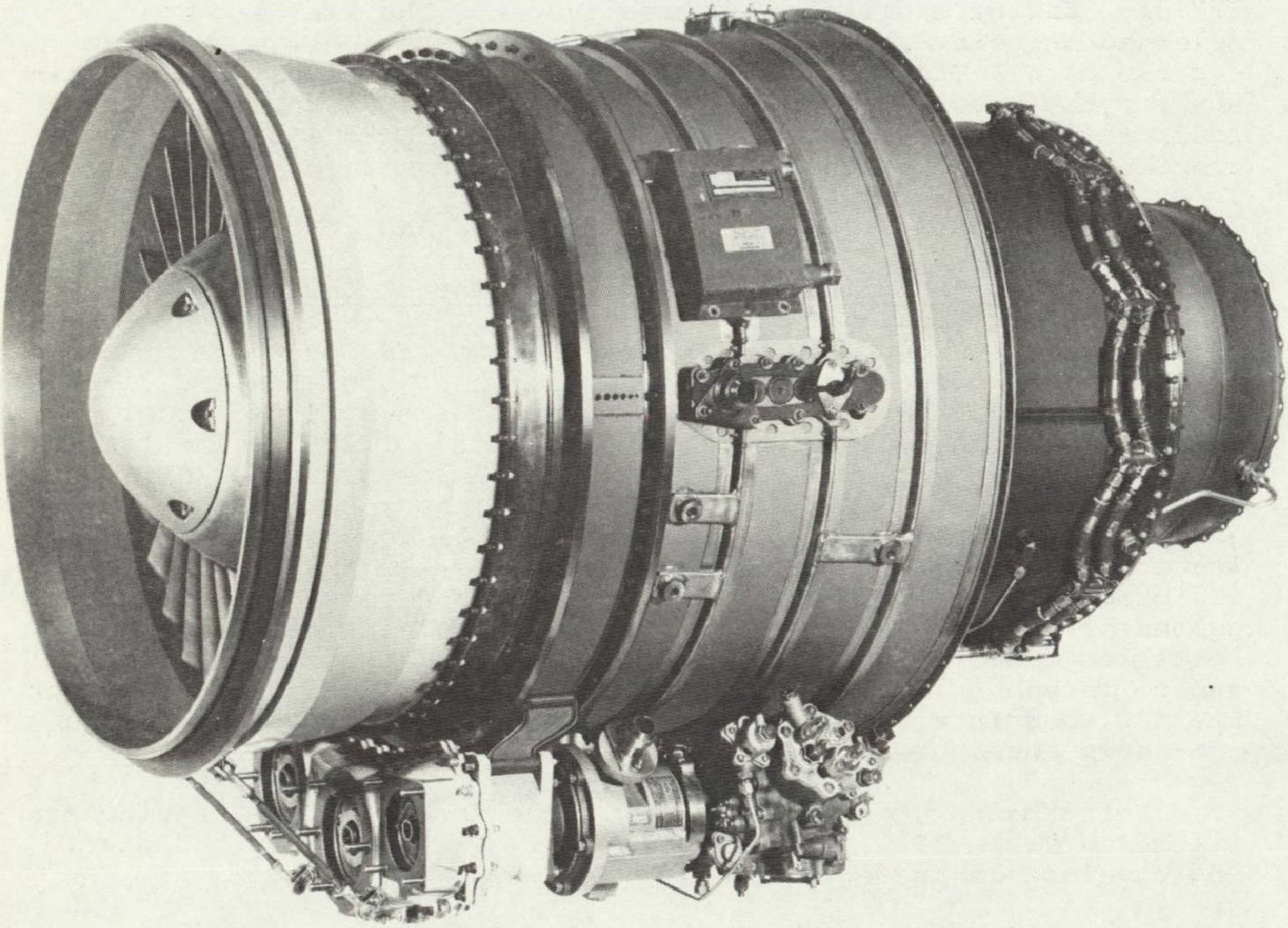

Figure 2. Left-Front View of AiResearch Model TFE731 Turbofan Engine.

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ENGINE WEIGHT: 329 kg

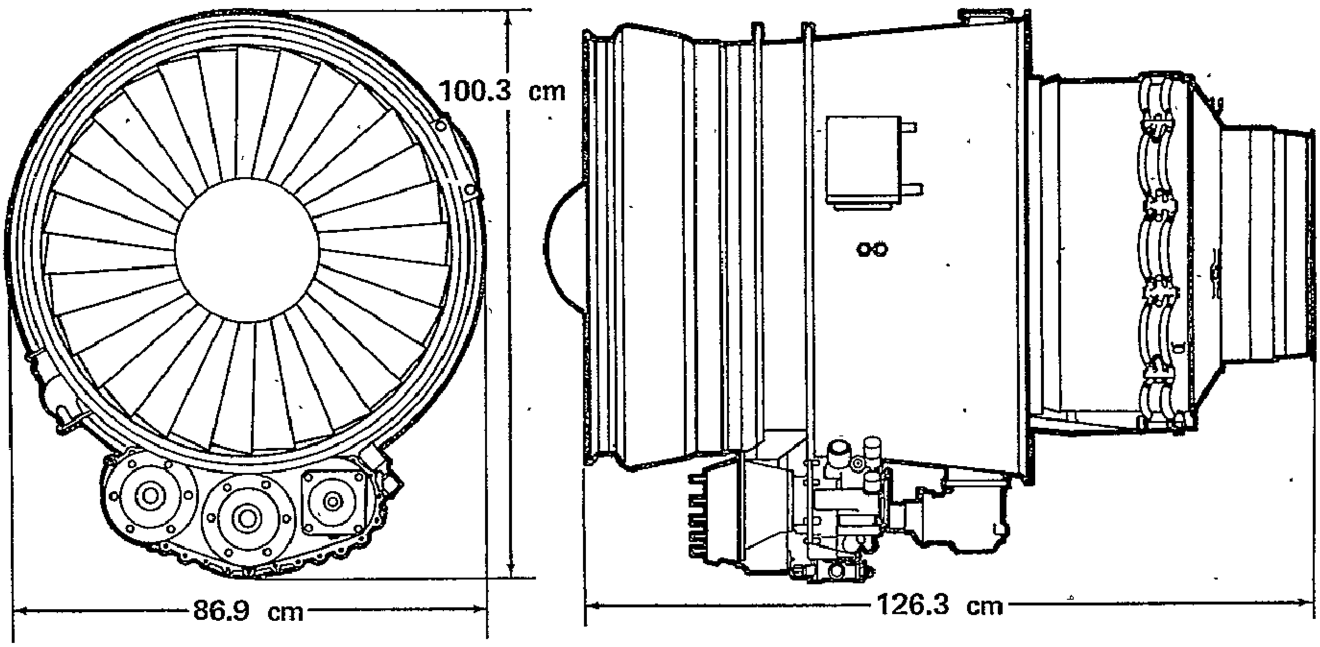


Figure 3. Engine Envelope Dimensions.

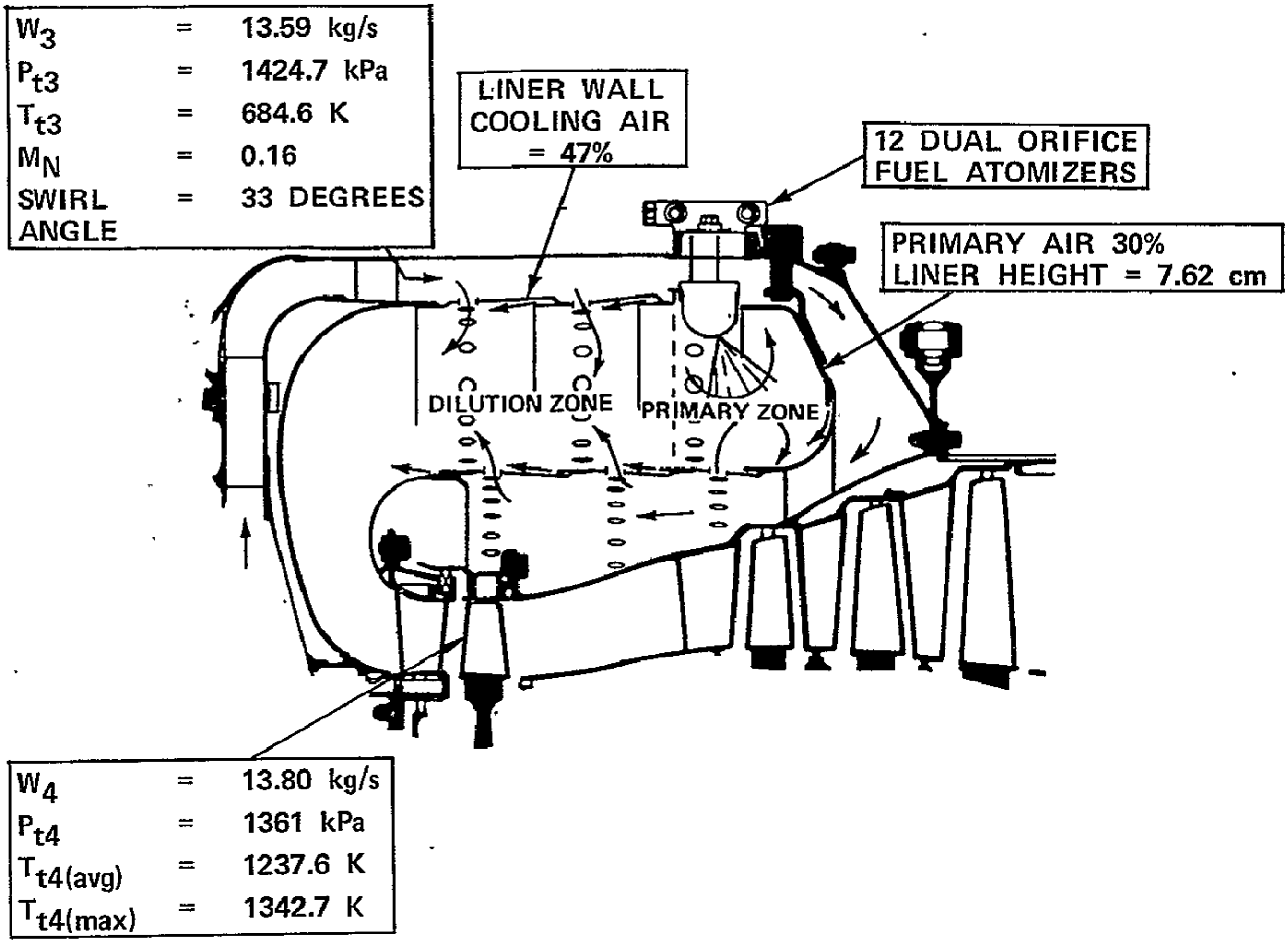


Figure 4. Reverse-Flow Annular Combustor System, Sea-Level, Standard-Day, Static Conditions.

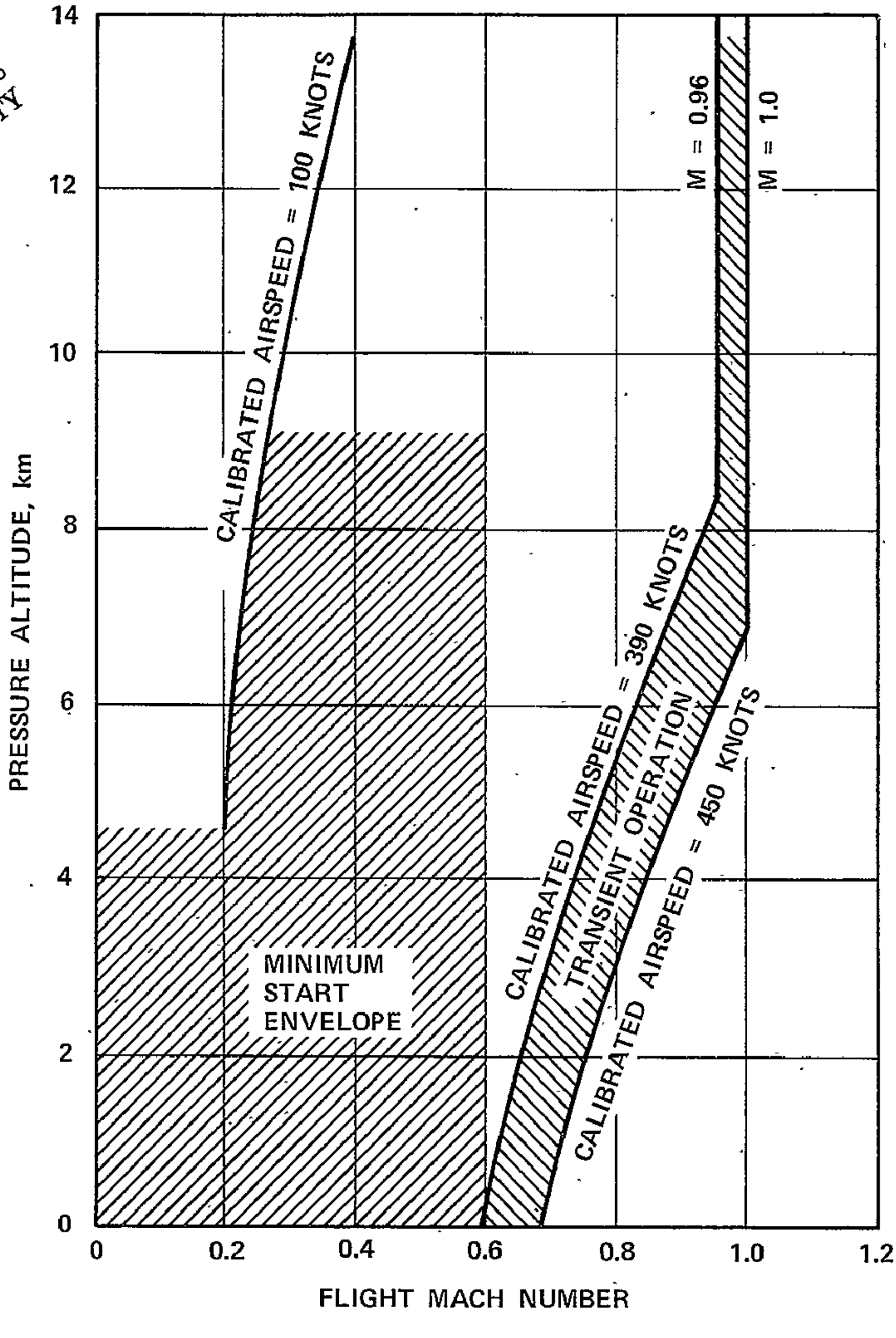


Figure 5. Engine Flight Envelope.

2. Model TFE731-2 Combustion System Description. - The Model TFE731-2 combustor is of 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 12 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 fuel flow between the primary and secondary flow circuits. Ignition and engine acceleration are 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.

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. These data, together with the program goals, are shown in Table V for the taxi-idle and simulated takeoff points.

C.- TEST RIG AND FACILITIES

1. Pressure Rig and Instrumentation. - The pressure rig was originally designed for use in the development of the combustion system for the production Model TFE731 Turbofan Engine. Only minor modifications and the refurbishment of hot-end components were required for its use during Phases I and II of this 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, and ensured 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, and contained the combustor-exit instrumentation. The inlet instrumentation was mounted on the combustor plenum in the vicinity of the compressor deswirl vanes. A listing of the instrumentation is given in Tables VI and VII for each of the combustor concepts tested in Phase II.

2. Combustor Inlet Instrumentation. - Figure 7 shows the circumferential location of the combustor inlet instrumentation for Concept 2. There were four total-pressure rakes located at 90-degree intervals around the plenum. Probe angles were adjustable with respect to the axial position, and the probes were set to compensate for the airflow swirl angle of approximately 35 degrees to obtain the maximum total-pressure value. These total-pressure

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

Parameter	Taxi-Idle	Takeoff
Combustor airflow, kg/s	2.31	13.59
Compressor discharge total pressure, kPa	202.1	1425.0
Combustor pressure loss, percent	3.0	4.5
Compressor discharge temperature, K	369.9	684.6
Combustor discharge temperature, K	754.4	1257.6
Combustor discharge pattern factor	0.35	0.19
Combustor fuel flow, kg/hr	87.3	754.3

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.

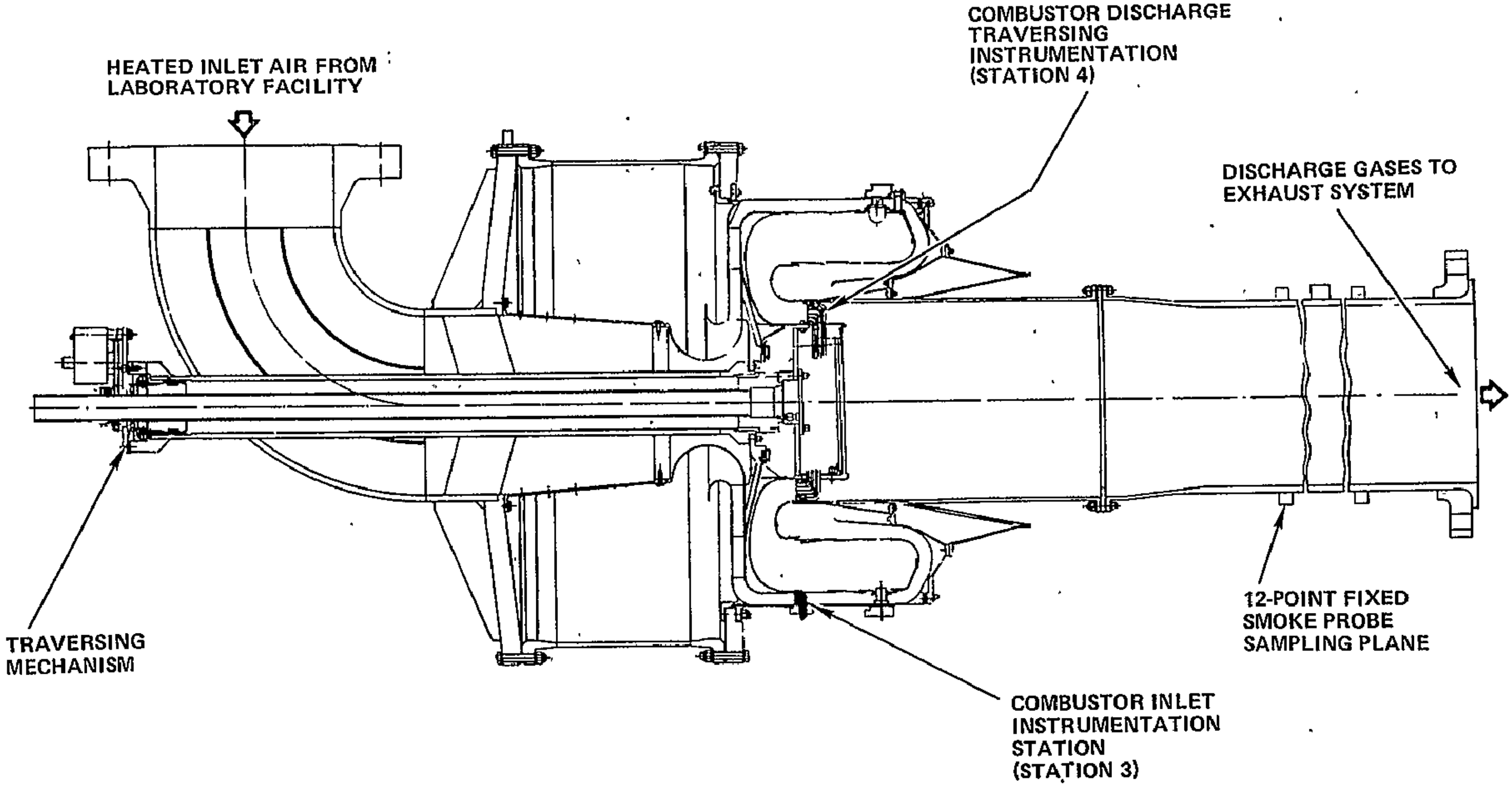


Figure 6. Full-Scale Reverse-Flow Annular Combustor Test Rig

TABLE VI. - COMBUSTOR PRESSURE RIG INSTRUMENTATION LIST, CONCEPT 2.

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

TABLE VII. COMBUSTOR PRESSURE RIG INSTRUMENTATION LIST, CONCEPT 3.

Parameter	Symbol	Angular Position Degrees	Immersion cm	Sensor Type
Combustor Inlet Static Pressure	P_{S31}	60	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S32}	150	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S33}	240	0	0.140 cm. Dia. Tap
Combustor Inlet Static Pressure	P_{S34}	330	0	0.140 cm. Dia. Tap
Combustor Inlet Total Pressure	P_{T31}	356	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T32}	86	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T33}	176	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Pressure	P_{T34}	266	0.89	0.3175 cm. Dia. Pitot Tube
Combustor Inlet Total Temperature	T_{T31}	42	0.89	CA Thermocouples bead-
Combustor Inlet Total Temperature	T_{T32}	132	0.89	type half-shielded
Combustor Inlet Total Temperature	T_{T33}	222	0.89	
Combustor Inlet Total Temperature	T_{T34}	312	0.89	
Combustor Discharge Static Pressure	P_{S41}	Rotating Rake	0	0.175 cm. Dia. Tap
Combustor Discharge Total Pressure	P_{T41}		0.34	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T42}		0.77	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T43}		1.28	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T44}		1.82	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T45}		2.32	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Pressure	P_{T46}		2.86	0.3175 cm. Dia. Pitot Tube
Combustor Discharge Total Temperature	T_{T41}		0.35	Pt/Pt and 10% Rh
Combustor Discharge Total Temperature	T_{T42}		0.77	Thermocouple shielded
Combustor Discharge Total Temperature	T_{T43}		1.28	
Combustor Discharge Total Temperature	T_{T45}		2.33	
Combustor Discharge Total Temperature	T_{T46}		2.85	
Sample Gas Temperature	T_{5G1}	-	-	CA Thermocouples shielded
Sample Gas Temperature	T_{5G2}	-	-	CA Thermocouples shielded

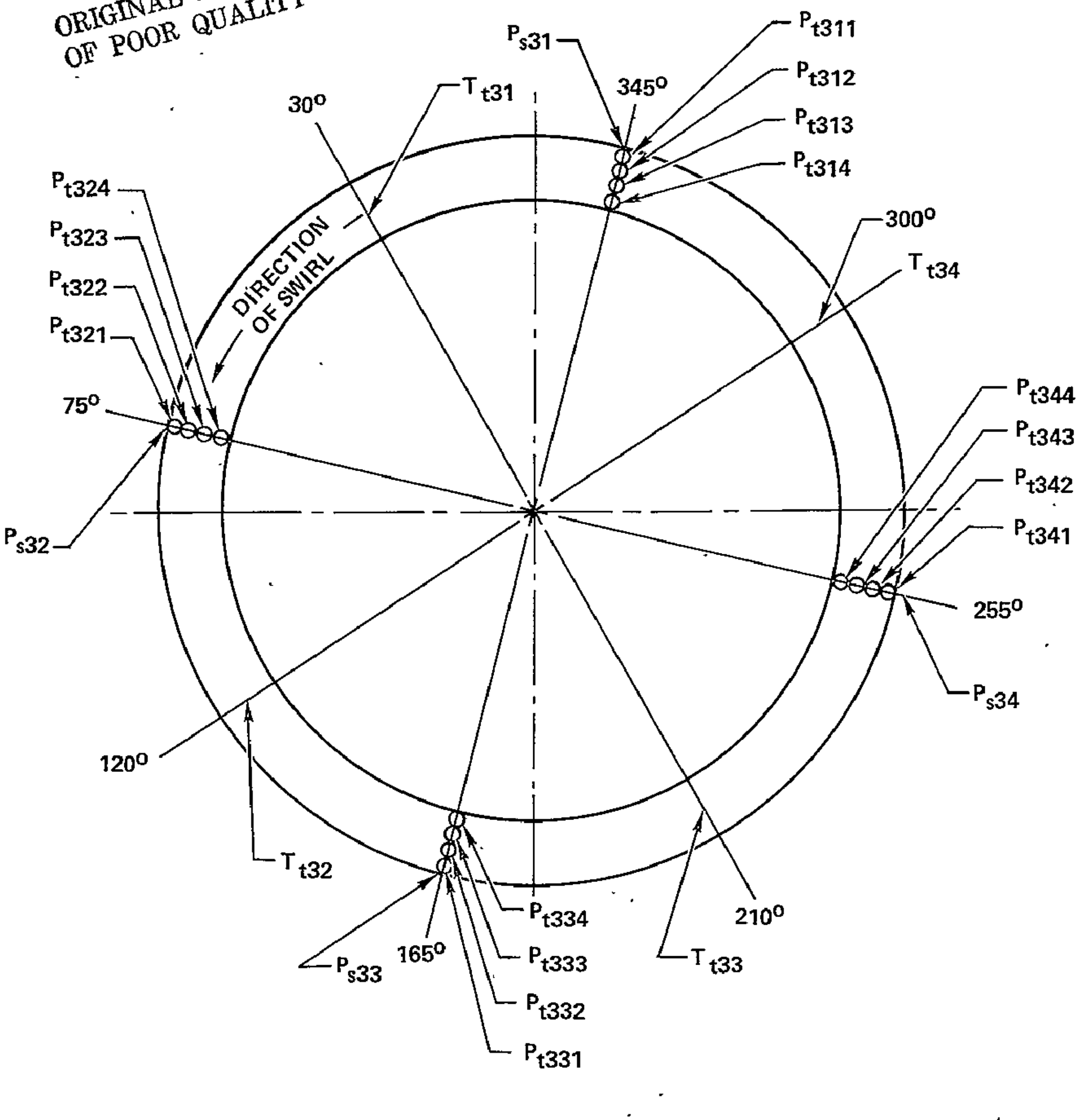


Figure 7. Circumferential Location of Inlet Instrumentation for Concept 2 (View Looking into Combustion Chamber Liner).

rakes consisted of four-element probes identical to the probes used in Phase I. Immediately upstream of each total-pressure rake was a static-pressure wall tap 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 Chromel-Alumel with a closed bead. The bead was immersed halfway into the inlet channel.

For Concept 3, because the premixing/prevaporizing annulus extended upstream beyond the deswirl vanes, the inlet instrumentation station was moved upstream of the deswirl vanes. Circumferentially, the instrumentation stations were spaced at 12 equal intervals, with four points 90 degrees apart used for the total pressure, static pressure, and inlet temperature (see Figure 8). As a result of the instrumentation position, single-element total-pressure probes were used.

3. 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 that 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. These rig instrumentation lines were terminated at the end of the shaft, and connected to facility lines. The emissions rake consisted of four 3.17-mm diameter stainless-steel probes that were connected to a common 6.35-mm 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 cooling water. 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 to 811 K sample temperature.

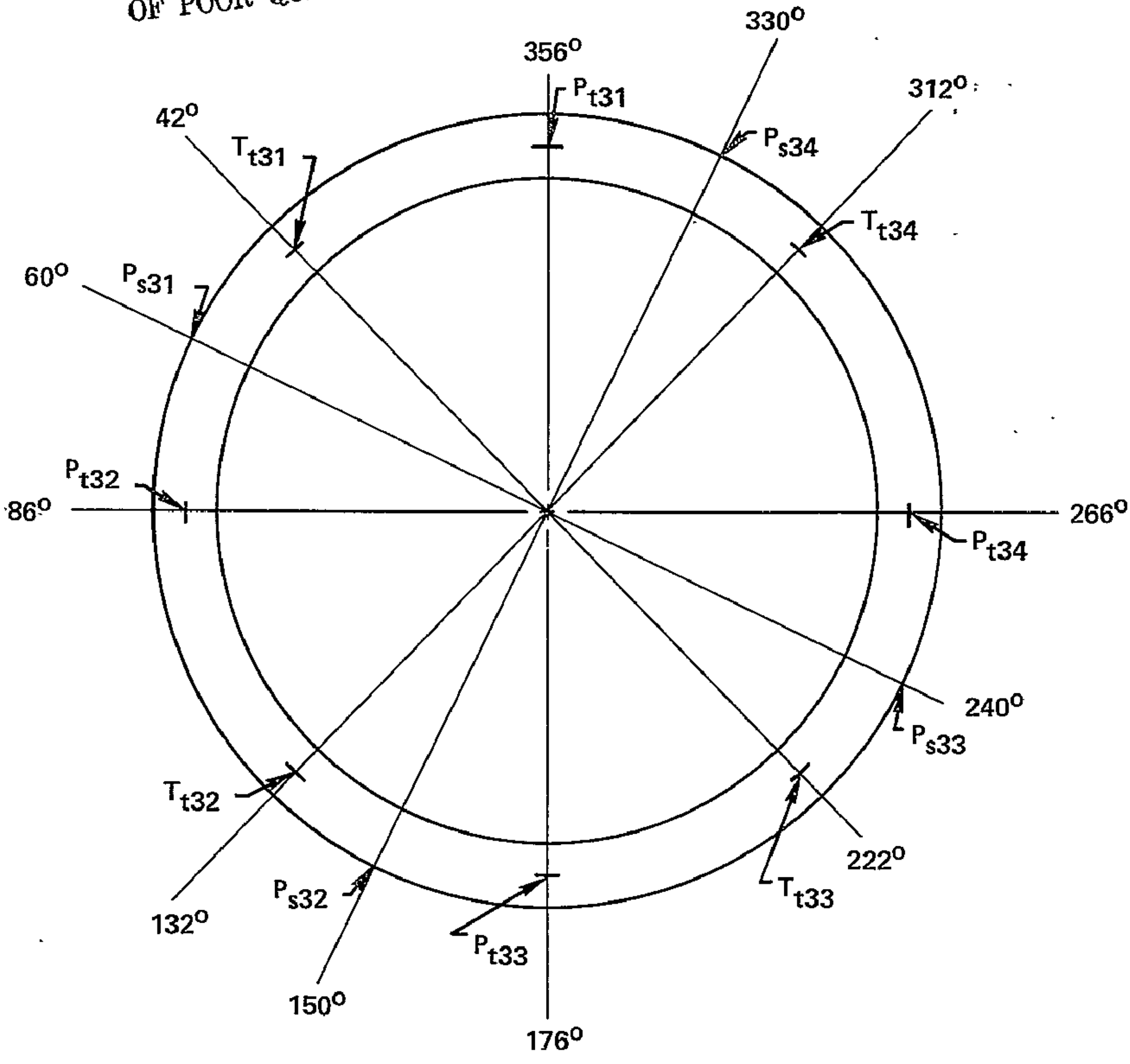


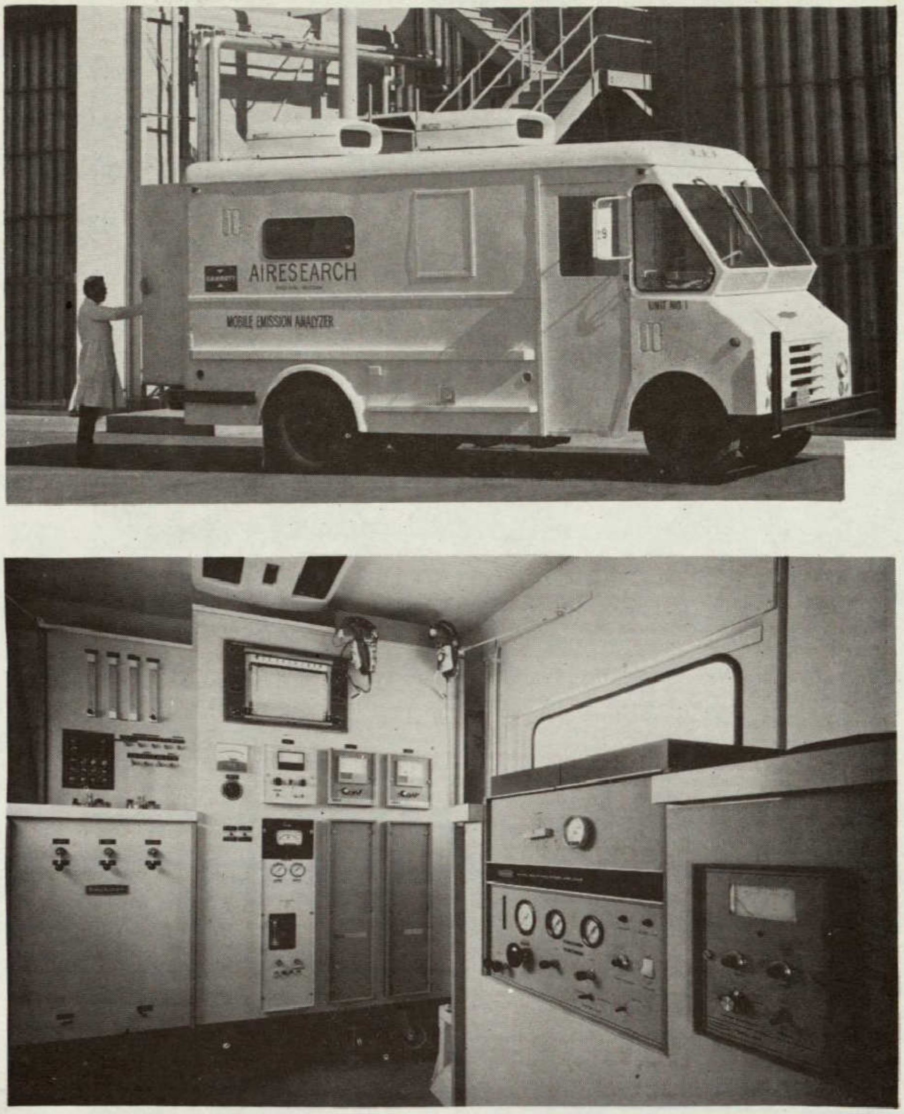
Figure 8. Circumferential Location of Inlet Instrumentation for Concept 3 (View Looking into Combustion Chamber Liner.)

In addition to the emissions 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 6.35-mm stainless-steel probes externally manifolded and inserted through the rig tailpipe. Each tube had three 0.8-mm orifices drilled through the wall and spaced on centers of equal areas for the tailpipe.

4. 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 9 and 10. 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 11, and the particulate analyzer flow system schematic is shown in Figure 12. This equipment is described in the following paragraphs.

5. 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 determining the presence of oxides of nitrogen (NO_x) over a range from 0 to 10,000 ppm
- A Beckman Model 402 hot flame-ionization-detection hydrocarbon analyzer capable of discriminating unburned hydrocarbons (HC) in the sample over a range of 5 ppm to 10 percent
- A Beckman Model 315B carbon monoxide (CO) 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 (CO_2) is not specifically required for the determination of pullutant 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).



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

Figure 9. Gaseous Exhaust Emissions Measurement Instrumentation

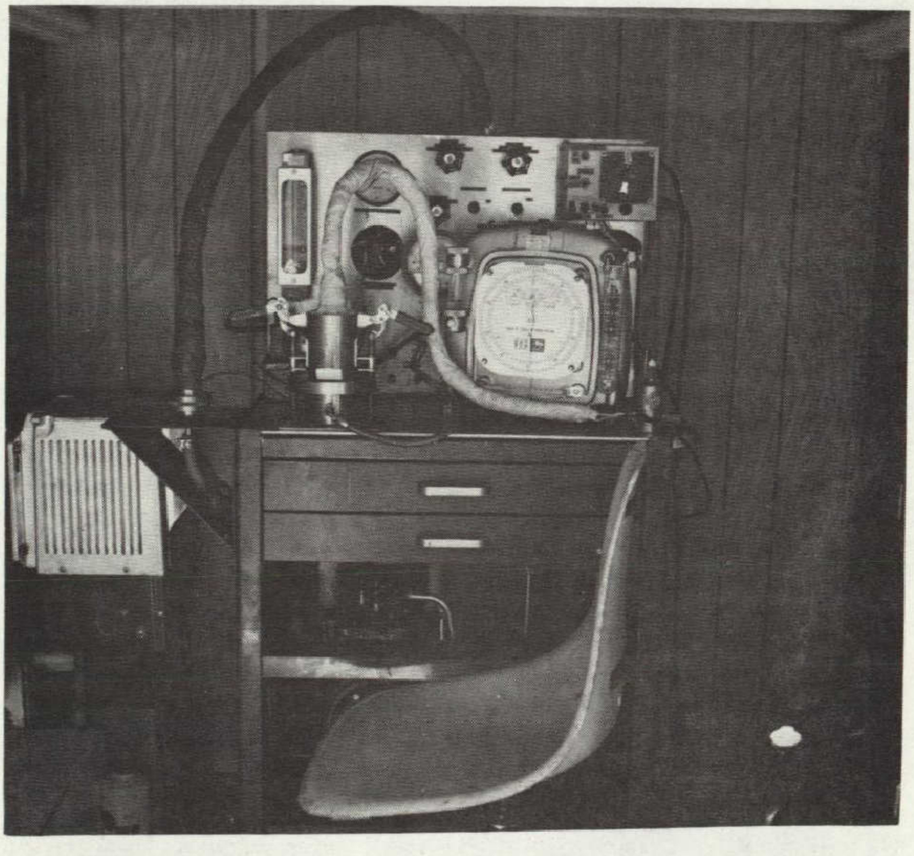


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Figure 10. Mobile Smoke Analyzer.

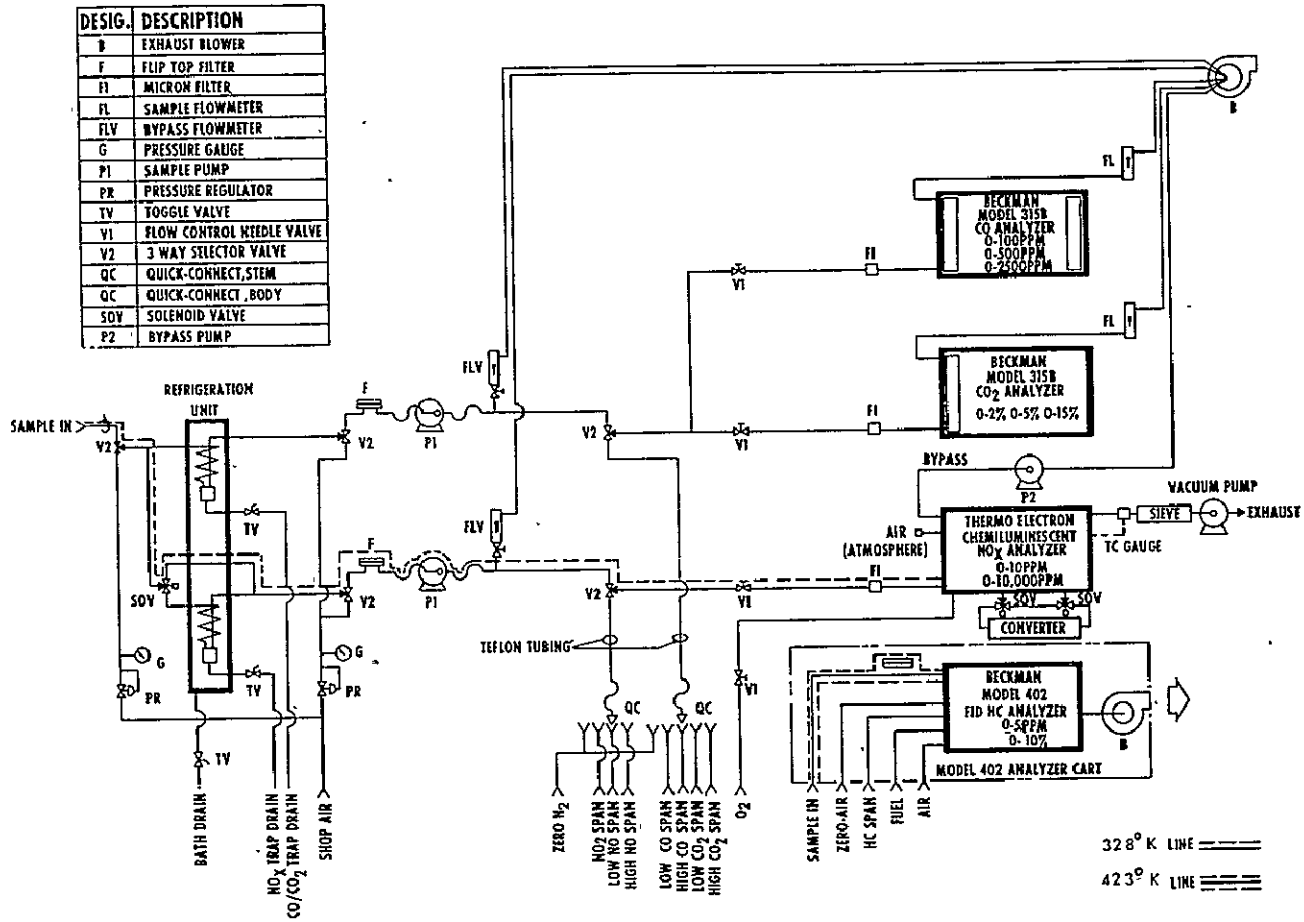

Figure 11. Exhaust Gas Analyzer Flow System.

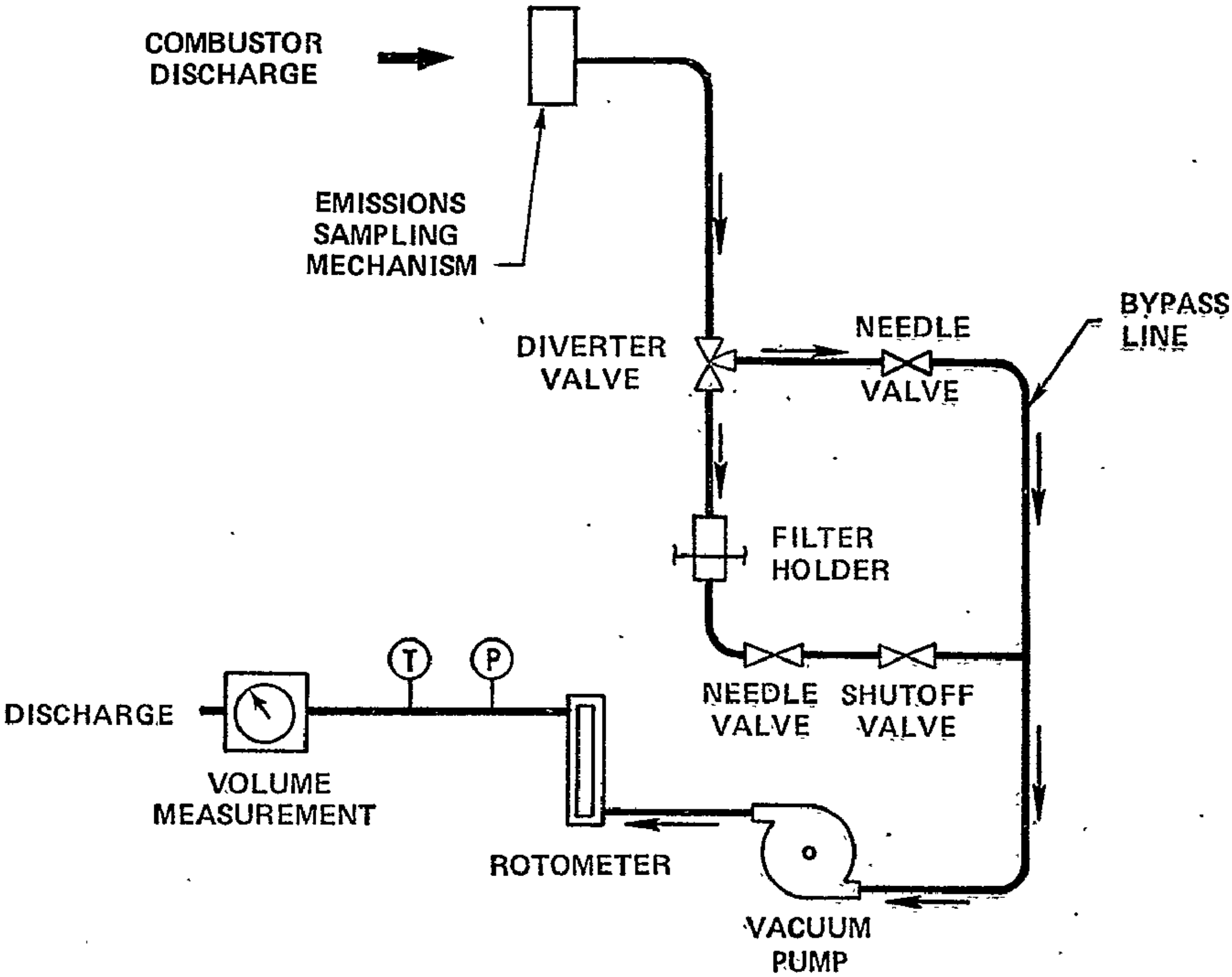

Figure 12. Particulate Analyzer Flow System.

All instruments, zero gases, and span gases are kept at a constant temperature to avoid drift. The equipment is capable of continuous monitoring of NO_x, HC, CO, and CO_2 in exhaust gases. The zero and span gases used to calibrate the instruments are given in Table VIII.

6. Particulate Emissions Sampling and Analysis Equipment. - Sample size measurements were made with a Precision Scientific Wet Test Meter accurate to within $\pm$0.005 standard cubic meter. Wet test pressure and temperature were measured within $\pm$68 Pa and 0.50 K, respectively. Sample flow measurements were conducted with a Brooks Rotometer Model 110, accurate to within $\pm$0.017 m^3/min. A Duo-Seal Model 1405 vacuum pump, with a free-flow capacity of 0.0057 m^3/min and no-flow vacuum capability of 1 micron, was used. Reflectance measurements were conducted with a Welch Densichron Model 3837 photometer.

7. Data Acquisition. - All of the combustor rig pressure, temperature, and emissions data were transmitted in terms of counts from the test facility to a high speed data acquisition system. The computer processed the data in real time and returned it in engineering units to the test stand for display on a cathode ray tube (CRT). The CRT display included emission indices, carbon balance, measured fuel/air ratios, and the combustor inlet conditions. A sample display is shown in Figure 13, and an explanation of the symbols and units is given in Table IX. Selected data was also read manually for convenience and verification. Fuel flow rate and inlet air humidity were read only by manual means and input using thumbwheels. The computer controlled the combustor discharge instrumentation rake and stepped the rake in 10-degree increments at 14-second intervals. Data scans were taken at 7-second intervals synchronized with the rake steps; one additional scan was taken after the rake had completed a 350-degree rotation to account for the delay time of the emissions instruments. Therefore, 73 data scans were averaged for each test condition. Following each traverse, the average temperature, pattern factor, and average exhaust gas species concentrations and indices were displayed on the CRT as shown in Figure 14. Post-test data reduction consisted of printing all the acquired data in engineering units for review, and writing the data on magnetic tape for further data reduction and permanent storage.

8. Combustion Component Test Facility. - The combustion facility has the capability of supplying up to 4.08 kg/s 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.

TABLE VIII. - 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 52.0 ppm 105.0 ppm	Air Products
NO in N_2	16.9 ppm 46.5 ppm 109.0 ppm	Scott Research Labs
CO in N_2	65.0 ppm 250.0 ppm 440.0 ppm	Air Products Matheson Air Products
CO_2 in N_2	1.05% 1.97% 3.05%	Scott Research Labs

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OFFSET 08:27:47.5 RECORD 08:59:10.4

COND NO	=	2.0	PSIAV	=	27.45	TE2	=	870
HUM	=	800.	PTI1	=	27.8	TE3	=	865
ORFP	=	200	PTI2	=	28.0	TE4	=	890
ORFT	=	780.	PTI3	=	27.6	TE5	=	900
ORFDP	=	0.412	PTI4	=	28.5	TE6	=	910
WI	=	307.	PTIAV	=	27.975	TEAV	=	880
AORFP	=	56.	TI1	=	203	TEMX	=	910
AORFT	=	53	TI2	=	190	VREF	=	25.46
AORFDP	=	0.20	TI3	=	200	RNOX	=	100.
WA	-	2.0	TI4	=	195	NOX	=	15.8
ADP	=	20.	TIAV	=	197	NOXEI	=	2.56
WT	=	309	PSE	=	25.9	RCO	=	2500.
WFPP	=	35	PTE1	=	25.8	CO	=	702.9
WFP	=	181.	PTE2	=	25.9	COEI	=	69.28
WFSP	=	0.	PTE3	=	26.0	RCO2	=	5.
WFS	=	0.	PTE4	=	26.5	CO2	=	1.95
WF	=	181.	PTE5	=	26.2	RHC	=	500.
FAM	=	0.0098	PTE6	=	26.5	NC	=	147.1
PSI1	=	27.3	PTEAV	=	26.5	HCEI	=	8.288
PSI2	=	27.5	PLOSS	=	0.0527	ETAE	=	97.643
PSI3	=	27.1	TE1	=	846.	FAE	=	0.0099
PSI4	=	27.9						

Figure 13. Typical CRT Display of Combustor Data (Non-Metric).

TABLE IX. LEGEND FOR CRT DISPLAY.

SYMBOL	UNITS	EXPLANATION
		FIRST COLUMN
HUM	PPM	Inlet or specific humidity
ORFP	PSIA	Orifice pressure
ORFT	°F	Orifice temperature
ORFDP	PSIA	Orifice ΔP
WI	PM	Orifice flow rate, inlet airflow
AORFP	PSIA	Air-assist orifice pressure
AORFT	°F	Air-assist orifice temperature
AORFDP	PSIA	Air-assist orifice ΔP
WA	PM	Air-assist flow rate
ADP	PSIA	Difference between air-assist manifold pressure and rig inlet total pressure
WT	PM	Total airflow rate
WFPP	PSIA	Difference between primary fuel pressure and rig inlet total pressure
WFP	PHR	Primary fuel flow
WFSP	PSIA	Difference between secondary fuel pressure and rig inlet total pressure
WFS	PHR	Secondary (premix) fuel flow
WF	PHR	Total fuel flow
FAM	--	Measured fuel-air ratio
PSI1,4	PSIA	Inlet static pressures
		SECOND COLUMN
PSIAV	PSIA	Average of four inlet static pressures
PTI1	PSIA	Average of first four inlet total pressures PTI1, PTI2, PTI3, PTI4
PTI2	PSIA	Average of second four inlet total pressures, PT21, PT22, PT23, PT24
PTI3	PSIA	Average of third four inlet total pressures, PT31, PT32, PT33, PT34
PTI4	PSIA	Average of fourth four inlet total pressures, PT41, PT42, PT43, PT44
PTIAV	PSIA	Average of all 16 inlet total pressures
TI1,4	°F	Inlet total temperature
TIAV	°F	Average of four inlet total temperature
PSE	PSIA	Discharge static pressure
PTE1,6	PSIA	Discharge total pressures - Number 1 refers to inner position
PTEAV	PSIA	Average of six discharge total pressures
PLOSS	--	Combustor total pressure loss
TEV	°F	Discharge total temperature - Number 1 refers to inner position
		THIRD COLUMN
TE2,6	°F	Discharge total temperature
TEAV	°F	Average of six discharge total temperatures
TEMX	°F	Maximum of six discharge total temperatures
VREF	FPS	Combustor reference velocity
RNOX	PPM	Maximum value of selected NOX range
NOX	PPM	NOX concentration in wet exhaust gas
NOXEI	GM/KG FUEL	NOX emission index
RCO	PPM	Maximum value of selected CO range
CO	PPM	CO concentration in wet exhaust gas
COEI	GM/KG FUEL	CO emission index
RCO2	PCT	Maximum value of selected CO2 range
CO2	PCT	CO2 concentration in wet exhaust gas
RHC	PPM	Maximum value of selected HC range
HC	PPM	HC concentration in wet exhaust gas
HCEI	GM/KG FUEL	HC emission index
ETAE	--	Combustion efficiency from emissions
FAE	--	Fuel-air ratio from emissions

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SUMMARY OF 360 DEG ROTATION

OFFSET 08:27:47.5			START RECORD 08:33:36.1			NO. OF RECORDS 73		
WI	=	308.	TIAV	=	200.	CO	=	652.9
WA	=	2.0	PSE	=	26.0	COEI	=	54.55
WT	=	310.	PTEAV	=	26.6	CO2	=	2.33
WFP	=	181.	PLOSS	=	0.0534	HC	=	73.6
WFS	=	0	TEAV	=	885.	HCEI	=	3.513
WF	=	181.	TEMX	=	920	ETAE	=	98.409
FAM	=	0.0098	VREF	=	25.5	FAE	=	0.010
PSIAV	=	27.5	NOX	=	19.6	PF	=	0.051
PTIAV	=	28.1	NOXEI	=	2.69			

Figure 14. Typical CRT Display of Average Values (Non-Metric).

Pressure from 0 to 34.5 MPa can be measured with the use of pressure transducers. These transducers were used to measure those parameters necessary for the determination of airflow rate. Rig pressures were measured with a Scanivalve transducer.

Temperatures were measured as follows:

- o Combustor inlet - chromel-alumel thermocouples (289 to 1367 K)
- o 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 automatically.

D.- ENGINE TEST FACILITY AND INSTRUMENTATION

1. Facility. - The Model TFE731 Engine is tested in a facility of approximately 372 square meters (4000 ft2) containing two thrust-stand cells and supporting areas. The test cells, control modules, staging areas, and a high-speed digital data acquisition system are all housed in a single structure. This test facility, shown in Figure 15, is utilized for development, qualification, and production testing of AiResearch prime propulsion turbofan engines, having thrust capabilities of up to 22 kN (5000 lbf).

2. Instrumentation. - The gaseous emissions measurement equipment is mobile, and the same equipment described previously is used during engine tests. The fixed emissions probe, which is mounted in the plane of the engine core exhaust duct, has 12 sampling points, and conforms to EPA regulations.

Engine instrumentation consists of a total of 44 thermocouples, three pressure transducers connected to 88 pressure probes via Scanivalves, two transducers measuring thrust, two speed indicators, and a turbine fuel-flow meter. The output of the instrument is fed to a digital computer, which corrects and statistically averages the raw data to produce 21 measured engine parameters, including combustor inlet pressure and temperature. To record a performance data point, three data scans are taken at 15-second intervals, and the three sets of data are averaged. The computer then calculates the engine performance parameters. Combustor airflow is calculated from the known effective area of the primary nozzle, the known turbine cooling airflow, and the measured LP turbine discharge pressure and temperature.

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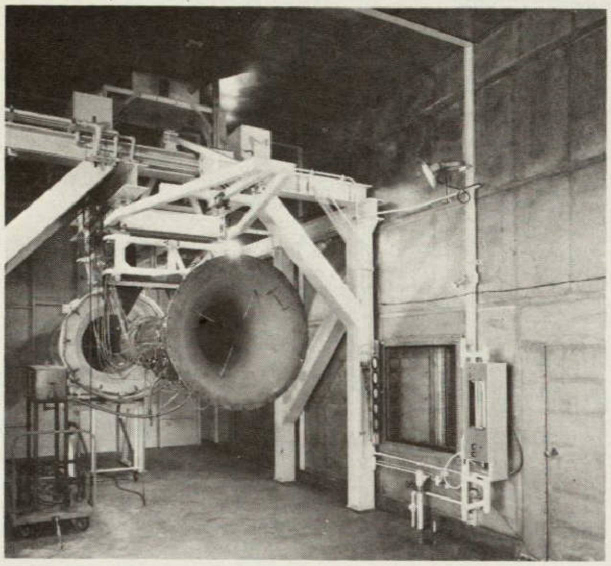
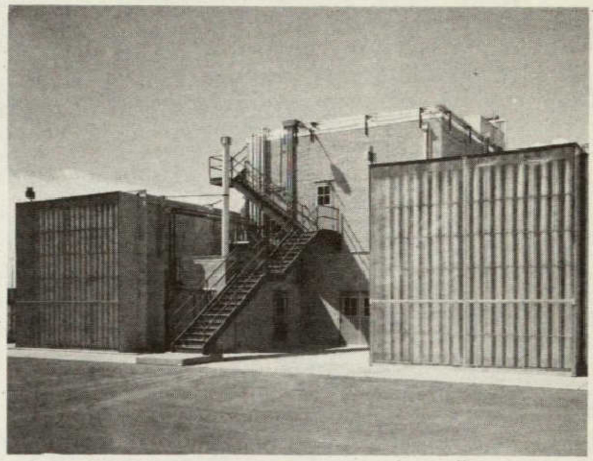


TYPICAL TEST CELL



DUAL TEST FACILITY FOR
TURBOFAN/TURBOJET ENGINES

ENGINE TEST CONSOLE

DATA-ACQUISITION SYSTEM

Figure 15. Propulsion Engine Test Facility.

E.- TEST PROCEDURES AND CONDITIONS

1. Rig Tests. - The pressure rig testing was divided into two phases; the first involved the refinement testing of 10 combustor configurations (five for each concept); and the later phase entailed the optimization of the most promising configuration. The objectives of these two test phases differed as to their respective test procedures; therefore, the test procedure for each phase will be discussed separately.

a. Combustor Refinement Tests. - The purpose of this test phase was to develop the two combustion system concepts through a series of rig tests, modifications, and retests. Five configurations of each concept were evaluated, with each configuration undergoing approximately 10 hours of on-point testing.

The test objectives were to develop a combustion system(s) that simultaneously meets all program emission goals, while at the same time demonstrates combustion-performance characteristics that are equal or superior to those of the present production configuration. To attain this objective, a series of tests were performed. These tests are described in the following sections.

(1) Isothermal Pressure Loss. - This test was the first to be performed for a new configuration. Its purpose was to determine that adequate pressure drop was available across the combustor to ensure sufficient mixing. The pressure losses of the combustion systems were evaluated at non-burning conditions by flowing a series of four combustor-reference velocities that encompass the burner operating range. Figure 16 is the test facility instruction sheet that was used for this test.

(2) Emission and Performance Tests. - The objectives of these tests were to establish the emission values and performance characteristics of the configurations at the four LTO cycle points (taxi-idle, approach, simulated climb, and simulated takeoff) and at a simulated cruise condition of M = 0.8 at 12,192 m. Figure 17, the test facility instruction sheet used for these tests, shows the required conditions.

The procedure for ignition was to first set the combustor inlet air to the start conditions detailed in the test instructions (see Figure 17, Condition 1). The ignition unit was activated and after a 5-second delay, the fuel was turned on. If there was no light-off within 5 seconds, the ignition was deactivated, and the fuel-flow rate increased by 2.27 kg/hr. The fuel was then shut off to allow the rig airflow to purge the unburned fuel from the rig for a minimum of 2 minutes before repeating the ignition process. This procedure was repeated until ignition occurred, or a maximum fuel-flow rate of 140 kg/hr was attained.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Date ____________________

C100 - COMBUSTION CELL TEST REQUEST

EWO: ____________________ **Test Title:** Isothermal Pressure Loss

Test Request 1

Applicable Unit: TFE731-2

Combustion Chamber Liners:

1. Various 3. ______ 5. ______
2. ______ 4. ______ 6. ______

Igniter Various **Atomizer** Various

Ignition Unit Various **Ignition Lead** Various

Cell Test Rig 3551400 **Fuel** None

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Operating Conditions:

Cond. No.	Airflow Data							Combustor Data					Corr. Flow Lb/Sec
	Flow, Lb/Min	Orifice Size	$\sigma\Delta P$ "H_2O	P_o PSIG	T_o °F	ΔP "H_2O	σ	T_{in} °F	P_{in} "HgA	P_{in} "Hgg	T_{disch} °F	W_{fuel} Lb/Hr	
1	259	8 x 6	36.0	50	225	10.9	3.3	200	58.3		200	0	2.5
2	311	8 x 6	52.0	100	225	8.8	5.9	200	58.3		200	0	3.0
3	363	8 x 6	71.0	100	225	12.1	5.9	200	58.3		200	0	3.5
4	415	8 x 6	93.0	100	225	15.8	5.9	200	58.3		200	0	4.0

Remarks:

Figure 16. Test Facility Instruction Sheet, Isothermal Pressure Loss.

Date ____________________

C100 - COMBUSTION CELL TEST REQUEST

EWO: ____________________ Test Title: Emission and Performance Tests - LTO Cycle Plus Cruise

Test Request 2

Applicable Unit: TFE731-2

Combustion Chamber Liners:

1. Various 3. ______ 5. ______
2. ______ 4. ______ 6. ______

Igniter Various Atomizer Various

Ignition Unit Various Ignition Lead Various

Cell Test Rig 3551400 Fuel ASTM D1655-73, Type Jet A

Operating Conditions:

Cond. No.	Airflow Data							Combustor Data					
	Flow, Lb/Min	Orifice Size	σΔP "H_2O	P_o PSIG	T_o °F	ΔP "H_2O	σ	T_{in} °F	P_{in} "HgA	P_{in} "Hgg	T_{disch} °F	W_{fuel} Lb/Hr	Remarks
1	171.6	8 X 6	15.8	50	110	4.0	4.0	100	59.7		1100	165	Ignition
2	305.5	8 X 6	50.5	100	220	8.5	5.9	206	59.7		898	193	Taxi-idle
3	772.0	8 X 6	328.0	200	465	40.1	8.2	448	157.0		1235	532	Approx.
4	530.3	8 X 6	152.5	200	719	23.8	6.4	699	122.0		1716	496	Cruise
5	531.1	8 X 6	155.0	200	760	25.0	6.2	739	122.0		1695	469	Climbout
6	522.1	8 X 6	149.5	200	790	24.7	6.0	772	122.0		1768	482	Takeoff
7	522.1	8 X 6	149.5	200	270	14.4	10.4	250	122.0		900	350	Shutdown

Remarks:

Figure 17. Test Facility Instruction Sheet, Emission and Performance Tests.

Once ignition was attained, the inlet and discharge conditions were set to Condition 2, the taxi-idle condition. A data point was taken following a 2-minute stabilizing period. The data point included a discharge temperature and gaseous emission traverse, as previously described. Discharge total pressure was read at four circumferential positions 90 degrees apart. Smoke was not measured at any of the taxi-idle points.

Upon completion of testing at taxi-idle the rig was transitioned to Condition 3, the approach combustor condition. A data survey, as described above, was made following a 2-minute stabilizing period. In a similar manner, the rig was set to Conditions 4, 5, and 6, which represent the simulated cruise, climb, and takeoff power settings, respectively. A data survey was made following a 2-minute stabilization period. Care was taken to avoid over-temperature operation of the rig when smoke measurements were obtained at several high-power conditions.

Parametric evaluations were made at each test condition, and entailed the determination of the effect on pollutant levels of such factors as fuel/air ratio and primary-zone residence time. The effects of swirler variable geometry on Concept 2, and fuel staging on Concept 3, were evaluated during this testing.

To shut down the rig, the combustor was set to Condition 7. Once this condition was established, the fuel was shut off and the air-purge system was activated and maintained until the combustor inlet and exit air temperatures were below 394 K.

(3) Wall Temperature Tests. - To determine the wall temperatures of selected combustor configurations the combustors were painted with temperature-sensitive paint. The rig was brought up to the simulated takeoff condition (Condition 6, Figure 17) as quickly as possible, and the correct geometry or fuel-flow split set. The rig remained at this condition for a minimum of 10 minutes. At least one data scan was taken during this time. At the completion of the test, the rig was shut down as described in the preceding paragraph. The combustor was removed from the rig, and isothermal lines drawn and identified. The combustor was then photographed in four views to obtain a complete record of the liner-wall temperatures.

(4) Ignition, Altitude Relight, and Stability Tests. - To determine the ignition, altitude relight, and stability characteristics of the various combustion systems, a series of test points were evaluated and compared to the performance of the present production combustor. The test points were a combination of combustor reference velocities, inlet pressure, and inlet temperatures that represent the corners of the ignition, altitude relight, and operational envelopes of the Model TFE731-2 Engine. The criteria for successful performance was ignition, altitude relight, and blowout fuel air ratios less than those measured for the production configuration.

(a) Ignition and Altitude Relight Test Procedure. - The procedure for the ignition and altitude relight points is described below:

- The proper combustor inlet conditions were set.

- With the ignition off, the fuel was turned on and set to a predetermined value.

- The fuel was then shut off, and the combustor airflow was used to purge the accumulated fuel from the combustor (purge was for a minimum of 2 minutes).

- The ignition was turned on, and after approximately a 5 second delay the fuel was turned on. If ignition occurred, the fuel was shut off and the rig exit temperature cooled down to within 5 K of the inlet temperature before the next attempt was made. If no ignition occurred within 5 seconds, the ignition was shut off and the fuel-flow rate was reset to the new test level and shut off. Airflow was allowed to purge fuel from the combustor for at least 2 minutes.

- The ignition fuel-flow rate was established when the combustor sustained ignition three successive times within 2 seconds after manifold pressurization was indicated. If the ignition time was longer than 2.0 seconds, the fuel-flow rate was increased by 2 to 3 kg/hr for the next attempt.

  A two-channel recorder was used to measure the time between the initiation of fuel flow and ignition. One channel was connected to a pressure transducer to measure manifold fuel pressure; the other channel was connected to a combustor-discharge thermocouple. The time for ignition to occur was measured from the point a steady fuel pressure was attained to the first indications of a rise in combustor exit temperature.

(b) Stability Test Procedure. - For the stability tests, the procedure was as follows:

- With the combustor burning, the required inlet conditions were set.

- The fuel flow was gradually reduced while inlet conditions were maintained until the combustor blew out.

- o The fuel flow was shut off and air purge of the fuel system was immediately activated.
- o The fuel flow and fuel pressure at blowout were recorded.

b. Combustor Optimization Tests. - At the completion of the refinement tests, one combustor concept was selected for further testing. The ultimate objective of the Phase II rig testing was to produce a combustion system that meets the 1979 EPA emission goals, has satisfactory combustor performance, and is geometrically compatible with the engine envelope. The purpose of the optimization tests was to ensure that these objectives were met. The type of testing and the procedure was identical to that conducted in the refinement tests previously described; however, the testing was more extensive and complete. A total of three test configuration were evaluated in the optimization test phase. The testing of each configuration took approximately 17 hours.

2. Engine Tests. - Two TFE731-2 engine tests were conducted for the purpose of obtaining emissions correlations between the engine and test rig. The engine test procedure was as follows: A 12-point emissions probe conforming to the EPA regulations (Ref. 1) was mounted at the exhaust plane of the engine primary nozzle. The engine HP spool was spun up to approximately 10,000 rpm by an air turbine starter; and the engine computer was engaged, which brought the engine up to idle speed. The engine was accelerated to the desired thrust level and allowed to stabilize for several minutes before data acquisition. The maximum thrust level was limited either by the HP turbine discharge temperature (1133 K), or by the LP compressor speed (19,676 rpm).

F.- DATA REDUCTION AND CALCULATION PROCEDURES

Data taken during combustion testing was read from a magnetic tape and reduced by a computer program using a high-speed digital computer. The program consists of three subprograms; (a) combustor discharge temperature survey, (b) combustor performance, and (c) emissions data reduction and analysis. These subprograms are described in the following sections.

1. Combustor Discharge Temperature Survey. - This data reduction subprogram takes thermocouple readings and prints the resultant temperatures in both tabular and figure (plot) forms. The subprogram can accept up to a maximum of 12 radial and 60 circumferential positions. Inoperative thermocouples may be deleted at the discretion of the operator. The temperatures recorded at each circumferential position are listed by column for each thermocouple (see Figure 18). The average, maximum, and minimum temperatures, and the temperature-spread factor are computed for each

RUN 154 PT 8 PAP22800? REV 8 77 NOZ .3 SPACERS -2 PLATE -2 HI6 JPS

UNIT 321 S/N 7 TEST 560 SCAN, 35

THERMOCOUPLE NO.		1	2	3	4	5	6	7	8	9	10	11	12	RADIAL VALUES-			
RADIUS, IN.		4.46	4.62	4.83	5.03	5.24	5.44	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00	AVG	MAX	MIN	SPREAD
	ANGLE, DEG.																
1	0.0	1812.	1837.	1872.	1926.	1954.	1963.	0.	0.	0.	0.	0.	0.	1894.	1963.	1812.	151.
2	10.0	1896.	1885.	1862.	1829.	1804.	1784.	0.	0.	0.	0.	0.	0.	1843.	1896.	1784.	112.
3	20.0	1874.	1913.	1933.	1926.	1911.	1890.	0.	0.	0.	0.	0.	0.	1908.	1933.	1874.	59.
4	30.0	1880.	1903.	1972.	1959.	1991.	2018.	0.	0.	0.	0.	0.	0.	1945.	2018.	1880.	138.
5	40.0	1930.	1942.	1942.	1934.	1928.	1917.	0.	0.	0.	0.	0.	0.	1932.	1942.	1917.	25.
6	50.0	1849.	1920.	1979.	2024.	2038.	2026.	0.	0.	0.	0.	0.	0.	1973.	2038.	1849.	189.
7	60.0	1812.	1829.	1838.	1866.	1877.	1888.	0.	0.	0.	0.	0.	0.	1852.	1888.	1812.	76.
8	70.0	1914.	1877.	1831.	1784.	1760.	1740.	0.	0.	0.	0.	0.	0.	1818.	1914.	1740.	175.
9	80.0	1906.	1933.	1928.	1886.	1840.	1790.	0.	0.	0.	0.	0.	0.	1881.	1933.	1790.	143.
10	90.0	1793.	1849.	1880.	1899.	1888.	1871.	0.	0.	0.	0.	0.	0.	1863.	1899.	1793.	106.
11	100.0	1785.	1801.	1807.	1823.	1821.	1806.	0.	0.	0.	0.	0.	0.	1807.	1823.	1785.	38.
12	110.0	1798.	1840.	1871.	1893.	1897.	1896.	0.	0.	0.	0.	0.	0.	1866.	1897.	1798.	99.
13	120.0	1834.	1824.	1804.	1801.	1799.	1815.	0.	0.	0.	0.	0.	0.	1813.	1834.	1799.	34.
14	130.0	1986.	1951.	1908.	1842.	1784.	1714.	0.	0.	0.	0.	0.	0.	1864.	1986.	1714.	272.
15	140.0	1940.	1994.	2018.	2007.	1979.	1942.	0.	0.	0.	0.	0.	0.	1980.	2018.	1940.	78.
16	150.0	1803.	1862.	1908.	1974.	2006.	2033.	0.	0.	0.	0.	0.	0.	1931.	2033.	1803.	231.
17	160.0	1863.	1826.	1787.	1779.	1785.	1820.	0.	0.	0.	0.	0.	0.	1810.	1863.	1779.	84.
18	170.0	1908.	1913.	1885.	1831.	1790.	1754.	0.	0.	0.	0.	0.	0.	1847.	1913.	1754.	159.
19	180.0	1837.	1903.	1966.	2014.	2021.	2009.	0.	0.	0.	0.	0.	0.	1958.	2021.	1837.	184.
20	190.0	1863.	1854.	1835.	1848.	1865.	1903.	0.	0.	0.	0.	0.	0.	1861.	1903.	1835.	68.
21	200.0	1824.	1862.	1869.	1860.	1838.	1818.	0.	0.	0.	0.	0.	0.	1845.	1869.	1818.	51.
22	210.0	1709.	1747.	1777.	1834.	1871.	1908.	0.	0.	0.	0.	0.	0.	1808.	1908.	1709.	199.
23	220.0	1757.	1725.	1693.	1689.	1676.	1666.	0.	0.	0.	0.	0.	0.	1701.	1757.	1666.	91.
24	230.0	1809.	1810.	1781.	1732.	1693.	1676.	0.	0.	0.	0.	0.	0.	1750.	1810.	1676.	134.
25	240.0	1787.	1799.	1809.	1834.	1849.	1863.	0.	0.	0.	0.	0.	0.	1824.	1863.	1787.	76.
26	250.0	1902.	1866.	1817.	1758.	1701.	1642.	0.	0.	0.	0.	0.	0.	1781.	1902.	1642.	260.
27	260.0	1906.	1914.	1891.	1838.	1787.	1740.	0.	0.	0.	0.	0.	0.	1846.	1914.	1740.	175.
28	270.0	1820.	1871.	1902.	1926.	1923.	1910.	0.	0.	0.	0.	0.	0.	1892.	1926.	1820.	107.
29	280.0	1845.	1831.	1817.	1837.	1868.	1919.	0.	0.	0.	0.	0.	0.	1853.	1919.	1817.	102.
30	290.0	1877.	1876.	1860.	1829.	1793.	1762.	0.	0.	0.	0.	0.	0.	1833.	1877.	1762.	115.
31	300.0	1826.	1846.	1849.	1854.	1849.	1843.	0.	0.	0.	0.	0.	0.	1845.	1854.	1826.	28.
32	310.0	1908.	1872.	1828.	1785.	1757.	1746.	0.	0.	0.	0.	0.	0.	1816.	1908.	1746.	162.
33	320.0	1920.	1949.	1953.	1919.	1866.	1809.	0.	0.	0.	0.	0.	0.	1903.	1953.	1809.	144.
34	330.0	1809.	1859.	1885.	1930.	1963.	1995.	0.	0.	0.	0.	0.	0.	1907.	1995.	1809.	187.
35	340.0	1806.	1810.	1812.	1824.	1829.	1832.	0.	0.	0.	0.	0.	0.	1819.	1832.	1806.	27.
36	350.0	1815.	1840.	1843.	1828.	1807.	1784.	0.	0.	0.	0.	0.	0.	1819.	1843.	1784.	59.

CIRCUMFER. VALUES-	1	2	3	4	5	6	7	8	9	10	11	12
AVERAGE TEMP.	1850.	1865.	1866.	1864.	1856.	1847.	0.	0.	0.	0.	0.	0.
MAXIMUM TEMP.	1986.	1994.	2018.	2024.	2038.	2033.	0.	0.	0.	0.	0.	0.
MINIMUM TEMP.	1709.	1725.	1693.	1689.	1676.	1642.	0.	0.	0.	0.	0.	0.
SPREAD, MAX-MIN	277.	268.	325.	335.	362.	391.	0.	0.	0.	0.	0.	0.
SPREAD, MAX-AVG	136.	129.	153.	160.	182.	186.	0.	0.	0.	0.	0.	0.
STANDARD DEVIATION	58.	56.	66.	78.	91.	105.	0.	0.	0.	0.	0.	0.
MAX TEMP GRADIENT	152.	132.	140.	195.	231.	255.	0.	0.	0.	0.	0.	0.
MAX TEMP GRAD/INCH	196.	164.	166.	222.	253.	269.	0.	0.	0.	0.	0.	0.
PATTERN FACTOR	.131	.122	.144	.151	.174	.179	0.000	0.000	0.000	0.000	0.000	0.000

PATTERN FACTORS BASED ON INLET TEMP OF 808.

ALL TEMPS ARE FAHRENHEIT

THERMOCOUPLE JUNCTIONS ARE PLATINUM/PLATINUM 10 RHODIUM

OVERALL VALUES BASED ON-	STRAIGHT AVERAGE	WEIGHTED BY AREAS	INPUT AVG
AVERAGE	1858.	1858.	1850.
MAXIMUM	*****	2038.	*****
MAXIMUM	*****	2038.	*****
MINIMUM	*****	1642.	*****
TOTAL SPREAD, MAX-MIN	*****	396.	*****
AVG TO PEAK SPREAD, MAX-AVG	180.	180.	188.
PATTERN FACTOR BASED ON SINGLE AVERAGE	.171	.172	.180
PATTERN FACTOR, (T MAX - RAKE AVG) / (INPUT AVG - T INLET)	.173	.173	

Figure 18. Typical Combustor Discharge Gas Temperature Data Display, TFE731-2 Combustion Rig (Non-Metric).

radial position and for each circumferential location. A straight overall average, and an average weighted by the areas determined by the thermocouple radial locations, are also printed. The temperature-spread factor or pattern factor is calculated using both straight and weighted-average temperatures. The average, maximum, and minimum radial temperatures are plotted as a function of their angular position (Figure 19), showing the circumferential variations. Each thermocouple is given a different symbol, and all the readings of each individual thermocouple are connected by lines.

2. Combustor Performance. - The combustor performance subprogram uses fuel rotameter flow data to calibration curve values, calculates combustion efficiency from an enthalpy balance, and calculates the following additional parameters:

- Inlet airflow
- Air-assist airflow
- Measured fuel/air ratio
- Average inlet and discharge pressures and temperatures
- Combustor pressure drop
- Reference velocity
- Inlet air specific humidity
- Volumetric heat-release rate
- Combustor loading and blowout parameters

A separate performance sheet is not printed; but the performance parameters are included on the test summary sheet.

3. Emission Data and Calculation Procedure.

a. Emission Data Processing Procedure. - The voltage output of the gaseous emissions analysis equipment was transmitted from the test facility to a computer-generated magnetic tape. The millivolt data was then processed into ppm concentrations on the main digital computer, and the equations used to calculate emission indices, carbon balance, fuel/air ratio, and combustion efficiency were those in SAE ARP 1256 (Ref. 4).

In addition, the voltage output of the gaseous analysis equipment was recorded on a moving strip chart as ppm concentrations. This chart provided a permanent record of each emission trace, and aided in making visual qualitative and quantitative evaluations of circumferential patterns.

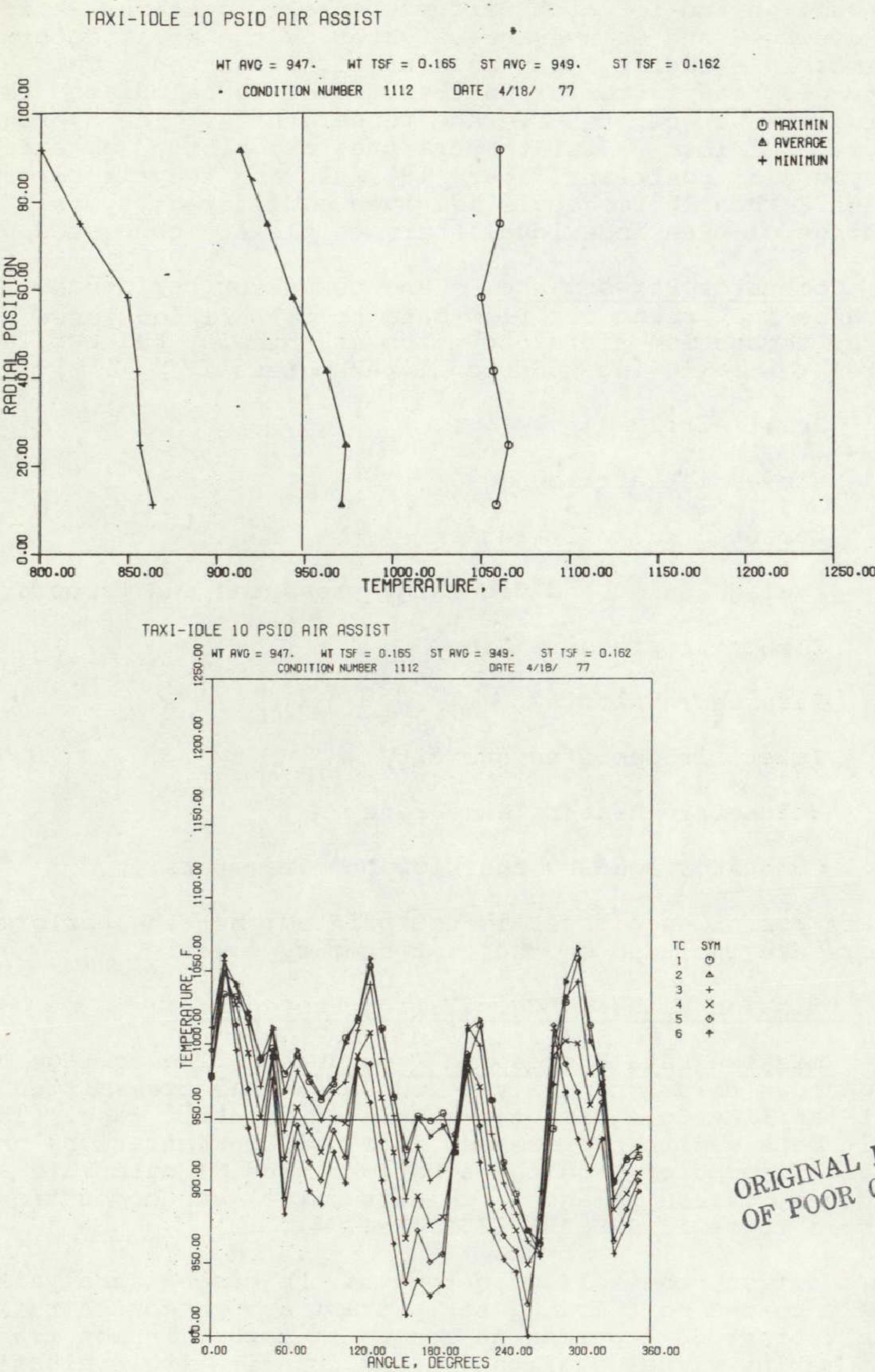

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Figure 19. Typical Circumferential Gas Temperature Variations at Turbine Inlet Section (Non-Metric).

The emission data-reduction subprogram takes the millivolt readings of the emission analysis equipment and converts them into emission volumetric concentrations, emission indices in grams per kilogram of fuel, and EPA parameters in pounds per 1000 pound-thrust hour per LTO cycle. For both the emission indices and EPA parameters, the volumetric concentrations of the pollutant species are corrected to concentrations in wet exhaust gas from a combustion process with dry air. The CO and CO_2 recordings are considered dry data because of the use of a desiccant in the sampling train. They need only to be corrected for the amount of water vapor formed by the combustion process. The samples of HC and NO_x are not dried, and must be corrected for the initial amount of water vapor in the air to obtain the concentrations needed for the emission indices. In addition, since the FID hydrocarbon analyzer is calibrated with propane, the HC concentrations are multiplied by 3 to convert to equivalent CH_4 concentrations. The fuel/air ratio is calculated using dry concentrations, and combustion efficiency is calculated using concentrations converted to that in wet exhaust gas from a combustion process with dry air (wet concentrations).

The pollutant concentrations recorded during the rotation of the emissions probe are listed by column for each specie as typified in Figure 20. Each specie and the radially averaged discharge temperature were also plotted as a function of their angular position (Figure 21) showing the circumferential variation. The value at any particular circumferential location was approximate, since the emission analysis equipment response time was greater than the pause time (14 seconds) of the emission probe; however, the circumferential variation of fuel air ratio indicated the degree of mixing of the combustion system at the exhaust plane.

The emission data processing procedure was similar in the case of engine data, with the exception that emission data were taken with a fixed averaging probe in the engine exhaust, and therefore no circumferential or radial variations were measured.

b. <u>EPAP Adjustment Procedure and Calculations</u>. - The emission indices appearing in this report are not corrected for variations in the combustor operating conditions, with the exception of humidity. All reported NO_x emission indices have been corrected to standard-day humidity, 6.34 g H_2O/kg air.

As explained in the following paragraphs, corrections were made to the emissions indices in order to calculate the EPA parameters (EPAP). The EPA emission standards are expressed in terms of a parameter 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.

******************NASA T1 CONCEPT III 3550975-3 DATA PAGE 39 COND 26-3 ***************

CONDITION NUMBER = 263 SPECIFIC HUMIDITY = .00031 LB/LB

FUEL IS AVK FUEL H/C = 1.93 STOI F/A = .06822 L H V = 18470.

CIRCUMFERENTIAL VARIATION OF EMISSIONS DATA

EMISSION SPECIES		CO	UHC	NOX	CO2	
		PPMV	PPMC	PPMV	PERCENT	F/A RATIO
	ANGLE,DEG.					
1	0.0	174.6	6.2	1.6	1.60	.00786
2	10.0	252.6	33.9	1.2	1.20	.00595
3	20.0	319.8	56.3	.9	1.03	.00522
4	30.0	371.3	55.8	.9	1.01	.00511
5	40.0	351.2	23.7	1.0	1.17	.00588
6	50.0	255.4	8.1	1.4	1.61	.00792
7	60.0	185.4	7.8	1.6	1.66	.00813
8	70.0	186.8	12.2	1.0	.93	.00461
9	80.0	200.4	17.7	.6	.71	.00356
10	90.0	263.7	23.4	.6	.71	.00359
11	100.0	287.5	12.2	1.1	1.17	.00582
12	110.0	234.6	3.9	1.7	1.78	.00874
13	120.0	258.2	4.8	2.2	2.07	.01014
14	130.0	277.7	5.0	1.9	1.89	.00931
15	140.0	295.9	8.7	1.8	1.73	.00852
16	150.0	305.7	19.7	1.3	1.34	.00669
17	160.0	288.9	26.6	1.1	1.18	.00587
18	170.0	329.8	35.0	.9	1.05	.00530
19	180.0	365.6	35.6	.9	1.15	.00578
20	190.0	391.7	32.4	.9	1.16	.00586
21	200.0	385.9	38.9	.9	1.13	.00571
22	210.0	339.8	24.6	1.1	1.35	.00674
23	220.0	254.0	16.7	1.3	1.54	.00761
24	230.0	272.1	19.5	1.5	1.76	.00868
25	240.0	319.8	23.6	1.8	1.99	.00980
26	250.0	371.3	34.8	1.8	1.94	.00959
27	260.0	404.9	55.8	1.8	1.85	.00921
28	270.0	455.8	108.8	1.3	1.42	.00716
29	280.0	407.8	90.2	.8	.99	.00507
30	290.0	334.0	48.9	.8	.95	.00483
31	300.0	294.5	18.2	1.1	1.38	.00684
32	310.0	279.1	12.3	1.7	1.88	.00925
33	320.0	300.1	18.5	2.0	2.11	.01034
34	330.0	318.4	20.1	2.0	2.11	.01038
35	340.0	259.5	8.1	1.8	1.99	.00976
36	350.0	242.9	6.8	2.1	2.04	.01000

	CO	UHC	NOX	CO2
AVERAGE VALUE	301.0	270.7	13.4	1.46
MAXIMUM VALUE	455.8	108.8	2.2	2.11
MINIMUM VALUE	174.6	3.9	.6	.71
SPREAD,MAX-MIN	281.1	104.9	1.6	1.40
ANGLE OF MAX VALUE	270.0	270.0	120.0	330.0

ALL EMISSIONS CONCENTRATIONS CORRECTED TO CONCENTRATION IN WET EXHAUST FROM COMBUSTION WITH DRY AIR

UNBURNED HYDROCARBON CONCENTRATIONS GIVEN AS PPM BY VOLUME AS CARBON

EMISSION VALUES AT EACH CIRCUMFERENTIAL LOCATION ARE APPROXIMATE SINCE STEADY STATE WAS NOT REACHED

Figure 20. Typical Emissions Survey Data (Non-Metric).

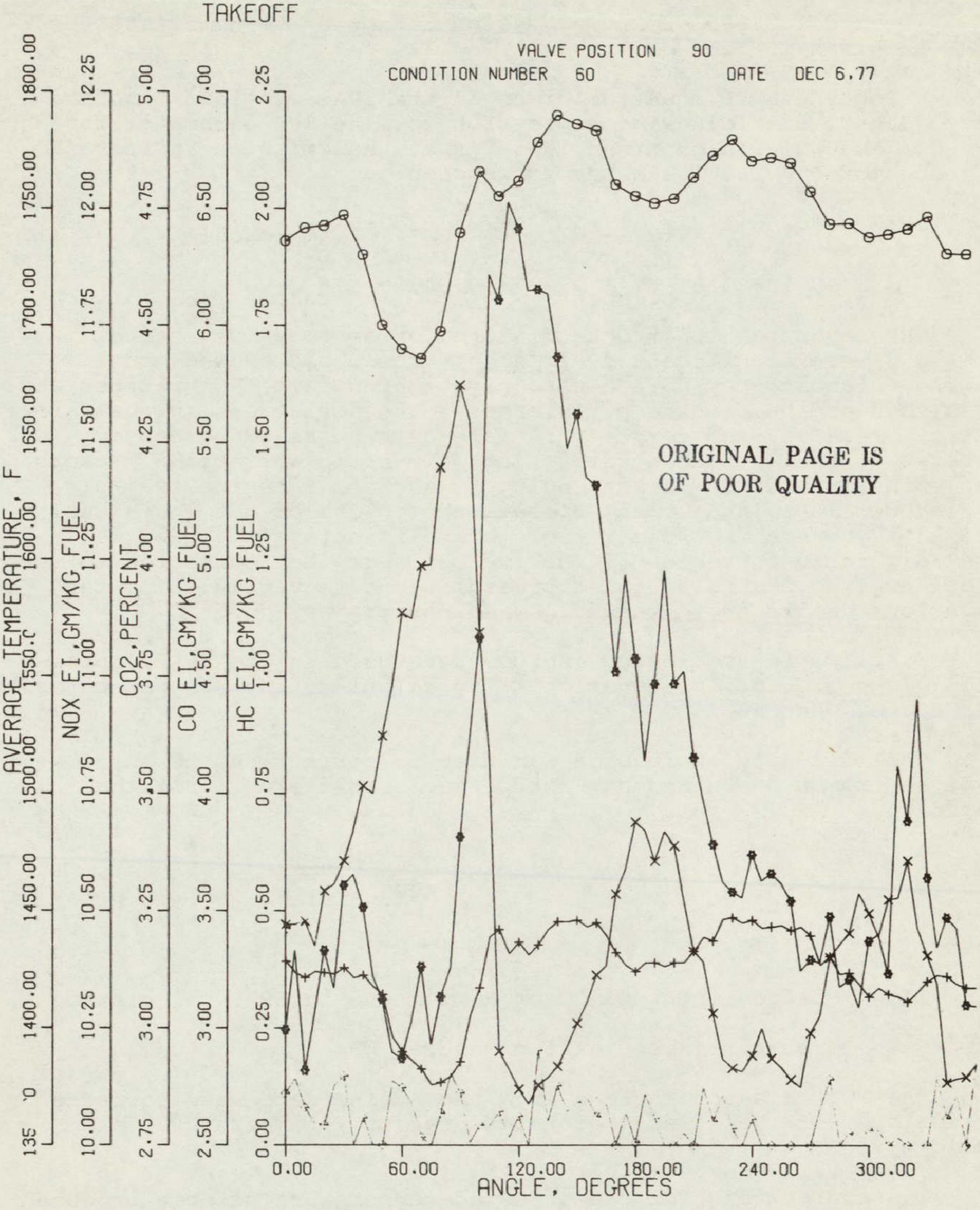

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Figure 21. Typical Emissions Concentrations as a Function of Sample Probe Angular Position. (Non-Metric).

The Model TFE731-2 Engine design data used to calculate the EPAP is given in Table X.

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

$$EPAP = 0.26511\ EI_{taxi-idle} + 0.12252\ EI_{approach} + 0.18823\ EI_{climbout} + 0.04253\ EI_{takeoff} \quad (1)$$

The combustor inlet data measured on development engine S/N 7353 were significantly different from those of the model engine, standard-day data due to high ambient air temperatures and less-than-nominal engine performance. The deviations in fuel/air ratio, pressure, and temperature were as high as 10 percent. Because of the lack of accurate fuel/air ratio correction factors, the emission indices corresponding to the model engine fuel/air ratios were obtained by interpolation of plots of the individual emissions versus fuel/air ratio, thus eliminating the need for a fuel/air ratio correction. The indices were then corrected to the model engines combustor inlet pressures and temperatures by the equations described in the following paragraphs.

Finally, the corrected indices were used in the EPAP expression given previously (equation 1) to calculate the EPA parameters for HC, CO, and NO_x.

The following expression was used to correct the HC and CO indices from the engine data for pressures different from the standard.

$$EI_{CORR.} = EI_{MEAS.} \frac{P_{T3\ MEAS.}}{P_{T3\ STD.}} \quad (2)$$

where:

EI = Emission index of CO or HC for use in EPAP calculation

P_{T3}= Combustor inlet total pressure, kPa

The NO_x emission indices from the engine data were corrected as follows for the effects of inlet pressure, temperature, and humidity.

The corrections for pressure and temperature effects produced a maximum combined increase of 31 percent. The humidity correction produced a maximum reduction of 6 percent.

TABLE X.- MODEL TFE731-2 ENGINE DESIGN DATA, SEA-LEVEL STATIC, STANDARD-DAY CONDITIONS

Engine Mode	Net Thrust, kN	Fuel Flow kg/hr	Combustor Inlet Total Temp., K	Combustor Inlet Total Pressure, kPa	Combustor Fuel/Air Ratio
Taxi-idle	0.9	87.3	369.9	202.1	0.0105
Approach	4.7	241.4	504.5	531.8	0.0115
Climbout	14.0	667.6	665.9	1301	0.0147
Takeoff	15.6	754.3	684.6	1425	0.0154

$$EI_{CORR.} = EI_{MEAS.} \left(\frac{P_{T3\ STD.}}{P_{T3\ MEAS.}}\right)^{\eta} \left[e^{(T_{T3\ STD.} - T_{T3\ MEAS.})/288}\right] \left[e^{19(H_{MEAS.} - H_{STD.})}\right] \quad (3)$$

where:

EI = Emission index of NO_x for use in EPAP calculation

P_{T3} = Inlet total pressure, kPa

T_{T3} = Inlet total temperature, K

H = Inlet specific humidity, g H_2O/g air

H_{STD} = 0.00634 g H_2O/g air

η = Pressure correction exponent

The NO_x pressure-correction (η) was calculated to be 0.35 at the takeoff mode for four engine/rig correlation tests, and 0.29 at the climbout mode. Three of the tests were conducted with a production TFE731-2 combustion system, and one was performed with the Concept 2 system. The correction factor is not in agreement with the 0.5 value more commonly used throughout the industry. Data from the General Electric Clean Combustor Program (Ref. 5) suggests that a η term lower than 0.5 results from testing a combustor designed to operate with a near-stoichiometric primary zone, but that η approaches 0.5 as the primary zone is leaned out. This could explain the low value of η for the correlation tests run with a production combustion system, which has a near-stoichiometric primary zone, but does not explain the Concept 2 results. It was decided that to correct engine data for combustor inlet pressure variations from the standard only the more commonly used $\eta = 0.5$ exponent would be utilized.

In the case of the combustor rig data, the fuel/air ratio and combustor inlet temperatures were adjusted to the standard values and no corrections were necessary. However, the rig was limited to a pressure of 414 kPa at the climbout and takeoff modes. The EPAP values for the rig were calculated by two methods: (1) the more conservative method did not correct the HC and CO indices at takeoff and climbout modes for the effects of pressure, and a pressure correction exponent of 0.5 was used to correct NO_x. (2) The second method corrected the HC and CO data by the inverse of the pressure ratio (equation 2) and the following pressure correction exponents were used at takeoff and climbout, respectively: 0.35 and 0.29. Both methods used equation 3 to correct NO_x for pressure and humidity (temperature correction excluded). The maximum reduction in the index due to humidity corrections was 13 percent. The previously given EPAP expression (equation 1) was used for both methods to calculate the EPA parameters for HC, CO, and NO_x.

c. <u>Test Summary Sheets</u>. - In addition to the temperature and emission survey printouts, the data reduction program printed a summary of the test results as shown in Figure 22. The summary included a description of the combustor configurations tested; pollutant concentrations and indices from the emission data-reduction subprogram were listed next for each test condition, followed by the combustor performance parameters and the average combustor discharge temperature and pattern factor.

The data-reduction program also punched selected performance parameters on cards for each test condition. These cards were then input into a separate program to calculate the EPA parameters. Test conditions corresponding to the LTO cycle operating modes could therefore be selected from any test. An example of the EPA parameter computation summary for rig data is shown in Figure 23. HC and CO emissions were corrected by the inverse pressure ratio between engine and rig conditions for the climbout and takeoff operating modes. Similarly, NO_x emissions were corrected using a pressure exponent for the climbout and takeoff modes. The NO_x values were also corrected to standard-day humidity conditions for all four LTO power settings.

```
************************************** NASA T1 POLLUTION REDUCTION PROGRAM TEST RESULTS **************************************
CONCEPT NO. 2  TEST  OPTIMIZATION 1      COMBUSTOR P/N   3551401-8     AIR HUMIDITY,GM H2O/KG AIR .0466   TEST DATE DEC 15,77
FUEL MANIFOLD   AIRBLAST DLN 36212               SWIRLERS  ASSEMBLY 3551403-2 WELDED OPEN, NO LINKAGE
COMB REF AREA,IN2   253.4      COMB VOLUME,IN3  1149.0       FUEL  AVK        ATOMIC H/C RATIO    1.928          LHV,BTU/LB  18470.
                                   HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))
******************************************************************************************************************************
```

CONDITION NO/VALVE POSITION	40/90	50/90	60/90
ENGINE OPERATING MODE	CRUISE	CLIMBOUT	TAKEOFF
CARBON DIOXIDE			
PERCENT BY VOLUME,WET	3.173	3.019	3.154
CARBON MONOXIDE			
PPM BY VOLUME,WET	70.642	64.895	40.343
RATE,LB/HR	2.168	2.008	1.231
GM PER KG OF FUEL	4.460	4.306	2.565
UNBURNED HYDROCARBONS- PPM AS CARBON,WEIGHTS AS CH4			
PPM BY VOLUME,WET	.267	.059	.027
RATE,LB/HR	.005	.001	.000
GM PER KG OF FUEL	.010	.002	.001
TOTAL OXIDES OF NITROGEN(NO+NO2) AS NO2			
PPM BY VOLUME,WET	66.445	66.420	75.537
RATE,LB/HR	3.349	3.376	3.785
GM PER KG OF FUEL	6.890	7.240	7.888
GM/KG FUEL,HUMIDITY CORR	6.114	6.424	6.999
SAE SMOKE NUMBER			
COMB EFFIC FROM EMISSIONS	99.894	99.899	99.940
FA RATIO FROM EMISSIONS	.01556	.01479	.01545
EQUIVALENCE RATIO,EMISSIONS	.22816	.21687	.22654
TEMP SPREAD FACTOR	.063	.053	.043
TOTAL PRESSURE LOSS,PERCENT	6.040	6.384	6.261
AIR HUMIDITY,GM H2O/KG AIR	.047	.047	.047
COMB INLET AIRFLOW,LB/SEC	8.868	9.024	8.802
INLET CORR. AIRFLOW,LB/SEC	3.325	3.454	3.396
PILOT ASSIST AIRFLOW,LB/MIN	0.000	0.000	0.000
COMB TOTAL AIRFLOW,LB/SEC	8.756	8.911	8.691
INLET TOTAL PRESSURE,PSIA	58.533	58.372	58.655
INLET STATIC PRESSURE,PSIA	57.036	56.809	57.102
DISCHRG TOTAL PRESSURE,PSIA	54.998	54.646	54.983
DISCHRG STATIC PRESSURE,PSIA	49.851	49.148	49.389
INLET TOTAL TEMP,DEG F	699.046	741.070	772.434
DISCHRG AVERAGE TEMP,DEG F	1716.005	1707.130	1780.775
COMB EFFIC FROM ENTHALPY	101.634	102.553	102.259
TOTAL FUEL FLOW,PPH	486.083	466.250	479.792
PRIMARY FUEL FLOW,PPH	486.083	466.250	479.792
PRIMARY FUEL PRESS,PSID	0.000	0.000	0.000
PRIMARY NOZZLE F/N	0.000	0.000	0.000
FA RATIO FROM MEASURED FLOWS	.01542	.01453	.01533
ASSIST AIR TEMP,DEG F	91.016	110.116	118.897
COMB REF VELOCITY,FT/SEC	37.444	39.643	39.473
HEAT RATE BTU/HR-ATM2-FT3 E6	3.445	3.344	3.415
LOADING W/P**1.75/V/E(T/540)	.13718	.12976	.11842
PILOT AIR ASSIST PRESS,PSID	0.000	0.000	0.000

Figure 22. Typical Test Results Summary (Non-Metric).

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XYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXYXY

** EPA CYCLE EMISSIONS COMPUTATION SUMMARY **

CONDITION NUMBER 2000
CONCEPT NO. 2 TEST OPTIMIZATION 1 COMBUSTOR P/N 3551401-8 AIR HUMIDITY,GM H2O/GM AIR .0000466 TEST DATE DEC 13,77
FUEL MANIFOLD PRESSURE ATOM. PAP 239444 SWIRLERS ASSEMBLY P/N 3551403-2 SEALED SHUT

CONDITION NUMBER 3000
CONCEPT NO. 2 TEST OPTIMIZATION 1 COMBUSTOR P/N 3551401-8 AIR HUMIDITY,GM H2O/GM AIR .0000466 TEST DATE DEC 13,77
FUEL MANIFOLD PRESSURE ATOM. PAP 239444 SWIRLERS ASSEMBLY P/N 3551403-2 SEALED SHUT

CONDITION NUMBER 5090
CONCEPT NO. 2 TEST OPTIMIZATION 1 COMBUSTOR P/N 3551401-8 AIR HUMIDITY,GM H2O/GM AIR .0000466 TEST DATE DEC 15,77
FUEL MANIFOLD AIRBLAST DLN 36212 SWIRLERS ASSEMBLY 3551403-2 WELDED OPEN, NO LINKAGE

CONDITION NUMBER 6090
CONCEPT NO. 2 TEST OPTIMIZATION 1 COMBUSTOR P/N 3551401-8 AIR HUMIDITY,GM H2O/GM AIR .0000466 TEST DATE DEC 15,77
FUEL MANIFOLD AIRBLAST DLN 36212 SWIRLERS ASSEMBLY 3551403-2 WELDED OPEN, NO LINKAGE

NOX CORRECTION PRESSURE EXPONENT AT CLIMBOUT = .500 NOX CORRECTION PRESSURE EXPONENT AT TAKEOFF = .500
HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))
HC AND CO EMISSIONS CORRECTED AT CLIMBOUT AND TAKEOFF BY THE RIG TO ENGINE PRESSURE RATIO

****

MODE CONDITION NUMBER	TAXI-IDLE 2000	APPROACH 3000	CLIMBOUT 5090	TAKEOFF 6090	TOTAL PER CYCLE
TIME IN MODE,MINUTES	26.000	4.500	2.500	.500	33.500
RATED POWER,PERCENT	5.717	29.996	89.960	100.040	
THRUST,LB	200.080	1049.850	3148.610	3501.390	
LB THRUST-HR	86.701	78.739	131.192	29.178	
ACTUAL RIG PRESSURE,PSIA	28.460	76.082	58.370	58.655	
ENGINE PRESSURE,PSIA	29.319	77.137	188.658	206.633	
FUEL FLOW,LB/HR (RIG FUEL FLOW RATE FOR SIMULATED IDLE BLEED)	192.577	532.297	1471.982	1663.127	
** HYDROCARBON EMISSIONS (HC) **					
INDEX,LB HC/1000 LB FUEL	3.880	.112	.002	.001	
INDEX,LB HC/1000 LB FUEL,CORRECTED FOR PRESSURE	3.880	.112	.001	.000	
RATE,LB HC/HR	.747	.060	.001	.000	
MASS,LB HC	.324	.004	.000	.000	.328
MASS,PERCENT OF TOTAL CYCLE	98.63	1.36	.01	.00	100.0
CYCLE,LB HC/1000 LB THRUST-HR PER CYCLE					1.008
** CARBON MONOXIDE EMISSIONS (CO) **					
INDEX,LB CO/1000 LB FUEL	42.950	4.125	4.306	2.565	
INDEX,LB CO/1000 LB FUEL,CORRECTED FOR PRESSURE	42.950	4.125	1.332	.728	
RATE,LB CO/HR	8.271	2.106	1.961	1.211	
MASS,LB CO	3.584	.165	.082	.010	3.841
MASS,PERCENT OF TOTAL CYCLE	93.32	4.29	2.13	.26	100.0
CYCLE,LB CO/1000 LB THRUST-HR PER CYCLE					11.788
** TOTAL OXIDES OF NITROGEN EMISSIONS (NOX) **					
INDEX,LB NOX/1000 LB FUEL	2.580	5.311	7.240	7.888	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR HUMIDITY	2.289	4.712	6.424	6.999	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR BOTH PRES. AND HUMIDITY	2.289	4.712	11.549	13.137	
RATE,LB NOX/HR	.441	2.508	17.000	21.848	
MASS,LB NOX	.191	.188	.708	.182	1.270
MASS,PERCENT OF TOTAL CYCLE	15.05	14.82	55.79	14.34	100.0
CYCLE,LB NOX/1000 LB THRUST-HR PER CYCLE					3.897

Figure 23. Typical EPA Parameter Computation Summary (Non-Metric).

CHAPTER III

RESULTS AND DISCUSSION

A.- COMBUSTION RIG TESTS

During this Phase II program, two distinct combustor configuations and subsequent modifications were designed, fabricated, and tested. The first configuration was a continuation of the Phase I Concept 2 design. This design utilized 20 air-assisted airblast fuel injectors inserted through the combustor dome. The dome air swirlers, through which the nozzles were inserted, each had an annular plenum with a butterfly valve for the purpose of controlling the airflow rate through the swirler. This enabled the control of the combustor primary-zone equivalence ratio ($\emptyset_{PZ}$) as a means of minimizing emission levels.

In the second configuration, a continuation of the Phase I Concept 3 design, the combustor consisted of two axially-staged combustion zones. The pilot zone, operational at all power settings, was fueled by 20 air-assisted airblast fuel nozzles inserted through the dome. The main combustion region was downstream of the pilot zone, and was operated at power settings above taxi-idle. At the approach setting a range of fuel-flow splits between the pilot and the main combustion region were evaluated, and some tests were run on pilots only. This region was fueled by 40 pressure atomizers, from which fuel was injected into a premixing/prevaporizing (PM/PV) annulus prior to being injected into the combustor. These two combustion system concepts are shown in Figures 24 and 25.

With the use of variable geometry, a Concept 2 configuration produced simulated takeoff NO_x levels of 6.8 g/kg fuel. At taxi-idle this same configuration had a measured HC value of 3.9 g/kg fuel. Both of these levels were lower than the program goals. The taxi-idle CO amount was in excess of the program goal by 43 percent. While this is considerably above the program goal, past experience has shown that rig CO values are higher than those measured on the engine, and some reduction from the measured rig values may be available.

The Concept 3 PM/PV combustion system produced NO_x levels of nearly half the program goal. A takeoff NO_x emission index of 3.6 g/kg fuel was achieved while maintaining a combustion efficiency equivalent to that of the production system. With the use of air-assist, the taxi-idle HC and CO values were also reduced below program goals to 0.7 and 17.9 g/kg fuel, respectively. The combustion efficiency at approach was maintained at a high level by minimizing the amount of premix fuel. Smoke emissions were found to be zero at takeoff, and well below the visible limit at approach.

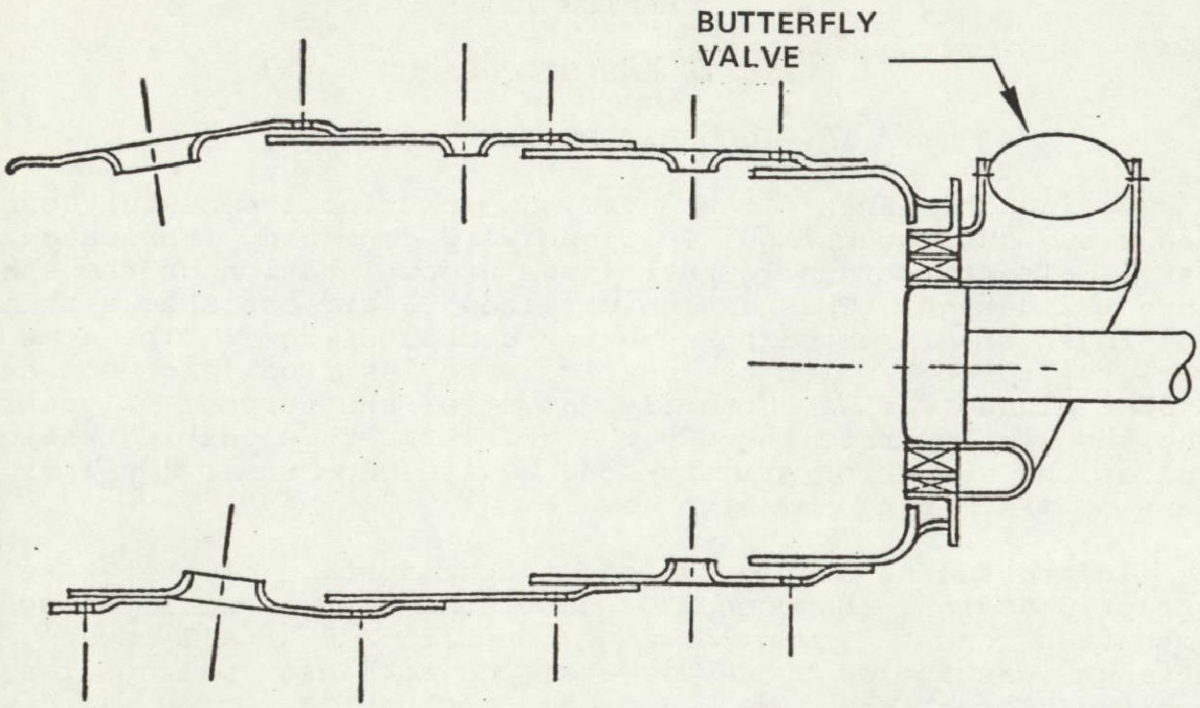


Figure 24. Concept 2 Combustor Configuration.

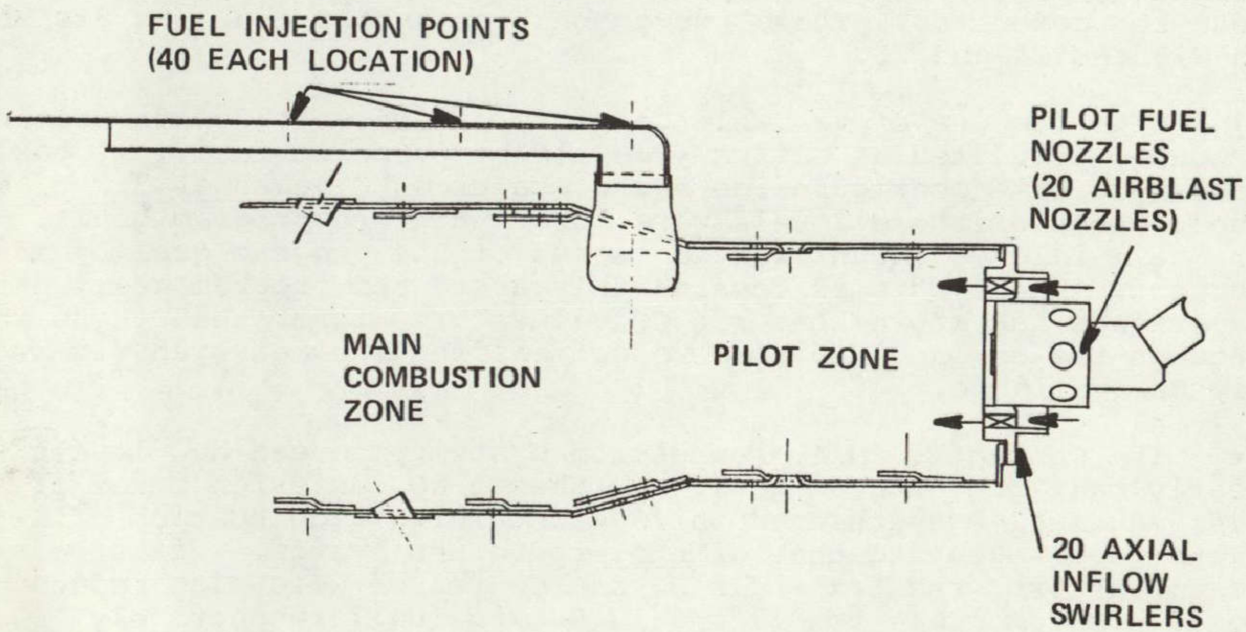


Figure 25. Concept 3 Combustor Configuration.

The emission results from the best overall configuration are tabulated below for both concepts. The program goals are also shown for comparison.

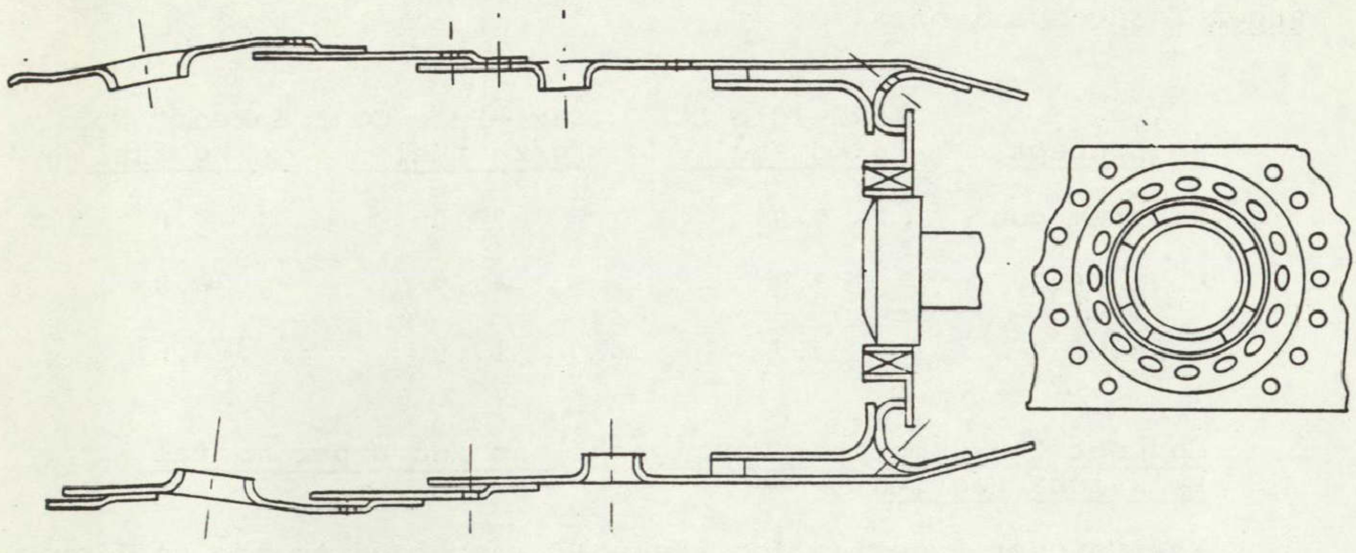
Concept	Taxi-Idle HC g/kg fuel	Taxi-Idle CO g/kg fuel	Takeoff NO_x g/kg fuel
Program goal	6.0	30.0	7.0
Concept 2	3.9	42.9	6.8
Concept 3	0.7	17.9	3.6

1. Concept 2 - Combustor Configurations and Experimental Emissions Results

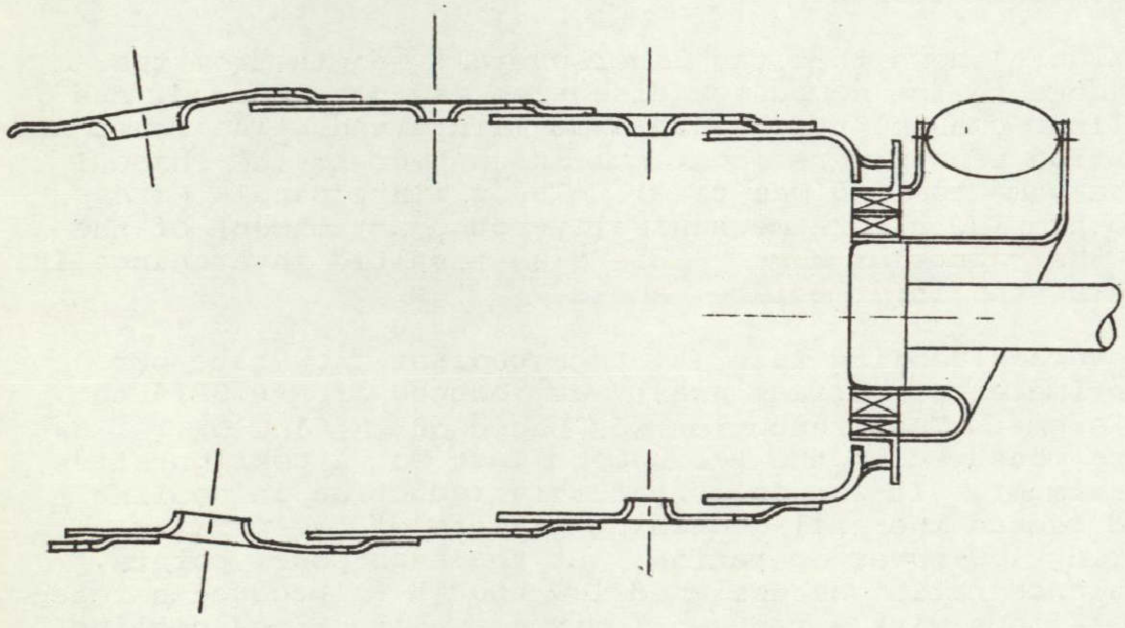
The Concept 2 design for Phase II was based on the configuration that produced the best overall emissions and combustor performance results during Phase I. This was the Refinement Test No. 2 configuration. The design philosophy for Phase II was to maintain a similar primary-zone equivalence ratio, airflow splits, orifice sizes and locations, and air-swirler characteristics as the Refinement Test No. 2 design. Figure 26 shows a comparison of the Phase I Refinement Test No. 2 combustor and the Phase II original design.

The figure shows that the liner overall length from the combustor dome to the combustor discharge was not changed, and that the liner channel height was also maintained. The inner and outer dilution panels were identical in contour to the Phase I design (the same tooling was used). The primary panels were changed to provide a more mechanically-sound attachment of the panels to the combustor dome. This also resulted in a change in the length of the intermediate panels.

The overall cooling rate (average coolant flow rate per square centimeter of surface area) was reduced from 0.0214 to 0.0140 $kg/s/cm^2$. This reduction was based on the low wall temperature measured on the Refinement Test No. 2 configuration (1090 K maximum). It was felt that this reduction in cooling flow would reduce the wall-quenching effects of the primary panels during low-power operation. At the high-power points, the equivalence ratio was designed low enough to produce a relatively cool flame with a reduced luminosity, thus less cooling was required.



(a) Phase I Refinement Test No. 2 Configuration



(b) Phase II Refinement Test No. 1 Configuration

Figure 26. Phases I and II Concept 2 Configurations Comparison.

The orifice numbers and locations were maintained similar to the Refinement Test No. 2 configuration; however, the primary orifices were moved 1.27 cm toward the dome. This was necessitated by the shorter primary panels of the new design. Orifice sizes were adjusted to provide airflow splits close to those of the Phase I design.

The combustor dome swirlers involved the greatest change from the Phase I design. In the Refinement Test No. 2 configuration it was necessary to modify the existing swirlers by adding eloxed orifices around the perimeter of the swirler, which produced a counter-rotating flow field. However, more orifices were required in the combustor dome surrounding the individual swirlers to attain the desired primary-zone equivalence ratio (see Figure 26). This configuration did not lend itself to variable-geometry hardware, therefore, a new swirler was designed. The new swirler is shown in Figure 27. The swirler had two concentric annuli with axial vanes to produce counter-rotating flow. The annuli were sized for equal airflow, with the total open area being approximately equal to the combined open area of the modified swirler and dome of the Refinement Test No. 2 combustor. Attached to the inlet side of the swirler was an annular housing that contained a butterfly valve for the purpose of metering the swirler airflow. The 20 valves were connected through a series of linkages to a unison ring, which simultaneously actuated all of the valves. A picture of a valve housing as shown in Figure 28.

The design of the air-assisted airblast fuel nozzles used in Phase II was slightly modified from the Phase I configuration to prevent coking of the air-assist passages. The new design had been used in other applications, and had demonstrated coking-free operation. The Sauter mean diameter (SMD) of the fuel-droplets was found to be 25 percent larger than those of the Phase I hardware when tested without air-assist; however, at air-assist pressures above 200 kPa the droplet sizes were identical. Figure 29 contains two views of the fuel nozzle. The boss on the nozzle pad is the housing for the variable-geometry linkage, which connects to the stem of the swirler housing butterfly valve.

During Phase II, five refinement and three optimization tests were performed. The results of these tests indicate that all of the emissions can be reduced to below program goals. At taxi-idle this would require operation with 5 percent combustor inlet air bleed, in order to meet the CO requirements. Also, past experience has shown that rig CO values are higher than those measured on an engine, and some reduction in taxi-idle CO may be expected during engine testing.

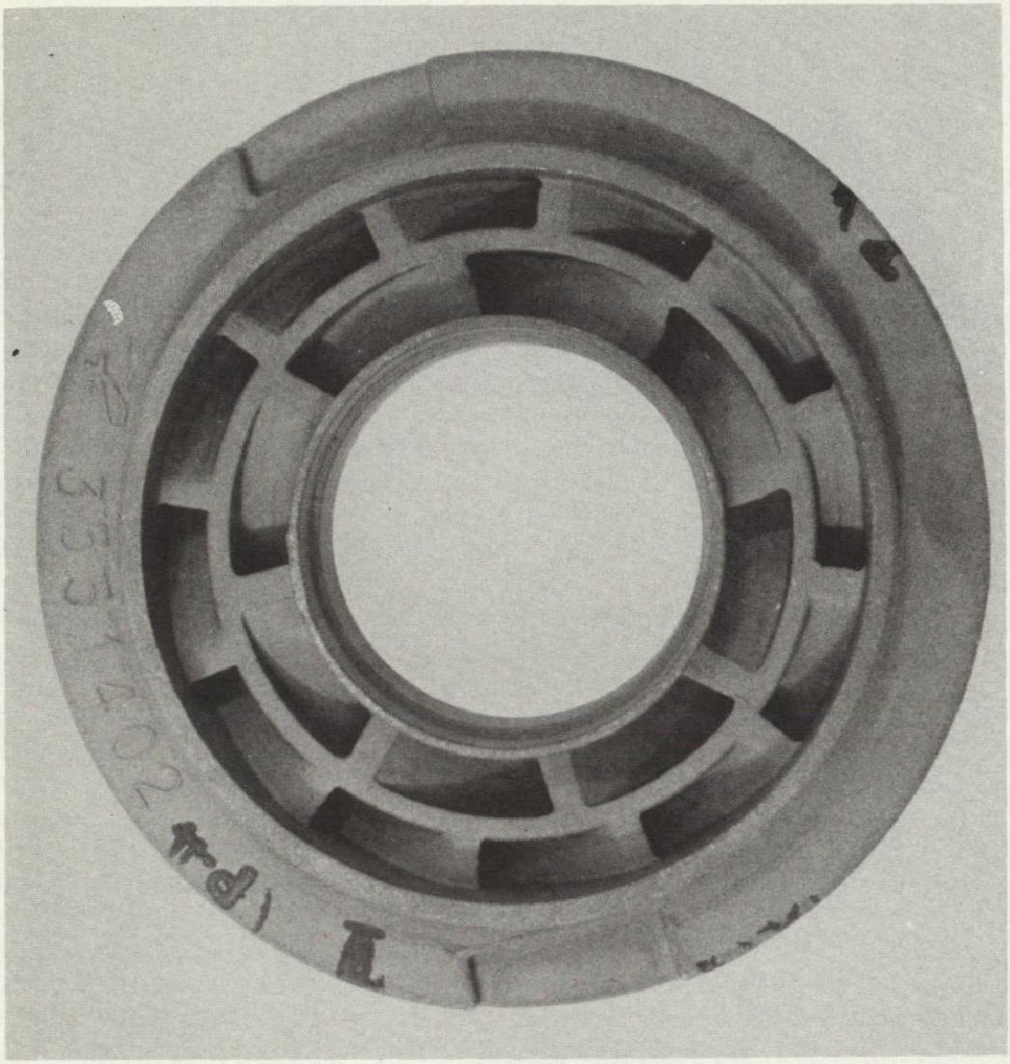


Figure 27. Swirler for Concept 2 Variable-Geometry Hardware.

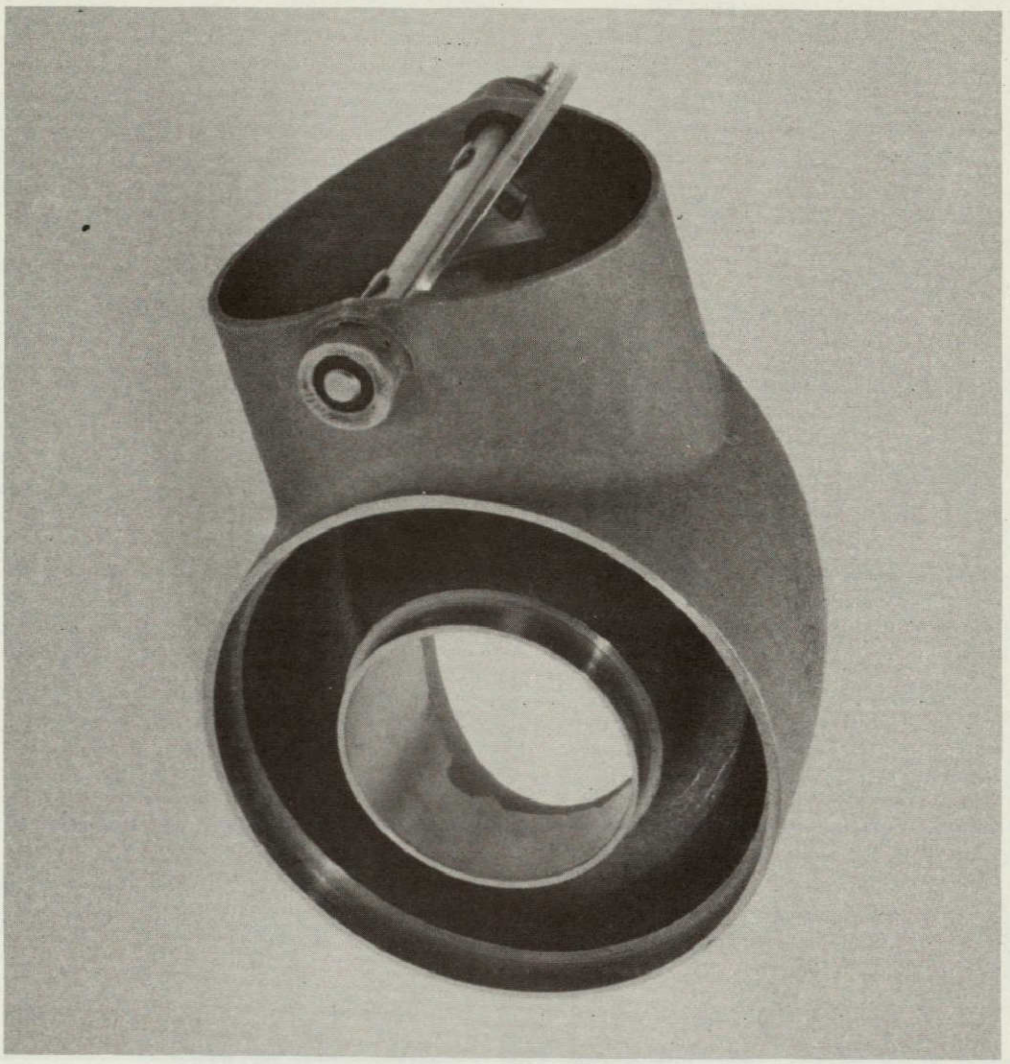
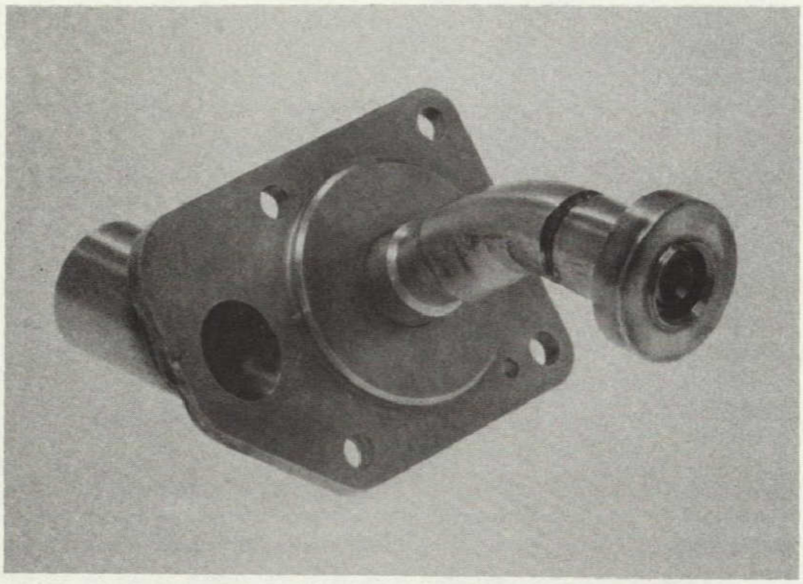
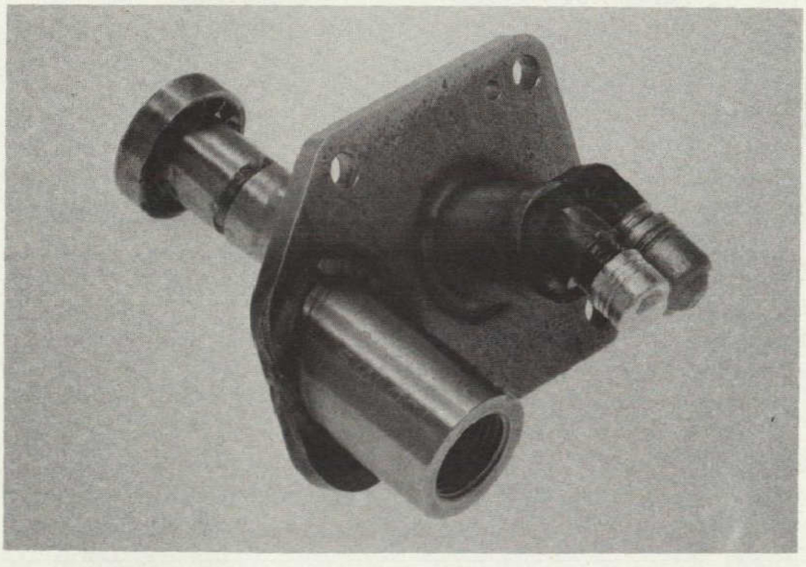


Figure 28. Concept 2 Valve Housing.



(A) FRONT VIEW



(B) REAR VIEW

Figure 29. Concept 2 Air-Assisted Airblast Fuel Nozzle.

The configuration of each of the tested designs are compared in Table XI, and the emission levels attained are summarized in Figure 30. A brief description of the configurations and the test results are presented in the following paragraphs. The complete test results are included in Appendix B.

a. Concept 2 - Refinement Test No. 1 - This configuration is shown in Figure 31. Prior to receiving the swirler housings for the butterfly valves, testing was performed on the Concept 2 combustor using fixed-geometry swirlers. The swirlers were the same axial-flow, counter-rotating hardware that were ultimately brazed to the swirler housings. The purpose of this test was to acquire baseline data at the high-power settings for comparison with data taken on the variable-geometry hardware.

The combustor was tested at four isothermal points to evaluate liner pressure-drop characteristics, and then tested at altitude cruise, climbout, and takeoff power settings, where combustor performance and emissions were measured. At the takeoff inlet conditions, a range of fuel/air ratios were tested to determine the effect on NO_x formation. Most test points were run with 34.5 kPa air-assist differential pressure on the fuel nozzles to ensure that there would be no carbon fouling. However, at cruise and takeoff, data were also measured with an air-assist differential pressure of 275.8 kPa.

The NO_x values at the climbout and takeoff points were appreciably higher than those measured on the Refinement Test No. 2 combustor of Phase I, as shown below. Increased air-assist pressure made little difference in the NO_x level. This trend was also demonstrated in Phase I with the Refinement Test No. 2 configuration.

Configuration	Climbout NO_x, g/kg fuel*	Takeoff NO_x, g/kg fuel*
Phase I Refinement Test No. 2 96.5 kPa Air-Assist	6.8**	6.5
Phase II Fixed-geometry, 34.5 kPa Air-Assist	7.1	8.2
Phase II Fixed-geometry, 275.8 kPa Air-Assist	-	8.4

*Rig data corrected to standard humidity conditions (see Chapter IIF3b for explanation)

**The Refinement Test No. 2 measured climbout data were corrected to the same air-assist pressure and scan conditions that produced the lowest takeoff NO_x value.

TABLE XI. CONCEPT 2 TEST CONFIGURATIONS.

Refinement Test No.	Modifications (Comparisons made to previous configuration)
1	(Compared to Phase I Refinement Test No. 2)
	o Primary panel cooling changed from convection-film to conventional impingement-film cooling
	o Primary orifices moved 1.27 cm toward dome
	o Intermediate orifices moved 0.76 cm downstream
	o Dome air injected through counter-rotating swirlers
2	o Primary orifices moved 1.04 cm downstream
3	o Intermediate orifices covered
4	o Primary panel cooling skirts extended
5	o Airflow splits of swirler changed. Small inner swirler airflow was not metered. Flow control was on the large outer swirler only.
Optimization Test No.	
1	o Primary panel cooling panels were shortened to the Refinement Test No. 1 configuration.
	o Pressuring atomizing fuel nozzles tested in addition to the air-assisted airblast design.
2	o Area of inner swirlers reduced by 2/3
3	o Area of inner swirlers reduced by 1/3
3a	o The entire inner swirlers blocked. The outer swirlers area were reduced to the area of the inner swirler.
3b	o Dilution zone open area doubled.
3c	o Swirler restored to the Optimization Test No. 1 configuration.

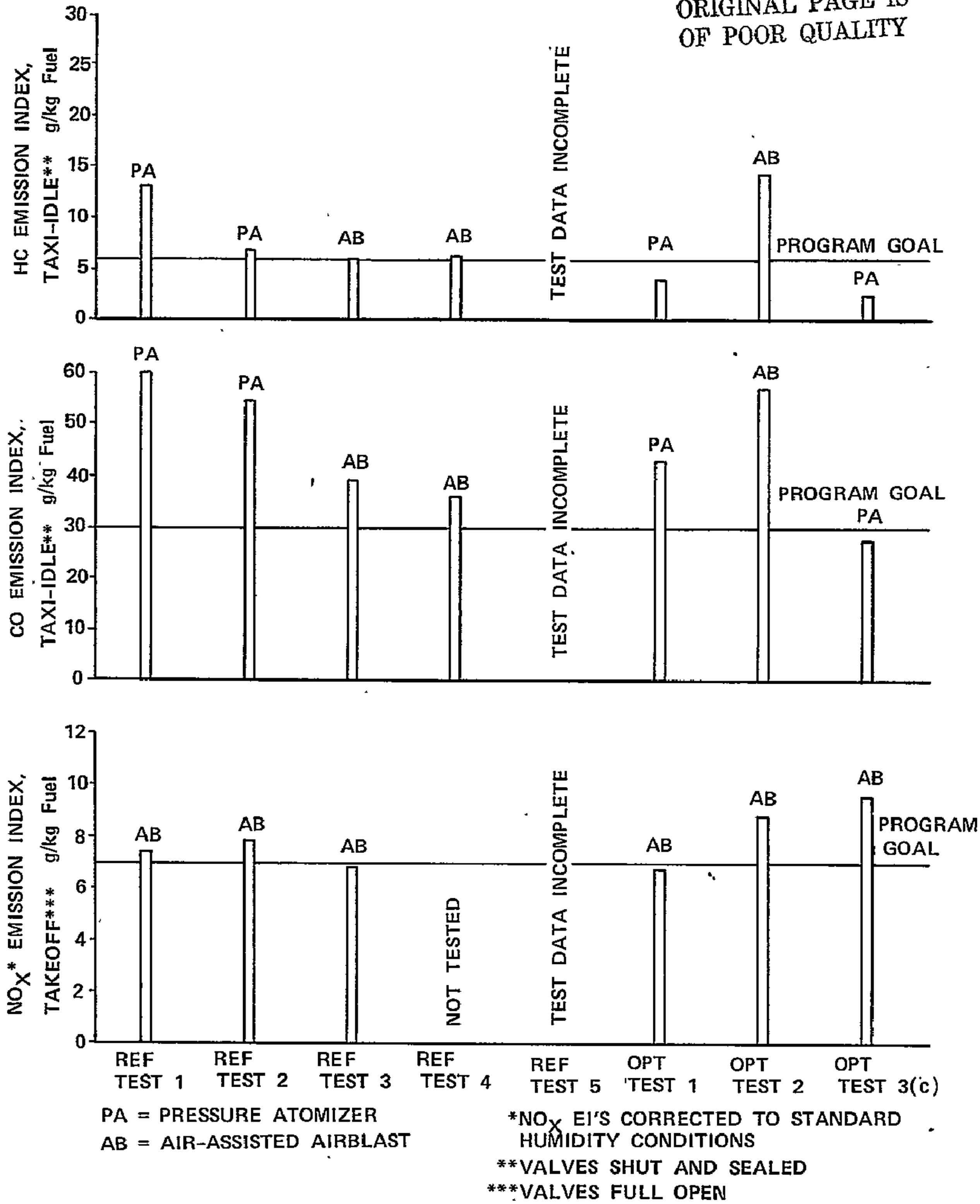


Figure 30. Summary of Emission Test Results, Concept 2.

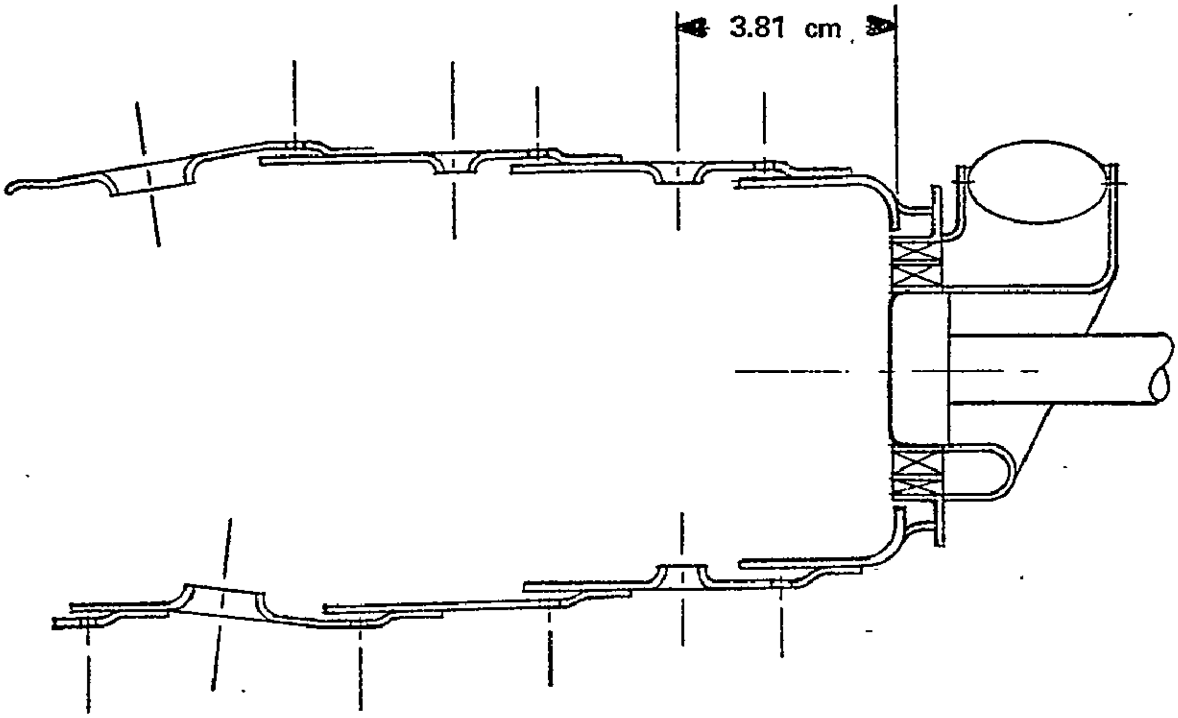


Figure 31. Concept 2, Refinement Test No. 1
Combustor Configuration.

At least part of this increase can be attributed to the change in test conditions between Phase I and Phase II. As a result of an improvement in the engine computer model to more accurately represent engine operating conditions, the climbout inlet temperature increased 13 K and the takeoff inlet temperature increased 56 K. The measured NO_x values, corrected to engine pressures using a pressure correction exponent of 0.5, are plotted as a function of combustor inlet temperature in Figure 32. The Lipfert curve of NO_x versus inlet temperature (Ref 6) is also shown for comparison. The test points parallel the Lipfert curve, indicating that the magnitude of the measured NO_x increase is related to the increase in inlet temperature.

At the cruise condition, the measured NO_x rig value was 7.0 g/kg fuel. The air-assist pressure made no significant difference in emission levels at either the cruise or the takeoff point. Combustion performance at all points tested was excellent. The pattern factors measured at takeoff and climbout were 0.047 and 0.058, respectively. Takeoff pressure loss was measured to be 5.8 percent.

Upon teardown inspection, the combustor and fuel nozzles were found to be in excellent condition with no carbon present on the nozzle tips, and no noticeably distorted areas on the combustor. The combustor was then painted with temperature-sensitive paint and rerun at the simulated takeoff point. Data scans were made with 34.5 and 0 kPa air-assist differential pressure. The emission levels and combustor-performance values compared closely with the previous test run at the takeoff power setting. The measured NO_x values, as a function of air-assist pressure, are shown below:

Configuration	NO_x, g/kg fuel*
0 kPa air assist, 3-3-77	8.9
34.5 kPa air assist, 2-26-77	8.2
34.5 kPa air assist, 3-3-77	8.3

*Rig values corrected to standard humidity conditions.

The data show that air assist makes a slight difference in the NO_x value.

Thermal-paint results indicated an extremely even wall-temperature distribution, with no unacceptable gradients or hot areas. The maximum wall temperature was 1000 K.

Initial combustor-rig tests using the variable-geometry hardware were conducted with the swirler flow-control devices valve angle individually set and adjusted. This was due to delays in fabrication of two of the variable-geometry linkage parts.

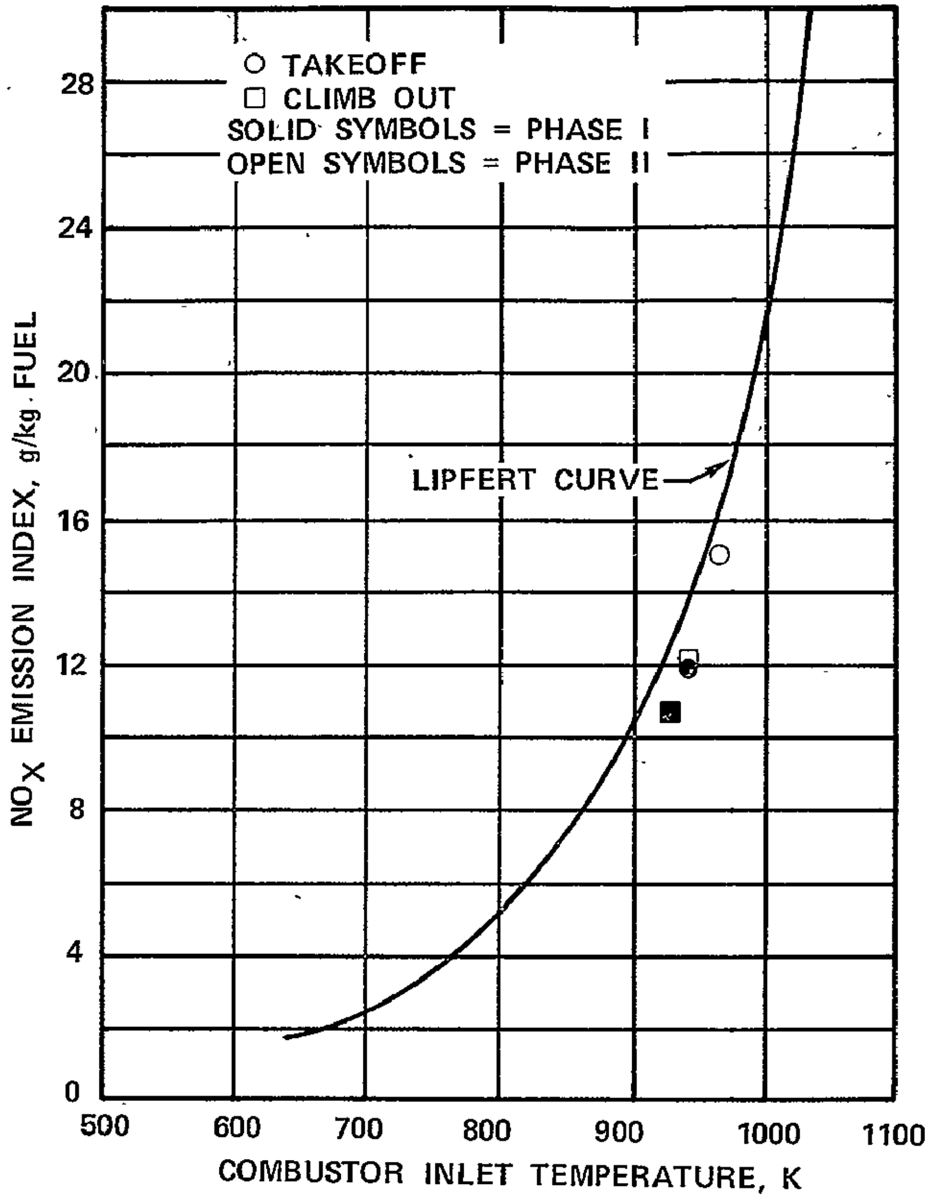


Figure 32. Measured NO_x As a Function of Combustor Inlet Temperature for Concept 2.

Testing was performed with the valves at the 0-, 15-, 30-, and 90-degree settings. Isothermal testing consisted of running a range of four combustor inlet corrected-airflow rates without combustion to determine combustor pressure loss. Emissions and combustor performance tests were run at taxi-idle, approach, cruise, climbout, and takeoff. With the valves in the 90-degree (full open) position, an additional test point was run at the Phase I takeoff condition to determine the effect of the operating-point change on emission levels.

Figure 33 is a plot of the isothermal test results, where combustor pressure loss is plotted as a function of corrected flow for the 0-, 30-, and 90-degree valve settings. Similar data are plotted for the fixed-geometry configuration that was previously tested. The data indicates an increase in the C_D of the swirler with the use of the butterfly valves. Comparing the results of the 90-degree valve setting for the higher corrected-flow rates for variable-geometry and fixed-geometry swirlers showed a lower pressure loss for the variable-geometry hardware. This indicates that the swirlers with the butterfly valves have a larger effective area. This was attributed to the valve housing design, which tended to recover part of the combustor inlet air velocity head.

The initial system combustion test was made with the swirler valves set to the 0-degree (closed) position. Attempts to light the combustor proved unsuccessful, and the valves were changed to the 90-degree position. Ignition was accomplished at the cruise inlet air temperature (approximately 650 K), and test data were taken at cruise, climbout, takeoff, and approach. This procedure was repeated with the valves set to the 30-degree position. Following the approach point, an attempt was made to run the rig at taxi-idle; however, the combustor sustained a blowout prior to reaching the proper operating condition.

At the takeoff and climbout points, with the valves set to the full-open position, the NO_x levels were lower than with the fixed-geometry swirlers; however, with the valves at 30 degrees, the NO_x levels were higher, as shown below:

	NO_x, g/kg fuel*	
Configuration	Climbout	Takeoff
Fixed-geometry swirlers	7.1	8.2
Valves set to 90 degrees	6.7	7.4
Valves set to 30 degrees	8.1	8.6

*Rig values corrected to standard humidity conditions.

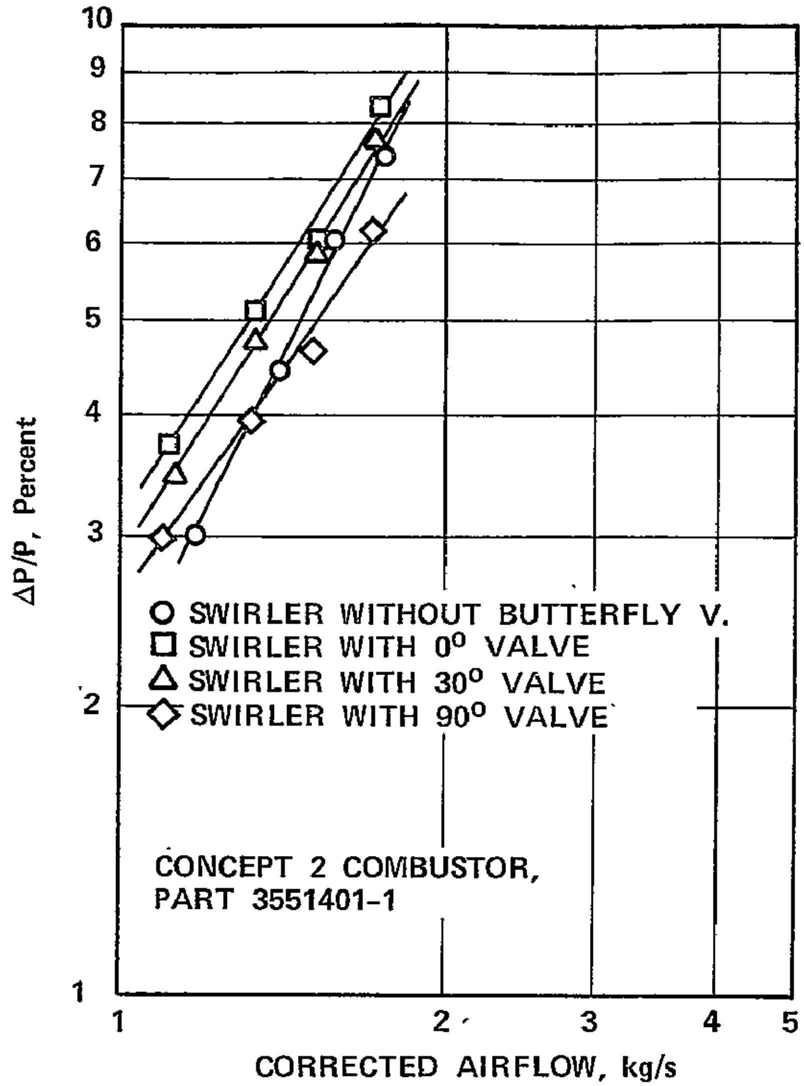


Figure 33. Combustor Pressure Loss as a Function of Corrected Airflow Rate for Various Valve Openings, Concept 2.

A test scan was also made with the valves in the 90-degree position at the Phase I takeoff point to determine the effect of inlet temperature on NO_x formation. The results of this test are shown below:

Test Point	NO_x, g/kg fuel*
Phase I conditions	6.9
Phase II conditions	7.4

*Rig values corrected to standard humidity conditions.

At approach, the combustion system appeared to be operating too lean. Even with the valves at the 30-degree position, the combustion efficiency was calculated to be only 98.9 percent; below the 99.5-percent goal.

Testing was then performed at taxi-idle and approach with the valve angle set to 0 and 15 degrees. At the taxi-idle point, both valve settings resulted in extremely high HC and CO values, as shown below. In addition to these points, a test scan was made with the 0-degree valve setting at the taxi-idle inlet conditions, with a 32-percent increase in fuel flow; and the emission data is included for comparison.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
0-degree valve setting	331.1	127.2
0-degree valve setting 32-percent high fuel flow	180.8	123.9
15-degree valve setting	275.1	128.3

These results are plotted in Figure 34 with combustion efficiency as a function of measured fuel/air ratio. The conclusion reached from this plot was that the reaction zone had insufficient mixing. This conclusion was supported by the fact that while both the 0- and 15-degree valve setting configurations had almost identical pressure-loss terms (4.5 percent), the 15-degree configuration had a 0.195 versus a 0.340 pattern factor for the 0-degree configuration, indicating that the 15-degree configuration had superior primary-zone mixing.

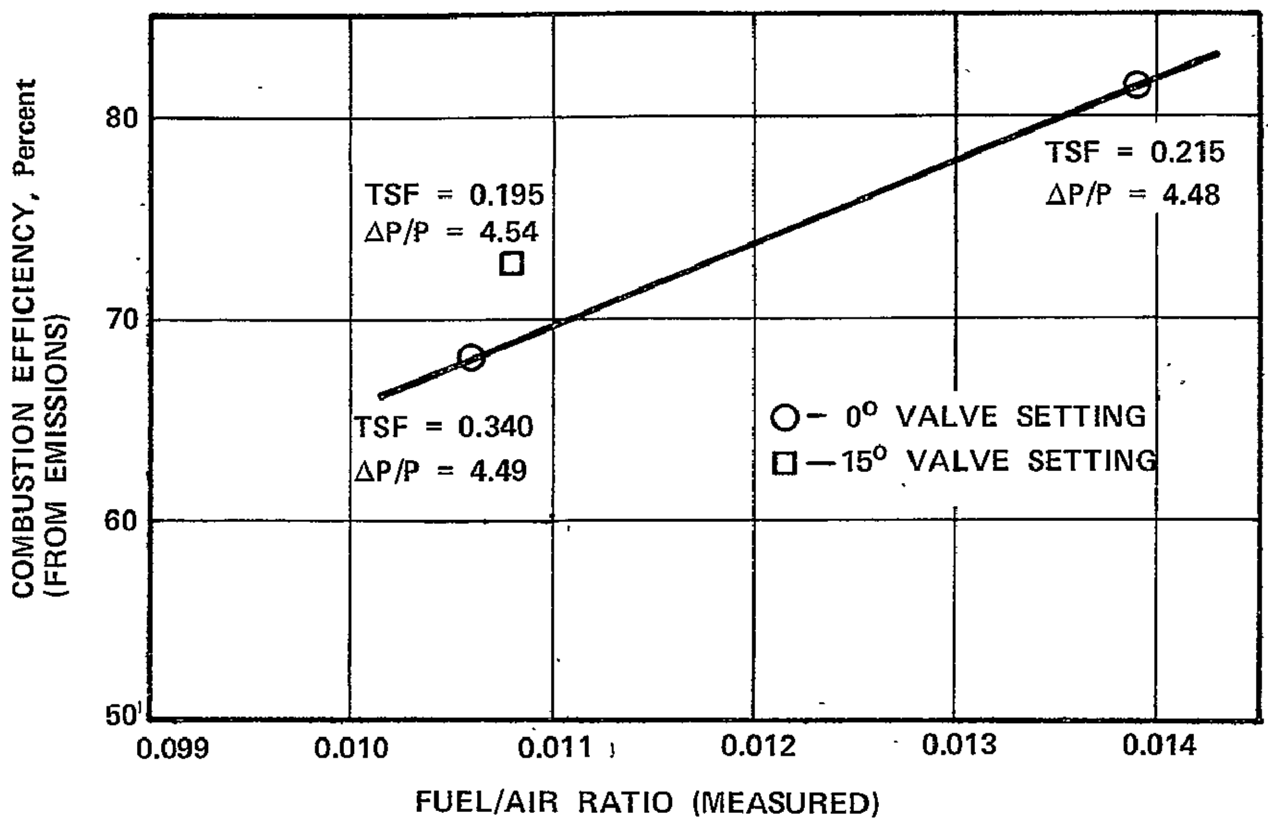


Figure 34. Taxi-Idle Combustor Efficiency as a Condition of Fuel/Air Ratio for 0- and 15-Degree Swirler Valve Setting.

A series of three tests was performed to verify the lack-of-mixing hypothesis. The first test configuration replaced the existing swirlers and air-metering valves with low-airflow swirlers (approximately equal to the airflow of the airblast fuel injectors). While this resulted in a less than optimum primary-zone equivalence ratio, the improved mixing of the swirler was being evaluated. In the second test configuration the low-airflow swirlers were replaced by the original swirlers with the air-metering valves; however, the valves were sealed closed to prevent air leakage. It was felt that the air leaking through the valves was of sufficient quantity to prevent the primary orifice air from being entrained upstream to form a recirculation zone with its attendent mixing. The third test configuration utilized the same swirler hardware as the second; however, the airblast fuel injectors were replaced with pressure atomizers. Previous test data had indicated that part of the high emission levels at taxi-idle could be attributed to poor fuel distribution. The mounting boss of these atomizers had no provision for the variable-geometry linkage, and therefore it was not installed. The results of these three tests, together with the data from the initial Refinement Test No. 1 and the program goals, are shown below.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
0-degree valve setting, airblast*	331.1	127.1
Small swirler, airblast*	93.5	64.6
Sealed 0-degree valve setting, airblast*	177.0	73.0
Sealed 0-degree valve setting, pressure atomizer. No variable-geometry linkage	13.1	60.3

*All tests with the airblast nozzles had air-assist differential pressure of approximately 379 kPa.

The configuration with the pressure atomizers and no variable-geometry linkage produced the greatest reduction; however, both HC and CO levels were greater than the program goals by approximately a factor of two.

b. Concept 2 - Refinement Test No. 2. - To further reduce taxi-idle emission levels, the inner and outer rows of primary orifices were relocated 1.04 cm downstream from their original position. The intent of this modification was to increase the combustor reaction zone to produce an increased residence time. Figure 35 is a sketch of the combustor.

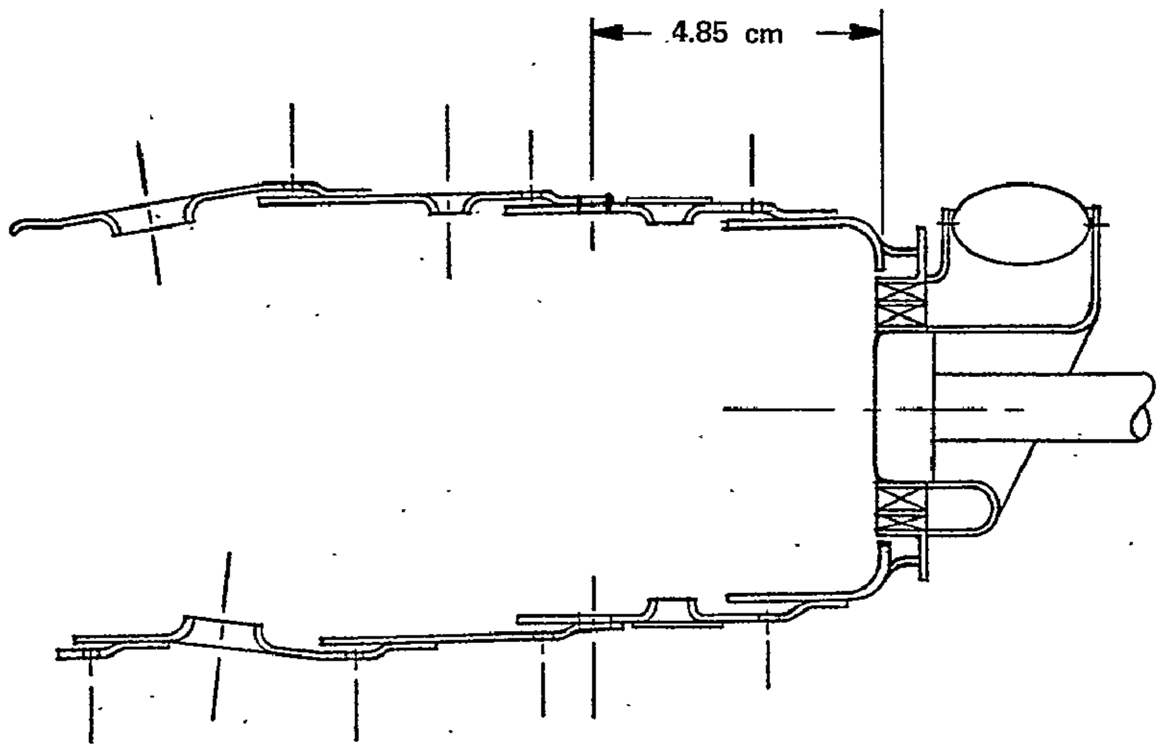


Figure 35. Concept 2, Refinement Test No. 2 Combustor Configuration.

The combustor was tested at taxi-idle with the valves at 0 degrees; and at approach, cruise, climbout, and takeoff with the valves at 0 and at 90 degrees.

Two tests were performed with this combustor at the taxi-idle power setting. One utilized the pressure atomizing fuel injectors, while in the other the pressure atomizers were replaced with the airblast injectors, with air-assist differential pressure maintained at 379 kPa differential for comparative purposes. For the test with airblast injectors, the variable-geometry linkage was not connected. Data from the previous test indicated that the linkage may have had a significant effect on the taxi-idle emission levels and this test was used to evaluate this linkage effect. For both tests, the air-metering valves were sealed closed. The HC and CO values from these tests are shown below, along with the data from the Refinement Test No. 1 points for comparison:

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Test No. 1, pressure atomizers	13.1	60.3
Test No. 2, pressure atomizers	7.0	54.3
Test No. 1, airblast, variable-geometry linkage connected	177.0	73.0
Test No. 2, airblast, variable-geometry linkage not connected	10.0	59.6

The following conclusions were drawn from the above test data:

- o With the pressure atomizers, the change in primary orifice position produced no significant reduction in CO, while HC was reduced by 47 percent (but was still above the program goal).
- o With the airblast injectors, CO was reduced by 18.4 percent; however, the HC was reduced 94 percent. Both species are greater than the program goals.
- o The taxi-idle emissions were not significantly different when the pressure-atomizing nozzles were replaced with airblast nozzles with the variable-geometry linkage not connected.

Based on the limited reductions in taxi-idle emissions with the pressure atomizers, it is unlikely that the orifice-pattern change was responsible for the dramatic change in pollutant levels with the airblast injectors. The airblast Refinement Test No. 2 was performed with the variable-geometry linkages disconnected, while the Refinement Test No. 1 configuration had the linkages intact. It is suspected that the linkages may have prevented some of the swirlers from seating properly on the combustor dome (due to dimensional stack tolerances required for assembly), resulting in air leakage in the vicinity of the fuel-injection point. This leakage could have produced local quenching, resulting in the high HC levels.

At the takeoff point with the valves at 90 degrees, the measured NO_x value was 7.9 g/kg fuel. While the takeoff NO_x level remained above the program goal of 7.0 g/kg fuel, the main concern was that the taxi-idle emission levels were still unacceptable.

c. Concept 2 - Refinement Test No. 3. - Analysis of the Refinement Test No. 1 and 2 taxi-idle test results indicated that the reaction zone may have extended downstream of the primary orifice jets, where it was quenched by the jets from the intermediate panel. Therefore, the Refinement Test No. 3 configuration consisted of covering the row of intermediate orifices. Figure 36 is a sketch of the Refinement Test No. 3 configuration.

The combustor was tested at taxi-idle, both with and without the variable-geometry linkage connected, and with and without the air-metering valves sealed. The combustor was also tested at the approach, cruise, climbout, and takeoff power settings. The variable-geometry actuation system was demonstrated at the higher power settings. Following the emission and performance tests, the combustor underwent ignition and stability tests with the air-metering valves in the 0-degree (closed) position.

At the taxi-idle power settings, a matrix of points were tested to evaluate the effect of air leakage between the air swirlers and the combustor dome, and the leakage through the air-metering valves. The first configuration had the variable-geometry linkage connected, with the valves set to the 0-degree setting but not sealed. The last test configuration had the linkage disconnected and the valves sealed shut. These configurations were tested at taxi-idle with 0-, 5-, and 10-percent simulated air bleed. The bleed condition was simulated by adjusting the combustor inlet conditions (airflow, pressure, and temperature) to those predicted by the engine computer model for the appropriate percentage bleeds. The effect of bleed is to raise the primary-zone equivalence ratio, thereby producing more efficient combustion. This is accomplished by reducing the airflow by bleeding, and then increasing the fuel flow to maintain the required thrust level. All points were tested with 379 kPa differential pressure on the air-assisted airblast nozzles. The HC and CO emissions indices are shown below for the zero-bleed condition:

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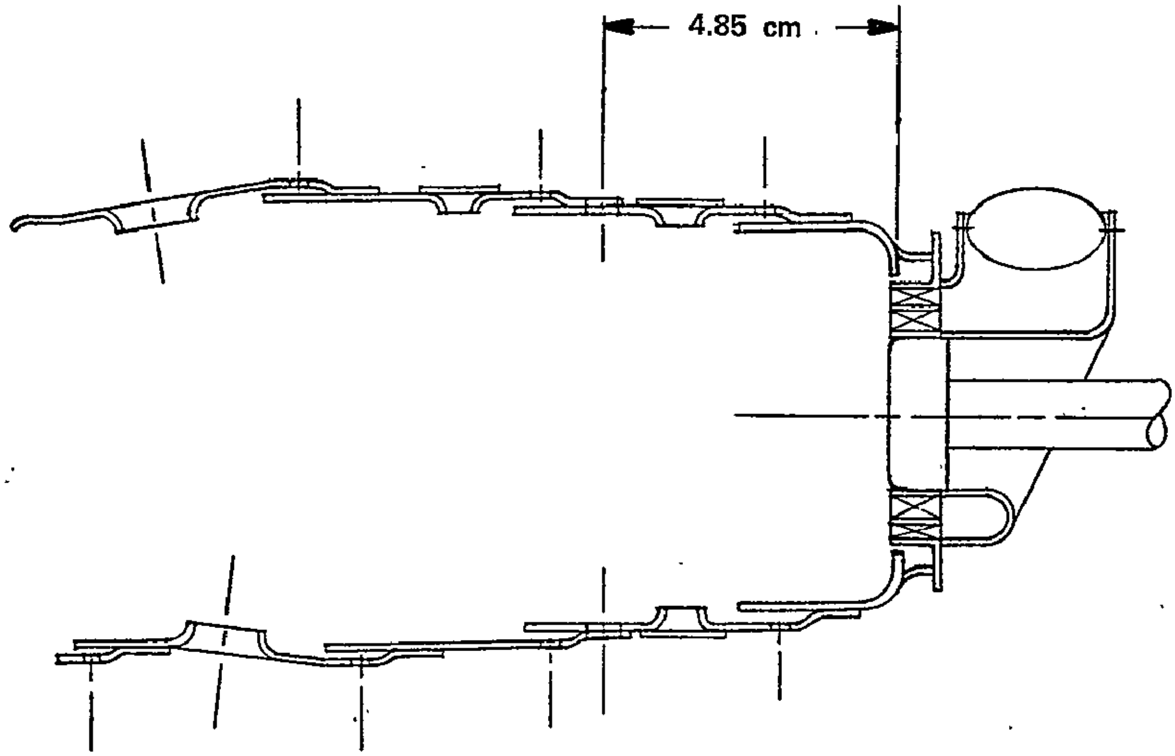

Figure 36. Concept 2, Refinement Test No. 3
Combustor Configuration.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Linkage connected, valves 0-degree, not sealed	41.6	67.8
Linkage disconnected, valves 0-degree, not sealed	29.3	61.5
Linkage disconnected, valves 0-degree, sealed shut	6.0	39.0

Figure 37 is a plot of combustion efficiency as a function of percentage simulated bleed for the three configurations. Test results indicate that the air leakage through the valves had a significant effect on pollutant formation. Also, by comparison with the Refinement Test No. 2 configuration results when tested under the same conditions, the CO level was reduced from 59.6 to 39.0 g/kg fuel. This indicates that the intermediate orifice air had an appreciable effect on CO quenching.

At the takeoff power setting with the air-metering valves set to the 90-degree (full open) position, NO_x was measured at 6.9 g/kg fuel. Although the NO_x goal of 7.0 g/kg fuel was met, the removal of intermediate orifices resulted in an increase in the temperature-spread factor from 0.06 (for the Refinement Test No. 2 configuration) to 0.24 (the program goal is 0.19).

During tests at the altitude cruise point, the variable-geometry air-metering valve angle was varied from 20 to 90 degrees. Although scan data was not taken, emission values were monitored with the sample rake in the 0-degree position. From these limited data it could be seen that NO_x decreased as the valves were opened, while the CO level increased and HC remained essentially unchanged.

An additional taxi-idle test was performed with the primary cooling orifices blocked. The purpose of the test was to determine if the primary-zone cooling film has a detrimental effect on HC and CO formation. The CO level was measured at 32.0 g/kg fuel with no air bleed. This was the lowest taxi-idle CO value attained for Concept 2 up to that time. It was hypothesised that the blocked wall cooling reduced quenching of the combustion reaction near the liner wall.

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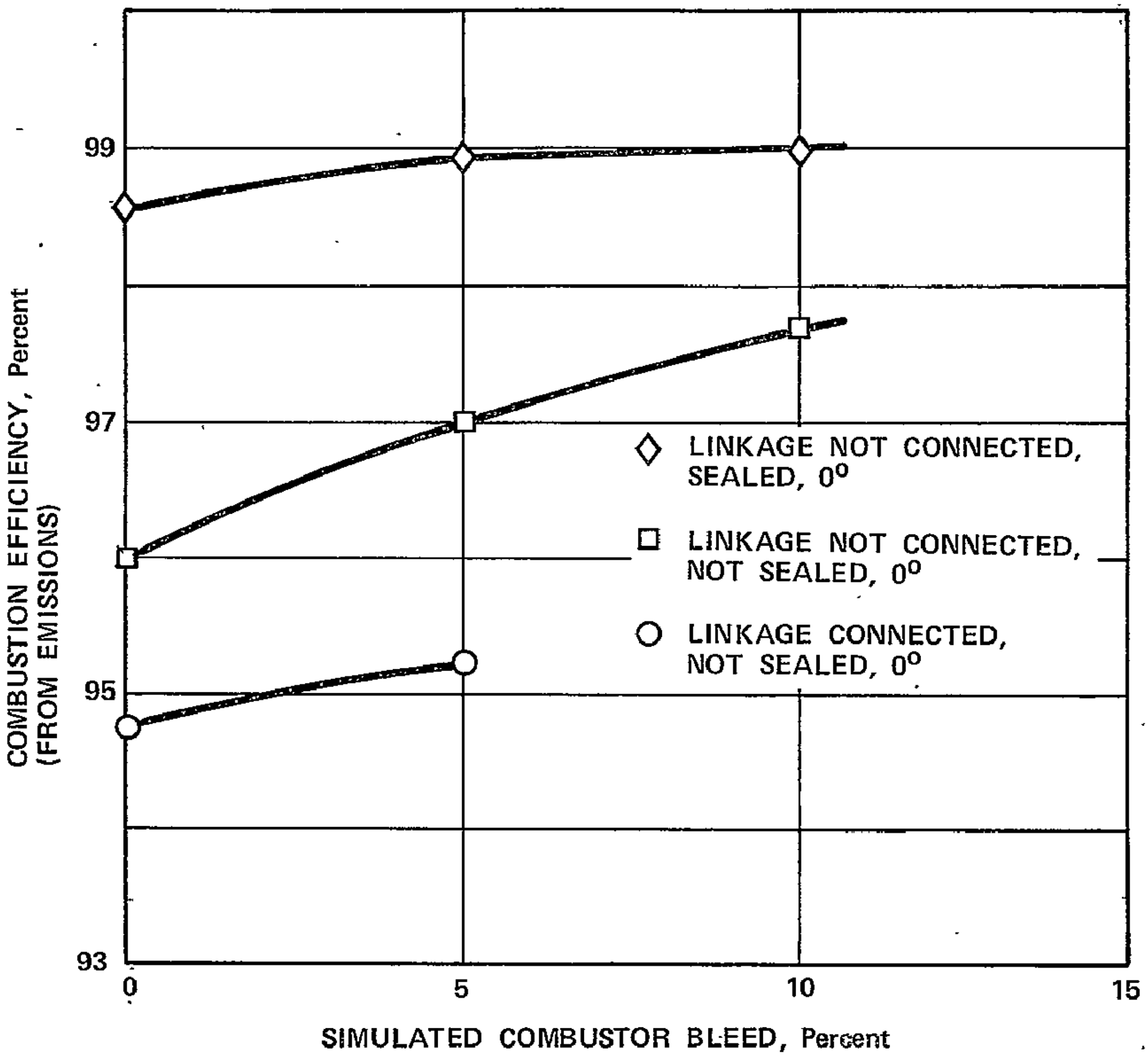

Figure 37. Combustion Efficiency As a Function of Simulated Bleed for Concept 2 Refinement Test No. 3 Configuration Air-Assisted/Airblast With 379 kPa Differential Assist Pressure.

d. Concept 2 - Refinement Test No. 4. - The Refinement Test No. 4 combustor configuration is shown in Figure 38. This configuration was identical to the Refinement Test No. 3 hardware, with the exception that the primary-zone cooling skirts were extended 1.09 cm. The purpose of this was to reduce the quenching effect of the cooling air.

The combustor was tested at only the taxi-idle condition with the butterfly valves sealed shut and the variable-geometry linkage disconnected. The test results are summarized below:

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Test No. 3, primary cooling blocked	4.3	32.0
Test No. 4 configuration	6.1	36.2

While the Refinement Test No. 4 configuration produced HC and CO values close to the program goals, teardown inspection revealed heavy carbon buildup on many of the swirler faces, as evidenced by Figure 39.

At this point it was decided that a small amount of dome airflow was needed to prevent carbon from forming in the dome. The air would have to enter the liner with sufficient velocity to sweep the wall surfaces, and in such a manner as to establish a more definite combustion region than was evidenced with the butterfly valves sealed shut. Therefore, the swirlers were redesigned, as shown in Figure 40. In the new design, the inner portion of the swirler had a lower airflow rate, and experienced full flow at all operating conditions. The outer portion had a higher flow rate than the previous design, and the flow rate was controlled by the butterfly valve. The total swirler flow rate remained unchanged.

To get preliminary data on this swirler configuration, a taxi-idle test was performed on the Refinement Test No. 4 combustor using fixed-geometry swirlers with the same open area, swirl angle, number of vanes, etc. as the inner portion of the new swirler design; the emission values are summarized below:

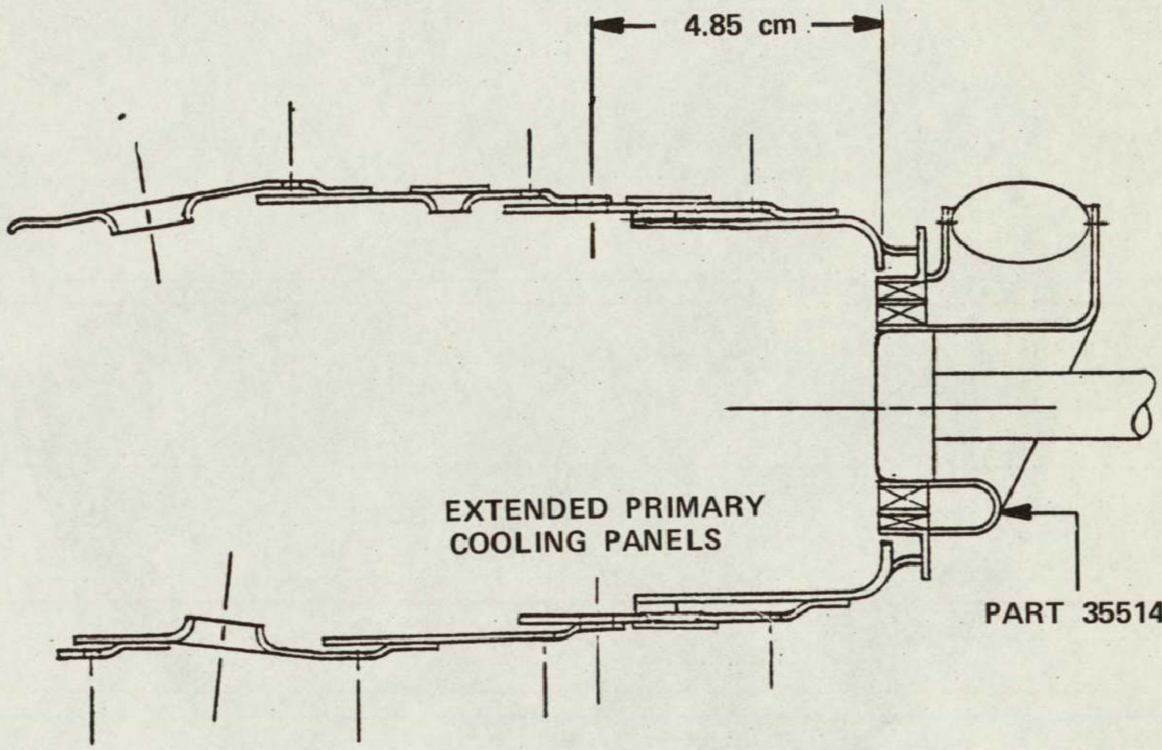

Figure 38. Concept 2, Refinement Test No. 4
Combustor Configuration.

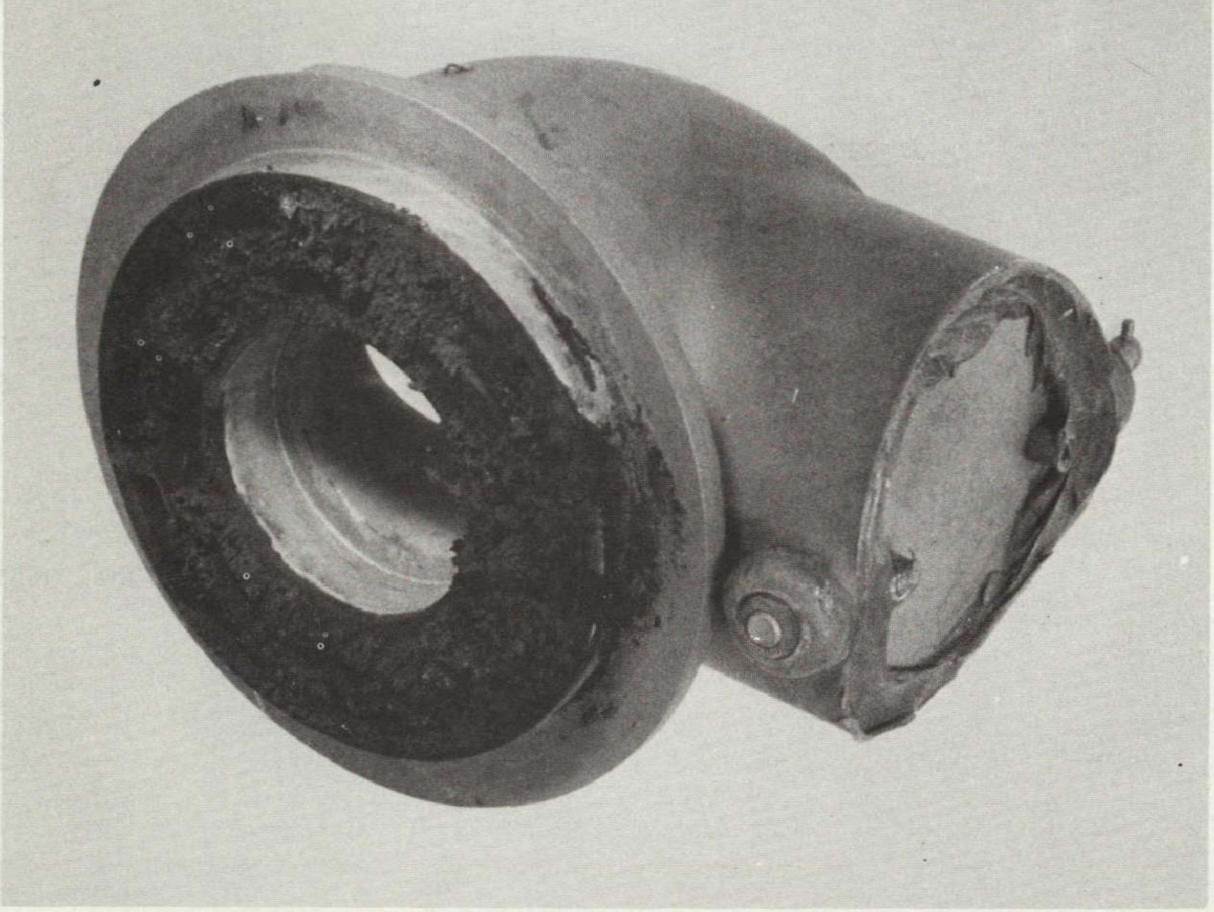

Figure 39. Concept 2 Swirler Showing Carbon Buildup.

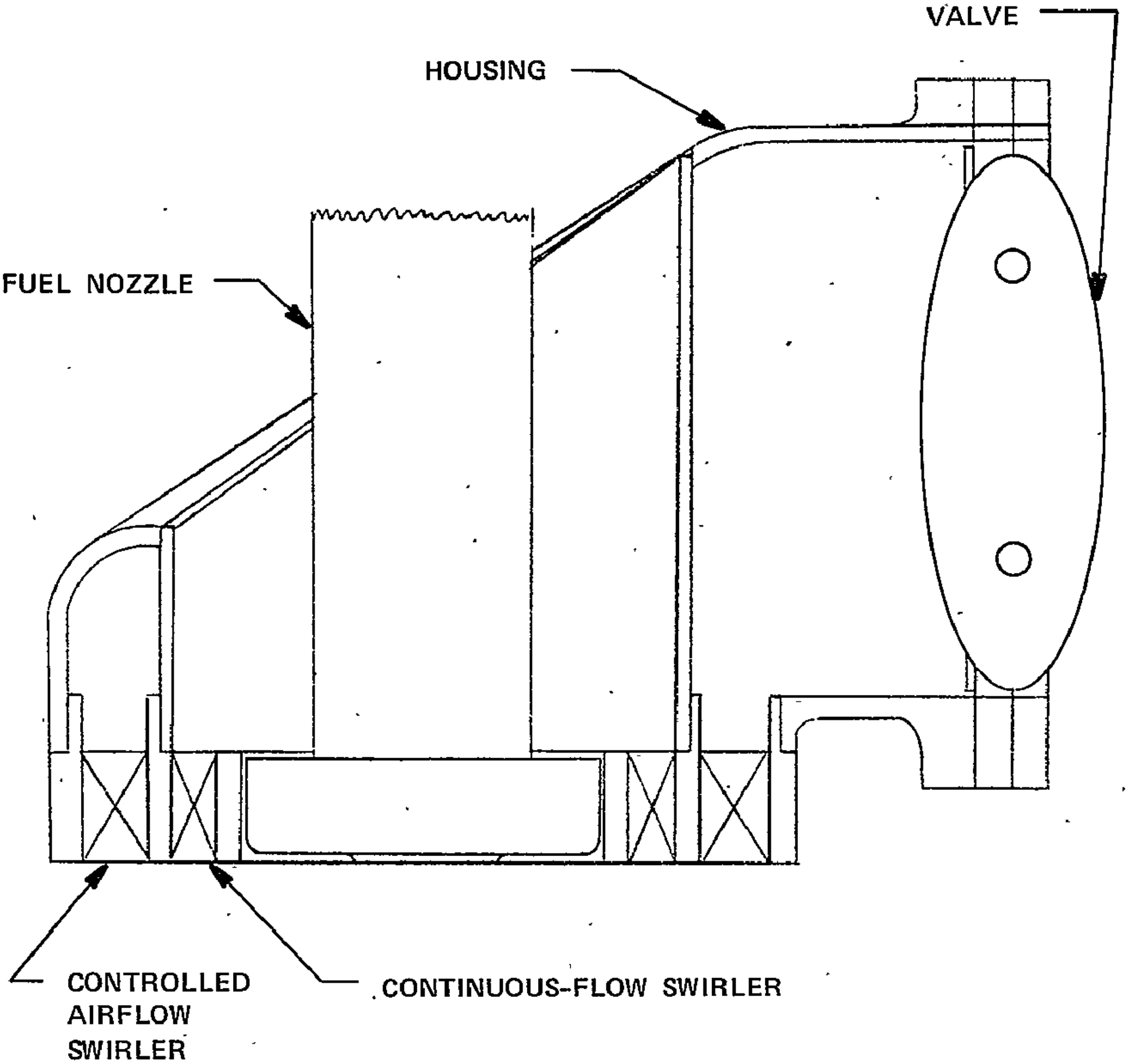

Figure 40. Redesigned Concept 2 Swirler.

Configuration	HC lb/kg fuel	CO lb/kg fuel
Program goal	6.0	30.0
Test No. 4, butterfly valves sealed	6.1	36.2
Test No. 4, small fixed-geometry swirler (P/N 3551447)	4.8	28.2

Teardown inspection revealed that the liner was clean of carbon; however, the measured pattern factor (in excess of 0.3) indicated that a combustor discharge seal problem may have developed. A trial build was made, and the seal area was inspected. It was discovered that the combustor was not sealing at its O.D. discharge, and a significant leak path existed. The reason for the leakage was that the diffuser/transition liner piece, which forms the seal with the combustor outer diameter, was severely distorted. This leakage was thought to have contributed greatly to the good test results shown above, as it caused an increase in the primary-zone equivalence ratio. A review of previous test results indicated this leak may have been present during the latter part of the Refinement Test No. 3 testing, but not before.

While the diffuser transition liner of the combustion rig was being reworked, the Refinement Test No. 4 system was installed in a similar combustion rig and retested. To facilitate emission measurements, the T1 exhaust-sampling rake was also installed in this rig.

The combustor was tested at taxi-idle with 0-, 5-, and 10-percent simulated air bleed. Air-assist pressure was maintained at 379 kPa for the three points. Emission measurements at the zero-bleed conditions are shown below, together with the results of the previous test and the program goals for comparison:

Configuration	HC g/kg fuel	CO g/kg fuel	TSF
Program goal	6.0	30.0	--
Test No. 4, fixed-geometry swirlers (with leakage)	4.8	28.2	0.373
Test No. 4, fixed-geometry swirlers (alternate rig - no leakage)	6.7	39.3	0.107

The data indicated an emission level close to what would be expected for the configuration; however, further combustor modifications were postponed until the completion of the first engine test, as described in Chapter III B.

e. Concept 2 - Refinement Test No. 5. - Upon completion of the new swirler fabrication and the repair of the diffuser/transition duct the newly designed swirlers were installed on the Test No. 4 combustor and installed in the NASA T1 combustion rig for testing. Based on the favorable results of the engine test (see Chapter III B), the combustor, with the exception of the swirlers, was not modified for the Test No. 5 configuration. Figure 41 is a sketch of the combustor.

Data were taken with various valve positions at the taxi-idle, approach, and climbout conditions. Emission levels, as a function of valve position, are shown in Figures 42 through 44. In general, NO_x values and combustion efficiency were decreased by opening the butterfly valve. The taxi-idle efficiency (90.4 percent) was poor compared with that of the previous test, and the temperature-spread factor (0.34) was high. Upon rig teardown, the swirler assembly and liner were found to be free of carbon; however, the teardown also revealed that a significant leak path existed between the outer liner of the combustor and the transition liner. In two locations the combustor outer discharge surface was actually outside the transition liner, rather than inside. The cause of leakage was a significant out-of-roundness in the combustor outer liner.

This concluded the refinement testing of Concept 2. Based on the results of this testing and the relative ease of adapting the concept to the TFE731-2 Engine, this system was selected to undergo further rig development during an optimization test phase in preparation for Phase III engine testing. The test results of Concept 3 demonstrated superior emission reductions at the four LTO power settings, as will be described in the following sections; however, difficulties associated with operation at approach, problems with fuel staging, and the lack of test data on the premix/prevaporizing system under engine pressure conditions would require considerably more rig development before the Concept 3 system would be ready for engine testing. Therefore, Concept 2 was selected.

f. Concept 2 - Optimization Test No. 1. - The Optimization Test No. 1 configuration of Concept 2 is shown in Figure 45. The combustor has the same hole pattern as the Refinement Test No. 5 configuration; however, the primary cooling panels were shortened to the length of the Test No. 3 configuration. This cooling panel design was more mechanically sound than the previous configuration, which had evidenced some buckling during Phase I testing and for this reason the first optimization test was run with

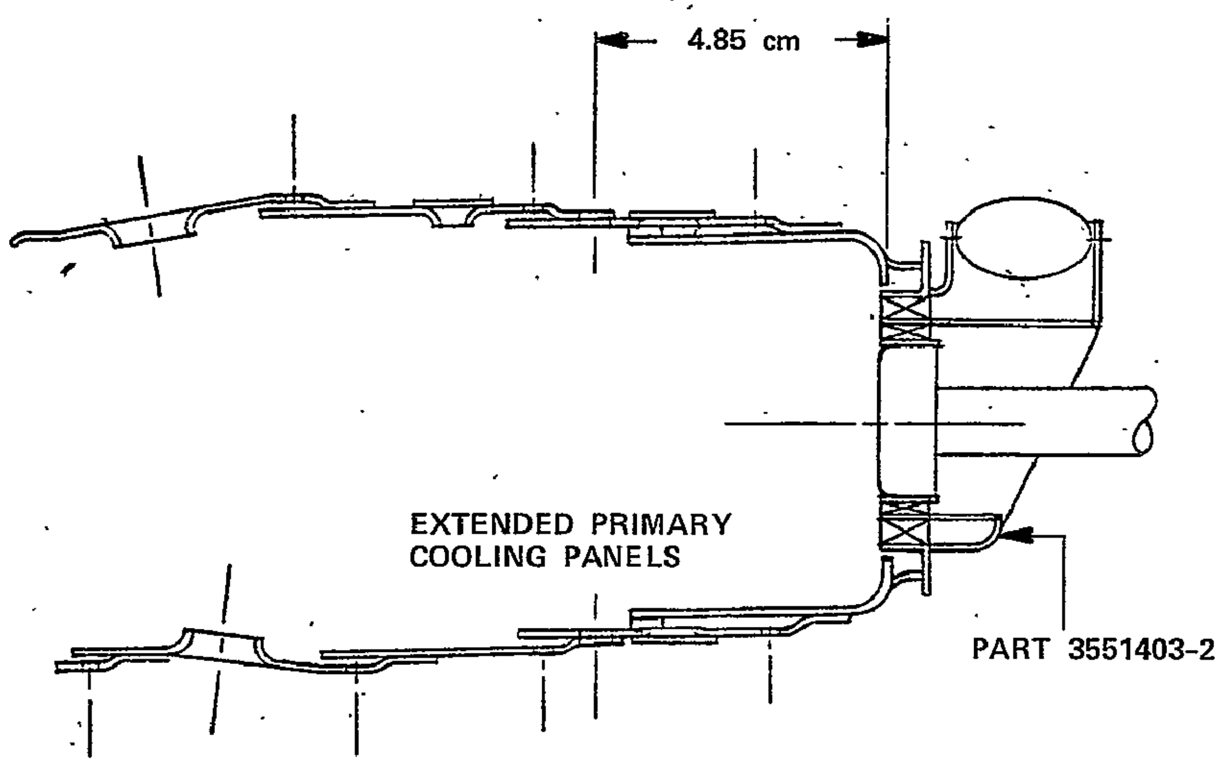

Figure 41. Concept 2, Refinement Test No. 5 Combustor Configuration.

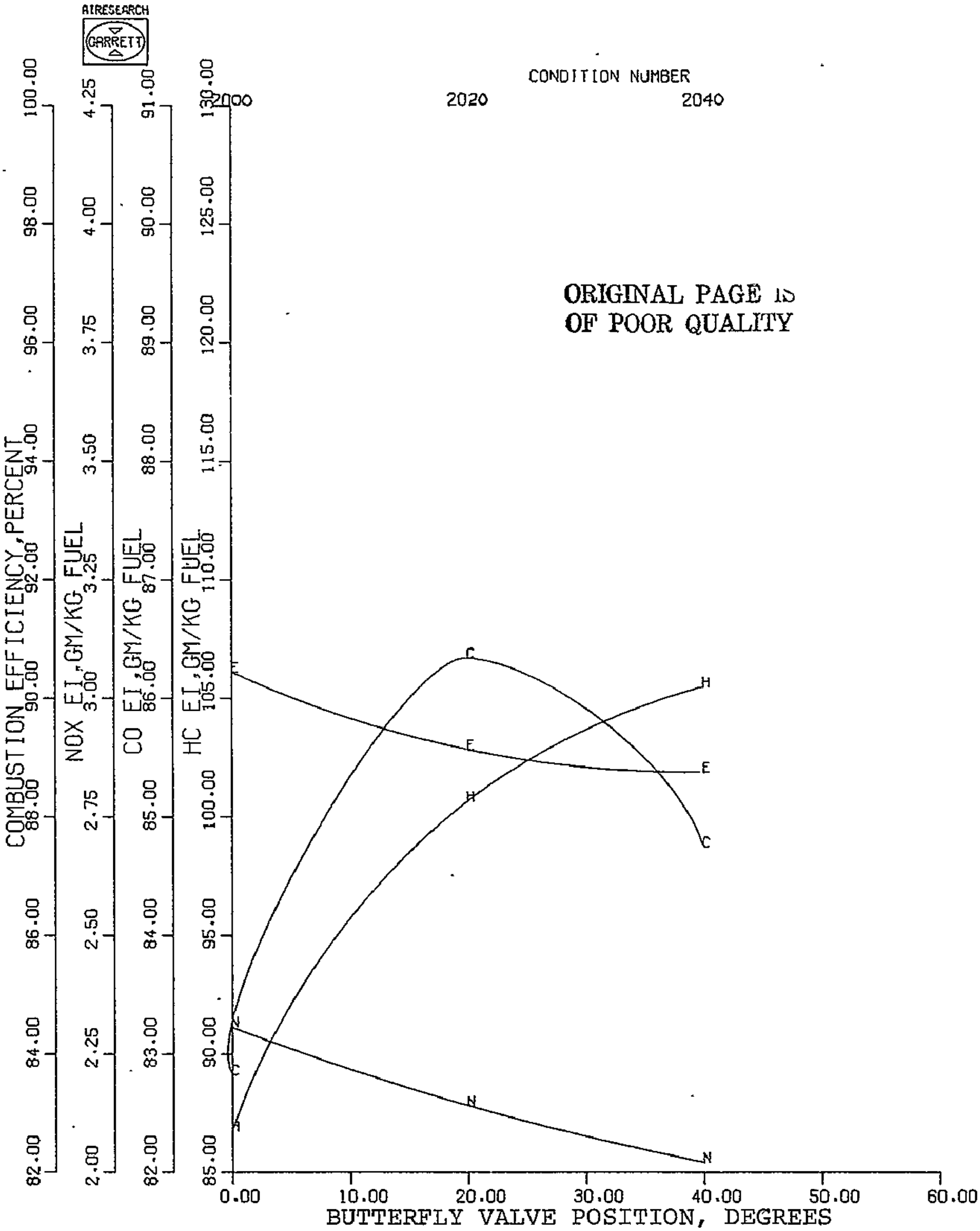

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Figure 42. Effect of Swirler Valve Position at Taxi-Idle.

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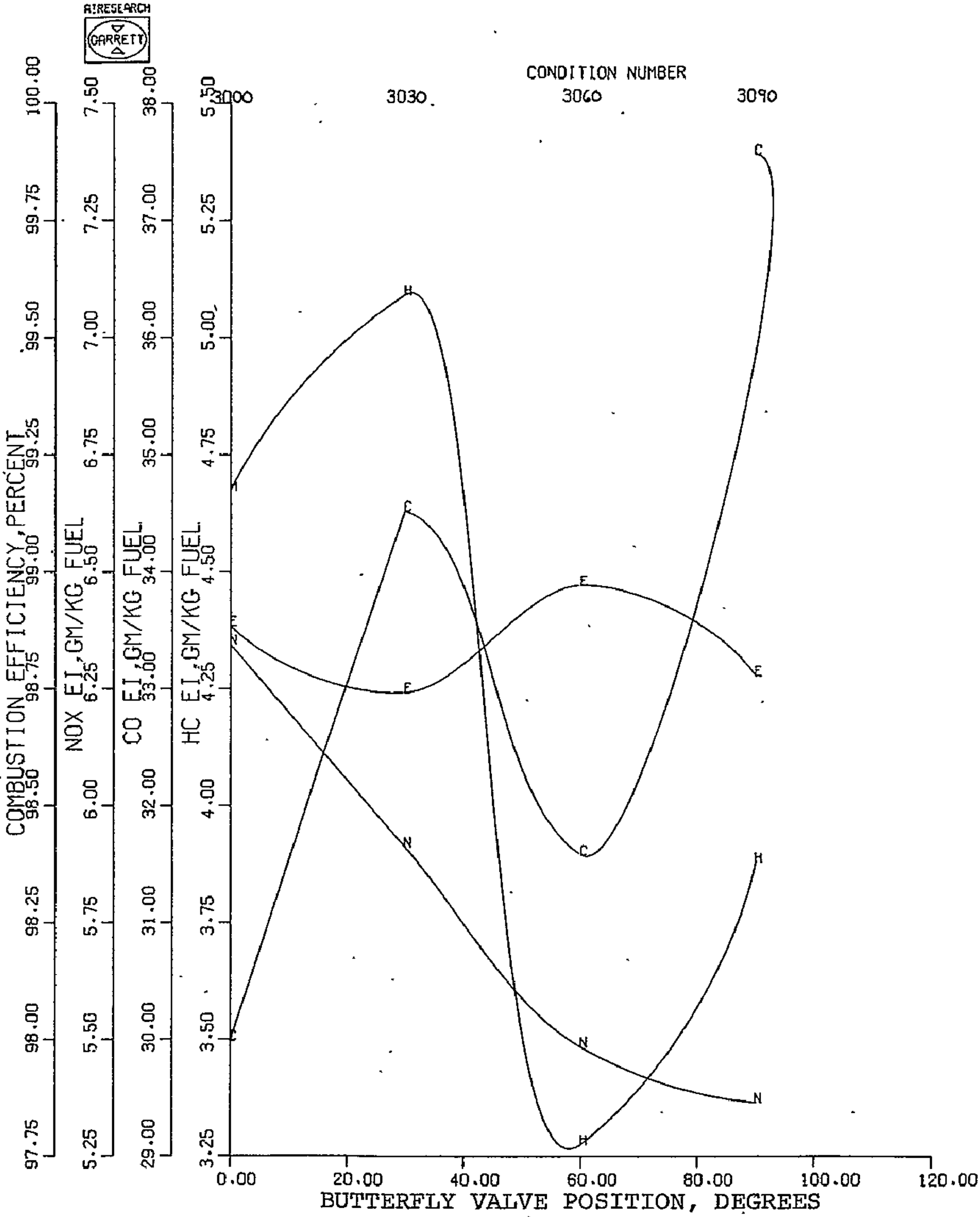

Figure 43. Effect of Swirler Valve Position
at Approach.

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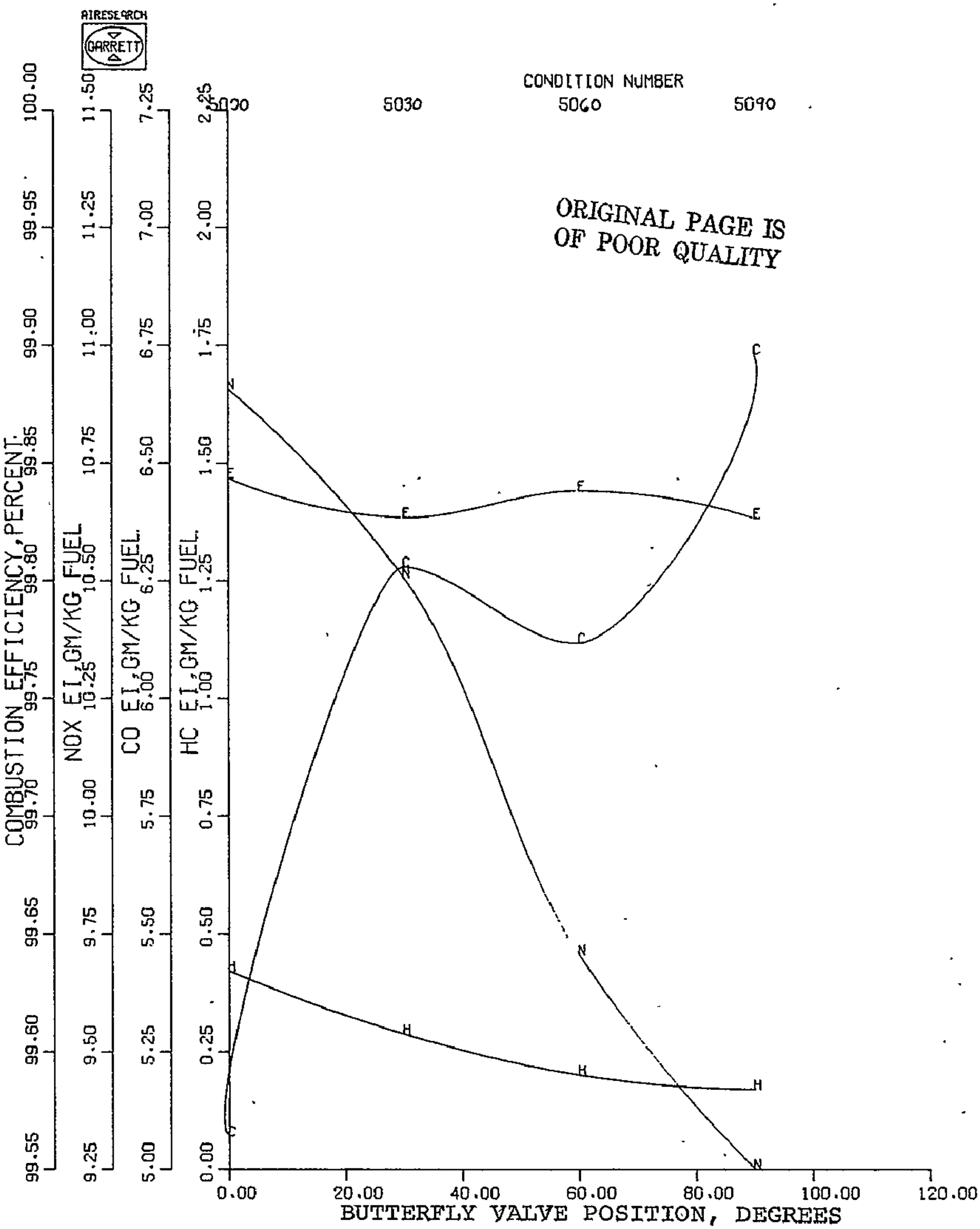


Figure 44. Effect of Swirler Valve Position at Climbout.

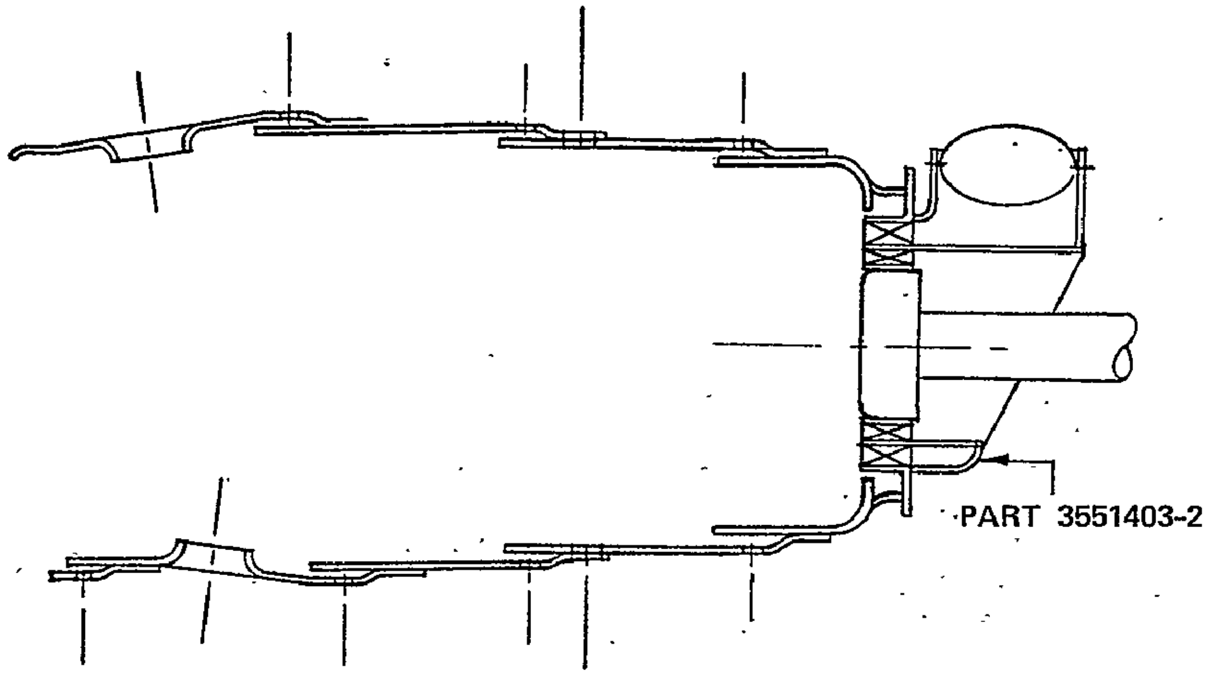


Figure 45. Concept 2, Optimization Test No. 1 ombustor Configuration.

this design. The combustor was newly fabricated, and there were no patched orifices. The swirler housing assemblies used for this test had the small inner swirler flowing at all power settings, with the variable flow control being on the outer swirler only.

The combustion system was run in several configurations and was also retested later in the program. Initially, the variable-geometry linkage was installed and extensive testing was done to evaluate the emission levels at all LTO power settings. The valve angles were varied during these tests to determine the optimum valve position for minimum emission levels, and to further evaluate the variable-geometry actuation system.

Following the above tests, a series of tests were conducted at the taxi-idle power settings. These tests were to evaluate the effect on emissions of air leakage through the large swirler valves, and air leakages resulting from the displacement of the swirlers by the mechanical linkage of the actuation system. The taxi-idle test results are summarized below:

Configuration	HC g/kg fuel	CO g/kg fuel	NO_x* g/kg fuel
Program goal	6.0	30.0	--
All variable-geometry linkage connected	77.8	86.2	1.9
Repeat of above	62.5	88.1	2.2
Valves sealed. No variable-geometry linkage	13.5	53.8	2.5
Valves sealed. Linkage connected.	5.2	44.9	2.5

*Corrected to standard humidity.

NOTE: All taxi-idle points were run with 379 kPa air-assist differential pressure.

The data indicated that air leakage through the swirler valves had a significant effect on low-power emissions. The best emission levels were attained with the valves sealed and the linkage connected. This was contrary to previous test results, where the installed linkage produced higher emission levels. The HC level met program goals, while the CO level was still high, but close to the value measured on the Test No. 4 combustor.

At the other power settings the following emission values were attained:

Configuration	Power Setting	HC g/kg fuel	CO g/kg fuel	NO_x* g/kg fuel
Valves closed, but not sealed. Linkage connected.	Approach	6.4	14.0	5.0
Valves 90 degrees, linkage connected.	Climbout	0.4	3.0	6.3
Valves 90 degrees, linkage connected.	Takeoff	0.2	2.1	6.8

*Corrected to standard humidity.

These points were run without air assist.

To verify the taxi-idle emission levels with the linkage installed this configuration was retested. At the no-bleed condition, HC and CO levels were considerably higher than the previous test results.

Configuration	HC g/kg fuel	CO g/kg fuel
Optimization Test No. 1 (10-19-77)	5.2	44.9
Optimization Test No. 1 (11-15-77)	17.5	60.0

Following this test the fuel nozzles were flow checked. Eleven of the 20 nozzles were found to have severe distortion of the fuel-spray cone when assist air was applied. The nozzles were cleaned and retested, however, the spray distortion persisted on the same 11 nozzles. It appeared that either the fuel nozzle air-assist passages were still dirty or that these passages were damaged resulting in distorted assist air flow. This characteristic was not present during previous flow tests, and the distortion was only present during air-assist operation. Evidently the change in the fuel nozzle spray quality occurred after the October 19 optimization No. 1 test.

After Optimization Tests No. 2 and No. 3 were completed, the combustor was restored to the Optimization Test No. 1 configuration. It was then tested at the taxi-idle and approach conditions, using the pressure atomizing fuel nozzles; and at the higher-power settings, using both the pressure atomizers and the airblast nozzles. The combustor was painted with temperature-sensitive paint prior to the high-power test to determine liner-wall temperatures. For the taxi-idle and approach tests, the air-swirler valves were sealed shut. At the high-power settings, the valves were set to 90 degrees. The variable-geometry linkage was not installed on any of the tests, and air assist was not used during the test with the airblast nozzles.

At taxi-idle, the configuration produced HC and CO levels similar to those measured on the October 19 test of this system:

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30
Optimization Test No. 1 (10-19-77)	5.2	44.9
Optimization Test No. 1 (12-13-77)	3.9	42.9

At the higher-power settings there was good repeatability with the airblast nozzles from the October 5 results, and the combustor produced similar results with the pressure atomizers.

Configuration	NO_x, g/kg fuel Climbout	Takeoff
Program goal	--	7.0
Optimization Test No. 1, airblast (10-5-77)	6.3	6.8
Optimization Test No. 1, airblast (12-15-77)	6.4	7.0
Optimization Test No. 1, pressure atomizers	6.3	6.9

g. Concept 2 - Optimization Test No. 2. - In an attempt to further reduce the taxi-idle emissions, the inner-swirler area of the swirler housings was reduced by tack welding shim-stock washers to the discharge of the swirlers. This was done because it was thought that the air going through the inner swirler might be quenching primary-zone reactions, both because of its quantity and, possibly, because of its point of entry, the inner swirler flow area was reduced by approximately two-thirds. The combustor liner remained unchanged from the previous test. Figure 46 is a sketch of the combustor.

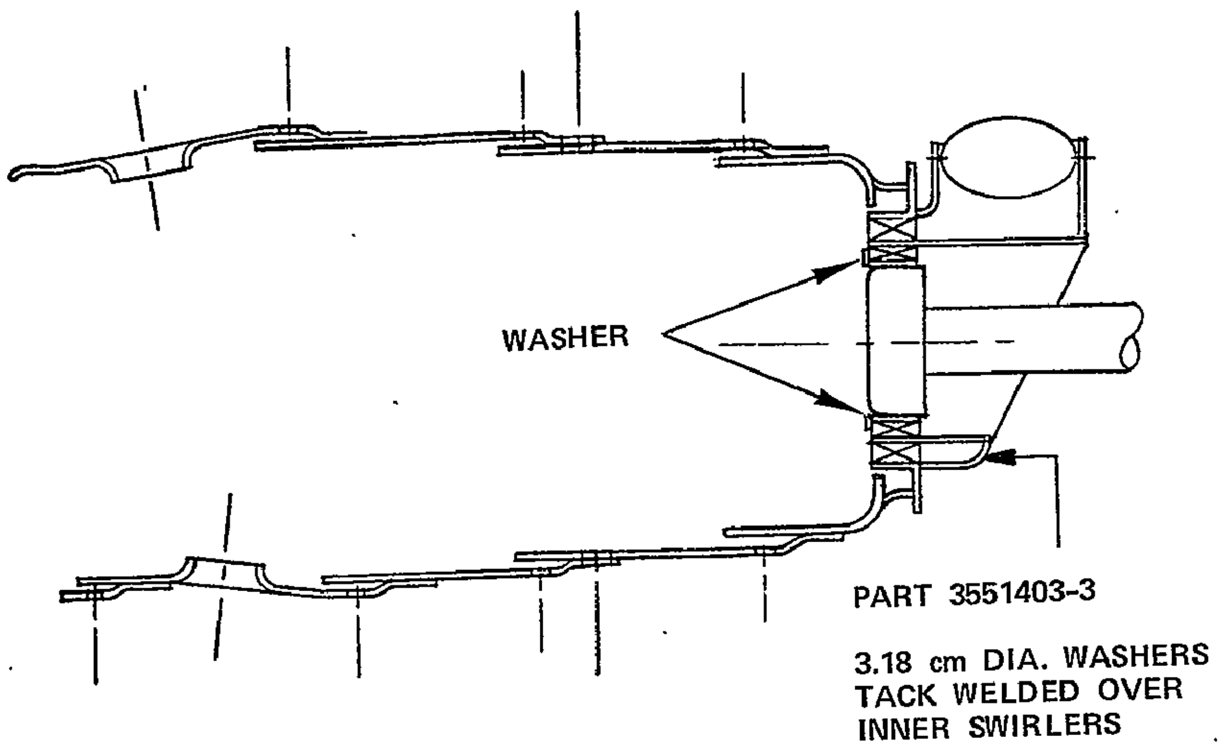


Figure 46. Concept 2, Optimization Test No. 2
Combustor Configuration.

The system was tested over the LTO power points and cruise. At taxi-idle, with the valves sealed and the linkage installed, the HC and CO levels were similar to the comparably connected Optimization Test No. 1 configuration. Again, the high values were attributed to the distortion of some of the spray cones by the air-assist air.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Optimization Test No. 1 (10-19-77)	5.2	44.9
Optimization Test No. 1 (11-15-77)	17.5	60.0
Optimization Test No. 2	14.1	57.2

At takeoff, the NO_x level was higher than that of the previous configuration.

Configuration	Climbout NO_x g/kg fuel	Takeoff NO_x* g/kg fuel
Program goal	--	7.0
Optimization Test No. 1	6.3	6.8
Optimization Test No. 2	7.9	8.8

*Corrected to standard humidity

h. Concept 2 - Optimization Test No. 3. - The Optimization Test No. 3 configuration of Concept 2 is shown in Figure 47. The combustor had the same hole pattern as the Optimization Test No. 1 and No. 2 combustors. The swirler housings were identical to the housings used in Optimization Test No. 1, with the exception that 3.05 cm diameter shimstock washers were tack welded over the inner swirlers to reduce the airflow.

The system was tested at taxi-idle with 0-, 5-, and 10-percent simulated air bleed. Air-assist differential pressure was maintained at 379 kPa. For these tests, the butterfly valves were sealed shut and the variable-geometry linkage was installed. At approach, cruise, climbout, and takeoff, the combustor was tested without air-assist, and with the valves in the 90-degree (full open) position.

At taxi-idle, the HC and CO results were essentially unchanged from the Optimization Test No. 2 results. The values are shown below, along with the program goals for comparison:

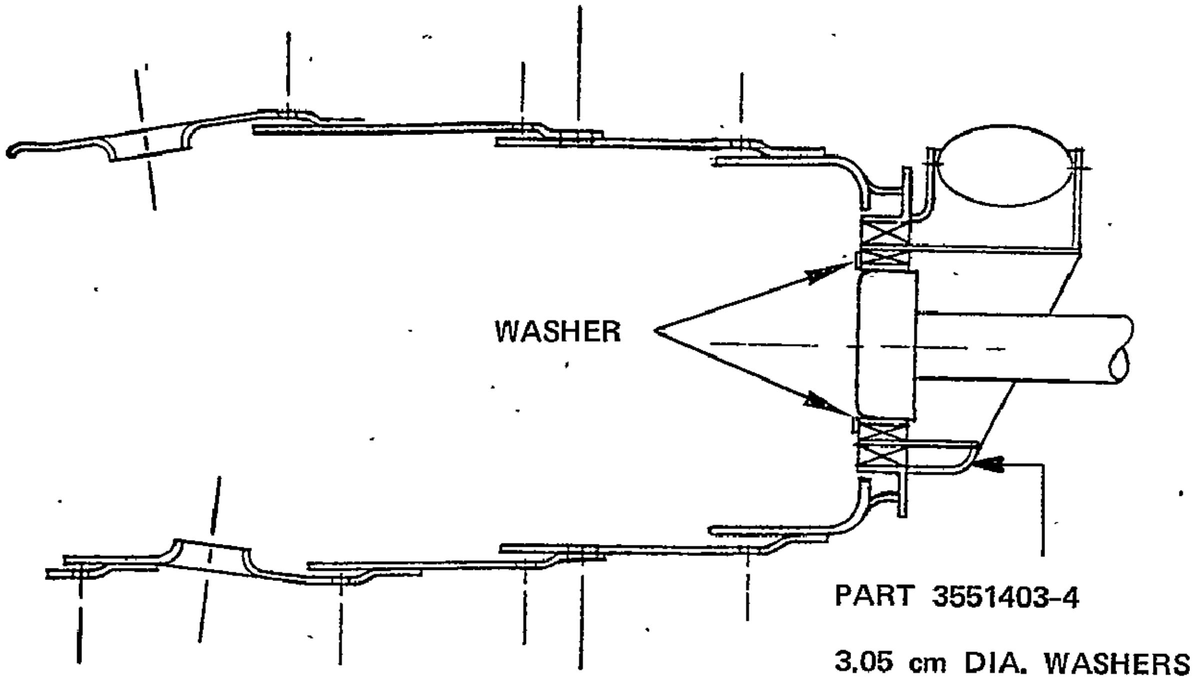


Figure 47. Concept 2, Optimization Test No. 3 Combustor Configuration.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Optimization Test No. 2	14.1	57.2
Optimization Test No. 3	13.1	56.6

At the high power setting, the NO_x values were slightly less than the previous configuration but still higher than the program goals:

Configuration	Climbout NO_x* g/kg fuel	Takeoff NO_x* g/kg fuel
Program goal	--	7.0
Optimization Test No. 2	7.9	8.8
Optimization Test No. 1	7.7	8.7

*NO_x values corrected to standard humidity conditions.

i. Additional Concept 2 Tests. - Following Optimization Test No. 3 evaluation, the rig testing was to have been concluded. However, the combustion system that produced the best overall emission performance, Optimization Test No. 1, had a taxi-idle CO level over 40.0 g/kg fuel. This was considerably above the program goal of 30 g/kg fuel, and it was decided that additional configurations would be tested in an attempt to reduce taxi-idle emission levels. Three additional configurations were tested, and are included as a part of the Optimization Test No. 3.

(1) Concept 2 - Additional Test No. 1. - The combustor-orifice pattern for this test remained unchanged from the Optimization Test No. 3 configuration; however, the swirlers were modified by tackwelding 4.47-cm diameter shimstock washers over the swirler discharge. This resulted in a larger diameter swirler with the same effective area as the Optimization Test No. 1 inner swirler. The basis for this modification came from Concept 3 Refinement Test No. 5, which indicated that a 10-percent increase in swirler diameter resulted in a reduction of approximately 25 percent in CO. Figure 48 is a sketch of the combustor.

The system was tested at taxi with 0-, 5-, and 10-percent simulated air bleed. Three air-assist differential pressures were evaluated at the zero-bleed condition (62, 172, and 379 kPa). The bleed-flow points were tested at 379 kPa only.

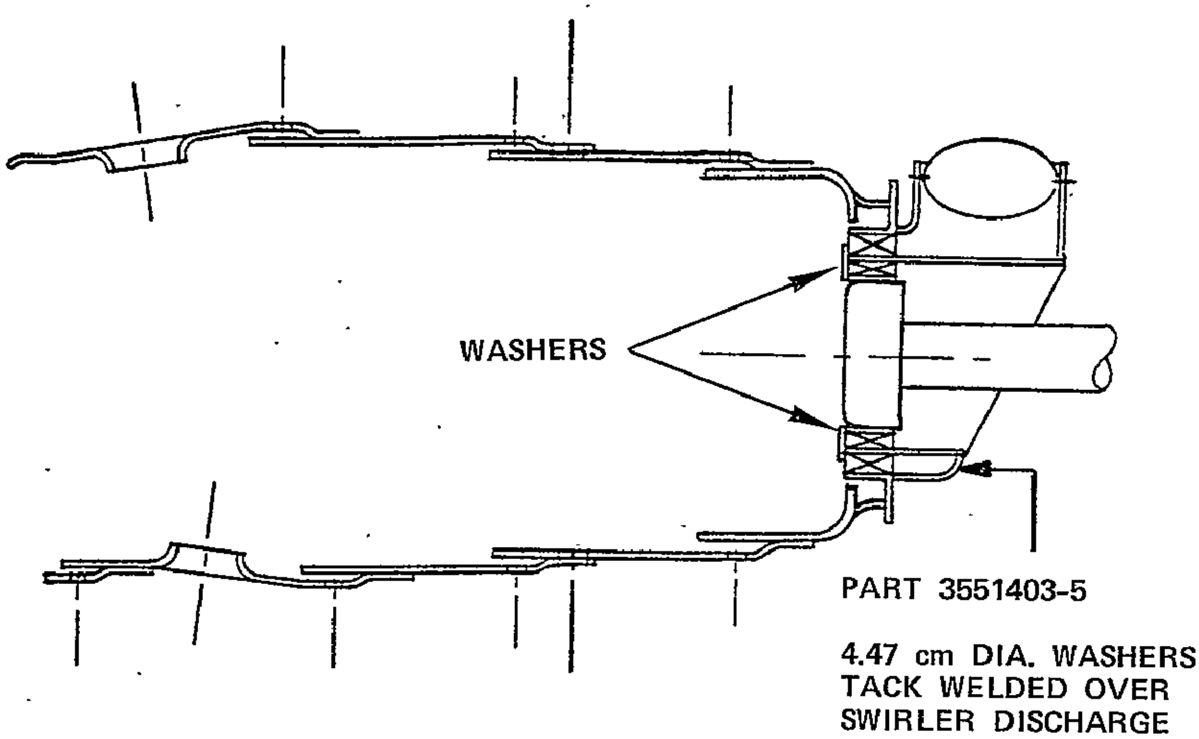


Figure 48. Concept 2, Additional Test No. 1
Combustor Configuration.

The test data revealed very high HC and CO values, with only small improvements as a function of increasing air-assist differential pressure.

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Optimization Test No. 1, 379 kPa AA*	5.2	44.9
Additional Test No. 1, 62 kPa AA	271.9	111.4
Additional Test No. 1, 172 kPa AA	236.9	112.2
Additional Test No. 1, 379 kPa AA	117.6	98.8

*AA = air assist differential pressure.

(2) Concept 2 - Additional Test 2. - In this test, the swirler geometry was maintained identical to the Additional Test No. 1 configuration (with the 4.47-cm diameter washers tackwelded to the discharge of the swirlers). The combustor was modified by the addition of eighty 1.077-cm diameter orifices to the dilution zone, essentially doubling the dilution-zone open area, and resulting in a higher primary-zone fuel/air ratio. The test was performed at taxi with 0-, 5-, and 10-percent simulated air bleed. Air-assist differential pressure was maintained at 379 kPa.

While reduced from the previous configuration, the emission levels were still high, as shown below:

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Optimization Test No. 1 (10-19-77)	5.2	44.9
Additional Test No. 1	117.6	98.8
Additional Test No. 2	81.6	72.7

(3) Concept 2 - Additional Test 3. - The combustor remained unchanged from the previous test, and the swirlers were returned to the Optimization Test No. 1 configuration by removing the shimstock washers. This combustor resembled Optimization Test No. 1 with regard to increased dilution-zone open area. The combustor was tested at taxi-idle with 0-, 5-, and 10-percent simulated bleed. The valves were sealed in the closed position. The system was tested with two fuel-injector systems: (a) the air-assisted airblast, and (b) simplex pressure atomizers. With the airblast

nozzles, air-assist differential pressure was maintained at 379 kPa, and the variable-geometry linkage was installed. The linkage was not installed with the pressure atomizers. The combustor was also tested at the high-power points using the airblast nozzles without air-assist.

The emission performance with the airblast nozzles was similar to the results on Optimization Test No. 1. With the pressure atomizers there was a dramatic improvement, as shown below:

Configuration	HC g/kg fuel	CO g/kg fuel
Program goal	6.0	30.0
Optimization Test No. 1 (10-19-77)	5.2	44.9
Additional Test No. 3 (Airblast)	14.9	43.9
Additional Test No. 3 (Pressure Atomizer)	2.5	27.3

The results with the pressure atomizers met the program goals with some margin. Previous comparative tests between the airblast nozzles without distortion and pressure atomizers on the Test No. 2 configuration resulted in the conclusion that there was little difference in emission performance between the two types of injectors at the taxi-idle power setting. Therefore, the higher emission levels with the airblast nozzles were attributed to the distorted fuel spray cone caused by defects and/or contamination in the air-assist passages.

For the high-power test, the pressure atomizers were replaced with the airblast nozzles, and the air-swirler valves were set to full open. The combustor was tested at approach, cruise, climbout, and takeoff. Air-assist pressure was not used during these tests.

The NO_x levels at the climbout and takeoff power settings were higher than those measured with the Optimization Test No. 1 configuration, as shown below:

Configuration	Climbout NO_x g/kg fuel	Takeoff NO_x* g/kg fuel
Program goal	--	7.0
Optimization Test No. 1	6.3	6.8
Additional Test No. 3 (10-5-77)	8.6	9.6

The higher NO_x value probably resulted from the higher primary-zone equivalence ratio obtained when the dilution-zone open area was increased.

2. Concept 3 - Combustor Configurations and Experimental Emissions Results. - The design of the premix combustor was based on the development tests performed during Phase I.

The pilot zone, located immediately upstream of the main combustion zone, was swirl stabilized and utilized 20 air-assisted airblast fuel nozzles inserted through the combustor dome. Airblast nozzles were tested in lieu of the pressure atomizers used in Phase I to minimize the pilot-zone contribution to NOx emissions. The pilot zone utilized a high equivalence ratio at taxi-idle to minimize HC and CO emissions. At higher power settings, the pilot-zone equivalence ratio was reduced to as low as possible to minimize NOx emissions, and yet maintain an adequate ignition source for the main combustion zone.

At high-power conditions, the main-zone fuel was injected into an annular premix passage upstream of the combustor by means of 40 simplex atomizing nozzles. The premix annulus had three fuel-injection points along its length, spaced at 7.6-cm intervals, to determine the minimum premix length necessary to produce low emission levels. The annulus was connected to 40 chutes that introduced the fuel/air mixture into the combustor downstream of the pilot zone. The main-zone fuel was mixed with a large quantity of air to produce a lean reaction zone to minimize NO_x emissions. Reducing the pilot-zone fuel flow decreased NO_x emissions; however, it also decreased combustion efficiency. This was due to an attendant reduction in the pilot-zone temperature, which was needed to ignite the premix fuel. Therefore, extensive testing was conducted to obtain the optimum fuel-flow split between the pilot and main-combustion zones at each of the three high-power conditions.

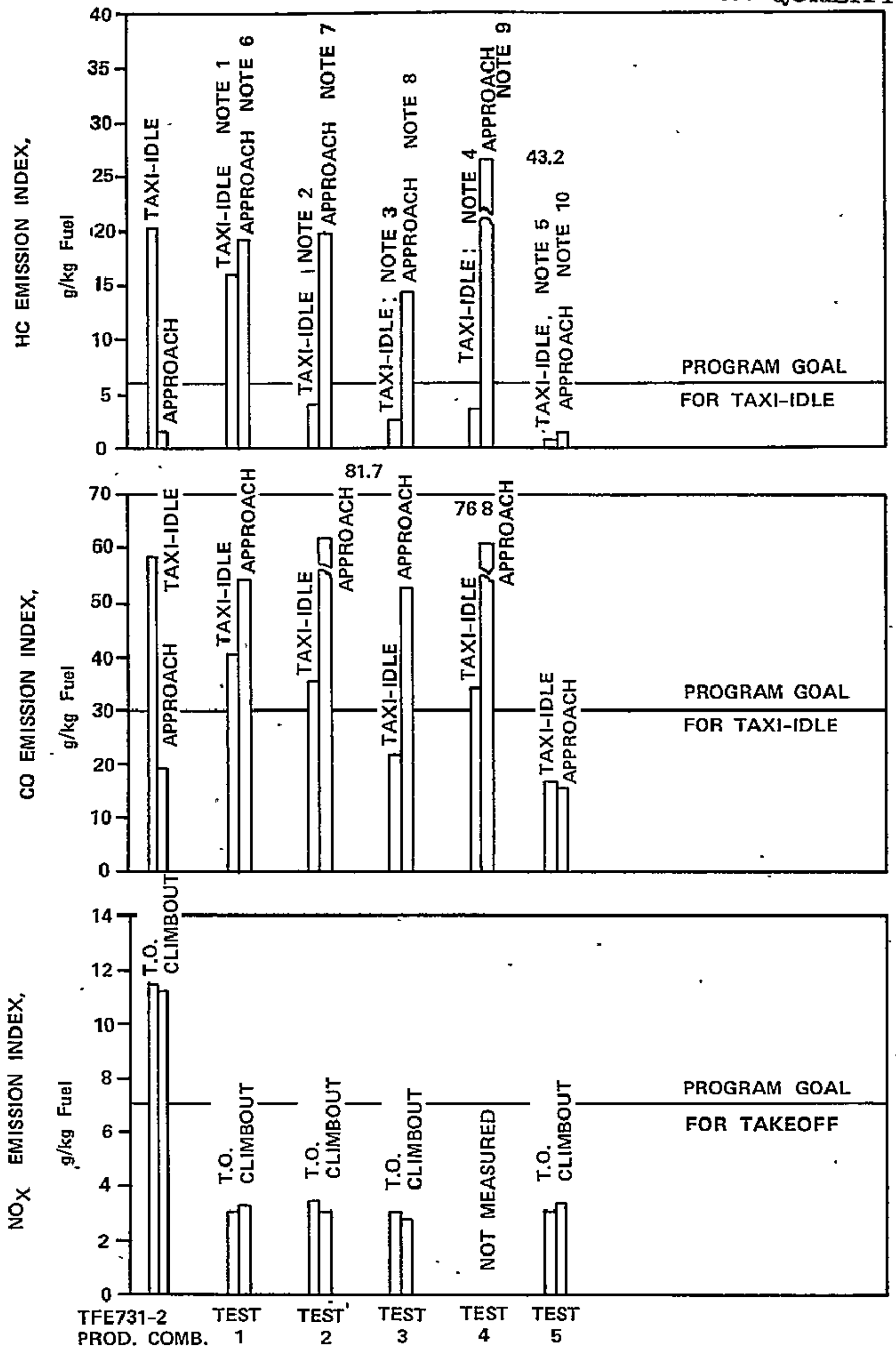
Several design improvements were made to the Phase I configuration, and are listed in Table XII along with the four modifications that were made to the initial configuration. The emphasis of the testing in this phase was on selecting a combustor swirler that gave the optimum degree of primary-zone mixedness. The optimum was that which produced high efficiency at taxi-idle, and a strong ignition source for the main combustion zone.

Takeoff NO_x emission levels well below the program goal (and comparable to the lowest Phase I values) were achieved while maintaining high combustion efficiency. At the taxi-idle condition, both HC and CO were within the program goals with the use of air assist. High efficiencies were achieved with staging at the approach condition by minimizing the premix fuel flow. The lowest emission levels achieved in the five refinement tests for all four engine power conditions are presented in Figure 49; and a discussion of each test is given in the following paragraphs.

TABLE XII

CONCEPT 3 TEST CONFIGURATIONS

Refinement Test No.	Modification (Comparisons made to Test No. 1)
1	(Compared to Phase I internal configuration) Increased premix airflow to 23 percent of total. Wall cooling in dilution reduced and air added to dilution.
	Additional cooling skirt added to inner primary panel. Film cooling immediately downstream of premix tubes changed to impingement cooling.
	Airblast nozzle tip design changed to eliminate carbon buildup.
2	Axial swirler changed to radial inflow swirler with same airflow.
	Premix tubes shortened by 5.0 cm
3	Radial swirler area increased 112 percent.
4	Pilot nozzles changed to pressure atomizers. Swirler changed to axial and area increased 55 percent.
5	Discharge diameter of radial swirler increased 10 percent.
	Swirl angle of swirler decreased 13 percent (two different sets of swirlers were tested).



NOTES:

1. 72 kPa Air-Assist Press.
2. 340 kPa Air-Assist Press.
3. 413 kPa Air-Assist Press.
4. No Air-Assist Possible
5. 402 kPa Air-Assist Press.
6. 15% Premix Fuel Flow
7. 16% Premix Fuel Flow
8. 7.6% Premix Fuel Flow
9. 15% Premix Fuel Flow
10. 1% Premix Fuel Flow

Figure 49. Summary of Emission Test Results, Concept 3.

a. <u>Concept 3 - Refinement Test No. 1.</u> - As can be seen in Figure 50, the premix/prevaporization (PM/PV) system consisted of an annulus surrounding the outer wall of the combustor, and extending from the diffuser deswirl vanes to the axial mid-point of the combustor. At this point, the PM/PV annulus was divided into 40 chutes that ducted the fuel/air mixture into the combustor. The inner and outer liners 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. The swirl angle was higher in the PM/PV annulus (55 degrees) than at the combustor inlet (35 degrees) since the premix air was not turned by the diffuser deswirl vanes; the higher swirl angle gave the advantage of a longer PM/PV residence time. Premix fuel was introduced through 40 equally spaced pressure atomizers with flow numbers of 0.68. Two premix lengths were investigated in this test, 7.6 and 15.2 cm.

Measurements were taken to determine the total pressure within the premix annulus in order to determine the circumferential airflow distribution and the premix airflow rate. The flow variations were considered to be acceptable, and much improved over that in Phase I. The premix flow rate was calculated to be 23 percent of the total flow, with the design point being 24 percent.

The pilot zone at the dome of the combustor was fueled by 20 air-assisted airblast nozzles inserted axially through the combustor endplate. The swirlers were of the axial type, and sized to produce a pilot zone equivalence ratio of 0.8 at taxi-idle.

The HC and CO values obtained at the taxi-idle condition are presented in Figures 51 and 52 as a function of air-assist pressure. It is estimated that to attain the HC and CO emission goals would have required air-assist differential pressures of approximately 150 kPa (data was taken only up to 72 kPa air-assist differential pressure).

The combustion efficiency, obtained with several pilot premix fuel-flow splits at the approach condition, is shown in Figure 53. The efficiency was a maximum with pilot-only operation, and was reduced significantly with increases in the premix fuel flow and corresponding decreases in pilot-zone fuel flow. The main-zone efficiency deteriorated because of the reduction in pilot-zone discharge temperature, which must be high in order to ignite the premix fuel. Comparison of data taken with 7.6- and 15.2-cm premixing lengths at the approach condition revealed no significant differences. The SAE smoke number was measured to be 9, with 15-percent premix fuel flow.

A series of points was run at the takeoff and climbout power conditions to evaluate the effect of the pilot premix fuel-flow split. NO_x emission values and combustion efficiency at takeoff are plotted versus fuel-flow split in Figures 54 and 55, respec-

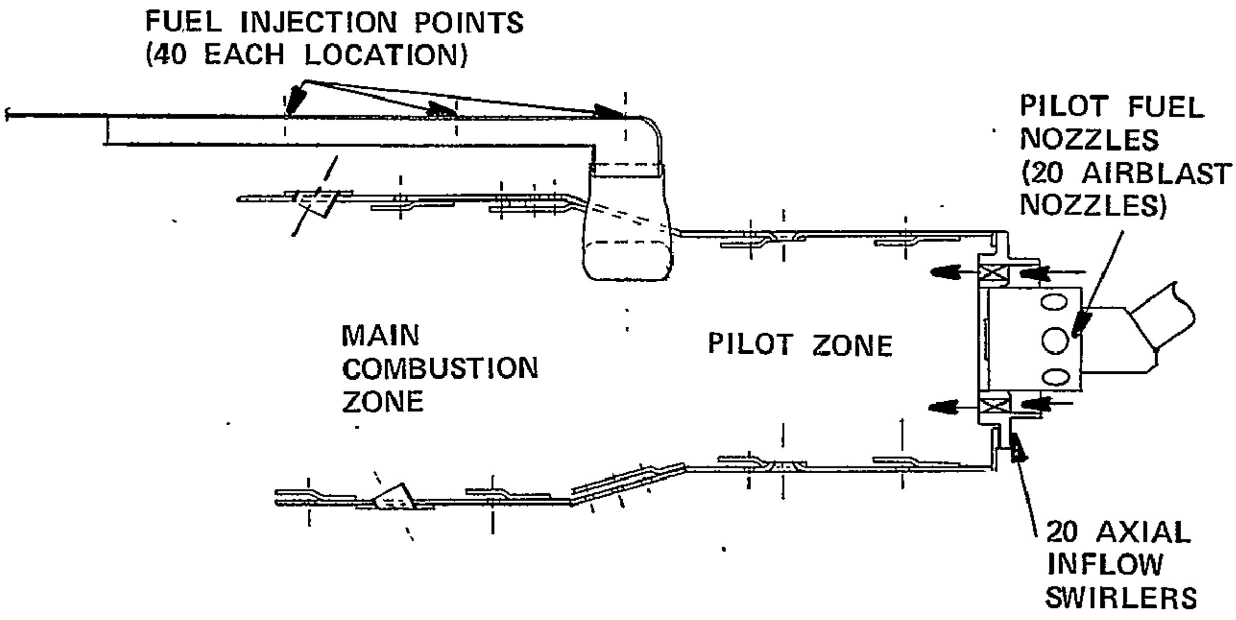


Figure 50. Concept 3, Refinement Test No. 1
Combustor Configuration.

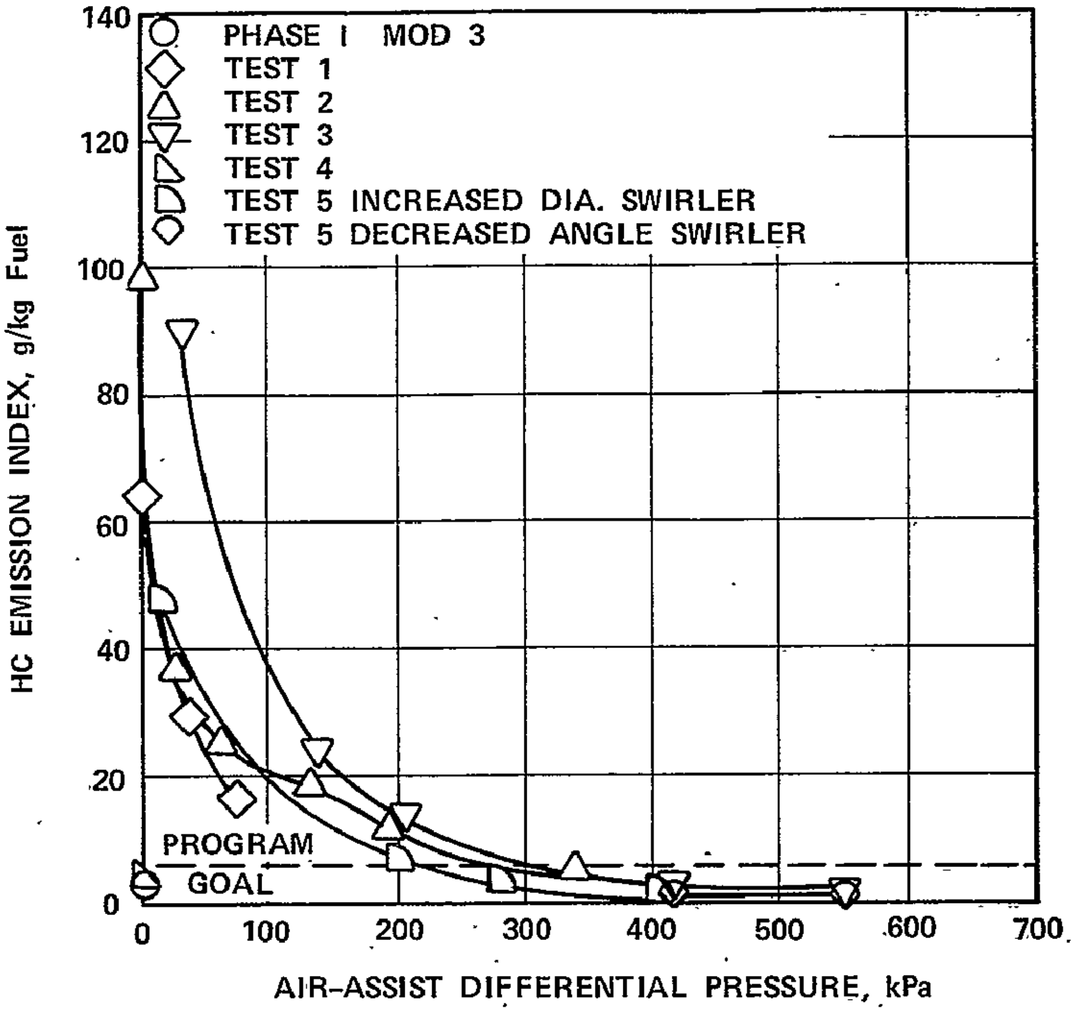


Figure 51. Effect of Air Assist on HC Emissions at Taxi-Idle.

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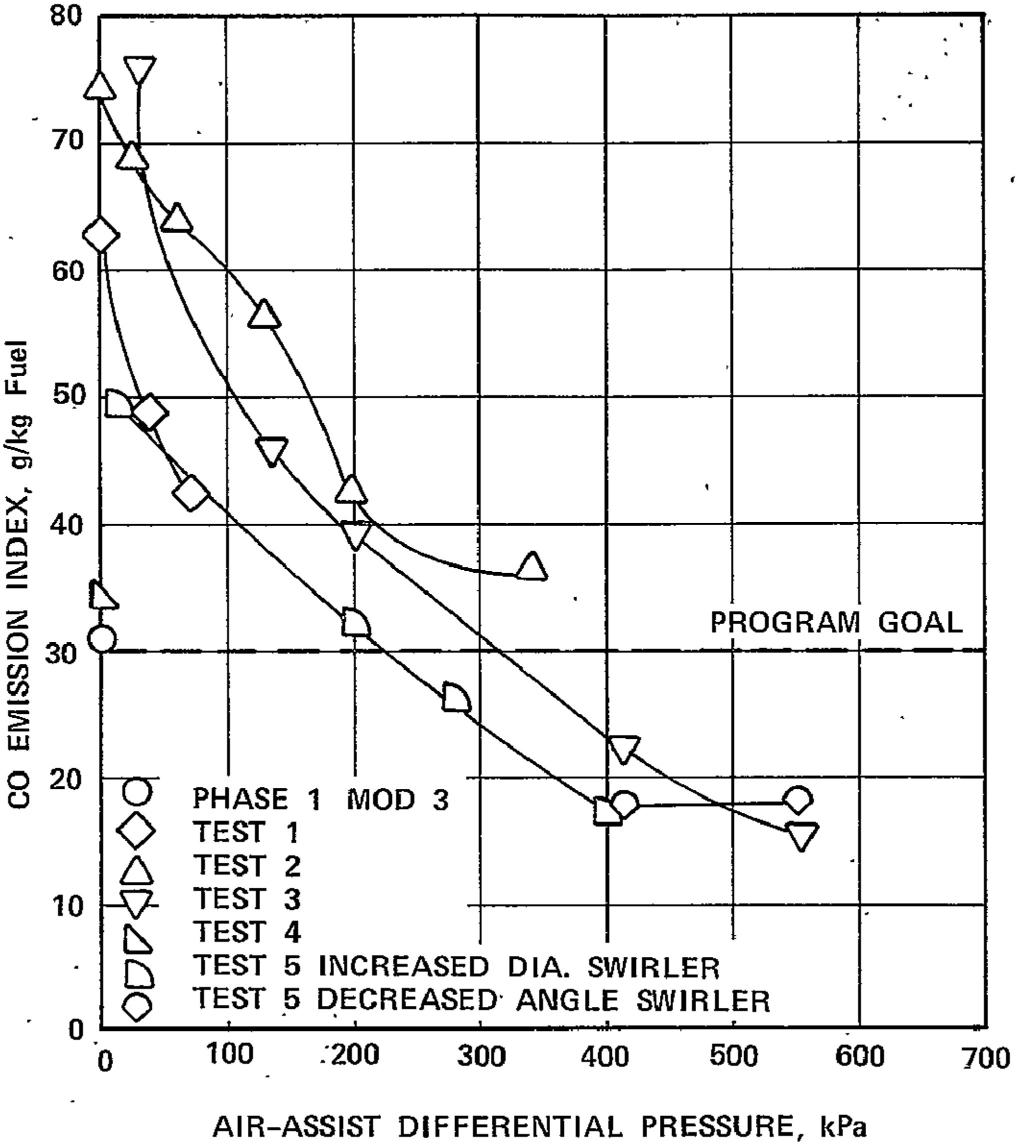

Figure 52. Effect of Air Assist on CO Emissions at Taxi-Idle.

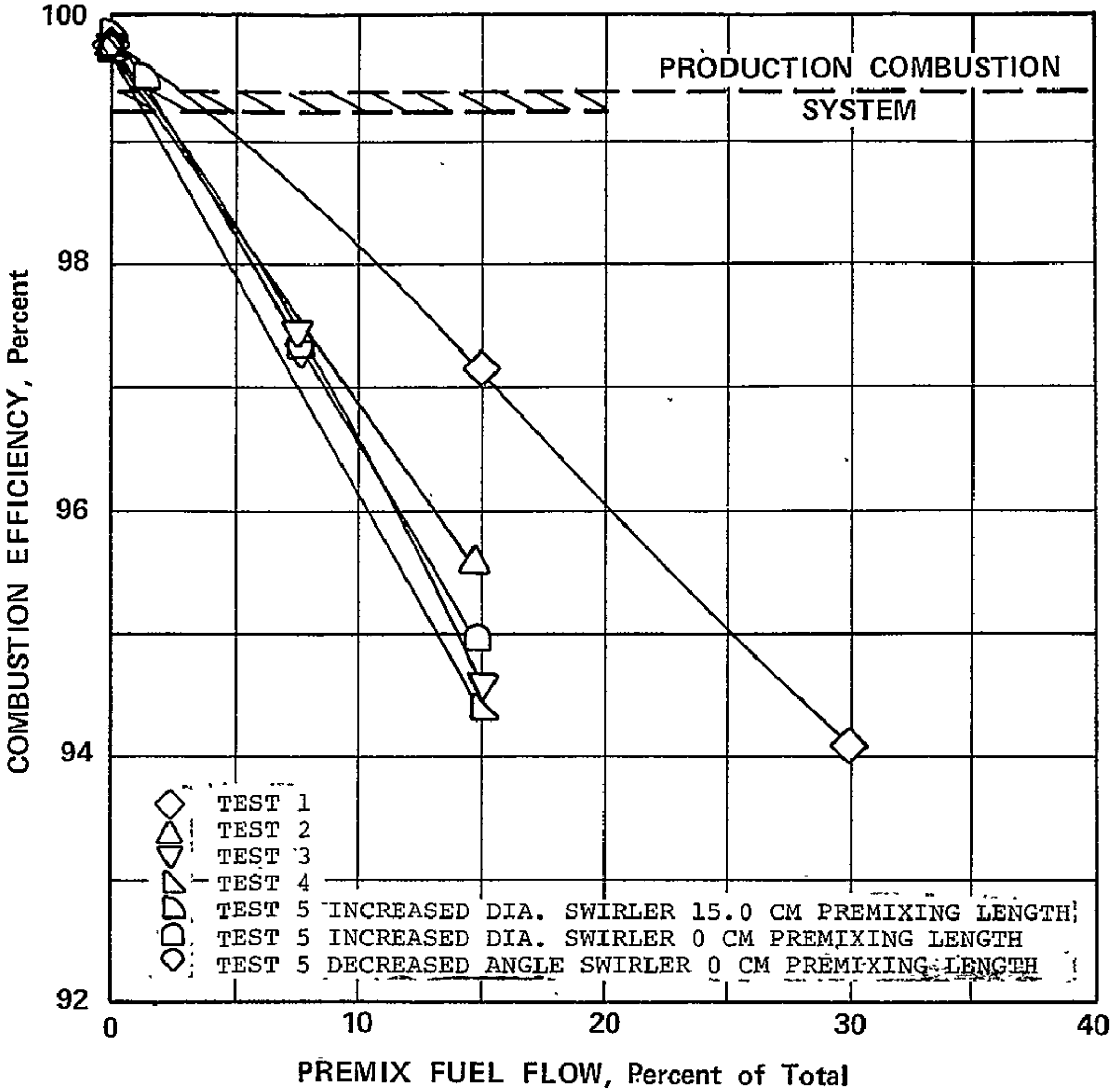

Figure 53. Effect of Fuel-Flow Split on Combustion Efficiency at Approach.

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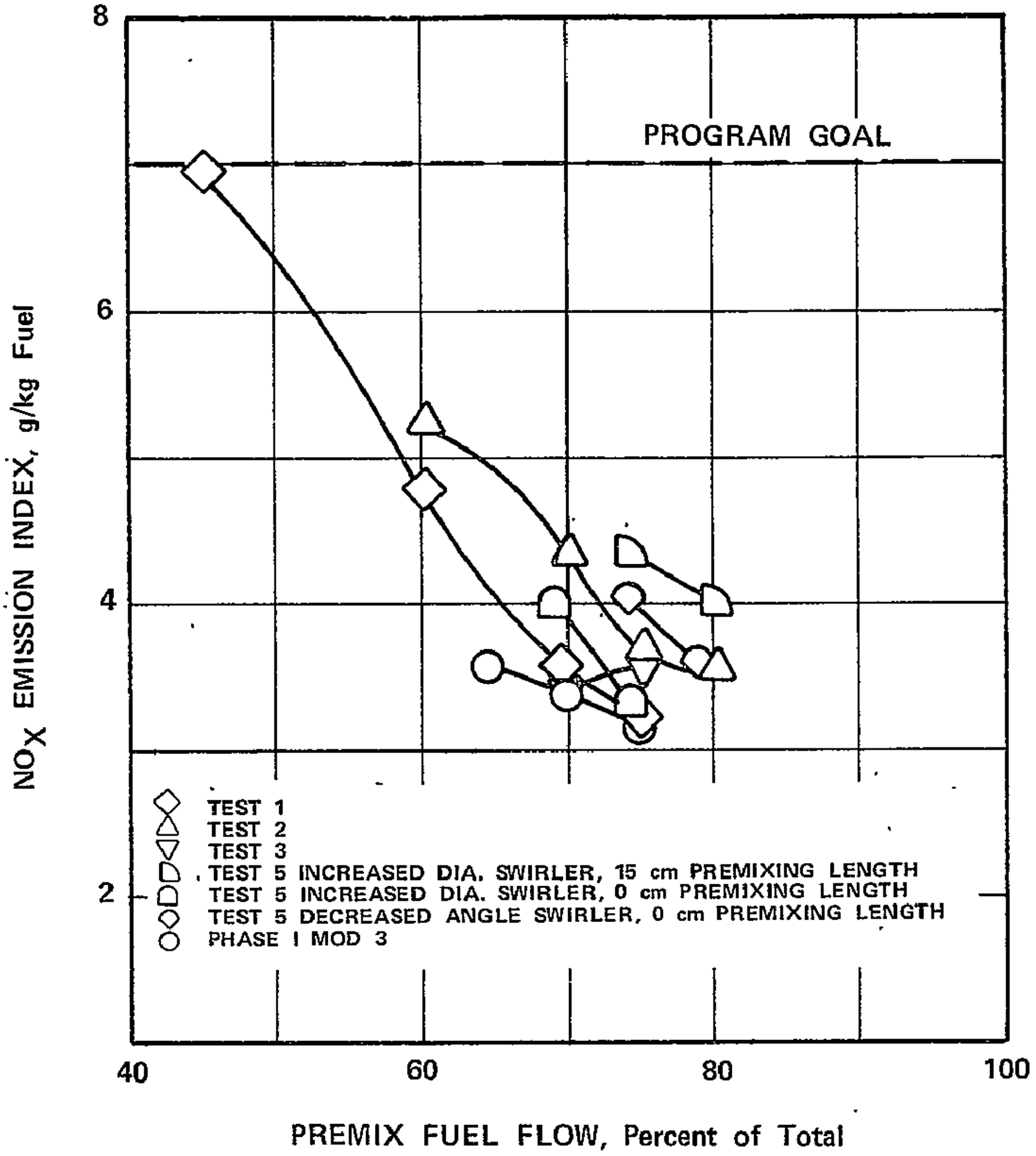

Figure 54. Effect of Fuel-Flow Split on NO_x Emissions at Takeoff.

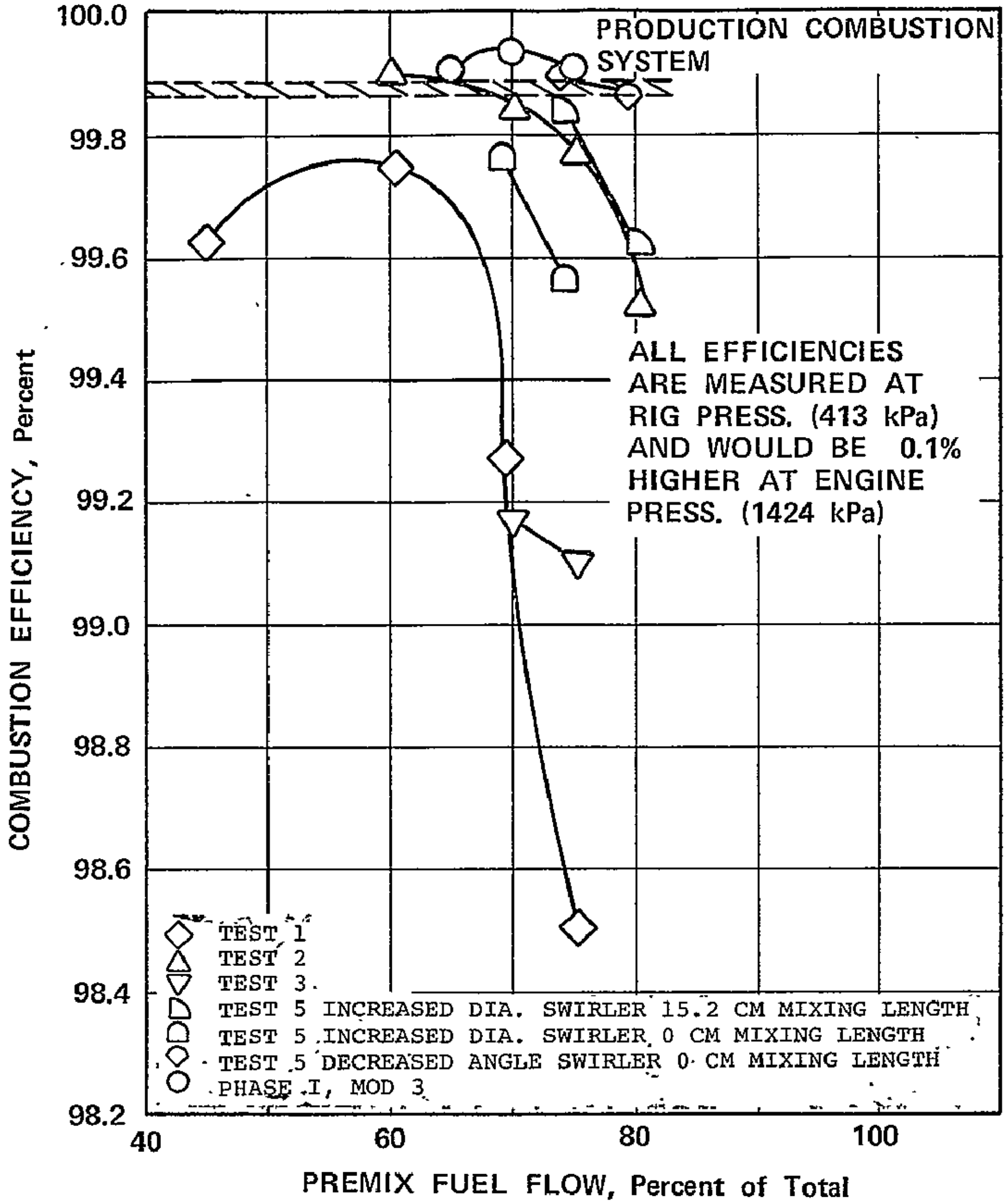

Figure 55. Effect of Fuel-Flow Split on Combustion Efficiency at Takeoff.

tively. The majority of the NO_x emissions were formed in the pilot zone, and therefore NO_x decreased with pilot fuel reductions and corresponding premix fuel increases. This configuration achieved the lowest NOx value (3.2 g/kg fuel) of any configuration tested; however, the combustion efficiency was unacceptably low (98.5 percent) at a premix fuel-flow rate of 75 percent of the total. Similar results were obtained at the climbout condition. The smoke number was measured to be zero at the rig simulated takeoff and climbout conditions.

b. Concept 3 - Refinement Test No. 2. - A cross-sectional drawing of the Refinement Test No. 2 configuration is given in Figure 56. The penetration of the premix tubes into the combustor was reduced by 0.5 cm to prevent damage due to high pilot zone temperatures occurring with pilot only operation at approach. In order to increase the strength of the ignition source for the main combustion zone, the swirlers were changed to decrease the pilot zone mixedness. The axial swirlers were replaced by radial-inflow swirlers which produced a smaller recirculation zone. The airflow through the swirler was maintained the same as the previous design.

At the taxi-idle condition, the HC emission values were brought below the program goal with approximately 300 kPa air-assist differential pressure; however, the CO emission level was in excess of the goal, even at an air-assist differential pressure of 340 kPa (see Figures 51 and 52).

The efficiency at the approach condition was lower than in Test No. 1, as can be seen in Figure 53. However, the combustion efficiency at takeoff (and similarly for climbout) showed a substantial improvement, as shown in Figure 55. A NO_x value of 3.5 g/kg fuel, well within the program goal of 7.0 g/kg fuel, was obtained with an efficiency of 99.5 percent. The smoke number was zero at both takeoff and climbout conditions.

c. Concept 3 - Refinement Test No. 3. - The Test No. 3 configuration differs from the Test No. 2 combustor in the swirler only. To evaluate the effect of a pilot-zone fuel/air ratio change, a radial-inflow swirler, sized to give an equivalence ratio of 0.67 at taxi-idle, was tested.

In spite of the lower equivalence ratio, the combustion efficiency achieved at taxi-idle (at air-assist differential pressures above 200 kPa) was higher than that obtained in Test No. 2. Air-assist differential pressures greater than 300 kPa produced HC and CO emission levels below the goals (see Figures 51 and 52). The discharge diameter of the Test No. 3 swirler was larger than that of the Test No. 2 swirler, and therefore the improvement in efficiency was due to the resulting increase in recirculation zone volume.

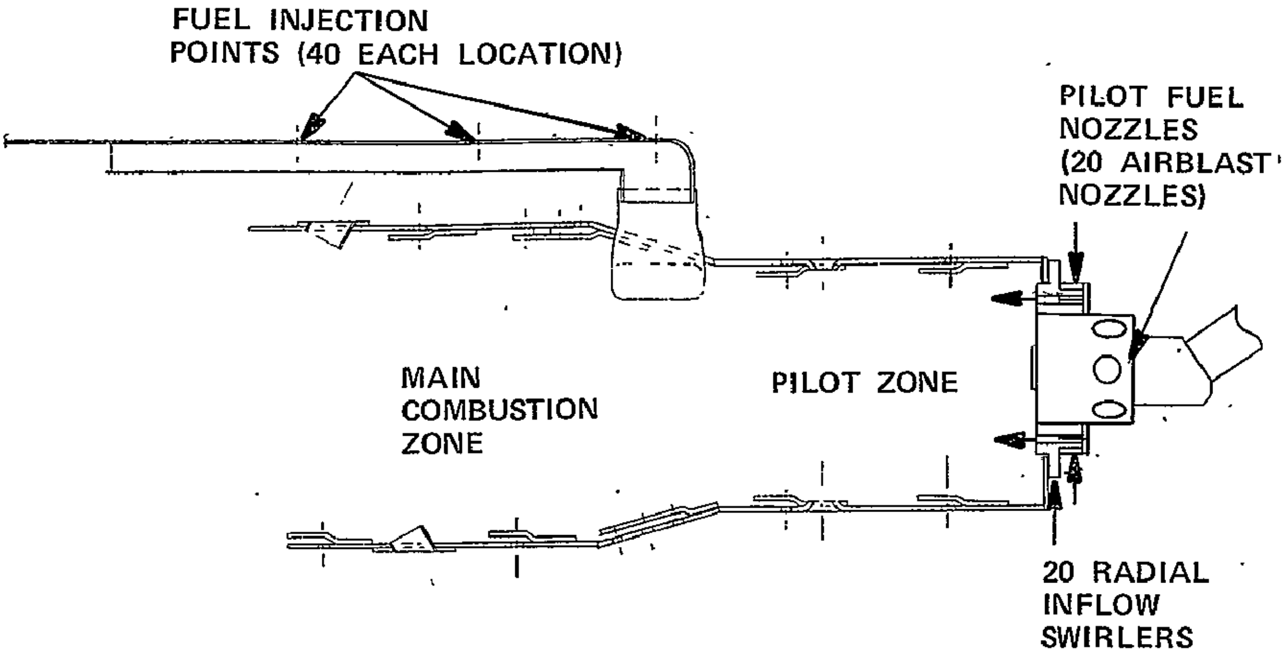

Figure 56. Concept 3, Refinement Test No. 2
Combustor Configuration.

The leaner pilot zone provided a less efficient main combustion zone ignition source, and the combustion efficiency at takeoff (99.2 percent) was lower than that of Test No. 2 (see Figure 55). The pilot-zone NO_x contribution was less, however, and the NOx levels were slightly lower than Test No. 2 emission values. The minimum NO_x value was 3.4 g/kg fuel, measured at a premix fuel-flow rate of 70 percent. The smoke number was again below measurable levels at rig pressure. The efficiency at approach was comparable to that of Test No. 2.

d. Concept 3 - Refinement Test No. 4. - In order to compare the performance of the Phase I and Phase II combustors, and to evaluate the performance of the Phase II airblast nozzles, a test was conducted with the Phase I pressure atomizers and swirlers. The flow number of the pilot nozzles was 0.68, and that of the premix nozzles was 0.9. The combustion system is illustrated in Figure 57.

The measured taxi-idle HC and CO emissions were somewhat above the results obtained with the last external configuration Phase I combustor, as shown in Figures 51 and 52. The HC value (4.0 g/kg fuel) was within the goal, but the CO value (34 g/kg fuel) was above the goal. The airblast nozzles required approximately 300 kPa air-assist differential pressure to match the performance of the pressure atomizers. The results indicate that the poor taxi-idle efficiency of the Phase II combustor at air-assist differential pressures below 300 kPa was due to the inferior atomization of the airblast nozzles. To further evaluate the performance of the airblast nozzles, fuel droplet size as Sauter mean diameter (SMD) measurements were taken using the AiResearch light-scattering apparatus, and are presented in Figure 58. The results showed little improvement in the SMD beyond 200 kPa air-assist differential pressure, yet the combustion efficiency in the rig tests increased significantly up to 400 kPa. This fact led to a swirl-angle test of the airblast nozzles using a traversing cobra probe, the results of which are given below:

Air-Assist Differential Press, kPa	Swirl Angle, Degrees
0	29.5
34.5	28.0
68.9	30.0
137.9	31.8
206.8	33.0
344.7	36.5

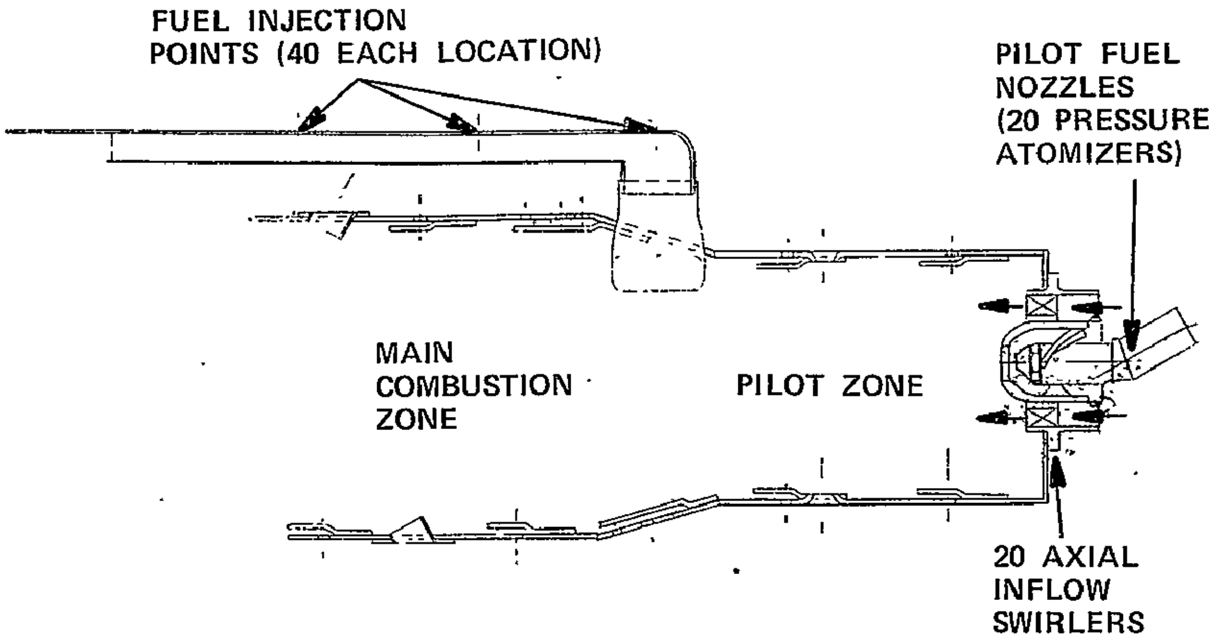

Figure 57. Concept 3, Refinement Test No. 4 Combustor Configuration.

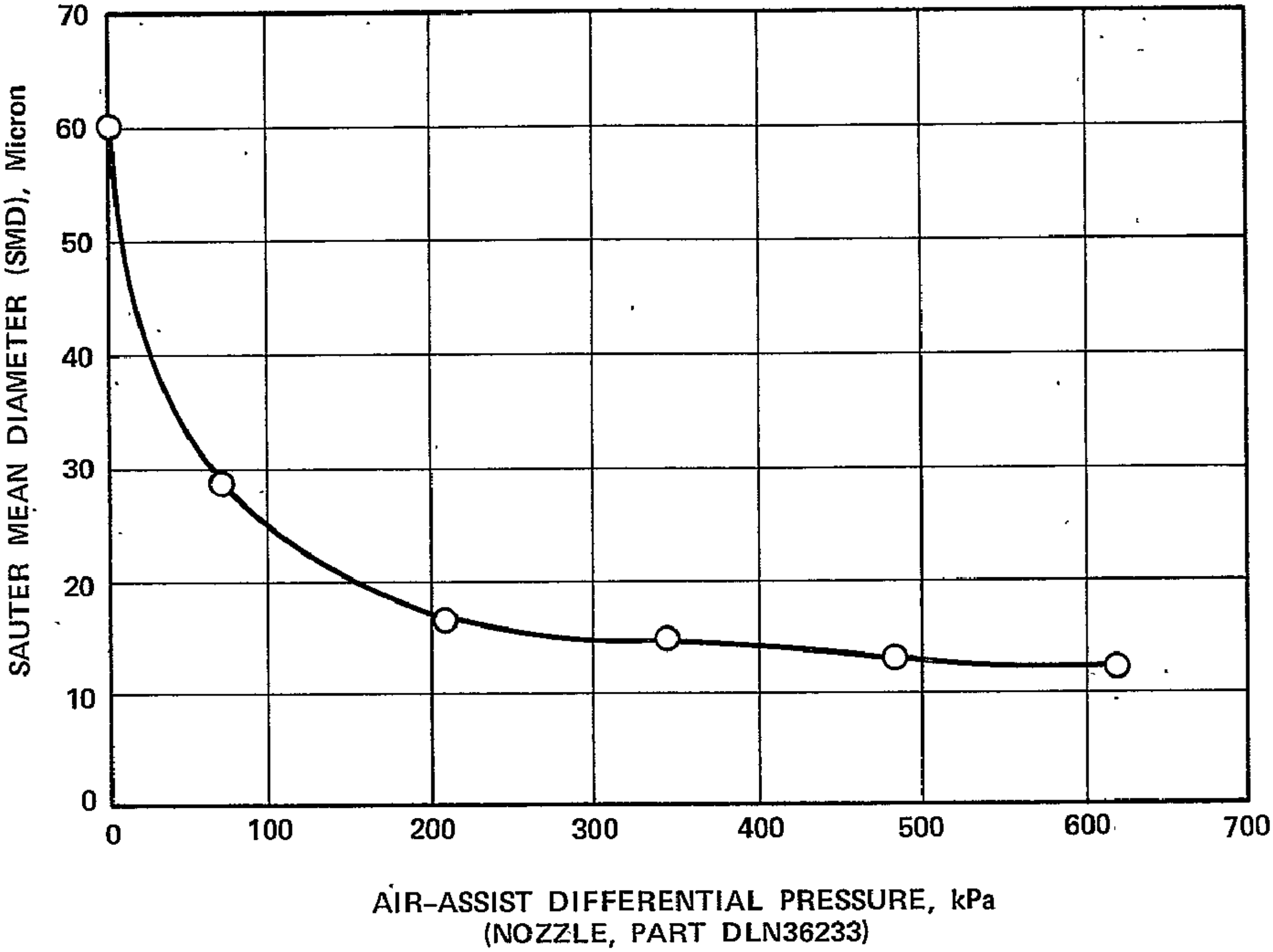

Figure 58. Effect of Air-Assist Pressure on Concept 3 Air-Assisted/Airblast Nozzle SMD at Taxi-Idle Conditions.

The swirl angle of the nozzle shroud discharge air was measured 2.5 cm from the nozzle, and increased 24 percent when the air-assist differential pressure was increased from 0 to 345 kPa. This increased swirl angle could result in an increased residence time, and therefore lower emissions.

The efficiency at the approach condition was slightly below that obtained with the airblast nozzles. The smoke number was measured at 14 with pilot-only operation, and dropped to 10 with 15-percent premix fuel flow. For comparison, the production combustion system produced a smoke number of 34 at the approach condition. The configuration was not tested at the high-power points.

e. <u>Concept 3 - Refinement Test No. 5</u>. - Based upon the results of Test No. 3, in which an increase in efficiency at taxi-idle was produced by a higher capacity radial swirler, a new swirler was designed with a 10-percent increase in diameter, but with the original flow area. The primary equivalence ratio was therefore restored to 0.8, and the swirlers were tested with the airblast nozzles. The length from the point of injection of the premix fuel to the premix tubes was varied during the testing from 15.2 cm to zero; that is, the fuel was injected directly into the combustor tubes, allowing little premixing to occur.

The increased-diameter swirlers produced a significant improvement in efficiency at taxi-idle compared to Tests No. 2 and No. 3. The emission goals were met with an air-assist differential pressure of approximately 225 kPa, as shown in Figures 51 and 52.

The combustion efficiency obtained at approach fell within the range of previous test data; however, a 99.5-percent efficiency (higher than that measured on a production combustion system) was achieved with 1-percent premix fuel flow. As shown in Figure 53, premix fuel flows up to 2.5 percent of the total would produce efficiencies equivalent to that of a production system. The Concept 3 combustion system could therefore be staged at approach, which is desirable for flight safety and engine-acceleration considerations. The measured smoke number was 20, with 15-percent premix fuel flow. The combustion efficiency at takeoff was measured to be approximately the same as that of Test No. 2. This was unexpected, since the larger recirculation-zone volume of the increased-diameter swirler should have produced a weaker ignition source for the main zone. The increased recirculation did lower the pilot-zone contribution to NO_x by increasing the mixedness, as shown in Figure 59.

The effect of a change in premixing length from 15.2 cm to zero is also shown in Figures 54 and 55. The amount of unvaporized fuel was greater in the case of the zero premixing length, and the available reaction time of the main combustion zone was

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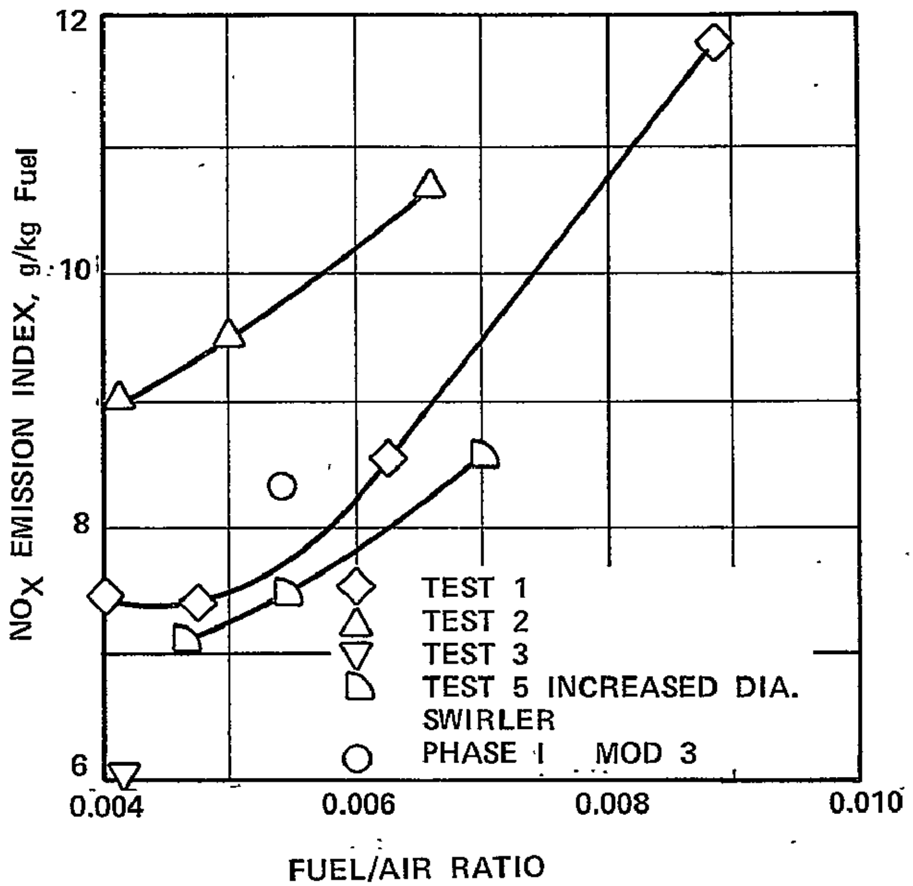

Figure 59. Effect of Fuel/Air Ratio on Pilot Zone NO_x Emissions.

therefore reduced by the time required to vaporize the liquid fuel. This resulted in lower efficiencies and lower NO_x values, as shown in Figures 54 and 55. The deterioration in efficiency was less than what would be expected with such a large decrease in the available premixing time. The calculated premixing time was reduced from 1.5 to less than 0.3 ms. It can therefore be inferred that the degree of premixing in the premix annulus was small. This conclusion was substantiated by flow-visualization tests conducted on a component rig consisting of a single premix nozzle, an annulus sector, and one premix tube. The fuel formed a film on the inner premix liner, and the majority of the fuel/air mixing occurred at the discharge of the premix tubes where the fuel film was broken up. The smoke number in the zero-premixing-length configuration was below measurable levels at the climbout and takeoff conditions.

Extensive fire damage was incurred by the premix annulus during Test No. 5, and the annulus and 15 premix chutes had to be replaced prior to the completion of the testing. A fire had developed (as evidenced by soot deposits) between the premix outer wall and the combustor plenum. The fire resulted in severe buckling of the outer wall in four places, which locally reduced the airflow, causing flashback through the premix chutes. The flashback burned away the premix outer wall in three locations, and damaged several chutes, as shown in Figure 60. The cause of the fire was believed to be a misalignment of the premix fuel nozzles and the orifices in the outer premix wall, allowing fuel to leak into the space between the plenum and premix wall.

In an effort to further reduce the pilot-zone mixedness to improve the main combustion zone efficiency, tests were conducted with a set of swirlers in which the swirl angle was changed from 60 to 52 degrees. The efficiencies at taxi-idle and approach were unaffected by the change, as can be seen in Figures 51, 52, and 53. The efficiency at takeoff and climbout was the highest of all the configurations tested, and was equivalent to that measured on the production combustion system. The NOx values were within the range of the previous data, and a level of 3.55 g/kg fuel was obtained with 80-percent premix fuel (see Figures 54 and 55). The swirlers were tested with the zero-premixing-length configuration.

B.- TFE731-2 ENGINE TESTS

During Phase II of this program, two different configurations of Concept 2 were tested in a development Model TFE731-2 Engine in order to assess the effect of increased combustor pressure on the combustor emission performance. It was not possible to simulate the engine pressure in the rig for the takeoff and climbout modes, and it was uncertain if the engine-to-rig correlation factors obtained on production combustors would be valid for Concept 2. It was also uncertain whether the difference in combustion efficiency between the engine and rig at taxi-idle would also occur when Concept 2 was tested.

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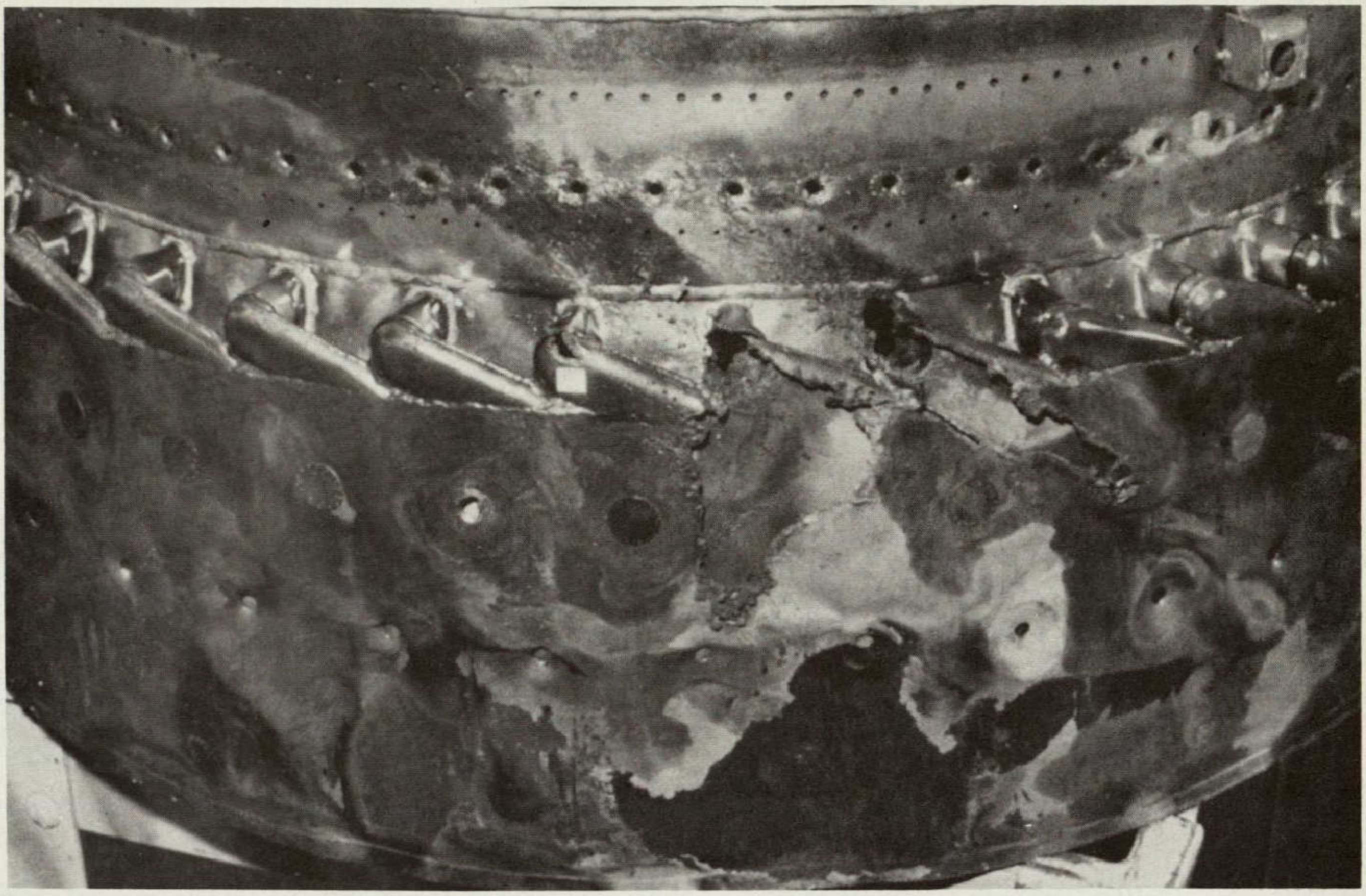


Figure 60. Damage to Concept 3 Test No. 5 Premix Fuel-Injection Chutes and Premix Passage.

For the first engine test, the best configuration at that time, Refinement Test No. 4, was installed in the engine primarily to establish the engine-to-rig correlation at taxi-idle. A fixed-geometry swirler, with the same flow area and swirl angle as the proposed inner swirler of the variable-geometry system, was used because low emission levels had been obtained with that configuration on the rig, and the variable-geometry system was being fabricated. Airblast nozzles were installed on the engine.

Four different air-assist flow rates were evaluated at taxi-idle, both in the engine and subsequently in the combustion rig. The ratio of rig-to-engine CO emission index varied from 1.5 to 2.0, depending upon the air-assist pressure. Similarly, the HC ratio varied from 1.9 to 3.3. These values compare favorably to the data taken in engine tests of three individual production combustion systems. The average ratio of rig-to-engine CO index for the three engine tests was 1.4, and for HC, 3.0. The combustion efficiencies measured on the engine on Concept 2 were from 0.5 to 1.1 percent higher than the measured rig values at the taxi-idle condition.

The second engine test evaluated the performance of the best configuration of Phase II, Optimization Test No. 1. The variable-geometry system could not be actuated on the engine (a variable-geometry system for the engine will be included in Phase III), and therefore the test was conducted in two phases. To evaluate the performance at takeoff and climbout, the butterfly valves were fixed in the open position, and the airblast nozzles were used. The combustor was coated with temperature-sensitive paint to determine liner temperatures. Because of less-than-nominal engine performance during the test, several engine seals were replaced and the test repeated. The engine performance improved, but remained below nominal. Data at four high-thrust conditions were taken to allow interpolation of the emissions indices as a function of fuel/air ratio. The relatively high ambient temperatures contributed to the requirement for this correction. The NO_x index at the standard takeoff fuel/air ratio of 0.0154, corrected for lower-than-standard pressure, temperature, and humidity, was 11.5 g/kg fuel; the goal was 10 g/kg fuel. The NO_x pressure-correction exponent (defined in the EPAP adjustment procedure and calculation section) was calculated to be 0.35 at both the takeoff and climbout conditions, which agrees well with the previous results on production systems (0.35 at takeoff and 0.29 at climbout). Four small, moderate-temperature (1090 K) regions that did not appear during rig tests were revealed on the outer liner by thermal paint; however, the remainder of the liner wall temperatures were acceptable (<980 K). The maximum smoke number was 20, which occurred at 50 percent of maximum available thrust, and is well below the goal of 40.

The purpose of the second phase of the last engine test was to determine the performance at taxi-idle and approach. The butterfly valves were fixed and sealed in the closed position, which allowed air to flow only to the inner swirlers. Pressure atomizers were used rather than airblast nozzles since previous rig tests had demonstrated higher efficiency with the atomizers. Again, data were taken at several thrust settings near the taxi-idle and approach conditions to allow interpolation. The combustion efficiency measured on the engine at taxi-idle was 0.6 percent higher than the measured rig values, similar to the results of the first engine test. The ratio of rig-to-engine CO emission index was 1.9, again similar to the first engine test; but the ratio for HC was 1.1, which is well below that previously measured. The results of the engine tests are discussed further and EPAP results given in Chapter IIID1.

C.- COMBUSTOR PERFORMANCE

In addition to the gaseous emission and smoke measurements made on the various combustor configurations, performance data were also taken. Pressure loss and pattern-factor data were taken for all test points for which the data were acquired by the digital data system. On the few times that data were manually recorded, pressure loss and pattern-factor data were usually taken. In many instances a configuration underwent extensive parametric evaluation at a particular power setting. For example; Concept 2 evaluated several valve angles at a takeoff point, or a range of air-assist pressures at a taxi-idle point. Similarly, Concept 3 usually evaluated a number of fuel-flow splits between the pilot and main combustion zone at a given power setting. The values in Table XIII represent the pressure loss and pattern factor that correspond to the test point that produced the lowest emission result. At taxi-idle, the points represent test points with no air bleed.

Wall-temperature tests were performed at the simulated takeoff condition whenever the emission and performance test data indicated that a given combustion system had the potential for meeting the program goals. Stability, ignition, and altitude relight tests were also run only on promising configurations.

1. Pressure Loss. - The present production combustion system has a pressure loss of 4.5 percent at the takeoff power setting, and the design criterion was to maintain this value as closely as possible in all configurations. The pressure loss on reverse-flow combustors is measured from the diffuser discharge (downstream of a set of deswirl vanes) to the stator inlet. For Concept 2, the pressure losses ranged from 4.4 to 6.0 percent for the various configurations. Optimization Test No. 1, which had the best emission performance, had a 6.0-percent value, and while this is higher than the goal, it is felt the pressure loss can be reduced if Phase III engine tests find it necessary. This may result in slight decrease in mixing and some increase in emission levels, but this effect is expected to be minimal. All Concept 3 combustors met the takeoff pressure-loss goal.

TABLE XIII. SUMMARY, PRESSURE LOSS AND PATTERN FACTOR

	Taxi-Idle		Takeoff	
	Pressure Loss, ΔP/P,%	Temperature Spread Factor	Pressure Loss, ΔP/P,%	Temperature Spread Factor
Concept 2				
Refinement Test 1	5.2	0.09	4.4	0.06
Refinement Test 2	6.1	0.25	4.5	0.06
Refinement Test 3	4.8	0.31	5.6	0.24
Refinement Test 4	10.1	0.11	---	--
Refinement Test 5	7.2	0.15	5.3	0.34
Optimization Test 1	8.1	0.09	6.0	0.10
Optimization Test 2	7.9	0.15	6.0	0.08
Optimization Test 3	8.2	--	5.8	0.15
Concept 3				
Refinement Test 1	6.7*	0.14	7.6*	0.19
Refinement Test 2	6.2*	0.15	3.7	0.28
Refinement Test 3	2.6	0.21	3.4	0.32
Refinement Test 4	2.6	0.21	---	--
Refinement Test 5	2.7	0.26	4.0	0.16

*Includes diffuser deswirl vane losses.

2. Exit Temperature Pattern Factor. - The program goal for takeoff pattern factor is a value less than 0.19. Table XIII indicates that all but two of the eight Concept 2 configurations tested were below the goal. The Refinement Test No. 5 value of 0.34 was attributed to an improper seal of the combustor discharge. Optimization Test No. 1 configuration was well below the goal, with a value of 0.10.

For Concept 3, the pattern factors for Tests No. 2 and No. 3 were higher than the program goal. This was attributed to cracks in the inlet section of the premix passage formed during testing, and to distortions of the passage occurring during assembly. The cracks and distortions were eliminated prior to the last test, and the pattern factor fell within the goal.

3. Combustor Durability. - The potential durability of the combustor designs was determined by the use of wall-temperature tests utilizing temperature-sensitive paint to cover the entire surface of the liner. The Concept 2 configurations were tested twice during Phase II; at the start of the program during Refinement Test No. 1, and during Optimization Test No. 1. Both tests revealed relatively low wall temperatures and shallow temperature gradients. Figure 61 is a picture of the Optimization Test No. 1 configuration following a simulated takeoff test on the combustion rig. The maximum measured wall temperature was 965 K, which is below the maximum temperature measured on the Model TFE731-2 production combustion system during rig tests.

Hot regions that occurred on the Phase I Concept 3 combustor (on the inner inclined wall, and immediately downstream of the outer primary orifices) were largely eliminated during Phase II by increased cooling. The liner temperatures were acceptable with the exception of hot (1200 K) areas near the combustor dome. Since these high-temperature regions did not appear in Phase I, it was concluded that they were caused by the pilot nozzles and/or swirlers, which are being modified for Phase III.

4. Ignition, Altitude Relight, and Stability. - On Concept 2, ignition and altitude relight were performed only on Refinement Test No. 3 configuration, and were found to be inferior to the present production system. This was attributed to a less-than-optimum igniter position. No development work was attempted to improve the ignition capability of the concept. Stability tests were performed on Refinement Test No. 3, and Optimization Tests No. 1 and No. 3. These tests indicated that the Refinement Test No. 3 configuration had combustion stability that was superior to the present production system, while the Optimization Tests No. 1 and No. 3 configurations were close to meeting this goal. These results are plotted in Figure 62.

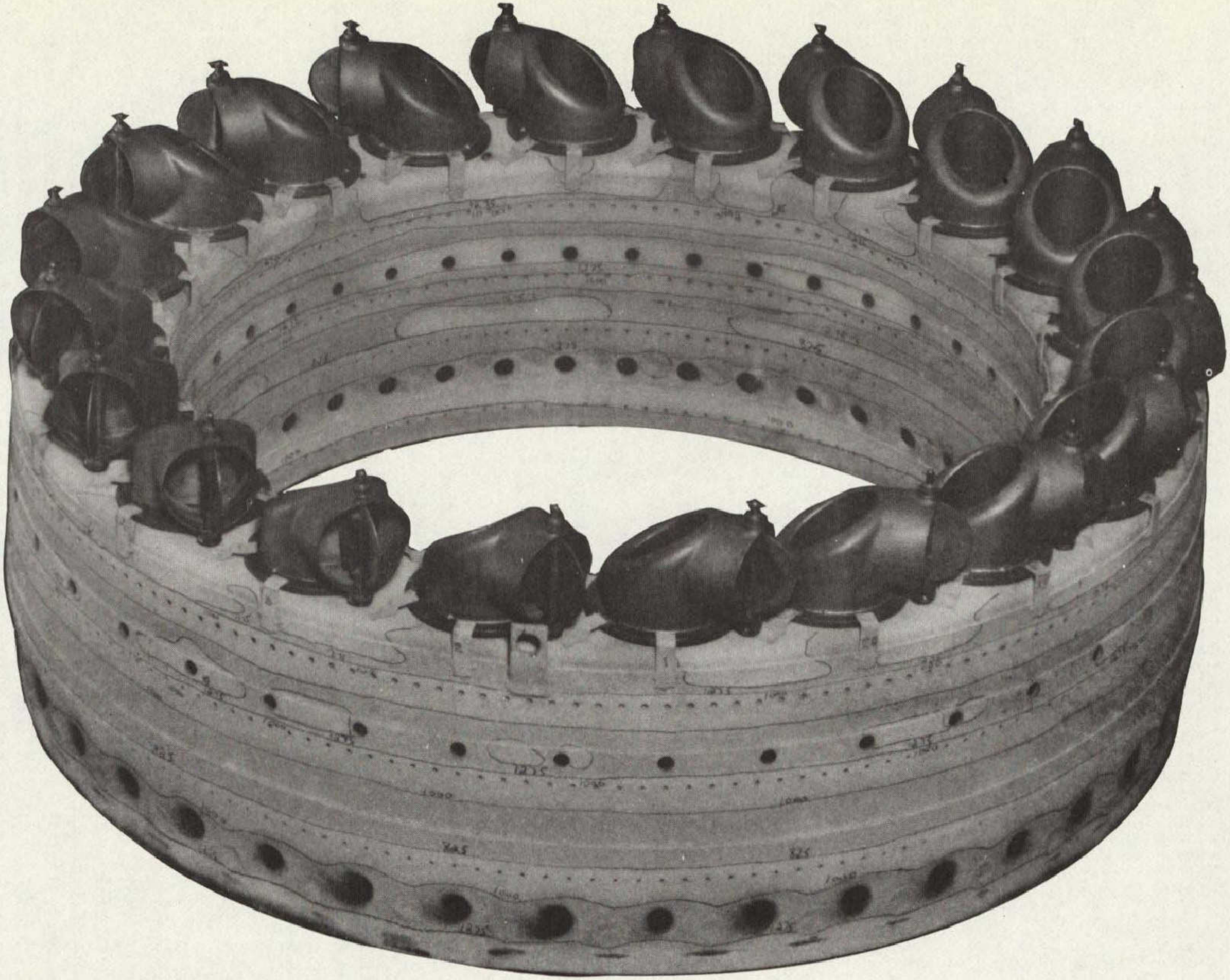


Figure 61. Temperature-Sensitive Paint Test Results, Optimization Test No. 1 (Concept 2).

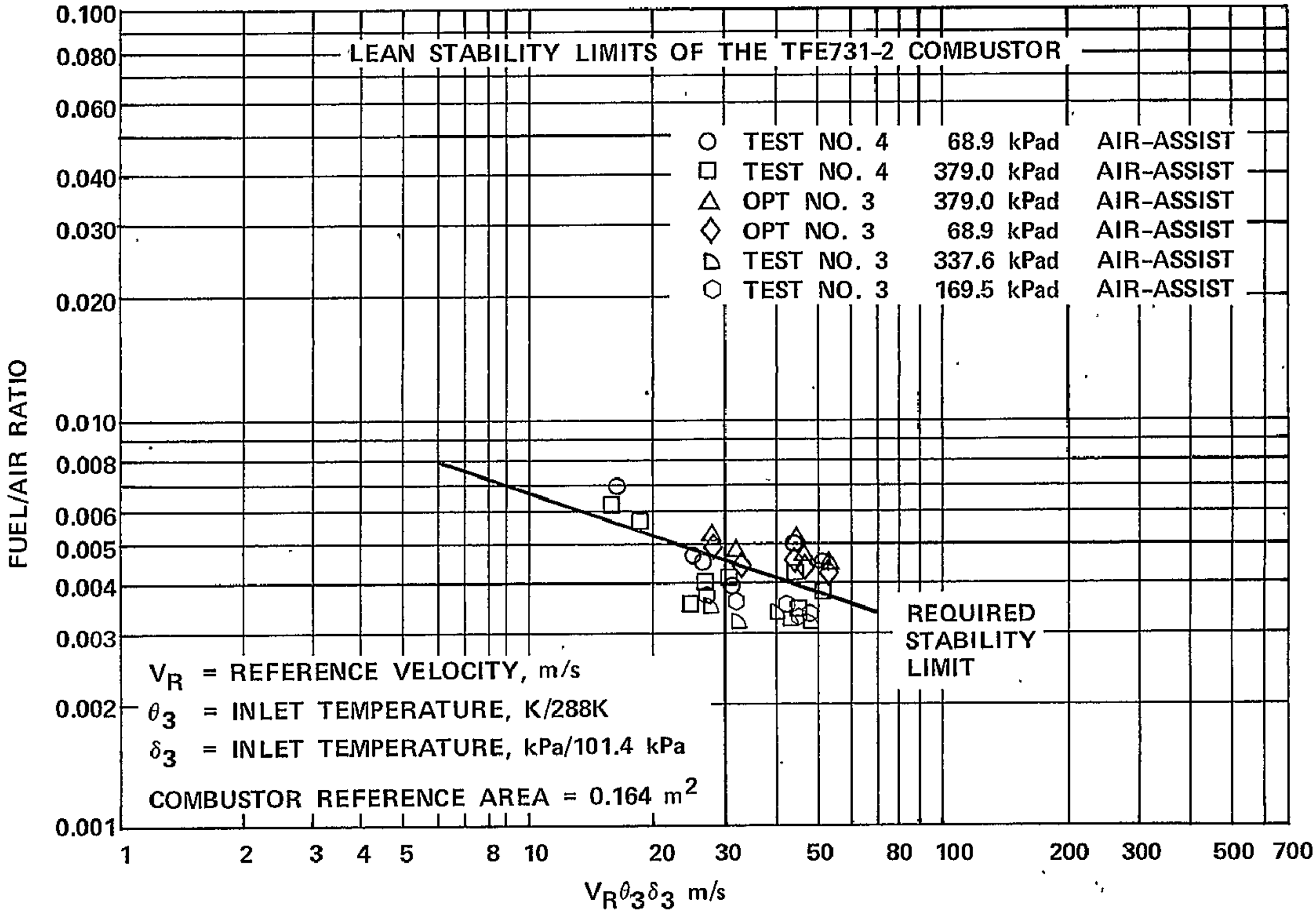


Figure 62. Lean Stability Limits - Concept 2.

The ignition and lean-stability limits for the Concept 3 combustor are illustrated in Figure 63. Although data points lie both above and below the production combustion system limits, it is considered that within-limits performance could be achieved with normal development efforts.

D.- ASSESSMENT OF EMISSION RESULTS

Significant reductions in combustion emission levels were attained during Phase II using engine-adaptable hardware. These results, while largely measured on a combustion rig, were in the case of Concept 2, substantiated by limited engine testing. While these reductions were achieved without sacrifice to combustor performance, both designs do involve an increase in the degree of complexity over the present production combustion system. An assessment of the emission results of each concept is discussed below.

1. Concept 2. - The first optimization test combustion system 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 Optimization Test No. 1 system was tested in the combustion rig and in a Model TFE731-2 development engine. Both results are presented.

As in Phase I for the combustion rig data, the LTO EPAP values were calculated by two methods. In the first, HC and CO emission indicies were uncorrected for all LTO power settings. NOx values were corrected to standard-day humidity conditions, and the climbout and takeoff NOx levels used a 0.5 exponent to correct for variations between rig and engine pressure levels at these points (see Chapter IIF3b, EPAP Adjustment Procedure and Calculations, for a description of the correction procedure).

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

- o HC and CO emission indicies at the climbout and takeoff point were corrected as the inverse function of the engine-to-rig combustor inlet pressure ratio.
- o The climbout and takeoff NOx values used a 0.29 and 0.35 exponent, respectively, on the pressure-correction term to correct measured rig values to engine conditions.

The latter pressure exponents were established during Phase I when combustion rig and engine tests were made on a production combustion system, and the emission values of the two tests compared. The adjustment procedure for the engine test data is also described in Chapter IIF3b.

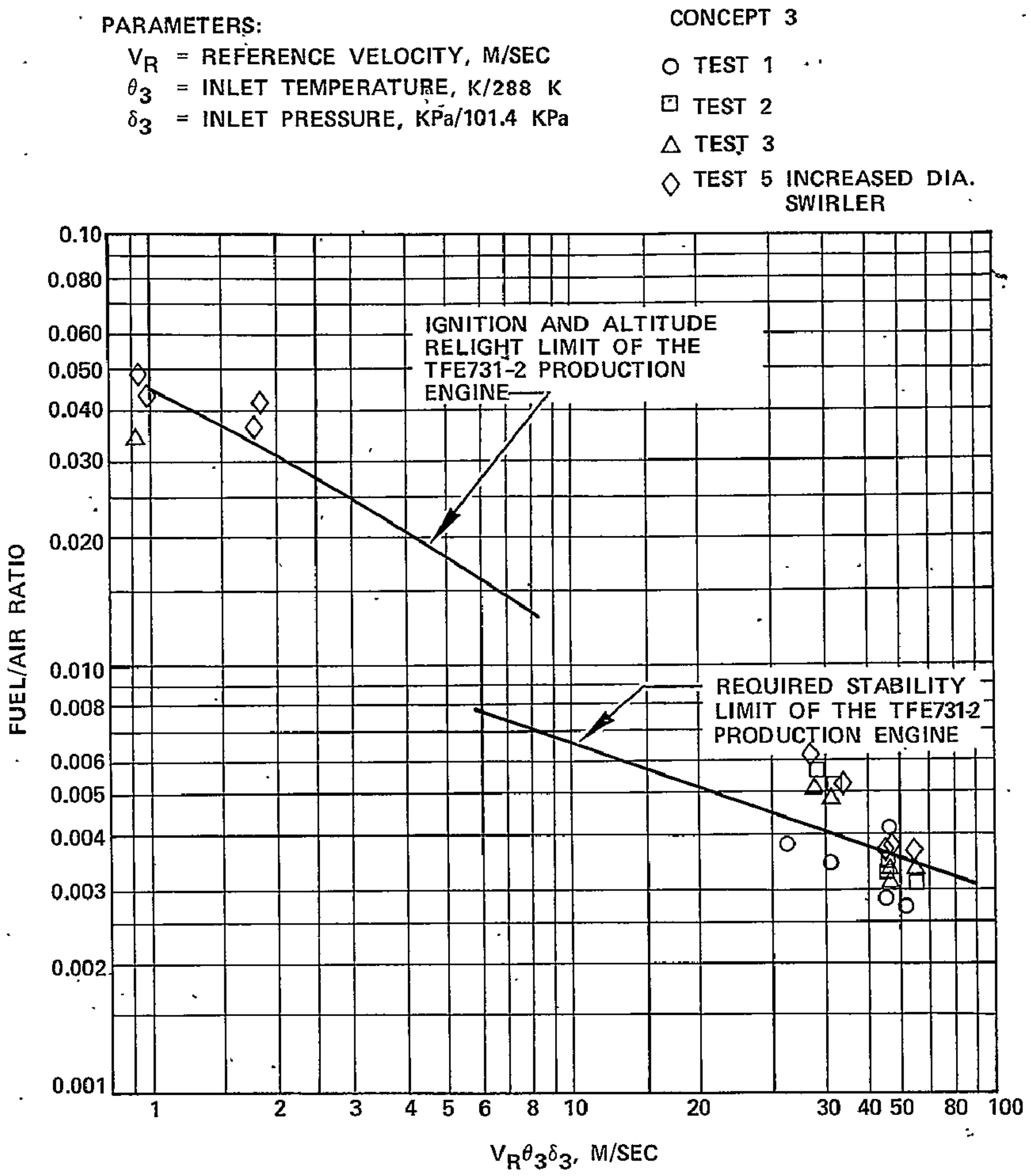


Figure 63. Concept 3 Ignition and Stability Limits.

The data presented represent the use of a variable-geometry combustion system with piloted airblast fuel injectors. At the taxi-idle and approach point, the valves that control airflow to the dome swirlers were closed and sealed. The fuel injectors used for this test were pressure atomizers. At the climbout and takeoff points, the valves were full open, and the fuel injectors were of an airblast design.

EPAP, lb/1000 lb thrust-hr/cycle

Pollutant	Program Goal	Rig Test: Correction Method #1	Rig Test: Correction Method #2	Engine Test
HC	1.6	1.01	1.01	0.96
CO	9.4	12.43	11.79	6.18
NO_x	3.7	3.90	3.33	3.89
Smoke	40.0	-	-	16.5

The engine test data show that the configuration meets the HC, CO, and smoke goals with some margin; and is close to meeting the NO_x goal. In comparing the engine and rig results, the EPAP values are misleading and it is necessary to show the individual emission indicies for both the rig and engine at all four of the LTO settings:

	HC g/kg fuel		CO g/kg fuel		NO_x g/kg fuel	
	Rig	Eng.	Rig	Eng.	Rig	Eng.
Taxi-Idle	3.88	3.32	42.95	21.78	2.58	3.05
Approach	0.12	0.71	4.13	2.24	5.31	6.28
Climbout	0.00	0.09	1.33	1.54	11.55*	10.30
Takeoff	0.00	0.09	0.73	0.78	13.14*	11.46

*Assumes a pressure correction exponent of 0.5.

The HC values at all power settings are close in value, with the exception of the approach point where the engine value is considerably higher. However, the lower engine value at taxi-idle compensates, and the overall HC EPAPs are almost identical. The same can be said for NO_x. The engine NO_x EI's are somewhat higher than the rig values at taxi-idle and approach, but are lower at the climbout and takeoff settings with the overall result being that the NO_x EPAPs are almost identical. The CO characteristics differ. In this case, the rig values at taxi-idle and approach are on the order of a factor of two greater than those of the engine, while at climbout and takeoff the values are almost the same.

These discrepancies are as yet unexplained. Previous engine-to-rig correlation tests had consistently demonstrated rig CO values considerably higher than those of the engine; however, rig HC levels were also on the order of 2.5 to 3 times the engine values, which is not the case in this instance. Additional engine and rig tests would be required to determine the cause of these variations, and this was beyond the scope of this Phase II program. For purposes of combustor design in Phase III, the engine test data will be considered valid. An attempt to resolve the discrepancy between engine and rig values will be made during Phase III testing.

2. Concept 3. - The low emission levels demonstrated in Phase I with an external premix/prevaporizing system were achieved in Phase II with a design more compatible with the TFE731 engine envelope. The LTO cycle EPAP values of Modification No. 3 of Phase I and of Refinement Test No. 5 of Phase II are compared below. The Refinement Test No. 5 results were adjusted by the two different methods previously described.

EPAP, lb/1000 lb thrust-hr/cycle

		Concept 3, Phase I Modification 3	Concept 3, Phase II Refinement Test 5	
Pollutant	Program Goal	Method 2	Method 1	Method 2
HC	1.6	0.5	0.9	0.6
CO	9.4	8.3	10.4	7.6
NO_x	3.7	2.4	2.9	2.6

The Phase II results were obtained with 413 kPa air-assist differential pressure at taxi-idle, a premix fuel flow at approach of 1 percent of the total, and zero length premixing at climbout and takeoff. The SAE smoke number was below measurable limits at the climbout and takeoff conditions (sampled at 414 kPa pressure), and was 14 at the approach condition with no premix fuel flow, measured at actual engine pressure (Test No. 4 configuration).

It is estimated that fuel staging at the approach condition, or even lower power settings, will be necessary to meet the required engine acceleration times. The Refinement Test No. 5 configuration used 1 percent of the total fuel flow for the premix (main combustion) zone during the approach operation in order to achieve low values of HC and CO emissions while maintaining fuel flow in the main combustion-zone manifold to reduce engine acceleration time due to manifold filling. However, a premix fuel flow of 1 percent at approach may be below the minimum practical engine fuel flow, and would not allow staging at power settings below approach. Therefore, emphasis in Phase III will be placed on improving the combustion efficiency with high premix fuel flows at approach by modifying the mixedness and increasing the residence time of the main combustion zone.

The results of Test No. 4 indicated that low emission levels could be achieved with pressure-atomizing nozzles at taxi-idle. Therefore, airblast nozzles with pressure-atomizer pilot nozzles will be tested in Phase III in order to diminish or eliminate the need for air assist.

Test No. 5 demonstrated that the emission goals could be achieved with little premixing of the main zone fuel and air. Thus, the premix annulus, which added greatly to the cost and complexity of the combustor, will be eliminated for Phase III, making Concept 3 essentially a staged combustor, rather than a premixing/prevaporizing combustor.

E.- CONTROL SYSTEM DEVELOPMENT

During Phase II, control activities involved determining the requirements for operation of the Concept 2 combustion system. This task was divided into two tasks: (a) the scheduling of fuel to the fuel nozzles, and (b) the activation of the variable-geometry hardware. As the development of Concept 2 produced changes in these areas, the control requirements were also changed. The configuration resulting from the Phase II study to proceed into Phase III utilizes piloted airblast fuel injectors and two-position air-control valves (full open and closed) to meter the air to the swirlers. The control requirements for each of these areas will be discussed below.

1. Fuel Scheduling. - The present production combustion system of the Model TFE731-2 Engine has an electronic fuel control that varies the fuel-flow rate. Fuel leaves the fuel control and enters a flow-divider valve where it is split. At low fuel flows, all of the fuel is directed through the small, primary circuit of the dual-orifice pressure atomizers. As the fuel-flow rate is increased, a point is reached at which the flow-divider valve opens and fuel then flows through both circuits. This type of design allows for the required fuel atomization during ignition and

low-power operation, and a relatively low pump pressure at the maximum flow conditions (takeoff and transients). The Concept 2 fuel delivery system is compatible with the existing fuel control/flow-divider valve installation. Only the pilot nozzles are fueled at the low-power points; and as the engine accelerates, the airblast system phases in so that at takeoff the majority of the fuel is flowing through the airblast part of the nozzles. The existing flow divider is adjustable, and the optimum point for phasing in the airblast nozzles can be determined during testing.

2. Variable-Geometry Actuation. - The valves of the variable-geometry system were connected through linkages to a unison ring. During Phase II, to actuate the valves, the ring was moved by lab hardware that consisted of an electric motor driving a worm gear-shaft arrangement. This system is not compatible with engine installation, and an electrohydraulic actuator has been chosen. The actuator identified for Phase III is an existing item, and is used to position compressor inlet guide vanes on the AiResearch Model ATF3 Turbofan Engine. The system can be manually activated by a switch on the test panel, as in rig checkout testing, or it can be connected to the engine electronic fuel control and made to actuate at a specified engine speed (or other specific engine parameters).

CHAPTER IV

CONCLUDING REMARKS

The results contained in this report document the activity conducted under the second phase of an intended three-phase program entitled Pollution Reduction Technology Program for Small Jet Aircraft Engines (Class T1). The overall objective of this program is to identify, develop, and demonstrate techniques capable of reducing emissions of unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke to levels below the standards proposed for implementation in 1979 by the Environmental Protection Agency. The combustion system from the AiResearch TFE731-2 Turbofan Engine is the baseline design for the program effort. The constraints placed upon the designs are that emissions reductions be obtained with no deterioration in combustion performance or durability levels, and with no changes to the engine envelope.

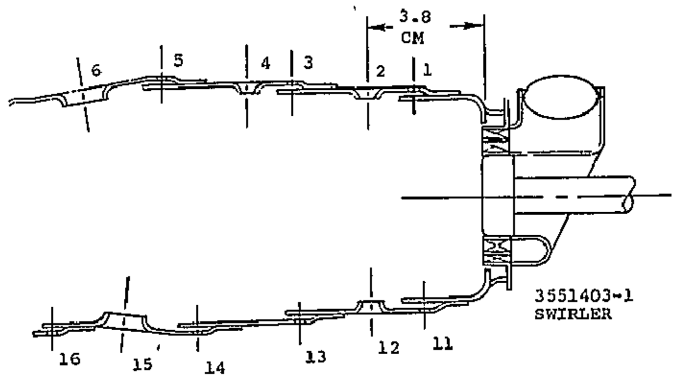
The Phase I program identified three conceptual approaches that involved increasing degrees of developmental complexity towards meeting the emissions goals. These approaches included advanced modifications to the existing TPE731-2 combustion system, an air-assisted/airblast combustion system, and a premix/prevaporization combustion system, identified as Concepts 1, 2, and 3, respectively. Combustion rig screening testing was conducted in Phase I to narrow down the candidate approaches to the best two. The Concept 2 airblast system and Concept 3 premix/prevaporization system were chosen to undergo further combustion rig development in Phase II. Phase I testing revealed that for Concept 2 at least two-position variable airflow to the fuel nozzle air swirlers was necessary to meet all emissions levels.

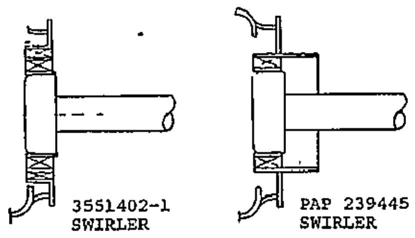
The purpose of Phase II testing was to develop the selected combustion systems through iterative rig testing to obtain combustion hardware, operation and performance that were compatible with the TFE731-2 Engine. In addition, two engine tests with rig-adapted hardware were provisioned for the purpose of obtaining engine-to-test rig emissions correlations. During Phase II one combustion system, the Concept 2 air-assisted/airblast system, was identified as having the most potential for meeting the program goals in a time-effective manner in that it would require the least amount of development to ensure engine geometric and operational compatibility. The development of the variable-airflow system continued in Phase II. Test results indicated that all emissions are close to the program goals.

The Phase III program, which has recently been contracted, will incorporate the Concept 2 airblast combustion system with variable-airflow air swirlers into a TFE731-2 Engine. The testing will entail engine evaluation of emissions of the EPA landing-takeoff points and selected intermediate points, as well as evaluation of acceleration/deceleration characteristics of the engine. These tests will serve as the demonstration of the selected low-emission technology approach. In addition, combustion rig testing will continue in Phase III on the Concept 3 premix/prevaporization combustion system in an effort to further develop this promising technological concept.

APPENDIX A

COMBUSTOR HOLE PATTERNS





Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm²	Airflow, % total Configuration A	B	C	D	E	F	G	H
1	Cooling	174	0.267	9.7	4.6	6.6	7.0	5.9	4.9	4.6	6.8	6.4
2	Plunged	40	0.635	12.7	6.2	9.0	9.5	8.0	6.5	6.2	9.2	8.6
3	Cooling	180	0.206	6.0	2.6	3.9	4.1	3.4	2.8	2.6	4.0	3.7
4	Plunged	80	0.554	19.3	8.5	13.0	13.7	11.4	9.1	8.5	13.3	12.4
5	Cooling	180	0.160	3.6	1.3	2.2	2.3	1.9	1.4	1.3	2.2	2.0
6	Plunged	40	0.932	27.3	11.4	17.5	18.5	15.3	12.2	11.4	18.0	16.6

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm²	Airflow, % total Configuration A	B	C	D	E	F	G	H
11	Cooling	120	0.267	6.7	2.7	4.0	4.2	3.5	2.9	2.7	4.1	3.8
12	Plunged	40	0.635	12.7	5.7	8.3	8.7	7.4	6.0	5.7	8.5	7.9
13	Cooling	120	0.206	4.0	1.6	2.4	2.6	2.1	1.7	1.6	2.5	2.3
14	Cooling	120	0.160	2.4	1.0	1.5	1.5	1.3	1.0	1.0	1.5	1.4
15	Plunged	40	0.932	27.3	13.2	18.8	19.7	16.8	14.0	13.2	19.2	18.0
16	Cooling	120	0.160	2.4	1.0	1.5	1.6	1.4	1.1	1.0	1.6	1.5

A 3551402-1 Swirlers, 80. cm², 35.2% Airflow, Airblast Nozzles, 8.7 cm², 3.5% Airflow

B 3551403-1 Swirlers, closed 8.6 cm², 4.9% Airflow, Airblast Nozzles, 8.7 cm², 5.0% Airflow

C 3551403-1 Swirlers, sealed, Airblast Nozzles, 8.7 cm², 5.2% Airflow

D 3551403-1 Swirlers, 15° open, 19.8 cm², 15.7% Airflow, Airblast Nozzles, 8.7 cm², 4.6% Airflow

E 3551403-1 Swirlers, 30° open, 44.8 cm², 3.10% Airflow, Airblast Nozzles, 8.7 cm², 4.0% Airflow

F 3551403-1 Swirlers, 90° open, 80 cm², 35.2% Airflow, Airblast Nozzles, 8.7 cm², 3.5% Airflow

G 3551403-1 Swirlers, sealed, Pressure Atomizers, 13.5 cm², 7.9% Airflow

H PAP239445 Swirlers, 16.8 cm², 9.3% Airflow, Airblast Nozzles, 8.7 cm², 4.8% Airflow

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

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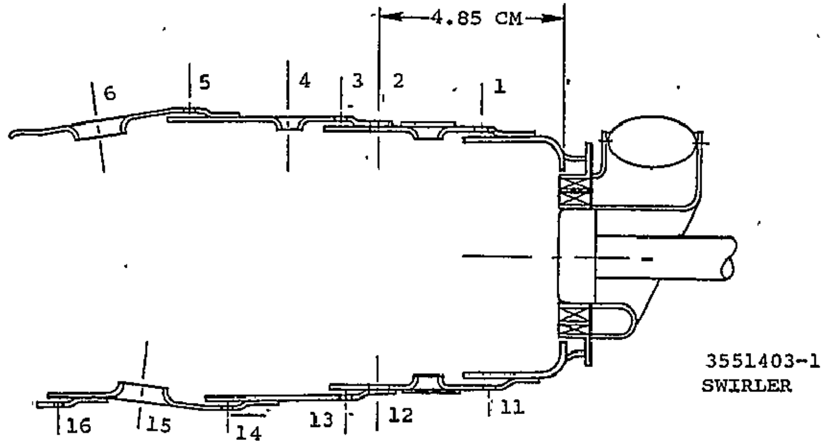


Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configuration A	B	C	D
1	Cooling	174	0.267	9.7	7.0	6.8	4.6	6.6
2	Plunged*	40	0.635	12.7	9.5	9.2	6.2	9.0
3	Cooling	180	0.206	6.0	4.1	4.0	2.6	3.9
4	Plunged	80	0.554	19.3	13.7	13.3	8.5	13.0
5	Cooling	180	0.160	3.6	2.3	2.2	1.3	2.2
6	Plunged	40	0.932	27.3	18.5	18.0	11.4	17.5

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configuration A	B	C	D
11	Cooling	120	0.267	6.7	4.2	4.1	2.7	4.0
12	Plunged*	40	0.635	12.7	8.7	8.5	5.7	8.3
13	Cooling	120	0.206	4.0	2.6	2.5	1.6	2.4
14	Cooling	120	0.160	2.4	1.5	1.5	1.0	1.5
15	Plunged	40	0.932	27.3	19.7	19.2	13.2	18.8
16	Cooling	120	0.160	2.4	1.6	1.6	1.0	1.5

A 3551403-1 Swirlers, sealed, Airblast Nozzles, 8.7 cm^2, 5.2% Airflow

B 3551403-1 Swirlers, sealed, Pressure Atomizer, 13.5 cm^2, 7.9% Airflow

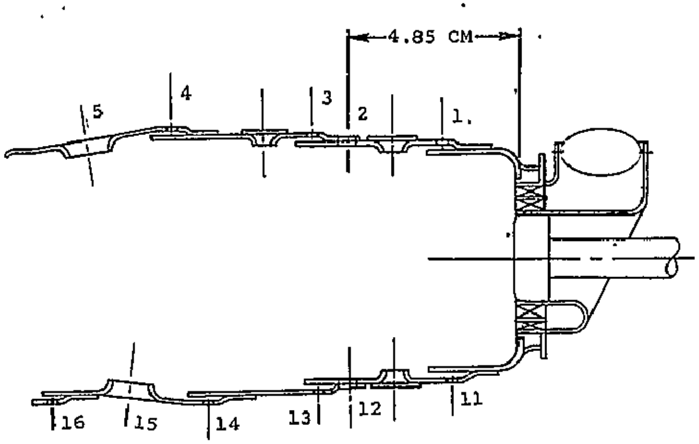
C 3551403-1 Swirlers, 90 open, 80 cm^2 35.2% Airflow, Airblast Nozzles, 8.7 cm^2, 3.5%

D 3551403-1 Swirlers, closed, 8.6 cm^2, 4.9% Airflow, Airblast Nozzles, 8.7 cm^2, 5.0%

*Orifice through 2.0 mm wall

Modifications: (Refer to Test 1)
1. Inner and outer primary orifices moved 1.0 cm downstream.

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



3551403-1
SWIRLER

Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configuration A	B	C	D	E
1	Cooling	174	0.267	9.7	7.5	5.0	7.3	8.0	--
2	Plunged	40	0.635	12.7	10.2	6.7	9.9	10.8	12.5
3	Cooling	180	0.206	6.0	4.4	2.8	4.3	4.7	5.5
4	Cooling	180	0.160	3.6	2.6	1.6	2.5	2.8	3.2
5	Plunged	40	0.932	27.3	20.7	13.1	20.1	22.1	25.6

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configuration A	B	C	D	E
11	Cooling	120	0.267	6.7	4.6	3.0	4.5	4.9	--
12	Plunged	40	0.635	12.7	9.6	6.3	9.3	10.2	11.7
13	Cooling	120	0.206	4.0	2.8	1.8	2.7	3.0	3.5
14	Cooling	120	0.160	2.4	1.7	1.1	1.7	1.8	2.1
15	Plunged	40	0.932	27.3	21.6	14.6	20.9	22.8	26.0
16	Cooling	120	0.160	2.4	1.8	1.2	1.7	1.9	2.2

A 3551403-1 Swirler, closed, 8.6 cm^2, 5.5% Airflow, Airblast Nozzles, 8.7 cm^2, 5.6% Airflow
B 3551403-1 Swirler, 90° open, 80 cm^2, 37.6% Airflow, Airblast Nozzles, 8.7 cm^2, 4.1% Airflow
C 3551403-1 Swirler, closed, 8.6 cm^2, 5.4% Airflow, Pressure Atomizers, 13.5 cm^2, 8.5% Airflow
D 3551403-1 Swirler, sealed, Airblast Nozzles, 8.7 cm^2, 5.9% Airflow
E 3551403-1 Swirler, sealed, Airblast Nozzles, 8.7 cm^2, 6.6% Airflow, Primary Cooling Blocked

Modifications: (Refer to Test 2)
1. Intermediate row of orifice on outer liner removed.

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

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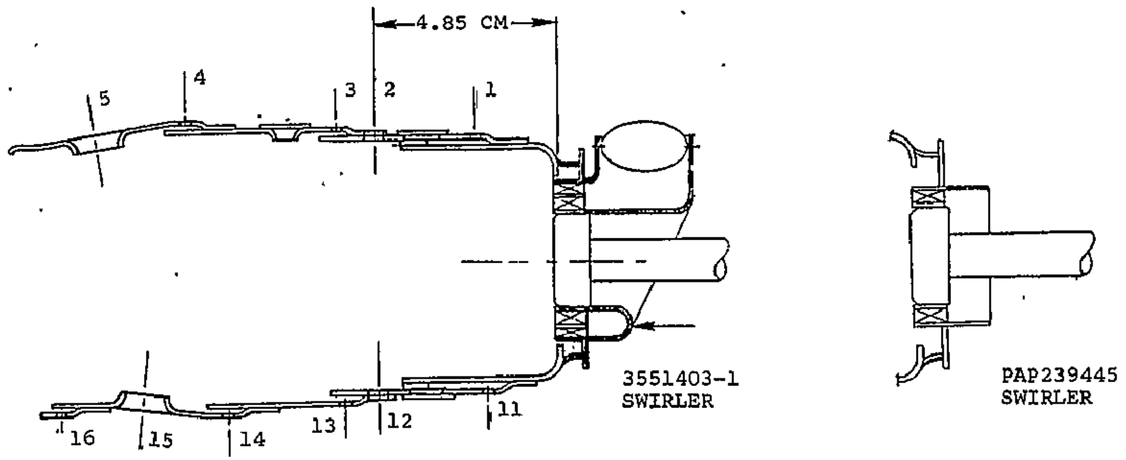


Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configur-ation A	B
1	Cooling	174	0.267	9.7	8.0	7.2
2	Plunged	40	0.635	12.7	10.8	9.7
3	Cooling	180	0.206	6.0	4.7	4.2
4	Cooling	180	0.160	3.6	2.8	2.4
5	Plunged	40	0.932	27.3	22.1	19.6

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % Total Configur-ation A	B
11	Cooling	120	0.267	6.7	4.6	4.4
12	Plunged	40	0.635	12.7	9.6	9.1
13	Cooling	120	0.206	9.0	2.8	2.7
14	Cooling	120	0.160	2.4	1.7	1.6
15	Plunged	40	0.932	27.3	21.6	20.5
16	Cooling	120	0.160	2.4	1.8	1.7

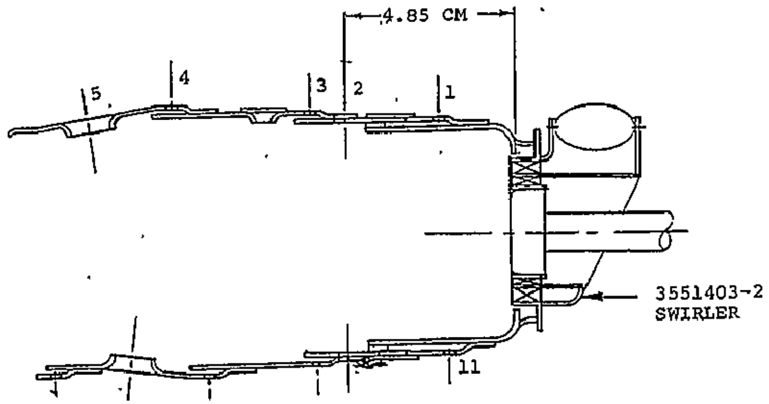
A 3551403-1 Swirlers, sealed, Airblast Nozzles, 8.7 cm^2, 5.9% Airflow

B 3551403-1 Swirlers, 16.8 cm^2, 10.4% Airflow, Airblast Nozzles, 8.7 cm^2, 5.4% Airflow

Modifications: (Refer to Test 3)

1. Primary cooling skirts extended 1.1 cm.

Figure A-4. Combustor Orifice Pattern Concept 2, Test 4



Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total configuration A	B	C	D	E
1	Cooling	174	0.267	9.7	7.2	6.8	5.2	5.1	5.0
2	Plunged	40	0.635	12.7	9.8	9.2	7.1	6.9	6.7
3	Cooling	180	0.206	6.0	4.2	4.0	3.0	2.9	2.8
4	Cooling	180	0.160	3.6	2.5	2.3	1.7	1.6	1.6
5	Plunged	40	0.932	27.3	19.7	18.6	13.9	13.5	13.1

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total configuration A	B	C	D	E
11	Cooling	120	0.267	6.7	4.4	4.2	3.2	3.1	3.0
12	Plunged	40	0.635	12.7	9.1	8.7	6.7	6.5	6.3
13	Cooling	120	0.206	4.0	2.7	2.6	1.9	1.9	1.8
14	Cooling	120	0.160	2.4	1.6	1.5	1.2	1.1	1.1
15	Plunged	40	0.932	27.3	20.6	19.6	15.3	15.0	14.6
16	Cooling	120	0.160	2.4	1.7	1.6	1.2	1.2	1.2

A 3551403-2 Swirlers, sealed, 15.9 cm^2, 9.8% Airflow, Airblast Nozzles, 8.7 cm^2, 5.4% Airflow

B 3551403-2 Swirlers, closed, 24.5 cm^2, 14.5% Airflow, Airblast Nozzles, 8.7 cm^2, 5.2% Airflow

C 3551403-2 Swirlers, 30° open, 70.3 cm^2, 34.2% Airflow, Airblast Nozzles, 8.7 cm^2, 4.3% Airflow

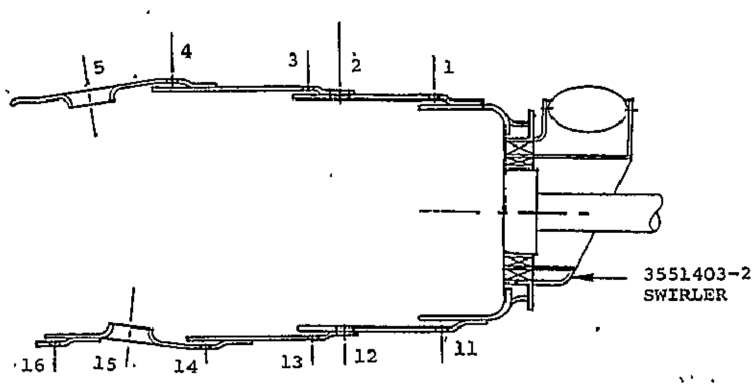
D 3551403-2 Swirlers, 60° open, 75 cm^2, 35.8% Airflow, Airblast Nozzles, 8.7 cm^2, 4.2% Airflow

E 3551403-2 Swirlers, 90° open, 80 cm^2, 37.6% Airflow, Airblast Nozzles, 8.7 cm^2, 4.1% Airflow

Modifications: (Refer to Test 4)

1. Inner swirler reduced in airflow and made independent of butterfly valve. Outer swirler made correspondingly larger

Figure A-5. Combustor Orifice Pattern, Concept 2, Test 5.



Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	A	B	C	D	E	F	G
					Airflow, % Total Configuration						
1	Cooling	174	0.267	9.7	7.2	6.8	5.2	5.1	5.0	7.0	4.9
2	Plunged	40	0.635	12.7	9.8	9.3	7.1	6.9	6.7	9.5	6.6
3	Cooling	180	0.206	6.0	4.2	4.0	3.0	2.9	2.8	4.1	2.8
4	Cooling	180	0.160	3.6	2.3	2.3	1.7	1.6	1.6	2.2	1.6
5	Plunged	40	0.932	27.3	19.7	18.6	13.9	13.5	13.1	19.1	12.4

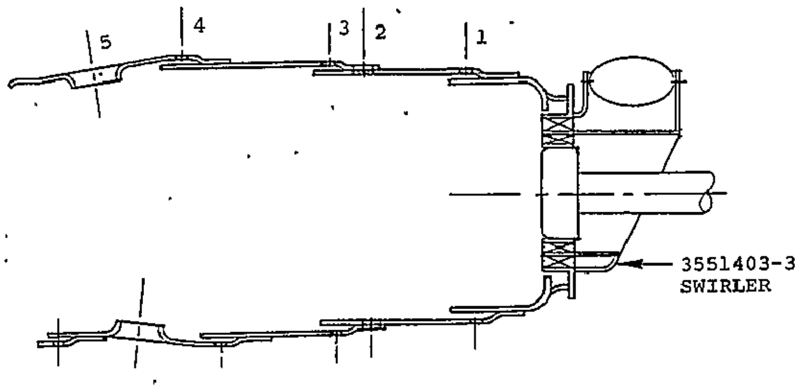
Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	A	B	C	D	E	F	G
					Airflow, % Total Configuration						
11	Cooling	120	0.267	6.7	4.4	4.2	3.2	3.1	3.0	4.3	3.0
12	Plunged	40	0.635	12.7	9.1	8.7	6.7	6.5	6.3	8.8	6.2
13	Cooling	120	0.206	4.0	2.7	2.6	1.9	1.9	1.8	2.6	1.7
14	Cooling	120	0.160	2.4	1.6	1.5	1.2	1.1	1.1	1.6	1.1
15	Plunged	40	0.932	27.3	20.6	19.6	15.3	15.0	14.6	19.9	14.3
16	Cooling	120	0.160	2.4	1.7	1.6	1.2	1.2	1.2	1.6	1.2

A 3551403-2 Swirlers, sealed, 15.9 cm^2, 9.8% Airflow, Airblast Nozzles, 8.7 cm^2, 5.4% Airflow
B 3551403-2 Swirlers, closed, 24.5 cm^2, 14.5% Airflow, Airblast Nozzles, 8.7 cm^2, 5.2% Airflow
C 3551403-2 Swirlers, 30° open, 70.3 cm^2, 34.2% Airflow, Airblast Nozzles, 8.7 cm^2, 4.3% Airflow
D 3551403-2 Swirlers, 60° open, 75 cm^2, 35.8% Airflow, Airblast Nozzles, 8.7 cm^2, 4.2% Airflow
E 3551403-2 Swirlers, 90° open, 80 cm^2, 37.6% Airflow, Airblast Nozzles, 8.7 cm^2, 4.1% Airflow
F 3551403-2 Swirlers, sealed, 15.9 cm^2, 9.6% Airflow, Pressure Atomizer, 8.7 cm^2, 8.2% Airflow
G 3551403-2 Swirlers, 90° open, 80 cm^2, 36.8% Airflow, Pressure Atomizer, 8.7 cm^2, 5.9% Airflow

Modifications: (Refer to Test 5)
1. Primary cooling skirts returned to original (Test 1) length

Figure A-6. Combustor Orifice Pattern Concept 2 Optimization Test 1.



Outside diameter							Inside diameter						
Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total configuration A	B	Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total configuration A	B
1	Cooling	174	0.267	9.7	7.6	5.2	11	Cooling	120	0.267	6.7	4.7	3.2
2	Plunged	40	0.635	12.7	10.3	7.0	12	Plunged	40	0.635	12.7	9.7	6.6
3	Cooling	180	0.206	6.0	4.5	3.0	13	Cooling	120	0.206	4.0	2.9	1.9
4	Cooling	180	0.160	3.6	2.6	1.7	14	Cooling	120	0.160	2.4	1.7	1.1
5	Plunged	40	0.932	27.3	21.0	13.9	15	Plunged	40	0.932	27.3	21.8	15.3
							16	Cooling	120	0.160	2.4	1.8	1.2

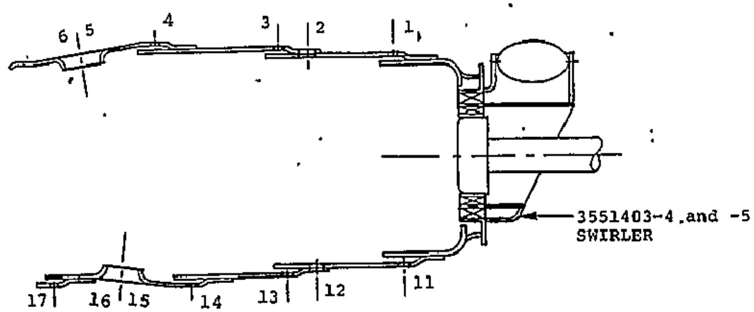
A 3551403-3 Swirlers, sealed, 6.9 cm^2, 4.4% Airflow, Airblast Nozzles, 8.7 cm^2, 5.6% Airflow

B 3551403-3 Swirlers, 90° open, 71 cm^2, 34.4% Airflow, Airblast Nozzles, 8.7 cm^2, 4.3% Airflow

Modifications: (Refer to Optimization Test 1)

1. Inner swirler reduced in area by 63%

Figure A-7. Combustor Orifice Pattern, Concept 2, Optimization Test 2.



Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm2	Airflow, % total Configuration A	B	C	D	E	F	G
1	Cooling	174	0.267	9.7	7.4	5.1	7.0	5.3	5.4	5.3	4.0
2	Plunged	40	0.635	12.7	10.0	6.9	9.5	7.2	7.3	7.2	5.4
3	Cooling	180	0.206	6.0	4.3	2.9	4.1	3.1	3.1	3.1	2.2
4	Cooling	180	0.160	3.6	2.5	1.6	2.4	1.8	1.8	1.8	1.2
5	Plunged	40	0.932	27.3	20.3	13.5	19.2	13.4	13.7	13.0	9.5
6	Flush	40	1.077	36.4	--	--	--	13.1	13.4	13.0	9.5

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm2	Airflow, % total configuration A	B	C	D	E	F	G
11	Cooling	120	0.267	6.7	4.5	3.1	4.3	2.9	2.9	2.9	2.2
12	Plunged	40	0.635	12.7	9.4	6.5	8.9	6.2	6.3	6.2	4.6
13	Cooling	120	0.206	4.0	2.8	1.9	2.6	1.8	1.9	1.8	1.3
14	Cooling	120	0.160	2.4	1.7	1.1	1.6	1.1	1.1	1.1	0.8
15	Plunged	40	0.932	27.3	21.2	14.9	20.2	14.3	14.6	14.3	10.8
16	Flush	40	1.077	36.4	--	--	--	13.6	13.8	13.5	10.5
17	Cooling	120	0.160	2.4	1.8	1.2	1.7	1.2	1.2	1.2	0.9

A 3551403-4 Swirlers, sealed, 11.5 cm^2, 7.3% Airflow, Airblast Nozzles, 8.7 cm^2, 5.5% Airflow

B 3551403-4 Swirlers, 90° open, 75.6 cm^2, 36.1% Airflow, Airblast Nozzles, 8.7 cm^2, 4.2% Airflow

C 3551403-5 Swirlers, 90° open, 19.6 cm^2, 11.8% Airflow, Airblast Nozzles, 8.7 cm^2, 5.3% Airflow

D 3551403-5 Swirlers, 90° open, 19.6 cm^2, 9.4% Airflow, Airblast Nozzles, 8.7 cm^2, 4.2% Airflow, Additional Dilution Orifices

E 3551403-2 Swirlers, sealed, 15.9 cm^2, 7.8% Airflow, Airblast Nozzles, 8.7 cm^2, 4.3% Airflow, Additional Dilution Orifices

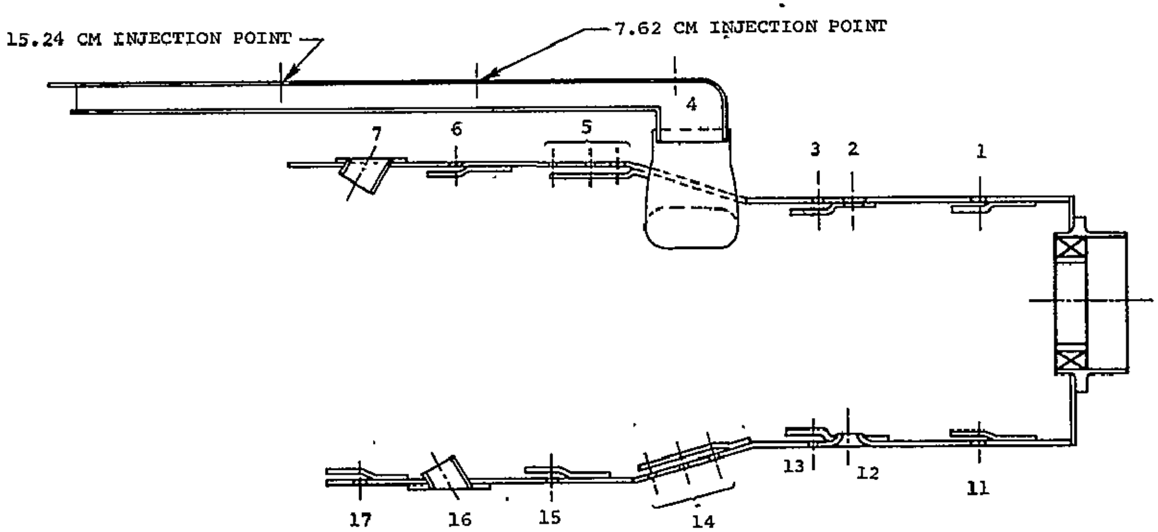
F 3551403-2 Swirlers, sealed, 15.9 cm^2, 7.7% Airflow, Pressure Atomizer, 13.5 cm^2, 6.5% Airflow, Additional Dilution Added

G 3551403-2 Swirlers, 90° open, 80 cm^2, 32.3% Airflow, Airblast Nozzles, 8.7 cm^2, 3.5% Airflow, Additional Dilution Added

Modifications: (Refer to Optimization Test 1)

1. Inner swirler reduced in area by 27.5% for Swirler 3551403-4
2. Inner swirler blocked off and outer swirler reduced in area by 69% for Swirler 3551403-5
3. Additional dilution orifices added for configurations D, E, F, and G

Figure A-8. Combustor Orifice Pattern, Concept 2, Optimization Test 3



Outside diameter						Inside diameter					
Row Number	Type of Orifices	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total	Row Number	Type of Orifices	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total
1	Cooling	180	0.204	5.91	3.3	11	Cooling	120	0.248	5.78	2.4
2	Plunged	80	0.298	5.60	3.2	12	Plunged	40	0.351	3.86	1.7
3	Cooling	180	0.143	2.91	1.6	13	Cooling	120	0.174	2.85	1.2
4	Premix air	40	--	48.84	22.7	14	Cooling	100/row	0.156	5.75	2.3
5	Cooling	100/row	0.154	5.56	2.5	15	Cooling	120	0.235	5.20	2.1
6	Cooling	180	0.154	3.34	2.7	16	Tubes	80	0.724	32.93	16.3
7	Tubes	80	0.914	52.5	24.0	17	Cooling	120	0.204	3.94	1.8

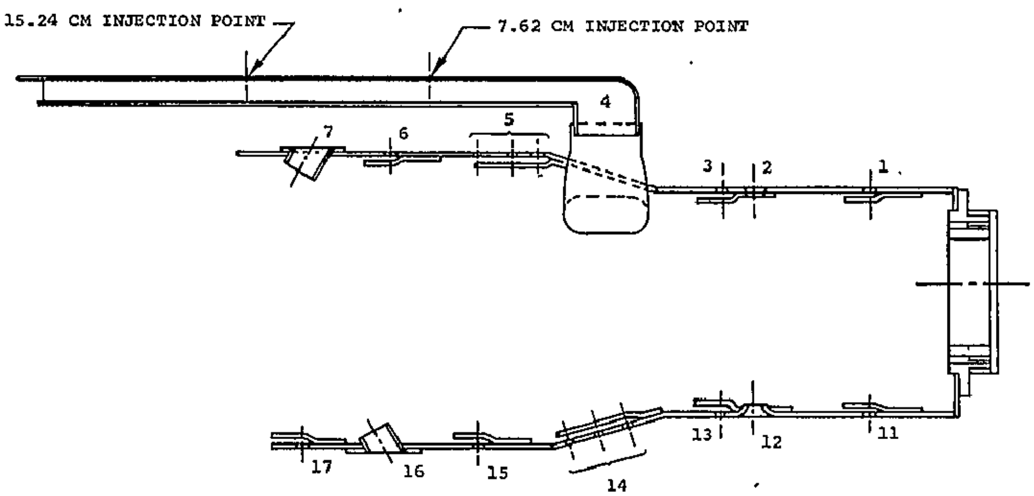
Swirlers - 20 axial P/N 3551447, Area = 17.3 cm^2, Airflow = 8.0%

Airblast Pilot Nozzles, DLN P/N 36233, Airblast Airflow = 2.9% maximum area

Area = 7.6 cm^2 = 2.1% nominal area

Tested at both 7.62 and 15.24 cm premix length injection points.

Figure A-9. Combustor Orifice Pattern, Concept 3, Test 1



Outside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total
1	Cooling	180	0.204	5.91	3.3
2	Plunged	80	0.298	5.60	3.2
3	Cooling	180	0.143	2.91	1.6
4	Premix air	40	--	48.84	22.7
5	Cooling	100/row	0.154	5.56	2.5
6	Cooling	180	0.154	3.34	2.7
7	Tubes	80	0.914	52.5	24.0

Inside diameter

Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area cm^2	Airflow, % total
11	Cooling	120	0.248	5.78	2.4
12	Plunged	40	0.351	3.86	1.7
13	Cooling	120	0.174	2.85	1.2
14	Cooling	100/row	0.156	5.75	2.3
15	Cooling	120	0.235	5.20	2.1
16	Tubes	80	0.724	32.93	16.3
17	Cooling	120	0.204	3.84	1.8

Swirlers - 20 Radial Inflow P/N 3551448-1, Area = 17.3 cm^2, Airflow = 8.0%

Airblast Pilot Nozzles, DLN P/N 36233, Airblast Airflow = 2.9% maximum area

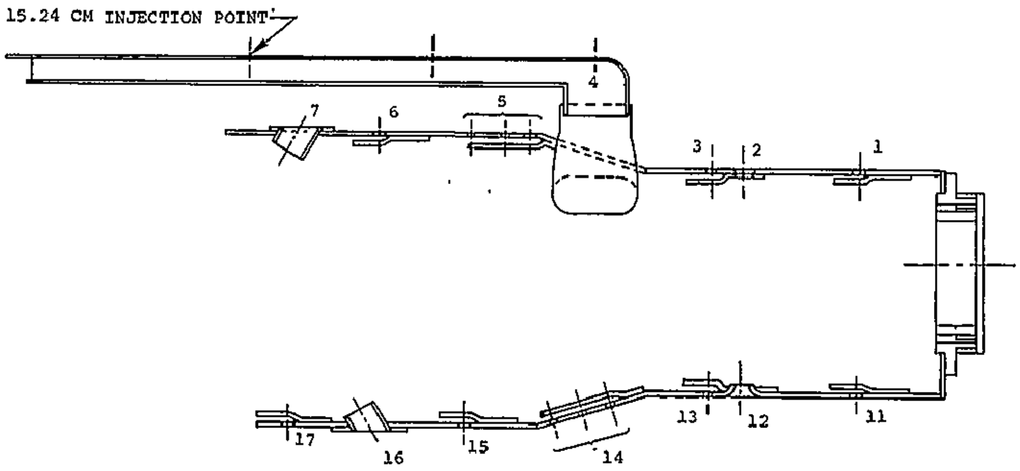
Area = 7.6 cm^2 = 2.1% nominal area

Test at both 7.62 and 15.24 cm premix length injection points

Modification: (Refer to Test 1)

1. Swirler changed to radial inflow with same area
2. Premix tubes shortened by 5.0 mm

Figure A-10. Combustor Orifice Pattern, Concept 3, Test 2



Outside diameter						Inside diameter					
Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm²	Airflow, % total	Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area cm²	Airflow, % total
1	Cooling	180	0.204	5.91	3.2	11	Cooling	120	0.248	5.78	2.3
2	Plunged	80	0.298	5.60	3.05	12	Plunged	40	0.351	3.86	1.6
3	Cooling	180	0.143	2.91	1.5	13	Cooling	120	0.174	2.85	1.1
4	Premix air	40	--	48.84	22.0	14	Cooling	100/row	0.156	5.75	2.1
5	Cooling	100/row	0.154	5.56	2.4	15	Cooling	120	0.235	5.20	1.9
6	Cooling	180	0.154	3.34	2.5	16	Tubes	80	0.724	32.93	15.3
7	Tubes	80	0.914	52.5	22.5	17	Cooling	120	0.204	3.94	1.7

Swirlers - 20 radial inflow, P/N 3551448-2, Area = 36.7 cm^2, Airflow = 12.9%

Airblast Pilot Nozzles, DLN P/N 36233, Area = 7.6 cm^2, Airblast Airflow = 2.8%

Tested at 15.24 cm premix length injection point

Modifications: (Refer to Test 1)

1. Swirler area increased 112%

Figure A-11. Combustor Orifice Pattern, Concept 3, Test 3.

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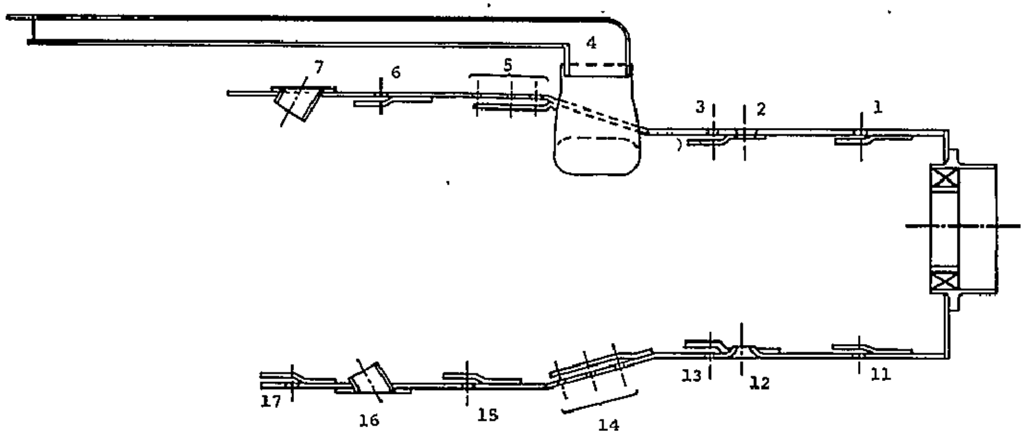


Outside diameter						Inside diameter					
Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total	Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total
1	Cooling	180	0.204	5.91	3.25	11	Cooling	120	0.248	5.78	2 35
2	Plunged	80	0.298	5.60	3.15	12	Plunged	40	0.351	3.86	1.65
3	Cooling	180	0.143	2.91	1.55	13	Cooling	120	0.174	2.85	1.2
4	Premix air	40	--	48.84	22.6	14	Cooling	100/row	0.156	5.75	2.1
5	Cooling	100/row	0.154	5.56	2.45	15	Cooling	120	0.235	5.20	2.05
6	Cooling	180	0.154	3.34	2.65	16	Tubes	80	0.724	32.93	16.0
7	Tubes	80	0.914	52.5	23.5	17	Cooling	120	0.204	3.94	1.75

Swirlers - 20 Axial, P/N 868787-2, Area = 32.3 cm^2, Airflow = 7.9%

Pressure Atomizers, Pilot Nozzles, Shroud Airflow = 4.5%

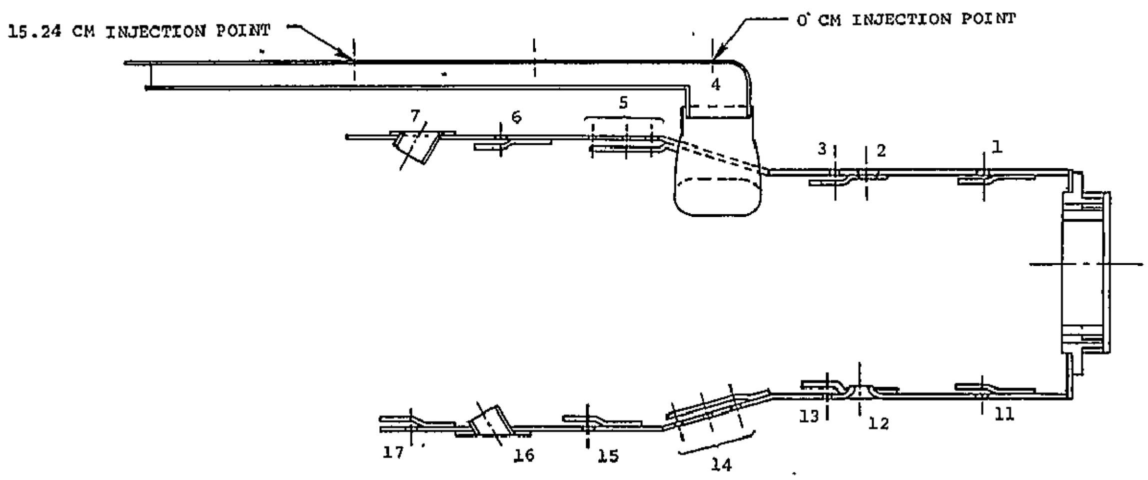
Tested with 0.68 flow number pilot nozzles, and 0.9 flow number premix nozzles; and with 0.9 flow number pilot nozzles, and 0.68 premix nozzles.

Modifications: (Refer to Test 3)

1. Pilot nozzles changed to pressure atomizers

2. Swirler changed to axial to accept atomizer nozzles

Figure A-12. Combustor Orifice Pattern, Concept 3, Test 4.



Outside diameter						Inside diameter					
Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total	Row Number	Type of Orifice	Number of Orifices	Diameter, cm	Total area, cm^2	Airflow, % total
1	Cooling	180	0.204	5.91	3.3	11	Cooling	120	0.248	5.78	2.4
2	Plunged	80	0.298	5.60	3.2	12	Plunged	40	0.351	3.86	1.7
3	Cooling	180	0.143	2.91	1.6	13	Cooling	120	0.174	2.85	1.2
4	Premix air	40	--	48.84	22.7	14	Cooling	100/row	0.156	5.75	2.3
5	Cooling	100/row	0.154	5.56	2.5	15	Cooling	120	0.235	5.20	2.1
6	Cooling	180	0.154	3.34	2.7	16	Tubes	80	0.724	32.93	16.3
7	Tubes	80	0.914	52.5	24.0	17	Cooling	120	0.204	3.94	1.8

A Swirlers - 20 Radial Inflow, P/N 3551448-4 and -5, Area = 17.3 cm^2, Airflow 8.0%

B Airblast Pilot Nozzles, DLN P/N 36233, Area = 7.6 cm^2, Airblast Airflow = 2.9%

Tested at both 0 and 15.24 cm premix length injection point with Swirler P/N 3551448-4

Tested at 15.24 cm length only with Swirler P/N 3551448-5

Modification: (Refer to Test 1)

1. Part 3551448-4 swirler has same flow area but discharge diameter increased 10%
2. Part 3551448-5 swirler has same flow area but slot to discharge area ratio changed to reduce swirl angle from 60° to 52°

Figure A-13. Combustor Orifice Pattern, Concept 3, Test 5.

APPENDIX B

EXPERIMENTAL TEST RESULTS

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CONCEPT NO. 2, REFINEMENT TEST NO. 1

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(February 26, 1977)																					
A-1A	4000	4.136	0.0093	0.0625	0.0625	*0000	644.6	4.203	11.387	0.061	0.292	0.01530	0.01615	3.29	2.922	0.836	6.956	99.858		33.3 kPa AA	Cruise
	4000	4.143	0.0269	0.0625	0.0625	*0000	645.8	4.155	11.562	0.057	0.292	0.01527	0.01594	3.25	4.100	0.582	6.921	99.852		278.9 kPa AA	
	5000	4.143	0.0098	0.0589	0.0589	*0000	665.9	4.133	12.004	0.058	0.292	0.01439	0.01512	3 09	3.220	0.501	7.067	99 880		38.3 kPa AA	Climb
	6300	4.067	0.0094	0.0228	0 0228	*0000	681.5	4.171	11.959	0.074	0.292	0.00568	0.00588	1.17	54.879	6.898	5.907	98.104		37 6 kPa AA, f/a = 0.006	
	6200	4.062	0.0095	0.0353	0.0353	*0000	683.8	4.153	12.030	0.047	0.317	0.00879	0.00900	1.83	22.068	1.209	7 062	99.375		37.6 kPa AA, f/a = 0.009	
	6100	4.029	0.0093	0.0470	0.0470	*0000	684.5	4.192	11.823	0.057	0.317	0.01182	0.01233	2.52	5.011	0.545	7.655	99.834		34.3 kPa AA, f/a = 0.012	Takeoff
	6000	4.089	0.0092	0.0606	0.0606	*0000	686.6	4.195	12.047	0.047	0.236	0.01500	0.01541	3.14	1.914	0.437	8.205	99.917		34.3 kPa AA	
	6000	4.058	0.0261	0.0606	0.0606	*0000	684.2	4.215	11.848	0.053	0.236	0.01512	0.01552	3.17	2.663	0.217	8.434	99.918		272.3 kPa AA	
(March 3, 1977)																					
A-1A	6000	3.995	0.0095	0.0607	0.0607	*0000	685.1	4.180	11.788	0.050	0.273	0.01539	0.01611	3.28	1.956	0.229	8.287	99.934		36.5 kPa AA	Takeoff
	6000	3.973	*00000	0.0607	0.0607	*0000	685.2	4.185	11.709	0.132	0.273	0.01547	0.01622	3.31	2.514	0.261	8.917	99.918			
(March 30, 1977)																					
A-1F	4090	4.000	0.0124	0.0623	0.0623	*0000	646.4	4.125	11.244	0.071	0.348	0.01578	0.01601	3.227	19.633	3.83	5.765	99.202		53.0 kPa AA	Cruise
	5090	4.050	0.0101	0.0591	0.0591	*0000	664.8	4.114	11.754	0.065	0 348	0 01478	0.01530	3.096	17.677	1.39	6.659	99.462		30.1 kPa AA	Climb
	6290	3.938	0.0098	0.0361	0.0361	*0000	678 3	4.174	11.474	0.083	0.348	0.00927	0.00952	1.894	52.027	7.493	5.898	98.125		27.8 kPa AA, f/a = 0.009	
	6190	3.984	0.0100	0.0474	0.0474	*0000	680.3	4.144	11.729	0.070	0.348	0.01205	0.01230	2.480	28.869	2.117	6.548	99.135		28.8 kPa AA, f/a = 0.012	
	6090	3.990	0.0103	0.0607	0.0607	*0000	682.3	4.107	11.905	0.064	0.348	0.01541	0.01571	3.188	12.041	0.524	7.399	99.671		32.4 kPa AA	Takeoff
	6091	4.029	0.0102	0.0626	0.0626	*0000	667.1	4.141	11 649	0.069	0.348	0.01574	0.01600	3.244	12.665	0.477	6.860	99.660		30 7 kPa AA, Phase I Cond.	
	3090	5.843	0.0127	0.0672	0.0672	*0000	503.5	5.214	10.137	0.089	0 348	0.01166	0.01168	2.292	56.816	17.208	3.374	97.154		34.85 kPa AA	Approach
(March 31, 1977)																					
A-1E	4030	3.995	0.0106	0.0623	0.0623	*0000	642.6	4.127	11.150	0.114	0.255	0.01580	0.01637	3.325	7.514	1.008	7.473	99.735		31.9 kPa AA	Cruise
	5030	4.028	0.0106	0.0591	0 0591	*0000	666.1	4.157	11.573	0.117	0 255	0.01487	0.01517	3.090	6.527	0.333	8.115	99.817		31.9 kPa AA	Climb
	6030	3.971	0.0107	0.0607	0.0607	*0000	682.2	4.130	11.764	0.114	0.255	0.01548	0.01579	3.215	5.765	0.340	8.755	99.835		33.5 kPa AA	Takeoff
	3030	5.886	0.0130	0.0672	0.0672	*0000	506.1	5.363	9.962	0.181	0.255	0.01157	0.01189	2.390	34.845	3.455	4.930	98.876		32.7 kPa AA	Approach
(April 12, 1977)																					
A-1B	2000	2.312	0.0047	0.0242	0.0242	*0000	369.3	2.029	7.494	0.340	0.174	0.01060	0.01066	1.42	127.162	331.124	0.873	67.964		46.5 kPa AA	Taxi-idle
	2100	2.322	0.0048	0.0320	0.0320	*0000	369.8	2.025	7.551	0.215	0.174	0.01394	0.01425	2.28	123.923	180.834	1.021	81.223		50.4 kPa AA, f/a = 0.014	
A-1D	2015	2.272	0.0046	0.0242	0.0242	*0000	371.3	2.027	7.415	0.195	0.273	0.01079	0.01068	1.53	128.358	275.067	0.867	72.853		46.8 kPa AA	
	3015	5.808	0.0052	0.0672	0.0672	*0000	505.7	5.313	9.904	0.146	0.273	0.01173	0.01230	2.47	18.978	10.244	4.860	98.655		5.7 kPa AA	[illegible]oach
(May 4, 1977)																					
A-1H	2001	2.344	0.0250	0.0242	0.0242	*0000	372.0	2.003	7.776	0.352	0.149	0 01046	0.01120	2.04	64.618	93.535	2.014	90.275		379.2 kPa AA	Taxi-idle
	2101	2.351	0.0250	0.0294	0.0294	*0000	372.4	2.006	7.788	0.300	0.149	0.01265	0.01323	2.49	59 635	58.846	2.251	93.435		379.2 kPa AA, f/a = 0.013	

CONCEPT NO. 2, REFINEMENT TEST NO. 1 (CONTD)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments
(May 6, 1977)																				
A-1C	2002	2.324	0.0257	0.0242	0.0242	*0000	371.5	2.016	7.629	0.413	0.180	0.01055	0.01125	1.87	72.997	176.967	1.667	82.760		369.2 kPa AA
	2102	2.320	0.0130	0.0242	0.0242	*0000	370.9	2.004	7.655	0.354	0.180	0.01057	0.01140	1.87	87.649	182.321	1.479	81.946		133.4 kPa AA Taxi-idle
	2202	2.321	0.0256	0.0294	0.0294	*0000	374.0	2.008	7.703	0.205	0.180	0.01281	0.01342	2.56	56.351	47.984	2.251	94.465		370.0 kPa AA, f/a=0.013
(May 13, 1977)																				
A-1G	2003	2.292	*00000	0.0242	0.0242	*0000	372.0	2.066	7.359	0.090	0.112	0.01069	0.01077	2.12	60.347	13.069	2.247	97.434		Taxi-idle
	2103	2.297	*00000	0.0294	0.0294	*0000	372.6	2.072	7.369	0.089	0.112	0.01294	0.01306	2.62	33.676	2.729	2.572	98.968		f/a = 0.013

CONCEPT NO. 2, REFINEMENT TEST NO. 2

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(May 25, 1977)																					
A-2B	2004	2.226	*00000	0.0242	0.0242	*0000	373.1	2.013	7.365	0.248	0.137	0.01102	0.01090	2.16	54.337	6.969	2.747	98.110		Pilot nozzles - pres. atomizer PAP239444	Taxi-idle
	2104	2.230	*00000	0.0294	0.0294	*0000	373.0	2.014	7.373	0.196	0.137	0.01333	0.01204	2.41	41.297	3.347	2.870	98.735		Pilot nozzles - pres. atomizer PAP239444, f/a = 0.013	
A-2A	2005	2.313	0.0245	0.0242	0.0242	*0000	371.5	2.012	7.633	0.114	0.149	0.01060	0.01063	2.10	59.558	10.038	2.731	97.718		Pilot nozzles - DLN airblast 36212	
	2105	2.267	0.0245	0.0294	0.0294	*0000	374.8	2.023	7.506	0.116	0.149	0.01311	0.01306	2.59	51.252	5.489	2.810	98.313		Pilot nozzles - DLN airblast 36212, f/a = 0.013	
(June 1, 1977)																					
A2-D	4000	3.950	0.0085	0.0623	0.0623	*0000	642.9	4.132	10.965	0.104	0.211	0.01598	0.01595	3.25	3.720	0.189	8.234	99.896		373.1 kPa AA	Cruise
	5100	4.022	0.0104	0.0587	0.0587	*0000	661.5	4.126	11.514	0.110	0.211	0.01479	0.01448	2.96	4.024	0.209	8.181	99.887		408.2 kPa AA	Climb
	6400	3.955	0.0104	0.0604	0.0604	*0000	681.3	4.145	11.613	0.123	0.211	0.01548	0.01541	3.14	2.872	0.249	9.154	99.911		406.3 kPa AA, low T_3	Takeoff
	6000	3.968	0.0104	0.0604	0.0604	*0000	684.0	4.130	11.739	0.107	0.211	0.01543	0.01584	3.23	3.031	0.251	8.582	99.907		407.8 kPa AA	
	6100	3.933	0.0104	0.0470	0.0470	*0000	683.4	4.148	11.560	0.109	0.211	0.01211	0.01189	2.43	5.877	0.081	9.271	99.855		406.0 kPa AA, f/a = 0.012	
	3000	5.832	0.0130	0.0672	0.0672	*0000	512.2	5.258	10.145	0.108	0.211	0.01168	0.01157	2.35	19.203	0.869	5.040	99.472		536.4 kPa AA	Approach
(June 7, 1977)																					
A-2C	4090	3.976	0.0085	0.0623	0.0623	*0000	642.3	4.156	11.003	0.050	0.224	0.01588	0.01448	2.93	21.396	0.556	6.860	99.448		371.0 kPa AA	Cruise
	5090	4.027	0.0105	0.0587	0.0587	*0000	668.9	4.114	11.722	0.058	0.224	0.01477	0.01412	2.87	12.307	0.183	7.659	99.694		409.7 kPa AA	Climb
	6090	3.923	0.0105	0.0604	0.0604	*0000	682.3	4.099	11.690	0.055	0.224	0.01560	0.01497	3.05	5.873	0.137	7.943	99.850		411.2 kPa AA	Takeoff

CONCEPT NO. 2, REFINEMENT TEST NO. 3

Configuration – Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index – CO	Emission Index – HC	Emission Index – NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(June 14, 1977)																					
A-3A	2000	2.314	0.0250	0.0242	0.0242	*0000	373.8	2.026	7.615	0.194	0.124	0.01060	0.01079	2.06	67.787	41.647	2.076	94.752		368.6 kPa AA	Taxi-idle
	2100	2.182	0.0246	0.0256	0.0256	*0000	375.5	2.024	7.209	0.212	0.124	0.01186	0.01229	2.36	63.178	36.790	2.370	95.287		368.4 kPa AA, f/a = 0.012	
(June 16, 1977)																					
A-3B	4090	3.812	0.0103	0.0623	0.0623	*0000	647.1	4.056	10.851	0.253	0.249	0.01656	0.01658	3.36	14.756	0.367	6.052	99.621		40.6 kPa AA	Cruise
	5090	3.878	0.0103	0.0587	0.0587	*0000	666.3	4.051	11.388	0.249	0.249	0.01534	0.01539	3.12	14.426	0.309	6.273	99.634		42.2 kPa AA	Climb
	6090	3.779	0.0103	0.0604	0.0604	*0000	680.4	4.053	11.322	0.244	0.249	0.01620	0.01625	3.30	10.656	0.229	6.874	99.729		42.2 kPa AA	Takeoff
(June 20, 1977)																					
A-3A	2000	2.273	0.0259	0.0242	0.0242	*0000	376.0	2.007	7.611	0.228	0.180	0.01079	0.01047	2.03	61.457	29.301	2.183	95.984		372.1 kPa AA	Taxi-idle
	2100	2.285	0.0262	0.0303	0.0303	*0000	379.4	2.092	7.396	0.203	0.180	0.01342	0.01315	2.58	53.423	19.994	2.544	96.989		380.8 kPa AA, 5% bleed	
	2200	2.133	0.0262	0.0325	0.0325	*0000	380.0	2.018	7.162	0.179	0.180	0.01543	0.01530	3.01	49.197	13.379	2.623	97.669		377.7 kPa AA, 10% bleed	
	3000	5.797	0.0222	0.0672	0.0672	*0000	506.3	5.297	9.917	0.141	0.180	0.01175	0.01175	2.40	9.491	0.198	5.569	99.759		121.7 kPa AA	Approach
A-3C	2000	2.234	*0000	0.0242	0.0242	*0000	370.5	2.010	7.356	0.361	0.180	0.01097	0.01046	1.96	68.061	64.210	1.805	92.767		No bleed	Taxi-idle
	2100	2.226	*0000	0.0303	0.0303	*0000	377.9	2.040	7.362	0.372	0.180	0.01377	0.01293	2.58	40.190	7.981	2.410	98.354		5% bleed	
	2200	2.126	*0000	0.0325	0.0325	*0000	377.6	2.063	6.936	0.359	0.180	0.01548	0.01490	2.99	31.737	4.439	2.722	98.864		10% bleed	
(June 23, 1977)																					
A-3D	2000	2.303	0.0166	0.0242	0.0242	*0000	374.9	1.998	7.639	0.311	0.112	0.01065	0.00937	1.88	39.657	6.639	2.594	98.485		869.4 kPa AA, low T_3	
	2000	2.307	0.0165	0.0242	0.0242	*0000	377.7	1.996	7.721	0.300	0.112	0.01062	0.00922	1.85	38.983	6.045	2.722	98.553		869.4 kPa AA	Taxi-idle
	2100	2.245	0.0165	0.0303	0.0303	*0000	380.5	2.060	7.328	0.273	0.112	0.01365	0.01224	2.46	32.474	3.373	2.838	98.940		863.2 kPa AA, 5% bleed	
	2200	2.156	0.0165	0.0325	0.0325	*0000	374.0	2.045	6.962	0.282	0.112	0.01526	0.01439	2.89	32.089	2.876	2.851	98.993		878.5 kPa AA, 10% bleed	
	3000	5.836	0.0136	0.0672	0.0672	*0000	509.6	5.209	10.105	0.353	0.112	0.01167	0.01124	2.30	5.602	0.230	5.061	99.848		713.8 kPa AA	Approach
(June 27, 1977)																					
A-3E	2000	2.321	0.0166	0.0242	0.0242	*0000	375.6	1.998	7.731	0.313	0.174	0.01056	0.00994	1.99	41.532	6.333	2.802	98.467		371.4 kPa AA	Taxi-idle
(July 6, 1977)																					
A-3F	2000	2.324	0.0158	0.0242	0.0242	*0000	375.0	1.986	7.813	0.389	0.199	0.01055	0.00999	2.01	31.995	4.295	2.922	98.871		375.3 kPa AA	
	2100	2.204	0.0156	0.0303	0.0303	*0000	376.7	2.054	7.181	0.316	0.199	0.01391	0.01357	2.74	26.289	1.906	3.040	99.214		368.3 kPa AA, 5% bleed	Taxi-idle
	2200	2.192	0.0156	0.0325	0.0325	*0000	375.4	2.064	7.078	0.278	0.199	0.01501	0.01479	2.98	24.933	1.501	3.086	99.282		368.1 kPa AA, 10% bleed	

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
CONCEPT NO. 2, REFINEMENT TEST NO. 4 (July 20, 1977)																					
A-4A	2000	2.325	0.0251	0.0242	0.0242	*0000	373.2	1.961	7.834	0.295	0.180	0.01054	0.00987	1.98	36.200	6.132	2.673	98.611		378.4 kPa AA	Taxi-idle
(July 23, 1977)																					
A-4B	2000	2.247	0.0170	0.0242	0.0242	*0000	375.0	1.998	7.453	0.373	0.168	0.01091	0.00989	2.00	28.163	4.754	2.755	98.920		375.0 kPa AA	
	2100	2.169	0.0170	0.0303	0.0303	*0000	375.5	2.051	7.023	0.301	0.168	0.01413	0.01288	2.60	24.556	3.272	2.945	99.135		377.6 kPa AA, 5% bleed	Taxi-idle
	2200	2.094	0.0170	0.0325	0.0325	*0000	376.8	2.022	6.900	0.346	0.168	0.01571	0.01476	2.98	23.383	2.475	3.058	99.233		374.4 kPa AA, 10% bleed	
(August 3, 1977)																					
A-4B	2001	2.282	0.0170	0.0242	0.0242	*0000	373.7	1.834	7.205	0.107	0.174	0.01074	0.01038	2.08	39.292	6.715	2.643	98.487		362.6 kPa AA	
	2101	2.260	0.0168	0.0303	0.0303	*0000	377.7	1.860	7.096	0.075	0.174	0.01356	0.01343	2.71	25.607	3.172	2.950	99.119		359.1 kPa AA, 5% bleed	Taxi-idle
	2201	2.141	0.0166	0.0325	0.0325	*0000	377.5	1.871	6.653	0.072	0.174	0.01537	0.01528	3.08	23.729	2.676	3.163	99.207		357.6 kPa AA, 10% bleed	

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CONCEPT NO. 2, REFINEMENT TEST NO. 5
(September 28, 1977)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
A-5B	2000	2.359	0.0170	0.0242	0.0242	*0000	374.6	1.990	7.929	0.415	0.043	0.01039	0.01091	1.98	82.829	86.759	2.047	90.441		378.9 kPa AA	Taxi-idle
C	2020	2.348	0.0170	0.0242	0.0242	*0000	375.3	1.990	7.901	0.372	0.043	0.01044	0.01103	1.97	86.341	100.675	1.900	89.138		378.9 kPa AA, swirler valve 20° open	Taxi-idle
C	2040	2.342	0.0170	0.0242	0.0242	*0000	377.0	1.990	7.916	0.307	0.043	0.01047	0.01098	1.95	84.750	105.484	1.793	88.754		378.9 kPa AA, swirler valve 40° open	Taxi-idle
B	3000	5.742	*00000	0.0672	0.0672	*0000	508.8	5.278	9.918	0.423	0.043	0.01186	0.01168	2.35	29.991	4.675	5.629	98.884			Approach
C	3030	5.825	*00000	0.0672	0.0672	*0000	510.7	5.313	10.043	0.420	0.043	0.01169	0.01110	2.23	34.518	5.089	5.245	98.742			Approach
D	3060	5.865	*00000	0.0672	0.0672	*0000	510.9	5.315	10.105	0.362	0.043	0.01161	0.01161	2.34	31.578	3.275	4.866	98.970			Approach
E	3090	5.867	*00000	0.0672	0.0672	*0000	511.8	5.294	10.179	0.402	0.043	0.01161	0.01154	2.32	37.548	3.879	4.760	98.776			Approach
B	5000	4.092	*00000	0.0587	0.0587	*0000	663.3	4.083	11.945	0.268	0.043	0.01454	0.01445	2.95	5.071	0.422	9.677	99.844			Climb
C	5030	4.085	*00000	0.0587	0.0587	*0000	662.9	4.107	11.837	0.277	0.043	0.01456	0.01383	2.82	6.280	0.288	9.322	99.827			Climb
D	5060	4.095	*00000	0.0587	0.0587	*0000	666.1	4.108	11.929	0.308	0.043	0.01453	0.01421	2.90	6.118	0.201	8.612	99.838			Climb
E	5090	4.093	*00000	0.0587	0.0587	*0000	666.4	4.104	11.932	0.348	0.043	0.01453	0.01432	2.92	6.732	0.171	8.208	99.827			Climb
E	6090	4.066	*00000	0.0604	0.0604	*0000	683.6	4.122	12.108	0.336	0.043	0.01506	0.01472	3.00	5.299	0.033	9.127	99.872			Takeoff
E	6090	4.075	0.0107	0.0604	0.0604	*0000	681.6	4.126	12.079	0.337	0.043	0.01502	0.01483	3.02	6.283	0.050	8.808	99.848		104.2 kPa AA	Takeoff
(October 23, 1977)																					
A-5A	2000	2.198	0.0222	0.0242	0.0242	*0000	374.1	2.025	7.274	0.147	0.047	0.01101	0.01100	2.18	52.057	9.185	2.599	97.970		374.4 kPa AA, linkage installed	Taxi-idle
	2100	2.151	0.0222	0.0303	0.0303	*0000	376.6	2.083	6.960	0.116	0.031	0.01407	0.01395	2.78	40.022	5.839	2.968	98.546		368.7 kPa AA, 5% bleed linkage installed	Taxi-idle
	2200	2.016	0.0222	0.0325	0.0325	*0000	377.9	2.075	6.560	0.117	0.031	0.01611	0.01574	3.15	34.932	4.267	3.274	98.804		369.6 kPa AA, 10% bleed linkage installed	Taxi-idle
	2000	2.178	0.0234	0.0242	0.0242	*0000	375.7	2.013	7.279	0.127	0.031	0.01111	0.01106	2.21	46.640	5.624	2.511	98.410		377.2 kPa AA without linkage	Taxi-idle
	2100	2.089	0.0234	0.0303	0.0303	*0000	377.8	2.107	6.695	0.107	0.031	0.01449	0.01451	2.90	38.594	4.040	2.871	98.738		368.2 kPa AA, 5% bleed without linkage	Taxi-idle
	2200	2.023	0.0234	0.0325	0.0325	*0000	377.4	2.097	6.503	0.104	0.031	0.01606	0.01592	3.18	35.566	3.064	3.015	98.895		369.8 kPa AA, 10% bleed without linkage	Taxi-idle
	3000	5.685	*00000	0.0672	0.0672	*0000	505.9	5.339	9.688	0.300	0.025	0.01183	0.01236	2.53	4.946	0.372	6.118	99.851			Approach

CONCEPT NO. 2, OPTIMIZATION TEST NO. 1

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(October 5, 1977)																					
A-6B	2000	2.340	0.0159	0.0242	0.0242	*0000	375.6	2.041	7.741	0 152	0.037	0.01048	0.01097	2.00	86.162	77.819	1.875	91.147		375.6 kPa AA	
C	2020	2.329	0.0159	0 0242	0.0242	*0000	376.1	2.074	7.581	0.149	0.037	0.01053	0.01098	1.97	88.263	94.717	1.750	89.616		373.8 kPa AA, swirler valve 20° open	Taxi-idle
C	2040	2.316	0.0159	0.0242	0.0242	*0000	376.6	2.041	7.674	0.211	0.037	0.01059	0.01106	1.95	92.853	111.052	1.632	88.075		376.6 kPa AA, swirler valve 40° open	
E	5090	3.963	*00000	0.0587	0.0587	*0000	663.8	4.089	11.645	0.108	0.037	0.01501	0.01607	3.27	3.048	0.424	6.305	99.891			Climb
E	6090	3.927	*00000	0.0604	0.0604	*0000	681.0	4.088	11.840	0.101	0.037	0.01559	0.01650	3.36	2.138	0.502	6.777	99.906			Takeoff
(October 6, 1977)																					
A-6B	2000	2.291	0.0163	0.0242	0.0242	*0000	377.5	2.098	7.420	0.129	0.025	0.01070	0.01072	1.98	88.118	62.536	2.151	92.442		372.0 kPa AA	
B	2100	2.297	0.0163	0.0266	0.0266	*0000	376.9	2.148	7.247	0.101	0.025	0.01175	0.01159	2.18	82.467	47.389	2.235	93.903		368.2 kPa AA, f/a = 0.0115	
B	2200	2.275	0.0163	0.0294	0.0294	*0000	377.3	2.183	7.063	0.116	0.025	0.01307	0.01292	2.46	76.146	39.420	2.375	94.751		366.6 kPa AA, f/a = 0.013	Taxi-idle
B	2300	2.228	0.0163	0.0303	0.0303	*0000	379.9	2.185	6.948	0.118	0.025	0.01376	0.01361	2.60	74 528	34.839	2.394	95 191		367.8 kPa AA, 5% bleed	
B	2400	2.154	0.0163	0.0325	0.0325	*0000	379.2	2.195	6.666	0.117	0.025	0.01528	0.01515	2.91	69.220	28.637	2.476	95.860		366.2 kPa AA, 10% bleed	
B	3000	5.768	*00000	0.0672	0.0672	*0000	511.5	5.487	9.732	0.271	0.025	0.01181	0.01274	2.59	14.028	0.279	5.029	99.646			
C	3030	5.800	*00000	0.0672	0.0672	*0000	512.0	5.457	9.844	0.098	0.025	0.01174	0.01240	2.52	16.658	0.332	4.637	99.579			
D	3060	5.827	*00000	0.0672	0.0672	*0000	507.0	5.435	9.838	0.158	0.025	0.01169	0.01219	2.46	27.301	0.726	4.331	99.294			Approach
E	3090	5.813	*00000	0.0672	0.0672	*0000	505.9	5.357	9.944	0.149	0.025	0.01172	0.01209	2.42	43.275	1.759	4.073	98.828			
E	4090	3.991	0.0079	0.0623	0.0623	*0000	637.3	4.183	11.021	0.119	0.025	0.01582	0.01627	3.31	4.365	0.101	6.241	99.888		43.9 kPa AA	Cruise
E	4060	3.964	0.0079	0 0623	0 0623	*0000	642.8	4.196	10.998	0.119	0.025	0.01593	0.01625	3.31	2.735	0.125	6.886	99.925		42.4 kPa AA	
E	5060	3.991	*00000	0.0587	0.0587	*0000	668.2	4.177	11.575	0.105	0.025	0.01491	0.01552	3.17	2.029	0.145	7.518	99.940			Climb
(October 17, 1977)																					
A-6A	2000	2.497	0.0113	0.0242	0.0242	*0000	376.1	2.039	7.638	0.118	0.060	0.0106	0.0105	2.08	53.837	13.528	2.529	97.547		376.5 kPa AA	
	2100	2.190	0.0113	0.0302	0.0302	*0000	379.1	2.041	7.312	*0000	0.060	0.0136	0 0143	2.83	40.335	9.329	2.861	98.233		376.5 kPa AA, 5% bleed	Taxi-idle
A-6A	2200	2.109	0.0113	0.0325	0.0325	*0000	380.0	2.031	7.062	*0000	0.060	0.0154	0.0158	3.15	37.598	8 108	2.993	98.404		377.1 kPa AA, 10% bleed	
(October 19, 1977)																					
A-6A	2000	2.326	0.0232	0.0242	0.0242	*0000	370.6	2.019	8.561	0.118	0.450	0.0104	0.0114	2.27	44.898	5.161	2.476	98.491		378.2 kPa AA	
	2100	2.209	0.0218	0.0303	0 0303	*0000	375.7	2.080	7.108	0.122	0.450	0.0137	0.0143	2.87	33.159	3.821	2.648	98.885		372.2 kPa AA, 5% bleed	Taxi-idle
	2200	2.200	0.0216	0.0325	0.0325	*0000	376.8	2.087	7.071	0.107	0.450	0.0148	0.0154	3.09	32.763	3.062	2.764	98.961		371.5 kPa AA, 10% bleed	
(November 15, 1977)																					
A-6A	2000	2.245	0.01449	0.0242	0.0242	*0000	370.1	2.109	7.053	0.205	0.047	0.01078	0.01074	2.11	59.908	17.450	2.502	97.060		367.0 kPa AA	
	2001	2.246	0.01452	0.0242	0.0242	*0000	369.5	2.113	7.029	0.210	0.047	0.01078	0.01067	2.09	59.460	18.396	2.507	96.988		Repeat of 2000	
	2100	2.133	0.01449	0.0303	0.0303	*0000	375.8	2.169	6.606	0.166	0.047	0.01419	0.01388	2.76	40.354	8.466	2.951	98.308		364.0 kPa AA, 5% bleed	Taxi-idle
	2200	2.041	0.01447	0.0325	0.0325	*0000	375.7	2.141	6.394	0.151	0.047	0.01592	0.01546	3.08	35.512	6.686	3.090	98.578		364.0 kpa AA, 10% bleed	
	2002	2.244	0.01450	0.0242	0.0242	*0000	370.1	2.108	7.065	0.190	0.047	0.01079	0.01070	2.10	57.077	18.235	2.576	97.058		Repeat of 2000	
(December 9, 1977)																					
A-6F	2000	2.253	*00000	0.0242	0.0242	*0000	377.0	1.992	7.636	0.120	0.047	0.01075	0.01094	2.16	59.288	11.461	2.325	97.600			
	2100	2.186	*00000	0.0303	0.0303	*0000	379.8	2.056	7.206	0.121	0.047	0.01385	0.01406	2.80	39.552	6.926	2.598	98.462		5% bleed	Taxi-idle
	2200	2.085	*00000	0.0325	0.0325	*0000	379.9	2.028	6.960	0.116	0.047	0.01558	0.01587	3.17	35.970	5.317	2.753	98.687		10% bleed	
	3000	5.833	*00000	0.0613	0.0613	*0000	506.7	5.265	10.082	0.112	0.047	0.01051	0.01146	2.34	7.388	0.404	4.638	99.791			Approach

CONCEPT NO. 2, OPTIMIZATION TEST NO. 1 (CONTD)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., °K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.		Comments
(December 13, 1977)																					
A-6F	2000	2.271	*00000	0.0242	0.0242	*0000	371.3	1.962	7.694	0.093	0.047	0.01066	0.01094	2.19	42.945	3.880	2.291	98.649			Taxi-idle
	2100	2.144	*00000	0.0303	0.0303	*0000	376.4	2.034	7.080	0.094	0.047	0.01412	0.01444	2.92	23.837	1.413	2.581	99.315		5% bleed	Taxi-idle
	2200	2.123	*00000	0.0325	0.0325	*0000	375.9	1.997	7.131	0.086	0.047	0.01531	0.01582	3.19	22.279	1.048	2.625	99.384		10% bleed	Taxi-idle
	2001	2.278	*00000	0.0242	0.0242	*0000	370.8	1.969	7.679	0.106	0.047	0.01063	0.01095	2.19	43.448	4.653	2.254	98.570			Taxi-idle
	3000	5.821	*00000	0.0671	0.0671	*0000	504.2	5.246	10.056	0.114	0.047	0.01152	0.01220	2.50	4.125	0.112	4.712	99.893			Approach
(December 15, 1977)																					
A-6E	4090	3.971	*00000	0.0612	0.0612	*0000	643.7	4.036	11.413	0.063	0.047	0.01542	0.01556	3.17	4.460	0.010	6.114	99.894			Cruise
	5090	4.041	*00000	0.0587	0.0587	*0000	667.1	4.025	12.083	0.053	0.047	0.01453	0.01479	3.02	4.306	0.002	6.424	99.899			Climbout
	6090	3.942	*00000	0.0604	0.0604	*0000	684.5	4.044	12.031	0.043	0.047	0.01533	0.01545	3.15	2.565	0.001	6.999	99.940			Takeoff
(December 19, 1977)																					
A-6G	4090	3.937	*00000	0.0616	0.0616	*0000	642.7	4.032	11.318	0.091	0.047	0.01566	0.01602	3.26	3.859	0.957	6.023	99.825			Cruise
	5090	4.017	*00000	0.0587	0.0587	*0000	666.1	4.037	11.960	0.082	0.047	0.01462	0.01495	3.05	4.266	0.122	6.268	99.889			Climbout
	6090	3.939	*00000	0.0604	0.0604	*0000	684.2	4.002	12.160	0.144	0.047	0.01534	0.01560	3.18	2.708	0.035	6.902	99.933			Takeoff

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.		Comments
CONCEPT NO. 2, OPTIMIZATION TEST NO. 2 (October 26, 1977)																					
A-7A	2000	2.267	0.0141	0.0242	0.0242	*0000	369.8	1.999	7.541	0.150	0.050	0.0107	0.0111	2.17	57.217	14.120	2.008	97.415		380.3 kPa AA	Taxi-idle
	2100	2.120	0.0146	0.0302	0.0302	*0000	374.7	2.069	7.172	0.099	0.050	0.0137	0.0139	2.77	38.870	8.384	2.487	98.350		373.3 kPa AA, 5% bleed	Taxi-idle
	2200	2.109	0.0145	0.0325	0.0325	*0000	374.7	2.064	6.827	0.091	0.050	0.0154	0.0163	3 25	30.843	7.155	2.794	98.647		373.6 kPa AA, 10% bleed	Taxi-idle
(October 30, 1977)																					
A-7B	3090	5.684	*00000	0.0672	0.0672	*0000	501.8	5.364	9.534	0.105	0.075	0 01183	0.01249	2.51	33.588	3.090	4.657	98.939	10		Approach
	4090	3.872	*00000	0.0623	0.0623	*0000	640.0	4.161	10.681	0.145	0.056	0.01610	0.01636	3.33	7.380	0.271	7 532	99.803	8		Cruise
	5090	3.948	*00000	0.0591	0.0591	*0000	664.6	4.159	11.320	0.095	0.050	0.01498	0.01534	3.12	6.279	0.246	7.878	99.831	6		Climb
	6090	3.850	*00000	0.0607	0.0607	*0000	681 8	4.138	11.383	0.078	0.047	0.01577	0.01595	3.25	4.799	0.246	8.790	99.866	4		Takeoff

CONCEPT NO. 2, OPTIMIZATION TEST NO. 3

Configuration – Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index – CO	Emission Index – HC	Emission Index – NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments
(November 3, 1977)																				
A-8B	3090	5.361	0.01438	0.0672	0.0672	*0000	506.7	4.888	9.954	0.188	0.047	0.01254	0.01274	2.55	38.428	3.622	4.471	98.778		42.3 kPa AA; Approach
	4090	3.863	*00000	0.0614	0.0614	*0000	644.1	4.080	10.924	0.142	0.047	0.01589	0.01618	3.29	7.898	0.154	7.726	99.801		Cruise
	5090	3.884	*00000	0.0587	0.0587	*0000	661.0	4.054	11.340	0.185	0.047	0.01512	0.01512	3.08	5.675	0.078	7.693	99.860		Climb
	6090	3.862	*00000	0.0604	0.0604	*0000	684.3	4.114	11.507	0.150	0.047	0.01565	0.01574	3.21	4.298	0.032	8.665	99.896		Takeoff
(November 4, 1977)																				
A-8B	2000	2.285	0.0205	0.0242	0.0242	*0000	372.0	2.023	7.467	*0000	0.050	0.0106	0.0108	2.12	56.613	13.076	2.289	97.521		371.6 kPa AA
	2100	2.184	0.0205	0.0302	0.0302	*0000	376.5	2.079	7.040	*0000	0.050	0.0139	0.0138	2.76	37.388	7.005	2.661	98.506		366.1 kPa AA, 5% bleed; Taxi-idle
	2200	2.119	0.0204	0.0325	0.0325	*0000	377.0	2.051	6.888	*0000	0.050	0.0154	0.0157	3.13	32.651	4.091	2.809	98.873		368.9 kPa AA, 10% bleed
(November 22, 1977)																				
A-8C	2090	2.337	0.01217	0.0242	0.0242	*0000	375.1	2.024	7.715	0.172	0.047	0.01036	0.01099	1.91	98.778	117.574	1.812	87.363		380.0 kPa AA
	2090	2.341	0.00445	0.0242	0.0242	*0000	374.9	2.014	7.769	0.174	0.047	0.01034	0.01106	1.61	111.373	271.918	1.219	73.529		63.3 kPa AA
	2090	2.342	0.00759	0.0242	0.0242	*0000	374.5	2.027	7.715	0.168	0.047	0.01034	0.01098	1.66	112.213	236.927	1.200	76 578		173.3 kPa AA
	2090	2.365	0.01210	0.0242	0.0242	*0000	375.6	2.023	7.831	0.172	0.047	0.01024	0.01066	1.86	99.826	113.962	1.645	87.655		377.5 kPa AA; Taxi-idle
	2190	2.256	0.01207	0.0303	0.0303	*0000	378.9	2.073	7.341	0.131	0.047	0.01342	0.01393	2.60	76.653	55.496	2.060	93.329		372.9 kPa AA, 5% bleed
	2290	2.177	0.01196	0.0325	0.0325	*0000	379.5	2.047	7.184	0.122	0.047	0.01493	0.01538	2.93	67.600	40.645	2.186	94.845		372.2 kPa AA, 10% bleed
(November 28, 1977)																				
A-8D	2090	2.227	0.00803	0.0242	0.0242	*0000	371.5	2.030	7.277	0.142	0.047	0.01087	0.01117	1.86	89.919	165.316	1.589	83.384		372.0 kPa AA; Taxi-idle
(November 30, 1977)																				
A-8D	2090	2.285	0.01261	0.0242	0.0242	*0000	375.0	2.036	7.536	0.119	0.047	0.01059	0.01100	2.02	72.705	81.561	2 032	91.135		374.4 kPa AA
	2190	2.199	0.01254	0.0303	0.0303	*0000	379.0	2.099	7.097	0.086	0.047	0.01376	0.01371	2.63	56.379	38.671	2.564	95.282		368.3 kPa AA, 5% bleed; Taxi-idle
	2290	2.133	0.01251	0.0325	0.0325	*0000	378.6	2.042	7.072	0.083	0.047	0.01523	0.01509	2.92	53.881	30.457	2.720	96.061		374.7 kPa AA, 10% bleed
(December 6, 1977)																				
A-8G	3090	5.910	*00000	0.0672	0.0672	*0000	504.7	5.198	10.351	0.059	0.047	0.01138	0.01169	2.36	29.748	2.529	4.543	99.078		Approach
	4090	4.070	*00000	0.0616	0.0616	*0000	645.1	4.044	11.723	0.060	0.047	0.01515	0.01559	3.18	5.542	0.098	8.238	99.861		Cruise
	5090	4.092	*00000	0.0587	0.0587	*0000	666.7	4.034	12.225	0.051	0.047	0.01436	0.01470	3.00	4.281	0.083	8.597	99.892		Climbout
	6090	4.047	*00000	0.0604	0.0604	*0000	684.5	4.034	12.412	0.059	0.047	0.01494	0.01530	3.12	3.516	0.055	9.549	99.912		Takeoff
(December 2, 1977)																				
A-8E	2000	2.286	0.01254	0.0242	0.0242	*0000	373.3	2.053	7.498	0.076	0.050	0.0106	0.0109	2.15	43.91	14.90	2.835	97.66		375.1 kPa AA
	2100	2.200	0.01252	0.0302	0.0302	*0000	378.9	2.082	7.193	0.065	0.050	0.01375	0.0138	2.74	39.65	8.68	3.44	98.306		372.3 kPa AA, 5% bleed
	2200	2.114	0.01250	0.0325	0.0325	*0000	380.4	2.048	7.163	0.072	0.050	0.0154	0.0153	3.04	38.01	6.08	3.65	98.573		375.8 KPa AA, 10% bleed; Taxi-idle
A-8F	2000	2.278	*00000	0.0242	0.0242	*0000	377.9	2.041	7.610	0.084	0.050	0.0106	0.0110	2.21	27.34	2.45	2.98	99.142		
	2100	2.189	*00000	0.0302	0.0302	*0000	377.5	2.093	7.101	0.070	0.050	0.0138	0.0140	2.82	29.88	0.61	3.305	99.243		5% bleed
	2200	2.104	*00000	0.0325	0.0325	*0000	379.7	2.037	7.071	0.260	0.050	0.0155	0.0156	3.14	32.40	0.49	3.77	99.195		10% bleed

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
CONCEPT NO. 3, REFINEMENT TEST NO. 1 (January 29, 1977)																					
A-9	0201	5.791	*00000	0.0671	0.0671	*0000	551.1	5.281	10.050	0.229	0.435	0.01173	0.01171	2.39	8.491	1.500	6.116	99.669		7.6 cm mixing length	Approach Pilot only
	0201	5.760	*00000	0.0671	0.0671	*0000	551.1	5.293	9.964	0.217	0.435	0.01179	0.01168	2.38	8.072	1.233	6.173	99.702		7.6 cm mixing length	Approach
(January 28, 1977 MANUAL DATA ONLY)																					
	0102	2.309	*00000	0.0249	0.0249	*0000	371.6	1.997	7.81	*0000	0.250	0.01079	0.0125	2.20	59.52	125.76	1.837	87.57			Taxi-idle
	0152	2.322	0.0121	0.0249	0.0249	*0000	371.6	1.986	7.86	0.125	0.250	0.0107	0.0112	2.18	46.609	29.56	2.536	96.31		34.4 kPa AA	
	0112	2.326	0.0164	0.0249	0.0249	*0000	371.6	1.986	7.88	*0000	0.250	0.0107	0.0109	2.12	48 76	29.19	2.668	96.29		68.9 kPa AA	
	0153	2.321	0.0113	0.0275	0.0275	*0000	371.6	2.008	7.76	*0000	0.250	0.0118	0.0125	2.47	42.07	2.995	2.932	97.47		34.4 kPa AA	
(February 18, 1977)																					
	0211	5.922	0.0279	0.0671	0.0671	*0000	503.9	5.289	10.352	0.127	0.242	0.01147	0.01210	2.47	6.925	0.251	7 701	99.815		80.5 kPa AA, 7.6 cm mixing length	
	0251	5.962	0.0192	0.0671	0.0671	*0000	500.4	5.316	10.297	0.123	0.242	0.1139	0.01215	2.48	7 352	0.172	7.697	99.812		34.6 kPa AA	
	0201	5.952	*00000	0.0671	0.0671	*0000	498.5	5.359	10.153	0.152	0 242	0.01141	0.01193	2.44	7.383	0.122	7.351	99 816		Pilot only	Approach
	0202	5.994	*00000	0.0670	0.0572	0.0098	500.0	5.366	10.215	0.287	0.242	0.01132	0.01140	2 23	56.637	22.790	5.436	96.669		15% secondary fuel	
(February 19, 1977)																					
	0201	5.912	*00000	0.0671	0.0671	*0000	503.9	5.299	10.326	0.135	0.367	0.01149	0.01246	2.54	7.675	0.413	6.717	99.783		Pilot only, 7.6 cm mixing length	
	0202	5.891	*00000	0.0668	0.0569	0.0098	503.2	5.361	10.149	0.289	0.367	0.01148	0.01229	2.41	54.550	19.626	5.230	96.995		15% secondary W_f	
	0203	5.866	*00000	0.0664	0.0469	0.0195	503.7	5.286	10.269	0.260	0.367	0.01146	0.01215	2.22	95.615	87.812	3.211	90.048		29% secondary W_f	Approach
	0253	5.900	*00000	0.0664	0.0469	0.0195	502.7	5.302	10.267	0.252	0.367	0.01140	0.01246	2.23	97.608	90.606	3.263	89.756		29% secondary Wf 34.4 kPa secondary AA	
	0204	5.910	*00000	0.0670	0.0518	0.0151	503.2	5.341	10.224	0.325	0 367	0.01147	0.01237	2.35	75.146	41.361	4.363	94.604		22.5% secondary W_f	
	0409	4.034	*00000	0.0150	0.0150	*0000	682.7	4.136	12.242	0.183	0.367	0.00378	0.00418	0.86	3.699	1.755	7.559	99.759		Pilot only f/a = 0.004	Takeoff
(March 24, 1977)																					
	0403	3.920	*00000	0.0593	0.0330	0.0263	685.3	4.062	12.436	0.578	0.261	0.01533	0.01635	3.33	2.262	1.910	11.977	99.779		45% secondary W_f, 15.2 cm mixing length	Takeoff
	0499	4.001	*00000	0.0334	0.0334	*0000	685.8	4.102	12.592	0.106	0.398	0.00845	0.00885	1.81	4.098	2.608	11.818	99.675		Pilot only f/a = 0.009	
(March 25, 1977)																					
	0403	3.929	*00000	0.0607	0.0334	0.0273	683.2	4.079	12.344	0.142	0.236	0.01565	0.01553	3.16	2 840	3.481	6.961	99.628		45% secondary W_f, 15.2 cm mixing length	
	0404	3.911	*00000	0.0608	0.0242	0.0365	686.2	4.093	12.296	0.145	0.261	0.01574	0.01549	3.15	3.739	1.880	4.781	99.747		60% secondary W_f, 15.2 cm mi-ing length	
	0405	3.900	*00000	0.0605	0.0182	0.0423	685.0	4.084	12.278	0.188	0.261	0.01572	0.01508	3.04	19.628	3.062	3.526	99.270		70% secondary W_f, 15.2 cm mixing length	
	0406	3.921	*00000	0.0608	0.0150	0.0458	682.8	4.083	12.316	0.199	0.261	0.01571	0.01487	2.97	36.222	7.415	3.196	98.497		75% secondary W_f, 15.2 cm mixing length	
	0456	3.971	0.0164	0.0608	0.0150	0.0458	683.3	4.084	12.472	0.201	0.267	0.01552	0.01546	3.06	41.625	10.758	2.745	98.077		75% secondary W_f, 41 kPa AA	Takeoff
	0459	3.928	0.0155	0.0150	0.0150	*0000	680.9	4.118	12.200	0.098	0.249	0.00388	0.00401	0.82	11.383	2.350	7.455	99.526		Pilot only f/a = 0.004 33.3 kPa AA	
	0458	3.941	0.0159	0.0182	0.0182	*0000	681.6	4.098	12.321	0.123	0.242	0.00469	0.00475	0.98	5.543	1.667	7.379	99.723		Pilot only f/a = 0.0047 36.7 kPa AA	
	0408	3.934	*00000	0.0182	0.0182	*0000	680.6	4.122	12.194	0.115	0.249	0.00470	0.00469	0.96	6.479	1.858	7.317	99.685		Pilot only f/a = 0.0047	
	0457	3.975	0.0159	0.0242	0.0242	*0000	681.1	4.080	12.480	0.122	0.236	0.00618	0.00624	1.28	3.668	1.183	8.528	99.810		Pilot only f/a = 0.0062 39.4 kPa AA	

CONCEPT NO. 3, REFINEMENT TEST NO. 1 (CONTD)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
											(March 26, 1977)										
A-9	0256	5.820	0.0205	0.0470	0.0470	*0000	504.8	5.289	10.373	0.117	0.261	0.00818	0:00844	1.73	8.445	0.898	5.345	99.723	36	Pilot only f/a = 0.008 33.9 kPa AA	Approach
	0255	5.813	0.0210	0.0571	0.0571	*0000	502.4	5.279	10.334	0.136	0.323	0.00994	0.00957	1.96	7.778	0.668	5.403	99.758	44	Pilot only f/a = 0.010 36.6 kPa AA	Approach
	0252	5.853	0.0207	0.0671	0.0571	0 0100	501.7	5.279	10.412	0.142	0.373	0.01160	0.01172	2.28	86.762	9.157	5.000	97.156	9	15% secondary W_f 36.0 kPa AA 15.2 CM mixing length	Approach
	0253	5.808	0.0206	0.0670	0.0470	0.0201	502.7	5.270	10.358	0.194	0.336	0.01169	0.01146	2.13	132.350	31.936	3.796	94.085	9	30% secondary W_f 37.8 kPa AA	Approach
	0353	4.025	0.0157	0.0590	0.0326	0.0265	665.1	4.103	12.229	0.167	0.286	0.01486	0.01486	3.03	3.673	0.558	5.705	99.865	0	45% secondary W_f 33.8 kPa AA	Climb
	0303	4.025	*00000	0.0590	0.0326	0.0265	665.6	4.105	12.233	0.171	0.273	0.01485	0.01490	3.01	19.287	2.681	6.359	99.311	0	45% secondary Wf 33.8 kPa AA	Climb
	0354	4.036	0.0155	0.0589	0.0236	0.0353	665.8	4.094	12.313	0.196	0.311	0.01477	0.01490	3.03	11.786	1.088	3.356	99.627	0	60% secondary W_f 37.9 kPa AA	Climb
	0355	4.065	0.0152	0.0590	0.0148	0.0442	665.5	4.104	12.363	0.184	0.311	0.01471	0.01423	2.74	61.697	31.411	2.231	95.793	0	75% secondary W_f 35.1 kPa AA	Climb
	0405	3.970	*00000	0.0608	0.0182	0.0426	685.1	4.115	12.387	0.210	0.261	0.01551	0.01539	3.11	16.520	1.846	3.511	99.449	0	70% secondary W_f	Takeoff
	0703	3.976	*00000	0.0622	0.0342	0.0280	644.0	4.132	11.574	0.146	0.261	0.01584	0.01644	3.32	10.856	4.928	5.819	99.312	0	45% secondary W_f	Cruise
	0753	4.012	0.0148	0.0622	0.0342	0.0280	642.7	4.100	11.767	0.161	0.273	0.01570	0.01586	3.23	3.370	1.342	5.304	99.803		45% secondary W_f 35.0 kPa AA	Cruise
	0754	4.057	0.0148	0.0624	0.0249	0.0375	642.8	4.119	11.842	0 186	0.298	0.01558	0.01569	3.19	8.005	1.395	3.538	99.689		60% secondary W_f 35.0 kPa AA	Cruise
	0755	4.006	0.0148	0.0625	0.0187	0.0437	643.2	4.128	11.664	0.220	0.280	0.01579	0.01592	3.19	28 749	5.968	3.133	98.800		70% secondary Wf 35.0 kPa AA	Cruise
											(March 28, 1977)										
	0102	2.279	*00000	0.0242	0.0242	*0000	369.8	2.041	7.608	0.249	0.224	0.01076	0.01007	1.89	62.808	63.795	2.414	92.927			Taxi-idle
	0152	2.316	0.0127	0.0242	0.0242	*0000	369.8	2.010	7.861	0.136	0.224	0.01058	0.01023	2.00	48.722	29.062	2.199	96.305		37.7 kPa AA	Taxi-idle
	0112	2.318	0.0158	0.0242	0.0242	*0000	369.8	2.019	7.836	0.137	0.211	0.01058	0.01011	2.00	42.218	16.246	2.518	97.582		72.0 kPa AA	Taxi-idle

CONCEPT NO. 3, REFINEMENT TEST NO. 2

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(March 17, 1977)																					
A-10	1102	2.337	*00000	0.0244	0.0244	*0000	370.5	2.018	8.029	0.112	0.239	0.01056	0.01109	2.11	55.343	54.548	2.474	93.913			
	1152	2.330	0.0123	0.0244	0.0244	*0000	369 2	2.047	7.840	0.130	0.239	0.01059	0.01098	2.15	46.420	24.372	2.753	96.770		47.7 kPa AA	Taxi-idle
	1112	2.354	0.0169	0.0244	0.0244	*0000	366.9	2.041	7.904	0.145	0.261	0.01048	0.01098	2.17	45.564	16.254	2.769	97.502		75.9 kPa AA	
	1113	2.353	0.0168	0.0292	0.0292	*0000	372.9	2.042	8.023	0.064	0.261	0.01257	0.01327	2.64	38.430	11.580	3.208	98.080		75.9 kPa AA, f/a = 0.013	
	1251	5.682	0.0251	0.0671	0.0671	*0000	497.8	5.293	10.079	0.087	0.261	0.01195	0.01220	2.49	9.205	0.548	6.791	99.735		Pilot only 7.6 cm length	
	1252	5.777	0.0175	0.0676	0.0571	0.0106	495 6	5.245	10.308	0.123	0.261	0.01186	0.01176	2.27	81.710	19.805	5.263	96.341		16% secondary W_f	Approach
	1253	5.800	0.0175	0.0664	0.0469	0.0195	493.2	5.159	10.504	0.120	0.261	0.01159	0.01176	2.10	124.903	75.712	3.658	90.421		29% secondary W_f	
(March 18, 1977)																					
	1457	3.971	*00000	0.0242	0.0242	*0000	678.6	4.142	12.348	0.144	0.267	0.00618	0.00662	1.35	4.195	10.155	8.550	99 011		Pilot only f/a = 0.006	
	1458	3.949	*00000	0.0182	0.0182	*0000	675.3	4.090	12.426	0.125	0.267	0.00468	0.00498	1.02	6.961	6.268	7.987	99 286		Pilot only f/a = 0.005	Takeoff
	1459	3.965	*00000	0.0150	0.0150	*0000	677.1	4.114	12.389	0.138	0.267	0.00384	0.00423	0.87	9.164	3.834	7.732	99.448		Pilot only f/a = 0.004	
(April 18, 1977)																					
	1102	2.220	*00000	0.0242	0.0242	*0000	381.5	2.013	7.422	0.164	0.137	0.01106	0.01201	2.16	74.232	98 841	2.345	89.584			
	1152	2.225	0.0062	0.0242	0.0242	*0000	382.6	2.047	7.335	0.247	0.162	0.01104	0.01087	2.08	68.601	36.683	2.341	95.169		27.3 kPa AA	
	1112	2.261	0.0089	0.0242	0.0242	*0000	382.3	2.018	7.558	0.165	0.162	0.01086	0.01082	2.10	63.867	24.772	2.488	96.325		62.4 kPa AA	
	1122	2.265	0.0144	0.0242	0.0242	*0000	381.9	2.027	7.533	0.194	0.140	0.01084	0.01081	2.12	56.196	17.944	2.811	97.104		132.2 kPa AA	
	1132	2.268	0.0196	0.0242	0.0242	*0000	382.3	2.033	7.523	0.200	0.137	0.01083	0.01080	2.15	42.334	11.041	3.039	98.036		198.1 kPa AA	Taxi-idle
	1162	2.269	0.0298	0.0242	0.0242	*0000	382.7	2.031	7.544	0.209	0.137	0.01082	0.01078	2.17	36.180	4.148	3.066	98.785		339.7 kPa AA	
	1163	2.312	0.0297	0.0291	0.0291	*0000	385.7	1.990	7.907	0.203	0.224	0.01273	0.01301	2.61	37.486	2.460	3.293	98 902		342.3 kPa AA, f/a = 0.013	
	1164	2.070	0.0294	0.0218	0.0218	*0000	383.8	2.018	6.940	0.213	0.224	0.01067	0.01070	2.15	33.020	4.450	3.266	98.833		336.2 kPa AA, f/a = 0 0106	
	1165	2.077	0.0294	0.0263	0.0263	*0000	384.6	2.033	6.923	0.213	0.149	0.01280	0.01293	2.60	32.807	3.436	3.416	98.927		335.4 kPa AA, f/a = 0.0125	
(April 19, 1977)																					
	1457	3.947	0.0122	0.0242	0.0242	*0000	686.3	4.209	11,377	0.172	0.236	0.00622	0.00661	1.36	5.521	0.830	10.669	99.797		30.3 kPa AA, pilot only f/a = 0.006	
	1458	3.952	0.0128	0.0181	0.0181	*0000	684.7	4.162	11,495	0 181	0.255	0.00464	0.00501	1.03	8.882	0.876	9.510	99.714		38.3 kPa AA pilot only f/a = 0.005	
	1459	3.992	0.0124	0.0150	0.0150	*0000	684,6	4,168	11,600	0,238	0,286	0.00382	0.00409	0.84	13.329	1.225	9.028	99 579		361 kPa AA pilot only f/a = 0.004	
	1454	3.967	0.0120	0.0608	0.0242	0.0365	690.7	4.173	11.613	0.148	0.249	0.01552	0.01594	3.25	3.549	0.146	5.219	99.904		36.6 kPa AA, 60% secondary fuel, 15.2 CM mixing length	Takeoff
	1455	3.959	0.0114	0.0607	0.0181	0.0426	685.3	4.210	11.393	0.250	0.230	0.01552	0.01588	3.23	6.006	0.250	4.338	99.837		34.2 kPa AA, 70% secondary fuel	
	1456	3.970	0.0115	0.0608	0.0150	0.0458	685.3	4.200	11.454	0.278	0.230	0.01552	0.01616	3.29	8.123	0.409	3.668	99.773		35.4 kPa AA, 75% secondary fuel	
	1406	3.973	*00000	0.0608	0.0150	0.0458	688.2	4.194	11.527	0.285	0.230	0.01551	0.01612	3.27	9.773	0.545	3.612	99 722	0	75% secondary fuel	
	1450	3.977	0.0110	0.0606	0.0120	0.0486	683.5	4.200	11.448	0.293	0.211	0.01544	0.01603	3.24	15.580	1.305	3.544	99.519	0	33.8 kPa AA, 80% secondary fuel	
	1355	4.018	0.0112	0.0588	0.0176	0.0411	669.4	4.214	11.286	0.260	0.205	0.01481	0.01529	3.10	14.616	1.132	3.117	99.557	0	34.5 kPa AA, 70% secondary fuel	Climbout
	1755	3.971	0.0113	0.0626	0.0190	0.0436	647.6	4.197	10.830	0.269	0.205	0.01596	0.01646	3.34	9.479	0.671	3.518	99.718	0	70% secondary fuel, 35.9 kPa AA, 15.2 CM mixing length	Cruise
	1756	3.994	0.0113	0.0625	0.0156	0.0469	646.5	4.193	10.884	0.287	0.205	0.01584	0.01635	3.31	15.020	1.442	3.341	99.520	0	75% secondaru fuel, 36.1 kPa AA	

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CONCEPT NO. 3, REFINEMENT TEST NO. 2
(April 20, 1977)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
A-10	1255	5.803	0.0142	0.0569	0.0569	*0000	506.1	5.330	9.742	0.173	0.447	0.00994	0.01058	2.16	11.649	0.636	6.512	99.670		Pilot only, f/a = 0.010	Approach
	1256	5.771	0.0159	0.0469	0.0469	*0000	507.5	5.349	9.683	0.198	0.447	0.00822	0.00874	1.78	13.642	1.369	6.460	99.559		Pilot only, f/a = 0.008	
	1253	5.881	0.0160	0.0669	0.0469	0.0201	507.6	5.322	9.918	0.209	0.435	0.01152	0.01173	2.06	123.945	94.483	3.282	88.797		30% secondary fuel, 15.2 cm mixing length	
	1252	5.861	0.0163	0.0668	0.0569	0.0099	509.1	5.336	9.886	0.168	0.385	0.01154	0.01192	2.28	84.736	28.183	5.285	95.535		15% secondary fuel, 15.2 cm mixing length	
	1257	5.770	0.0167	0.0668	0.0569	0.0099	510.5	5.327	9.764	0.202	0.298	0.01172	0.01227	2.42	49.651	16.148	5.463	97.416		15% secondary fuel with fuel sectoring	
	1258	5.845	0.0163	0.0669	0.0469	0.0201	507.6	5.345	9.803	0.412	0.360	0.01159	0.01233	2.46	31.166	11.522	4.134	98.256		30% secondary fuel with fuel sectoring	

CONCEPT NO. 3, REFINEMENT TEST NO. 3

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
	(April 22, 1977)																				
A-11	2152	2.242	0.0095	0.0241	0.0241	*0000	379.5	2.039	7.410	0.202	0.323	0.01089	0.01103	2.00	76.024	89.589	1.738	90.353		32.7 kPa AA	
	2122	2.257	0.0205	0.0241	0.0241	*0000	381.0	2.023	7.542	0.216	0.205	0.01082	0.01074	2.11	45.715	23.798	2.507	96.837		136.2 kPa AA	
	2132	2.287	0.0267	0.0241	0.0241	*0000	380.0	2.038	7.571	0.231	0.186	0.0168	0.01049	2.09	39.414	12.517	2.700	97.975		203.7 kPa AA	Taxi-idle
	2162	2.291	0.0491	0.0241	0.0241	*0000	378.6	2.044	7.526	0.189	0.186	0.01066	0.01081	2.19	22.315	2.892	2.819	99.221		413.8 kPa AA	
	2182	2.300	0.0640	0.0241	0.0241	*0000	378.9	2.048	7.549	0.214	0.186	0.01062	0.01079	2.20	15.414	1.580	2.737	99.499		551.8 kPa AA	
	(April 23, 1977)																				
	2409	3.954	*00000	0.0150	0.0150	*0000	680.7	4.179	11.379	0.128	0.348	0.00385	0.00415	0.84	38.784	6.828	6.065	98.489		Pilot only f/a = 0.004	
	2406	3.912	*00000	0.0608	0.0150	0.0458	693.5	4.134	11.602	0.299	0.311	0.01575	0.01618	3.25	25.486	3.392	3.582	99.103		75% secondary fuel, 15.2 cm mixing length	Takeoff
	2456	3.958	0.0126	0.0608	0.0150	0.0458	694.7	4.154	11.707	0.333	0.336	0.01557	0.01603	3.21	31.624	5.797	3.264	98.748	0	75% secondary fuel, 33.7 kPa AA	
	2405	3.942	*00000	0.0609	0.0182	0.0427	692.4	4.152	11.625	0.322	0.304	0.01566	0.01592	3.20	25.098	2.687	3.399	99 174		70% secondary fuel	
	2305	4.003	*00000	0.0589	0.0177	0.0411	674.2	4.161	11.472	0.335	0.304	0.01490	0.01525	2.98	54.614	18.483	2.766	97.094	0	70% secondary fuel	
	2304	4.023	*00000	0.0587	0.0235	0.0353	674.1	4.155	11.540	0.180	0.236	0.01479	0.01525	3.05	35.282	5.248	3.283	98 710		60% secondary fuel	Climb
	2303	3.999	*00000	0.0622	0.0342	0.0280	676.3	4.169	11.469	0.141	0.217	0.01575	0.01632	3.32	9.643	0 211	5.335	99.755		45% secondary fuel	
	2704	4.022	*00000	0.0626	0.0250	0.0375	654.9	4.145	11.236	0.212	0.217	0.01575	0.01622	3.26	25.469	2.990	3 395	99.139		60% secondary fuel	Cruise
	2703	3.974	*00000	0.0623	0.0342	0.0281	655.6	4.210	10.941	0.148	0.217	0.01588	0.01635	3.32	11.711	0.392	4.955	99.690		45% secondary fuel	
	2502	4.504	*00000	0.0521	0.0443	0.0078	507.8	4.158	9.726	0.214	0.217	0.01173	0.01212	2.29	88.661	37.843	3.774	94.595		15% secondary fuel	
	2500	4.498	*00000	0.0522	0.0483	0.0040	509.2	4.176	9.698	0.234	0.217	0.01176	0.01202	2.37	53.742	14.629	4.663	97.453		7.5% secondary fuel	Approach
	2501	4.488	*00000	0.0522	0.0522	*0000	510.3	4.166	9.720	0.234	0.298	0.01179	0.01234	2.52	11.242	0.221	5.798	99.716		Pilot only	

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CONCEPT NO. 3, REFINEMENT TEST NO. 4

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(April 29, 1977)																					
A-12	3103	2.233	*00000	0.0194	0.0194	*0000	374.3	2.026	7.276	0.203	0.224	0.00878	0.00916	1.79	57.427	22.615	2.093	96.665		f/a = 0.009, 0.68 FN pilot nozzles	Taxi-idle
	3102	2.247	*00000	0.0242	0.0242	*0000	381.1	2.039	7.407	0.215	0.186	0.01093	0.01128	2.27	34.161	4.030	3.057	98.843			Taxi-idle
	3103	2.242	*00000	0.0291	0.0291	*0000	382.5	2.033	7.437	0.203	0.186	0.01313	0.01354	2.73	26.010	1.206	3.595	99.282		f/a = 0.013	Taxi-idle
	3206	5.802	*00000	0.0445	0.0445	*0000	505.6	5.336	9.710	0.150	0.373	0.00777	0.00831	1.70	7.438	0.355	5.134	99.794		Pilot only f/a = 0.008	Approach
	3203	5.812	*00000	0.0671	0.0445	0.0226	506.0	5.338	9.732	0.209	0.323	0.01169	0.01195	1.98	121.405	148.750	1.760	84.096		34% secondary fuel, 15.2 cm mixing length, 0.9 FN premix nozzles	Approach
	3502	4.516	*00000	0.0521	0.0444	0.0077	505.8	4.160	9.694	0.170	0.298	0.01168	0.01215	2.30	76.754	43.212	3.532	94.404		15% secondary fuel	Approach
(May 1, 1977)																					
	4102	2.257	*00000	0.0242	0.0242	*0000	377.3	2.039	7.361	0.278	0.249	0.01088	0.01117	2.18	51.017	27.659	2.222	96.374		0.9 FN pilot nozzles	Taxi-idle
	4103	2.220	*00000	0.0291	0.0291	*0000	377.7	2.058	7.181	0.270	0.249	0.01326	0.01371	2.73	36.323	10.237	2.754	98.248		f/a = 0.013	Taxi-idle
	4501	4.552	*00000	0.0522	0.0522	*0000	503.8	4.158	9.734	0.303	0.373	0.01162	0.01186	2.42	12.043	0.269	5.591	99.693	14	Pilot only	Approach
	4502	4.530	*00000	0.0518	0.0441	0.0077	504.3	4.157	9.703	0.258	0.336	0.01159	0.01174	2.22	81.640	42.152	3.726	94.382	10.5	15% secondary fuel, 0.68 FN premix nozzles, 15.2 cm mixing length	Approach

CONCEPT NO. 3, REFINEMENT TEST NO. 5

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal × 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
(May 27, 1977)																					
A-13A	5409	3.970	*00000	0.0150	0.0150	*0000	679.3	4.124	11 537	0.222	0.435	0.00384	0.00402	0.82	30.555	5.586	6.988	98.791		Pilot only f/a ≈ 0.004	Takeoff
	5102	2.325	0.0039	0 0241	0.0241	*0000	387.7	2.069	7.673	0.215	0.186	0.01050	0.01061	2.04	49.273	47.473	2.466	94.677			Taxi-idle
	5162	2.338	0.0415	0 0241	0.0241	*0000	382 8	2.032	7.760	0.260	0.162	0.01045	0.01081	2 20	17.219	0.976	3.026	99.509		402.4 kPa AA	
	5132	2.312	0.0287	0.0241	0.0241	*0000	381.9	2.042	7.612	0.231	0.162	0.01056	0.01066	2.14	32.152	6.744	2 988	98.652		202.2 kPa AA	
	5142	2.339	0.0349	0.0241	0.0241	*0000	379.5	2.055	7.603	0.246	0.162	0.01044	0.01062	2.15	26.022	2.982	2.998	99.126		280.7 kPa AA	
(June 22, 1977)																					
A-13A	5406	3.938	*00000	0.0615	0.0158	0.0457	686.1	4.100	11.563	0.270	0.112	0.01582	0.01595	3.25	5.240	0.411	4.323	99.841		75% secondary fuel, 15.2 cm mixing length	
	5400	3.955	*00000	0.0610	0.0123	0.0488	681.3	4.080	11.593	0.264	0.112	0.01563	0.01564	3.17	13.612	0.713	3.991	99.617		80% secondary fuel	Takeoff
	5409	3.956	*00000	0.0156	0.0156	*0000	683.6	4.056	11.698	0.233	0.112	0.00399	0.00434	0.89	7.437	0.885	7.782	99.747		Pilot only f/a ≈ 0.004	
(September 25, 1977)																					
A-13A	5200	5.787	*00000	0.0670	0.0619	0.0051	510.9	5.328	9.828	0.207	0.071	0.01173	0.01303	2.57	41.294	19.076	5.100	97.355		7.6% secondary fuel, 0 mixing length	
	5202	5.794	*00000	0.0668	0.0569	0.0099	512.5	5.275	9.972	0.213	0.075	0.01167	0.01269	2.43	54.971	42.837	4.282	94.949	20.5	15% secondary fuel	Approach
	5203	5.829	*00000	0.0670	0.0470	0.0201	509.5	5.314	9.901	0.198	0.075	0.01165	0.01234	2.18	77.907	115.790	2 573	88.011	11	30% secondary fuel	
	5207	5.842	*00000	0.0872	0.0470	0.0402	511.7	5.266	10.055	0.191	0.062	0.01512	0.01580	2.85	69 438	95.255	2.701	90.011	7.5	46% secondary fuel	
	5406	3.935	*00000	0.0614	0.0157	0.0457	683.2	4.040	11.789	0.153	0.062	0.01579	0.01564	3.17	9.864	2.389	3.308	99.558	0	74% secondary fuel	Takeoff
	5405	3.903	*00000	0.0614	0.0189	0.0426	691.1	4.092	11.673	0.160	0.062	0.01594	0.01557	3.17	5.932	1 138	4.003	99.761	0	70% secondary fuel	
	5305	3.953	*00000	0.0595	0.0182	0.0413	671.0	4.123	11.399	0.149	0.062	0.01525	0.01526	3.08	19.496	1.866	3.419	99.378	0	69% secondary fuel	Climb
	5705	3.928	*00000	0.0631	0.0192	0.0439	651.4	4.100	11.051	0.158	0.062	0.01627	0.01624	3.29	11.555	2.382	3 452	99.519		69.5% secondary fuel	Cruise
	5204	5.828	*00000	0.0672	0.0520	0.0152	509.3	5.327	9.871	0.260	0.068	0.01167	0.01208	2 35	54.683	29.551	5.084	96.122	17	22 6% secondary fuel with fuel sectoring	Approach
	5200	5.815	*00000	0.0670	0.0619	0.0051	512.9	5.308	9.961	0.211	0.068	0.01167	0.01230	2.44	42.899	13.843	6.171	97.777	23	7.6% secondary fuel, with fuel sectoring	
	5203	5.839	*00000	0.0670	0.0470	0.0201	510.5	5.315	9.938	0.416	0.056	0.01163	0.01184	2.26	61.695	43.948	5.009	94.694	8	30% secondary fuel with fuel sectoring	
(October 1, 1977)																					
A-13B	6162	2.214	0.0224	0.0249	0.0249	*0000	383.2	2.043	7.311	0.212	0.056	0.01138	0.01129	2.30	17.917	0.701	3.107	99.517		414.7 kPa AA	Taxi-Idle
	6182	2.252	0.0276	0.0249	0.0249	*0000	384.4	1.983	7.690	0.200	0.050	0.01119	0.01109	2.25	17.863	0.443	2.964	99.541		551.6 kPa AA	
	6500	4.440	*00000	0.0522	0.0483	0.0040	511.5	4.140	9.665	0.174	0.050	0.01191	0.01251	2.47	43.336	18.813	5.318	97.330		7.6% secondary fuel, 0 mixing length	Approach
	6406	3.843	*00000	0.0615	0.0158	0.0457	684.3	4.141	11.185	0.199	0.081	0.01621	0.01617	3.29	3.812	0.202	4.029	99.893		74% secondary fuel	Takeoff
	6400	3.891	*00000	0.0612	0.0125	0.0486	686.3	4.138	11.366	0.163	0.081	0.01592	0.01595	3.25	5.001	0.115	3.548	99.872		80% secondary fuel	
	6306	3.895	*00000	0.0596	0.0153	0.0442	670.9	4.122	11.172	0.152	0.081	0.01548	0.01519	3.09	9.515	0.309	3.363	99.749		74% secondary fuel	Climb
	6506	4.424	0.0105	0.0365	0.0365	*0000	507.5	4.183	9.467	0.196	0.050	0.00836	0.00884	1.80	19.149	1.119	5.061	99.451		Pilot only f/a ≈ 0.009	Approach
	6503	4.448	*00000	0.0521	0.0365	0.0156	507.5	4.131	9.642	0.378	0.050	0.01187	0.01211	2.36	59.085	21.656	3.879	96.710		30% secondary fuel with sectoring of both pilot and secondary nozzles	
	6507	4.450	*00000	0.0523	0.0458	0.0065	509.9	4.132	9.688	0.318	0.050	0.01190	0.01207	2.39	50.915	11.191	4.806	97.821		12.4% secondary fuel with sectoring of both pilot and secondary nozzles	

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CONCEPT NO. 3, REFINEMENT TEST NO. 5
(November 20, 1977)

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon, Balance	CO_2 Percent by Volume	Emission Index -- CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments	
A-13A	5409	3.794	*00000	0.0158	0.0158	*0000	681.3	4.176	10.908	0.355	0.047	0.00417	0.00464	0.95	10.556	1.411	7.095	99.628		Pilot only f/a = 0.004	Takeoff
	5408	3.790	*00000	0.0189	0.0189	*0000	683.1	4.135	11.032	0.355	0.047	0.00498	0.00544	1.12	6.607	1.007	7.463	99.756		Pilot only f/a = 0.005	
	5407	3.807	*00000	0.0250	0.0250	*0000	683.9	4.114	11.159	0.290	0.047	0.00657	0.00703	1.45	3.947	0.637	8.589	99.851		Pilot only f/a = 0.007	
	5201	5.655	*00000	0.0671	0.0671	*0000	512.3	5.282	9.667	0.216	0.047	0.01186	0.01266	2.58	6.888	0.320	6.248	99.810		Pilot only	Approach
	5208	5.628	*00000	0.0671	0.0663	0.0008	514.6	5.264	9.694	0.228	0.047	0.01192	0.01274	2.59	15.269	1.421	6.134	99.516		One percent premix, 15.2 cm mixing length	

APPENDIX C

ENGINE/RIG CORRELATION TEST RESULTS

Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Primary Fuel Flow, kg/sec	Secondary Fuel Flow, kg/sec	Inlet Total Temp., K	Inlet Total Pressure, Pascal × 10^{-5}	Ref. Velocity, m/sec	Temp. Spread Factor	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.		Comments

NASA T1 RIG REFINEMENT TEST NO. 4

(September 17, 1977)

A-4B	2001	2.013	0.0059	0.0247	0.0247	*0000	400.0	1.889	7.592	0.102	0.087	0.01245	0.01242	2.45	49.845	13.388	2.679	97.653		69.8 kPa AA	Taxi-idle
	2003	2.017	0.0110	0.0247	0.0247	*0000	400.1	1.894	7.583	0.121	0.087	0.01243	0.01243	2.48	40.484	8.154	2.732	98.332		207.2 kPa AA	
	2005	2.019	0.0166	0.0247	0.0247	*0000	399.8	1.896	7.579	0.143	0.087	0.01242	0.01235	2.48	31.027	3.280	2.645	98.982		379.0 kPa AA	
	2007	2.020	0.0190	0.0247	0.0247	*0000	400.4	1.898	7.584	0.119	0.087	0.01241	0.01240	2.50	30.594	2.631	2.604	99.050		457.2 kPa AA	
	2103	2.366	0.0115	0.0266	0.0266	*0000	407.4	2.039	8.436	0.101	0.087	0.01140	0.01152	2.31	37.250	4.159	2.757	98.759		211.9 kPa AA	
	2105	2.370	0.0168	0.0266	0.0266	*0000	409.2	2.042	8.473	0.133	0.087	0.01138	0.01159	2.34	30.292	2.101	2.746	99.103		376.3 kPa AA	
	3103	3.939	0.0145	0.0501	0.0501	*0000	492.5	3.528	9.813	0.084	0.087	0.01289	0.01316	2.69	6.477	0.378	4.594	99.814		210.3 kPa AA	15% max. thrust

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Configuration - Ref. Appendix A Figure	Condition No.	Total Combustor Airflow, kg/sec	Air-Assist Flow, kg/sec	Total Fuel Flow, kg/sec	Thrust, N	Comb. Inlet Temp., K	Inlet Total Pressure, Pascal x 10^{-5}	Ref. Velocity, m/sec	Eng. Inlet Temp., K	Eng. Inlet Press., Pa x 10^{-5}	Inlet Air Humidity, gm/kg	Fuel/Air Ratio, Metered	Fuel/Air Ratio, Carbon Balance	CO_2 Percent by Volume	Emission Index - CO	Emission Index - HC	Emission Index - NO_x Corr. for Humidity	Gas Sample Combustion Efficiency	SAE Smoke No.	Comments
TFE731-2 ENGINE S/N 7353-23B/01 REFINEMENT TEST NO. 4 (September 6, 1977)																				
A-4B	1	2.085	0.0055	0.0252	894.1	NM	1.878	--	312.4	0.969	10.48	0.0122	0.0121	0.43	28.03	6.999	2.98	98.725		69 kPa AA; Taxi-idle
	2	2.110	0.0010	0.0251	899.0	↓	1.892	↓	312.0	↓	↓	0.0119	0.0119	2.40	20.864	2.447	2.895	99.294		207 kPa AA
	3	2.090	0.0151	0.0251	883.4		1.892		312.4			0.0120	0.0120	2.38	20.899	1.455	2.579	99.380		379 kPa AA
	4	2 083	0.0180	0.0252	894.1		1.878		312.7			0.0121	0 0115	2.33	19.337	1.189	2.706	99.441		462 kPa AA
	5	2.367	0.0153	0.0267	1085.8		2.072		312.7			0.0113	0.0110	2.24	20.786	1.471	2.818	99.382		379 kPa AA 250 lbs thrust
	6	2.282	0.0104	0.0272	1085.8		2.072		313.1			0.0119	0.0111	2.26	16.944	1.535	3.088	99.466		207 kPa AA 250 lbs thrust
	7	5.462	0.0114	0.0770	4648.4		5.070		311.9			0.0142	0.0144	2.94	2.118	0.297	6.776	99.924		138 kPa AA; Approach
	8	5.288	0.0	0.0767	4586.1		5.028		313.5			0.0145	0.0144	2.94	2.119	0.238	6.947	99.929		No air assist
	9	3.933	0.0115	0.0503	2781.9		3.563		312.8			0.0128	0.0126	2.58	3.675	0.271	4.938	99.890		207 kPa AA; 15% max thrust
TFE731-2 ENGINE S/N 7353-27A OPTIMIZATION TEST NO. 1 (March 15, 1978)																				
A-6E	1	NM	0.0	0.216	14145.3	698.2	13.259	--	259.9	0.978	2.945	NM	0.0172	3.51	0.65	0.29	12.93	99.96	16	Takeoff
	2	↓	0.0	0.212	13700.5	698.2	12.914	↓	↓	0.978	↓	↓	0.0170	3.45	0.66	0.30	13.04	99.96	16.5	Climbout
	3		0.0	0.176	11476.4	662.6	11.259			0.979			0.0158	3.22	1.32	0.32	10.00	99.94	18	70% max thrust
	4		0.0	0.118	7468.6	594.3	7.812			0.980			0.0140	2.86	6.16	0.48	6.70	99.81	20	50% max thrust
	5		0.0	0.0775	4555.0	527.0	5.400		296.5	0.982			0.0125	2.53	24.35	1.22	4.67	99.32		Approach
	6		0.0160	0.0254	889.6	382.6	2.017		296.5	0.983			0.0110	2.10	92.81	28.36	2.00	95.33		Taxi-idle [1]
NOTE 1: 379 kPa Air Assist																				
TFE731-2 ENGINE S/N 7353-27A/B OPTIMIZATION TEST NO. 1 (April 7, 1978)																				
A-6E	1	12.15	0.0	0.202	13261.9	695.8	12.58	11.80	297.9	0.967	3.998	0.0166	0.0167	3.39	0.45	0.10	11.69	99.98		Takeoff
	2	11.49	0.0	0.183	12161.4	678.7	11.79	11.61	297.6	↓	↓	0.0159	0.0159	3.25	0.71	0.11	10.38	99.97		Climbout
	3	10.29	0.0	0.152	10185.5	647.2	10.14	11.53	297.3			0.0148	0.0150	3.05	1.65	0.11	8.44	99.95		70% max thrust
	4	7.59	0.0	0.1055	6843.6	586.4	7.25	10.79	298.1			0.0139	0.0138	2.81	6.13	0.18	6.20	99.84		50% max thrust
	5	5.15	0.0	0.068	4066.6	517.9	4.85	9.66	297.7			0.0132	0.0125	2.53	26.84	1.35	4.34	99.25		Approach
	6	2.126	0.0160	0.247	887.9	385.7	1.926	7.42	298.7			0.0116	0.0110	2.10	98.04	23.09	1.94	95.67		Taxi-idle [2]
NOTE 2: 379 kPa Air Assist																				
TFE731-2 ENGINE S/N 7353-27A/01 OPTIMIZATION TEST NO. 1 (April 20, 1978)																				
A-6F	1	2.41	0.0	0.0253	885.6	390.7	1.952	8.14	302.7	0.971	3.41	0.0105	0.0115	2.32	22.233	3.385	3.067	99.18		Taxi-idle
	2	2.72	↓	0.0288	1094.4	403.8	2.177	8.86	302.2	↓	↓	0.0106	0.0116	2.36	15.491	1.748	3.167	99.482		Taxi-idle [3]
	3	3.82		0.0412	1996.8	453.8	3.116	9.77	302.6			0.0108	0.0114	2.32	6.204	1.263	3.972	99.743		15% max thrust
	4	5.55		0.0704	4053.7	528.7	5.003	10.30	302.0			0.0127	0.0130	2.65	2.131	0.716	6.166	99.887		Approach
	5	2.28		0.0237	796.1	385.65	1.836	8.41	303.0			0.0104	0.0113	2.28	23.648	3.138	2.910	99.168		Sub-idle
NOTE 3: 250 lbs thrust																				

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APPENDIX D

ABBREVIATIONS AND SYMBOLS

LP	Low Pressure
HP	High Pressure
HC	Unburned Hydrocarbons
CO	Carbon Monoxide
NO_x	Oxides of Nitrogen
CO2	Carbon Dioxide
LTO	Landing-Takeoff
EPA	Environmental Protection Agency
EPAP	EPA Parameter
EI	Emissions Index
T_T	Total Temperature
P_T	Total Pressure
H	Specific Humidity
PM/PV	Premixing/Prevaporizing
$\emptyset_{PZ}$	Primary Zone Equivalence Ratio
C_D	Flow Coefficient
SMD	Sauter Mean Diameter
TSF	Temperature Spread Factor

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