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POLLUTION TECHNOLOGY PROGRAM, CAN-ANNULAR COMBUSTOR ENGINES FINAL REPORT

by

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FOREWORD

This document describes the work conducted by Pratt & Whitney Aircraft Division of United Technologies Corporation during the Pollution Technology Program, Can-Annular Combustor Engines. This final report was prepared for the National Aeronautics and Space Administration (NASA) Lewis Research Center in compliance with the requirements of Contract NAS3-18548.

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SUMMARY

The objective of this Pollution Reduction Technology Program was to generate and demonstrate the technology required to develop commercial CTOL (conventional take-off and landing) aircraft engines with lower exhaust emissions. This report describes the results of a 16-month program directed at the JT8D-17 (EPA class T4) aircraft engine. Although the JT8D-17 engine was selected as the base engine for this program, the technology developed will be applicable to other engines with can-annular combustor systems.

The overall program was accomplished by means of the design, fabrication, experimental combustor rig testing, and assessment of results for a series of three combustor elements. The three concepts evaluated under this program represent increasing potential for achieving the program emission goals but with attendant increases in complexity and difficulty of development and adaption to an operational engine.

Program Element I consisted of minor modifications to the existing JT8D combustor and fuel system such as the evaluation of air atomizing fuel nozzles and changes in the air flow distribution of the combustor. Program Element II addressed advanced versions of the two-stage Vorbix (vortex burning and mixing) combustor. Vorbix combustors, included under the National Aeronautics and Space Administration/Pratt & Whitney Aircraft (P&WA) Experimental Clean Combustor Program and other P&WA programs, have exhibited potential for significant emissions reduction. Program Element III evaluated two-stage combustor schemes which employed vaporized fuel as a means of controlling flame stoichiometry for attaining minimum emission levels. Emphasis was placed on oxides of nitrogen (NO_X) reduction at high power operating conditions.

Various configurations within each of these concepts, involving a total of 20 test configurations, were evaluated for emissions, performance and relight characteristics. Testing was conducted in a single segment test rig simulating a 40° segment of the JT8D engine including compressor discharge, diffuser struts and air cooled turbine entrance transition duct. The combustor rig test conditions for this program matched the actual JT8D-17 power levels specified by the Environmental Protection Agency (EPA) for the calculation of EPA parameters (EPAPs).

Combustor test rig results indicate that significant reductions were made to emission levels of the current production JT8D combustor by the concepts in all three program elements. One of the Element I single-stage concepts reduced carbon monoxide (CO) to near, and total unburned hydrocarbons (THC) and smoke emission levels below the 1979 EPA standards with little or no improvements in NO_X. The two-stage advanced Vorbix concept evaluated in Program Element II achieved the THC standards, but the CO and NO_X values were higher than the EPA standards; both the CO and NO_X EPAPs were reduced to approximately 50% of the baseline or production JT8D combustor and smoke levels were marginally acceptable. Although the Element III prevaporized-premixed concept reduced the high power NO_X to a level 20% below the Element II results, there was no improvement on an EPAP basis relative to the advanced Vorbix combustor.

Emphasis has been given to documentation of emissions reduction potential in this combustor rig assessment program. Relative ranking of the concepts and comparison with the program goals has been done on this basis. Combustor performance was measured in conjunction with the emissions tests, and a number of deficiencies have been identified which will require further development. In addition, such items as transient stability and long term cyclic durability can only be determined in actual engine testing, which was not undertaken in this program.

CHAPTER I: INTRODUCTION

The objective of the Pollution Reduction Technology Program, Can-Annular Combustor Engines is to generate and demonstrate the technology required to develop commercial CTOL aircraft engines with lower exhaust emissions. This is to be accomplished by means of the design, fabrication, experimental combustor rig testing, and assessment of results for a series of combustor concepts.

The deteriorating air quality in metropolitan areas has become an item of concern over the past several years. Aircraft have been implicated due to the proximity of airports to these areas. Additionally, recent studies have indicated there may be potential problems associated with certain aircraft exhaust emissions released at high altitudes. While the overall contribution of gas-turbine powered aircraft to atmospheric pollution is small compared to other sources, it is of concern and an area where advanced technology has the potential to reduce pollutant levels.

Various government-sponsored studies have been conducted to define the problem and, in the case of pollution around airports, have resulted in the issuance of emission standards by the Environmental Protection Agency (EPA). These standards establish maximum emission levels in gas-turbine engine exhaust for carbon monoxide (CO), total unburned hydrocarbons (THC), oxides of nitrogen (NO_X) and smoke at altitudes below 915 meters.

The concern for pollutants released by aircraft engines at high altitudes relates primarily to depletion of the ozone layer in the stratosphere through reaction with the oxides of nitrogen. This problem has been studied under the Department of Transportation's Climatic Impact Assessment Program. The Report of Findings from this program concluded that control of emission of oxides of nitrogens at high altitude may be required in the future.

Pratt & Whitney Aircraft has been conducting a number of technology development efforts addressed to the EPA emission standards for commercial aircraft engines. A significant part of this effort has been the Experimental Clean Combustor Program, sponsored by the National Aeronautics and Space Administration - Lewis Research Center. This is a three phase, multi-year effort specifically directed at the EPA Class T2 - JT9D engine family. Under this program, three advanced combustor concepts were screened for emissions reduction potential in rig tests, and two of these were further refined in additional rig test preparatory to selection of a single concept for engine demonstration testing. The third phase of this program, consisting of full scale engine testing of the single most promising concept, is currently in progress. The combustor concepts investigated in the Experimental Clean Combustor Program have demonstrated the capability to meet the EPA standards for THC and smoke, and to substantially reduce the emissions of CO and NO_X from current day levels.

The National Aeronautics and Space Administration initiated the Pollution Reduction Technology Program (PRTP) in response to the need to develop technology for the reduction of emissions covering a range of aircraft engine types. This report describes the results of a program directed at the EPA Class T4 engines, which comprise the various models of the P&WA JT8D engine family. The JT8D-17 engine was selected as the base engine for this program; however, the technology developed would be transferrable to any engine using can-annular combustors.

PROGRAM GOALS

Pollution Goals

The pollution goals for this program are based on the EPA standards established for Class T4 which are applicable to the JT8D engine. These goals, expressed as integrated EPA Parameters, are:

POLLUTANT	EPA PARAMETER
Carbon Monoxide	4.3 lb CO/1000 lb thrust-hr/LTO cycle
Total Hydrocarbons	0.8 lb THC/1000 lb thrust-hr/LTO cycle
Oxides of Nitrogen	3.0 lb NO_2*/1000 lb thrust-hr/LTO cycle
Smoke	Maximum SAE Smoke Number of 25

*Nitrogen Dioxide equivalent of all the Oxides of Nitrogen

Screening tests of the various combustor configurations were conducted at five power levels, corresponding to the four EPA power points idle, approach (30%),climbout (85%) sea level takeoff (100%) and simulated high altitude cruise. A hypothetical set of emission indices which would satisfy the EPA CO, THC and NO_x standards can be determined by a proportional reduction of the current JT8D-17 emission levels at the four EPA power points. The resultant CO and THC indices at idle and NO_x index at sea-level take-off are shown below. Since the EPA standards are in the form of an integrated parameter, other sets of emission indices would also suffice.

POLLUTANT	EMISSION INDEX	OPERATING CONDITION
Carbon Monoxide	12.2 g CO/kg fuel	idle
Total Hydrocarbons	2.1 g THC/kg fuel	idle
Oxides of Nitrogen	5.2 g NO_2/kg fuel	take-off

Performance Goals

The combustor performance goals for this program are as follows:

Combustion Efficiency	$\geqslant$ 99% (all conditions)
Total Pressure Loss	$<$ 8.3% (cruise)*
Exit Temperature Pattern Factor	0.25 (take-off and cruise)

*Typical maximum JT8D-17 cruise operating conditions:

Altitude = 9140 m, M_N = 0.8, T_3 = 613K, P_3 = 6.83 atm

PROGRAM PLAN

The Phase I program was subdivided into three elements. Each successive element represented a greater potential for achieving the program emission goals but with increasing complexity and/or difficulty in combustor development, as well as increased difficulty in adapting the combustor concept to the JT8D engine. Each program element was accomplished in four tasks: Task I, Preliminary Design; Task II, Final Design; Task III, Fabrication and Installation; Task IV, Combustor Assessment Test. During the Task IV tests, the following areas were investigated: oxides of nitrogen reduction, carbon monoxide and total hydrocarbon pollutant reductions, combustor performance and durability, and altitude relight capability. Task V consisted of assessment of results for one or two of the most promising configurations from each program element, with emphasis on the problem areas associated with incorporating the selected configurations in a JT8D engine.

Program Element I consisted of minor modifications to the existing JT8D combustor and fuel system. These modifications included evaluation of air atomizing fuel nozzles and changes in the airflow distribution of the JT8D combustor.

Program Element II addressed advanced versions of the Vorbix (vortex burning and mixing) combustor. Vorbix combustors, evaluated under the NASA/P&WA Experimental Clean Combustor Program (Ref. 1) and other P&WA programs, have exhibited potential for significant emissions reduction. Relative to program Element I, Element II hardware was more complex and the difficulty in adapting this hardware to an operational engine was increased.

Program Element III evaluated combustor schemes which employ vaporized fuel as a means of controlling flame stoichiometry for attaining minimum emission levels. Emphasis was placed on NO_x reduction at high power operating conditions. While variable geometry may be necessary with pre-vaporization to provide minimum emissions and stable burning over the full engine operating range, it was not investigated in this program. This program element, while having the highest potential for meeting the program goals, represented the greatest difficulty of development and adaptation to the JT8D engine.

The Phase I program was completed according to the following schedule (Figure 1).

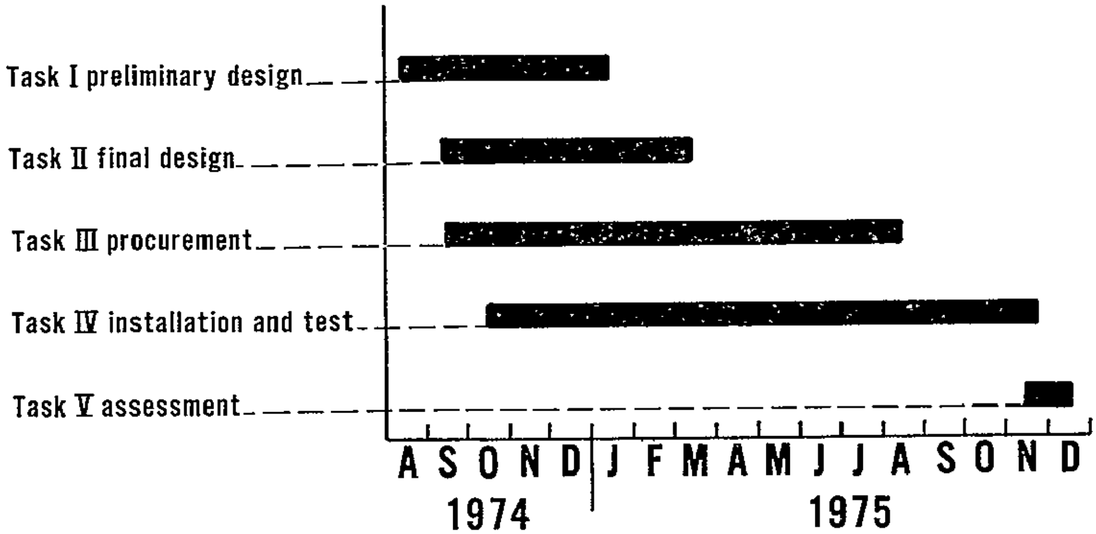


Figure 1 Program Schedule

CHAPTER II: EQUIPMENT AND PROCEDURES

GENERAL DESCRIPTION OF THE JT8D-17 ENGINE AND COMBUSTOR

Engine Description

The JT8D-17 engine model was selected as the baseline for this experimental program. This engine is the current production version of the JT8D engine, which is in widespread use throughout the commercial transport fleet. The JT8D turbofan engine is an axial flow, dual-spool, moderate bypass-ratio design. It utilizes a two stage fan and a four stage low-pressure compressor driven by a three-stage low-pressure turbine, and a seven-stage high-pressure compressor driven by a single-stage high-pressure turbine. Figure 2 is a cross-section of the JT8D-17 showing the mechanical configuration. Key specifications for this engine are listed in Table I.

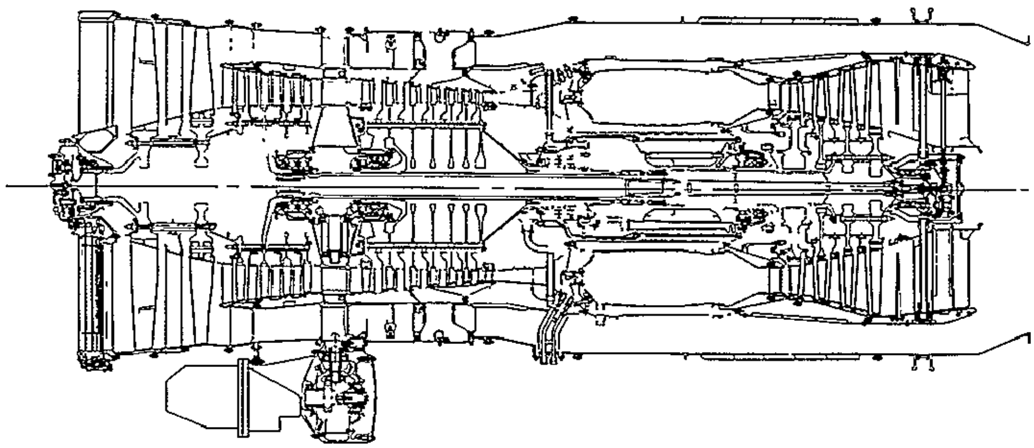


Figure 2 Cross-Section of JT8D-17 Engine

TABLE I

KEY SPECIFICATIONS OF THE JT8D-17 ENGINE

Weight (kg)	1510.5
Length (m)	3.045
Maximum Diameter, cold (m)	1.080
Pressure Ratio	16.9
Airflow Rate (kg/s)	148.3
Maximum Sea-Level Static Thrust (kN)	71.2
Cruise Performance	
Mach Number	0.8
Altitude (m)	9140
Thrust (kN)	18.9
Specific Fuel Consumption (kg/Ns)	2.273×10^{-5}

Combustor Description

The JT8D-17 combustor section consists of nine tabular combustion chambers in a can-annular arrangement. Each chamber contains one centrally located duplex fuel nozzle. Two of the chambers are equipped with spark igniters. The nine combustion chambers are interconnected by tubes for flame propagation during starting. Each combustion chamber is of welded construction comprised of a series of formed sheet metal cylindrical liners. Each chamber is supported at the front by the fuel nozzle strut and a mount pin, and at the rear by a sliding joint at the face of the turbine inlet transition duct. A cross-sectional schematic of the JT8D-17 combustor is shown in Figure 3 and its key operating parameters are listed in Table II.

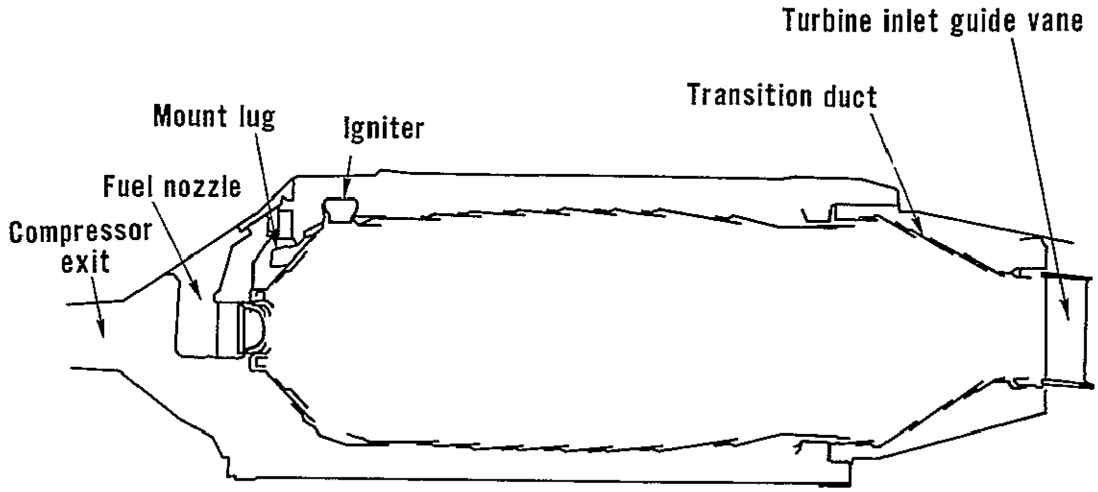


Figure 3 *Cross-Sectional Schematic of the Baseline JT8D-17 Combustor*

TABLE II

KEY OPERATING PARAMETERS OF THE JT8D COMBUSTOR

Compressor Exit Axial Mach Number	.42
Compressor Discharge Temperature (K)	714
Combustor Temperature Rise (K)	633
Average Combustor Exit Temperature (K)	1348
Combustor Section Pressure Loss (%)	8.2
Combustor Exit Temperature Pattern Factor	.39
Burner Length (cm)	45.4

Note: All data for standard day sea-level static take-off conditions

Baseline Engine Pollution Levels

Exhaust emission data were measured for the baseline engine combustor in engine and rig tests. A set of nine combustors were tested in an experimental engine operated on a JT8D-17 cycle in a sea-level test stand. The combustor was also tested in a single can sector rig installed at the P&WA high pressure test facility. This test facility is capable of exactly simulating the complete range of JT8D-17 combustor inlet conditions. Emission sampling in the test rig was accomplished with an instrumented turbine inlet guide vane pack with manifold sampling ports in the leading edges of the vanes.

The results of these tests are shown as emission indices (EI) in Table III along with the EI target values for idle, approach, climb and sea-level take-off (SLTO) conditions. The engine and rig EI's are corrected to standard day temperature and pressure and to an ambient humidity of 6.3g H_2O/kg dry air. Except for the total unburned hydrocarbons at high power settings (SLTO and climb), large reductions in pollutant levels are required to meet the EI goals.

TABLE III

EMISSION INDEX GOALS AT JT8D-17 POWER LEVELS
COMPARED TO BASELINE

	CO			THC			NO_x		
Mode	Goal	Eng.	Rig	Goal	Eng.	Rig	Goal	Eng.*	Rig*
Idle	12.2	40.9	44.5	2.1	11.4	12.8	3.2	4.0	3.7
Approach (30% SLTO)	1.1	10.4	7.5	0.40	0.80	0.67	4.2	8.2	8.5
Climb (85% SLTO)	0.20	0.84	0.89	0.13	0.10	0.04	5.1	18.6	20.0
SLTO	0.16	0.67	0.55	0.11	0.10	0.03	5.2	22.7	24.4

*Specific humidity = 6.3 grams of water per Kilogram of dry air

Table IV presents a comparison of the baseline engine and rig emission levels with the standards established for class T4 engines by the U. S. Environmental Protection Agency in terms of the EPA parameter (EPAP). The EPAP integrated the emission rates at idle, approach, climb and take-off over a specified landing, take-off (LTO) cycle (Ref. 2). The EPAP values contained in Table IV have been calculated from the EI's in Table III. Except for the smoke number, substantial reductions are required for the JT8D-17 to meet the EPA standards.

TABLE IV

EPAP PROGRAM EMISSION GOALS COMPARED TO BASELINE

Pollutant	EPA Parameter	Current JT8D-17 Engine Emissions Data	JT8D-17 Rig
CO	4.3	15.3	16.1
THC	0.8	4.0	4.4
NO_x	3.0	7.8*	8.2*
Smoke (SAE Number)	⩽ 25	25-30	25-30

*Specific humidity = 6.3 grams of water per kilogram of dry air

COMBUSTOR CONFIGURATIONS TESTED

The three concepts evaluated under this program represent increasing potential for achieving the program emission goals but with attendant increases in hardware complexity, development difficulty and adaption to an operational engine. Schematics showing the details of the various configurations and air flow schedules are presented in Appendix A. The concepts and configurations for each program element are briefly described in the following sections.

Element I Combustor Configurations

The objective of the Element I program was to determine the magnitude of emissions reduction obtainable with minimal changes to existing combustion section hardware. Prior to emission considerations, the conventional direct-injection, single-stage combustor was optimized for high power performance consistent with reasonable idle combustion efficiency, stability, altitude relight, etc. The fuel-air mixture in such a combustor may be characterized as non-homogeneous, with a wide spectrum of local equivalence ratios. At engine idle, the combustor operates under adverse conditions of low inlet air temperature and pressure, and low fuel flow. In addition, low fuel injection pressure for the conventional dual orifice fuel nozzle at these conditions results in poor atomization. The combined effect of these factors, together with the overall lean primary zone equivalence ratio, is to promote irregular burning, premature quenching of the CO oxidation reaction, and consequently reduced combustion efficiency. At high engine power settings, physical limitations on fuel evaporation and fuel-air mixing favor stoichiometric burning, with consequent high NOx formation rate. The key ingredients for emission improvement in a conventional direct-injection combustor are therefore, improved control of the burning fuel air mixture equivalence ratio, via improved fuel-air mixture preparation, and manipulation of the combustor primary and secondary zone air schedules. Since Element I was confined to single-stage concepts, a compromise between the competing requirements for control of idle and high power emissions was necessary. The modifications investigated include airblast fuel nozzles, primary zone airflow distribution, and fuel-air carburetion. Six Element I configurations were evaluated. Appendix A contains detailed schematics and flow schedules for the Element I configurations. The following sections discuss specific features of the Element I concepts and describe the configurations.

Primary Zone Air Flow Distribution

The Element I configurations may be classified in terms of the primary zone airflow distribution, either "lean" or "rich" when compared to the baseline JT8D-17 production combustor. The terms lean and rich represent deviation from the baseline, rather than an absolute value of average primary zone equivalence ratio.

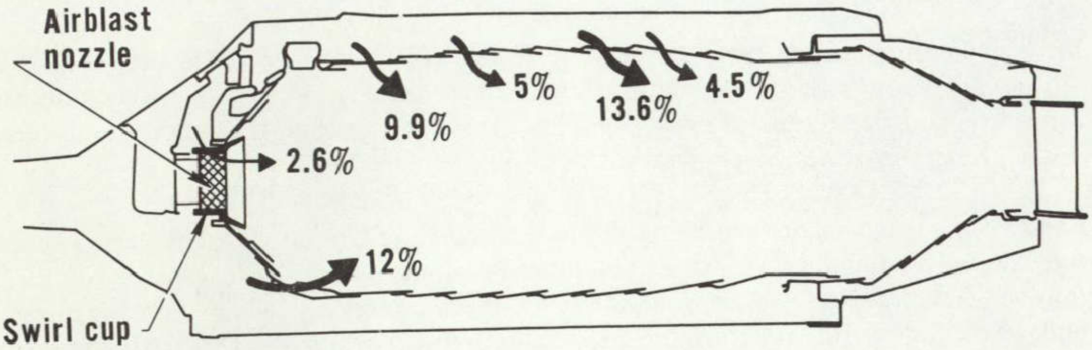
The design of the lean and rich front end burners proceeded from prior experience. These concepts had reduced high power NO_x in in-house programs by approximately 30-50% (Ref. 3). However, since the fuel and air were not well mixed, excessively lean or rich mixtures, on a bulk basis, were required before the NO_x reduction was achieved. This approach compromises other aspects of burner operation. Lean front end burners tend to have problems with lighting, lean blowout, altitude relight and low power emissions. Rich front end burners tend to produce excessive smoke and carbon, while improving CO and THC at idle. Since these problems are due to large mixture inhomogeneity in the front end, better fuel preparation, including the use of airblast nozzles, was incorporated in the Element I lean and rich combustor configurations. A general emissions prediction model (Ref. 4) was utilized to analytically select specific combustor configurations for fabrication and testing.

Fuel Preparation

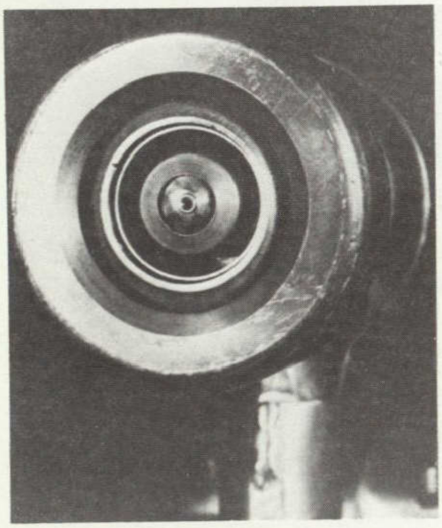
Airblast Nozzles

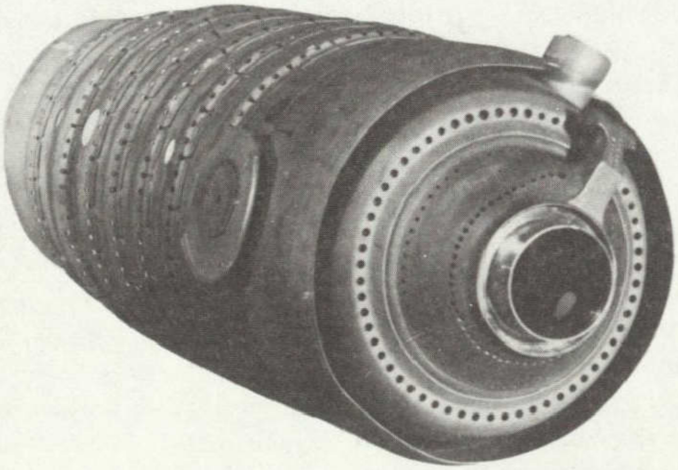
Two airblast nozzles were chosen for investigation. Nozzle #1 is a scaled version of a nozzle which had demonstrated some effectiveness in reducing high power smoke and low power CO and THC emissions during an in-house engine development program. The nozzle is a dual orifice type comprised of a conventional pressure-atomizing primary surrounded by an annular, aerating secondary. This nozzle was designed to provide the same primary/secondary fuel schedule as the production pressure-atomizing fuel nozzle. The airblast secondary fuel passage consists of an annular fuel swirl chamber from which the fuel issues in a conical sheet. Adjacent inner and outer jets of swirling air promote atomizing and fuel-air mixing close to the nozzle face. In this particular model, nozzle air swirl is impacted counter to the direction of the production burner swirler air. Since this nozzle was designed as a direct replacement for the production JT8D nozzle, neither fuel nozzle support nor burner can rework were necessary.

The second airblast nozzle configuration was selected during the test phase of this contract because of very favorable low power emissions and high power smoke levels produced during in-house development programs. This nozzle, shown in Figure 4 with the lean front end configuration (I-4), incorporates a pressure-atomizing primary and airblast secondary, and is similar in concept to airblast nozzle # 1. The significant design difference is that this nozzle tip features a dynamic air feed whereas nozzle # 1 relies on a static air feed. Airblast nozzle # 2 required increased primary fuel pressure and reduced secondary fuel pressure when compared to the production JT8D-17 nozzle. The production fuel nozzle support was modified to minimize blockage of airflow to the airblast nozzle tip. Furthermore, the production burner required rework to accept this larger diameter nozzle.



Lean primary zone with airblast nozzle II





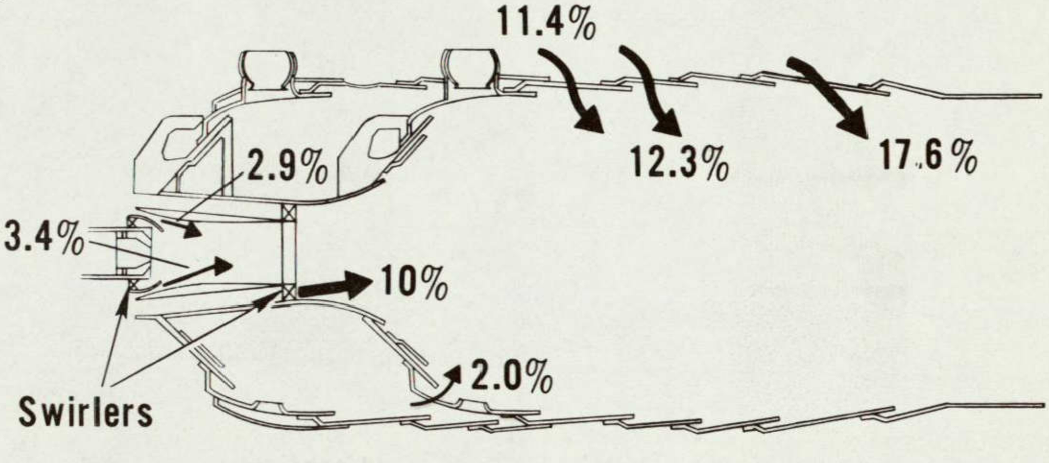
Nozzle II

Lean front end configuration I-4

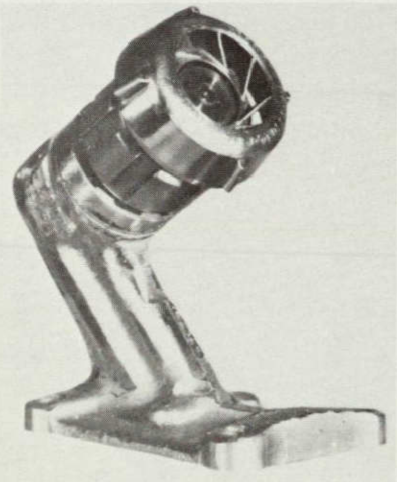
Figure 4 Element I Airblast Nozzle Configuration I-4

Carburetor Tube Front Ends

The carburetor tube concept, shown in Figure 5, was intended to provide additional improvement in fuel-air mixture preparation. This design is perhaps outside the intended scope of Element I. However, by fitting the burner with a "falsehead" made from a second JT8D burner, the JT8D diffuser aerodynamics remain substantially unaltered and this burner could be installed in an existing JT8D engine. The carburetor tube design features three annular air streams for control of fuel spreading and primary zone stoichiometry. The original configuration was developed through testing at a high pressure fuel spray facility. An air gap and radial inflow swirler at the head of the carburetor tube were incorporated to eliminate wall wetting of the premixing tube. Primary zone mixing is enhanced by a counter rotating secondary air swirler located at the carburetor tube exit. Air from the diffuser exit is channeled directly to this flame stabilizing swirler through an annulus concentric with the carburetor tube. A suitable low blockage pressure atomizing nozzle was selected for this combustor. Autoignition calculations indicate that the premixing tube has a satisfactory safety margin.



Tube 1 (57-3A)



Nozzle and inlet swirler

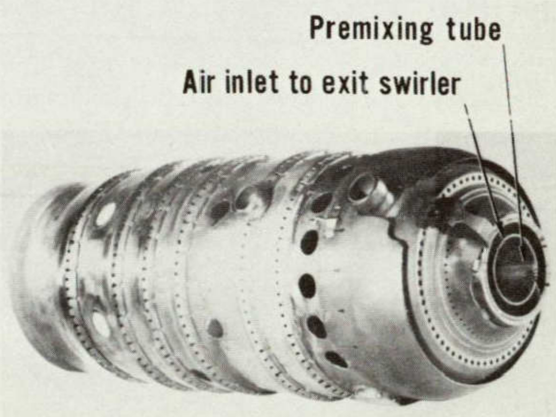


Figure 5 Element I Carburetor Tube Configuration I-5

A second carburetor tube configuration was tested in Element I. This represents a further refinement to the carburetor tube concept, based on flow visualization tests in an air flow rig. Idle conditions were simulated on the front end of the carburetor tube burner while water was used to simulate fuel spray. Wall wetting of the swirl lip exit and front end louvers was observed with the original configuration. Following the testing of 12 configurational changes, wall wetting was minimized by the use of a converging-diverging nozzle attached to the exit of the secondary swirler, along with an extension to the premixing tube. The revised configuration is shown in Figure 6.

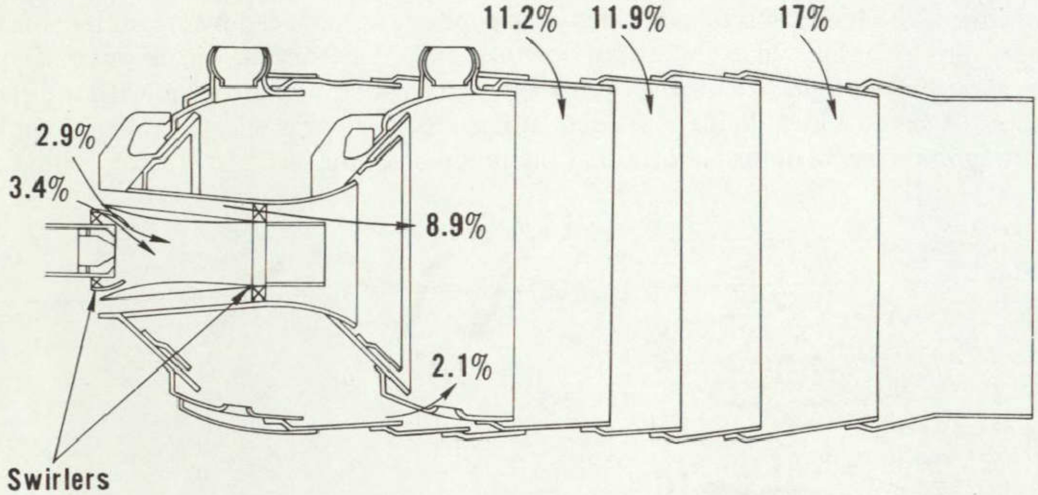


Figure 6 Schematic of Element I Carburetor Tube Configuration I-6

Configurations Tested

Table V lists the configurations tested in Element I. The first configuration shown, I-1, investigated the simple addition of an airblast nozzle to a production JT8D-17 combustor. This configuration represents nothing more than a nozzle substitution.

Configuration I-2 was based on a previous in-house development program, with an annular combustor and new airblast nozzle, which led to low levels of CO, THC and smoke. The JT8D-17 production burner was redesigned to duplicate the equivalence ratio and residence time history of the improved emissions burner with the same airblast nozzle design. Although the burner geometries are markedly different, the combustion hole penetrations were matched using the analytical model (Ref. 4). This configuration represents an enriched primary zone relative to the baseline.

Configuration I-3 is a modified version of I-2, in which the general emissions prediction model was used to analytically optimize the air distribution for reduced idle CO and THC. Additional dome air was provided to improve smoke levels.

TABLE V

ELEMENT I CONFIGURATIONS

Configuration	Fuel Injector	Primary Bulk* Air Schedule Classification
I-1	Airblast Nozzle I	Baseline
I-2	Airblast Nozzle II	Rich
I-3	Airblast Nozzle II	Rich
I-4	Airblast Nozzle II	Lean
I-5	Carburetor I with Pressure Atomizing Nozzle	Lean
I-6	Carburetor II with pressure Atomizing Nozzle	Lean

*Primary zone combustion airflow relative to baseline.

Configuration I-4 (Figure 4) represents an attempt to reduce high power NO_X using a lean front end and airblast nozzle. The strategy is limited both by the difficulty of providing a lean, well mixed fuel-air mixture in a direct injection system, and by the adverse impact on idle CO, THC and stability. The analytical model was employed to strike a compromise between high and low power emission considerations. Engine performance requirements, such as stability and relight, were also considered while designing this configuration for NO_X reduction.

The carburetor tube configurations I-5 and I-6 utilize pressure atomizing fuel nozzles and are classified as lean front end concepts with improved fuel air preparation to investigate NO_X reduction capability at high power.

Element II Advanced Vorbix Combustor Concept

The second program element consisted of the evaluation testing of nine configurations of the two-stage advanced vorbix (vortex burning and mixing) combustor concept. The vorbix combustor concept has evolved from earlier swirl combustion research at P&WA. The specific design selected for Element II represents a logical extension of previous designs in the direction of improved engine adaptability, while maintaining or improving the essential emission reduction features.

Concept Definition

A schematic and photograph of the initial Element II combustor configuration (II-1) are shown in Figures 7 and 8. Features of the Vorbix concept are an appropriately sized, swirl-stabilized pilot zone, a reduced height throat section axially separating the pilot and main burning zones, and an array of swirlers for the introduction of main zone combustion air. Main combustion zone fuel is introduced at the throat location. In its present can-annular form, six cold to hot gas interfaces are created by the hot pilot gas and the air inflow from the six air injection swirlers arranged circumferentially about the burner centerline.

The relatively large amount of air introduced through the main swirlers, coupled with an increased mixing rate at the hot/cold gas interface acts to minimize residence time in the high temperature reaction zone. Dilution air is introduced downstream of the six swirlers.

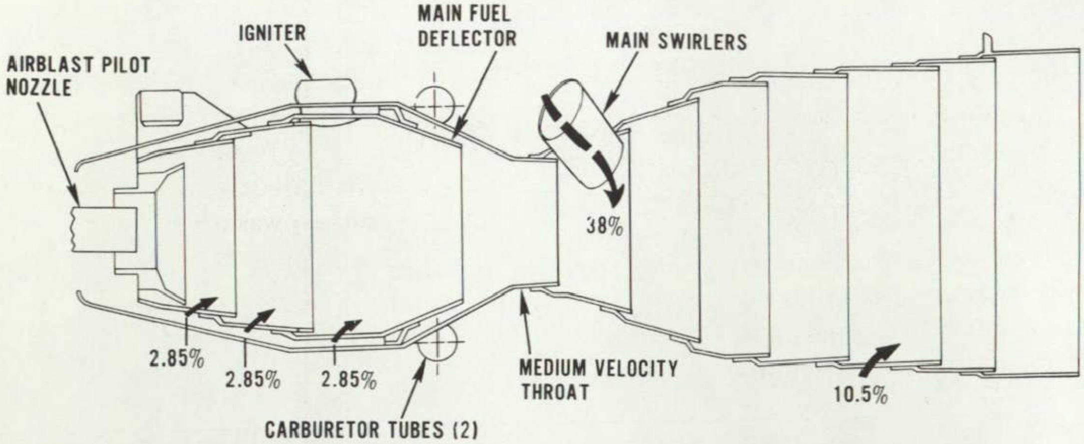


Figure 7 Schematic of Element II Vorbix Combustor, Configuration II-1

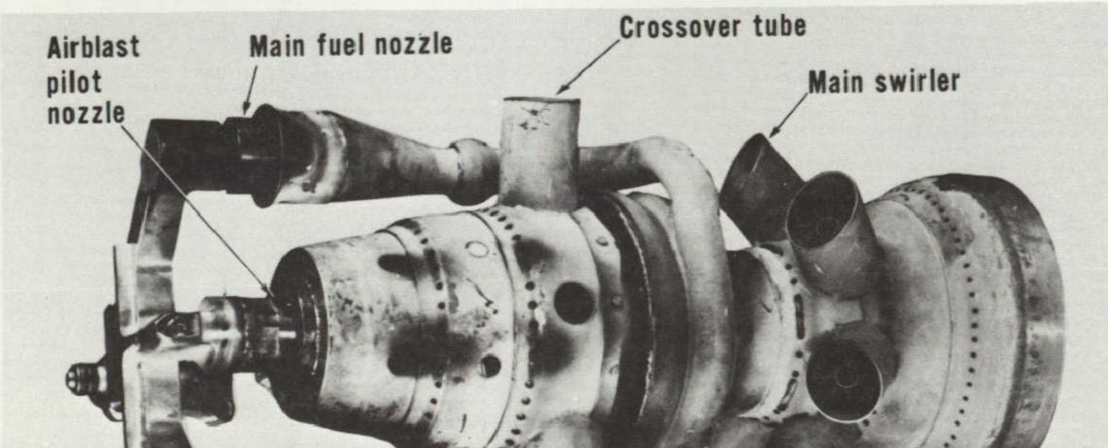


Figure 8 Element II Vorbix Combustor, Configuration II-1

The pilot zone design was derived from the best performing Element I airblast nozzle configuration. The same nozzle (airblast nozzle # 2) was used as an airflow scheme similar to that which provided good low power emissions in Element I was employed.

The element II vorbix combustor concept differs significantly from previous vorbix designs in the manner in which the main fuel is supplied and injected into the burner. Two pressure atomizing fuel nozzles are located in the same axial plane as the pilot nozzle, mounted on a common support (Figure 8). The main fuel is mixed with air at the front of the combustor, swirled about the exterior of the pilot through two carburetor tubes, and then injected into the hot pilot gas at the throat section. The main fuel system was designed to operate at an equivalence ratio of approximately 10 at sea-level take-off operating conditions. This high equivalence ratio at take-off provides adequate autoignition safety margin for the range of fuel flow and compressor discharge temperature and pressure. For a fixed value of liner pressure loss, the precise equivalence ratio at any power setting is a function of the quantity of fuel which evaporates in the carburetor tube. Functional advantages of the carburetor tube main fuel system are bolt-in replacement for the current production JT8D fuel injector, and elimination of the need for internal pressurized fuel manifolds usually required for two-stage can-annular systems.

Configuration Descriptions

A list of the Element II configurations is presented in Table VI. As previously mentioned, burner hole patterns and design details are presented in Appendix A. Configuration II-2 incorporated a number of revisions to correct problems of hot gas aspiration and fuel spillage encountered in the test of the initial configuration. The significant items were addition of a hood enclosing the pilot zone and revision of the main carburetor tubes to reduce inlet area and fuel injector blockage. The pressure-atomizing main fuel nozzles utilized in configuration II-1 were replaced by low pressure, air atomizing fuel injectors. A photograph representative of configurations II-2 through II-9 is shown in Figure 9.

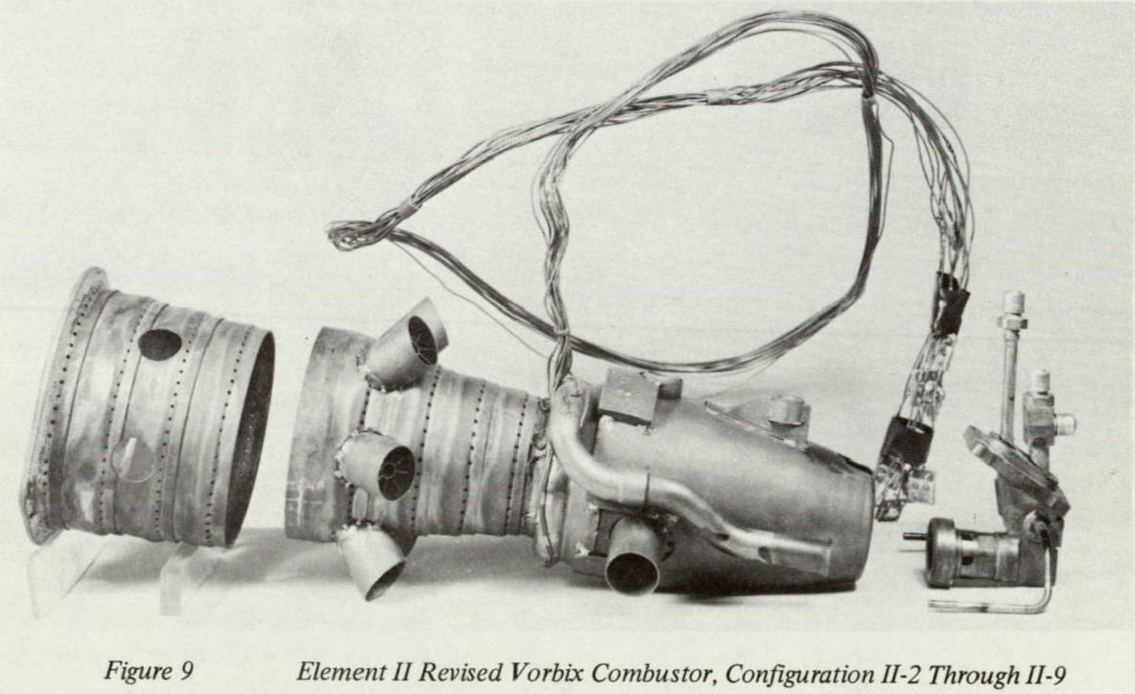


Figure 9 Element II Revised Vorbix Combustor, Configuration II-2 Through II-9

Parametric Variations

An objective of the Element II test program was to experimentally investigate parametric variation of those design parameters thought to be of importance. These are briefly summarized by category in the following sections.

Throat Velocity

Previous work with the vorbix combustor concept had identified throat velocity as a primary design variable. Increased throat velocity appears to promote the rate of mixing in the main combustion zone, with consequent reduction of NO_x at high power and premature quenching of CO at low power (pilot only fueled). The Element II vorbix combustor was designed to accommodate four different diameter throat assemblies. The four assemblies provided nominal throat velocities at SLTO of 60, 80, 100 and 120 m/sec. The calculations were made for a nominal pilot-main fuel split of 10% - 90%. Geometric change of throat diameter permitted assessment of this design variable for fixed pilot zone air flow. The actual level of throat velocity attained is of course dependent on pilot zone airflow, combustor inlet conditions, and pilot zone fuel-air ratio.

Main Zone Carburetor Tube Discharge Geometry

Two alternate carburetor tube discharge arrangements were investigated in Element II. The first of these, incorporated in configurations II-1 and 2, consisted of a circumferential ring of 24 evenly spaced holes, with the fuel-air mixture directed parallel to the throat wall by a convectively cooled deflector (shown in Figure 7). The subsequent configurations utilized an array of six larger injection holes without the wall deflector. This modification was intended to reduce combustion in the vicinity of the throat cooling louver discharge area for improved louver durability. The effect of reduced carburetor tube equivalence ratio was investigated in configuration II-9 by increasing carburetor tube metering area by 26%.

Main Combustion Zone Airflow Distribution

The main combustion zone was designed to minimize NO_x at SLTO. The two principal components of main zone airflow are metered by the swirlers and aft liner dilution holes.

Swirlers – Several different approaches were taken to investigate the effect of the 6 main stage swirlers on emissions. These included swirler axial location, swirler center tube jet penetration, and quantity of swirler airflow. Table VI summarizes the various combinations of these factors tested during Element II. The axial location of the swirlers was shifted from louver 5 to louver 7 for the last four configurations. This change acted to reduce main zone residence time and increase pilot zone residence time. Swirler center tube airflow was varied by adding blockage rings to the swirler center tubes. These rings installed at the downing blockage rings to the swirler center tubes. These rings installed at the downstream face of the tube, reduced the exit area by 59%. Overall swirler airflow was varied by adding blockage rings to the swirlers. These rings were of 2 sizes: 0.254 cm wide and 0.508 cm wide, and were also installed on the downstream face of the swirlers. Through the combination of the swirler blockage and center tube blockage, 4 different swirler airflow levels were evaluated.

TABLE VI

ELEMENT II CONFIGURATIONS

Configuration	Hood	Main Fuel Injector Type	Deflector	Throat Dia. (cm)	Main Swirler Location	Number of Main Fuel Injector Feed Holes	Main Swirlers Blockage Rig Width (cm)	ID of Swirler Centertube (cm)	Pilot Airflow % Wab	Main Swirler Airflow % Wab	Main Airflow Row 9	Dilution % Wab Row 10	Remarks
II-1	No	a	Yes	6 6	Louver 5	24	–	794	23.1	38	10.5	–	Additional Throat Cooling Compared to II-1 Capture Area of Main Fuel Tubes Reduced And Moved to a More Stable Flow Area
II-2	Yes	b	Yes	6 6	Louver 5	24	.254	.794	26 4	27	21.5	–	
II-3	Yes	b	No	5.8	Louver 5	6	.254	.508	24.3	25	21.5	–	Additional Throat Cooling Compared to II-2 More Cooling at Ignitor and Crossover Tube Location Number of Pilot Combustion Holes in Rows 2 and 3 Doubled and Diameters Reduced to Maintain Area
II-4	Yes	b	No	5 8	Louver 5	6	508	508	24 3	15	28	4	Additional Throat Cooling Compared to II-3
II-5	Yes	b	No	7 1	Louver 5	6	508	508	24.3	15	28	4	
II-6	Yes	b	No	7.1	Louver 7	6	.508	.508	24.3	15	28	4	
II-7	Yes	b	No	8 1	Louver 7	6	.508	.508	24.3	15	28	4	
II-8	Yes	b	No	8.1	Louver 7	6	508	508	27.1	15	28	–	
II-9	Yes	b	No	8.1	Louver 7	6	508	508	24.9	15	30	–	Diameter of Main Fuel Injector Feed Holes Increased to Give 26% More Flow

MAIN FUEL INJECTOR TYPE.

a Pressure/Atomizing Nozzles
b Low Pressure Drop, Low Blockage Air/Atomizing Injectors

The concept was evaluated in the two stage design shown in Figure 10. A direct liquid injection, premix type pilot stage provides the heat required to vaporize the main fuel while allowing for efficient low power operation. A perforated plate flameholder was utilized to stabilize the pilot zone combustion. The flameholder design was configured in three conical sections to provide suitable locations for the igniter and crossover tubes. The inlet passage was designed with a clean aerodynamic entrance and sized for an inlet effective area equal to the flameholder hole effective area. Pilot fuel was provided by a production JT8D fuel nozzle support modified to accept a low blockage variable area pressure atomizing nozzle. The pilot was designed to burn at an equivalence ratio of approximately 1.0 at idle to provide good stability, light-off and low levels of CO and THC.

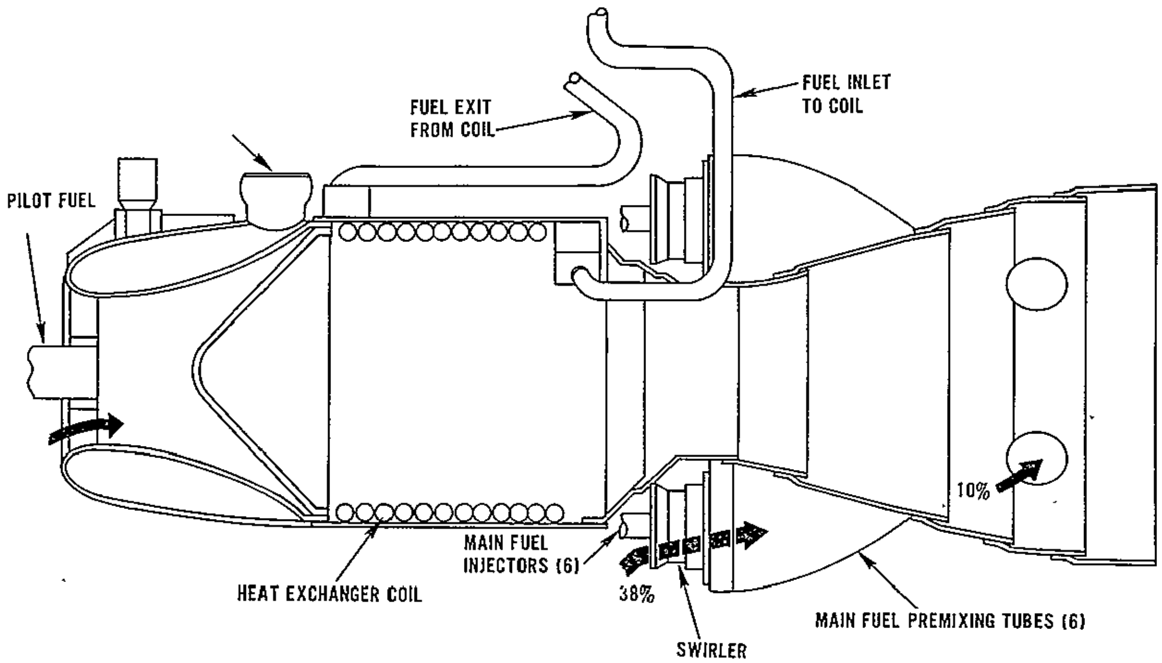


Figure 10 Schematic of Initial Element III Two-Stage Prevaporized-Premix Combustor

The aft liner assembly contains the throat section and high power or main combustion zone. A throat velocity of 100 m/sec at SLTO was selected to establish the throat diameter. To approach a homogeneous gaseous fuel-air mixture, the vaporized fuel is injected into swirling air at the inlet of the six premixing tubes. The tubes were sized to allow maximum residence time for mixing within the constraints of auto ignition (Ref. 6). Tube airflow was set to provide an equivalence ratio of 0.65 at SLTO. Although bellmouths were added at the entrance of the six premixing tubes to provide an undistorted inlet profile, flow visualization tests identified slight recirculation immediately downstream of the swirlers. The problem was eliminated by the installation of a skirt on the swirler to effect a more gradual increase in flow area.

The main zone fuel system is shown schematically in Figure 11. This arrangement represents a substantial departure from current design practice and is the feature which will require the greatest attention before this concept can be considered for engine development. The regenerative heat exchanger was sized to provide fuel temperatures in the range 590 to 700K at SLTO operation with the pilot burning at an equivalence ratio of 0.75. The heat exchanger was fabricated by forming a 0.79 cm Inconel tube into a 12 coil helix, and makes up a major part of the pilot zone wall. Fuel is first heated at pressures above critical within the heat exchanger, and then flash vaporized and distributed uniformly to the 6 premix tubes by a pressurization/distribution valve manufactured by the Delavan Manufacturing Company. Since it was necessary to provide approximately constant fuel pressure for a wide range of fuel flows, the valve incorporates a variable metering area feature. The fuel pressure drop is taken at the valve, with equilibrium to combustor pressure and concurrent flash vaporization occurring within the fuel injector tubes. Bypass operation was also provided as a means of adjusting fuel temperature.

The fuel pressurization/distribution valve and all fuel line connections are made external to the burner case. This represents a substantial departure from conventional practice in that multiple fuel line penetrations of the burner case are required. No serious attempt was made to solve engine application problems for this type of fuel system. The system as described is of experimental combustor rig quality only, intended to be suitable for proof-of-concept testing.

Configurations Tested

Five configurations were tested in Element III. A summary of the configurations is presented in Table VII. Testing of configurations III-1 and III-2 was limited to idle operation due to durability problems encountered with the pilot zone flameholder. In order to expedite the program, a pilot design derived from the Element II Vorbix concept was adopted for configurations III-3 through III-5. A cross section and photograph of the final configuration, representative of III-3 through III-5, is shown in Figure 12.

For the fixed geometry Element III concept, it is apparent that the low equivalence ratios at approach and other low power operating points will tend to produce unstable operation and poor combustion efficiency. Configurations III-4 and III-5 evaluated the effect of staging to 3 of the 6 main fuel injectors. An alternate approach to improving part-power operation in a fully premixed combustor system would be to incorporate variable geometry premix tube air metering area. Variable geometry was not investigated in this program.

Configuration III-5 provided an evaluation of the effect of heated pilot fuel, again utilizing flash vaporization from the critical pressure to provide vapor fuel. An auxiliary electric fuel heater installed at the test stand was used for this test. The pressure atomizing primary passage of the pilot nozzle was enlarged to pass the required quantity of gaseous fuel.

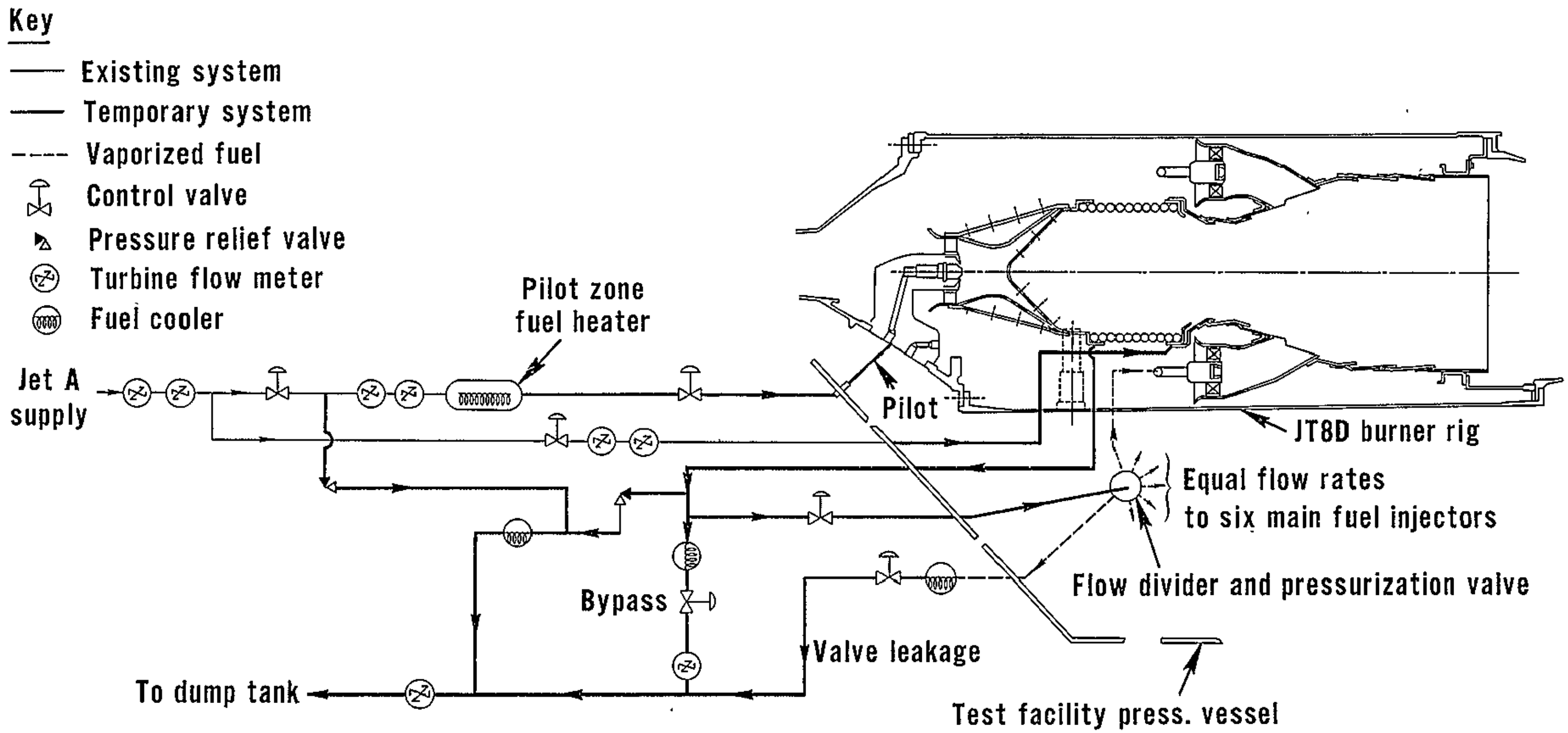


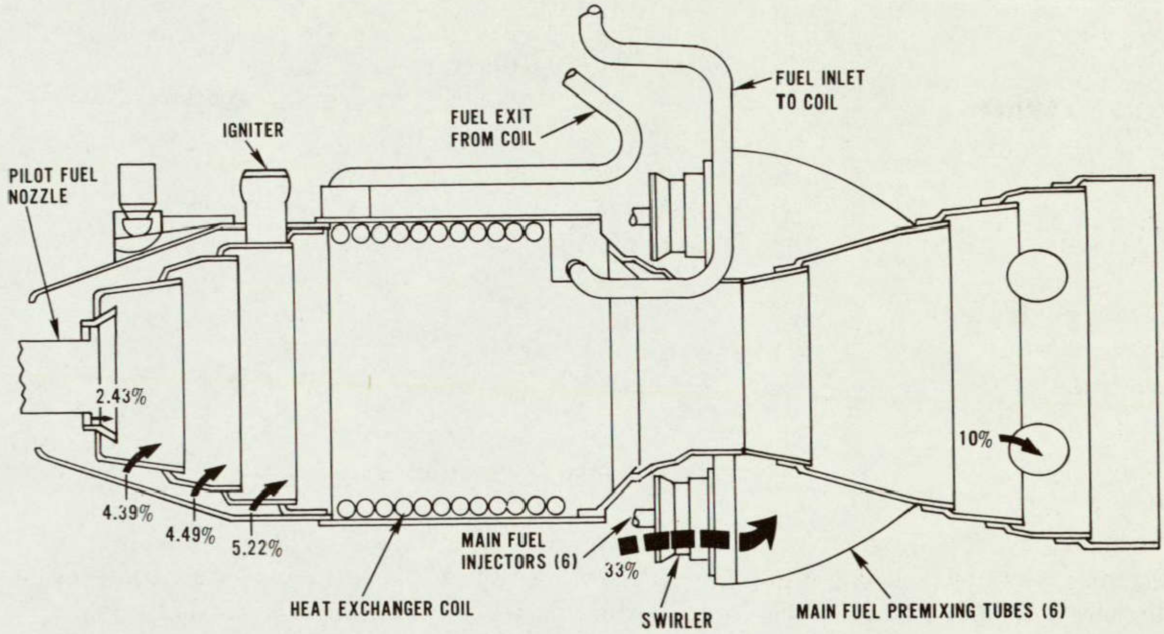
Figure 11 *Element III Main Fuel System*

TABLE VII

ELEMENT III CONFIGURATIONS

Configuration	Pilot Airflow $\% W_{AB}$	Main Premix Tube Airflow $\% W_{AB}$	Dilution Airflow $\% W_{AB}$	*Main Premix Tube Equivalence Ratio	Number of Main Zone Fuel Injectors	Comments
III-1	11	38	20	0.56	6	Premix Pilot Design
III-2	17	38	10	0.56	6	Premix Pilot Design
III-3	16	33	10	0.64	6	Airblast Nozzle Pilot Design
III-4	16	33	10	1.28	3	Airblast Nozzle Pilot Design
III-5	16	33	10	1.28	3	Airblast Nozzle Pilot Design

*Based on a 20% Pilot/80% Main Zone Fuel Split



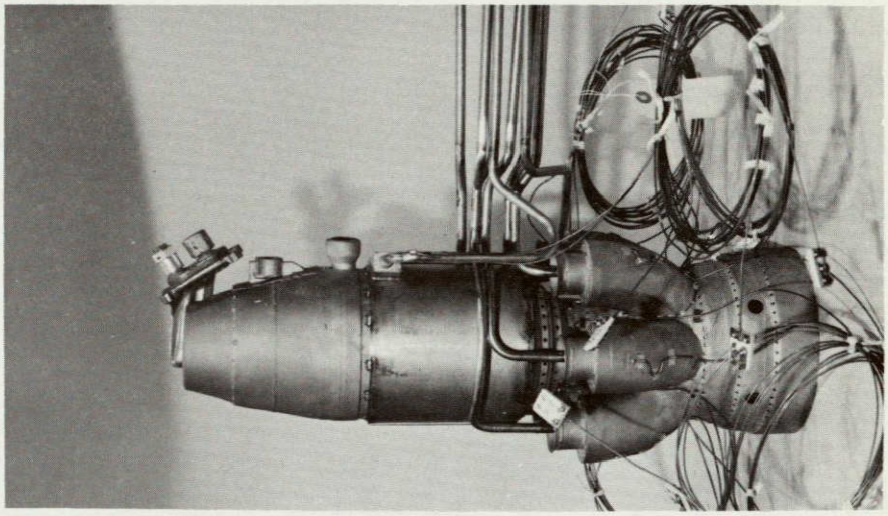


Figure 12 Element III Prevaporized-Premix Combustor

TEST FACILITIES AND EQUIPMENT

All emissions and performance evaluations, except the altitude relight tests, were conducted in a high pressure test facility, X-904 stand, located at P&WA's Middletown test facility. The altitude relight tests were conducted in an altitude test facility, X-306 stand, located at the Rentschler Airport Laboratory in East Hartford. Airflow capability for the two facilities is presented in Table VIII. A comprehensive description of both facilities is contained in Reference (1).

TABLE VIII

TEST FACILITY CAPABILITIES

Capability	X-904 Stand High Pressure Facility	X-306 Stand Altitude Relight Facility
Air supply (kg/sec)	11.34	4.54
Pressure (atm)	47.6	0.066
Temperature (K)	922 Max.	226 Min.

Test Rig and Instrumentation

A schematic and photograph of the JT8D combustor rig installation are presented in Figures 13 and 14. This rig simulates a 40° sector of the JT8D engine including compressor discharge, diffuser struts, and air cooled turbine entrance transition duct. In addition, provisions were made for extracting OD and ID bleeds in amounts representative of the turbine cooling air requirements of the JT8D-17 engine. This allowed a more precise simulation of the JT8D-17 engine operating conditions.

Combustor inlet temperatures and pressures were monitored in the high pressure facility by an array of 4 Chromel-Alumel total temperature thermocouples, 5 total pressure rakes, each having five measurement ports, and 7 wall static pressure taps. This instrumentation was arranged in a fixed array at a plane simulating the axial position of the last compressor stage. Combustor inlet humidity was monitored using a Model 2740 Foxboro Dewcell Humidity meter. Air at a low mass flow rate was extracted from the test stand inlet duct and directed through the humidity meter.

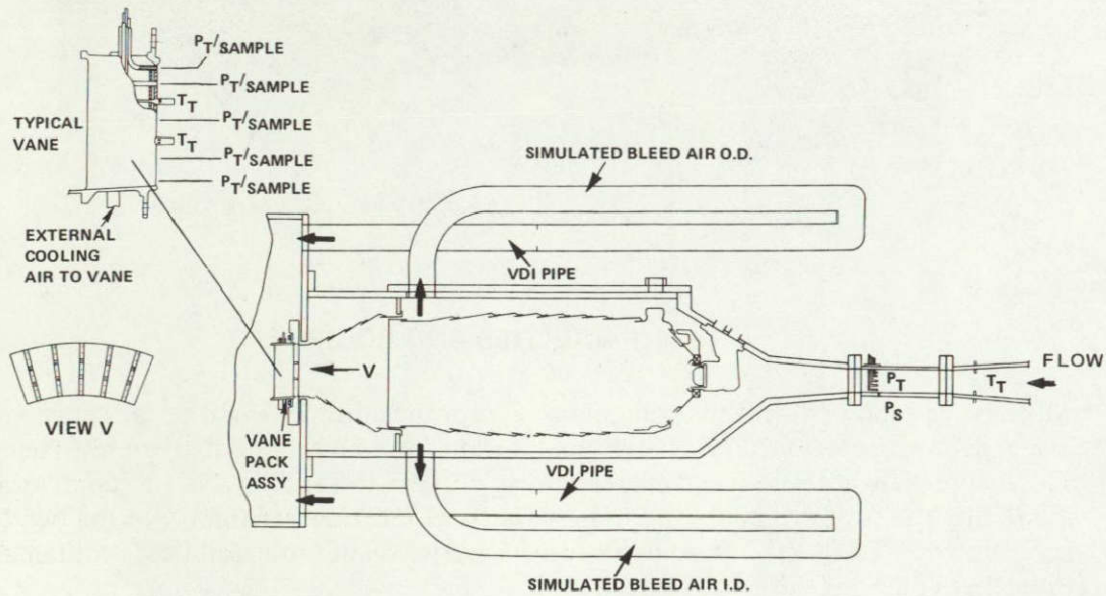


Figure 13 *Schematic of JT8D Combustor Rig*

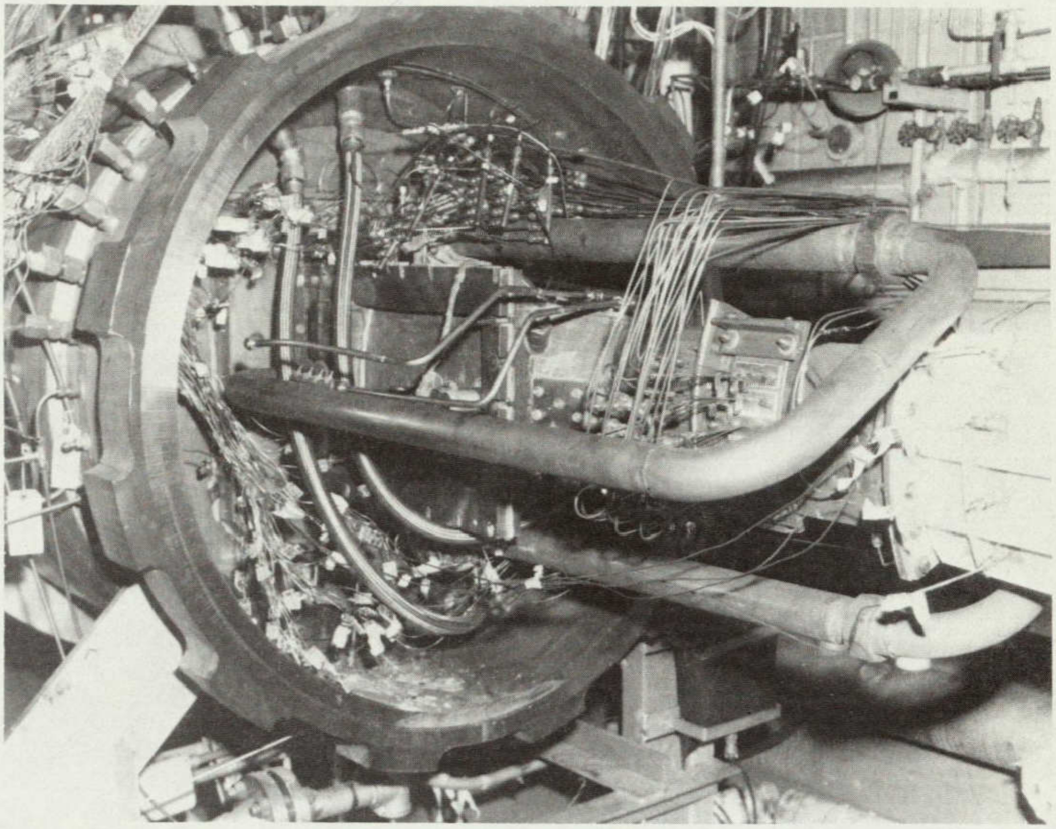


Figure 14 *JT8D Combustor Rig*

Within the combustor, static and total pressures were measured at locations required for determining system pressure loss and air flow distribution. Since these measurements were used to confirm the design values, they were taken only for the initial test runs of each program element. Liner temperatures were measured during most tests by means of temperature sensitive paints or thermocouples. The paint was used during the initial Element II tests to detect potentially troublesome areas, such as the throat, which would require monitoring during subsequent tests. Thermocouples were also used to monitor specific loations in the diffuser case and shrouds to detect external burning or liner overheating. Sniffers were used to detect the presence of unburned hydrocarbons in the shroud areas as indications of aspiration or fuel leakage.

Combustor exit temperatures and pressures were measured by a fixed instrumentation array mounted in an air cooled vane pack. Figure 15 is a photograph of the vane pack which consists of 7 production JT8D turbine vanes. As shown, the five center vanes are each instrumented with 5 sampling/pressure ports and two thermocouples. The thermocouples were located near the center of each vane to concentrate temperature measurements in the expected hot areas. Since the average exhaust temperature can be calculated from performance and emission measurements, pattern factor could be estimated with a limited number of thermocouples.

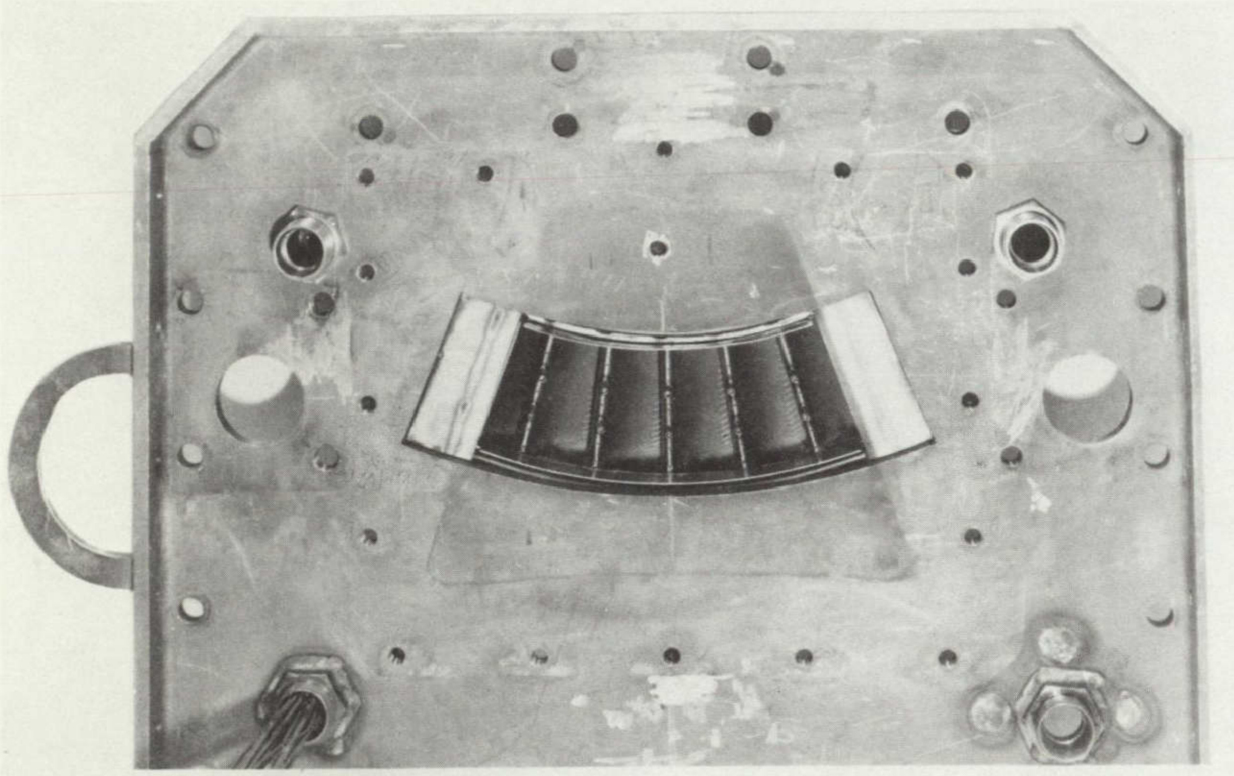


Figure 15 Combustor Exit Instrumentation Vane Pack

The vane pack was used throughout the program to sample combustor exhaust gases. The 25 sampling/pressure ports were connected to a common plenum to provide a representative gas sample. Valves were provided for isolating the five radial sampling positions if more detailed emission measurements were required. Sample flow was interrupted when measurement of total pressure was made.

The altitude relight tests were conducted with sufficient exit plane temperature instrumentation to determine the lit or unlit status of the combustor. A closed circuit television system was used to observe the flame propagation and to verify the stability conditions.

Exhaust Emissions Analysis Instrumentation

Gas samples were anlayzed using equipment and techniques which, with minor exceptions, conformed to the U. S. Environmental Protection Agency standards described in reference (2). The gas analysis system is shown schematically in Figure 16 and the instrumentation is listed in Table IX. Details of gas analysis instrumentation are presented in reference (1).

TABLE IX

EXHAUST GAS INSTRUMENTATION

Gas Constituent	Detection Method and Instrument
THC	Flame ionization detector - Beckman Model 402
NO_x	*Chemilumensence NO_x analyzer - Thermo Electron Corporation Model 10A
NO	**Nondispersive infrared - Beckman Model 315Al
NO_2	**Nondispersive ultraviolet - Beckman Model 255A
CO	Nondispersive infrared - Beckman Model 315A
CO_2	Nondispersive infrared - Beckman Model 315A
O_2	Polarographic - Bechman Model 715

* Primary NO_x Measuring System
** Backup NO_x Measuring System

Smoke Measurements

Smoke concentrations in the combustor exhaust were measured using a smoke meter that conforms to the specifications of the SAE ARP 1179 (Ref. 7). Figure 17 shows a schematic of the system. The smoke measuring system is a semi-automatic electromechanical device which incorporates a number of features to permit the recording of smoke data with precision and relative ease of operation. One of these features is a time controlled, solenoid activated main sampling valve (Valve A in Figure 17), having "closed", "sample", and "bypass" positions. In addition, this timing system operates a bypass system around a positive displacement volume measurement meter to ensure that the meter is in the circuit only when a sample is being collected or during the leak check mode.

Data Acquisition and Recording System

Most of the combustor rig data obtained in the high pressure test facility was recorded automatically and processed in real time on a XDS Sigma Computer. Raw data were transmitted from the test stand to the computer via a telephone link. The computer then reduced the data and converted it to the desired engineering units. The results were then returned to the test stand cathode ray tube display for review. A printed output was provided that included raw and reduced exhaust gas species concentrations, emission indices and carbon balance fuel-air ratio, as well as the test rig operating conditions and pertinent performance information.

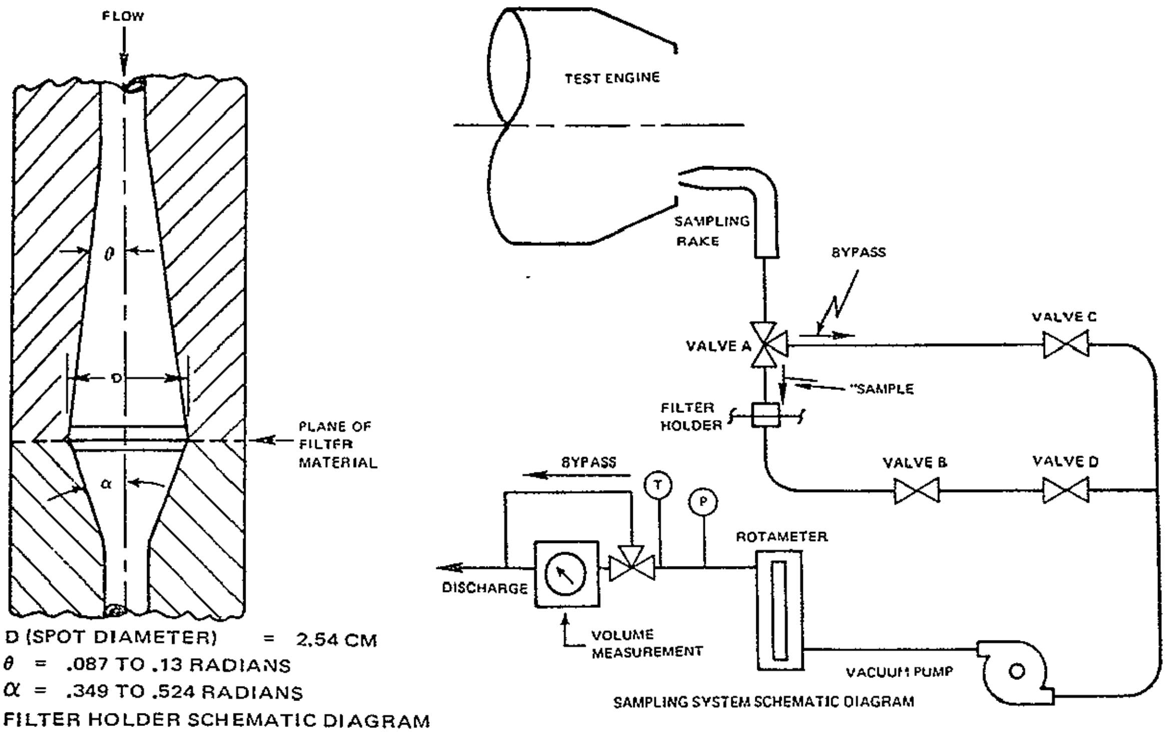


Figure 17 *Schematic of Smoke Measuring System*

TEST CONDITIONS

JT8D-17 Engine Operating Conditions

The combustor rig test conditions selected for this program match the actual JT8D-17 engine conditions specified by the EPA (Ref. 2) for the calculation of EPAPs. These test conditions, listed in Table X, correspond to idle, approach, climb, and SLTO. In addition, selected configurations were tested at a simulated high altitude cruise condition, because of recent concern for pollutants released by aircraft engines into the stratosphere. During the latter stages of this program, the JT8D-17 design table was revised based on the latest P&WA engine tests. This revision primarily affected the idle conditions, and some of the latter tests in this program were conducted at both the original and revised idle conditions. However, all idle emissions quotes are made at the original idle conditions since data are not available at the revised conditions for most combustor configurations tested. All testing was conducted using fuel that conformed to the American Society for Testing and Materials (ASTM) Specifications Jet-A.

2.4.2 Parametric Variation of Rig Operating Conditions

Parametric variations of combustor fuel-air ratio were investigated for most of the combustor concepts at both the idle and sea-level take-off operating conditions. Variations in inlet temperature and reference velocity were investigated for selected configurations. The ranges of these variations are shown in Table XI.

TABLE X

SINGLE SEGMENT RIG OPERATING CONDITIONS
FOR EMISSIONS TESTING

JT8D-17 Mode	Total Inlet Pressure (atm)	Total Inlet Temperature (K)	Combustor Total Airflow (kg/sec)	Combustor Fuel Flow (kg/sec)	Fuel-Air Ratio
Idle (w/o customer Bleed)	2.87	412	1.58	0.0158	0.0100
Idle (Revised)	2.47	393	1.37	0.0161	0.0117
Approach 30% Power	6.83	535	3.43	0.0384	0.0112
Cruise 50% Power	6.83	613	3.24	0.0480	0.0148
Climb 85% Power	15.08	678	6.67	0.1094	0.0164
SLTO 100% Power	17.40	714	7.46	0.1357	0.0182

TABLE XI

RANGE OF VARIATION OF SEGMENT RIG OPERATING CONDITIONS

Parameter	Idle	Sea-Level Take-Off
Inlet Total Temperature (K)	410-450	640-760
Fuel-Air Ratio	.006-.012	.016-.020
Reference Velocity (%)	± 25	± 25

At intermediate and high power conditions, the pilot-to-main fuel flow split was varied for most of the two-stage configurations, while maintaining the total fuel flow. The resulting data provided a basis for determining the optimum fuel distributions between the pilot and main burners and also permitted definition of the trends relating fuel distribution, combustion efficiency, and emissions.

Altitude Stability and Relight Test Conditions

Altitude stability and relight tests were conducted on selected combustor configurations. Ignition was evaluated during the relight tests; however, flame propagation could not be evaluated in the single segment rig. Actual engine combustor inlet and pressure conditions were duplicated, while fuel flow and airflow levels were scaled for the single sector rig utilized for these tests. The range of conditions that were set are shown on the JT8D windmilling envelope Figure 18.

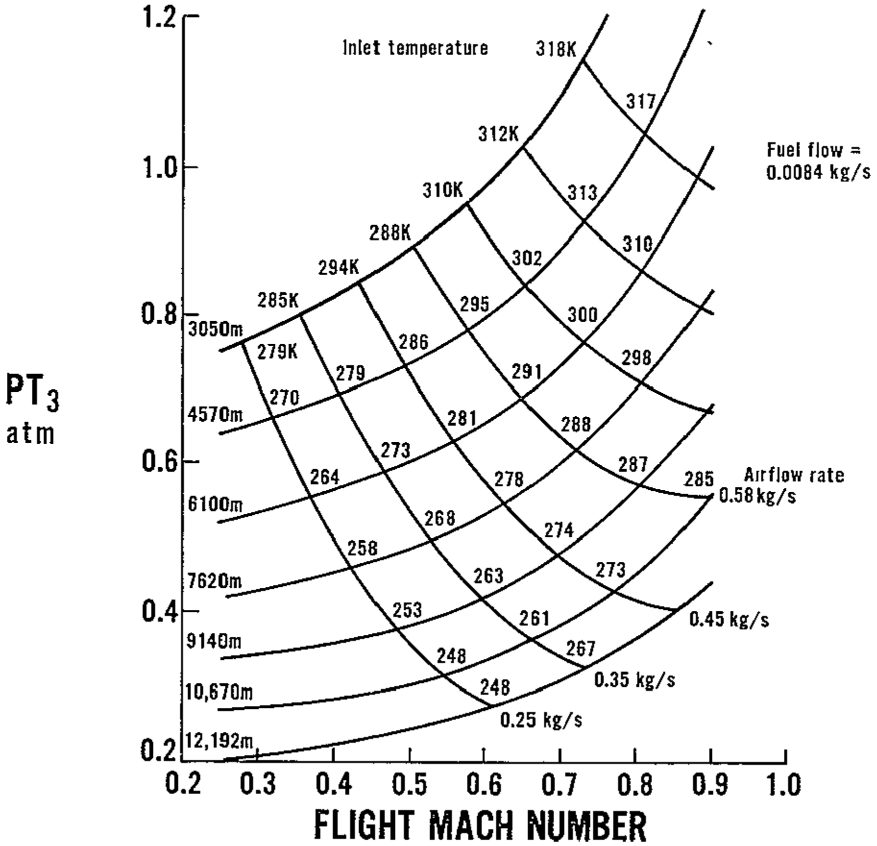


Figure 18 Altitude Stability and Relight Test Conditions

EMISSION DATA CALCULATION PROCEDURE

Emission Data Processing Procedure

The raw emissions data generated at each test condition were transmitted directly to an on-line computer for processing. The voltage response of the gaseous constituent analyzers was first converted to an emission concentration based on the calibration curves of each instrument, and then used to calculate emission indices, carbon balance fuel-air ratios and combustion efficiency. The equations used for these calculations were equivalent to these specified in SAE ARP 1256 (Ref. 8). Since the instrumented vane pack allowed extraction of a single representative gas sample, acquisition time was minimized and the processed emissions data were usually available within a few minutes of setting a test condition.

Adjustment Procedure

While every effort was made to set exact design conditions for the test runs, it was rarely possible to set test conditions to precisely match the design point fuel-air ratio. Therefore, the data have been corrected to design condition by interpolation, using plots of emissions as functions of the metered fuel-air ratio. The data for oxides of nitrogen have been corrected for humidity effects at all operating conditions. Where correction of oxides of nitrogen emissions data to design point conditions was not possible by interpolation, extrapolation was accomplished using the following equation (Ref. 9). These corrections were small, generally not exceeding 5%.

$$NO_x\ EI\ corr. = \left(NO_x\ EI\ meas.\right)\left(\frac{P_{t4\ corr.}}{P_{t4\ meas.}}\right)^{0.5}\left(\frac{V_{ref.\ meas.}}{V_{ref.\ corr.}}\right)\left(\frac{T_{t5\ corr.}}{T_{t5\ meas.}}\right)$$

$$\left(e^{18.8\ (H_{meas.} - H_{corr.})}\right)\left(e^{\left[\frac{T_{t4\ corr.} - T_{t4\ meas.}}{288}\right]}\right) \qquad (1)$$

where:

NO_x EI = Emission index of oxides of nitrogen

P_{t4} = Inlet total pressure (atm)

T_{t4} = Inlet total temperature (K)

$V_{ref.}$ = Reference velocity (m/s)

H = Inlet specific humidity (g H_2O/g air)

T_{t5} = Combustor exit temperature (K) and subscripts:

corr. = Relates to value at corrected condition

meas. = Relates to value at measured condition

EPAP Calculation

The U. S. Environmental Protection Agency emission standards for aircraft engines are expressed in terms of an integrated EPA parameter (EPAP). This parameter combines emission rates at the engine idle, approach, climb, and take-off operating modes, integrated over a specified landing, take-off cycle (Ref. 2). The equation for this calculation is as follows:

$$EPAP_i = \frac{\Sigma^j \frac{t_j}{60} W_{Fj} EI_{ij}}{\Sigma^j \frac{t_j}{60} F_{Nj}} \quad \text{(lbm pollutant/1000 lbf thrust-hr/LTO cycle)} \quad (2)$$

where:

EI = emission index (lbm pollutant/1000 lbm fuel)
t = time at engine mode (min)
F_N = net thrust (lbf)
W_F = fuel flow rate (lbm/hr)

and subscripts:

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

The engine data used to calculate the EPAP are presented in Table XII, and were obtained from the JT8D-17 design table.

TABLE XII

JT8D-17 ENGINE DATA FOR EPAP CALCULATION

Engine Mode	Time (t) ~ min	Net Thrust (F_N) ~ lbf	Fuel Flow (W_F) ~ lbm/hr
Idle	26	1040	1131
Approach	4	4800	2743
Climb	2.2	13600	7817
SLTO	0.7	16000	9694

Substituting the engine data from Table 2.5-I, Equation (2) becomes:

$$EPAP_i = 0.3366\ EI_{i\ Idle} + 0.1256\ EI_{i\ Approach} + 0.1969\ EI_{i\ Climb} + 0.0777\ EI_{i\ SLTO}$$

2.6 COMBUSTOR PERFORMANCE DATA CALCULATION PROCEDURE

The combustor performance parameters presented in this report were either measured directly or calculated from measured data. Table XIII contains a summary of these performance parameters and indicates whether they were measured or calculated.

TABLE XIII

SUMMARY OF REPORTED COMBUSTOR PERFORMANCE PARAMETERS

Parameter	Symbol	Units	Measured	Calculated
Total Airflow	W_{a4}	kg/s	x	
Total Combustor Airflow	W_{ab}	kg/s		x
Pilot Fuel Flow	$W_{f\ pilot}$	kg/s	x	
Main Fuel Flow	$W_{f\ main}$	kg/s	x	
Inlet Total Temperature	T_{t4}	K	x	
Inlet Total Pressure	P_{t4}	atm	x	
Reference Velocity	V_{ref}	m/s		x
Pattern Factor	PF	---		x
Inlet Air Humidity	H	g H_2O/kg air	x	
Fuel-Air Ratio	f/a	---		x
Pressure Loss	$\Delta P_t/P_t$	---		x
Combustion Efficiency	η_c	%		x

Calculated Parameters

Total Combustor Airflow

The total combustor airflow is determined by subtracting the measured bleed flows from total airflow.

Reference Velocity

The reference velocity (V ref) is defined as that flow velocity that would result if the total combustor airflow, at the compressor discharge temperature and static pressure, were passed through the combustor liner at the maximum cross-sectional area. This area is 0.0247 m^2 for the JT8D combustor, tested in this program.

Pattern Factor

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

$$PF = \frac{T_{t5\,max.} - T_{t4}}{T_{t5\,ideal} - T_{t4}} \tag{3}$$

where:

$T_{t5\,max.}$ = Highest local temperature observed at the combustor exit plane (K)

$T_{t5\,ideal}$ = Ideal combustor exit temperature based on measured combustor fuel-air ratio and inlet conditions (K)

T_{t4} = Combustor inlet temperature (K)

Fuel-Air Ratio

Both metered and carbon balance derived fuel-air ratios (f/a) have been calculated and recorded for all configurations tested in this program. The metered, or performance fuel-air ratio, is simply the ratio of fuel flow to total combustor airflow and can be measured quite accurately. Fuel-air ratio can also be determined by using gas sample data to determine the carbon balance of the exhaust gases. This second method is generally considered to be a less accurate means of characterizing the combustor operating point due to uncertainties associated with the gas sampling process. The carbon balance fuel-air ratio is appropriate; however, for estimation of fuel mass flow rate in the calculation of emission index. The metered value of fuel-air ratio is used throughout this report for the purpose of data presentation.

Pressure Loss

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

$$\Delta P_t/P_t = \frac{P_{t5} - P_{t4}}{P_{t4}} \tag{4}$$

where:

P_{t5} = Average Combustor exit total pressure

P_{t4} = Average combustor inlet total pressure

Combustion Efficiency

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

$$\eta_c = 100 - 100 \left(\frac{4343X + 21500Y}{18.4\,(10)^6} \right) \tag{5}$$

where:

X = measured carbon monoxide concentration in g/kg fuel

Y = measured total unburned hydrocarbon concentration in g CH_4/kg fuel

CHAPTER III RESULTS AND DISCUSSION

EXPERIMENTAL EMISSION RESULTS

This section presents a summary of the emission results by combustor concept. The summarized results include EPAP's; emission indices at idle, approach, climb, sea-level take-off and cruise conditions; plots showing results of parametric variations; and discussion of the effects of significant configurational changes. As previously discussed, the emission indices listed as "goals" in the summary tables are one set of hypothetical values which satisfy the EPAP program goals, and are intended to indicate the magnitude of emission reduction required.

The tabulated data presented in this section has been corrected to design point conditions as discussed previously. The various configurations tested in this program are described in Chapter II and Appendix A. Detailed tabulations of the data obtained with each configuration are presented in Appendix B.

Element I

The emissions test results obtained for the six Element I configurations are presented in two tables with goal and baseline values included for comparison purposes. Table XIV summarizes the EPAP's and smoke numbers for each configuration and Table XV summarizes the emission indices at the four design operating conditions.

TABLE XIV

ELEMENT I EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP NO_X	EPAP CO	EPAP THC	Maximum Smoke Number
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25–30
Airblast Nozzle				
I-1	–	–	–	25
I-2	7.42	5.05	0.05	28
I-3	7.86	4.77	0.77	49
I-4	7.54	6.91	1.46	12
Carburetor Tube				
I-5	–	–	–	1
I-6	5.78	51.98	22.55	2

TABLE XV

ELEMENT I EMISSION INDEX SUMMARY

	Emission Index (g/kg)*											
	Idle			Approach			Climb			SLTO		
Configuration	NO_x	CO	THC	NO_x	CO	THC	NO_x	CO	THC	NO_x	CO	THC
Goal	3.2	12.2	2.1	4.2	1.1	0.4	5.1	0.2	0.13	5.2	0.16	0.11
JT8D-17 Baseline	3.7	44.5	12.8	8.5	7.5	0.67	20.0	0.89	0.04	24.4	0.55	0.03
Airblast Nozzle												
I-1	3.08	70.8	58.6	8.77	7.16	0.86			—	32.87	0.59	0.16
I-2	4.27	13.35	0.09	7.42	3.16	0.12	17.81	0.59	0.00	19.82	0.54	0.01
I-3	4.25	12.83	1.93	8.25	2.51	0.81	18.5	0.52	0.06	22.48	0.4	0.15
I-4	3.28	19.3	3.7	6.45	2.45	1.54	18.6	0.41	0.07	25.25	0.36	0.09
Carburetor Tube												
I-5	1.08	140.0	77.8	—	—	—	—	—	—	18.52	0.4	0.03
I-6	1.52	136.5	64.8	6.15	46.8	5.81	15.48	0.66	0.02	18.67	0.33	0.05

*Emission index for THC expressed as equivalent methane (CH_4)

EPAP and Smoke Number

The results for the airblast nozzle configurations, I-1 thru I-4, show significant improvements for CO, up to 70%, and THC, up to 99%, and a slight improvement in NO_X. Only the THC values met the 1979 goals established by the EPA, with the CO level slightly above and the NO_X level well above the goals. The EPAP's indicate that the airblast nozzle configurations are capable of significantly reducing CO and THC levels, with slight reductions in NO_X level.

The smoke numbers listed in Table XIV indicate that two of the airblast nozzle configurations failed to meet the smoke goal. However, test results are available for a combustor run in both the test rig and an experimental JT8D engine which indicate that the engine smoke levels are consistently below the corresponding rig levels. This is attributed to dilution by the fan bypass airflow. The correlation factor developed from these tests indicates that combustors tested in the rig with smoke numbers of 35 or less would meet the goal of 25 when run in an engine. Figure 19 illustrates the agreement obtained between engine and corrected rig values. Applying the correction factor to the smoke number results (Table XIV) indicates that only configuration I-3 failed to meet the goal.

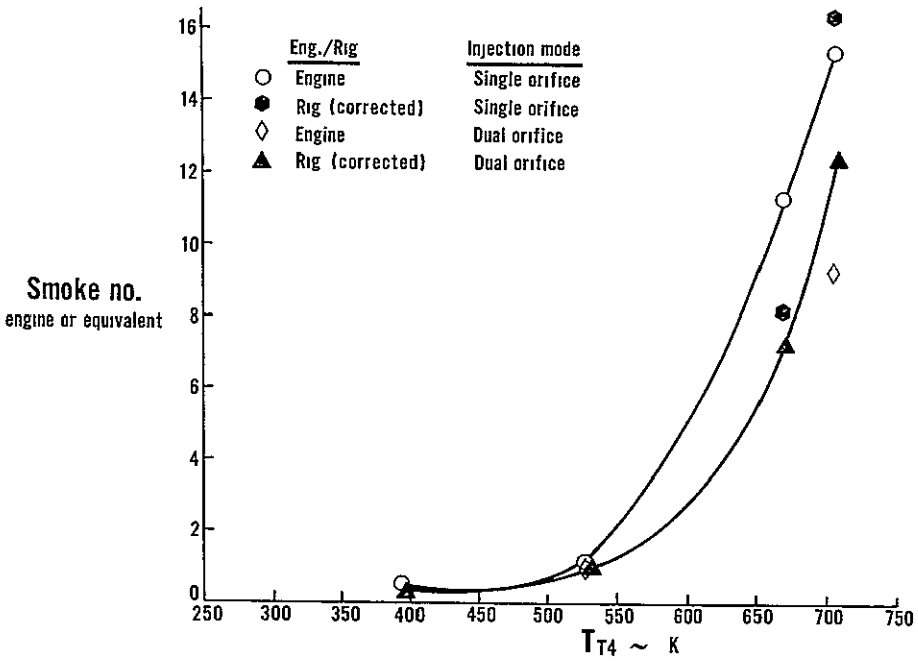


Figure 19 *Comparison of Engine and Corrected Rig Smoke Numbers for Airblast Fuel Nozzle and Modified JT8D-17 Combustor*

Emission Indices

Idle – As shown in Table XV, configuration I-1 produced much higher idle CO and THC levels with only a slight reduction in NO_x, relative to the baseline levels. This illustrates that the simple substitution of an airblast nozzle in the baseline combustor is not adequate to improve emissions, and emphasizes the need for integrated design of the nozzle and combustor air distribution to take advantage of the improved fuel-air mixture preparation which the airblast nozzle offers. Configurations I-2, I-3 and I-4, which used the second airblast nozzle along with primary zone airflow modifications, resulted in significant reductions in idle CO (71%) and THC (99%), relative to the baseline levels, with only slight increases in the NO_x level at idle. As shown in Table XV, the levels for CO and THC either met or were close to the levels required to meet the EPAP goals.

High Power Operation – Except for configuration I-1, NO_x levels were near or below the baseline values for sea-level take-off (SLTO) and climb. It is significant that the dramatic reductions in idle CO and THC levels were achieved without an increase in high power NO_x. In terms of the EPAP requirements, the CO and THC levels obtained at high power are substantially equivalent to the baseline values.

Intermediate Power Operation – At the approach operating condition, emission indices for CO and NO_x were equivalent to or slightly below the baseline values, while THC levels were generally above the baseline. Emissions were not measured at cruise conditions for any of the airblast nozzle configurations. However, since the NO_x emissions (the pollutant of greatest concern at altitude) varied only slightly from the baseline levels, cruise NO_x could be expected to approximate the baseline emission index of 11.0.

Effect of Primary - Secondary Fuel Split

The design of airblast nozzle # 2 featured a conventional pressure-atomizing primary fuel passage, surrounded by an airblast secondary fuel passage. Figure 20 shows the effect of the primary-secondary fuel split on the carbon monoxide emission levels. For the three configurations shown, the lowest levels were obtained with all primary fuel and the highest with all secondary fuel. This is attributed to the good atomization of the primary fuel produced by the pressure atomizing nozzle operating with high differential pressure.

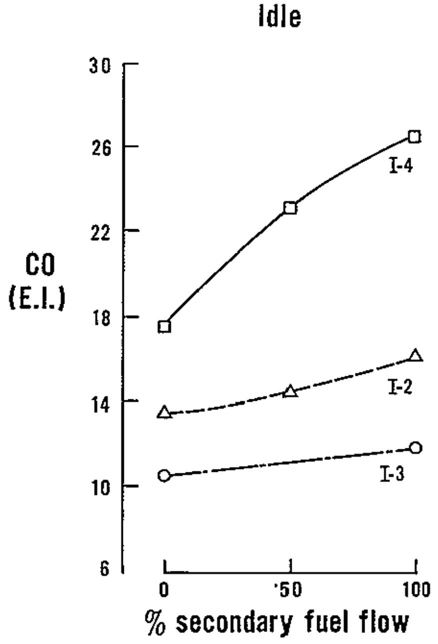


Figure 20 *Effect of Nozzle Primary-Secondary Fuel Flow Split on Idle CO Emissions for Element I Airblast Nozzle Configurations*

Carburetor Tube Configurations

EPAP's and Smoke Numbers

The two carburetor tube configurations were designed primarily to reduce high-power NO_X emission levels by achieving lean fuel-air burning through better fuel preparation. The EPAP's listed in Table XIV for the carburetor tube design demonstrate the effectiveness of this design in reducing the high power NO_X emission rate. The NO_X level, although still above the program goal, is 30% below the baseline. The CO and THC EPAP's are quite high for the carburetor tube scheme, due to poor CO and THC levels at low power operation. Very low values of smoke number were measured, consistent with lean, well-mixed operation at high power.

Emission Indices

Idle — The emission levels at the idle condition (Table XV) for CO and THC are excessively high while the NO_X levels are significantly below both the baseline and goal values. The high CO and THC levels are the result of the low equivalence ratios in the front end of this combustor concept at low power conditions.

High Power Operation – The results in Table XV for the SLTO and climb conditions show that the carburetor tube concept was successful in attaining the design objective of reduced NO_x at high power. The NO_x level was reduced by about 25%. CO levels were reduced by 40% at SLTO and 26% at climb while THC levels were below the goal at both conditions.

Intermediate Power Conditions – The reduction in NO_x at approach conditions was about 28% but the NO_x level was still above the goal. CO and THC levels were excessively high, as in the idle test results, demonstrating again the poor emissions characteristic of this concept at lower power settings. Emissions were not measured at cruise for the carburetor tube configuration but the NO_x level could be expected to be below the baseline index of 11.0 since there was a decrease in NO_x at the other power settings.

Overall Element I Results

Figure 21 is a graphical presentation of the significant Element I results. The curves shown in Figure 21 indicate that the better Element I configurations bear a common relationship to the peak primary zone equivalence ratio calculated from the analytical model (Ref. 4). This peak equivalence ratio occurs in the immediate vicinity of the fuel nozzle and is affected by the inflow of air around the nozzle and subsequent fuel droplet vaporization. The airblast nozzle configurations were optimized for good low-power emission characteristics. This identifies, once again, one of the basic problems in reducing gas turbine engine emissions, i.e., the trade-off between low NO_x at high power and low CO and THC at low power. The inlet condition or combustor design changes that minimize NO_x formation tend to increase the CO and THC levels. CO and THC can be seen increasing rather rapidly while the NO_x level is leveling off at the lean equivalence ratios. There is limited potential for overall emissions control with a single-stage combustor, and a two-stage combustor or other advanced concept is necessary for simultaneous control of low and high power emissions.

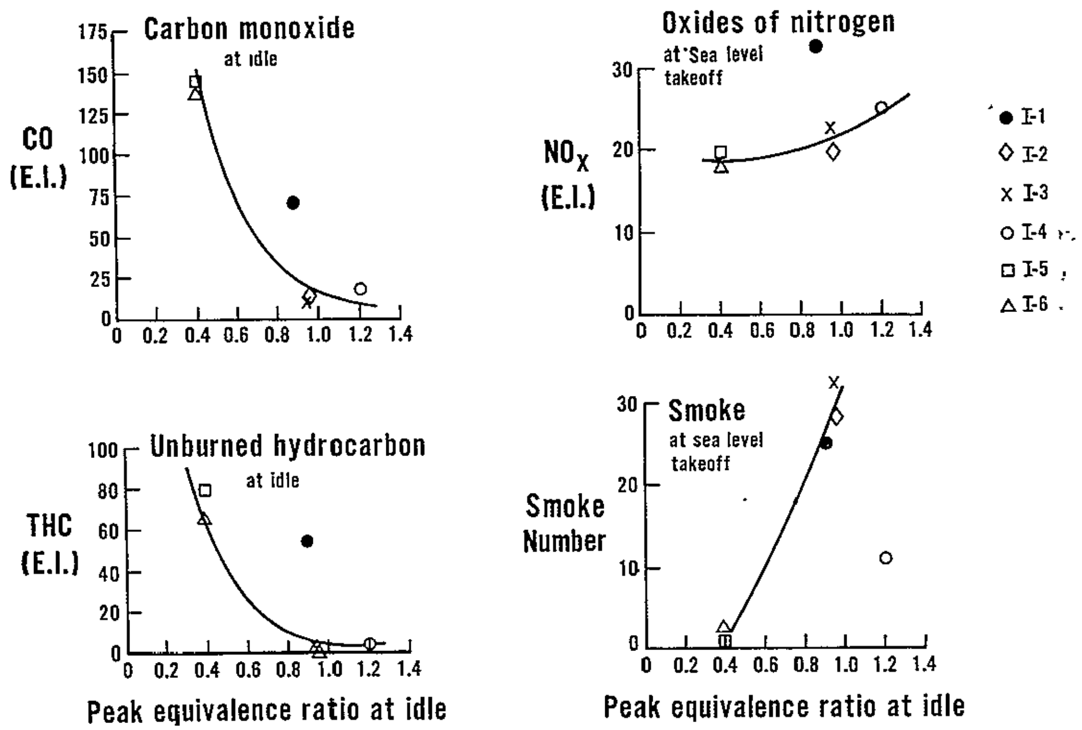


Figure 21 *Element I Emissions and Smoke Number as a Function of Peak Equivalence Ratio at Idle*

Element II

The emission test results for the nine Element II configurations are presented in two tables, with program goals and baseline values included for comparison purposes. Table XVI summarizes the EPAP's and smoke numbers for each configuration. Table XVIII summarizes the emission indices at the four design operating conditions and includes representative subsonic cruise (9140 m, Mach 0.8) emission indices.

Since the vorbix combustor concept employs two burning zones, the results presented in Tables XVI and XVII correspond to specific values of pilot/main fuel split at each of the simulated engine power settings. The pilot/main fuel distribution was a primary test variable, and data were selected for inclusion in the EPAP calculation on the basis of best simultaneous control of all three gaseous emissions. Both burning zone was fueled at the cruise, climb and SLTO operating conditions, while only the pilot zone was fueled at the idle and approach power settings. The effect of pilot/main fuel flow split on emission levels is discussed separately. In addition, the vorbix combustor was fitted with a duplex pilot zone fuel nozzle, consisting of a pressure-atomizing primary passage and a low - ΔP, aerating secondary passage. The division of pilot fuel flow between the two passages had a minor effect on emission levels, also discussed later. Data corresponding to secondary-only operation of the pilot fuel nozzle were selected for inclusion in Tables XVI and XVII.

TABLE XVI

ELEMENT II EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP			Maximum
	NO_X	CO	THC	Smoke Number
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25 - 30
II-1	—	—	—	—
II-2	—	—	—	—
II-3	4.52	22.75	0.76	38
II-4	4.65	20.60	0.60	31
II-5	4.61	12.30	0.29	31
II-6	4.59	10.45	0.14	18
II-7	4.75	8.71	0.17	30
II-8	4.49	10.84	0.28	26
II-9	4.39	8.93	0.18	27

EPAP and Smoke Number

The results in Table XVI indicate that the advanced vorbix combustor concept provided substantial reductions in all of the gaseous emissions, while maintaining smoke levels comparable to the baseline combustor. The CO and NO_X levels were reduced to approximately 50% of the baseline value but were still above the EPAP goals. The THC level was reduced to below the EPA standard.

A review of the smoke numbers presented in Table XVI indicate that only one configuration achieved the goal of 25. However, most configurations should meet the smoke goal when engine fan stream dilution is taken into account.

Emission Indices

Idle

A review of the idle emissions in Table XVII indicates that the two-stage combustor concept was effective in reducing the low power emissions compared to the JT8D-17 baseline. NO_X was reduced up to 35%, CO by 58%, and THC by 98% of the respective baseline values. The NO_X and THC emission levels were reduced below the hypothetical goals, with CO remaining slightly higher.

TABLE XVII

ELEMENT II EMISSION INDEX SUMMARY *

	Idle					Approach					Climb				
		EI (g/kg)					EI (g/kg)					EI (g/kg)			
Configuration	% Pilot Fuel	NO_x	CO	THC	Comb Eff.	% Pilot Fuel	NO_x	CO	THC	Comb. Eff.	% Pilot Fuel	NO_x	CO	THC	Comb. Eff.
Goal		3.2	12 2	2.1			4.2	1.1	0 4			5.1	0.2	0 13	
JT8D-17 Baseline		3.7	44.5	12.8			8.5	7 5	0 67			20 0	0.89	0.04	
II-1	100	2 3	93.2	8.6	96 80	100	4.51	31.61	1.75	99.05		–	–	–	
II-2	100	2.8	56 5	2 5	98.37	100	5.13	16.23	0.69	99 54		–	–	–	
II-3	100	2 42	57.6	2.05	98 41	100	4.57	15 38	0 36	99.59	25	11 08	5.42	0.09	98.86
II-4	100	2 55	52.8	1.15	98.40	100	4.56	11.07	0 38	99 69	25	11.04	5.5	0 43	99.82
II-5	100	2.54	29 4	0 58	99.23	100	5.23	6.89	0 1	99.83	20	11 12	6.0	0.35	99 82
II-6	100	2 74	24.8	0.4	99 36	100	5.24	6 42	0 00	99.85	20	10 19	5.26	0.00	99.88
II-7	100	2 82	19 7	0 26	99.50	100	6.12	4.91	0.07	99 88	20	10.55	5 8	0.34	99.82
II-8	100	2.56	21 7	0.31	99 45	100	5.2	5 39	0 04	99.87	40	10 85	8.0	0.5	99.75
II-9	100	2 66	18.9	0.25	99 52	100	5.75	4 89	0 14	99.87	15	9.3	7.76	0 32	99.78

	SLTO					Cruise				
		EI (g/kg)					EI (g/kg)			
Configuration	% Pilot Fuel	NO_x	CO	THC	Comb Eff	% Pilot Fuel	NO_x	CO	THC	Comb. Eff
Goal		5 2	0 16	0 11			–	–	–	
JT8D-17 Baseline		24 4	0 55	0 03			11 0	–	–	
II-1		–	–	–			–	–	–	
II-2	37	12 88	5 42	0.26	99 84		–	–	–	
II-3	20	12.24	4.61	0.1	99.88		–	–	–	
II-4	20	13.46	4.62	1.02	99.77		–	–	–	
II-5	20	11 75	4.55	0.22	99.87	20	6.38	11.3	2 29	99 47
II-6	20	12.2	3.5	0.02	99.91	20	6.04	10 5	0.72	99 67
II-7	15	12.24	4.14	0.04	99.87	20	6 69	14.4	1 44	99.49
II-8	15	10 81	16 49	0 97	99 50	30	7.31	14 6	2.63	99 35
II-9	20	12.06	5.46	0.15	99.85	40	7 22	5.17	0 13	99.89

*Emission index for THC expressed as equivalent methane (CH_4)

High Power Operation

At the sea-level take-off (SLTO) and climb conditions, significant NO_X reductions of 56% and 54% were achieved, but these levels were still above the goal. Several of the configurations produced THC levels below the goal values. In contrast to these encouraging results, the CO levels were well above the baseline values. The high CO levels at these high power operating conditions are apparently associated with the introduction of fuel into the main combustion zone, since such levels were not present in the single-stage Element I tests. Modest CO reduction, at the expense of increased NO_X level, is available by manipulation of the pilot/main fuel flow split. However, CO emission index would remain above the baseline and goal values for all configurations tested.

Intermediate Power Operation

Emission results for approach and cruise are also presented in Table XVII. At the approach operating condition as with the idle results, the baseline values were reduced for all three emissions with essentially all THC eliminated with configuration II-6. The lowest NO_X levels were only slightly higher than the goal. However, the CO levels were well above the goal and would be somewhat higher with both pilot and main burning zones fueled.

For those configurations tested at cruise conditions, the NO_X levels were significantly below the baseline level. However, the observed CO emission index, representing approximately 0.25% of the fuel heating value, may be unacceptable from the point of view of aircraft fuel consumption.

Parametric Variation

Pilot-Main Fuel Split

During the testing of configuration II-9, the effect of pilot to main fuel split on emission indices was fully investigated. Figure 22 summarizes the result, at approach, climb and sea-level take-off test conditions. In order to achieve the lowest overall emissions, it was beneficial to increase the fraction of pilot fuel flow at all three operating conditions. At approach, all three emission indices decreased when all of the fuel was introduced through the pilot nozzle. At climb and SLTO, increasing the percentage of pilot fuel reduced THC and CO emissions considerably while increasing NO_X only slightly.

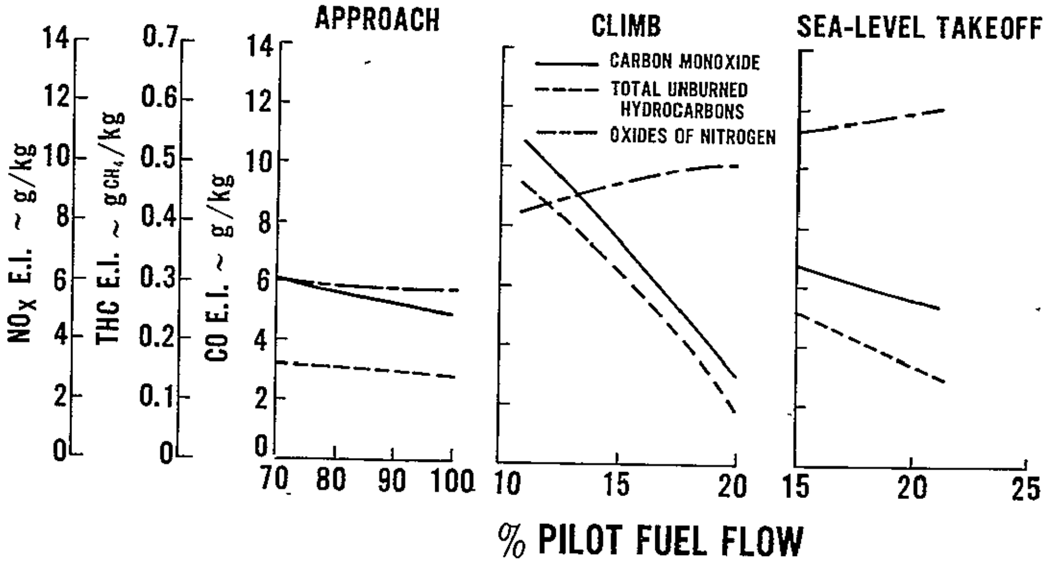


Figure 22 *Effect of Pilot-Main Zone Fuel Flow Split on Emissions at Approach, Climb and SLTO Conditions*

Throat Velocity

Figure 23 illustrates the strong effect of throat velocity on emission levels for the three configurations (II-4, 5 and 6) where this parameter was varied by throat diameter change only. An examination of the figure reveals that THC and CO emission indices are reduced significantly at both idle and SLTO as throat velocity is decreased. The NO_X emission index increased only slightly at SLTO with reduction in throat velocity. This was one of the most significant results of the Element II testing, in that this geometric change was able to provide a substantial reduction in CO and THC emission levels with little or no NO_X penalty. The increase in throat diameter and corresponding increase in pilot volume could very well be affecting the recirculation zone in the pilot. A larger recirculation zone could provide increased reaction time for the oxidation of THC and CO.

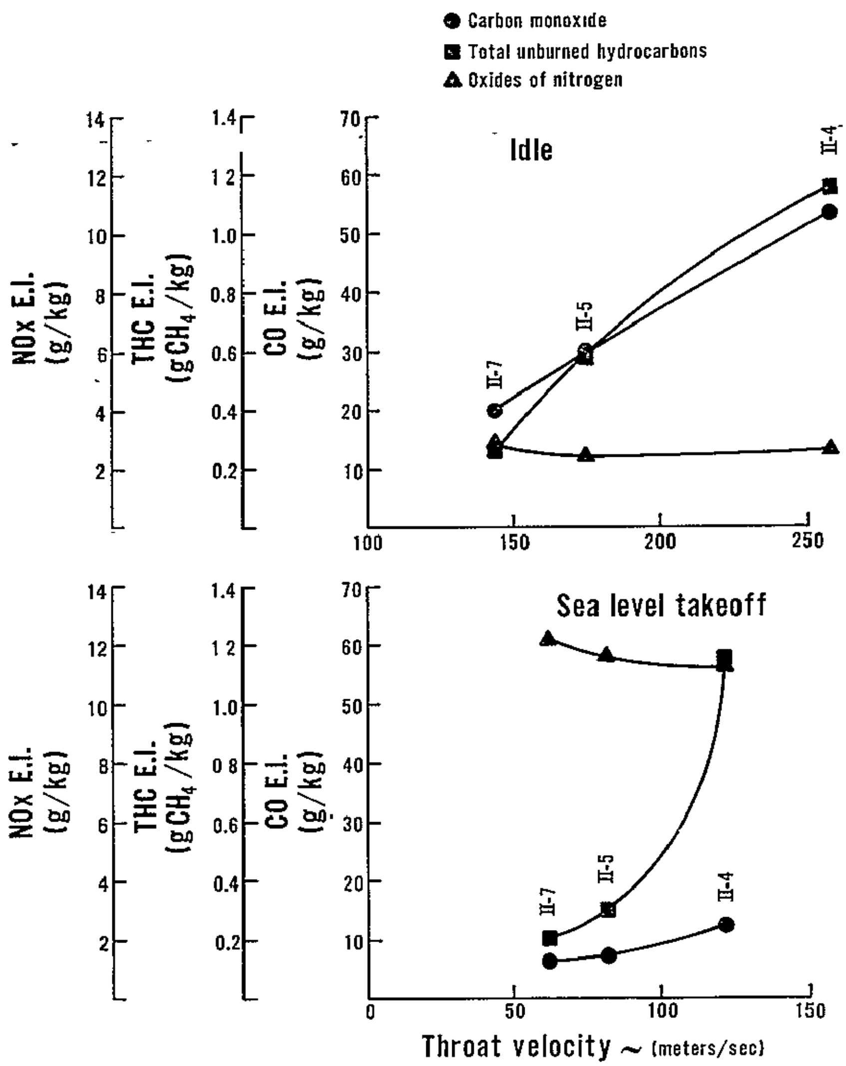


Figure 23 *Results of Parametric Evaluation of Throat Velocity Variation on Element II Emission Levels*

Pilot Nozzle Primary - Secondary Fuel Split

Figure 24 shows the effect of pilot nozzle primary to secondary fuel split on emission indices for configuration II-9 at four operating conditions. At idle and approach, the lowest emission indices were obtained with fuel supplied through the secondary port of the nozzle. At climb and SLTO, there was little apparent effect shown by pilot nozzle fuel split. This trend was observed for all of the Element II configurations and may be due to the degree of aeration in the nozzle or to air/fuel interaction in the pilot. It should be noted that the reverse was true in Element I, i.e., better THC and CO emissions indices at idle on the primary system. This seems to indicate that pilot geometry is affecting the combustion process. The recirculation region that develops may be entirely different in the two Elements due to changes in combustor geometry. Other factors, such as the pilot equivalence ratio, further complicate the formulation of general conclusions.

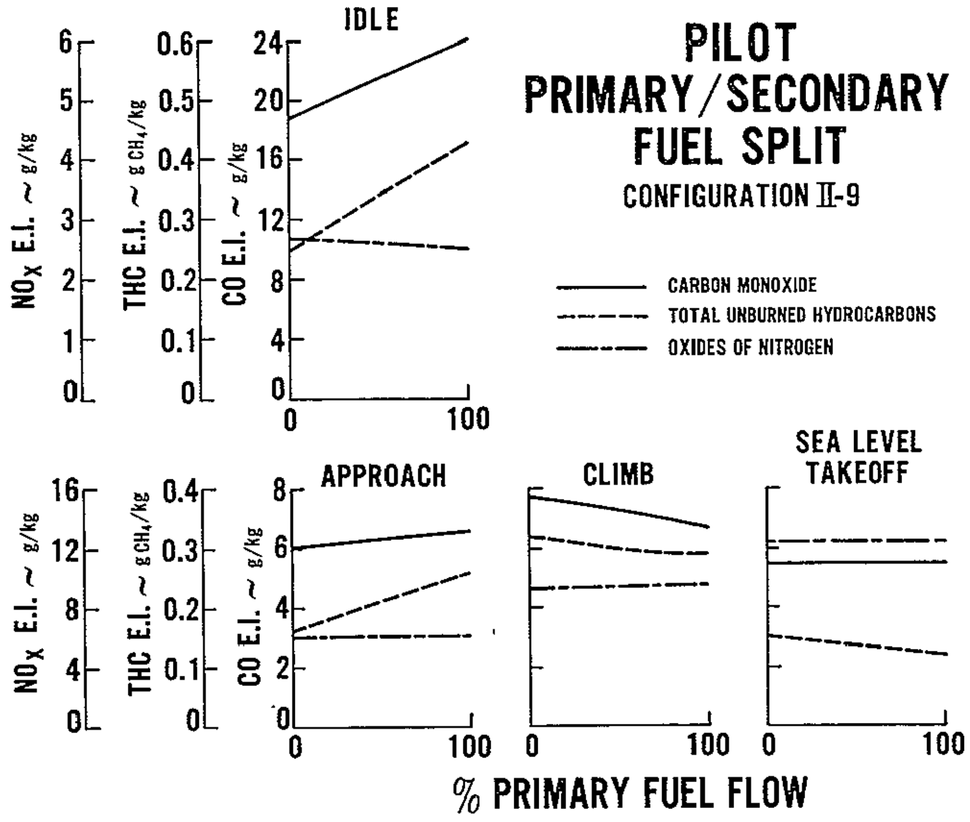


Figure 24 *Effect of Pilot Nozzle Primary - Secondary Fuel Split on Emissions for Element II Configuration II-9*

Main Zone Airflow Distribution

In configuration II-6, the main stage swirlers were located 2 louvers further downstream to investigate one type of main zone airflow distribution change. Referring to the table of EPAPs, (Table XVI), it can be seen that emissions were reduced, with the greatest reductions occurring in THC and smoke number. These reductions can be attributed to a reduction in main zone residence time and an increase in pilot zone residence time. The effect of redistributing the main zone airflow between the swirlers and aft liner dilution holes was evaluated in configurations II-3 and II-4, and found to have little or no effect on emissions over the range of redistribution considered.

Element III

The emissions test results for five Element III configurations are presented in two tables. Table XVIII summarizes EPAP's and smoke numbers and Table XIX the emission indices at the four design operating conditions plus cruise. The baseline and goal values are included for comparison purposes. As in the case of the Element II combustors, emission indices have been quoted at specific values of pilot/main fuel split. The particular values of fuel split were selected on the basis of best simultaneous reduction of CO, THC and NOx at each of the EPA power points, and are identified in Table XIX.

TABLE XVIII

ELEMENT III EPAP AND SMOKE NUMBER SUMMARY

Configuration	EPAP NO_x	CO	THC	Maximum Smoke	Comments
Goal	3.0	4.3	0.8	25	
JT8D-17	8.2	16.1	4.4	25-30	
III-3	4.6	14.32	0.42	2	6 main zone injectors fueled at climb & SLTO. All pilot approach
III-4&5*	5.1	14.5	1.5	2	3 main zone injectors fueled at approach, climb and SLTO
III-3&4	4.2	17.0	1.7	2	3 main zone injectors fueled at approach and 6 at climb and SLTO

*Climb and SLTO emission indices from configuration III-5

TABLE XIX

ELEMENT III EMISSION INDEX SUMMARY*

	Idle					Approach					Climb				
		EI (g/kg)					EI (g/kg)					EI (g/kg)			
Configuration	% Pilot Fuel	NO_x	CO	THC	Comb. Eff.	% Pilot Fuel	NO_x	CO	THC	Comb. Eff	% Pilot Fuel	NO_x	CO	THC	Comb. Eff.
Goal		3 2	12.2	2.1			4 2	1.1	0 40			5.1	0.20	0.13	
JT8D-17 Baseline		3 7	44.5	12 8			8 5	7.5	0.67			20.0	0 89	0.04	
III-1	100	2 94	76.2	1 91	97.97		4.70	17.10	0 25	99 31		–	–	–	
III-2	100	3.04	45.1	8 21	97.98	100	3 22	59.47	307 04	62 72		–	–	–	
III-3	100	3 68	27.8	0.56	99.27	60	7.91	7 77	0 47	99.76	19	7.86	17.28	0.79	99.5
III-4	**100	3.68	27.8	0 56	99 27	100	4 85	29.19	10.53	98 08		–	–	–	
III-5	100	2 91	34.2	1 43	99.02	50	–	–	–		39	11.59	6.09	0.10	99.84

	SLTO					Cruise				
		EI (g/kg)					EI (g/kg)			
Configuration	% Pilot Fuel	NO_x	CO	THC	Comb. Eff	% Pilot Fuel	NO_x	CO	THC	Comb. Eff.
Goal		5.2	0.16	0.11			–	–	–	
JT8D-17 Baseline		24 4	0.55	0 03			11.0	–	–	
III-1		–	–	–			–	–	–	
III-2		–	–	–			–	–	–	
III-3	19	10 04	7.26	0.29	99 79	47	2 51	166.30	256.26	66 13
III-4		–	–	–		47	7.42	12.19	0 27	99.68
III-5	27	12.62	4 22	0.10	99.89	43	6.59	23.88	1.80	99.23

* Emission index for THC expressed as equivalent methane (CH_4)

* Repeated from configuration III-3

EPAP and Smoke Number

Although this combustor program suffered a high percentage of incomplete tests, sufficient data were obtained to calculate EPAP's for three Element III configurations. The first configuration for which test results over the full range of conditions were recorded was III-3. Table XVIII indicates that reductions of approximately 50% in NO_x and 10% in CO were obtained compared to the baseline, while the THC goal was met. These values of EPAP correspond to operation of only the pilot zone at approach. Attempts to ignite the main zone at the approach power point with fuel supplied to all six premix tubes were unsuccessful.

The number of active main zone fuel injectors was reduced from 6 to 3 for configurations III-4 and III-5. The purpose of this modification was to increase main zone tube equivalence ratio to a level where efficient operation of the main zone at the approach condition was possible. Data from configurations III-4 and III-5 have been combined to calculate EPAP's for operation of the combustor with three main zone premix tubes fueled at the approach, climb and take-off power points. The increase in the EPAP above the goal level is attributable to the increase in the THC emission index at the approach power point.

Data from configurations III-3 and III-4 were combined to calculate a third set of EPAP's for the Element III combustor corresponding to operation of the main zone with 3 injectors at approach and 6 at climb and SLTO. As shown in Table XVIII, this mode of operation resulted in the best NO_x EPAP, at some sacrifice in both CO and THC.

Smoke was virtually eliminated in both the 6 and 3 injector configurations.

Emission Indices

Idle

The first two configurations tested were premixed pilot designs with perforated flameholders. Both combustors experienced flameholder burnout during idle operation and were not tested at high power conditions. The poor idle emissions and the durability problems encountered in these tests are indicative of poor pilot airflow distribution.

The third Element III configuration incorporated a redesigned pilot derived from the best Element II design. The combustor was tested over the full range of operating conditions without operational or durability problems. Compared to the baseline emission indices (see Table XIX), reductions were achieved for CO and THC while NO_x was unchanged. The CO emissions were also approximately 25% less and NO_x 25% higher than the values predicted from the Element II test results. This could be the result of the increased pilot volume required for the heat exchanger installation.

Evaluation of the pilot with vaporized fuel was attempted as part of the configuration II-5 testing. However, a pilot flameout occurred before a fuel temperature corresponding to 100% vaporization was reached. Figure 25 shows the effect of increased fuel temperature on idle CO emission up to the point of instability. The CO emission index was unaffected to a temperature of 422K. Between 422K and 478K, a decrease in CO EI of approximately 10% took place. This temperature range approximately corresponds to the initial boiling point of Jet-A fuel. Although an accurate determination of the percent vaporization present at 478K is not possible due to the inability to predict the cooling effect of the 412K inlet air, the observed trend agrees with that reported by Norgen and Ingebo (Ref. 10). In that experiment, propane was used to simulate vaporized fuel, and a 36% decrease in CO was achieved at 100% vaporization. Figure 25 also shows the effect of the poorer atomization that occurs when supplying fuel through the enlarged primary port instead of the secondary utilized in the earlier III-3 configuration. The vaporized system would have had to reduce the CO level by at least 20% before proving beneficial.

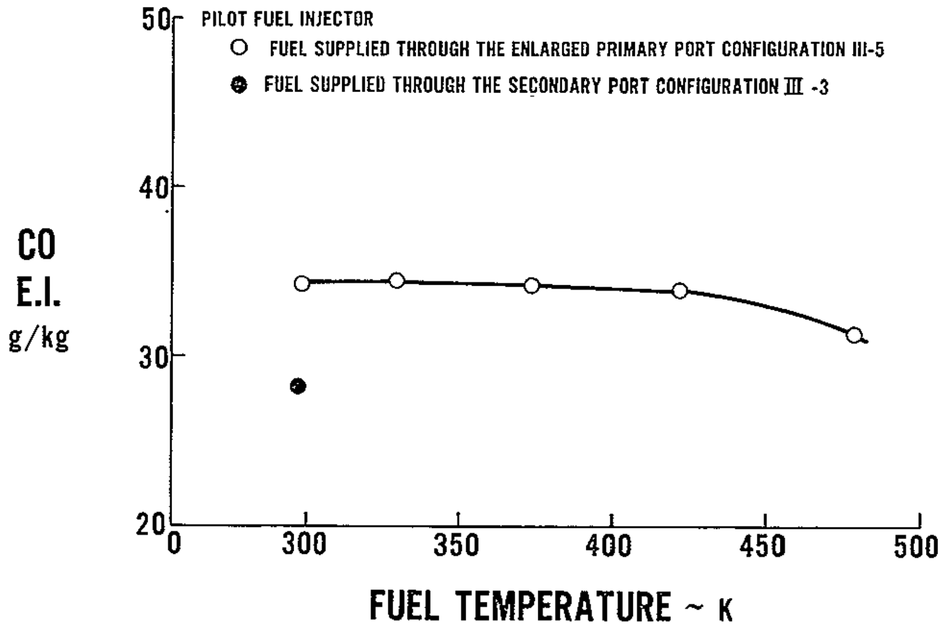


Figure 25 Effect of Fuel Temperature on Idle CO Emission for Element III Configurations

High Power

Successful high power operation with vaporized main zone fuel was first achieved with the configuration III-3. The best emission levels resulting from testing over a range of pilot to main fuel splits at each operating condition above idle are presented in Table XVI. Although the results at SLTO were not as low as would be expected for an ideally premixed, prevaporized system, the NO_x EI was reduced approximately 60% relative to the baseline.

Several pilot only test points were evaluated at SLTO inlet conditions to determine the relative NO_x contributions of the pilot and main zone. Figures 26 and 27 show that optimizing the pilot to main zone fuel split for overall NO_x and CO emission levels is essentially a process of offsetting an emission increase in one zone against a corresponding reduction in the other. For this combustor design, the large pilot NO_x contribution at high pilot fuel flow necessitated operating at higher than desired main zone equivalence ratio.

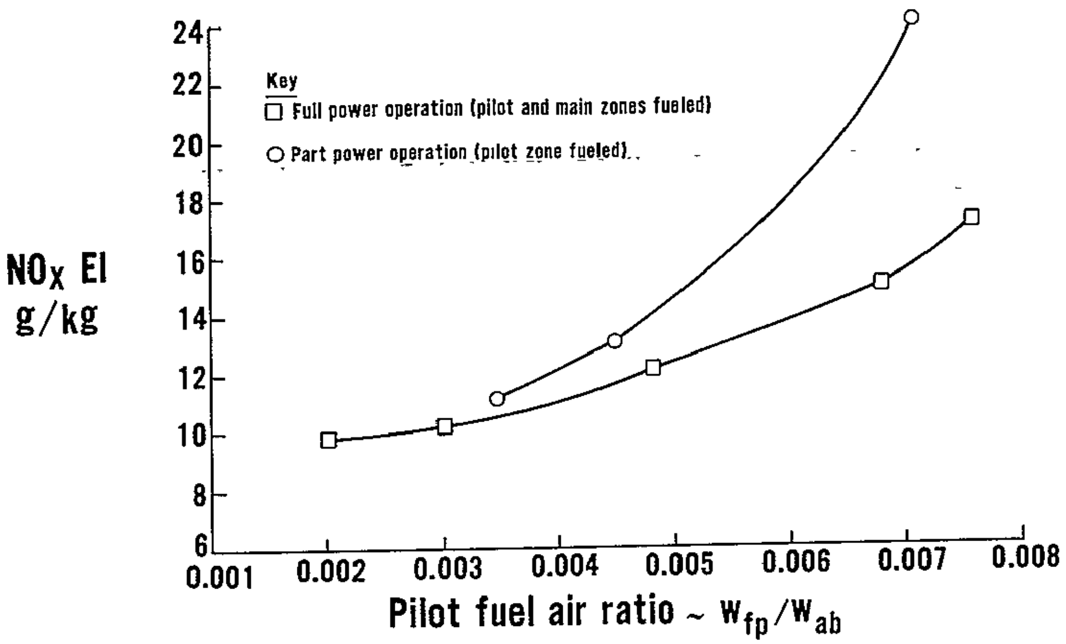


Figure 26 *Element III NO_x Emission Levels as a Function Pilot Burner Fuel-Air Ratio at SLTO Conditions*

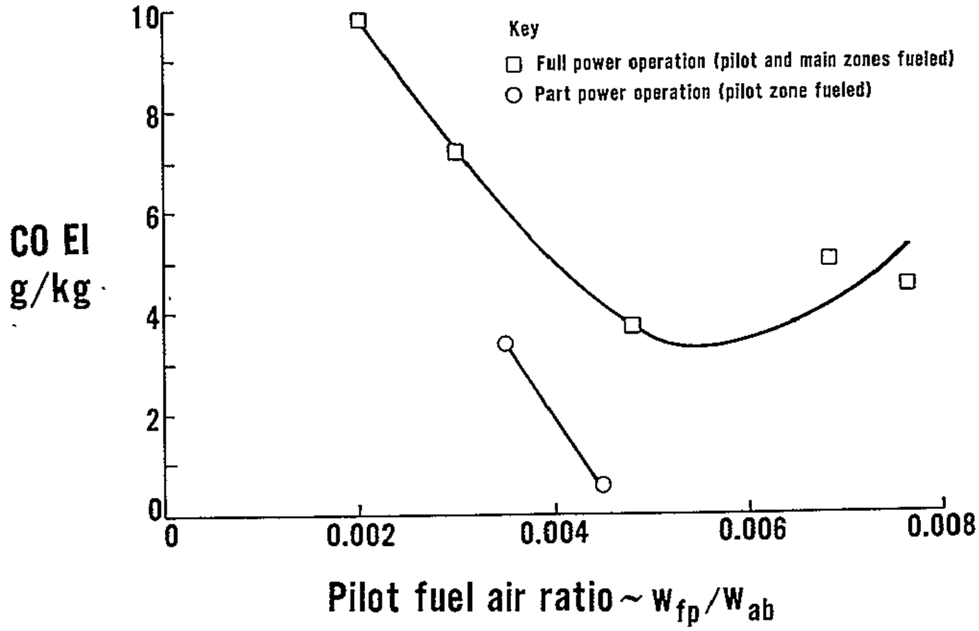


Figure 27 *Element III CO Emission Levels as a Function of Pilot Burner Fuel-Air Ratio at SLTO Conditions*

The effect of main zone premix tube equivalence ratio can be examined by comparison of the third and fifth configurations. In the fourth and fifth configurations, fuel was supplied to the main zone through only three injectors, effectively doubling the premix tube equivalence ratio when compared to six tube operation (configuration III-3). Data presented in Table XIX for configurations III-3 and III-5 at the climb and SLTO power points indicate an increase in NO_X and decreases in CO and THC for three tube operation.

Intermediate Power

Although testing with configuration III-4 was limited to the approach and cruise conditions, sufficient data were obtained to assess the benefit of reducing the number of main-stage injectors at these conditions. The approach emissions obtained for both pilot only six tube operation of configuration III-3 and staged/three tube operation of configuration III-4 are presented in Table XIX. As shown in the Table, compared to the all pilot approach point of configuration III-3, staged operation with three tubes fueled provided a 39% reduction in NO_X with moderate increases in CO and THC.

Staging the main zone to three injectors was also required for efficient combustion at the cruise condition. With six injectors, the best efficiency in dual stage operation was 66%, while efficiencies of 99% were possible with three injectors. Even with three injectors, the best CO levels were still more than twice as high as the best Element II results.

Heat Exchanger Operation

To maintain heat exchanger fuel temperatures at desired levels, it was necessary to bypass some of the heat exchanger fuel flow at most operating conditions. A portion of the heat generated in the pilot was therefore removed. To evaluate this effect on combustor performance, test points were taken at various heat exchanger fuel flows while holding combustor inlet conditions and fuel-air ratio constant. It was found that heat removal had negligible effect on emissions at both the idle and sea-level take-off power points. It was therefore unnecessary to correct emission data for heat removal by the bypassed fuel flow.

Attempts to evaluate the main zone performance at various degrees of fuel pre-vaporization were unsuccessful due to the apparent inability to reduce fuel temperature low enough to overcome the heat supplied by the inlet air within the premix tubes. Reference 11 found that complete vaporization of pressure atomized droplets of JP5 fuel could be accomplished within 2.7 ms at 833 K and 4 atmospheres pressure. The 1 ms residence time within the premix tubes was evidently sufficient to produce the additional heat for vaporization even at the lowest attainable fuel temperature of 526°K, since NO_X emissions remained constant as the fuel temperature was reduced to 526°K. As discussed in Ref. 11, this is indicative of the absence of liquid fuel droplets, the presence of which would increase NO_X substantially.

ASSESSMENT OF EMISSION RESULTS

A summary of the EPAPs and emissions indices for the best configurations within each program element are presented in Tables XX and XXI, respectively.

An examination of the NO_x EPAP's reveals that each concept reduced NO_x relative to the JT8D baseline, but that none achieved the goal. NO_x emission characteristics corresponding to simulated sea-level static engine operation are presented in Figure 28 for each of the concepts investigated. Comparison is also made to the baseline and one set of hypothetical EI goals. As shown, both two-stage burners, representing Elements II and III, produced significant high power NO_x reductions, but fell short of the desired goal. The Element III concept demonstrated slightly greater NO_x reduction at high power, attributable to the prevaporizing feature of main zone. The Element II concept, however, had the lower NO_x EPAP due to the emphasis placed on the idle and approach emission indices in the EPAP calculation (Ref. 2). The Element I configurations produced slightly better high power NO_x levels than the baseline due to improved fuel preparation. However, the single-stage designs have limited potential for further significant NO_x reduction.

The lowest CO and THC emissions were attained by the Element I configuration utilizing airblast nozzle # 2. In particular, configuration I-2 listed in Table XX produced EPAPs lower than the THC goal and very close to the CO goal. However, the single-stage carburetor tube concept (I-6), which incorporates a lean front end for NO_x control at high power, illustrates how readily idle CO and THC can be compromised for relatively modest additional NO_x reduction.

TABLE XX

EPAP COMPARISON

Configuration	EPAP NO_x	EPAP CO	EPAP THC	Maximum Smoke
Goal	3.0	4.3	0.8	25
JT8D-17 Baseline	8.2	16.1	4.4	25-30
Airblast Nozzle I-2	7.42	5.05	0.05	28
Carburetor Tube I-6	5.78	51.98	22.55	2
Advanced Vorbix I-9	4.38	8.93	0.18	27
Prevaporized, Premixed III-3	4.56	14.30	0.43	2

TABLE XXI

EMISSION INDEX COMPARISON

	Idle			Approach			Climb			SLTO			Cruise		
Configuration	NO_x	CO	THC	NO_x	CO	THC	NO_x	CO	THC	NO_x	CO	THC	NO_x	CO	THC
Goal	3.2	12.2	2.1	4.2	1.1	0.40	5.1	0.20	0.13	5.2	0.16	0.11	–	–	–
JT8D-17 Baseline	3.7	44.5	12.8	8.5	7.5	0.67	20.0	0.89	0.04	24.4	0.55	0.03	11.0	–	–
Airblast Nozzle I-2	4.27	13.35	0.09	7.42	3.16	0.12	17.81	0.59	0.00	19.82	0.54	0.01	–	–	–
Carburetor Tube I-6	1.52	136.5	64.8	6.15	46.8	5.81	15.48	0.66	0.02	18.67	0.33	0.05	–	–	–
Advanced Vorbix II-9	2.65	18.9	0.25	5.75	4.89	0.14	9.30	7.76	0.32	12.06	5.46	0.15	7.22	5.17	0.13
Prevaporized, Premixed III-3	3.68	27.8	0.56	7.91	7.77	0.47	7.86	17.28	0.79	10.04	7.26	0.29	2.51	166.3	256.26

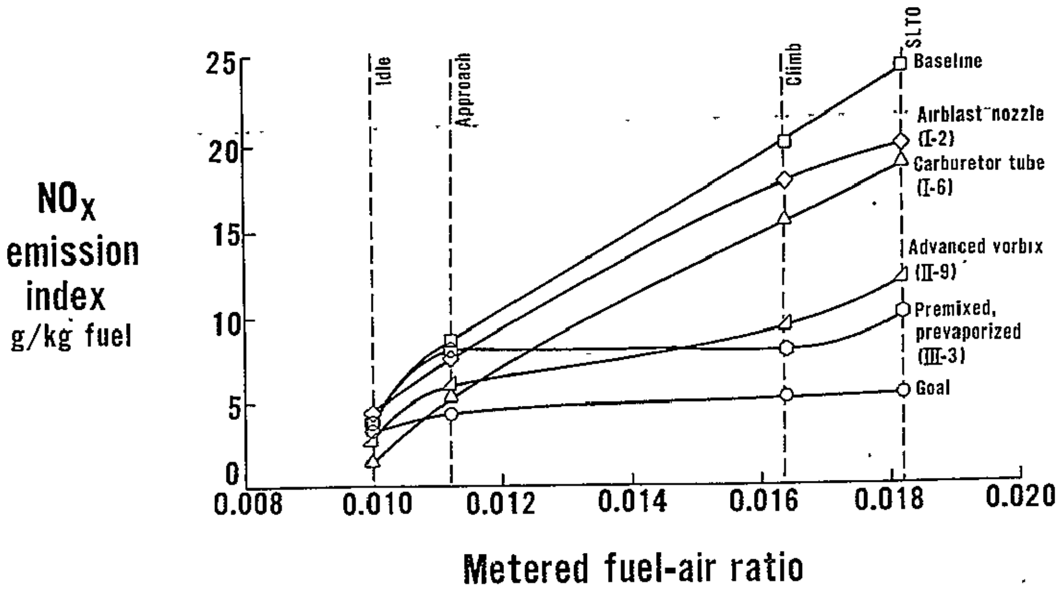


Figure 28 Summary of NO_x Emission Results at Simulated Engine Operation

The representative configurations from Elements II and III also produced THC EPAPs below the goal level and reduced CO EPAPs relative to the baseline. Both of these reductions are the result of improved pilot performance attributable to the better fuel preparation and distribution developed during the single-stage combustor tests of Element I. Application of the two-stage concepts for NO_x control resulted in increased CO and THC levels at climb and SLTO, when compared to the baseline and Element I configurations. This is illustrated in Figures 29 and 30. Because of this characteristic, the CO and THC EPAPs for the two-stage concepts do not achieve the levels of the best single-stage concepts.

The ultimate emissions reduction potential of the two-stage combustor concepts is affected by operational problems encountered at intermediate power operation. For example, the Element II configurations exhibited reduced combustion efficiency (and hence increased levels of CO and THC) when the main burning zone was fueled at the approach power point. Since pilot only operation at approach is accompanied by an increase in NO_x emission index, a decision which favors either the NO_x or the CO and THC EPAP values must be made. A similar NO_x - CO, THC trade-off versus pilot/main fuel split was encountered at the higher power operating points. Thus, depending on the particular regulation format being addressed, the absolute CO, THC and NO_x emission levels for a given level of technology are open to manipulation. For this reason, the values presented in Tables XX and XXI represent rather arbitrary choices. An analogous situation exists for the Element III combustor concept. This concept exhibited reduced stability limits which resulted in poor efficiency at the cruise condition. Since cruise power could not be attained with pilot only operation, the main zone was staged to three injectors to obtain acceptable efficiency. For a non-variable geometry combustor, restriction to three premix tubes results in a substantial increase in NO_x emission index at the higher power operating points.

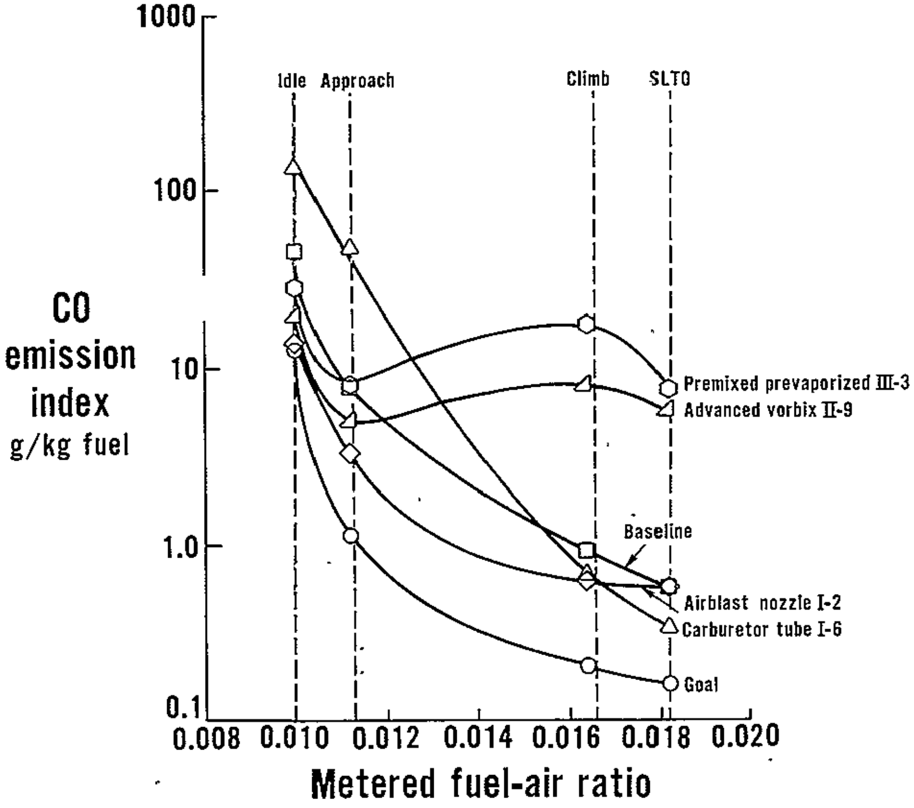


Figure 29 *Summary of CO Emission Results at Simulated Engine Operation*

Two additional control techniques, water injection and external gas assist fuel atomization, were not investigated in this program. These control techniques both fall within the definition of Element I, and have been well documented in previous work. Water injection has been shown to produce large reductions in high power NO_X levels in conventional combustors (Ref. 12 and 13). Significant reductions in low power emissions have been achieved by external assist fuel atomization (Ref. 14). This approach reduces CO and THC emissions by injecting compressed air at high pressure through the secondary flow passage of a standard duplex fuel nozzle.

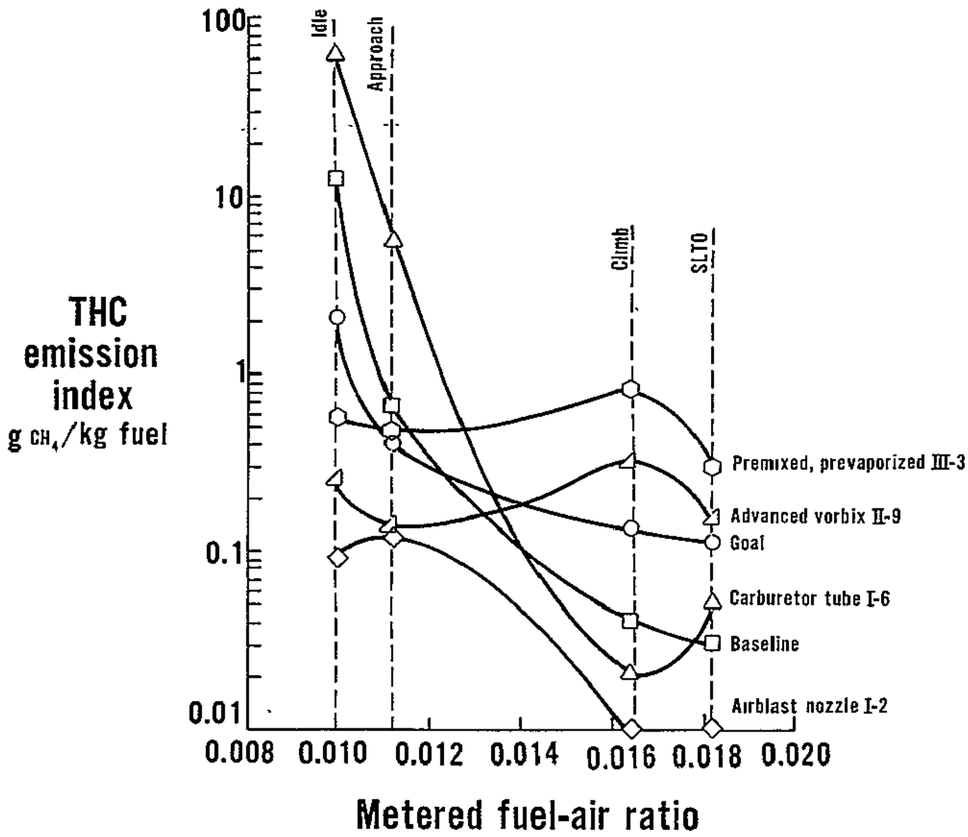


Figure 30 *Summary of THC Emission Results at Simulated Engine Operation*

COMBUSTOR PERFORMANCE

In addition to the combustor emission measurements already discussed, performance parameters were recorded or calculated. A summary of system pressure loss, pattern factor and idle lean blowout parameters are presented in Table XXII. Altitude stability and relight characteristics were measured for one Element I and one Element II configuration and are presented in Figures 31 through 34. These performance measurements along with durability and coking characteristics are discussed in the following sections.

Pressure Loss

The measured values of overall system pressure loss listed in Table XXII are generally below the goal level (8.3%) except for the initial Element II configurations. Airflow distribution problems which were subsequently corrected, accounted for the high pressure loss for these configurations.

TABLE XXII

SUMMARY OF COMBUSTOR PERFORMANCE RESULTS

Configuration	Cold Flow System Pressure Loss (%)	SLTO Pattern Factor	Idle Lean Blow-out Fuel-Air Ratio
Goal	$\leqslant 8.3$	$\leqslant 0.25$	–
Baseline	8.1	0.28	0.003
I-1	7.3	0.26	–
I-2	7.6	0.29	–
I-3	7.1	0.33	0.0015
I-4	7.0	0.14	0.004
I-5	7.3	0.39	–
I-6	7.5	0.27	0.003
II-1	8.9	–	–
II-2	8.0	–	–
II-3	8.6	0.36	–
II-4	7.8	0.26	–
II-5	7.5	0.25	–
II-6	7.1	0.19	< 0.004
II-7	7.5	0.41	< 0.002
II-8	7.1	0.43	0.004
II-9	7.5	0.65	–
III-1	6.0	–	–
III-2	7.4	–	–
III-3	7.7	0.20	–
III-4	7.5	–	–
III-5	7.5	0.28	–

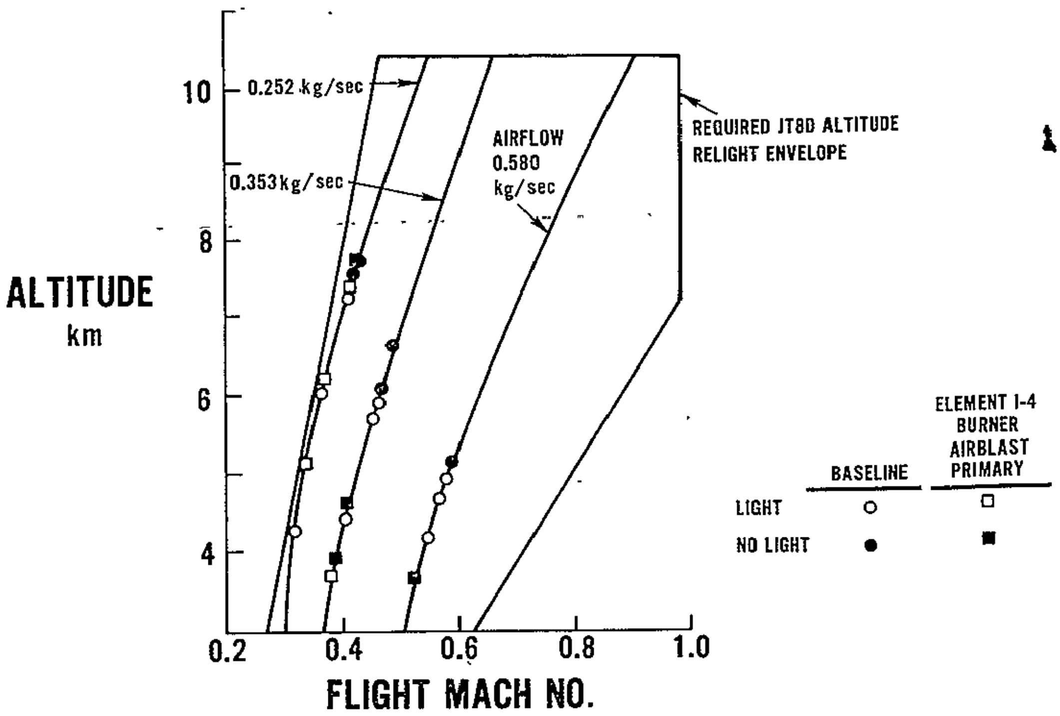


Figure 31 *Altitude Relight Characteristics of the Baseline and Element I Configuration I-4*

SYMBOL	RUN NO.	FUEL TEMP , K	INLET TEMP , K	BURNER CONFIG.	NOZZLE
○	1	255.4	255.4	BASELINE	PRESSURE ATOMIZING
□	2	255.4	255.4	I-4	PRESSURE ATOMIZING - PRIMARY
△	3	255.4	255.4	I-4	AIRBLAST - SECONDARY

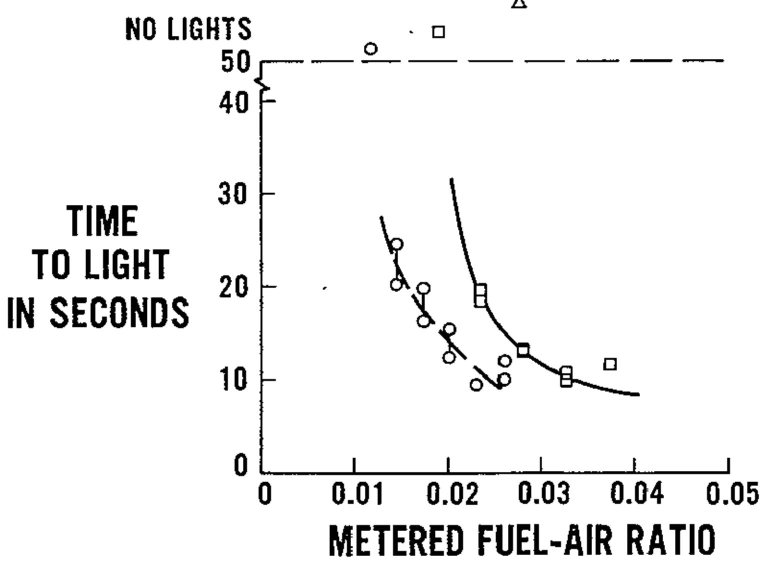


Figure 32 *Sea-Level Starting Results for Element I Airblast Nozzle Configuration I-4*

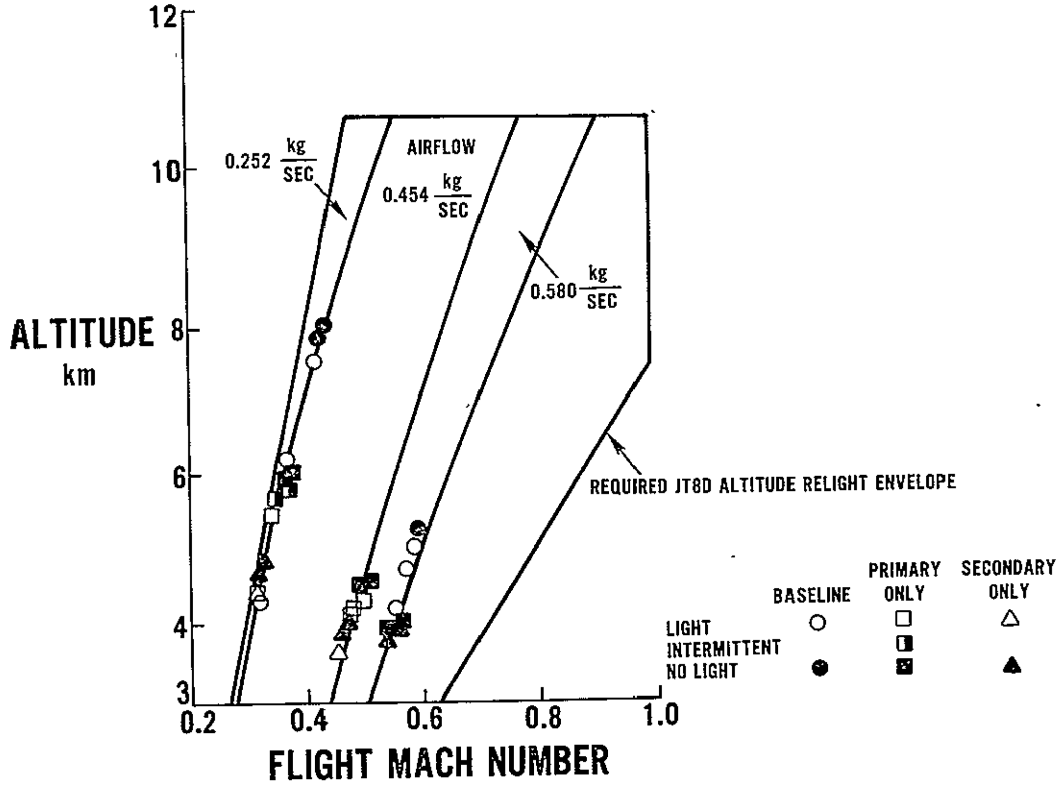


Figure 33 *Altitude Relight Results for Element II Configuration II-9*

SYMBOL	FUEL TEMP, K	INLET T_{T4}, K	BURNER CONFIGURATION	NOZZLE
△	294.3	255.4	II-9	AIRBLAST - SEC.
□	288.7	255.4	II-9	PRESSURE ATOMIZING - PRI.
----	255.4	255.4	BASELINE	PRESSURE ATOMIZING

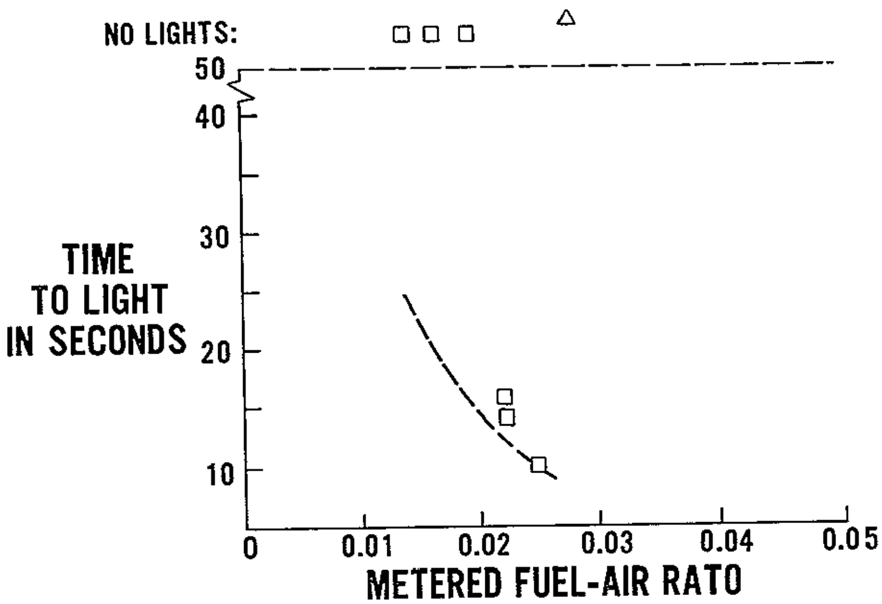


Figure 34 *Sea-Level Starting Results for Element II Configuration II-9*

Pattern Factor

The pattern factor results acquired in this program were determined from observed maximum combustor exit plane temperature, based on readings of ten or fewer thermocouple elements, and the computed average exit temperature, based on metered fuel-air ratio and actual combustor inlet conditions. For this reason the quoted values of pattern factor should be considered as minimum values, with the actual values probably being considerably higher. The data presented in Table XXII are intended for relative comparison of the various configurations. Meaningful radial exit temperature profile information could not be determined from the small number of thermocouple data.

A review of the data presented in Table XXII shows that most of the pattern factors calculated for these combustor configurations exceed the goal of 0.25, but for the most part are not unusual for the early stages of combustor development. The aerating nozzle configurations tested in Element I are particularly attractive in this regard. The later Element II configurations indicate pattern factor to be a problem area, particularly since the quoted figures would tend to understate the actual levels. However, on one attempt made during the Element II test program, significant improvement was realized in pattern factor. Dilution air was increased by 10% and the pattern factor was reduced from 0.36 in configuration II-3 to 0.26 in configuration II-4. The pattern factor values quoted for Element III, while attractively low, are based on very few functioning thermocouples.

Idle Lean Blowout

Idle lean blowout data were taken for selected combustor configurations and the results are presented in Table XXII. The configurations tested demonstrated good idle stability with fuel-air ratios less than or equal to 0.004 in all cases. It should be noted that idle pressure and flow levels were maintained during the rig lean blowout tests. In an engine subjected to a snap deceleration, fuel flow would drop essentially instantaneously, while the inertia of the rotating machinery would slow the response of the airflow. Since this lag results in a transient fuel-air ratio that occurs at pressure and temperature levels higher than the idle values, the rig values of lean blowout may be considered conservative from an operational point of view.

Altitude Stability and Relight Characteristics

Altitude stability and relight tests were conducted on one Element I and one Element II combustor to assess the capability of low emission combustors to satisfy current engine relight requirements. The Element III combustor was not tested for altitude stability and relight.

The Element I combustor stability and relight tests were conducted with aerating nozzle configuration I-4 which featured lean primary zone equivalence ratio. This combustor configuration was selected for relight evaluation since it was expected to exhibit the greatest deficiency among the aerating nozzle configurations.

As shown in Figure 31, this combustor recorded generally poorer altitude relight than the baseline JT8D-17 burner. Relight altitude was the same at the low airflow of 0.252 kg/sec, but lighting was more difficult at the higher airflows. Figure 32 compares the sea level starting characteristics of this burner with the current JT8D-17 baseline. Sea-level starting was investigated with fuel introduction either through the pressure atomizing primary nozzle passage or through the aerating secondary passage. The Element I combustor was found to exhibit deficient starting characteristics on primary, and failed to light on secondary.

The Element II stability and relight tests were conducted on advanced vorbix configuration II-9. This configuration was selected as providing the best overall emissions characteristics of the Element II combustors. As shown in Figure 33, this combustor also recorded poorer altitude relight than the baseline combustor. The aerating secondary fuel nozzle passage was again found more difficult to light. Figure 34 presents the sea level starting results and indicates that lights were obtained on the pressure-atomizing primary fuel system only.

Although the Element III concept was not tested for either altitude relight or sea level starting, it should exhibit similar characteristics to that of the Element II combustor since a similar pilot zone is utilized.

Element III Heat Exchanger Operation

Because of the importance of regenerative heating in the prevaporized/premix concept, heat exchanger operation was closely monitored during all tests. Heat exchanger capacity was found to be adequate for the desired range of fuel temperature. A representative fuel temperature vs flow rate relationship is shown in Figure 35.

The variable flow divider valve used during the Element III program to flash vaporize and meter fuel to the 6 main stage injectors demonstrates a viable approach. The operation of the valve was monitored during all tests and did not show indications of plugging. However, after periods of inactivity, the valve would seize in the closed position and have to be mechanically freed. This could be corrected in a future design by providing better seals between sliding surfaces.

Internal fuel system coke formation is a major concern in a design of this type. Post-test inspection revealed only minor carbon deposits on the inner walls of the heat exchanger, pressurization/distribution valve, and supply tubes. Figure 36 is a microsection of a fuel tube wall magnified to show the carbon deposit. This tube was located at the exit of the heat exchanger and was used for the entire Element III program without cleaning. Table XXIII summarizes the times at various fuel temperatures that were accumulated with this fuel tube. Although the carbon buildup experienced in these tests was not severe enough to affect combustor operation, it was sufficient to indicate a severe potential problem for eventual aircraft engine application.

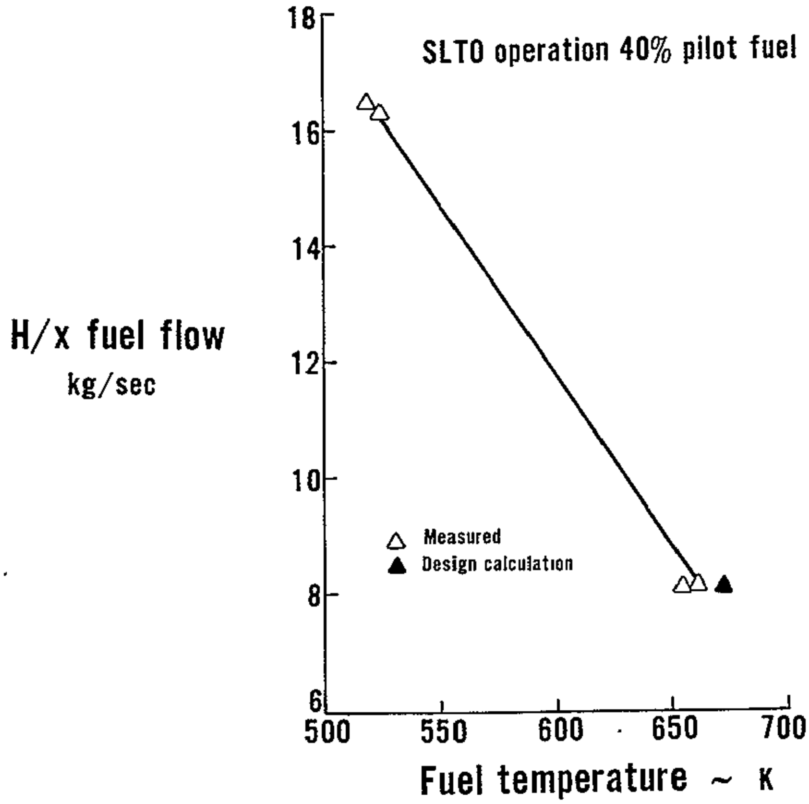


Figure 35 *Element III Heat Exchanger Performance at SLTO Operation*

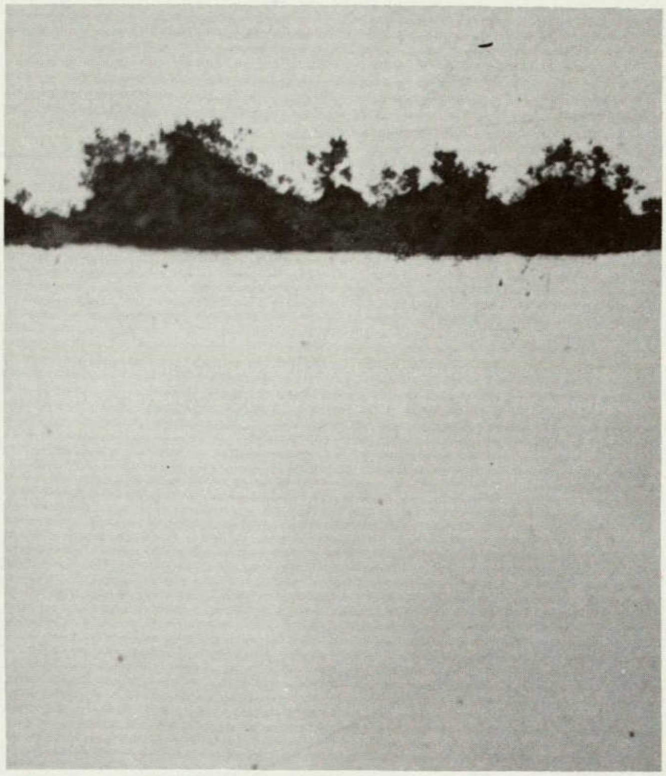


Figure 36 *Microsection of Element III Fuel Tube Showing Carbon Deposit (MAG 500X)*

TABLE XXIII

TIME AND TEMPERATURE HISTORY FOR THE HEAT EXCHANGER EXIT FUEL TUBE

Temperature Range, K	Approximate Hours
420 - 478	8
478 - 533	3
533 - 589	6
589 - 644	4
644 - 700	5

Combustor Durability

Durability problems were encountered in all combustor concepts except the carburetor tube configurations of Element I. These problems, detected through the use of temperature sensitive paints, skin thermocouples, diagnostic testing and post-test inspection, were generally localized and related to specific design deficiencies. Durability problems encountered with the Element II and III concepts were addressed in subsequent configuration modifications during the test programs, and the final configurations of these program elements were improved. These modifications are listed by configuration in Appendix A.

The durability problems encountered during testing of the Element I aerating nozzle configurations (I-1 through I-4) were caused by overheating due to deficient cooling airflow at the primary zone louvers. Partial deterioration of the swirl cup was revealed during testing of configuration I-2, and configurations I-3 and I-4 sustained some damage to the first and second louvers (Figure 37).

Figure 37 *Damage to First and Second Louvers of Element I Configuration I-3 Due to Overheating*

The Element II advanced vorbix configurations exhibited durability problems in several areas during the short time they were run in the test rig. During the test of configuration II-1, fuel aspiration caused burning outside of the fuel feed tubes. Modifications, based on the results of diagnostic testing in a water flow visualization facility, were incorporated in configuration II-2. These modifications, listed in Figure A-8, Appendix A, solved the aspiration problems. However, severe throat area damage occurred during the testing of configuration II-2. Modifications to reduce main zone burning in the vicinity of the throat louvers, and to provide more effective throat cooling were made to configuration II-3 (Figure A-9, Appendix A). Only minor throat damage (Figure 38) resulted from testing of configuration II-3. An additional increase in throat cooling airflow provided adequate durability for the later Element II rig tests.

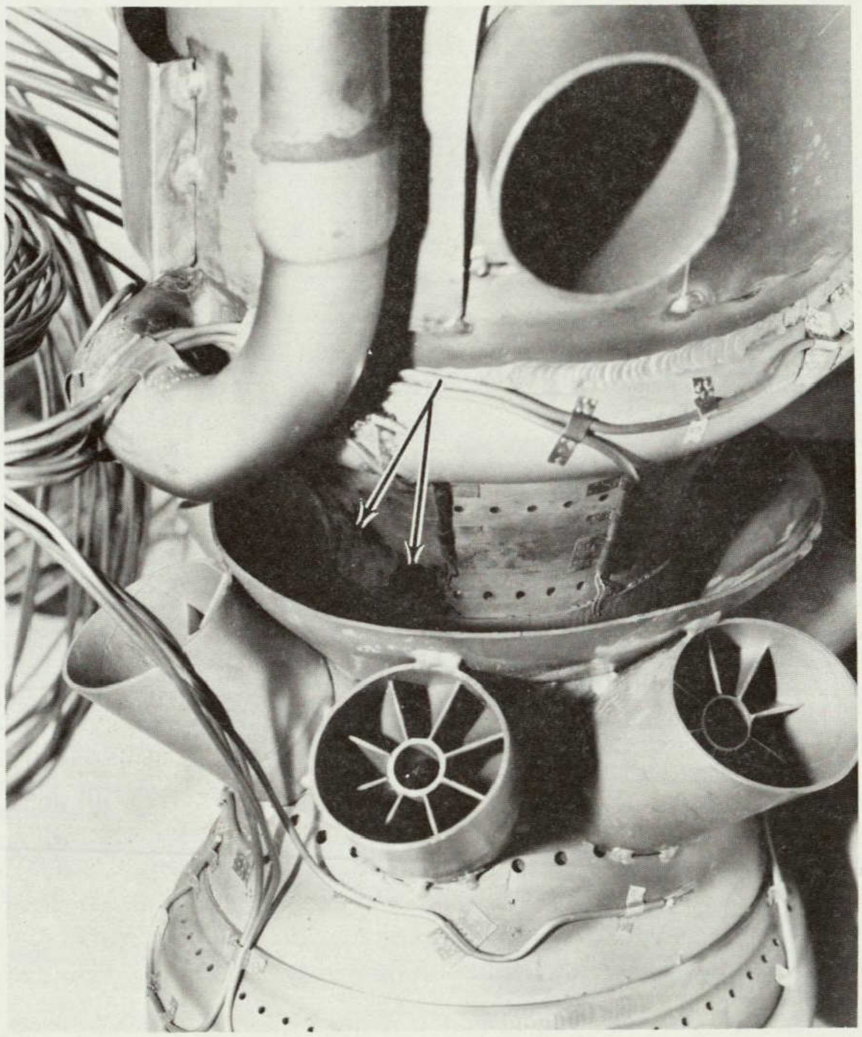


Figure 38 Minor Throat Damage to Element II Configuration II-3

Testing of the initial Element III configuration III-1 resulted in severe damage to the pilot flameholder, especially downstream of the nozzle support (Figure 39). In configuration III-2, a smaller nozzle and fuel nozzle support were used to eliminate an apparent recirculation area thought to be the cause of the flameholder damage; however, severe flameholder damage again occurred. An aerating pilot assembly, similar to that used in Element II, was used in configuration III-3 and subsequent testing was free of this type of damage.

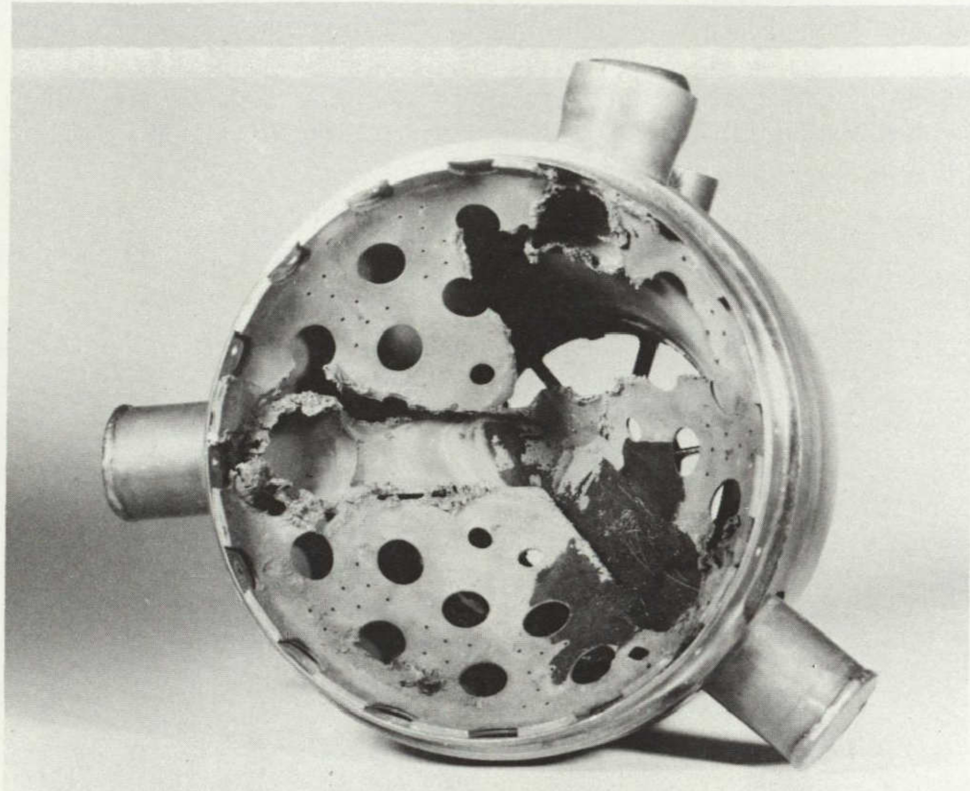


Figure 39 Severe Damage to Pilot Flameholder, Element III Configuration III-1

Carbon Deposits

Combustor liner carbon deposits proved to be a reoccuring problem in all three of the program elements. In the aerating nozzle configurations investigated in Element I, the downstream face of the fuel nozzle was the prevalent area of carbon formulation. This is illustrated in Figure 40. Lesser amounts of carbon were also encountered on the swirl cup and first and second louvers. It is felt that these coking problems can be eliminated with proper refinements to the aerating nozzle and front end flow distribution. The carburetor tube configurations displayed slight carbon deposits.

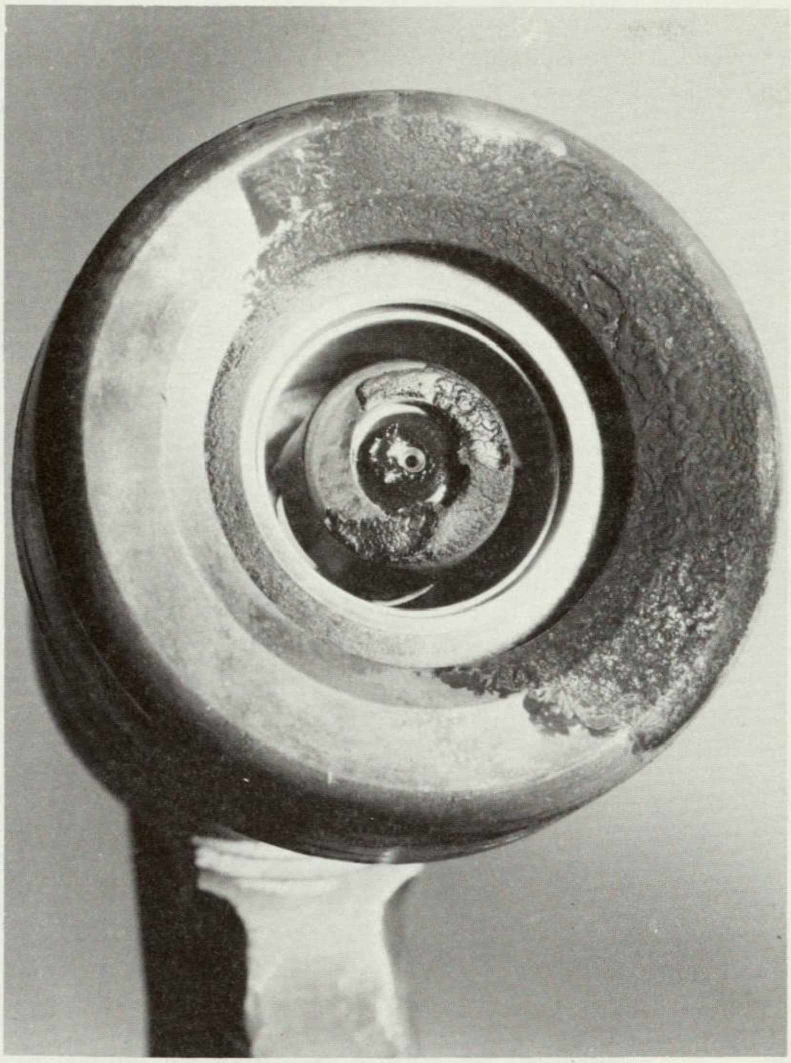


Figure 40 Carbon Deposits on Element I Fuel Nozzle Face

In the advanced vorbix Element II combustors, carbon deposits were detected at several locations. Deposits were observed on the face of the pilot fuel nozzle, similar to those shown in Figure 41. There are additionally some carbon observed in the tip of the main fuel injector and on the wall of the main fuel carburetor tubes coincident with the fuel injector location. This is probably indicative of less than ideal airflow uniformity at the carburetor tube inlet. More severe carbon deposits were encountered inside the combustor liner just downstream of the main fuel tube feed holes (Figure 42).

Minor carbon deposits were encounted in the Element III combustor tests, principally around the swirler skirts in the main fuel premixing tubes.

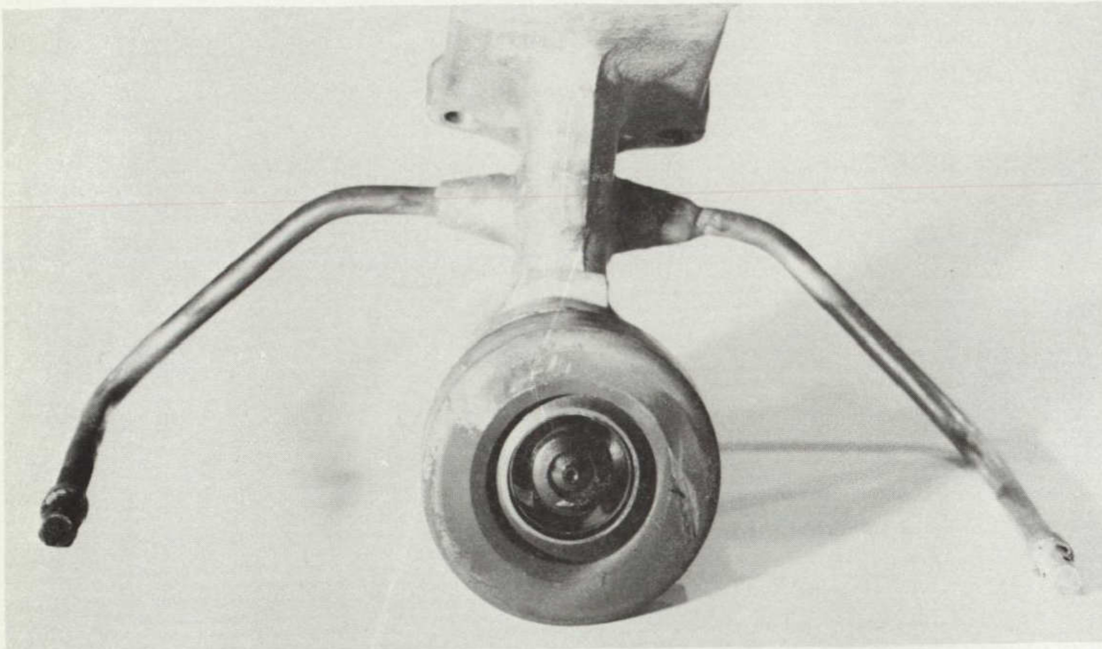


Figure 41 *Carbon Deposits on Element II Fuel Nozzle Face*

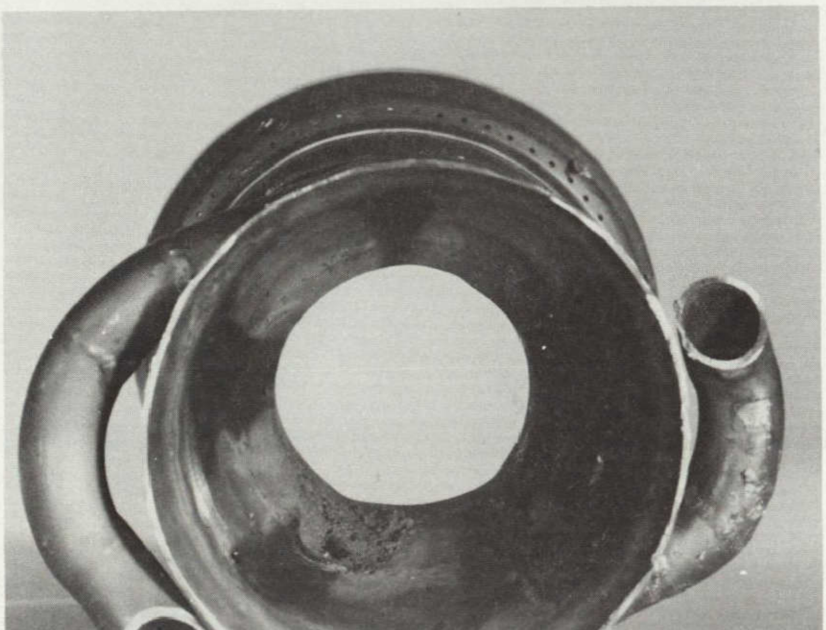


Figure 42 *Carbon Deposits on Element II Combustor Liner*

COMBUSTOR PERFORMANCE STATUS

The overall operational and performance status of the three combustor concepts is summarized in Table XXIV with respect to the amount of further development required to meet the performance goals and engine operational requirements. This table is somewhat optimistic in that a) improving one performance characteristic is likely to adversely affect another performance or emission characteristic; b) a limited amount of time has been spent assessing all aspects of performance, especially for Element III; c) results are derived from single-segment burner rig data only.

TABLE XXIV

SUMMARY OF OVERALL PERFORMANCE AND OPERATIONAL STATUS

	Development Status		
	Element I (aerating nozzle)	Element II	Element III
Pressure loss	1	1	1
Pattern factor	2	2	2
Combustion Efficiency			
at low power		1	1
at cruise power	—	1	3
at high power	1	1	1
Idle Stability (lean blowout)	1	1	1
Altitude relight	2	2	—
Durability	2	2	3
Carboning and nozzle coking	2	2	3

1. currently meets goals or requirements
2. should meet goals or requirements with development
3. additional technology development required

ENGINE CONSIDERATIONS

The combustor designs generated for all three program elements were specifically intended for application to the JT8D-17 engine. In addition to physical requirements of combustor size and burner system pressure loss, all combustor concepts were designed with cooling and structural durability criteria to satisfy JT8D-17 operation. As a result, no major flowpath of structural changes should be required to adapt the concept from this program to a production JT8D-17 engine. However, it is obvious that the Element II and III two-stage approaches are considerably more complex than the more conventional single-stage Element I approach. In addition the Element II and III concepts will require increased fuel control capability, substantially so in the case of Element III.

Element I configuration I-2 would require only minimal changes to the present production engine hardware. It has been designed as a true replacement for the existing combustor and fuel nozzle, and as such requires no modification to the existing burner case, fuel control, etc. In addition to a hole pattern change and modification to the primary zone swirl cup, a set of airblast nozzles is substituted for the production dual orifice fuel nozzles now in service. This nozzle change would require a modification to the fuel nozzle support assembly. A recalibrated pressurization and dump (P&D) valve may be required. Operational problems such as tailoring pattern factor and radial profile, poorer cold starting and relight characteristics and coking of the nozzle and dome faces will require traditional development programs prior to incorporation in production engines. Engine cyclic endurance testing would be required to identify durability problems that may not have been detected during this rig program.

The Element II advanced Vorbix concept will require completely new combustor liners and fuel nozzle/support assemblies. Additionally, there will be modification to the fuel control and external fuel manifolding system. The Element II concept is still considered to be a direct replacement for the current production combustor in that no modification to the engine diffuser and burner cases or transition duct is required. The combustor system hardware is more complex in that this is a two-stage concept requiring two additional fuel sources for the main stage as well as a complex throat section containing 6 air swirlers. Revision to the fuel control system, to provide pilot-stage operation at idle, and pilot-plus-main operation at higher power levels will be necessary. The degree of fuel management needed to separately control the pilot and main fuel flows, independent of the total fuel flow, will require use of a percent split valve. Although Element II emission values have been quoted for pilot-only operation at approach, it remains to be proven that this arrangement will allow acceptably rapid acceleration to full power. It is considered desirable to fuel both pilot and main zones at approach for this reason. Regardless of the operating mode selected for approach operation, it is imperative that the fuel flow respond promptly and continuously as the flow schedule passes through the staging point. Additional plumbing may be required to allow fuel to recirculate between the engine fuel pump and a main fuel manifold staging valve in order to minimize fill times. The main fuel injector system may be the source of further operational problems within an engine. A fuel-rich main tube equivalence ratio is believed to be required to prevent autoignition. This may result in a significant carbon deposit problem. There is additionally the possibility of main fuel tube autoignition during transient engine deceleration or during an emergency shutdown, when fuel downstream of the main staging valve can drain into the hot premixing tubes. These potential problems need to be explored further in engine testing. Tailoring of pattern factor and radial profile in the Element II combustor will be more difficult because less dilution air is available.

The premixed, prevaporized concept evaluated in Element III will require major changes to both the burner and engine system hardware. Since the heated main fuel is metered and distributed to the main fuel injectors outside the burner case, this is no longer a direct replacement for the existing combustor liner and fuel nozzle support assembly. Although the fuel system arrangement utilized in these tests was intended for experimental use only, even a refined fuel system is sure to impact the nacelle arrangement. This will make incorporation in an existing production engine model very unattractive.

The problems associated with a dual-stage fuel system outlined for the Element II concept will be compounded by the presence of heated fuel, the requirement that fuel pressure be held approximately constant independent of flow rate, and the probable requirement for return of heated fuel to the aircraft fuel supply. The Element III concept has been shown to provide unacceptable combustion efficiency at intermediate power settings when configured as a two-stage system. Although individual control of the 6 fuel injectors is not anticipated, the ability to supply fuel selectively to a limited number of injectors will be necessary. This, in effect, will add a third stage to the fuel control system. An alternate means of addressing this problem, not investigated in this program, is to provide variable premix tube airflow metering geometry. Control system complexity will be increased in either event.

Although the early stage of development makes it difficult to define all of the problem areas with the Element III concepts, it is apparent that a major redesign of the fuel system is required. To allow bypassing a portion of the heat exchanger fuel flow, a system for filtering and cooling heated fuel will have to be designed and any problems associated with fuel composition changes at high temperature assessed. In the Element III design, heat exchanger wall temperature was held within limits and fuel vaporization was prevented upstream of the pressurization valve in order to minimize internal fuel system coke formation. Nonetheless, some coke formation was observed in the course of the Element III testing. More powerful means of eliminating internal coke formation in the presence of heated fuel are not currently available. Provisions will therefore have to be made for cleaning carbon deposits from all tubes exposed to high temperatures. Szetela (Ref. 15) successfully used a hot air purge to clean carbon from tubes in which No. 2 home-heating fuel was vaporized. The fuel was heated at lower pressure in the referenced study. However, a comparison of electron micrographs of carbon deposits observed in this program and the referenced study indicated a similar carbon structure. It is therefore reasonable to expect that ground support hot air purges at regular intervals could be used to clean the fuel system. Cleaning the fuel tubes will limit the carbon buildup to levels where heat exchanger temperature rise and pressure drop are not affected, but will not eliminate the problem of particles breaking loose and contaminating the system during combustor operation. This poses a potentially unresolvable problem, since a series of small diameter flow restrictions is required in the pressurization/distribution valve to maintain fuel pressure above the critical point.

At the present stage of development, the Element III concept must be considered basically unsuitable for aircraft gas turbine application. With improvements in main-zone mixture preparation and pilot design, this concept certainly holds the greatest potential for ultimate high power NO_x reduction of those concepts tested. Until the potential fuel system problems (coking, dependability of the pressurization system, etc.) can be studied in more detail and an acceptable means of staging can be devised, it will simply be premature to judge the merits of this system.

CHAPTER V: CONCLUDING REMARKS

Based on the results of this Pollution Reduction Technology Program, the approach of classifying combustor concepts in terms of deviation from current engine design practice and increasing difficulty of development has proven to be a useful means of characterizing emissions reduction potential. It is evident that minor modifications to the existing JT8D-17 combustor design are capable of significant reduction in low power emissions of CO and THC, approaching the 1979 EPA standards for these emissions. The Element I single-stage concepts, that achieved these low-power emission reductions, are also attractive from a development time and cost viewpoint. Attaining simultaneous control of CO and THC as well as NO_x emissions will require more advanced two-stage concepts with an attendant increase in complexity. The advanced Vorbix concept evaluated in Program Element II was found to achieve both high and low power emission reductions. NO_x emission reductions of approximately 50% were demonstrated at SLTO power. The CO and THC emissions at idle exceeded the levels obtained with the Element I concept; however, they were still well below the baseline JT8D-17 values. It appears that the advanced Vorbix concept will yield significant NO_x reduction at cruise while the single-stage Element I concept will not.

The prevaporized, premixed concept evaluated during Program Element III fell short of the NO_x reduction predicted for a prevaporized, premixed system. This result may demonstrate that simply injecting vaporized fuel into a swirling air stream and allowing it to mix for a predetermined length of time does not insure a completely homogeneous mixture. Since even minute pockets burning at higher equivalence ratio can produce significant increases in NO_x level; it is evident that future development must concentrate on achieving uniform fuel-air mixture preparation if the full potential of the concept is to be realized.

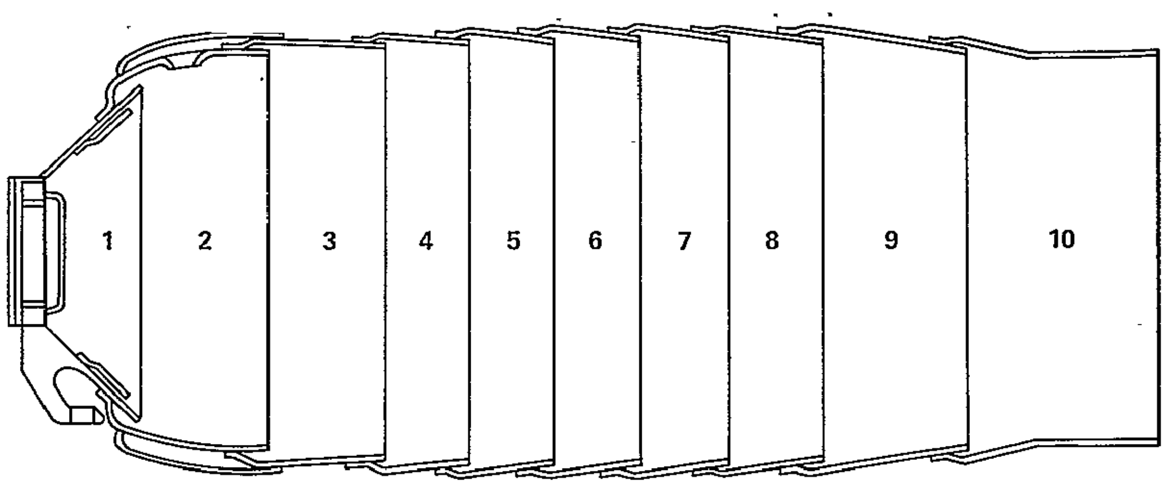
Emphasis has been given to documentation of emissions reduction potential in this combustor rig assessment program. Relative ranking of the concepts, and comparison with the program goals has been done on this basis. Combustor performance has been measured in conjunction with the emissions tests, and a number of deficiencies have been identified which will require further development. In addition, such items as transient stability and long-term cyclic durability can only be determined in actual engine testing.

It may be concluded from the results of this program that the complexity of a staged concept is required for simultaneous major reductions of all three gaseous emissions. However, the dramatic improvement in idle emissions of CO and THC demonstrated in Element I, combined with relatively minor modification of the current production hardware and attendant development confidence, makes this a very attractive choice for near-term application. It must be borne in mind that the emission levels demonstrated in this program represent technology only, and should not be considered representative of fully developed, engine-worthy hardware. Development of satisfactory performance characteristics and durability may tend to degrade the demonstrated emission reductions by an unknown amount. In addition to margin for development, it is likely that engine-to-engine variations and component degradation will also increase the emission levels continuously produced by a large fleet of in-service engines.

APPENDIX A

COMBUSTOR HOLE PATTERNS

ELEMENT I



FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.537 CM^2

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA., CM	AREA, CM^2
1	60	.157	1.169
2	14, 6, 40	.267, 356, 305	4 297
3	26, 6, 32	318, .381, .267	4 530
	4 SLOTS	1 049 x 318	1.246
4	56, 16	.239, 381	4 332
5	72	239	3.224
6	72	.213	2 574
7	72	.213	2 574
8	72	.213	2 574
9	72	.191	2 052
10	28, 44	.318, 191	3 471

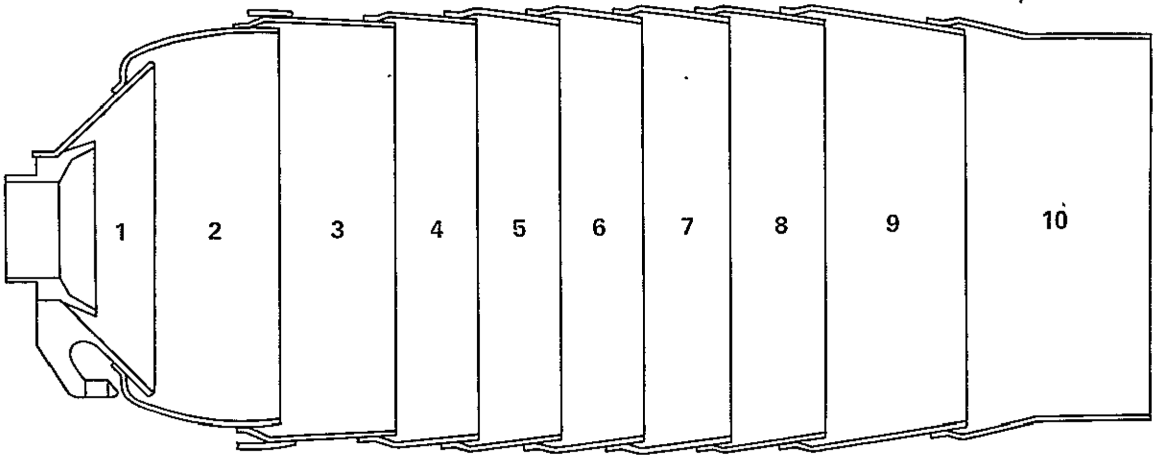
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA., CM	AREA, CM^2
2	7	1 092	6.555
3	7	.597	1.959
5	1, 2, 2	1.981, 1 392, 1 072	7.930
8	2, 3	1 854, 2.022	15.033
9	4, 1	2.167, 1 905	17.597

BASELINE JT8D - 17 COMBUSTOR WITH SUBSTITUTION OF AIRBLAST NOZZLE I FOR BASELINE DUAL-ORIFICE INJECTOR

Figure A-1 Liner Hole Pattern for Airblast Nozzle Configuration I-1

ELEMENT I



FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2

	LOUVER COOLING AIR METERING DIMENSIONS		
ROW	NO HOLES	DIA , CM	AREA, CM^2
1	53, 2	193, 366	1 761
2	4, 11, 30	356, 267, 305	3 201
3	15, 3, 15	318, 381, .267	2 368
	2 SLOTS	1.049 x 318	622
4	56, 8	239, 381	3 418
5	72	239	3 224
6	72	239	3 224
7	72	.239	3 224
8	72	.239	3 224
9	33, 20, 19	213, 292, 267	3.581
10	29, 43	381, 213	4.844

	COMBUSTION AIR METERING DIMENSIONS		
ROW	NO HOLES	DIA., CM	AREA, CM^2
1	5	873	2 994
3	4	1 905	11.401
5	5	2 540	25 335
8	5	2 032	16.215

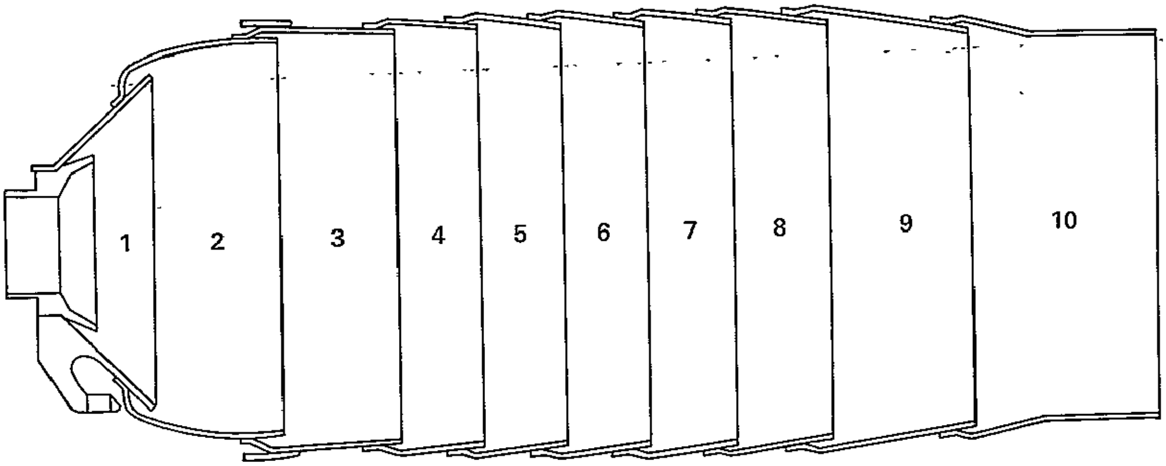
MODIFICATIONS TO CONFIGURATION I-1

REDUCED LEVELS OF FRONT END COOLING AND DILUTION AIR (RICH FRONT END)

SUBSTITUTION OF AIRBLAST NOZZLE II FOR NOZZLE I

Figure A-2 Liner Hole Pattern for Airblast Nozzle Configuration I-2

ELEMENT I



FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	55, 2	193, 366	1 819
2	4,11,30	356, 267, 305	3 201
3	15,3,15	318, 381, .267	2 368
	2 SLOTS	1 049 x 318	622
4	56, 8	239, 381	3 418
5	72	239	3.224
6	72	239	3.224
7	72	239	3 224
8	72	.239	3 224
9	33, 20, 19	.213, 292, 267	3 581
10	29, 43	.381, 213	4 844

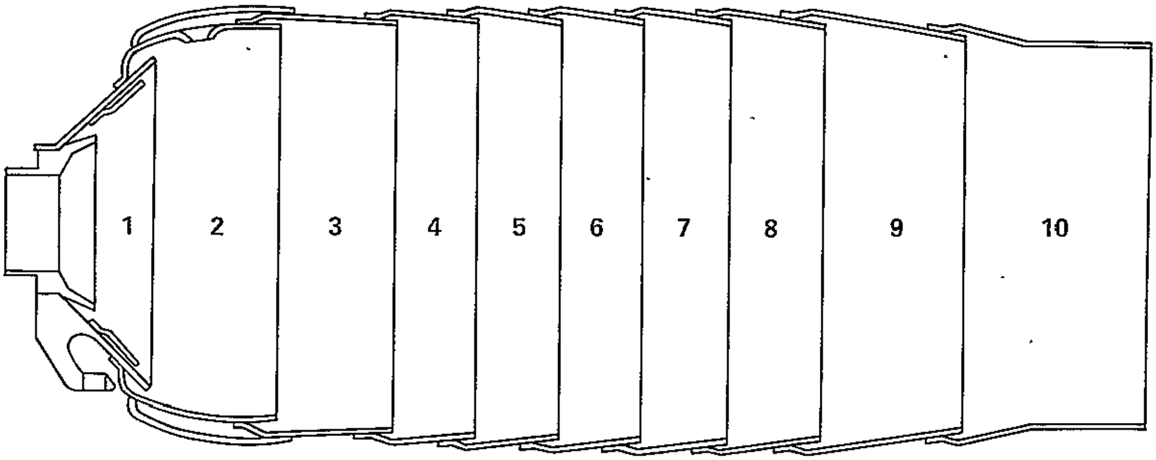
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	9	873	5.389
3	4	1 905	11 401
5	5	2 540	25 335
8	4	2 032	13 024

MODIFICATIONS TO CONFIGURATION I-2:
FRONT END AIRFLOW INCREASED

Figure A-3 Liner Hole Pattern for Airblast Nozzle Configuration I-3

ELEMENT I



FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	60	.157	1 169
2	14, 6, 40	267, 356, 305	4 297
3	26, 6, 32	318, 381, 267	4 530
	4 SLOTS	1 049 x 318	1 246
4	56, 16	.239, 381	4 332
5	72	.239	3 224
6	72	213	2 574
7	72	213	2 574
8	72	.213	2 574
9	72	191	2 052
10	28, 44	318, 191	3,471

COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA., CM	AREA, CM^2
2	6, 7	1 016, 1 092	11 443
3	7	1 441	11 419
5	5	1 190	5 561
8	5	1 935	14 711
9	5	1 102	4 768

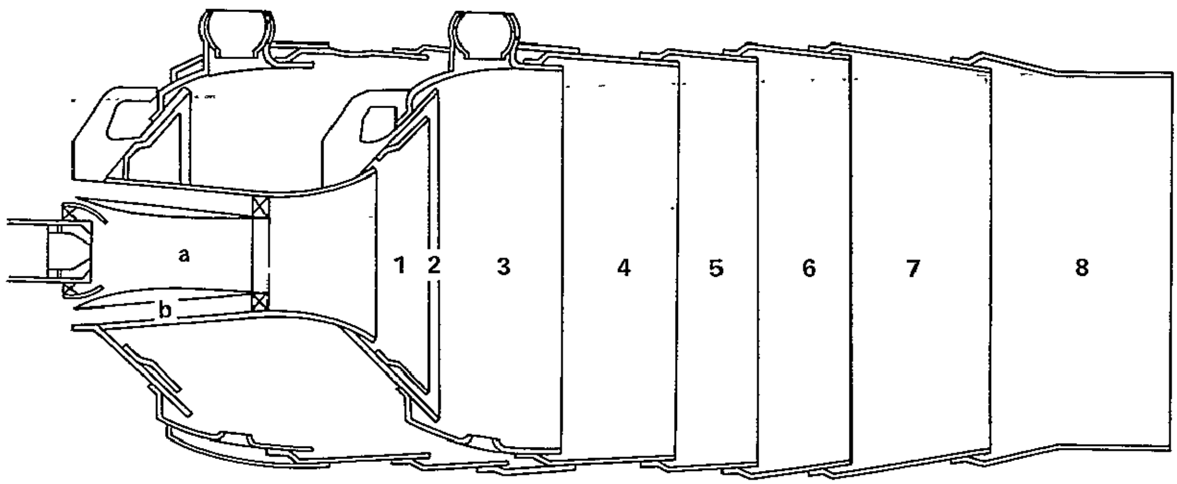
MODIFICATIONS TO CONFIGURATION I-1:

ADDITIONAL PRIMARY DILUTION AIR (LEAN FRONT END) SWIRL CUP ADDED

SUBSTITUTION OF AIRBLAST NOZZLE II FOR NOZZLE I

Figure A-4 Liner Hole Pattern for Airblast Nozzle Configuration I-4

ELEMENT I



CARBURETOR TUBE METERING AREA 9.711 CM^2
CARBURETOR TUBE FLOW SPLIT (a/b) 38/62

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	50	127	634
2	60	157	1 168
3	14, 6, 40	267, 356, 305	4 297
4	26, 6, 32	318, 381, 267	4 530
	4 SLOTS	1 049 x .318	1.246
5	72	.254	3.648
6	72	254	3.648
7	39, 33	290, .191	3.510
8	72	.211	2 514

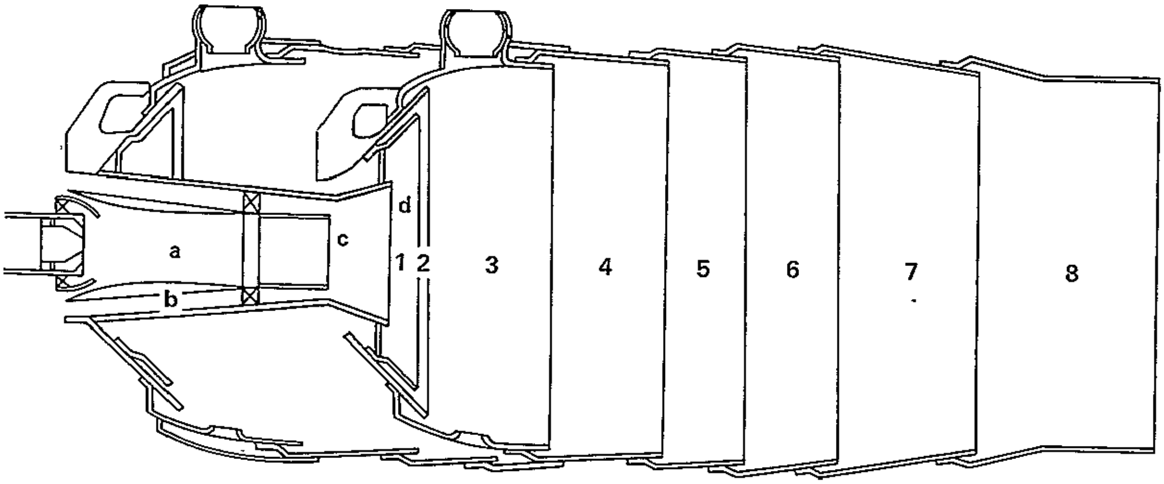
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
3	7	594	1 942
4	6	1 697	13 566
5	6	1 735	14 182
7	6	2 042	19 653

MODIFICATIONS TO BASELINE COMBUSTOR:
- PREMIXING TUBE WITH QUICK QUENCH EXIT SWIRLER ADDED
- ADDITIONAL PRIMARY DILUTION AIR
- PRESSURE ATOMIZING NOZZLE USED IN PLACE OF AIRBLAST NOZZLE

Figure A-5 Liner Hole Pattern for Carburetor Tube Configuration I-5

ELEMENT I



CARBURETOR TUBE METERING AREA 9.347 CM^2
CARBURETOR TUBE FLOW SPLIT (a/b) 41/59
ϕ_c 2.14 AT IDLE, 3.92 AT SLTO
ϕ_d 0.88 AT IDLE, 1.62 AT SLTO

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	30, 30	.132, .118	740
2	60	170	1.365
3	14, 6, 40	267, .356, 305	4.297
4	26, 6, 32	318, 381, 267	4.530
	4 SLOTS	1.049 x 318	1.246
5	72	254	3.648
6	72	254	3.648
7	39, 33	290, 191	3.510
8	72	211	2 514

COMBUSTION AIR METERING DIMENSIONS

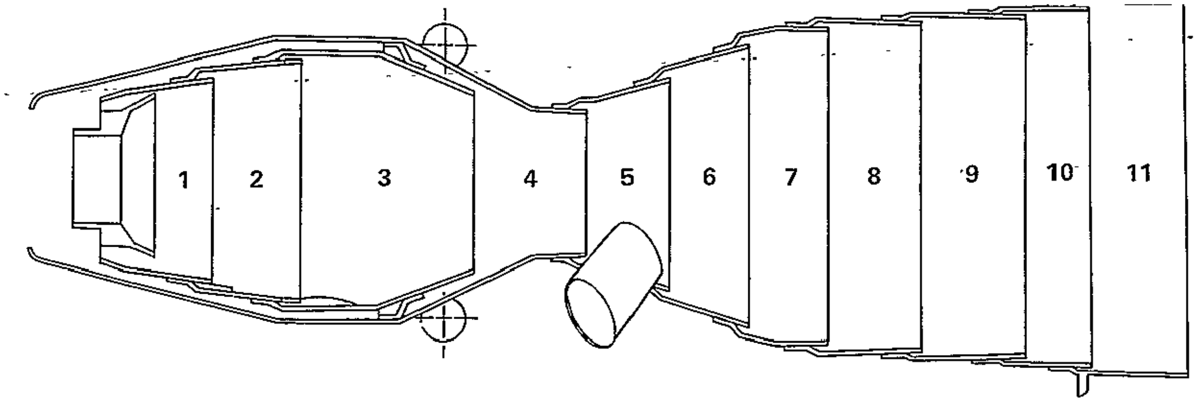
ROW	NO HOLES	DIA , CM	AREA, CM^2
3	7	594	1.942
4	6	1 697	13 566
5	6	1 735	14 182
7	6	2 042	19.653

MODIFICATIONS TO CARBURETOR TUBE I-5:
EXTENDED PREMIXING TUBE WITH ADDED CONVERGING/DIVERGING NOZZLE AFT OF EXIT SWIRLER

Figure A-6 Liner Hole Pattern for Carburetor Tube Configuration I-6

C-2

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.942 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 8.193 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	24	279	1.471
2	36	244'	1 677
3	40	279	2 445
4	40	203	1 297
5	28	254	1 419
6	36	254	1 819
7	60	165	1 284
8	56	203	1 813
9	60	.165	1 284
10	60	165	1 284
11	60	165	1 284

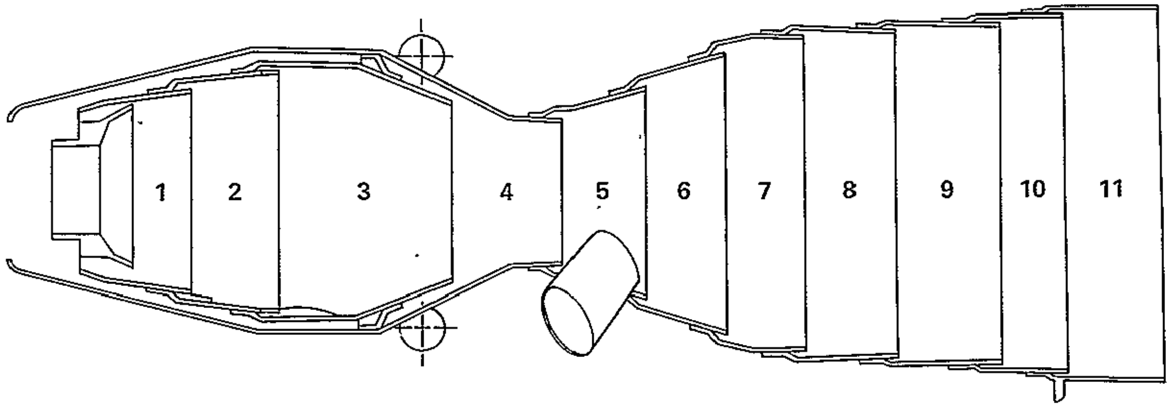
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	6	864	3 516
2	6	864	3.516
3	3	1 651	6 419
9	6	1 740	14 258

ELEMENT II BASELINE

Figure A-7 Liner Hole Pattern for Advanced Vorbix Configuration II-1

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.942 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 5.520 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	24	279	1 471
2	36	244	1 677
3	40	279	2.445
4	40	.254	2 027
5	28	.254	1 419
6	36	.254	1 819
7	60	165	1 284
8	56	.203	1 813
9	60	165	1.284
10	60	165	1.284
11	60	165	1.284

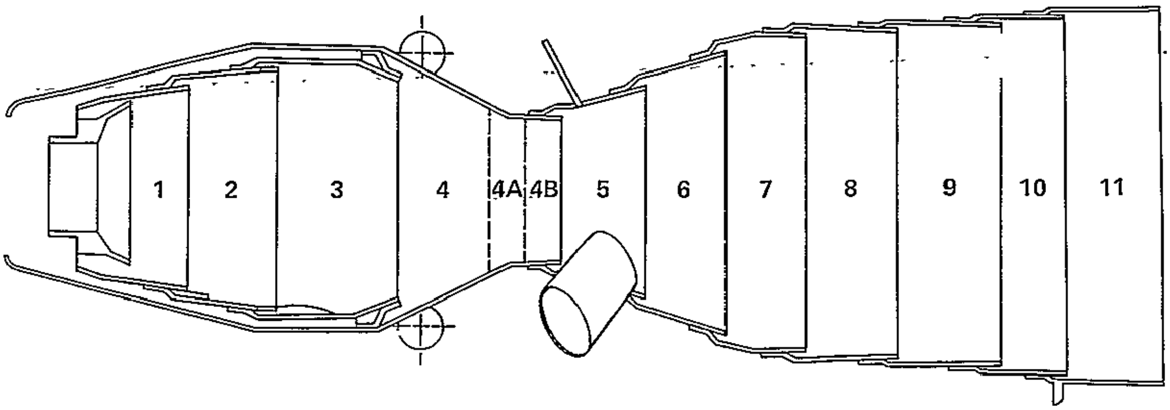
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	6	1 041	5 103
2	6	1.041	5 103
3	3	1 651	6.419
9	6, 6	1.740, 1 600	14 258, 12 000

MODIFICATIONS TO CONFIGURATION II-1:
- CAPTURE AREA OF SECONDARY PREVAPORIZING TUBES REDUCED AND MOVED TO A STABLE AND FULL FLOW AREA
- HOOD INSTALLED
- SECONDARY NOZZLES REPLACED BY LOW PRESSURE DROP, LOW BLOCKAGE TUBE INJECTORS
- REDUCED SECONDARY SWIRLER DILUTION AIR
- REDUCED PILOT EQUIVALENCE RATIO 20 PERCENT
- ADDITIONAL THROAT COOLING

Figure A-8 Liner Hole Pattern for Advanced Vorbix Configuration II-2

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 5.092 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR
METERING DIMENSIONS

ROW	NO HOLES	DIA . CM	AREA. CM^2
1	24	279	1 471
2	36	.244	1 677
3	40	279	2 445
4	40	305	2 916
5	28 6 SLOTS	254 1 588	3 632
6	36	.254	1 819
7	60	.165	1 284
8	56	.203	1.813
9	60	165	1 284
10	60	165	1 284
11	60	165	1 284
4A	40	.165	858
4B	36	165	.774

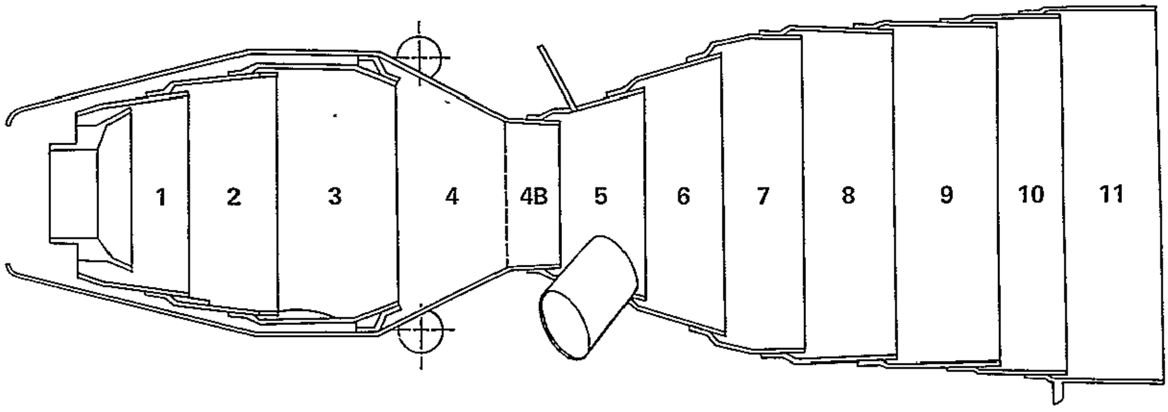
COMBUSTION AIR
METERING DIMENSIONS

ROW	NO HOLES	DIA CM	AREA CM^2
1	6	1 041	5 103
2	12	737	5 110
3	6	1 168	6 419
9	6 6	1 740 1 600	14 258 12 000

MODIFICATIONS TO CONFIGURATION II-2·
REDUCED THROAT DIAMETER WITH INCREASED COOLING (5 8 CM DIA)
BLOCKAGE DISK ADDED TO 6 SECONDARY SWIRLERS
DEFLECTOR REMOVED AND NUMBER OF SECONDARY FEED HOLES REDUCED TO 6 TO INCREASE PENETRATION
NUMBER OF PILOT COMBUSTION HOLES IN ROWS 2 AND 3 DOUBLED AND DIAMETERS REDUCED TO MAINTAIN AREA
ADDITIONAL COOLING AT IGNITOR AND CROSSOVER TUBE LOCATIONS

Figure A-9 Liner Hole Pattern for Advanced Vorbix Configuration II-3

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	24	.279	1.471
2	36	.244	1 677
3	40	279	2 445
4	40	305	2 916
5	28, 6 SLOTS	254, 1.588	3.632
6	36	254	1 819
7	60	165	1 284
8	56	.203	1 813
9	60	.165	1 284
10	60	165	1.284
11	60	.165	1.284
4B	36	.239	1 632

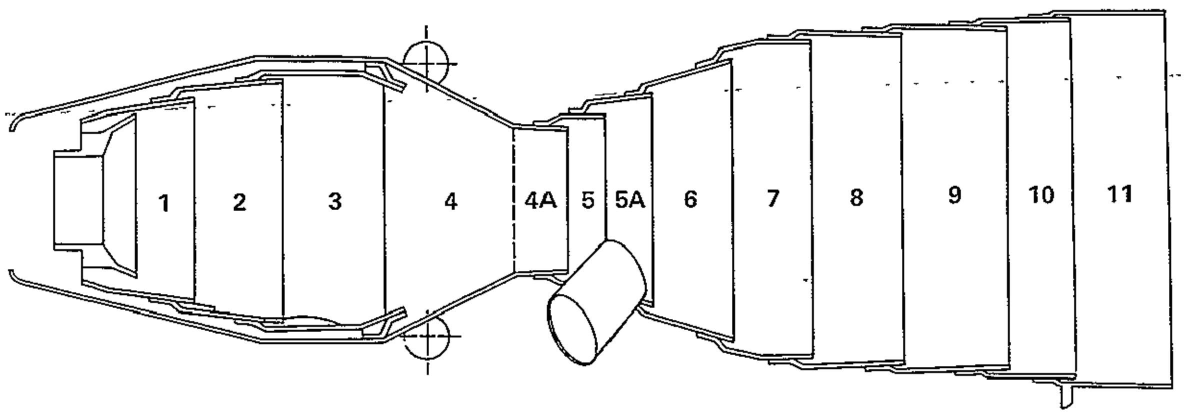
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA,CM^2
1	6	1.041	5.103
2	12	737	5 110
3	6	1 168	6 419
9	6	2 540	30.402
10	6	940	4.162

MODIFICATIONS TO CONFIGURATION II-3·
- SWIRLER AIRFLOW REDUCED 10 PERCENT
- DILUTION AIR IN ROW 9 INCREASED AND REDISTRIBUTED
- DILUTION AIR ADDED IN ROW 10
- INCREASED THROAT COOLING

Figure A-10 Liner Hole Pattern for Advanced Vorbix Configuration II-4

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	24	279	1.471
2	36	244	1 677
3	40	279	2 445
4	40	305	2 916
5	28 6 SLOTS	254 1.568	3 632
6	36	254	1.819
7	60	165	1.284
8	56	203	1 813
9	60	165	1 284
10	60	165	1 284
11	60	249	2.916
4A	40	170	.903
5A	36	249	1 748

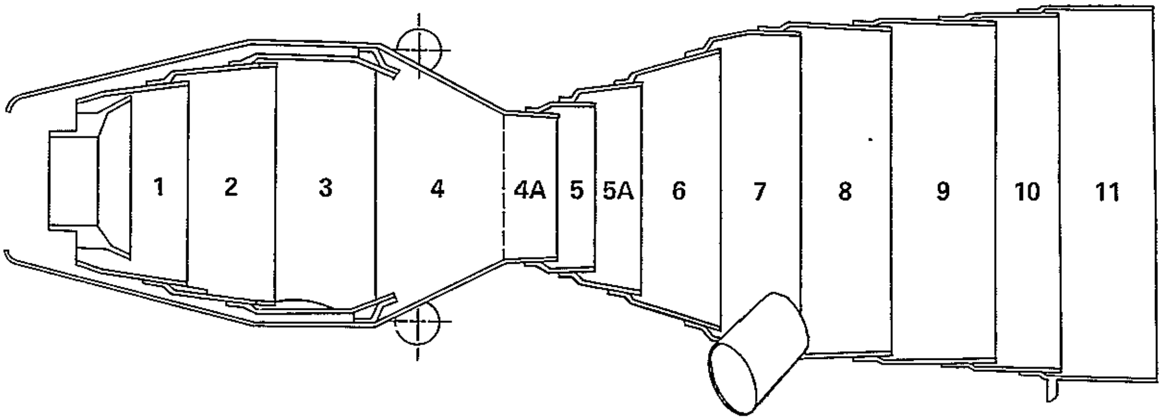
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	6	1 041	5.103
2	12	737	5.110
3	6	1 168	6 419
	6	2 540	30.402
10	6	940	4 162

MODIFICATIONS TO CONFIGURATION II-4
INCREASED THROAT DIAMETER (7.1 CM DIA)
ADDITIONAL LOUVER IN THROAT

Figure A-11 Liner Hole Pattern for Advanced Vorbix Configuration II-5

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR
METERING DIMENSIONS

ROW	NO HOLES	DIA., CM	AREA, CM^2
1	24	279	1.471
2	36	.244	1.677
3	40	279	2.445
4	40	305	2.916
5	28	254	1.413
6	36	254	1 819
7	60	165	1 284
8	56	.203	1 813
9	60	.165	1.284
10	60	165	1.284
11	60	.249	2.916
4A	40	170	.903
5A	36	249	1.748

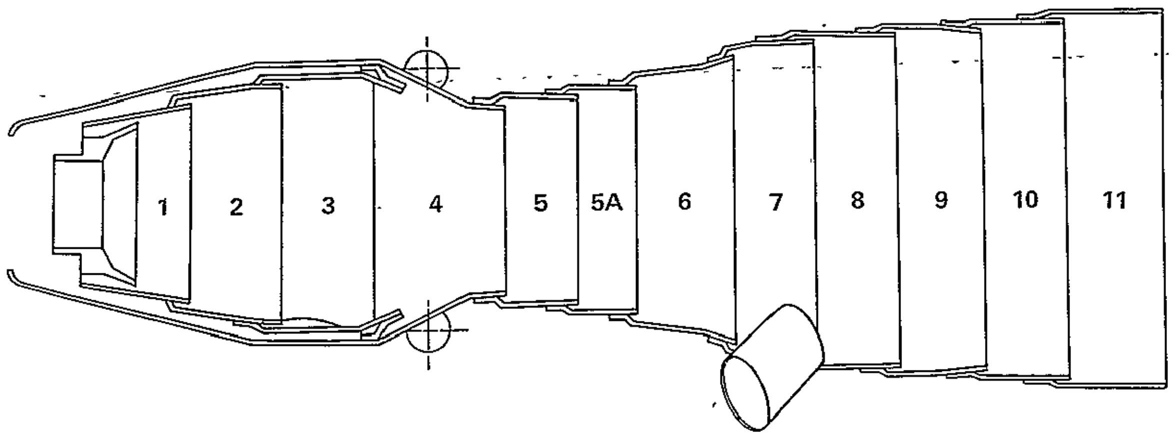
COMBUSTION AIR
METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	6	1.041	5 103
2	12	.737	5 110
3	6	1.168	6 419
9	6	2 540	30 402
10	6	940	4 162

MODIFICATIONS TO CONFIGURATION II-5:
SECONDARY SWIRLERS MOVED DOWN STREAM

Figure A-12 Liner Hole Pattern for Advanced Vorbix Configuration II-6

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA., CM	AREA, CM^2
1	24	279	1 471
2	36	244	1 677
3	40	.279	2 445
4	40	305	2 916
5	36	254	1 819
6	40	254	2.026
7	60	.165	1 284
8	56	203	1 813
9	60	165	1 284
10	60	.165	1.284
11	60	.249	2 916
5A	36	254	1 819

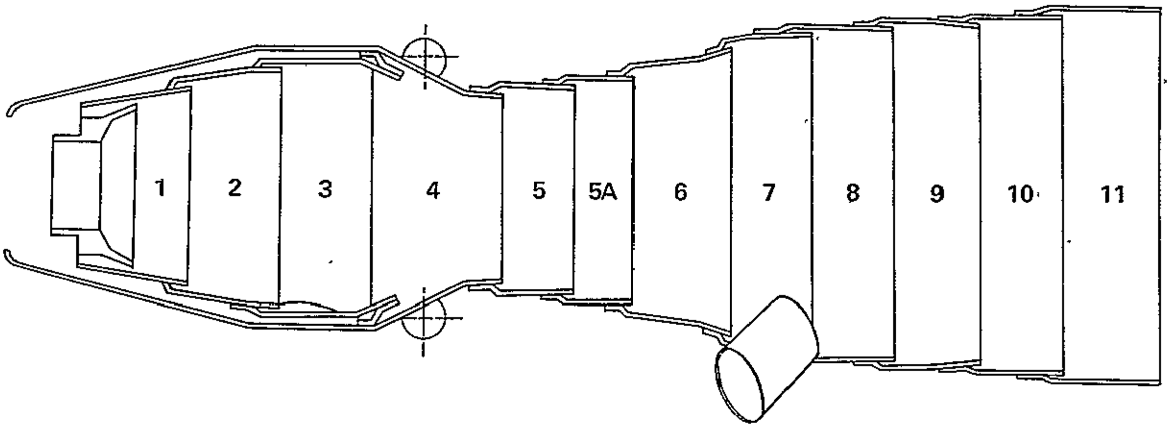
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	6	1 041	5.103
2	12	737	5 110
3	6	1.168	6 419
9	6	2 540	30 402
10	6	.940	4 162

MODIFICATIONS TO CONFIGURATION II-6:
INCREASED THROAT DIAMETER (8.1 CM DIA)

Figuer A-13 Liner Hole Pattern for Advanced Vorbix Configuration II-7

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.596 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR
METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
1	24	318	1.903
2	36	.244	1.677
3	40	279	2 445
4	40	305	2 916
5	36	.254	1 819
6	40	254	2 026
7	60	.165	1.284
8	56	203	1 813
9	60	165	1 284
10	60	165	1.284
11	60	249	2 916
5A	36	254	1 819

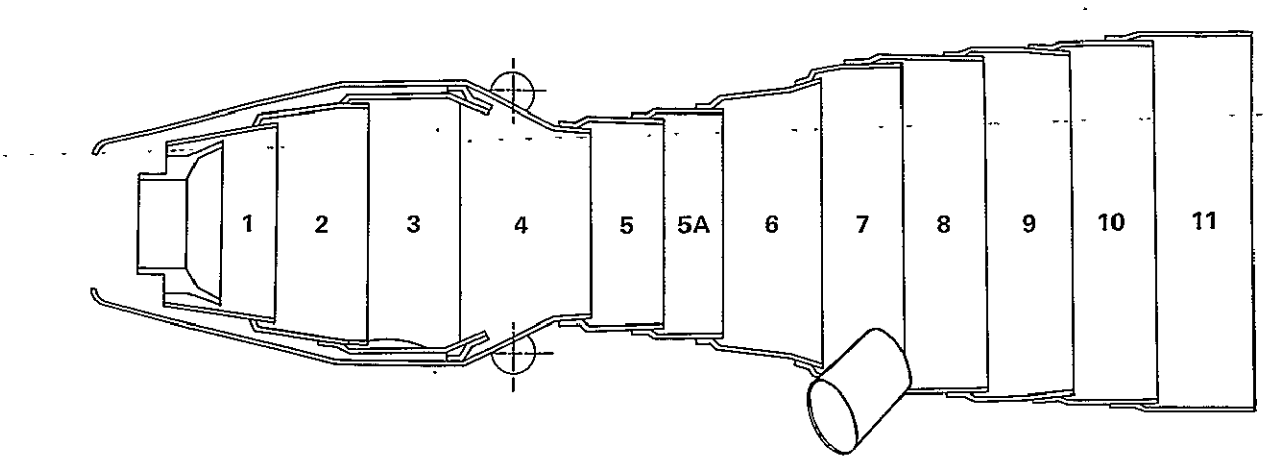
COMBUSTION AIR
METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	6	1 189	6 658
2	12	820	6 342
3	6	1 168	6 419
9	6	2 540	30.402

MODIFICATIONS TO CONFIGURATION II-7:
INCREASED PILOT AIRFLOW
PLUGGED ROW 10 COMBUSTION HOLES

Figure A-14 Liner Hole Pattern for Advanced Vorbix Configuration II-8

ELEMENT II



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN FUEL PREMIXING TUBE METERING AREA 0.748 CM^2 PER EACH OF 2 TUBES
MAIN SWIRLER EQUIVALENT METERING AREA 2.809 CM^2 PER EACH OF 6 SWIRLERS

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO HOLES	DIA., CM	AREA, CM^2
1	24	.279	1.471
2	36	.244	1 677
3	40	.279	2.445
4	40	305	2.916
5	36	254	1 819
6	40	.254	2 026
7	60	.165	1.284
8	56	203	1.813
9	60	.165	1.284
10	60	165	1.284
11	60	249	2 916
5A	36	.254	1 819

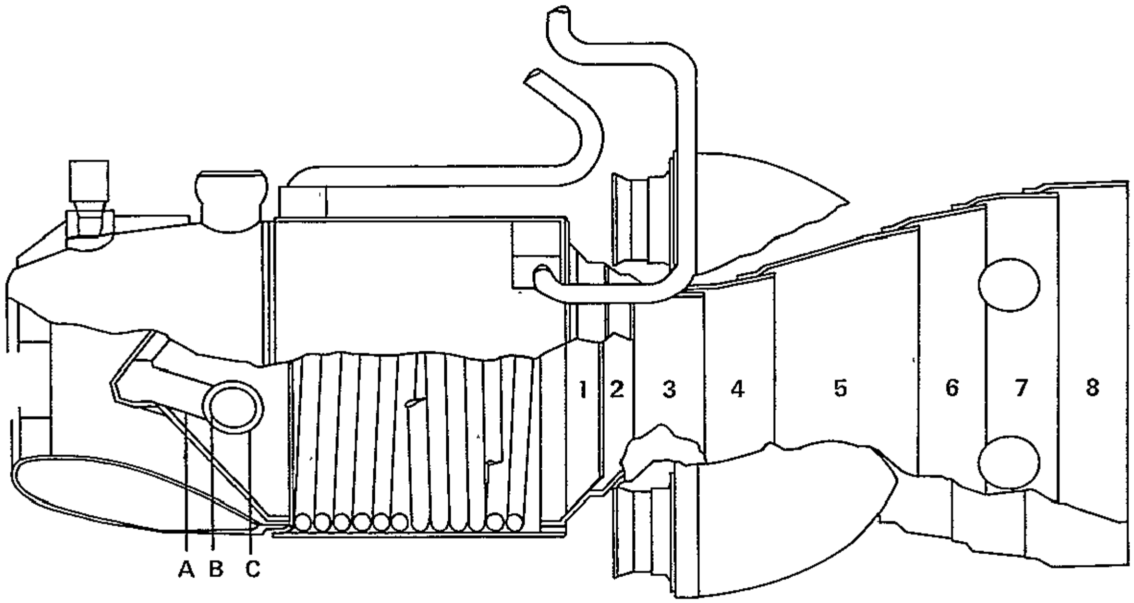
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
1	6	1 072	5.413
2	12	767	5.548
3	6	1.168	6 419
9	6	2 634	32 697

MODIFICATIONS TO CONFIGURATION II-8:
DECREASED PILOT AIRFLOW TO LEVEL OF CONFIGURATION II-7
INCREASED MAIN FUEL PREMIXING TUBE AIRFLOW
INCREASED MAIN COMBUSTION AIR

Figure A-15 Liner Hole Pattern for Advanced Vorbix Configuration II-9

ELEMENT III



MAIN PREMIXING TUBE SWIRLER EFFECTIVE METERING AREA 4.409 CM^2 PER EACH OF 6 TUBES
MAIN PREMIXING TUBE BLEED HOLES AREA 0.534 CM^2 PER TUBE; 12 HOLES, 0.238 CM DIA. PER HOLE

LOUVER COOLING AIR METERING DIMENSIONS

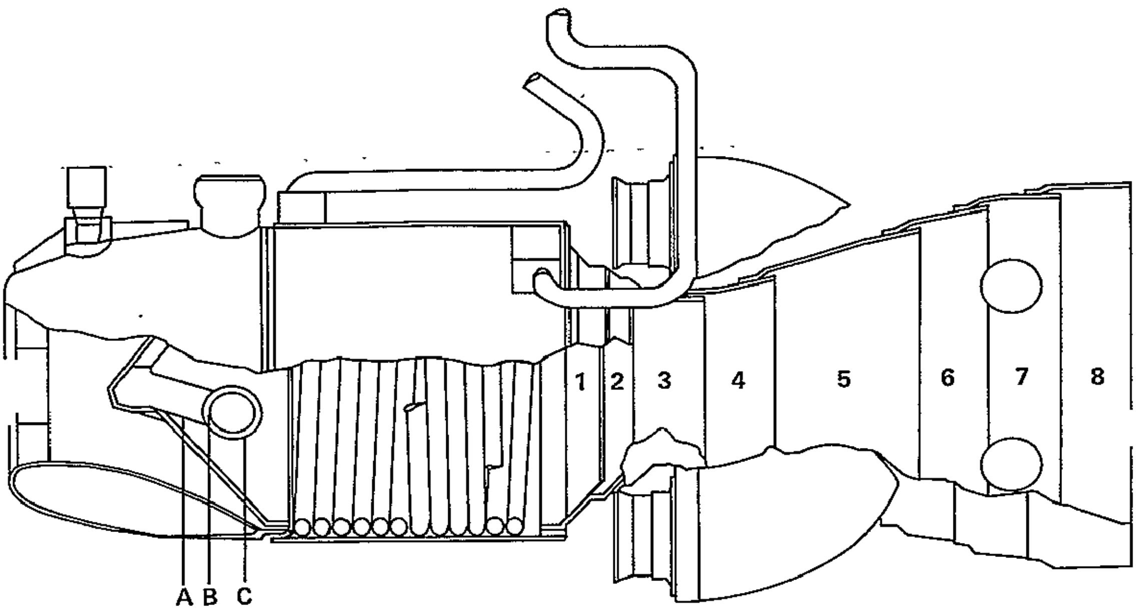
ROW	NO. HOLES	DIA., CM	AREA, CM^2
*	46	.102	373
1	27	279	1 655
2	32	279	1.962
3	23	.279	1.410
4	32	318	2 534
5	6	SLOTS	2.710
6	56	.241	2 561
7	60	211	2 094
8	60	211	2.094

* FLAMEHOLDER

COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA , CM	AREA, CM^2
A	4	559	981
B	7	1.041	5 962
C	10	1 041	8 518
7	6	2 540	30 402

Figure A-16 Liner Hole Pattern for Premixed, Prevaporized Configuration III-1



MAIN PREMIXING TUBE SWIRLER EFFECTIVE METERING AREA 4.409 CM^2 PER EACH OF 6 TUBES
MAIN PREMIXING TUBE BLEED HOLES AREA 0.534 CM^2 PER TUBE; 12 HOLES, 0.238 CM DIA. PER HOLE

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
*	148	.157	2 883
1	27	.279	1.655
2	32	279	1.962
3	23	279	1 410
4	32	318	2 534
5	6	SLOTS	2.710
6	56	.241	2 561
7	60	211	2 094
8	60	211	2.094

* FLAMEHOLDER

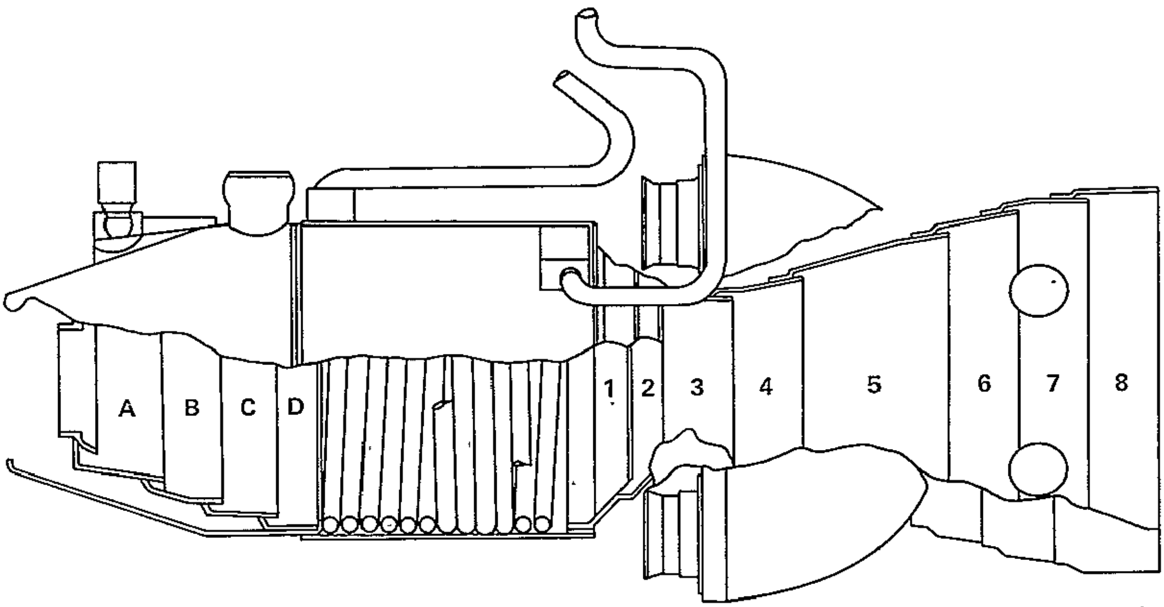
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
A	4	.762	1.824
B	7	1.041	5 962
C	10	1.041	8 518
7	6	1 168	6.433

MODIFICATIONS TO CONFIGURATION III-1:
INCREASED FRONT END AIRFLOW
LESS DILUTION AIR IN ROW 7

Figure A-17 Liner Hole Pattern for Premixed, Prevaporized Configuration III-2

ELEMENT III



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN PREMIXING TUBE SWIRLER EFFECTIVE METERING AREA 4.409 CM^2 PER EACH OF 6 TUBES
MAIN PREMIXING TUBE BLEED HOLES AREA 0.534 CM^2 PER TUBE; 12 HOLES, 0.238 CM DIA. PER HOLE

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA, CM	AREA, CM^2
A	24	.279	1 471
B	36	.244	1 681
C	40	.279	2 452
D	40	.279	2 452
1	27	279	1.655
2	32	279	1.962
3	23	.279	1.410
4	32	318	2.534
5	6	SLOTS	2 710
6	56	.241	2 561
7	60	.211	2 094
8	60	211	2 094

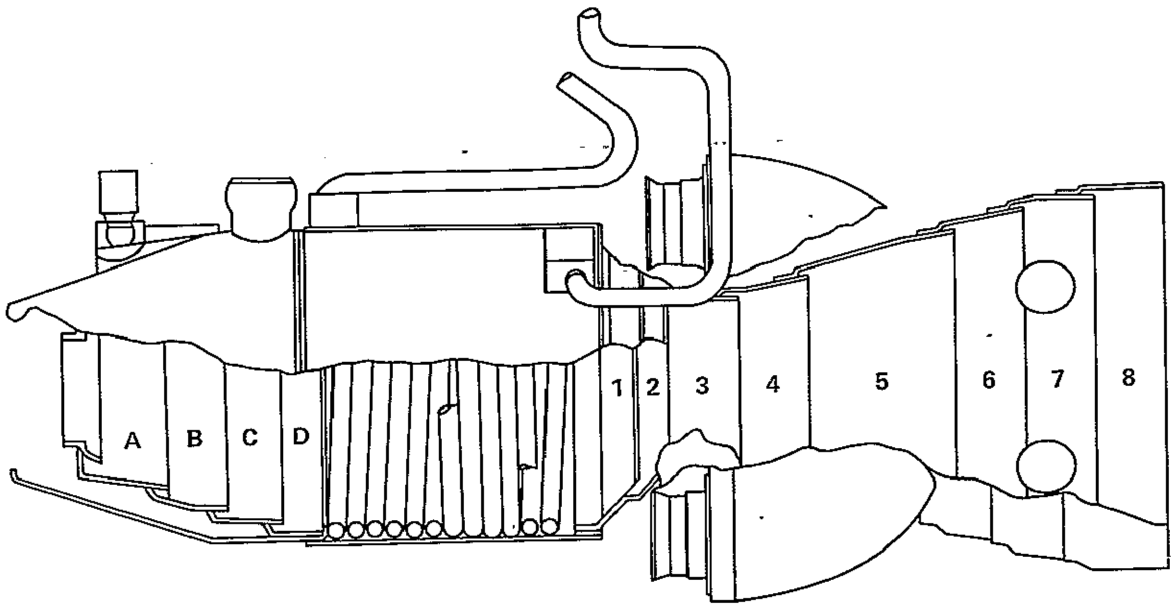
COMBUSTION AIR METERING DIMENSIONS

ROW	NO HOLES	DIA, CM	AREA, CM^2
A	6	1.072	5.414
B	12	767	5.546
C	6	1 168	6 433
7	6	1 168	6 433

MODIFICATIONS TO CONFIGURATION III-2
PILOT SIMILAR TO THAT OF ELEMENT II ADDED
AIRBLAST NOZZLE OF ELEMENT II USED

Figure A-18 Liner Hole Pattern for Premixed, Prevaporized Configuration III-3

ELEMENT III



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2
MAIN PREMIXING TUBE SWIRLER EFFECTIVE METERING AREA 4.409 CM^2 PER EACH OF 6 TUBES
MAIN PREMIXING TUBE BLEED HOLES AREA 0.534 CM^2 PER TUBE; 12 HOLES, 0.238 CM DIA. PER HOLE

LOUVER COOLING AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA., CM	AREA, CM^2
A	24	.279	1.471
B	36	.244	1.681
C	40	279	2 452
D	40	279	2.452
1	27	279	1.655
2	32	279	1.962
3	23	.279	1.410
4	32	318	2 534
5	6	SLOTS	2.710
6	56	241	2 561
7	60	211	2 094
8	60	211	2 094

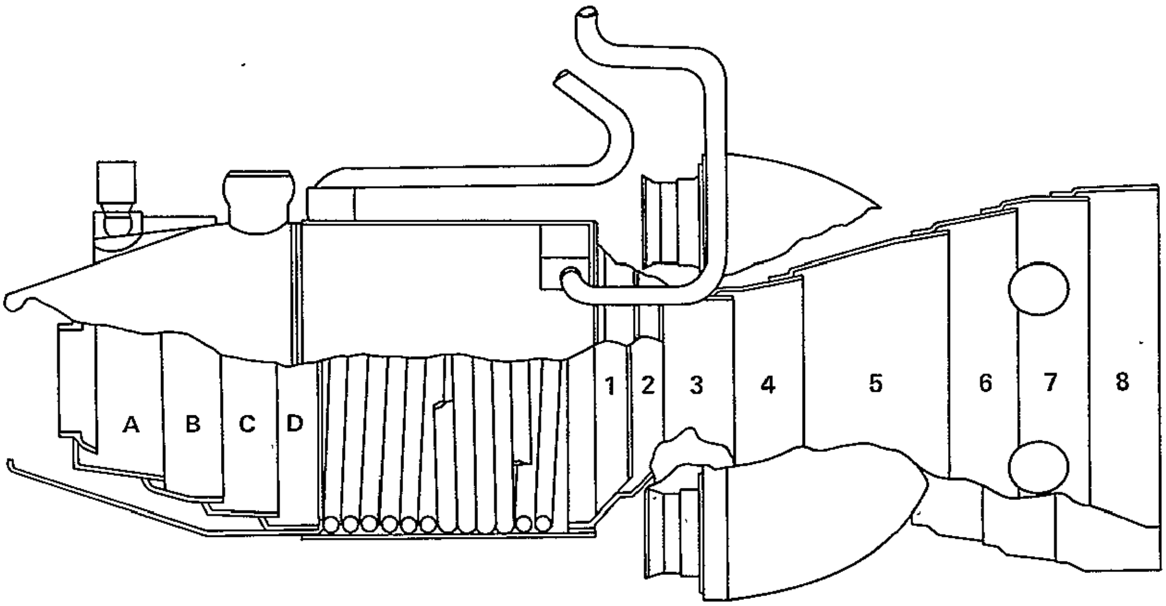
COMBUSTION AIR METERING DIMENSIONS

ROW	NO. HOLES	DIA., CM	AREA, CM^2
A	6	1.072	5 414
B	12	.767	5 546
C	6	1.168	6 433
7	6	1.168	6 433

MODIFICATIONS TO CONFIGURATION III-3:
3 OF THE 6 MAIN PREMIXING FUEL INJECTOR TUBES NOT USED

Figure A-19 Liner Hole Pattern for Premixed, Prevaporized Configuration III-4

ELEMENT III



PILOT FUEL INJECTOR AND PRIMARY SWIRLER EQUIVALENT METERING AREA 1.703 CM^2

MAIN PREMIXING TUBE SWIRLER EFFECTIVE METERING AREA 4.409 CM^2 PER EACH OF 6 TUBES

MAIN PREMIXING TUBE BLEED HOLES AREA 0.534 CM^2 PER TUBE; 12 HOLES, 0.238 CM DIA. PER HOLE

LOUVER COOLING AIR
METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
A	24	.279	1 471
B	36	244	1 681
C	40	279	2.452
D	40	279	2.452
1	27	.279	1 655
2	32	.279	1 962
3	23	.279	1.410
4	32	318	2 534
5	6	SLOTS	2.710
6	56	.241	2 561
7	60	211	2 094
8	60	211	2 094

COMBUSTION AIR
METERING DIMENSIONS

ROW	NO. HOLES	DIA , CM	AREA, CM^2
A	6	1 072	5.414
B	12	.767	5 546
C	6	1 168	6 433
7	6	1.168	6.433

MODIFICATIONS TO CONFIGURATION III-4·
VAPORIZED PILOT FUEL

Figure A-20 Liner Hole Pattern for Premixed, Prevaporized Configuration III-5

APPENDIX B

EXPERIMENTAL TEST DATA

ELEMENT I TEST RESULTS FOR AIRBLAST NOZZLE CONFIGURATION I-1

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONIXODE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
41	1.729	1 572	0162/	–	408 5	2 89	28 29	813 5	92.09	.00251	.01032	00990	70 43	54 87	3 27	–	5 SAMPLING PORTS
42	1 764	1 607	.0164/	–	408 4	2.89	28.82	810 2	91.98	0025u	01023	01120	70 72	56.06	3 30	–	3 SAMPLING PORTS
43	1.815	1.662	0132/	–	408.3	2 90	29 86	728 1	88.86	.00251	00802	.00781	73 53	82.03	3.60	–	
44	1.762	1 604	0085/.0074	–	407 6	2 94	28.25	797.1	91.46	.00245	.00989	00943	76 21	58 98	4 07	–	
51	3 588	3 280	0176/.0202	–	535 6	6 87	32.34	971.0	99.74	00190	01154	01129	7.16	0.86	10 13	–	
61	8.066	7 361	0197/ 1195	–	712 1	17.28	38.72	1358 6	99.97	00468	01876	01811	0.59	0.16	33.45	25	

ELEMENT I TEST RESULTS FOR AIRBLAST NOZZLE CONFIGURATION I-2

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
3	1 801	1.643	0163/	–	409 8	2.85	30 38	801.5	99 68	.00163	.00995	00963	13.40	0 09	4.68	–	
31	1 769	1 611	.0163/	–	408 0	2.86	29 67	807.9	99 67	00164	.01017	.01097	13.61	0 71	4.57	–	3 SAMPLING PORTS
4	1 776	1.619	0081/ 0082	–	408.5	2 93	28 90	804.4	99.62	00160	01006	01003	14 45	0.39	4 02	–	
5	1 810	1 652	/ 0165	–	409 0	2.82	30 61	803.8	99 59	00162	.01003	00994	16 18	0 35	4.10	–	
6	8.235	7.548	0196/ 1156	–	706.4	17 38	39 01	1332.4	99 99	.00156	01796	02102	0.54	0.01	21 95	28	
61	8 157	7 470	.0197/ 1148	–	710 3	17.37	38 78	1338 3	99.99	00156	.01804	02283	0 50	0 00	21.90	–	3 SAMPLING PORTS
62	8 224	7.546	0198/ 1104	–	707.5	17 40	39.03	1331.6	99 99	00157	01728	02031	0 54	0.00	22 70	–	
64	9 137	8 366	0197/ 1338	–	709 5	17.40	44 86	1347 2	99 99	00155	01835	02117	0.49	0.00	21 74	–	
65	6 474	5 921	0195/ 0892	–	706 9	17.84	28 66	1348 5	99.99	00155	.01846	02051	0 40	0 01	25.51	9	
8	7 436	6 822	0194/.0914	–	683 6	14.97	39.99	1260 9	99.99	00155	.01633	01851	0 59	0.00	18 64	–	
7	3 699	3.390	0167/ 0219	–	529 4	6 83	33.53	959.8	99 91	00155	01137	01279	3.16	0.12	8 00	–	
33	1 747	1 594	0129/	–	414 0	2.81	30 36	737 5	99.63	00154	.00811	00765	15 12	0 19	5 27	–	

ELEMENT I TEST RESULTS FOR AIRBLAST NOZZLE CONFIGURATION I-3

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.757	1 600	0160/	–	414.2	2.88	29.26	810.8	99.48	00156	01009	01008	12.83	1 93	4.63	–	
5	1.761	1 602	.0188/	–	413 1	2 92	28 61	875 5	99.61	.00157	01191	.01212	10.38	1 27	4 62	–	
6	1.779	1 628	.0129/	–	413.4	2.81	30 71	729 5	99 49	00158	00792	.00812	12.41	1.90	4 91	–	
10	3.763	3 448	0179/ 0213	–	541.1	6.77	35.17	972 3	99.85	00160	01143	01325	2 51	0.81	8.95	27	
101	3 794	3 476	0180/ 0223	–	536.7	6.80	35 04	975 9	99.87	00160	.01165	.01407	2 52	0 58	8.88	–	
11	7.307	6 703	0200/ 0884	–	685.2	14 86	39 51	1254 9	99 98	00162	01611	.01916	0.52	0.06	19 48	45	
12	8.039	7 373	.0204/ 1154	–	719.5	17.18	39 12	1356 5	99.99	00162	01838	02144	0 39	0.05	24 01	32	
12	8.168	7 491	0208/ 1160	–	720 1	17 20	39 87	1350 8	99 97	00157	01818	.02178	0 40	0 15	24.56	–	
13	8.158	7 494	0205/ 1104	–	718.8	17.06	40.15	1324 9	99.97	00158	01739	02073	0 43	0.20	24 44	46	
14	8.118	7.438	0203/ 1260	–	717 4	17 36	38 93	1394 9	99 95	00161	01968	.02269	0 38	0.31	25.21	49	
15	6 597	6 056	0197/ 0891	–	718 1	17 87	29 59	1340 0	99 99	00164	.01789	.02051	0 35	0 00	28.40	–	
16	9 491	8 707	0203/ 1380	–	720.0	17 28	48 02	1350 4	99 99	00166	.01818	.02154	0 38	0.00	22.55	–	
401	1 726	1 578	/ 0150	–	411.5	2.92	28.00	788 9	99.66	00170	00956	00999	11.85	0.49	4 61	–	
402	1 771	1.617	.0162/	–	411.6	3.01	27.92	809 1	99 73	.00169	.01011	.01040	10 46	0.21	4 31	–	
402	1 730	1.578	.0162/	–	412.6	2.95	27.79	819 0	99 73	00170	01036	01058	10 53	0.16	4 31	–	
17	1 634	1 492	.0155/	–	454 8	2.84	30.27	859.8	99.78	.00170	01044	01104	8.71	0.13	4 72	–	
18	1.717	1 569	0158/	–	432 5	2 90	29 51	828 8	99 76	00168	01013	01091	9 56	0.14	4 79	–	

ELEMENT I TEST RESULTS FOR AIRBLAST NOZZLE CONFIGURATION I-4

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 701	1 552	.0159/	–	410 8	2 86	28 19	815 6	99.15	.00175	01031	01028	17 64	3.92	3 57	–	
5	1 674	1.526	.0078/.0079	–	413 9	2 86	27 77	822 4	99.00	00168	01041	01061	23.11	4 13	3.82	–	
6	1 704	1 555	/.0160	–	415.0	2 88	28 33	818.6	98.79	00176	01029	.01034	26.52	5 23	3.62	–	
7	1 737	1.596	.0123/	–	412.2	2 89	28 74	718.6	99.00	00163	00766	.00838	33.46	1 92	3.55	–	
8	1 689	1 537	0185/	–	413.0	2 89	27 65	882 7	99 64	.00170	01211	01226	11 15	0 92	3 69	–	
9	3 664	3.365	0171/.0210	–	539 3	6.85	33 63	967.9	99 77	.00150	.01135	01226	2 45	1 54	7.28	–	
10	7.309	6.712	.0210/.0885	–	682 0	14 86	39.48	1255.2	99 98	.00152	.01620	.01760	0.41	0 07	19.43	–	
11	8 245	7 571	0197/.1173	–	714.0	17 60	39 07	1339 3	99 98	00151	01797	01966	0 36	0 09	27 31	12	
12	8.281	7.597	.0221/ 1273	–	710 9	17 43	39.59	1389.0	99 98	.00150	01965	02193	0 37	0.06	29 43	–	
13	8 148	7 478	0240/.1082	–	713 5	17 52	38 81	1326 4	99 97	.00150	.01758	01936	0 66	0 11	27.41	–	
14	9.326	8.562	0243/.1307	–	706.9	17 33	46.34	1337.5	99 99	.00149	.01811	.02092	0.36	0 06	25.30	–	
15	6.508	5 972	.0202/ 0899	–	706.8	17.37	29 69	1343 0	99.98	00148	01829	02036	0 30	0.10	36 07	–	

ELEMENT I TEST RESULTS FOR CARBURETOR TUBE CONFIGURATION I-5

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.706	1.555	.0161/	–	414 5	2.84	28 78	822.0	88 45	.00155	.01039	.01030	137 89	73 08	1 05	–	
5	1 800	1.651	0065/.0094	–	412 8	2 84	30 58	799 0	82 44	.00158	.00980	01025	163.03	119 72	0.72	–	
6	1.740	1.591	/ 0161	–	412 9	2.84	29 44	813.6	82 01	.00159	01020	.01014	170.14	122 59	1.67	–	
7	1.710	1.565	.0132/	–	413 9	2.82	29 31	750 8	85 44	.00164	00847	.00839	148 29	96 43	1 70	–	
8	1.762	1 606	.0187/	–	413 8	2 82	30.07	871.8	90.40	00167	01179	.01182	127 97	58.37	1 53	–	

ELEMENT I TEST RESULTS FOR CARBURETOR TUBE CONFIGURATION I-6

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 799	1.799	0161/	–	409 5	2.88	32 63	790 9	86 97	.00151	00889	00935	156 40	82 00	1.91	–	
7	1 764	1 764	0187/	–	410 9	2.81	32.83	859.3	90 74	.00153	.01058	01183	125 90	55 50	1 52	–	
8	1.772	1 772	0128/	–	413 3	2.87	32 27	721 5	83 94	00153	00708	00775	173 10	104 20	2.09	–	
10	3 776	3 776	.0179/ 0199	–	539 3	6.68	39 08	959 3	98.26	00148	01002	01127	46 80	5.81	5.77	–	
11	7.194	7 194	.0169/ 0903	–	677 9	15.00	41 12	1262 3	99.98	00153	01483	01671	0 66	0 02	15 48	–	
12	8 002	8 002	.0166/ 1178	–	711 5	17.36	41 39	1337 5	99 98	00157	01677	01885	0 31	0 74	19.22	2	
13	8 107	8 107	0165/ 1151	–	709 6	17.22	42 27	1309.5	99 99	.00157	.01619	.01865	0.30	0.06	19 08	–	
14	8 272	8 272	0167/ 1303	–	709 3	17.36	42 80	1361.5	99 99	.00156	01777	.02011	0.32	0.05	20 07	–	
401	1 696	1 696	0161/	–	411 1	2 92	29.90	821.7	90 23	.00121	00943	.01063	133 70	58.30	2 07	–	AIR ASSIST
402	1 703	1 703	0159/	–	413 8	2.88	30 85	817 6	90 09	.00125	.00929	.01071	138.40	58.70	2 30	–	
403	1 710	1.710	0160/	–	411 8	2 89	30 76	815 4	89 82	00134	.00929	01095	135.40	61.50	1 89	–	
404	1 735	1.735	0160/	–	412 3	2 88	31 21	809 9	89 07	00136	.00914	01078	143.10	66 80	1.81	–	
405	1 733	1 733	0163/ 0068	–	413 5	2.75	33 33	981.6	96 79	.00155	.01349	.01590	18.88	23.30	2 35	–	
406	1 732	1 732	0163/ 0097	–	413.3	2 78	32 67	1041 0	98 19	.00155	.01503	01810	12.77	12.80	2 46	–	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-1

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NIETROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.686	1 525	.0159/	–	422.6	2 82	29 34	830.4	96 51	00164	01041	01202	96.49	10.40	2 47	–	
5	1.712	1.552	0129/	–	414 9	2 88	28 52	744.5	97.74	.00165	.00828	.00944	80.68	3.05	2 70	–	
6	1 749	1.592	.0111/	–	411 6	2 87	29 22	691 1	98 10	00167	00695	00797	71 84	1.71	2 88	–	
7	1 712	1.558	.0102/	–	418 4	2 83	29 52	681 0	98 21	00169	00652	00738	67.40	1.69	3 04	–	
71	1.754	1 588	.0171/	–	413.5	2 87	29 32	837.5	96.24	.00169	.01084	.01287	97.71	12.44	2 43	–	
9	1 729	1 560	.0185/	–	410.5	2.89	28.34	871.8	95.39	.00170	.01187	01362	103 61	18 48	2 30	–	
10	3 931	3.579	.0383/	–	531.4	6.92	35.68	937.8	99.05	.00150	.01069	01211	31 61	1 75	4 47	15	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-2

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.656	1.501	0157/	–	414 8	2 87	27 42	839 4	98 31	00237	.01088	01296	57.39	2.83	3 02	–	
5	1 826	1.668	0130/	–	407.6	2 79	31 37	728 6	98.32	.00234	.00805	01002	64.18	1.40	3 02	–	
6	1.755	1.593	0174/	–	415 6	2 83	30 06	856 5	97.99	.00232	.01133	.01386	62 58	4.53	2.98	–	
61	1 718	1 544	0128/	0092	418 9	3 01	27.22	971.6	96.69	.00228	.01451	01709	70 57	14.04	3.02	–	
40	1 709	1.549	0159/	–	411.0	2.90	27 93	825 8	9o 38	00276	.01060	.01334	53 86	2.99	2.91	–	
41	1.688	1.528	/.0156	–	415 6	2 91	27 78	842 1	98.35	.00275	.01094	01373	53 65	3.28	2 98	–	
7	3.888	3.553	0180/ 0205	–	541 0	6 91	36 08	952.6	99.54	00165	01087	01374	16.23	0 69	5 31	–	
8	3 916	3 579	0183/.0117	.0095	538 6	7 02	35.49	956.9	98.97	.00172	01105	01323	25.72	3 65	6 13	–	
81	3.900	3.562	.0149/	.0219	539 4	6 97	35 67	958 9	98.39	.00174	01109	01273	40 89	5.52	6.19	–	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-3

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 720	1 554	.0159/	–	411.6	2 89	28 10	825 1	98 42	00299	.01057	01144	57.13	1.96	2.57	–	
41	1.747	1.579	0159/	–	408.6	2 91	28 30	816 4	98 38	00309	.01041	01143	57 75	2.17	2 55	–	
5	1.725	1 565	0130/	–	415 6	2 89	28 57	757 1	98 45	00301	00862	00961	57.62	1.63	2 58	–	
6	1 739	1 569	.0172/	–	410 0	2 88	28 66	852 3	98.40	00304	01136	01249	55 49	2 49	2.58	–	
61	1 753	1.583	0180/	–	412.6	2 87	29 03	868 8	98 35	00310	01176	01333	56.91	2 61	2 57	–	
62	1.329	1.199	0121/	–	411 8	2 87	21 02	819 7	98 86	00297	01042	.01149	41 88	1 30	2.84	–	
7	3 867	3 519	0386/	–	536 9	6 90	35 43	951 8	99 59	00241	01097	01167	15.38	0.36	4.67	25	
8	3 909	3 562	.0128/	0257	538.5	6.88	36 37	949 8	99 41	00193	01086	01159	23.39	0 37	5.46	9	
81	4 923	4 481	.0125/	0486	595.8	9.54	35 98	1096 5	99 37	00182	01365	01407	17 96	1 75	6 99	–	
82	5 049	4 600	.0250/	0364	593.1	9.49	37 07	1084 0	99 73	00181	01335	01437	8.04	0.65	7 13	–	
83	4 955	4 510	.0311/	0301	602.1	9.51	36 92	1099 4	99 83	00178	.01357	01453	7.21	0.03	7 14	–	CRUISE
84	5 037	4 587	.0370/	0241	591 9	9.53	36 71	1081 9	99 67	00177	01332	01423	9.70	0.87	6 67	–	
16	7.568	6.903	.0285/	0814	684 4	15.27	40.21	1248 5	99 86	00187	.01593	01590	5.42	0 09	11 45	32	
161	7 469	6 808	.0453/	0653	683 0	15 14	39 99	1257.8	99 73	00191	.01625	01620	7.85	0.73	10 71	–	
9	8 100	7 375′	0280/	1078	712.0	17 34	39 06	1350.9	99 88	00190	.01841	01754	4.61	0 10	12 92	38	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-4

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 844	1 678	0158/	–	410 5	2.88	30.47	792.2	98.08	00323	00970	00987	55 22	5 28	2 78	–	
5	1.845	1 687	.0128/	–	412 0	2 85	31 06	722 9	98.62	.00204	00778	.00840	55 02	0.73	2 68	–	
6	1 800	1 634	0169/	–	409 3	2.86	29.72	829.3	98.58	00206	.01072	.01121	54 88	1 09	2 60	–	
61	1 818	1 650	/.0170	–	409 8	2 89	29 84	814 0	98 09	00215	.01030	01092	60.33	4 17	2.41	–	
7	1.257	1 139	0121/	–	407 8	2.88	19.41	837.4	99.23	.00191	01099	01124	29 69	0 56	3 09	–	
4	1 812	1 651	0159/	–	412 4	2.86	30 20	803 0	98 62	00190	00993	01043	52.63	1.17	2.75	–	
8	3 694	3 377	.0176/.0212	–	539 0	6 86	33 52	972.4	99.69	.00165	.01149	.01119	11 07	0 38	5 17	25	
9	3.633	3.334	.0125/	0270	537.3	6 79	33.39	986.0	99 40	00187	01193	01129	20 11	1 11	5 76	–	
10	5 086	4 657	0066/	.0544	587 5	9 59	36 40	1071 8	87 99	00186	01314	01320	71.34	88 37	4 19	–	
11	5 082	4 650	0126/	.0488	601 6	9 61	36 98	1087 1	99 59	00190	.01323	.01341	10.50	1.41	7.17	–	CRUISE
111	5 020	4 588	0182/	.0430	596.8	9 62	36.16	1087 3	99 75	.00204	.01336	.01325	6.57	0.85	7.78	–	
13	7 473	6 836	0112/.0114	.0887	679 9	14.99	39 64	1255 9	99 67	00182,	.01628	.01629	9.85	0.83	11.16	–	
131	7 417	6 779	0112/ 0170	0828	680.8	15 01	39 16	1259 7	99 82	00197	.01638	.01669	5.50	0 43	11 58	18	
14	8 362	7 636	0139/	.1262	711.5	17 48	39 65	1348 3	99 57	00206	01835	.01919	12.42	1 15	11 68	–	
15	8 499	7 780	0139/ 0142	1102	712 1	17.47	40.54	1331 1	99 77	00200	01778	01865	4 62	1 02	13 47	31	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-5

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.662	1.531	.0157/	–	409.6	2 91	27 03	822 5	99.13	.00160	.01052	01131	33 76	0 65	2 85	–	
5	1.737	1 608	0128/	–	412.2	2.85	29.37	737.3	99 11	00170	00815	00901	33.72	0 79	2.64	–	
6	1 727	1.590	.0172/	–	411.4	2.93	28 13	847 0	99 12	.00162	.01115	01225	34 25	0 61	2 84	–	
7	1.294	1.193	.0121/	–	411 1	3 01	19.62	819.4	99.55	.00169	01040	01150	18 55	0 13	3.26	–	
71	1.391	1 277	.0158/	–	396.4	2.51	25.09	890 4	99 04	00156	.01273	01397	36 62	0 78	2 29	–	UPDATED IDLE
8	3.755	3.481	.0175/ 0204	–	536 3	6 82	34 82	948.8	99.83	.00224	01089	01227	6 89	0.10	5 40	19	
9	3.685	3 414	.0125/	0259	536.4	6 78	34.49	963.3	99 39	00210	01130	01270	16.82	1.79	5.49	–	
111	3 460	3 195	0099/	0382	617.6	6.83	36.88	1163.6	99 47	00203	01510	01662	11.32	2.29	6 56	–	CRUISE
112	3 511	3 245	0145/	.0349	611 5	6.85	36.85	1163 0	99.79	00189	.01524	.01680	7.06	0 38	7 88	–	
12	7 569	7 016	.0113/	0996	678 3	15 21	40 08	1240 2	99.56	.00174	01583	01717	13.74	0.97	9 69	17	
13	7 487	6 936	.0113/.0113	0886	678 0	15 18	39 41	1246.4	99.82	.00167	01603	01740	6.00	0.35	11 45	–	
14	8 177	7 564	.0137/	.1236	709 4	17 48	39.23	1341 5	99.80	00132	01816	.01940	7 12	0 30	12 10	25	
115	8 465	7 848	0137/.0141	.1108	708 0	17.38	41 00	1325.0	99.89	.00127	01767	01964	3 18	0.28	13 32	31	
16	8 430	7 823	.0137/.0141	.1015	712 4	17 46	40.99	1293.0	99.88	00134	01654	01878	4 05	0 18	13 61	–	
17	8 450	7.834	.0137/.0138	1161	709 4	17 42	40.76	1346.9	99.86	.00135	01833	02054	4 85	0.21	12 79	–	
4	1 725	1.596	0158/	–	414 5	2 89	28 97	814.4	99.17	00123	01017	01146	33 92	0 27	3 09	–	
41	1 731	1.602	0159/	–	414 4	2 90	29 05	813.6	99.16	.00131	01015	01162	34.15	0.33	3 04	–	AIR ASSIST
42	1 716	1 586	/.0166	–	419 2	2 93	28 53	829.4	99.24	.00133	01047	.01142	29.58	0.54	2.82	–	
72	1.545	1 426	0153/	–	391 0	2 51	28 05	822.8	98.72	00126	01098	.01248	45.45	1.76	2.31	–	UPDATED IDLE
73	1 543	1 427	0139/	–	391.3	2 48	28.65	785.8	98 73	00127	.00996	.01138	46.10	1.59	2.27	–	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-6

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMAR SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 698	1 567	0154/	–	413.5	2.88	28 19	809.1	99 18	00108	01004	01005	31.50	0.63	2.74	–	
5	1 657	1.530	.0126/	–	412.6	2 87	27 65	748 9	99 33	00114	.00844	00816	25.49	0.56	2.78	–	
6	1.620	1.496	.0106/	–	412 9	2 90	26 87	704 4	99 56	00109	.00725	.00726	17.15	0.34	2.86	–	
61	1 639	1 519	0083/	–	414 1	2.88	27.39	636.1	99.45	00112	00545	00636	18 66	0 93	2 97	–	
42	1 685	1 562	/ 0112	–	414.3	2.89	27.96	701.4	99.51	00112	00714	00806	18 00	0 59	3 18	–	
41	1 650	1.520	/ 0164	–	414 0	2 87	27 43	836 3	99 33	00113	01078	01200	26 71	0 35	2 98	–	
7	1 339	1 230	0133/	–	413 6	2.91	21.21	846 3	99.48	00132	01107	01270	21 00	0 25	3 26	–	
8	1 394	1 280	0161/	–	411 9	2.49	26.33	910.5	99.15	.00133	.01291	.01510	33.89	0 42	2.66	–	UPDATED IDLE
9	3 687	3 415	0174/ 0218	–	539.7	6.91	33.69	973.0	99.85	.00165	.01148	.01302	6 42	0 00	5 96	16	
10	3 621	3 354	0128/	.0263	542.8	6.88	33.58	984.2	99.59	00141	00172	.01371	13 41	0 84	5.88	8	
13	7 275	6.744	.0116/	.0997	679.1	15.12	38 13	1264.3	99.76	00161	.01655	01832	9 57	0 10	9 91	12	
14	7.176	6.651	.0116/.0120	.0875	678 0	15 07	37 93	1268 1	99 88	00145	01669	01841	5.26	0 00	11 15	17	
15	7 985	7.398	.0139/	.1236	716 7	17 52	38 35	1361 3	99 87	00129	01859	02065	5 28	0 07	11 91	14	
16	8 120	7.521	.0139/ 0147	1104	714 4	17 74	38 31	1355.9	99 91	00130	01848	.02085	3.50	0.02	13.47	18	
17	8 104	7 514	0139/ 0139	0993	712 6	17 41	39 08	1305.8	99.93	00139	.01694	01925	2.96	0.01	13.08	–	
18	8 179	7 583	0139/ 0138	1163	714 4	17.56	39.09	1372.0	99.94	.00132	.01899	02136	2 44	0 00	13 24	–	
12	3 441	3 178	0099/	.0384	610 5	6.82	36 23	1164.8	99 67	00148	01531	.01764	10 53	0 72	6 55	10	CRUISE
11	3.487	3 220	0144/	.0334	613 0	6 77	37.23	1154.0	99 82	.00155	01491	01711	7.14	0.12	7.42	–	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-7

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 712	1.581	0157/	—	411.8	2 88	28 57	814 8	99.33	00240	01027	01114	26.84	0.31	2.96	—	
5	1 675	1 547	.0128/	—	412 3	2 87	28 15	748.6	99 52	.00250	.00846	00884	18.79	0 31	2 83	—	
6	1 666	1.540	0112/	—	413.0	2 87	28 06	713.5	99 61	.00258	00751	00781	14 72	0 35	2.83	—	
61	1.719	1.595	0100/	—	413.1	2 89	28 82	673 8	99.58	00262	.00647	00692	15.18	0.53	2.93	—	
41	1.667	1.536	/ 0160	—	411 8	2.89	27 79	820.2	99.46	.00254	.01042	01052	21.66	0 26	3.10	—	
9	3 595	3.338	.0175/.0172	—	536.6	6 87	32 90	931 3	99 88	.00256	01039	01083	4 91	0 07	6 51	2	
10	3 678	3.410	.0123/	0266	537 5	6.98	33 22	970.0	99.36	00257	.01147	.01251	15.68	2.30	5.50	10	
14	7.180	6 658	0113/ 0112	.0874	676.5	15 13	37.61	1259.8	99 82	.00259	.01651	01717	5.80	0 34	11.26	32	
13	7.377	6 849	.0114/ 0050	.0940	684 1	15.29	38 80	1253 7	99.77	00251	01611	01727	7 62	0.41	10 77	30	
15	8 128	7.544	0132/	.1239	711.3	17 50	38 76	1342 6	99.83	.00245	01818	01946	6 05	0.20	12 76	21	
151	8.064	7.484	0136/.0072	1169	715.9	17 65	38 38	1353.6	99 90	.00228	.01840	01921	3.99	0 05	13 23	30	
17	7 950	7.367	0140/	.1360	711 4	17 16	38 61	1410 4	99.89	00221	.02036	02122	4.41	0 02	12 53	—	
18	7.954	7 391	.0137/	.1094	711 3	17.30	38 44	1295 8	99.81	.00221	.01669	01738	7.29	0 16	12 59	—	
12	3 449	3.193	0097/	.0379	607.6	6 86	35.84	1149.3	99.49	.00206	.01493	.01564	14.42	1.44	6.78	—	CRUISE
11	3.429	3.187	0142/	.0333	616.9	6 82	36.57	1158.2	99 79	.00194	.01495	01585	7.88	0.25	7.80	—	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-8

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBON EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
6	1 655	1.526	/ 0177	—	412 9	2.88	27.42	864 4	99 40	00078	01158	01081	24 29	0 19	2.80	—	
61	1.687	1 567	/ 0115	—	413 7	2 89	28 23	708.6	99 34	00079	00734	00708	21 71	1.22	2.66	—	
4	1.693	1.566	/ 0160	—	414.3	2 87	28 29	816.7	99.46	00077	01022	.00987	21 68	0 27	2 85	—	
41	1 716	1.588	/ 0161	—	415 4	2.86	29.07	814 0	99.25	.00077	01013	.00988	22.66	1 84	2.73	—	AIR ASSIST
8	3 708	3 448	/.0385	—	535 4	6.92	33.77	958 1	99 87	.00083	01115	01083	5 39	0 04	5.79	—	
9	3 652	3 389	/.0225	0153	534 7	6 85	33.56	958 1	99 63	.00081	.01116	01097	9 97	1 16	6 08	—	
9	3 648	3 388	/ 0238	0134	540 4	6 84	34 05	956.6	99 63	00078	01098	.01093	9 60	1 19	6.66	—	
10	3 617	3.351	/.0192	0212	537 9	6.87	33.06	992 3	99.62	.00081	01206	01198	11.28	0 94	6 08	—	
11	3 592	3 328	/ 0125	0269	535 3	6 90	32 58	982.4	99 72	00080	01185	01166	22 80	6.38	5 07	—	
14	7.382	6 852	/ 0123	0985	676.3	15 15	38 78	1250 2	99.11	.00082	01616	.01648	26.91	2 17	8 89	—	
15	7 247	6.716	/.0217	0893	675 9	15 23	37.79	1261 9	99.69	.00090	01654	.01642	10.49	0 57	9 92	23	
16	7.137	6.606	/ 0330	.0789	681.5	15 18	37.70	1279 4	99 66	.00098	.01694	01652	10.87	0 69	11 00	29	
161	7.391	6.863	/ 0446	.0677	680.3	15 15	39 12	1259.6	99 75	00095	.01635	01660	8.00	0 50	11 64	21	
42	1.355	1.252	/ 0124	—	413 0	2 88	21.71	803 5	99 52	00113	.00991	.00948	15.78	0.91	3 66	—	
12	3.539	3 271	/ 0141	.0337	618.7	6 90	37.53	1148 8	99 35	.00184	.01461	01453	14.63	2 63	7.36	—	CRUISE
13	3.524	3 257	/ 0192	.0288	610 8	6 89	36.87	1145 8	99 49	.00203	01474	.01448	11.62	1 98	8.09	—	
17	8.090	7 488	/ 0137	.1225	712 2	17 66	38 34	1344.3	99 41	.00234	01820	01860	18.86	1 21	11.05	20	
18	8.132	7 531	/.0202	.1164	712 8	17 66	38.47	1343 0	99.50	00238	.01815	01835	16.49	0 97	11.52	26	
19	8 244	7 640	/.0407	0973	712.7	17.53	39 47	1340 6	99.55	00236	01807	01837	14.90	0.80	13 31	22	

ELEMENT II TEST RESULTS FOR ADVANCED VORBIX CONFIGURATION II-9

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
3	1.518	1 400	0157/	–	396 0	2 44	28 84	854.4	99.15	.00084	01172	.01396	34.84	0.22	2 38	–	UPDATED IDLE
1	1 735	1 628	–	–	410 8	2 92	29 00	–	–	.00082	–	–	–	–	–	–	
4	1 710	1 582	0154/	–	410 8	2 83	28.91	810.4	99.38	00081	01014	01212	24.11	0.43	2 75	–	
5	1 720	1 595	0129/	–	411 9	2.89	28 71	735 1	99 60	.00083	.00809	.01011	15 06	0.40	2 70	–	
6	1 694	1.573	.0101/	–	411.0	2.84	28 66	685 6	99.61	.00081	00681	00784	12 88	0 77	2 64	–	
61	1.776	1.657	0090/	–	410 6	2 84	30 29	632.8	99.45	.00085	00545	00696	19 42	0,77	2.45	–	
7	1.743	1 613	/.0160	–	412 5	2.88	29 21	803 9	99 53	00090	00993	.01145	18.72	0 25	2 92	–	
71	1 734	1.611	/ 0125	–	414 6	2.86	29 40	724 6	99.65	.00085	00775	00890	12.55	0 49	2.87	–	
72	1.712	1 594	/.0094	–	414 0	2 86	29.10	653.8	99.26	00085	00591	00691	22.33	1.86	2.51	–	
8	3 864	3 589	/.0390	–	538.1	7.07	34 75	950 4	99.87	.00103	.01087	01201	4 89	0 14	6 25	–	
9	3.783	3 511	/.0282	.0123	537 6	6 95	34.52	972 7	99 84	00094	.01151	.01306	6.33	0 10	6.69	–	
91	3 783	3 509	/.0272	0115	536 7	7.04	34 01	954 8	99.84	.00093	01103	01226	6 05	0 16	6 65	–	
82	3 744	3.475	0387/	–	536.9	6.90	34 34	965 1	99.84	.00096	01132	01324	5 80	0 23	6 39	–	
92	3.714	3 447	0264/	0119	537.2	6 88	34.11	962 1	99 81	00094	01122	01321	6.61	0 26	6.77	–	
152	7.408	6 875	0225/	.0875	678.4	15 10	39.19	1250.5	99 92	00103	01612	01839	2 90	0 09	10 65	35	
142	7.254	6.729	0120/	.0978	679 0	14 99	38.79	1260.9	99 69	00157	.01645	.01896	10.83	0 47	8.94	43	
162	7.218	6 698	.0175/	0901	680 1	14 88	38.78	1253 3	99 81	00161	.01618	01918	6.68	0.29	10.14	27	
1621	7.229	6.717	.0089/.0087	0923	679.1	14.87	39.03	1258 9	99 79	.00153	.01638	01954	7 27	0 30	9.88	–	
1622	7.221	6 702	/ 0170	.0936	679 5	14 96	38.74	1264 0	99 78	00153	01653	.01966	7.76	0.32	9.93	27	
172	8.193	7.602	0206/	.1140	712 5	17 79	38.54	1334 9	99 78	00154	.01787	02115	7 85	0.28	12.43	32	
182	8 152	7.567	0281/	.1080	713.7	17 62	38.61	1339.5	99 86	00157	01798	02197	5 49	0 12	13 40	33	
202	7.983	7.410	.0210/	1008	717.9	17.76	37 73	1298.0	99 84	.00155	.01656	.01954	6 09	0.12	12.48	–	
212	7.927	7 328	.0211/	.1269	716 3	17 30	38.55	1410.2	99 84	00156	02019	.02338	6 19	0.10	12.76	–	
2121	7.986	7.402	/ 0210	.1166	711 1	17 62	37.65	1356.6	99 81	00147	01860	.02143	6 79	0.26	12.58	27	
18	8.026	7.443	/ 0293	.1086	714.1	17 72	37.88	1356.8	99 85	00151	01852	.02221	5.46	0.15	13 55	–	
12	3.476	3.217	/.0149	.0338	618 0	6 95	36.40	1166.0	99 86	00039	01512	.01744	5.17	0.13	7.60	–	
13	3.538	3.280	/.0194	0294	620 6	6 88	37.70	1160.6	99 89	00041	01489	.01762	4.26	0.12	8.39	–	CRUISE
122	3.527	3 266	.0151/	0328	615.7	6.90	37.17	1156 3	99.86	.00044	01488	01750	5.02	0.18	7.65	–	
132	3 603	3 343	.0195/	0287	612.0	6 91	37 54	1145.0	99 88	00045	.01464	.01768	4.47	0.10	7.87	–	

ELEMENT III TEST RESULTS FOR PREMIXED, PREVAPORIZED CONFIGURATION III-1

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1.769	1.647	0144	–	408.4	2 86	29 65	753.1	98 06	.00093	00871	.00935	70 00	2 46	3 52	–	
5	1 718	1.599	0124	–	408.8	2 82	29 68	717.0	98 12	.00091	00777	00825	65 47	2 85	3 69	–	
51	1 716	1.600	0103	–	408.0	2 78	29 66	663.1	98 52	.00088	00641	.00686	45.73	3 40	3 73	–	
52	1.774	1 662	0078	–	407.4	2 76	31 22	594.8	97 58	.00087	00470	.00514	28.33	15 01	2 84	–	
104	1.707	1 595	0077	–	407.0	2 75	30 00	599.8	97 94	.00087	00485	00501	28.21	11 93	2.65	–	HEAT EXCHANGER FLOW VARIATION
103	1.779	1 667	0077	–	406.7	2 75	31 28	591.5	98 16	.00080	.00464	00488	24.90	10 71	2.41	–	
106	1 732	1.616	0103	–	407 0	2 78	29 84	661.5	99 07	.00080	00639	00638	30 05	1 87	2.98	–	
107	1 767	1.652	0099	–	407 7	2 79	30 70	645.4	99 07	.00080	00597	00612	29.52	2 02	3 40	–	
8	3 729	3.477	.0361	–	532 5	6 91	33 91	928 1	99 31	.00101	01038	01189	17.10	25	4 90	–	
9	3 603	3.355	.0205	0137	533 9	6 88	33 07	922 6	97.70	00125	01018	01228	36.73	12.26	5.54	–	

ELEMENT III TEST RESULTS FOR PREMIXED, PREVAPORIZED CONFIGURATION III-2

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 858	1.723	0153	–	413 1	2.89	31 51	763.7	98 16	.00162	00887	00968	37 78	8 15	3.24	–	
5	1.866	1 732	.0127	–	412 4	2.87	31 74	704.3	98 40	.00172	00735	00795	27.66	8 07	3.12	–	
6	1.830	1 696	0113	–	408 5	2.92	30 47	673.7	98 58	.00172	00666	00690	20 66	7 99	3.07	–	
8	3 950	3 682	.0226	0149	545 6	6.69	38 96	933.7	62.72	.00211	01019	00970	59 47	307 04	2.35	–	
9	3 851	3.577	.0277	0190	546 5	6 82	36 95	1035 9	64.41	00200	01307	01242	104 06	283'53	2.46	–	

ELEMENT III TEST RESULTS FOR PREMIXED, PREVAPORIZED CONFIGURATION III-3

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 754	1 617	/ 0153	–	405.8	2 98	27.75	779.8	99.35	.00151	.00949	01232	24 60	.58	3 89	–	
5	1 734	1 602	/.0124	–	408.2	2.94	28.12	714.8	99.60	00157	.00773	01004	13.68	.66	3 39	–	
51	1.796	1.663	/.0124	–	408.0	2.93	29.14	704.8	99.58	00162	00746	01007	13.71	.79	3 35	–	
6	1.818	1.687	/.0108	–	408 0	2 91	29.91	663.7	98.70	.00152	.00642	00878	23 21	6 40	2.85	–	
8	3.735	3.456	/.0364	–	535 7	6 57	36.15	937 0	99 74	.00245	.01053	.01379	8.90	42	7 69	–	
81	3.719	3.441	/ 0360	–	535 0	6 79	34 49	934 3	99 76	00243	01047	01374	7.77	47	7 99	–	
11	3.456	3.197	/ 0225	0257	609.5	6.65	37 48	1157 6	66 13	00253	01505	01702	166.30	256 26	2 69	–	.CRUISE
13	7 331	6 767	/.0551	0618	674 1	15 21	38 01	1285 4	99.52	.00265	.01727	02134	17.16	62	15 37	–	
131	7 233	6 676	/.0543	0561	678 8	15 12	38 26	1265 9	99.31	.00262	.01653	02017	25.53	76	15.15	–	
132	7.386	6,831	/ 0453	0641	675 4	15 06	38 89	1245 4	99.27	.00269	.01602	01968	26.15	99	11 84	–	
1321	7.199	6 646	/ 0457	0598	679 8	14 93	38 60	1245 4	99.29	.00260	.01588	01907	26.89	.65	12 12	–	
14	7.135	6.588	/ 0407	0664	676 2	14 86	38 16	1254 3	99.26	.00261	.01626	01916	26.86	.87	10 70	–	
15	7.279	6.726	/ 0379	0724	676 7	15.04	38 47	1259 8	99 39	00257	.01641	01953	22 81	.64	10 10	1	
16	7 261	6 700	/ 0211	.0894	675.4	15.10	38.22	·1261.5	99 50	00256	.01650	01891	17 28	.79	8 22	1	
17	8 127	7 497	/ 0254	.1075	713.4	17.50	38.80	1333.7	99 79	00256	01772	02013	7 26	.29	10 47	1	
18	8 282	7 643	/ 0154	.1189	716.7	17.78	39.15	1337.6	99 68	00255	01757	01977	9 84	.73	10.38	–	
19	8 447	7.818	/.0382	.0945	714.2	17 41	40.68	1316.5	99 89	00257	01698	.02101	3 76	.20	11 92	–	
20	8 161	7 536	/.0517	.0810	716.0	17.44	39.38	1331.5	99 87	00259	01761	.02123	5 04	.14	15.61	–	
21	8 132	7 507	/.0572	.0816	718.0	17.52	39.07	1362.0	99 88	00258	01848	.02200	4.60	.06	18.56	2	
22	8 151	7 528	/.0513	.0815	711 8	17.32	39.32	1329.3	99.88	00260	01764	.02121	4 63	07	15.36	–	
23	8 297	7.666	/.0518	.0862	716.3	17 67	39 61	1350 4	99.90	.00238	.01799	02198	3.10	24	15 62	–	
24	7.803	7.247	/.0512	0196	718 0	16 98	39 00	1073 7	94 72	00236	.00977	.01175	86.09	27.77	16 93	–	

ELEMENT III TEST RESULTS FOR PREMIXED, PREVAPORIZED CONFIGURATION III-4

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 722	1 593	/.0130	–	410.4	3 00	27 32	734 3	99.44	00157	00818	01054	19.50	86	3.92	–	
9	3 730	3.455	/ 0249	0129	533.0	7 00	33 28	949.8	98.06	00206	01094	01440	33 53	9 80	6.19	–	
91	3 693	3 415	/.0151	0252	536 4	7 05	32.72	983.1	97 94	00219	.01180	.01475	31 17	11 33	4.84	–	
92	3 675	3 395	/ 0125	0299	534.4	7.07	32 27	1005 4	97 46	00221	.01249	.01520	35 04	14 70	4 80	–	
111	3 747	3 472	/ 0153	.0217	536.3	7 01	33 67	946 5	97.74	.00213	.01077	01369	32 54	12 79	4 84	–	
93	3 692	3 417	/.0180	.0181	533 7	6 99	32 83	936 5	98.08	00221	01057	01364	29 19	10 53	5.18	–	
94	3.738	3 464	/.0332	0053	534 3	7 03	33 35	956.5	96.53	00219	01110	01503	39.85	21 66	7.06	–	
11	3 513	3 243	/ 0267	0197	618.0	7 02	36 45	1140 4	99 39	00209	.01433	.01893	13 36	2 55	9 84	–	
11	3 564	3 294	/ 0240	0201	615.7	6 99	36 88	1106 5	–	00208	.01338	–	–	–	–	–	
12	3 592	3 319	/.0146	0312	613 6	7 03	36 67	1118.7	98.71	00209	01380	01662	16.23	7 77	6.75	–	CRUISE
121	3 517	3 249	/ 0202	0230	616.5	7.00	36 55	1104 8	99 28	00204	.01330	.01595	13 62	3 43	7.70	–	
121	3 635	3 362	/.0210	.0236	613.5	7 06	37 28	1100.9	99.68	00205	01327	01633	12 19	27	8 04	–	
121	3 584	3.363	/.0210	0240	613.3	7 05	36 86	1111 5	99 39	.00203	01359	01667	12 02	2 76	8 02	–	

ELEMENT III TEST RESULTS FOR PREMIXED, PREVAPORIZED CONFIGURATION III-5

TEST POINT	TOTAL AIR FLOW Kg/SEC	COMBUSTOR AIR FLOW Kg/SEC	PILOT FUEL FLOW PRIMARY/ SECONDARY Kg/SEC	MAIN FUEL FLOW Kg/SEC	INLET TOTAL TEMPERATURE K	INLET TOTAL PRESSURE ATM	REFERENCE VELOCITY M/SEC	IDEAL EXIT TEMPERATURE K	COMBUSTION EFFICIENCY	INLET HUMIDITY g/g AIR	FUEL AIR RATIO METERED	FUEL AIR RATIO CARBON BALANCE	CARBON MONOXIDE EMISSION INDEX	TOTAL HYDROCARBONS EMISSION INDEX	OXIDES OF NITROGEN EMISSION INDEX	SAE SMOKE NUMBER	COMMENTS
4	1 797	1.665	.0153/	—	408 9	2 98	28 65	771 5	98.92	.00174	00918	01440	34.05	2 34	3 40	—	
41	1.718	1.587	.0171/	—	411 4	2 90	28 37	835 4	99.02	.00162	.01078	.01442	34 22	1 43	3.39	—	
42	1.782	1.651	.0157/	—	409 9	2 90	29.53	785.9	99.02	00171	00953	.01446	34 87	1.34	3 35	—	
43	1.696	1.563	0168/	—	412 1	2.95	27.55	834 3	99 03	00174	.01073	.01549	36 10	0 99	3 41	—	
44	1 769	1 638	0147/	—	410 5	2.91	29.12	765.4	98 95	00169	.00898	01355	34 46	2 02	3 35	—	
45	1 719	1 587	0172/	—	410 5	2.90	28.27	836 5	99 03	00154	.01084	01407	33.98	1 44	3.42	—	
46	1 767	1 637	0186/	—	409 4	2.89	29.32	854 8	99 02	00156	.01136	01306	31.25	2 04	3.33	—	
47	3 653	3 383	0196/	0175	536 4	6.78	33.76	953.7	95 36	00192	.01096	01411	79.63	23 61	4.44	—	
11	3,412	3 149	.0198/	0261	612 8	6 91	35 25	1144.8	99.23	00201	.01458	.01799	23 88	1 80	7.14	—	CRUISE
12	3.394	3.124	.0144/	.0344	611 3	7 05	34 06	1177.0	99.09	00202	.01559	01827	27.16	2 27	6.07	—	
13	6.998	6.449	.0423/	.0669	680 5	15 21	36 57	1279.8	99.84	.00212	.01693	02019	6.09	0 10	13.32	3	
14	7.153	6.610	.0211/	.0866	681 3	15 13	37 79	1260 4	99.67	.00210	01630	.01855	11 73	0 46	9 84	—	
15	8 198	7.577	0343/	0928	707.1	17.56	38.61	1297 6	99.89	.00206	01677	01997	4 22	0 10	12.66	—	
16	8.221	7 613	.0297/	.0835	713 7	17.86	38 44	1242.0	99 83	00210	.01487	.01775	6.71	0 10	12.35	1	
17	8 093	7 560	.0341/	—	711 4	17 62	38 71	875 4	99.97	.00203	00452	.00638	0 58	0.13	13 72	—	
18	8.034	7.508	.0262/	—	717 1	17.47	39.34	843 1	99 90	.00209	.00349	00493	3 41	0 13	11 38	—	
13	7.311	6 769	.0409/	.0723	677.9	15 36	37 79	1270.9	98.21	00132	.01672	02026	64.43	2 32	11.01	—	
14	7 012	6 473	0213/	0827	676.5	15.13	36 66	1248.1	99.56	00127	.01606	01806	14.92	0 71	9.21	—	

LIST OF ABBREVIATIONS

CO	Carbon monoxide
EI	Emission index ~ g pollutant/kg fuel
EPA	U. S. Environmental Protection Agency
EPAP	EPA Parameter ~ lbm pollutant/1000 lbf thrust-hr/LTO cycle
FN	Net thrust ~ N, lbf
NO_x	Oxides of nitrogen
P	Pressure ~ atm
PF	Pattern factor
ΔP	Pressure loss ~ atm
SLTO	Sea-level take-off
T	Temperature ~ K
THC	Total unburned hydrocarbon
W_a	Airflow ~ kg/sec
W_f	Fuel flow ~ kg/sec
V	Velocity ~ m/sec
η_c	Combustor efficiency
LBO	Lean blow out

Subscripts

b	Burner
p	Pilot
t	Total condition
4	Compressor exit station
5	Turbine inlet station

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