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Wide Range Operation of Advanced Low NO_x Combustors for Supersonic High-Altitude Aircraft Gas Turbines

by

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16. Abstract

Over the past three years under two NASA-Lewis Research Center contracts, Solar Turbines International, an Operating Group of International Harvester, has been engaged in characterizing the NOx emissions and operation of two particular types of lean, premixed combustors, namely the Jet Induced Circulation (JIC) and Vortex Air Blast (VAB) systems.

An initial rig program tested these systems in small can combustor configurations and was concerned primarily with the NOx emissions at a simulated high-altitude, supersonic cruise condition. The VAB combustor demonstrated the capability of meeting the NOx goal of 1.0 g NO_2/kg fuel at the cruise condition (T_{in} = 833°K, P_{in} = 5 atm., T_{out} = 1778°K). In addition, the program served to demonstrate the limited low-emissions range available from the lean, premixed combustor.

A follow-on effort, the results of which form the basis of this report, was concerned with the problem of operating these lean, premixed combustors with acceptable emissions at simulated engine idle conditions. Various techniques have been demonstrated that allow satisfactory operation on both the JIC and VAB combustors at idle (T_{in} = 422°K, P_{in} = 3 atm., T_{out} = 917°K) with CO emissions below 20 g/kg fuel. These include degrees of variable geometry, fuel switching and fuel-staging designs.

The VAB combustor was limited by flashback/autoignition phenomena at the cruise conditions to a pressure of 8 atmospheres. The JIC combustor was operated up to the full design cruise pressure of 14 atmospheres without encountering an autoignition limitation although the NOx levels, in the 2-3 g NO_2/kg fuel range, exceeded the program goal.

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FOREWORD

The research program described within this report was conducted by the Research Department, Solar Turbines International, an International Harvester Group under Contract NAS3-19770, with Mr. Helmut F. Butze of the Air Breathing Engines Division, NASA-Lewis Research Center as Project Manager.

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1

SUMMARY

A test rig program was conducted with the scope of defining and demonstrating techniques that would allow the satisfactory wide range operation of two advanced types of lean, pre-mixed aircraft gas turbine combustor, namely the Vortex Air Blast (VAB) and Jet Induced Circulation (JIC) concepts.

The combustors differ basically in the manner whereby the reaction is stabilized and in the design of the fuel/air preparation system.

The JIC combustor utilizes a system of multiple air/fuel mixing tubes external to the combustor reaction zone proper to produce a well-mixed system. The mixing tubes are inclined towards the dome of the combustor and the impingement of the individual, mixed jets is the driving force for the establishment of the recirculation zone. In contrast, in the VAB combustor the reaction air and fuel are mixed within the vortex field produced by an inward, radial flow swirler. The resultant static pressure gradients in the reaction zone serve to produce the recirculation zone necessary for flame stabilization.

A previous Solar/NASA-Lewis Research Center program effort (reported in CR-134889) demonstrated both the basic low NOx potential of the JIC and VAB combustors at a simulated high-altitude supersonic cruise condition and the range limitations inherent in the operation of those lean, pre-mixed combustors.

The objective of the subject program, therefore, was to operate the combustors at a simulated engine idle condition and within the emission goals shown in Table 1 while meeting the emissions goals at the simulated engine high-altitude, supersonic cruise test point shown in Table 2.

Both combustors were rig tested in the form of reverse flow can combustors to facilitate modifications and changeover. At the cruise test point the combustors were configured as essentially reaction zones along with zero dilution port flow and only a minimal amount of convective cooling for the liner surfaces in order to minimize the reaction zone equivalence ratio, and hence NOx, at the required combustor outlet temperature.

The initial designs of the combustors were based on a total pressure drop of six (6) percent and a cruise reference velocity of 15.24 m/sec. The reaction zone diameter was 0.114 m in both cases.

The successful techniques demonstrated for idle operation are:

- Total Variable Geometry

  Reaction zone equivalence ratio control by area modulation of both reaction and dilution air ports.

- Variable Dilution

  Reaction zone equivalence ratio control by area modulation of the dilution ports only.

- Variable Dilution Plus Fuel Switching

  An extension of variable dilution requiring separate fuel injection positions for cruise and idle.

- Axial Fuel Staging

  Two-stage combustor with primary stage only for the idle operation.

The demonstrated techniques include both fixed and variable geometry concepts and the program effort was intended merely to define as many potential techniques as possible rather than a single optimum design. For example, the axial fuel-staged VAB and JIC combustor systems can demonstrate good performance at idle conditions and the cruise NOx of the VAB appears to be at least as good as the equivalent single-stage system. The overall systems are, however, somewhat longer than the single-stage combustors which is a distinct disadvantage. This must be weighed against the advantage of relative simplicity for the fixed-geometry system.

All of the successful techniques evaluated are applicable to an annular combustor configuration.

The cruise test point NOx performance of the JIC combustor essentially repeated the results of the first Solar/NASA-Lewis Research Center program with levels in the 2.5 g NO_2/Kg fuel range. Extending the effective mixing tube length within an acceptable combustor size by helical wrapping resulted in lower NOx levels but combustor failure prevented operation above 8 atmospheres whereas the original straight mixing tube was able to operate at the design pressure of 14 atmospheres. The cruise test point NOx level of the VAB combustor was 2.3 g NO_2/Kg fuel at 6.5 atmospheres. Combustor failure prevented operation above a combustor inlet pressure level of 8 atm.

The cruise NOx emissions levels of the hybrid VAB/JIC axial fuel-staged combustor were promising at low pressure levels with 1.0 g NO_2/Kg fuel at 3 atm. The higher design point combustor inlet pressures were not explored.

2

INTRODUCTION

The impact of gas turbine engine-powered aircraft on worldwide pollution can be defined within two major areas. First, the contribution of aircraft to the local air pollution of metropolitan regions and, second, the long-term effects on the chemical balance of the stratosphere of pollutants emitted from future generations of high-altitude, supersonic commercial and military aircraft.

Studies (Ref. 1) have demonstrated that the contribution of aircraft gas turbines to the air pollution problem of metropolitan areas is generally small overall compared to other sources except in the immediate areas surrounding major airports where the cumulative exhaust emissions tend to concentrate. Because of this, the U.S. Environmental Protection Agency (EPA) defined and issued emission standards (Ref. 2) designed to regulate the various exhaust pollutants within or near airports. These standards are scheduled to become effective in 1979. The "Experimental Clean Combustor Program (ECCP)" was initiated by NASA in order to generate the required combustion system technology advances.

The introduction of emissions, particularly NOx, into the stratosphere is a separate area of concern. Preliminary findings indicate that stratospheric oxides of nitrogen (NOx), may need to be limited to very low levels if, for example, ozone depletion with concomitant increases in sea-level radiation, are to be avoided (Ref. 3). As a result of these preliminary findings, NASA-Lewis Research Center initiated the Stratospheric Cruise Emission Reduction Program (SCERP) in 1976 with the objective of establishing and demonstrating the technology to reduce engine emissions to environmentally acceptable levels over the entire aircraft operating range with minimum adverse effects on performance, weight and complexity. The SCERP goals are twofold:

- Achieve a minimum of 6 to 10-fold reduction in subsonic cruise NOx emissions from current levels.
- Meet or exceed established EPA standards for the Landing and Take-off cycle (LTO).

The SCERP effort is directed towards the application of the lean reaction, pre-mixed combustor concept including the forced circulation and catalytic variants, for example.

A previous NASA/Solar experimental rig study investigated the low NOx potential of two distinct types of forced circulation, lean pre-mixed combustors, namely the Jet Induced Circulation (JIC) and Vortex Air Blast (VAB) combustors. This work was reported in NASA CR-134889 (November 1975) and defined both the basic low NOx potential of these two combustors at a simulated high-altitude, supersonic cruise condition and their operational range limitations.

The work reported in this document summarizes the results of an experimental rig test program that had as its objective the definition and demonstration of techniques that would allow the JIC and VAB combustors to operate stably with acceptable emissions at simulated engine idle without compromise to the low NOx emissions at the high-altitude supersonic cruise condition.

3

COMBUSTOR CONCEPTS

The design of the two combustion systems was based both on the program operational constraints and background experience from the first program investigations (CR-134889).

Both combustors are of the lean reaction, premixed family of well-stirred systems differing in both the type of fuel/air preparation device utilized and the manner in which the reaction is stabilized. NOx control is effected by minimizing the mean reaction zone equivalence ratio and the local equivalence ratio deviations that can cause high NOx levels.

The model combustors were tested as reverse-flow can configurations. Although realizing that the current practice in aircraft gas turbines of utilizing annular combustion systems will likely continue, it was initially decided that the efficacy of the design techniques could be demonstrated most cost effectively in can combustor form.

Similarly, while cognizant of the important role that inlet air maldistribution can play in the emissions signature displayed by a combustor this was not made an area of interest in the program and reverse flow configurations were adopted for ease of combustor changeover.

In order to minimize the reaction zone equivalence ratio at the cruise test point no dilution flow was incorporated at this condition other than the minimal amount of convective cooling applied to the combustor liners which is re-injected and mixed into the reaction zone products upstream of the emissions sampling plane.

The following sections describe the construction and operation of the two combustion systems.

3.1 JET INDUCED CIRCULATION (JIC) COMBUSTOR

A section through the JIC combustor is shown in Figure 1 and displays the salient points of the design. A photograph of the assembled combustor is given in Figure 2. To produce a reaction zone with a maximum degree of homogeneity, the reaction airflow and fuel flow are premixed for cruise operation in a system of four mixing tubes that are external to the reaction zone of the combustor and inclined at 30 degrees to the combustor axis. The fuel is air-blast atomized at the entrance to each mixing tube from a

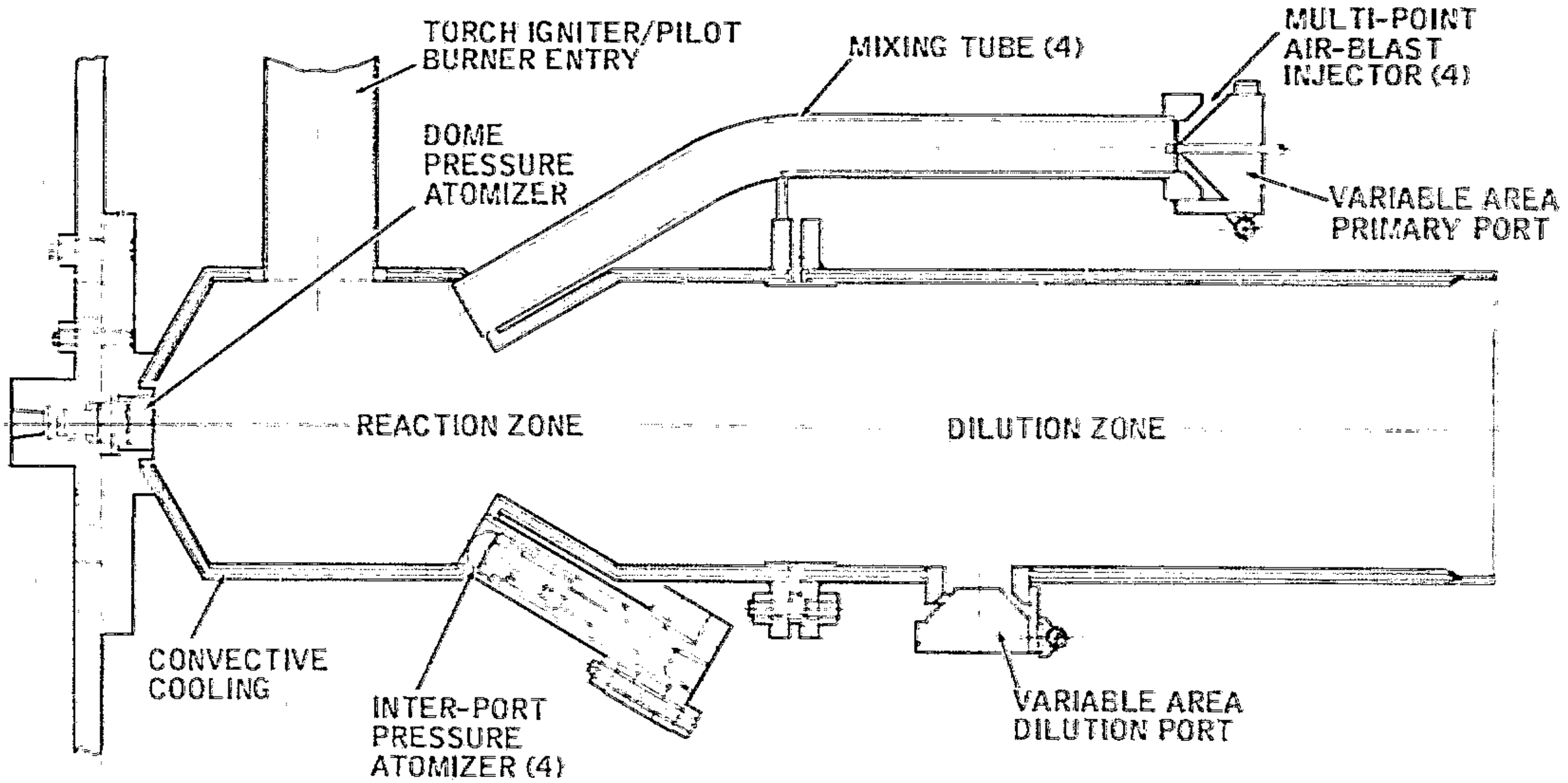

Figure 1. Jet Induced Circulation (JIC) Combustor Details

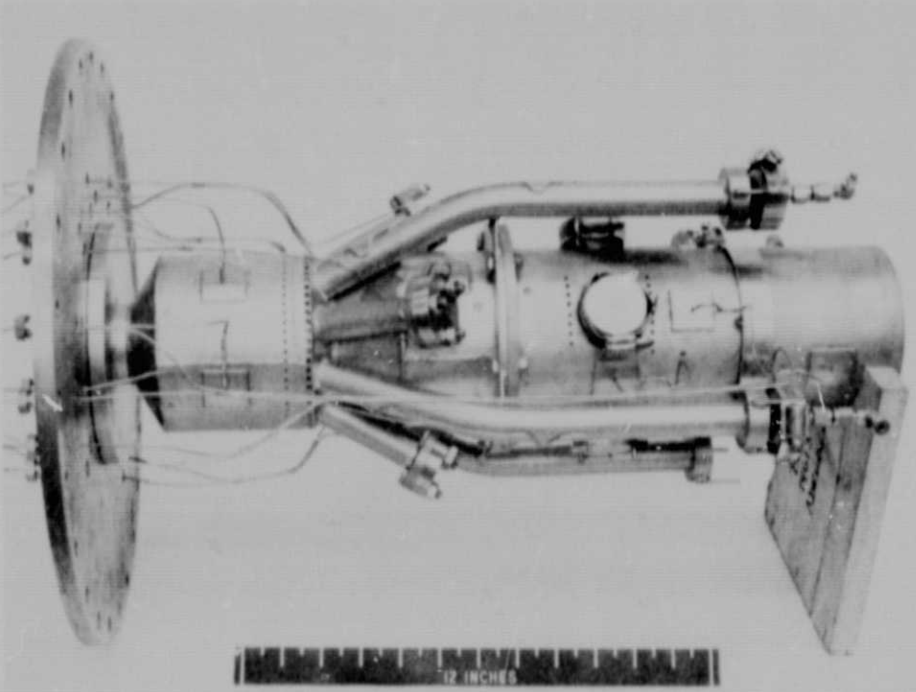

Figure 2. Jet Induced Circulation Combustor

multipoint injector rake 1.6 mm in diameter. The fuel is vaporized and mixed with the reaction air in the mixing tubes and emerges as a near-homogeneous jet into the reaction zone of the combustor. The four separate jets impinge toward the axis of the combustor forming two derived jets. The major derived jet flows upstream into the reaction zone toward the combustor dome, impinges on the dome, and then flows rearward toward the entering mixing-tube jets. The resultant recirculation pattern is anchored by the mixing-tube jets with a fraction of the reaction products being entrained into the mixing-tube jets to act as a continuous ignition source and the remainder of the products flowing out of the reaction zone between the mixing-tube jets. The minor derived jet flows rearward from the impingement point of the separate mixing- tube jets and is reacted partially in the dilution zone and partially by recirculation and entrainment into the mixing-tube jets.

The combustor design includes several features intended for potential use during idle operation, such as alternative fuel injection techniques and simulated variable-geometry. The alternative fuel injection techniques consist of a simplex pressure atomizer mounted in the dome of the combustor and a set of four simplex atomizers mounted between the mixing tube entries in the reaction zone. The variable-geometry design consists of a translating plug-port system for reaction zone and dilution-zone area control. No control mechanism was provided, and the required areas were set before each test run. The reaction and dilution zones are convectively cooled and ignition is by torch igniter firing into the reaction zone of the combustor. For normal running purposes, the torch igniter was isolated after ignition.

3.2 VORTEX AIR BLAST (VAB) COMBUSTOR

A section through the VAB combustor is given in Figure 3 and shows the major features of the design. A photograph of the combustor reaction zone is given in Figure 4.

In the VAB combustor premixing for cruise operation is accomplished within a radial, inflow swirler rather than with a system of mixing tubes as for the JIC combustor. The swirler radial inlet has a set of 24 flat vanes set at a nominal angle of 45 degrees. The axial, annular discharge section communicates with the reaction zone. The fuel is air-blast atomized from 24 separate multipoint rakes situated within each vane channel slightly upstream of the vane leading-edge diameter. The fuel is vaporized and mixed with the reaction air in the swirler passage and enters the reaction zone of the combustor as a near-homogeneous stream with a nominal outlet swirl cone included angle of 90 degrees. The radial static pressure gradients produced in the vortex serve to drive the reaction zone recirculation necessary for flame stabilization.

As in the JIC combustor, the VAB design includes several features intended for potential use during idle operation, such as alternative fuel injection techniques and simulated variable geometry. The alternative fuel injection techniques consist of either a simplex pressure atomizer or an air-blast atomizer mounted at the extreme end of the swirler centerbody. The variable-geometry design consists of the translating plug-port system for dilution area control and variable-angle swirl vanes for reaction zone area control. No control mechanism was provided and the required areas were set prior to each test run.

The reaction and dilution zones are convectively cooled and ignition is by torch igniter firing into the reaction zone of the combustor. For normal running purposes the torch igniter was isolated after ignition.

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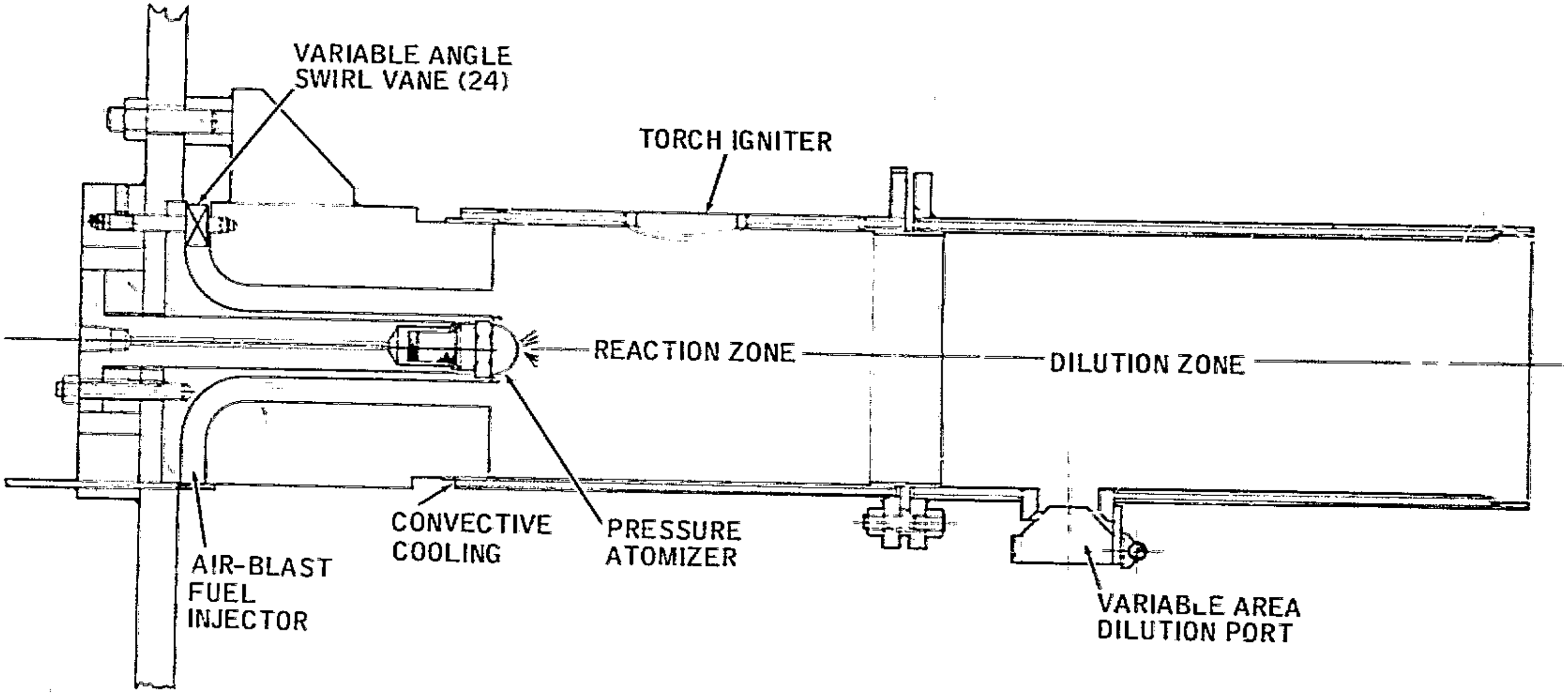

Figure 3. Vortex Air Blast (VAB) Combustor Details

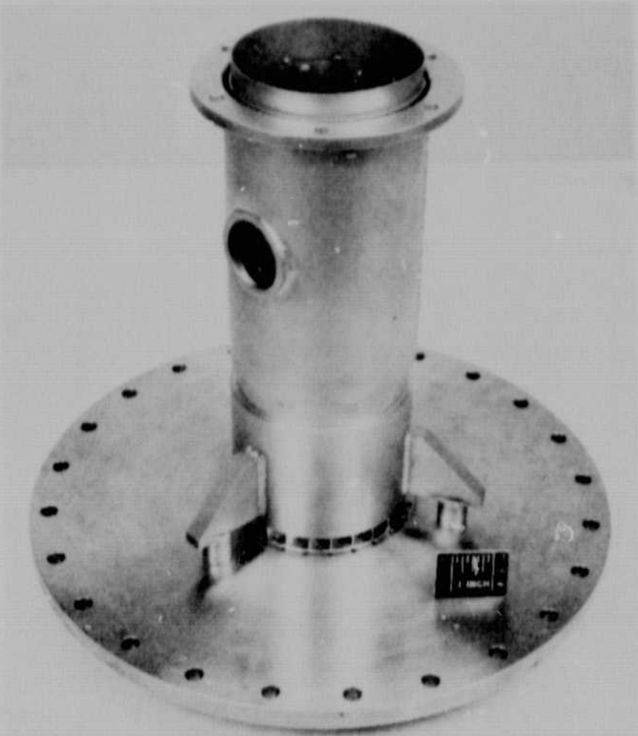

Figure 4. Vortex Air Blast Combustor

4

TEST FACILITY

4.1 FLOW PATH

A schematic of the test rig facility is shown in Figure 5. A description of the flow path is as follows:

The main air mass flow is controlled before entering a gas-fired, indirect, air preheater that raises the temperature from ambient to the required temperature at the combustor inlet. The flow then passes through a pipe section that contains a standard, ASME, sharp-edged orifice run for air-flow metering purposes before entering the instrumentation casing that reverses the flow through two straightening screens in series, from where it passes into the combustor test section. The combustors are therefore operating as reverse-flow configurations. This facilitates the changeover from one combustor type to the other as each uses a separate outer casing.

The exhaust flow from the combustor passes through the water-cooled inner duct of the instrumentation casing where, after emissions and temperature monitoring, the outlet exhaust gas is quenched by direct water injection. The operational combustor-outlet pressure level is provided by a variable butterfly back-pressure valve mounted downstream of the instrumentation casing. The flow finally exhausts to atmosphere through a silencer.

4.2 INSTRUMENTATION

The various instrumentation stations are shown for reference in the rig flow path schematic of Figure 5.

The air mass flow is metered with a standard, ASME, sharp-edged orifice run equipped with D and D/2 pressure taps. The orifice run upstream static pressure is taken at instrumentation station 1 and displayed on a Bourdon type gage. Orifice static depression is displayed on three water manometers and measured between stations 1 and 2 at points equally spaced circumferentially. Orifice flow total temperature is monitored with three C/A thermocouples equally spaced circumferentially at station 3.

The fuel temperature is measured with a single C/A thermocouple just upstream of the flow divider block that splits the main fuel flow into the separate and equal flows to each of the combustor injectors. The flow divider block

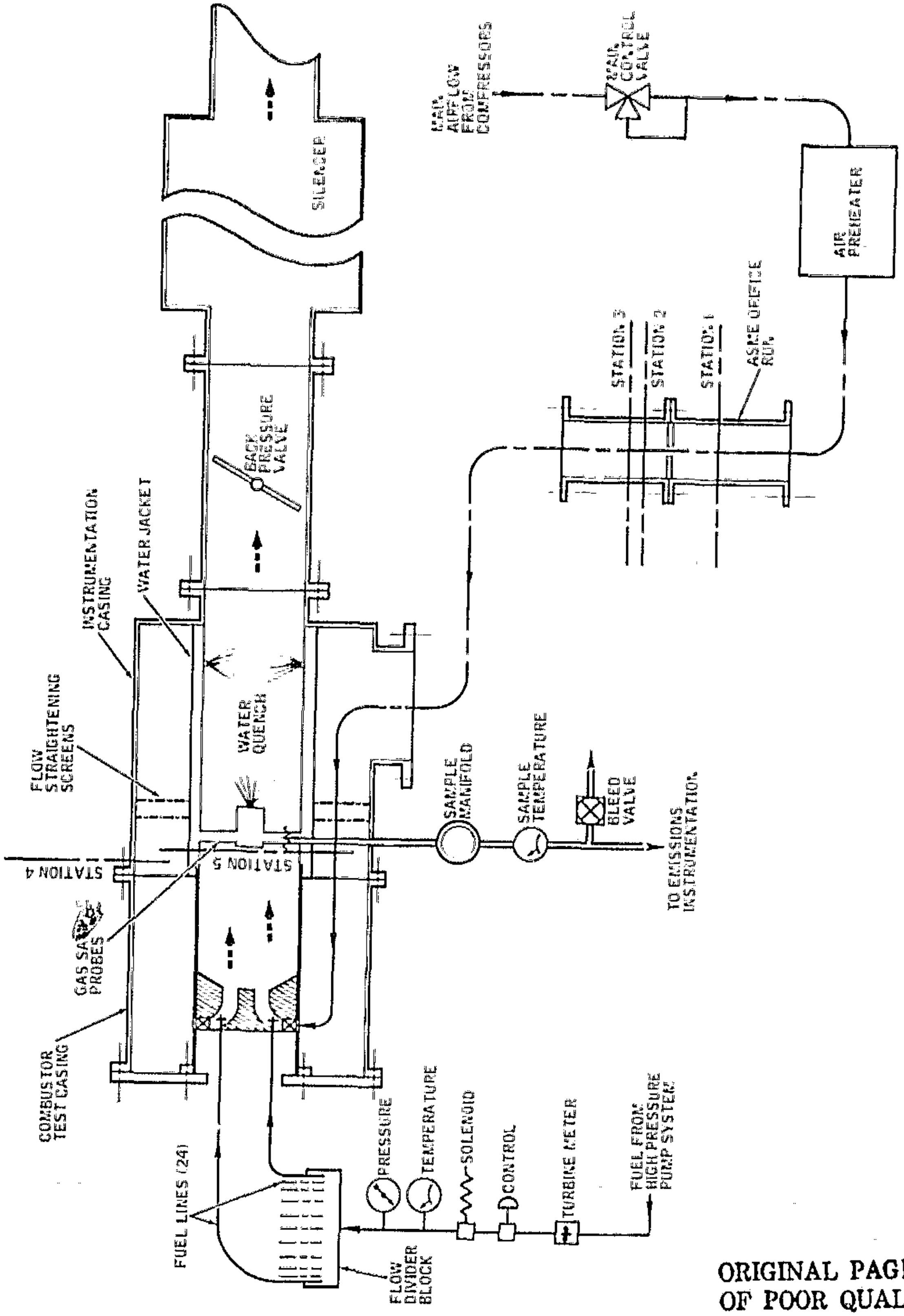

Figure 5. Test Rig Schematic

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upstream fuel pressure is indicated on a Bourdon type gage. Fuel flow rate is determined by a turbine meter installed in the delivery line. This is used as the primary fuel flow measurement. A secondary reading is obtained utilizing the pressure drop across the previously calibrated flow divider block.

The combustor inlet pressure and temperature are measured at station 4 downstream of the flow straightening screens. Due to the low inlet velocities involved, only static combustor inlet pressures and combustor pressure drops are taken. The combustor inlet pressure is displayed on a precision Bourdon-type gage and the combustor static-to-static pressure drop on three separate mercury manometers between stations 4 and 5 at points equally spaced circumferentially. The combustor inlet total temperature at station 4 is taken with three C/A thermocouples equally spaced circumferentially.

The combustor outlet temperature is measured at station 5 by a single Pt.R/Pt.R thermocouple (for reference and light-off indication purposes at the cruise test point) or six C/A thermocouples (idle test point). The thermocouple readout is through digital indicators and tape output.

The exhaust emissions sample is taken through a system of six, water-cooled, radial probes with six area-weighted sample points on each. The sample probe can be seen in Figure 6. The cooling water for the probe is discharged into the combustor exhaust stream downstream of the probes.

The samples from each of the radial rakes are discharged into a common manifold before passing to the sample line. The sample pressure is reduced to essentially atmospheric by bleeding the bulk of the flow to atmosphere before the sample enters a heated teflon line maintained at a constant 450°K along its length. Sample temperature at entry to the sample line is monitored with a single C/A thermocouple.

The emissions instrumentation includes the following:

- NDIR instrument for carbon monoxide and carbon dioxide
- FID detector for unburned hydrocarbons
- Chemiluminescent detector for nitrogen oxide with molybdenum coil NO_2 converter
- Von Brand smokemeter

Utilization of the emissions equipment and emissions data reduction is performed to the requirements of SAE ARP 1256 (Ref. 4).

A dew point meter is utilized to monitor the rig inlet air humidity. This reading is utilized to correct the observed NOx levels to a zero humidity figure using the correlation expression developed by Marchionna (Ref. 5). The correction factors were generally less than 5 percent as a result of the normally low-humidity conditions of the air supplied to the rig.

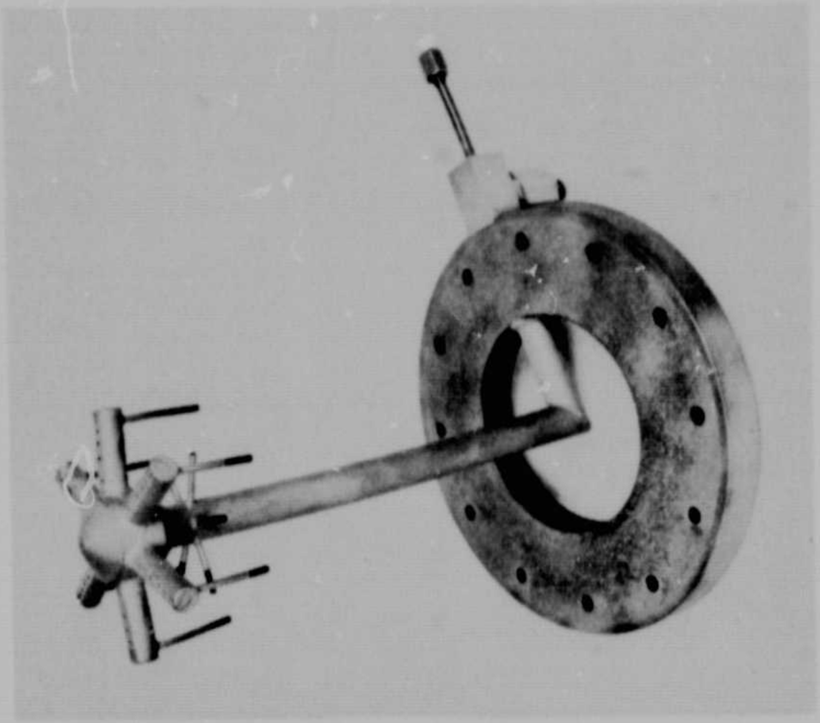

Figure 6. Gas Sampling Probe

4.3 TEST PROCEDURE

The test procedure adopted during the program was to establish the required levels of combustor inlet temperature, pressure and massflow. The fuel flow to the combustor was then modulated to give combustor outlet temperatures ranging from the design point down to a value just in excess of the lean stability limit of the system where the CO and UHC readings increase rapidly. Several data points were generally obtained between these two limits.

The emissions results represented in the body of the report are based on the exhaust gas analysis and the test fuel characteristics. The combustor temperature rise displayed is the ideal figure, including dissociation, computed from the fuel/air ratio obtained in turn from the exhaust analysis carbon balance using the calculation techniques of SAE ARP 1256. The direct measurements of air and fuel flow to the combustor were utilized as a check on the sampling accuracy. The fuel/air ratio calculated from the exhaust analysis agreed to within ±5.0 percent with that from the direct measurements.

5

RESULTS AND DISCUSSION

The following sections of this report cover the test results of the key combustor modifications at both the simulated engine idle and cruise conditions. Because of the close association between the reported program effort and a previous Solar/NASA-Lewis Research Center test program, a background section is provided which will assist in understanding the main thrusts of the development task.

5.1 BACKGROUND

As previously mentioned, it was the purpose of an earlier NASA/Solar experimental rig study to explore new combustor concepts designed to minimize the formation of NOx in aircraft gas turbines. Although the combustors were to have eventual application to aircraft gas turbines, the scope of the subject program did not include the demonstration of performance criteria such as exhaust pattern factor or altitude relight capability.

It was the primary goal of this first program to demonstrate that an NOx emission index of 1.0 g NO_2/kg fuel could be achieved with maximum carbon monoxide (CO) and unburned hydrocarbon (UHC) emission indices of 1.0 and 0.5 g/kg fuel, respectively, at a simulated supersonic cruise condition represented by a combustor inlet temperature and pressure of 833°K and 5 atmospheres, with a combustor outlet temperature of 1778°K on Jet-A1 fuel.

Of the two combustor concepts evaluated, the Vortex Air Blast demonstrated a superior emissions signature at the cruise condition, essentially meeting the cruise NOx goal of 1.0 g NO_2/kg fuel. The Jet Induced Circulation combustor demonstrated a NOx level of 2.1 g NO_2/kg fuel at the completion of the program.

An emissions signature of a VAB combustor obtained during the first contract is shown in Figure 7. The VAB combustor was configured as essentially a reaction zone with no dilution flow; hence the temperature rise indicated on the abscissa refers to the reaction zone. The NOx, CO and UHC characteristics depicted are typical of a well-stirred reactor, with the NOx a strong exponential function of reaction temperature. The CO and UHC characteristics are close to equilibrium levels over most of the operational range but increase sharply just prior to the lean stability point of the system. Because of the exponential NOx dependency on reaction temperature, the liner cooling air must be maintained at a minimum level so that the effective reaction-zone equivalence ratio is as low as possible. If an upper limit of

1 g NO_2/kg fuel is set for the NOx emissions and the VAB combustor is required to operate with a practical margin of stability and high combustion efficiency (i.e., on the horizontal section of the CO and UHC characteristics), the allowable range of reaction temperature is very limited. Because such advanced combustors must ultimately operate across the complete engine condition range from idle to takeoff, a secondary program objective was to evaluate the emission performance of the two combustors at inlet temperatures representative of an idle point.

The effect of low combustor inlet temperature can be seen in Figures 8 and 9 that depict the CO and NOx characteristics, respectively, obtained during the first program. These characteristics were obtained from the identical VAB combustor referred to in connection with Figure 7. As the inlet temperature is reduced, both the NOx and CO levels at a given reaction temperature progressively increase. This effect is due to a decrease in the driving force for the vaporization process resulting in a greater degree of nonuniformity, or "unmixedness" of the fuel-air charge entering the reactor. Upon combustion, the "unmixed" charge produces higher NOx levels because the deviations of the local equivalence ratio from the weighted average are higher.

The lean stability of the system, in terms of the minimum allowable reaction temperature before rapidly increasing CO levels occur, deteriorates as the combustor inlet temperature decreases. At an inlet temperature of 419°K, the lean limit of the combustor is at a combustor outlet temperature of approximately 1530°K; this is considerably higher than engine idle requirements, which are typically of the order of 920°K.

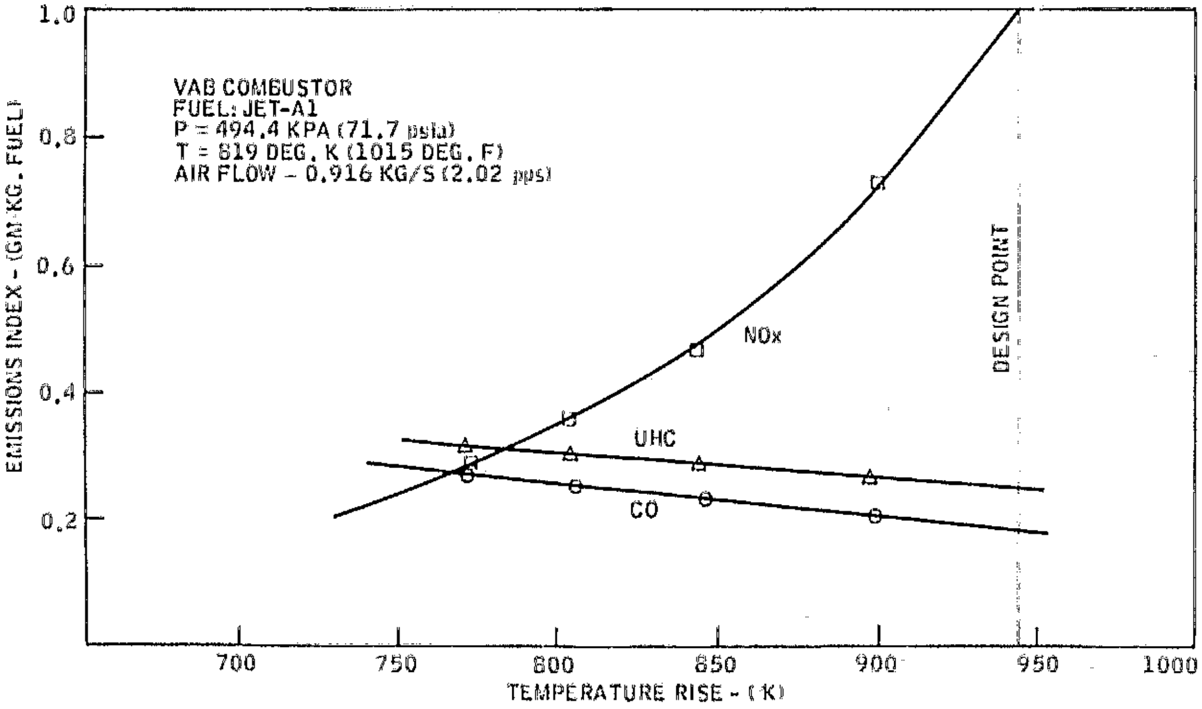

Figure 7. VAB Combustor Test Results

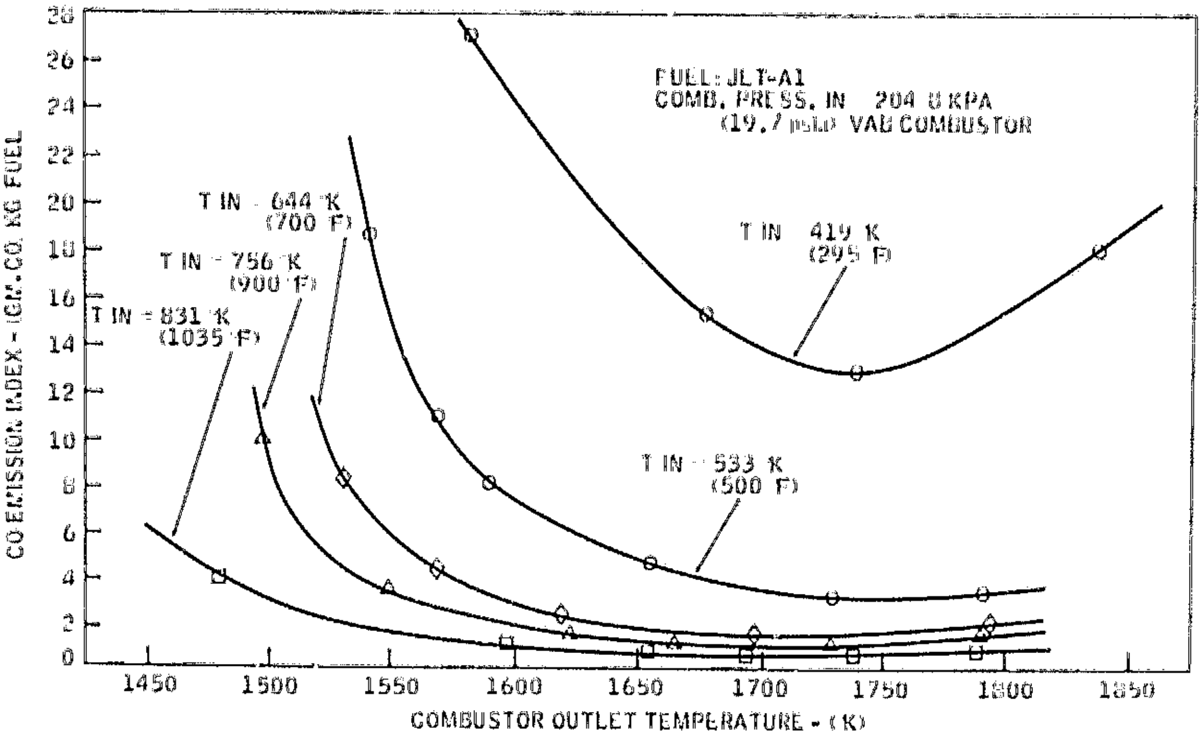

Figure 8. VAB Combustor CO Test Results - Effect of Combustor Inlet Temperature

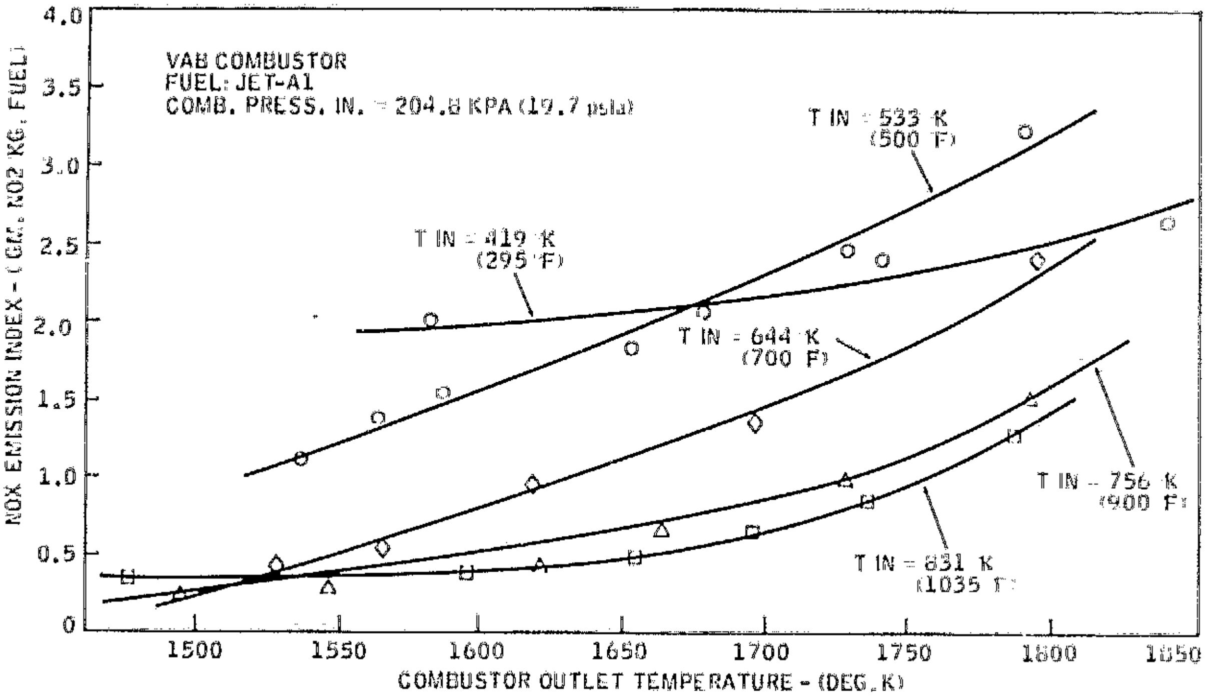

Figure 9. VAB Combustor NOx Test Results - Effect of Combustor Inlet Temperature

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Thus, a simple, lean, premixed constant-geometry combustor designed for minimum NOx at cruise cannot operate satisfactorily across the complete rang of engine conditions. The primary objective of the second program, the results of which form the basis of this report, was therefore to define and develop techniques that could be used with the JIC and VAB combustors to allow satisfactory low-emission idle operation without compromise to the NOx emissions at cruise.

5.2 PRELIMINARY TESTS

The results of the investigations on the JIC and VAB combustors during the first Solar/NASA-Lewis Research Center contract showed that the emission results from the final configurations of the two concepts that were tested differed significantly. At a combustor inlet pressure of 4.9 atmospheres and at a high combustor inlet temperature of 819°K, the VAB combustor demonstrated a NOx level slightly exceeding 1.0 g NO_2/kg fuel at the design point combustor-outlet temperature, while the JIC combustor produced twice that amount of NOx. There existed therefore, a considerable incentive to attempt further improvements to the JIC combustor in terms of optimizing the fuel preparation system and a preliminary test period was defined for a second program that included the evaluation of an increased mixing-tube length on the JIC combustor.

In addition, the preliminary test period included the definition of a fixed-geometry dilution port system for the JIC and VAB combustors in terms of axial location.

5.2.1 Effect of JIC Mixing Tube Length

In order to evaluate the effect of improved fuel-air preparation in the JIC combustor, a modification to the mixing tube length was made, shown in Figure 10, where the effective length of the mixing tube was increased by approximately 68 percent. This modification necessitated a comparable increase in the secondary zone length. The emissions test results for this configuration showed an improvement in the NOx emissions down to a level of 1.3 g NO_2/kg fuel from the previous best value of 2.1 g NO_2/kg fuel due to the greater degree of premixing. The complementary CO emissions index was 0.8 g NO_2/kg fuel.

5.2.2 Effect of Dilution Flow

As noted previously, the combustor screening tests were conducted on reaction zones with effectively zero dilution flow. This was done in order to minimize the reaction zone equivalence ratio at the cruise condition. Examination of the low inlet temperature characteristics shows that such a premixed reaction zone cannot operate, without some form of dilution airflow

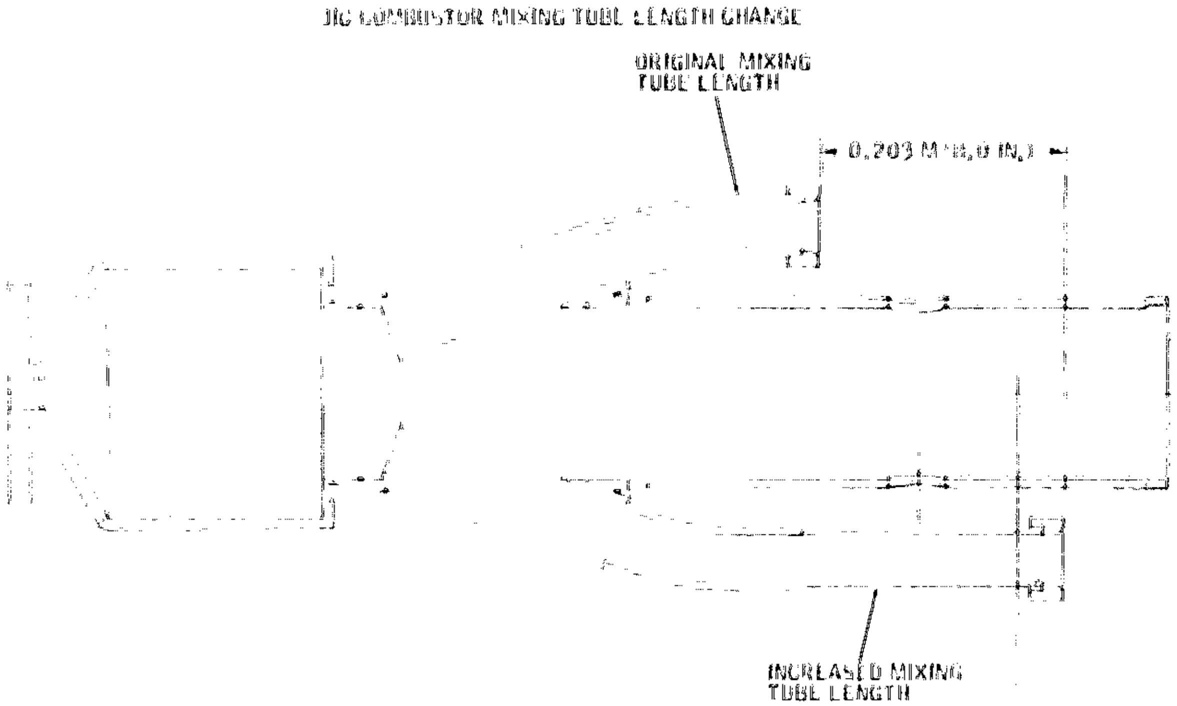

Figure 10. JIC Combustor Mixing Tube Modification - Increased Length

addition, at an overall equivalence ratio of 0.2, a level typical of an engine idle condition. The addition of dilution flow can be critical in determining the idle CO and UHC emissions; premature injection of the secondary air can freeze CO and UHC at unnecessarily high levels. In order to determine an acceptable position for dilution flow addition, an axial traverse of the JIC combustor length was made. The CO decay curve is shown in Figure 11 on which is indicated the selected position for the dilution ports.

A retest of the complete JIC combustor equipped with four, equally-spaced, fixed-geometry dilution ports produced identical idle emissions to those generated by the reaction zone alone when corrected for the overall flow split. This result confirmed that the introduction of the dilution flow had been effectively uncoupled from the reaction zone. Similar results were obtained from the VAB combustor.

5.3 IDLE TEST POINT

The simulated idle combustor test conditions and the program emission goals for Jet-A1 fuel are shown in Table 1. The following sections contain the principal emissions test results of the JIC and VAB combustor modifications.

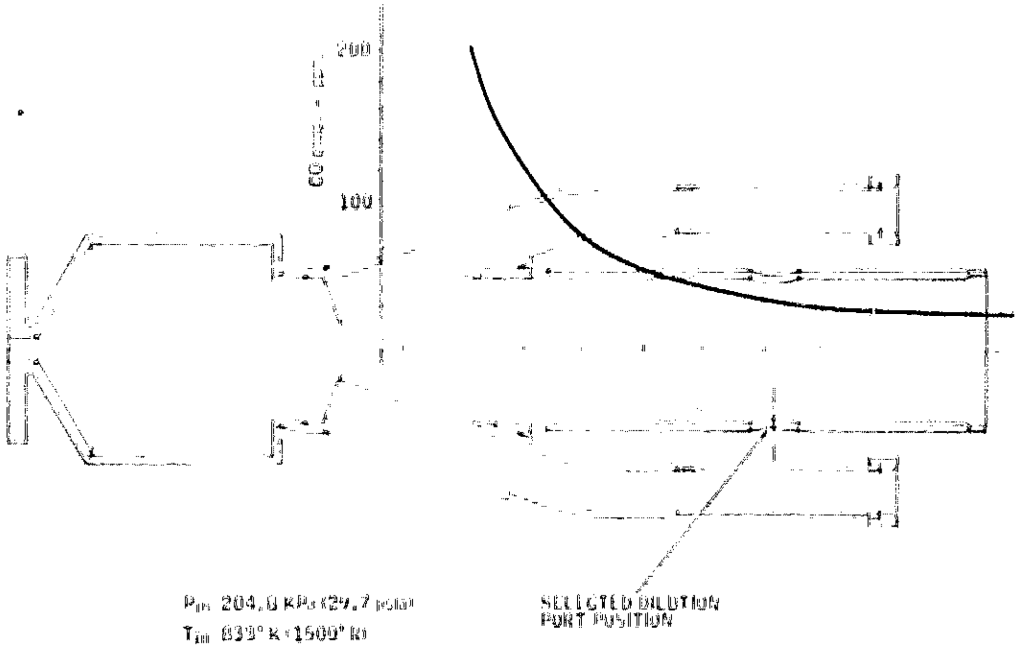

Figure 11. JIC Combustor Axial Traverse

Table 1

Test Conditions and Emission Goals - Idle

Test Conditions	Emission Goals - g/Kg Fuel
$P_{in.}$ = 30.4 N/cm^2 (3 atm)	CO - 20
$T_{in.}$ = 422 K (760 R)	UHC - 4
T_{out} = 917 K (1650 R)	

Several potential range control techniques for allowing satisfactory idle operation of the combustors were defined in the early program stages and included both fixed and variable-geometry methods of achieving reaction-zone equivalence ratio control. A summary of the techniques is shown in Table 2.

Table 2

Range Extension Techniques - Idle

IDLE OPERATION

FIXED GEOMETRY	VARIABLE GEOMETRY
• Fuel Switching	• Variable Dilution
• Vane Angle Change (VAB)	• Total Variable Geometry
• Axial Fuel Staging	

5.3.1 Fuel Switching

As previously demonstrated, the basic JIC or VAB reaction zone using the premixed fuel injection techniques at the cruise condition does not possess sufficient stability to operate at the idle test point. Variations in the type and positioning of the fuel injection system can, however, significantly improve the lean stability of the JIC and VAB reaction zones by deliberately introducing a greater degree of inhomogeneity in the reaction zone in terms of fuel-air distribution. This occurs at the expense of some increase in NOx emissions, which are not normally excessive at reaction temperatures close to the lean stability point. For the JIC combustor, the alternative fuel injection positions and techniques evaluated are shown in Figure 1 and consist of a dome pressure atomizer on the combustor axis and four inclined pressure atomizers mounted between the mixing tubes. In the VAB combustor, shown in Figure 3, a centerbody-mounted pressure atomizer and a multipoint air-blast atomizer were evaluated.

Most of these alternate fuel injection techniques improved the JIC and VAB reaction-zone lean stability to a varying degree, but none was successful in allowing operation of the reaction zone at engine idle with emissions within the program goals. This can be seen, for example, in Figure 12 which depicts the variation of the limiting reaction-zone outlet temperature for various VAB configurations and fuel injection techniques. The corresponding JIC results are shown in Figure 13. The limiting reaction-zone outlet temperature shown in both figures is defined as the temperature at which the CO emissions goal of 20.0 g/kg fuel is exceeded.

At the top of the scale in both figures the reaction-zone stability is shown using the premixed cruise fuel injection. Moving down the scale demonstrates how the stability can be improved by various fuel switching schemes and combustor configurations although none produced a sufficient degree of augmentation to allow operation of the reaction zone at the design idle outlet temperature of 917°K that is depicted at the bottom of the scale.

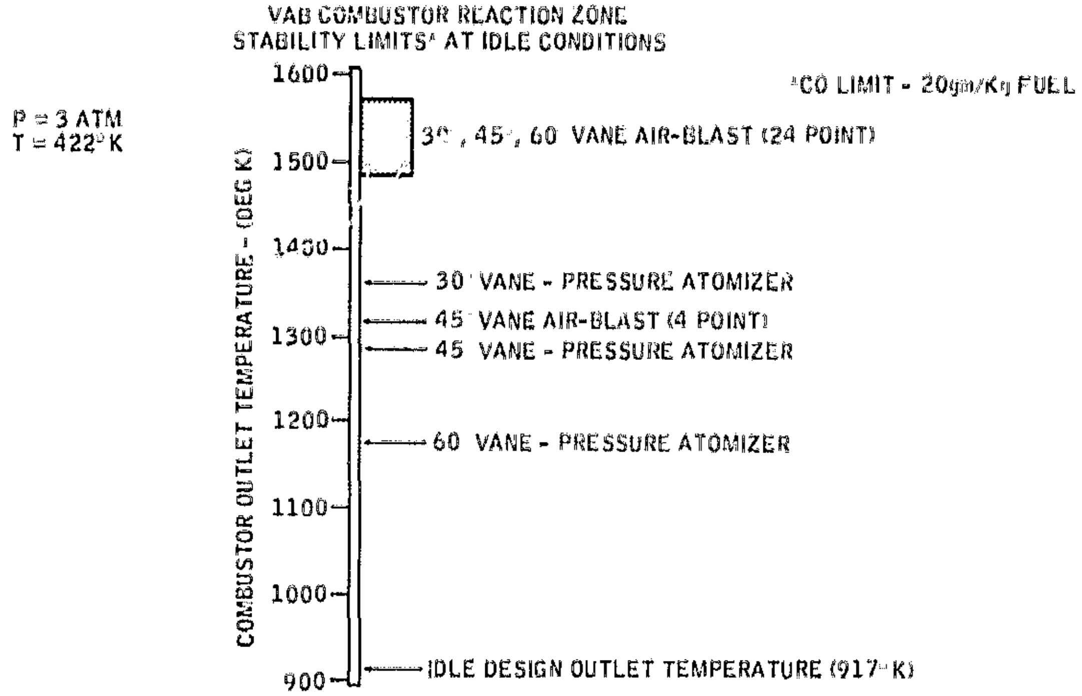

Figure 12. VAB Reaction Zone Stability Limits - Idle

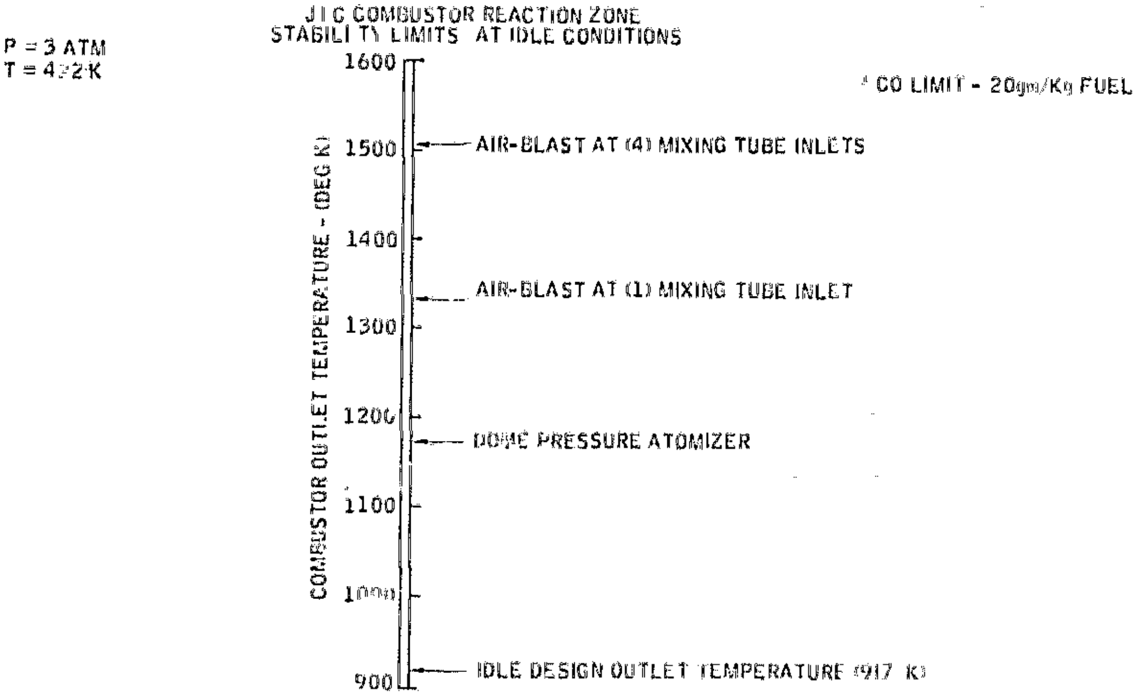

Figure 13. JIC Reaction Zone Stability Limits - Idle

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5.3.2 Variable Dilution

One range control technique that has been demonstrated is the use of variable geometry in the form of variable-dilution ports. At the cruise and takeoff engine conditions, the dilution ports are fully closed; thus, the combustor is essentially a reaction-zone and both the reaction-zone equivalence ratio and the NOx production levels are minimized. At the engine idle condition, the variable-dilution ports are fully open, so that the reaction-zone equivalence ratio is matched at a point where acceptable emissions and stability are attained.

Variable-area dilution ports are depicted in the schematic of the JIC can combustor, shown in Figure 1, where the area control is attained by a translating plug moving in and out of the port. By opening the dilution ports to their full extent, satisfactory idle operation can be achieved as shown by the emissions characteristic of Figure 14. The combustor operates at the required outlet temperature of 917°K with CO and UHC levels of 6.7 and 2.7 g/kg fuel, respectively. For these tests, the mixing-tube variable-geometry plugs were maintained in a full-open position. Similar results were attained with the VAB combustor and are depicted in Figure 15.

A potential problem area with this approach results from the wide range of movement required of the dilution ports in order that the areas match at an acceptable reaction-zone equivalence ratio. This produces combustor

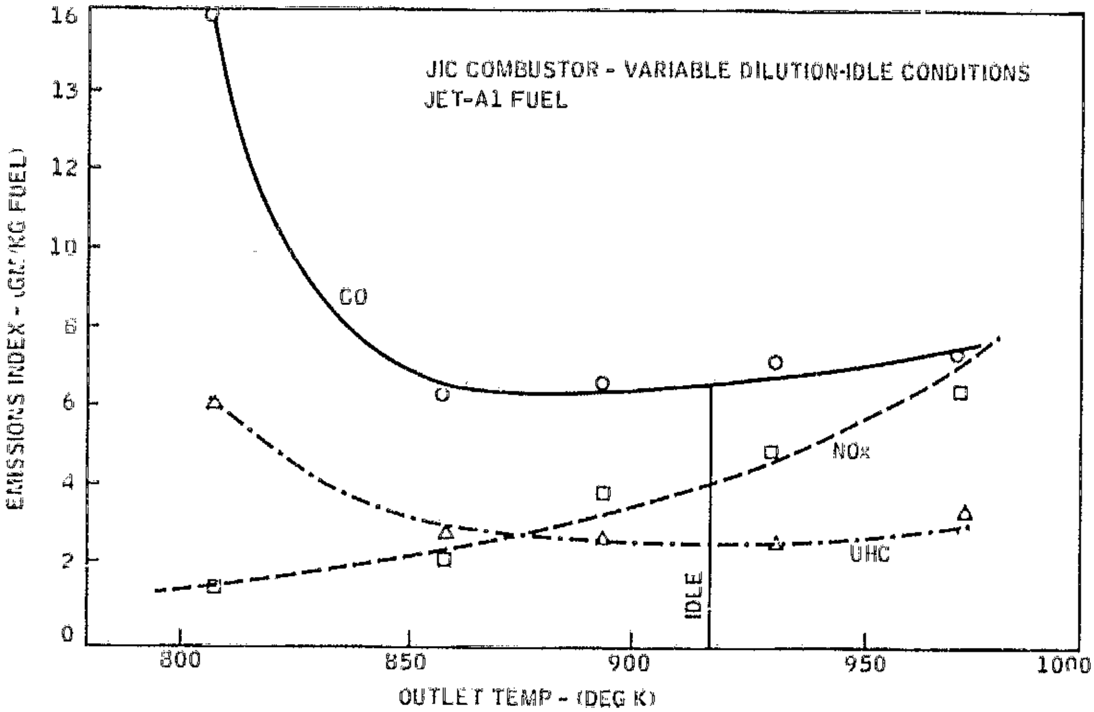

Figure 14. JIC Combustor With Variable Dilution - Idle

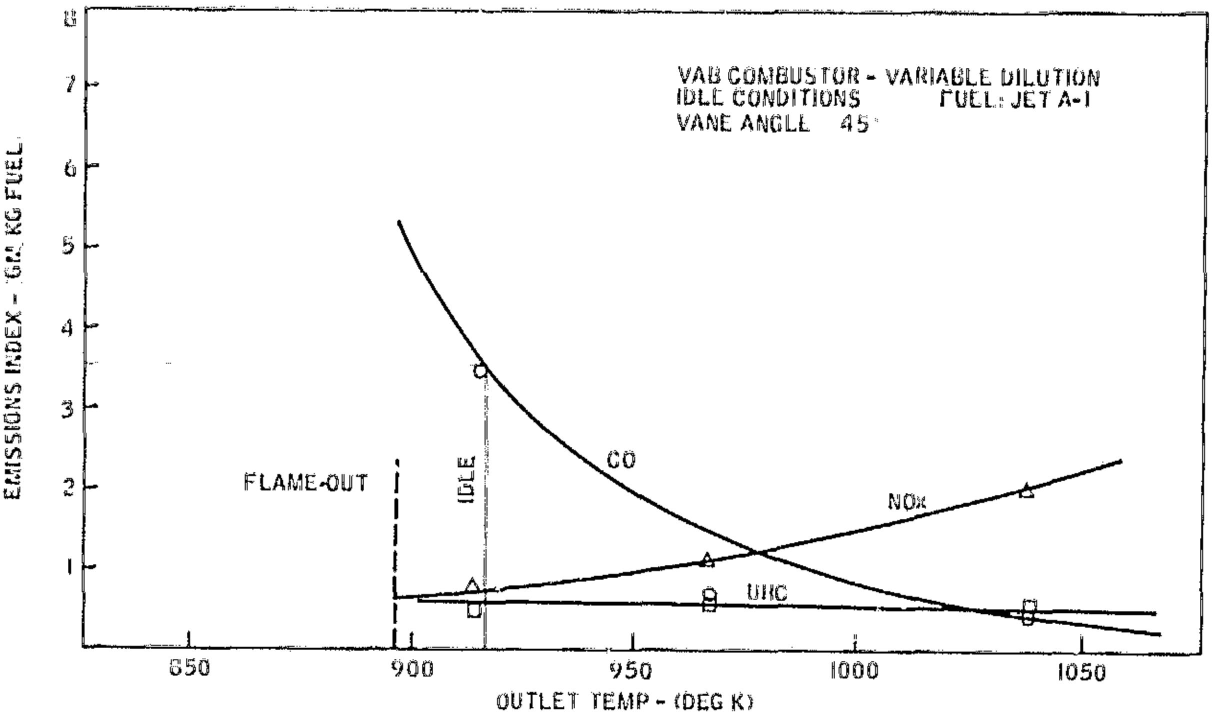

Figure 15. VAB Combustor With Variable Dilution - Idle

total-pressure drops at the idle condition that can be lower than 1.0 percent (depending upon the design-point pressure drop). The use of such low pressure-drop levels means low velocity in the combustor fuel preparation device and a potential for flashback. The test results of Figures 14 and 15 confirm, however, that both combustors in can configuration are capable of operating stably at these low pressure drops without any apparent flashback problems. The low pressure drop also means a deterioration in atomization quality when an air-blast injection system is used and poor dilution mixing, although the exhaust pattern factor is not normally an important consideration at the idle condition.

5.3.3 Total Variable Geometry

An extension of the variable-dilution technique is total variable geometry. Here the scheme involves modulation of both the dilution ports and the primary airflow register. For the JIC combustor this means reducing the mixing-tube inlet area by the use of translating plugs (Fig. 1); for the VAB combustor it means varying the swirl vane angle (Fig. 3). As for the simple variable-dilution system, no fuel switching is involved.

Total variable geometry allows the idle pressure drop to be maintained at levels higher than are possible with variable dilution alone. These higher levels enhance dilution penetration, mixing and fuel atomization although the problem of low mixture velocities in the fuel preparation device remains because most of the pressure drop is taken across the translating area-modulation plug (JIC) or vane throat (VAB). Some potential problem areas of the simple variable-dilution techniques can therefore be avoided at the expense of mechanical complexity.

The results of a series of simulated total variable-geometry tests are shown in Figure 16, where, with a constant dilution-port setting, the mixing-tube entry of the JIC combustor was varied from a full-open setting to a modulating plug position gap of 1.0 mm. The limiting CO outlet temperature is defined as that temperature at which the idle CO emissions goal of 20 g/kg fuel is exceeded. At the right hand end of the characteristic, the mixing-tube port is full open and the particular dilution-port gap used does not allow satisfactory idle operation; not until the mixing tube plug gap is closed down to below 1.6 mm is the CO goal of 20 g/kg fuel met at the idle outlet temperature. This is because as the mixing-tube plug gap is reduced, the reaction-zone equivalence ratio increases at a given overall temperature rise and the combustor outlet temperature at which the CO goal is exceeded, drops. The characteristic therefore shows that the combustor can operate at idle with satisfactory CO emissions when the primary-port setting is less than approximately 1.6 mm but this represents only one possible characteristic of a complete map depending upon the chosen idle combustor pressure drop.

A similar trend was demonstrated for the VAB combustor. By increasing the vane angle setting from 45 to 60 degrees (decreasing the vane channel throat area) the idle point CO emissions were decreased from the simple variable

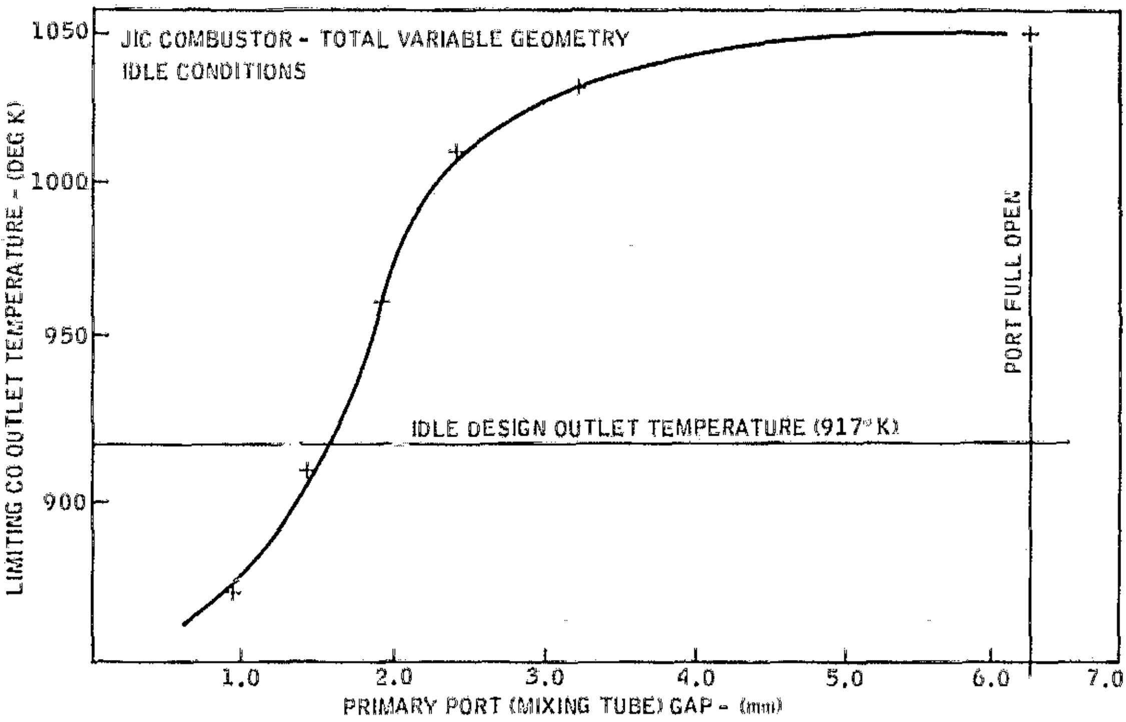

Figure 16. JIC Combustor With Total Variable Geometry - Idle

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dilution system level of 3.6 g/kg fuel to a value of 0.6 g/kg fuel, with a corresponding increase in the idle combustor pressure drop.

5.3.4 Fuel Switching Plus Variable Dilution

By taking advantage of the lean limit augmentation effect obtained from fuel switching, a variable-dilution system can be operated at idle that requires less dilution turn-down than the simple variable-dilution technique. This results in higher combustor pressure drop levels at idle without incurring an excessive cruise pressure drop. The effect of matching a VAB reaction zone at various equivalence ratios by varying the dilution-port setting is shown in Figure 17 for two types of fuel injection; a centerbody pressure atomizer and a centerbody air blast atomizer.

The results are summarized by plotting the CO obtained at the idle combustor-outlet temperature against the dilution-port gap setting. As the dilution-port gap is increased at a constant overall combustor temperature rise, the reaction-zone equivalence ratio increases and the CO level decreases.

The curves show that for both pressure and air-blast atomizers in the centerbody, a dilution-port gap greater than about 3.2 mm enables the combustor to match at idle with CO levels lower than the 20 g/Kg fuel goal. Without the reaction zone stability augmentation provided by the fuel switching, the CO goal would be exceeded at the 3.2 mm dilution-port setting with only a simple variable-dilution system.

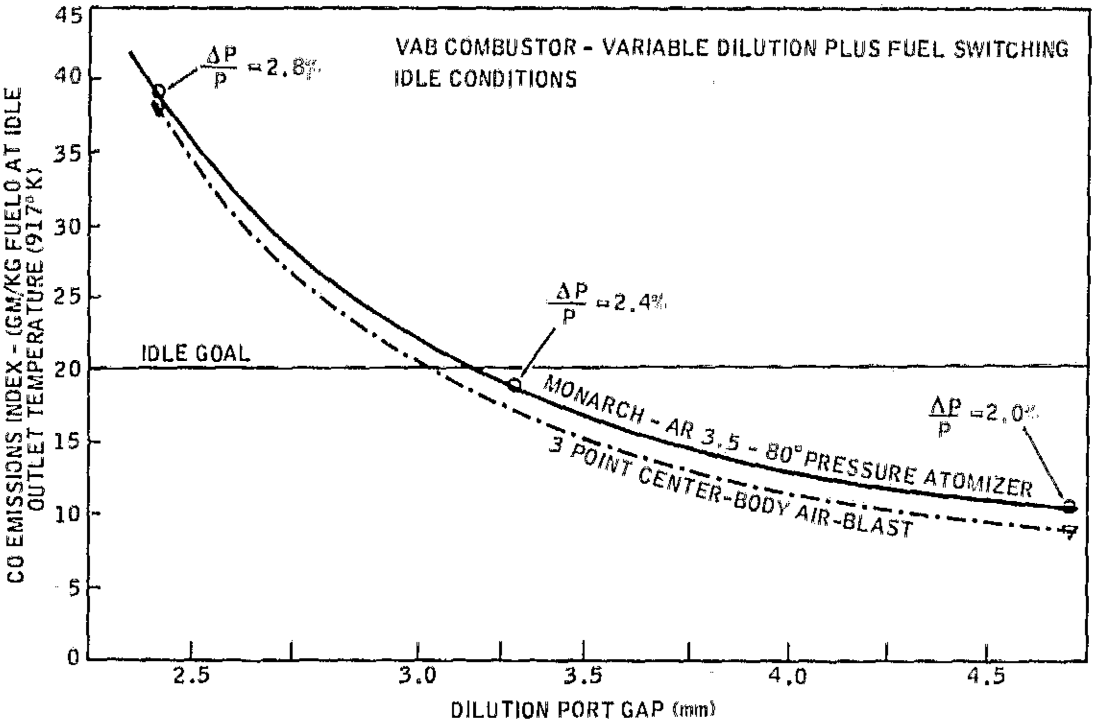

Figure 17. VAB Combustor With Variable Dilution Plus Fuel Switching - Idle

Because the required dilution-port setting to meet the idle CO goal is smaller with fuel switching, the idle combustor pressure drop is higher compared to the simple variable-dilution case and the results show more realistic pressure-drop levels in the 2-3 percent range compared to the less than one percent level for the variable-dilution technique without fuel switching. Similar results were demonstrated for the JIC combustor and are shown in Figure 18 for a pressure atomizer installed in the combustor dome.

In the results shown, fuel switching involves the use of an alternative type and position of fuel injector from the pre-mixed method used at cruise. It is possible, however, to obtain a similar, but lesser degree of stability augmentation from the use of circumferential fuel-staging. This takes the form on the VAB combustor of, for example, fueling only four out of the twenty-four fuel injection rakes at the vane inlets (Fig. 1) and in the JIC combustor by fueling only one of the four mixing-tube injector systems (Fig. 3). Although circumferential fuel-staging is a less efficient method of fuel switching, it does not require the addition of a separate fuel injection device to the combustor design.

Again, therefore, as with total variable geometry, some potential problem areas associated with the simple variable-dilution system can be avoided by the addition, in this case, of fuel injection system complexity.

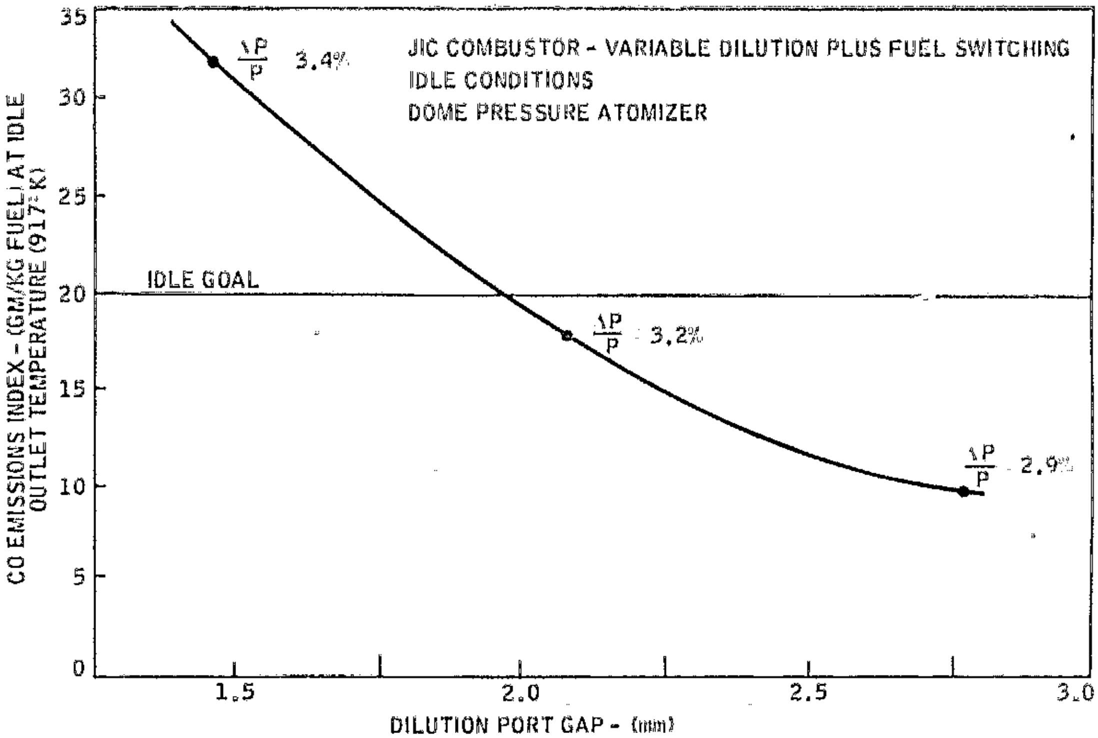

Figure 18. JIC Combustor With Variable Dilution Plus Fuel Switching - Idle

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5.3.5 Axial Fuel Staging

To evaluate the concept of axial fuel staging, the dilution zones of the JIC and VAB combustors were replaced by a secondary JIC type of reaction/dilution zone. The resulting arrangements are shown in Figures 19 and 20 depicting the axial fuel-staged JIC and VAB combustors, respectively.

The operation of the system is as follows. At the idle condition, the secondary JIC mixing tubes are unfueled and act as a conventional dilution system with fuel switching in the primary reaction zone, either JIC or VAB. At the cruise condition, both the primary reaction zone and the secondary JIC mixing tubes are fueled, with the flow split normally such as to produce a uniform equivalence ratio throughout the combustor. The system thus completely avoids the use of variable geometry.

A typical idle emissions characteristic of the VAB axial fuel-staged combustor where primary-zone fuel switching was used is shown in Figure 21 where the CO and UHC goals are met at the required outlet temperature. An idle emissions characteristic of the JIC axial fuel-staged combustor is shown in Figure 22 where, due to a mismatch between the primary and secondary stage mixing tube sizes, the CO idle goal of 20 g/kg fuel is exceeded at a combustor outlet temperature of 967°K rather than the design point of 917°K. Although the axial fuel-staged configurations possess the inherent simplicity of a fixed-geometry system, the combustor length is somewhat greater than the equivalent single-stage system length for the same reference velocity. This might be a significant disadvantage in some installations.

5.4 CRUISE TEST POINT

The simulated cruise combustor test conditions and emission goals for Jet-A1 fuel are shown in Table 3. The following sections contain the principal emissions test results at cruise of the JIC and VAB combustor configurations.

Both types of combustors were configured as reaction zones only, with the simulated variable-dilution ports blanked off. For the JIC combustor the mixing-tube inlets were set fully open and for the VAB combustor the swirler vanes were set at an angle of 45 degrees.

Although the cruise design combustor pressure was 14 atmospheres, tests were conducted beginning with considerably lower pressures and with progressive increases to the final design point in order to obtain as much information as possible about the performance of the combustors.

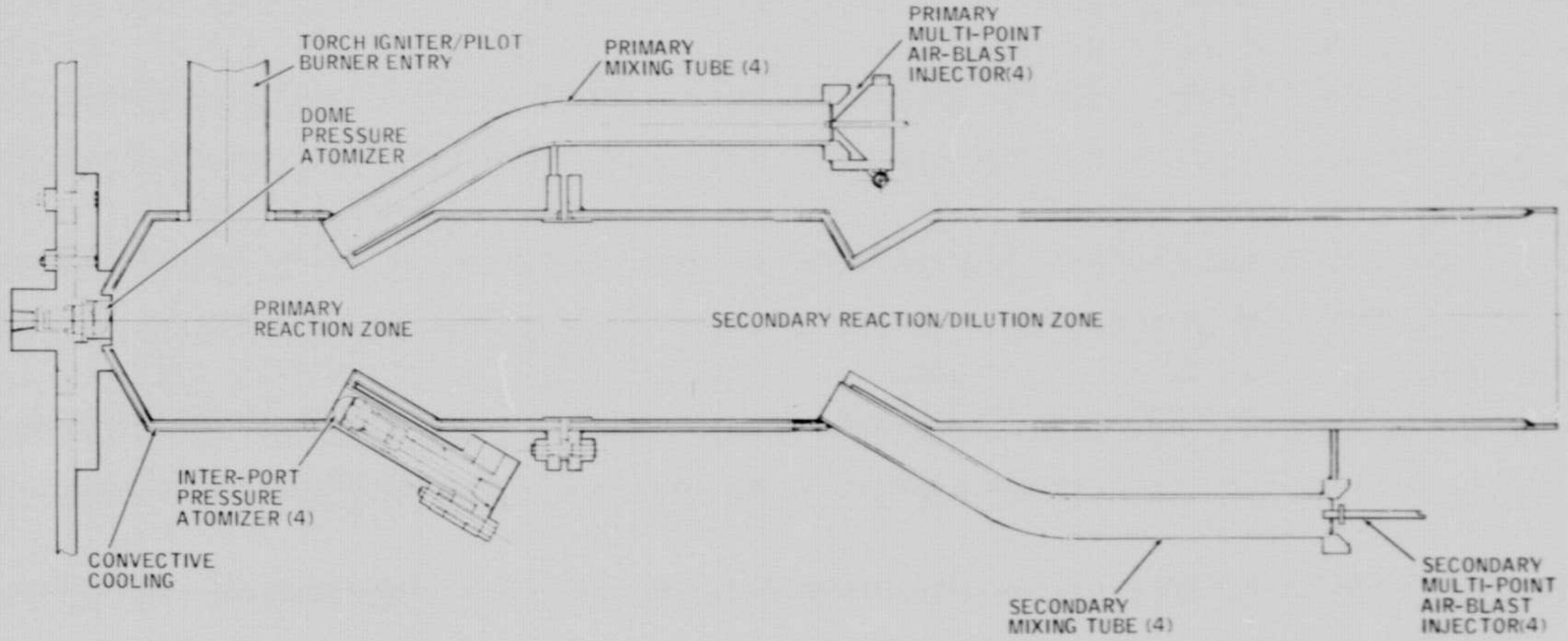

Figure 19. JIC Combustor Details - Axial Fuel-Staged

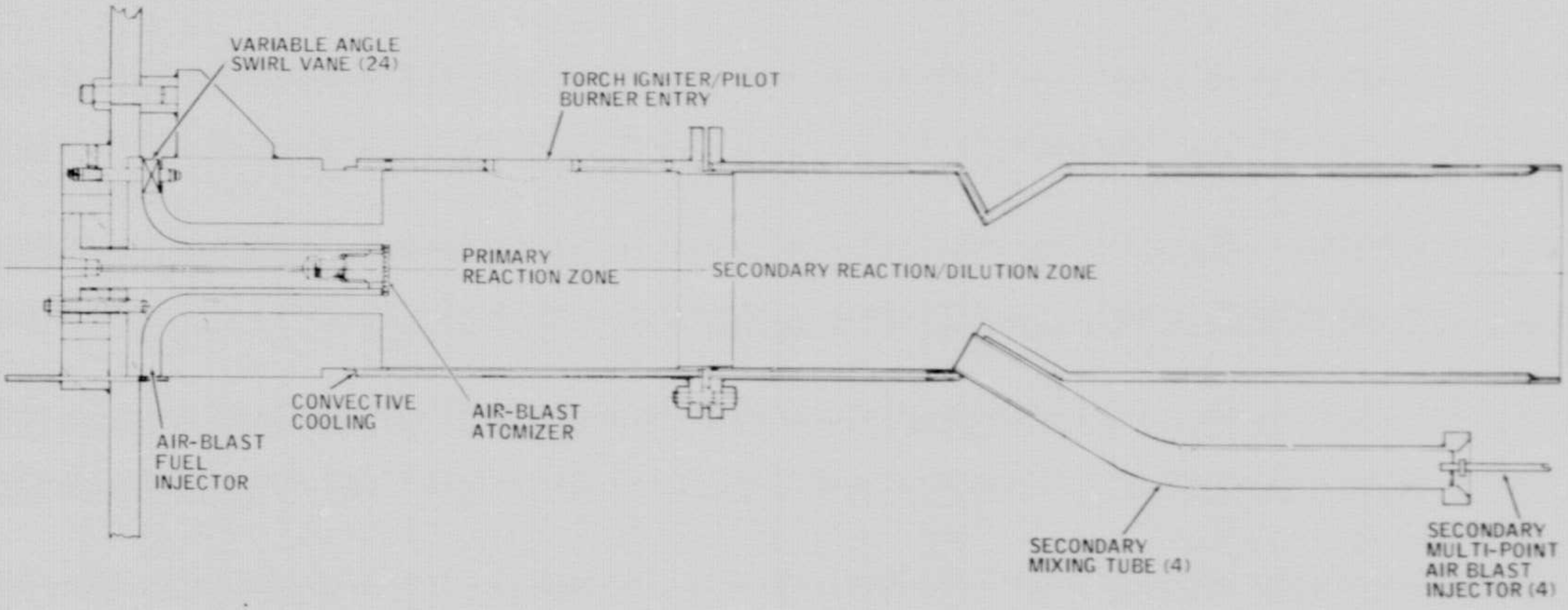

Figure 20. VAB Combustor Details - Axial Fuel-Staged

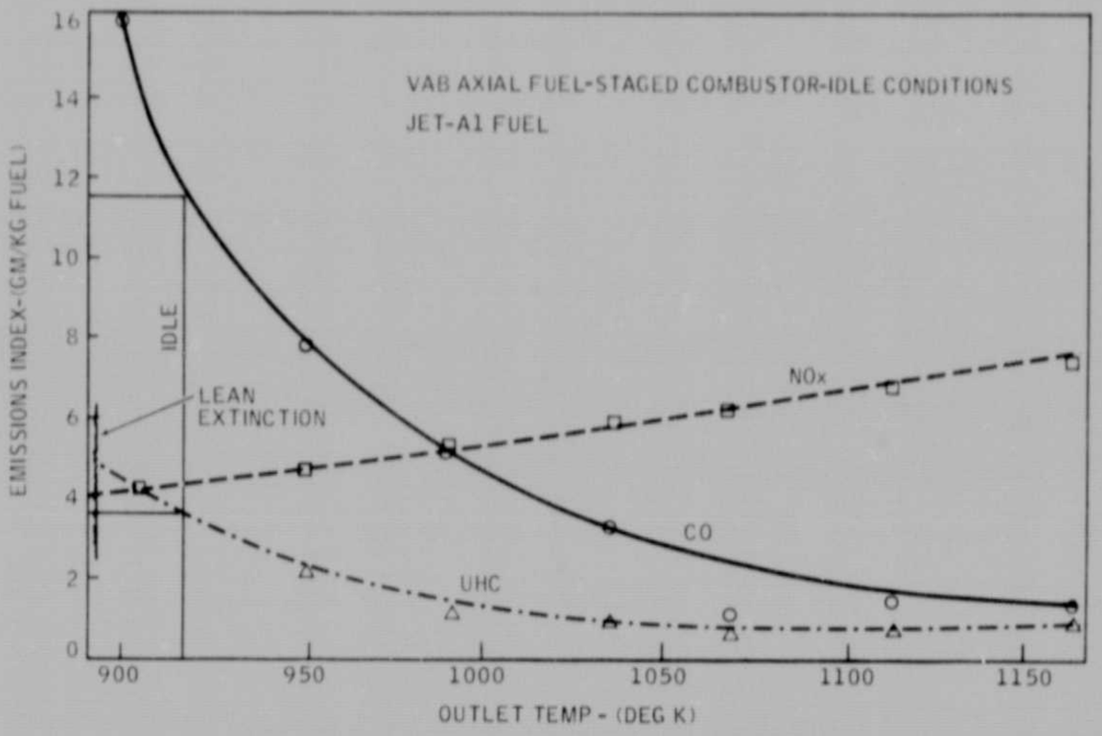

Figure 21. VAB Combustor With Axial Fuel-Staging - Idle

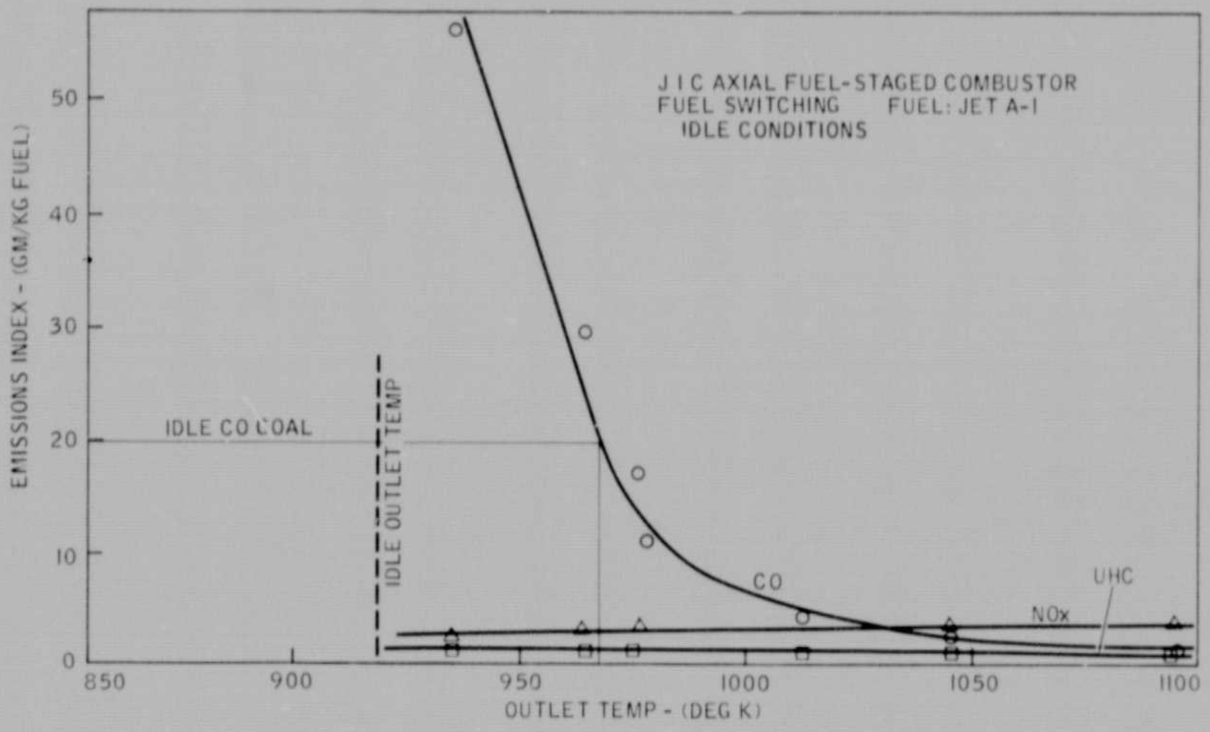

Figure 22. JIC Combustor With Axial Fuel-Staging - Idle

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Table 3

Test Conditions and Emission Goals - Cruise

Test Conditions	Emission Goals - g/Kg Fuel
$P_{in.}$ = 141.9 N/cm^2 (14 atm)	NOx - 1.0
$T_{in.}$ = 833 K (1500 R)	CO - 1.0
T_{out} = 1778 K (3200 R)	UHC - 0.5
	Smoke - 15 SAE

5.4.1 VAB Combustor - Single Stage

An emissions characteristic obtained from the VAB reaction zone at a combustor pressure of 6.5 atmospheres is shown in Figure 23. The full design pressure of 14 atmospheres was not tested as the combustor suffered a burn-out of the swirler centerbody section at a combustor pressure of approximately 8 atmospheres. Inspection of the damage revealed the probability that the swirler channel flow had been separating from the centerbody in the radial-to-axial transition bend and that this low-velocity, separated region had precipitated the damage either by direct contact with the reaction zone causing flashback or by the occurrence of autoignition in the long residence time secondary recirculations present in the separated region. The design point NOx level shown in Figure 23 is higher, at 2.3 g NO_2/kg fuel, than the results previously obtained with similar hardware (Fig. 7) that produced a NOx level of 1.0 g NO_2/kg fuel. It is considered likely that the aerodynamic design deficiency in the swirl channel of the later hardware is the cause of the NOx discrepancy, as separation in the axial section of the swirl channel increases the axial flow velocity component and effectively reduces the available channel premixing residence time. At the tested pressures up to 6.5 atmosphere, however, the VAB reaction zone did not display any noticeable variation of NOx level with combustor pressure level. This observation agrees with the results previously obtained with similar VAB hardware.

5.4.2 VAB Combustor - Axial Fuel-Staged

Only a preliminary, low-pressure evaluation of the axial fuel-staged VAB combustor was made and the results of this test are depicted in Figure 24. Although the design outlet temperature NOx level of 1.0 g NO_2/kg fuel appears

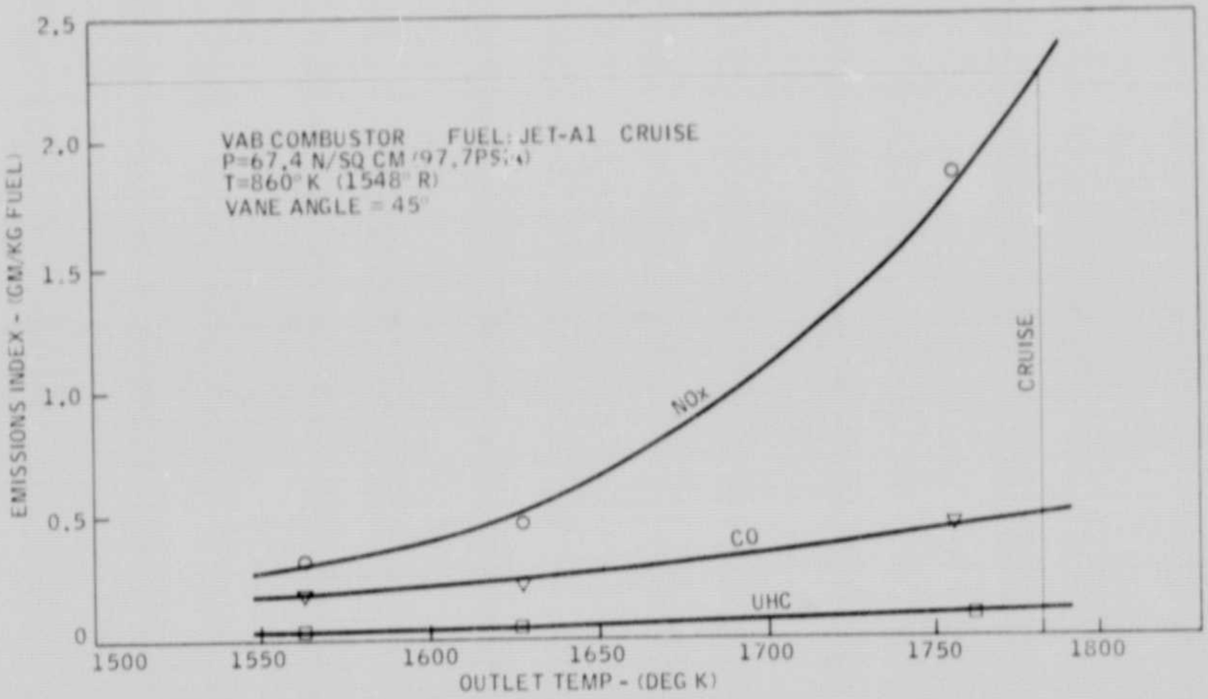

Figure 23. VAB Single Stage Combustor - Cruise

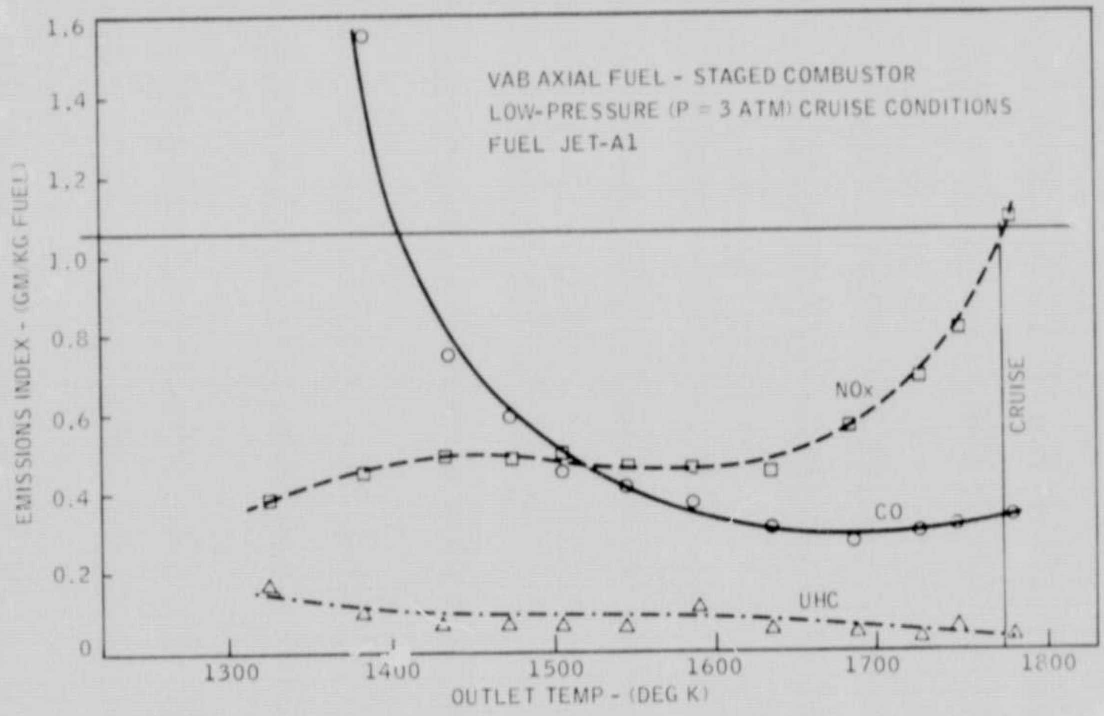

Figure 24. VAB Axial Fuel-Staged Combustor - Cruise

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promising it is likely that flashback/autoignition problems, similar to that experienced with the single-stage VAB reaction zone, would be encountered at a higher combustor pressure level.

The characteristic was obtained by fueling the primary VAB reaction-zone at a constant rate and progressively increasing the fuel flow to the secondary JIC reaction zone until, at the design outlet temperature, the equivalence ratios in the JIC and VAB reaction zones were equal; thus there existed an essentially homogeneous reaction temperature throughout the combustor. Varying the equivalence ratio split between the JIC and VAB zones either side of unity produced higher NOx levels.

5.4.3 JIC Combustor - Single Stage

A typical emissions characteristic obtained from the JIC reaction zone at a combustor pressure of 12.3 atmospheres is shown in Figure 25. The configuration tested was that depicted in Figure 1. Across a tested pressure range of from 3 to 14 atmospheres, the JIC combustor was found to display no significant pressure effect on NOx emissions outside of the normal experimental scatter of the results. The design point NOx level displayed in Figure 25 of 2.3 g NO_2/kg fuel corresponds to the results previously obtained with similar JIC hardware having an identical mixing-tube length. No autoignition in the mixing tubes was observed up to the design cruise pressure level of 14 atmospheres.

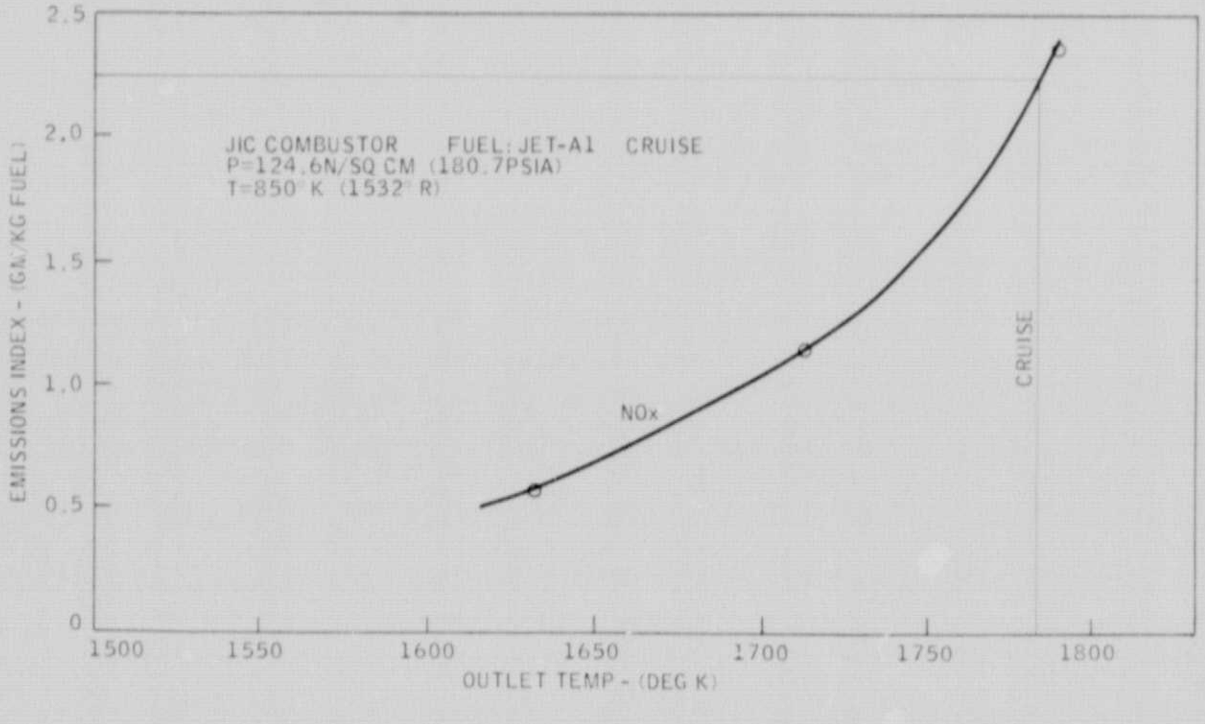

Figure 25. JIC Combustor - Cruise

An attempt to improve the basic NOx level of the JIC reaction zone was made by increasing the mixing-tube length by approximately 70 percent. In order to avoid an overall increase in the combustor length, the mixing tubes were wrapped in a helical fashion around the combustor while retaining the 30 degree final injection angle. At a combustor pressure of 5 atmospheres, the modification resulted in a reduction of the NOx to 1.6 g NO_2/kg fuel; however, failure of the mixing tubes occurred at a pressure of approximately 8 atmospheres. Inspection of the failure revealed that the mixing-tube burnout was probably not the result of a fundamental autoignition limitation but was initiated by penetrated weld joints in the mixing tubes that tripped the flow and caused a flashback or autoignition in the separated flow.

6

CONCLUSIONS

- Several range-augmentation techniques have been demonstrated that allow the lean-reaction, premixed aircraft gas turbine combustor to operate with low NOx emissions at engine cruise and acceptable CO and UHC levels at engine idle. Operation at idle with the CO and UHC within goals of 20 g/kg fuel and 4 g/kg fuel, respectively, is accompanied by zero smoke production. The range-augmentation techniques involve several combinations including variable geometry and fuel switching designs, namely

  - Total variable geometry
  - Variable dilution
  - Variable dilution plus fuel switching
  - Axial fuel staging

  The axial fuel-staging concept, as the only fixed-geometry technique, is attractive from a mechanical simplicity viewpoint but requires further development of the cruise operating condition emissions.

- Although the VAB combustor cruise NOx emissions did not meet the 1.0 g NO_2/kg fuel goal it is considered that this was due in large part to an aerodynamic deficiency in the design of the swirler channel. It is believed that a flow separation in the region of the radial-to-axial bend was causing fuel stratification and poor air/fuel mixing. In addition the separated region may have acted as a source for the flashback/autoignition combustor failure. An in-line flow VAB combustor, more representative of an actual aircraft engine layout, would utilize an axial swirler system, hence the design of the radial swirler utilized for the test program reported is not a basic limitation of the VAB concept.

- The JIC combustor demonstrated a cruise point NOx level in the range of 2.5 g NO_2/kg fuel without experiencing any autoignition problems. Significant improvements to this level may be possible with increases to the mixing-tube length without changes to the overall combustor envelope. The effects of wrapping the mixing-tubes and increased length on autoignition limits need to be further explored, however, especially at higher pressure levels representative of engine take-off conditions.

- Neither the JIC or the VAB combustors exhibited any noticeable pressure effect on NOx emissions over the tested ranges. Further information on the NOx pressure effect as a function of the degree of premixing is required before a complete explanation for this behavior can be formulated.

REFERENCES

1. "Aircraft Emissions: Impact on Air Quality and Feasibility of Control," U.S. Environmental Protection Agency, July 1973.

2. "Control of Air Pollution From Aircraft and Aircraft Engines," U.S. Environmental Protection Agency, Federal Register, Vol. 38, No. 126, July 1973.

3. Grobecker, A.J., Coroniti, S.C. and Cannon, R.H., Jr., "Report of Findings - The Effects of Stratospheric Pollution by Aircraft, Executive Summary," U.S. Dept. of Transportation, DOT-TST-75-50, December 1974.

4. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines," SAE Aerospace Recommended Practice, ARP 1256, 1971.

5. Marchionna, N.R., "Effect of Inlet-Air Humidity on the Formation of Oxides of Nitrogen in a Gas-Turbine Combustor," NAS TMX-68209, Lewis Research Center, 1973.