NASA CR—165518
Solar SR82-R-4621-36

National Aeronautics and
Space Administration

Investigation of a Low NOx Full-Scale Annular Combustor

SOLAR TURBINES INCORPORATED
SUBSIDIARY OF CATERPILLAR TRACTOR CO.
P.O. Box 80966, San Diego, CA 92138

8
NASA CR—165518
Solar SR82-R-4621-36

National Aeronautics and
Space Administration

Investigation of a Low NO_x Full-Scale Annular Combustor

By
P.B. Roberts and A.J. Kubasco

Prepared For
National Aeronautics and Space Administration
Lewis Research Center

Contract NAS3-20616

SOLAR TURBINES INCORPORATED
SUBSIDIARY OF CATERPILLAR TRACTOR CO
P O Box 80966, San Diego, CA 92138

1. Report No. NASA CR-165518	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Investigation of a Full-Size Low NOx Annular Combustor	5. Report Date February 1982 6. Performing Organization Code
7. Author(s) P. B. Roberts and A. J. Kubasco	8. Performing Organization Report No. SR82-R-4621-36 10. Work Unit No.
9. Performing Organization Name and Address Solar Turbines Incorporated a Subsidiary of Caperpillar Tractor Co. 2200 Pacific Highway San Diego, CA 92138	11. Contract or Grant No. NAS3-20616 13. Type of Report and Period Covered Contractor Final Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager: N. J. Sekas, Aero-Thermodynamics and Fuels Division
NASA-Lewis Research Center, Cleveland, OH 44135

16. Abstract

An atmospheric test program was conducted to evaluate a low NOx annular combustor concept suitable for a supersonic, high-altitude aircraft application. The lean premixed combustor, known as the Vortex Air Blast (VAB) concept, was tested as a 22.0 cm diameter model in the early development phases to arrive at basic design and performance criteria. Final demonstration testing was carried out on a full scale combustor of 0.66 m diameter. Variable geometry dilution ports were incorporated to allow operation of the combustor across the range of conditions between idle (T_{in} = 422 K, T_{out} = 917 K) and cruise (T_{in} = 833 K, T_{out} = 1778 K). Test results showed that the design could meet the program NOx goal of 1.0 g NO_2/kg fuel at a one-atmospheric simulated cruise condition.

17. Key Words (Suggested by Author(s)) Combustor, Exhaust Emissions, Fuel Vaporization, Air/Fuel Mixing, Oxides of Nitrogen	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 70	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF TABLES

FOREWORD

The research and development program described within this report was conducted by the Research Department of Solar Turbines Incorporated, a subsidiary of Caterpillar Tractor Company, under Contract NAS3-20616 with Mr. N.J. Sekas of the Aerothermodynamics and Fuels Division, NASA-Lewis Research Center, as Project Manager.

1

SUMMARY

An atmospheric pressure test rig program was conducted to evaluate the low NOx potential of a full-size, lean, premixed annular combustor designed to constraints typical of current aircraft systems.

Preliminary investigations were conducted with small-scale annular combustors of 21.6 cm (8.5 in.) diameter to define the basic configuration details and to provide a design bridge between the full-size unit and the small-scale can combustors investigated during programs previously reported.

Two advanced types of lean, premixed combustors were evaluated as small-scale annular units, namely, the Vortex Air Blast (VAB) and Jet Induced Circulation (JIC) concepts. The two concepts 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 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 necessary for flame stabilization.

The test program conducted on the JIC and VAB small-scale annular combustors resulted in the VAB combustor demonstrating a lower NOx signature than the JIC combustor and in being able to operate over the full range of conditions between idle and cruise without the requirement for the use of more than one fuel injection system. For these reasons, in addition to packaging constraints, the VAB combustor concept was selected for advancement to the full-size annular combustor design.

The atmospheric testing of the full-size annular VAB combustor on Jet-A fuel demonstrated the capability of operating at a simulated high-altitude supersonic cruise condition with NOx emissions below 1.0 gm/kg fuel. In addition, the testing showed that for the full range of low emissions operation, from idle to cruise, a variable dilution port system is necessary, but that fuel-switching can be avoided and a single fuel injection system used.

2

INTRODUCTION

The impact of gas turbine 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. Within this second area of concern, preliminary findings have indicated that stratospheric nitrogen oxides (NOx) might need to be limited to very low levels if, for example, ozone depletion with concommitant increases in sea-level radiation are to be avoided.

A previous Solar experimental rig study investigated the low NOx potential of two distinct types of forced circulation, lean premixed combustors, namely the Jet Induced Circulation (JIC) and the Vortex Air Blast (VAB) combustors. This work defined both the basic low NOx potential of these two combustors at a simulated high-altitude, supersonic cruise condition, and their operational range limitations. This work was previously reported in NASA CR-134889 (November 1975) and was followed by a second program intended to define range-augmentation techniques. These techniques were to allow the JIC and VAB combustors to operate stably with acceptable emissions at a simulated engine idle without compromise to the low NOx emissions at the high-altitude, supersonic cruise condition. The range-augmentation techniques successfully demonstrated and reported in NASA CR-135297 (October 1977) involved total variable geometry, variable dilution, variable dilution plus fuel switching, and axial fuel staging.

Both of these previous rig investigations were conducted on small-scale can combustors of 12.7 cm (5 in.) diameter to facilitate experimental modifications. It was recognized, however, that an evaluation of a full-size annular combustor configuration would be necessary before a realistic assessment could be made of the potential of the lean premixed combustion system. The work covered in this report summarizes the results of an experimental atmospheric pressure rig test program that had as its objective the extension of Solar's lean premixed combustor background to a full-size annular combustor of 0.66 m (26.0 in.) diameter designed to constraints typical of current aircraft systems. Some preliminary investigations were conducted with small-scale annular combustors of 21.6 cm (8.5 in.) diameter to define the basic configuration details and to provide a design bridge between the full-size and the small-scale can combustors.

The test program on the full-size annular combustor was restricted to atmospheric inlet conditions due to facility limitations. Future high-pressure testing of the full-size annular combustor is planned at a NASA-Lewis Research Center facility.

3

PRELIMINARY TEST PROGRAM - SMALL SCALE ANNULAR COMBUSTORS

To arrive at a full-size annular combustor design, a strategy was selected that involved the testing of small-scale annular combustors in order to establish basic design information and performance limitations.

The preliminary testing was necessary because previous investigations involving the combustion system concepts were carried out with can combustor configurations. The change to annular from can configurations resulted in significant modifications to the basic design and operation of the two concepts, thus a small-scale design bridge was considered necessary before moving to a full-size annular design.

3.1 COMBUSTOR CONCEPTS

The design of the two combustion systems was based on the program operational constraints and background experience from previous investigations (CR-134889 and CR-135297).

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.

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 cooling airflow applied to the combustor liners.

Both combustion systems were tested as straight-through axial flow configurations rather than the reverse flow systems that were adopted for Solar's previous 'proof-of-concept' investigations.

Both combustors are of annular construction with an outside diameter of 21.6 cm (8.5 in.) and an annulus width of 5.0 cm (2.0 in.). In order to utilize an existing rig facility, the exit sections of the combustors were modified to an equivalent can flow by closing the end of the inner liner. An air-cooled spider was used to support the inner liner concentrically with the outer liner.

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

PRECEDING PAGE BLANK NOT FILMED

3.1.1 Jet Induced Circulation (JIC) Combustor

A view of the assembled JIC combustor is shown in Figure 1.

The JIC concept uses a series of external mixing tubes in which to mix the fuel and reaction air. The fuel is vaporized and mixed with the reaction air emerging as a near-homogeneous jet into the reaction zone of the combustor. The jet flow is shown schematically in Figure 2 which contrasts the flow in an annular combustor to that in a can configuration.

In the annular combustor configuration the separate mixing tube jets impinge on the inner combustor liner to form two derived jets. The major derived jet flows upstream into the reaction zone toward the combustor dome, impinges on the dome, and then flows rearwards 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 jets to act as a continuous source of ignition. The remainder of the products flow out of the reaction zone between the mixing-tube jets. The minor derived jet flows rearward from the impingement point and is reacted partially in the secondary zone upstream of the dilution jets and partially by recirculation and entrainment into the mixing-tube jets. The key elements of the design are as follows:

- <u>Fuel Preparation</u>

  The fuel and reaction zone airflow are premixed in a series of eight mixing tubes equally spaced circumferentially around the reaction zone. The flow from the mixing tubes enters the reaction zone as jets inclined at an angle of thirty degrees to the burner axis which flow forward into the reaction zone. The length of the mixing tubes is dictated by fuel/air mixing rate and autoignition considerations but in order to keep within a maximum combustor length constraint the tubes are wrapped helically around the combustor with the inlets situated at the rear of the combustor (Fig. 3).

- <u>Fuel Injection</u>

  Two separate fuel injection systems are incorporated; one for cruise, the other for idle operation. The cruise fuel injection system consists of an air-blast fuel injector positioned at the entrance of each fuel/air mixing tube as shown in Figure 4. Each fuel injector consists of four radial spray bars which inject the fuel concurrently with the airflow through a total of sixteen orifices 0.8 mm (0.032 in.) in diameter.

  For idle operation a pressure-atomizing fuel system is used. This is shown in Figure 5 and consists of a series of eight simplex pressure atomizers mounted in the combustor dome.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

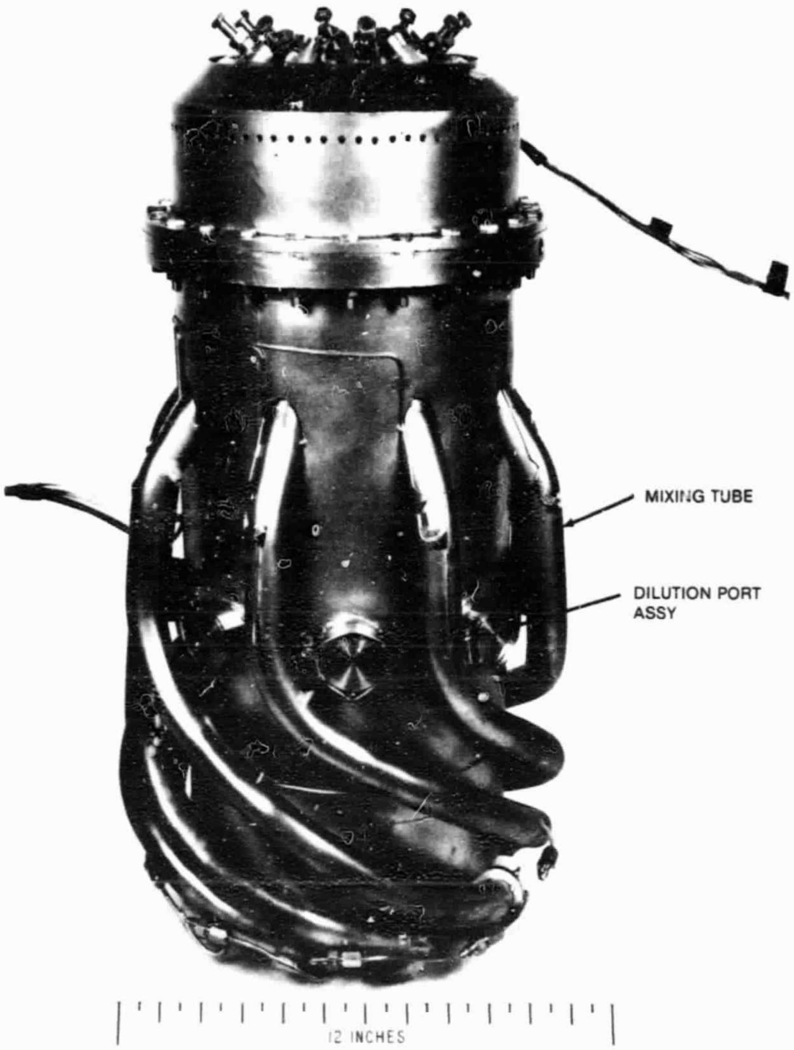

Figure 1. Small Scale Annular Jet Induced Circulation (JIC) Combustor

- Variable Geometry

  Provisions are made in the design for both variable reaction zone and dilution zone geometry. The variable dilution system is shown in Figure 1 where each of the eight dilution ports is associated with a translating plug which controls the effective area of the port. No mechanism is provided; the port setting is fixed prior to the start of each test run. Provision is made for a similar series of translating plugs at the inlet of each mixing tube.

- Wall Cooling System

  The initial design for the JIC liner cooling was a simple convective system as shown in Figure 6. The cooling air is admitted to the

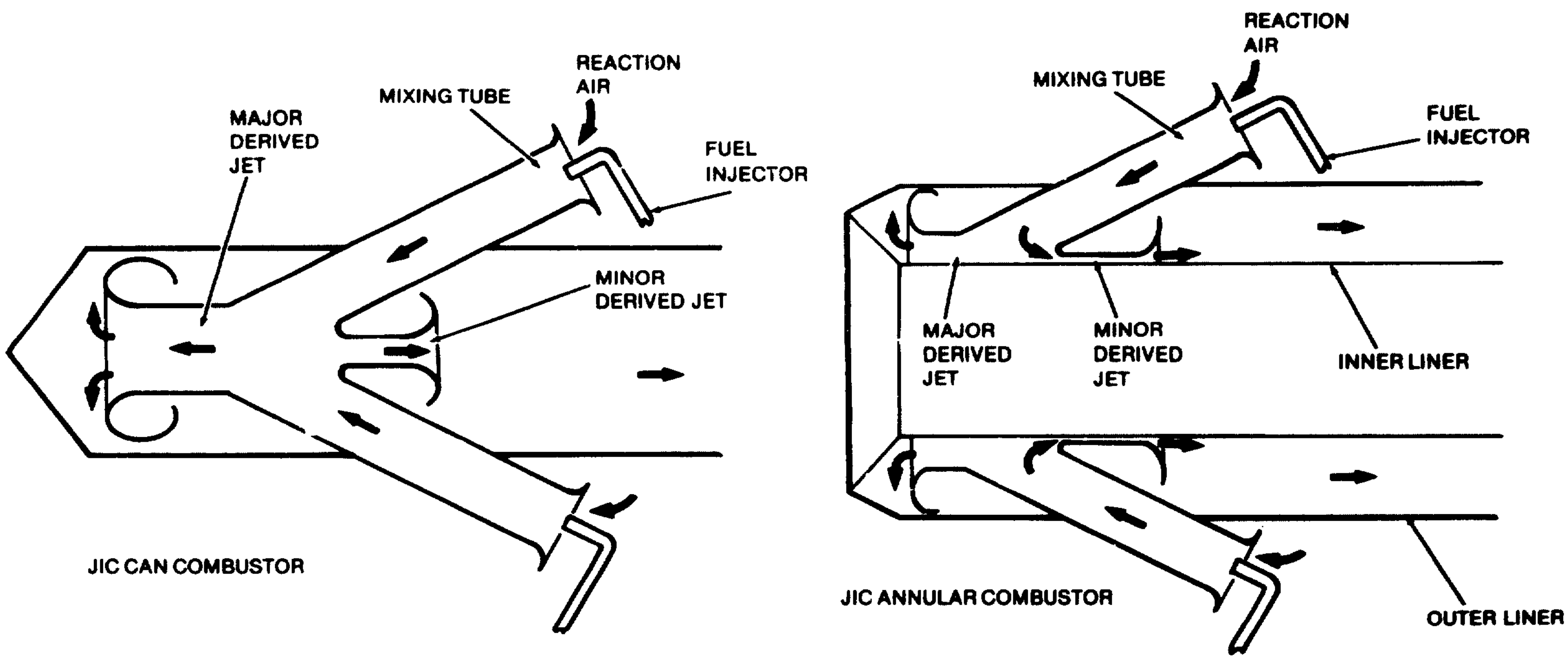

Figure 2. Jet Induced Circulation (JIC) Combustor Jet Flows

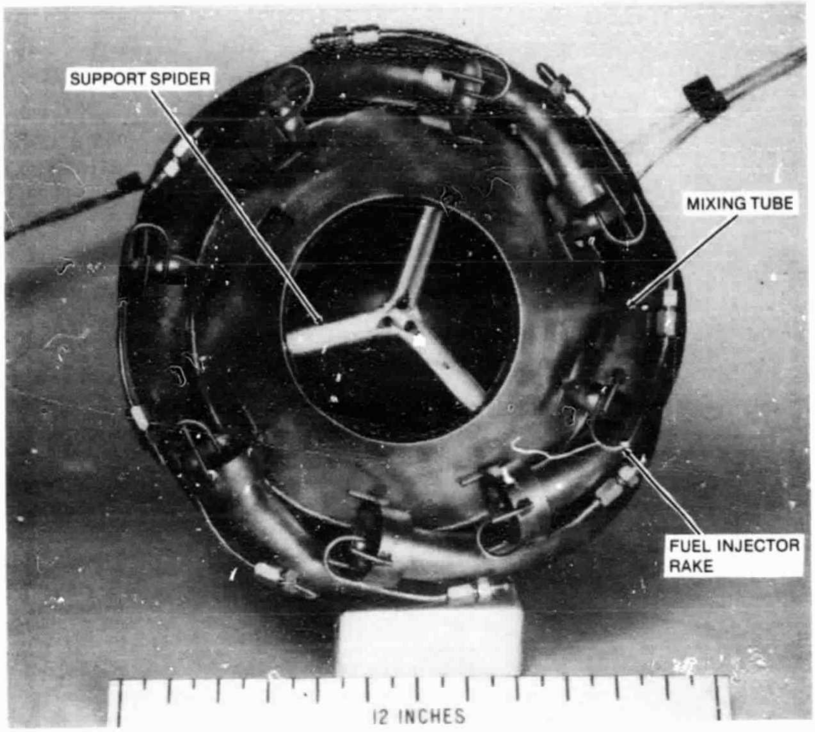

Figure 3. JIC Small-Scale Combustor Mixing Tube Inlets

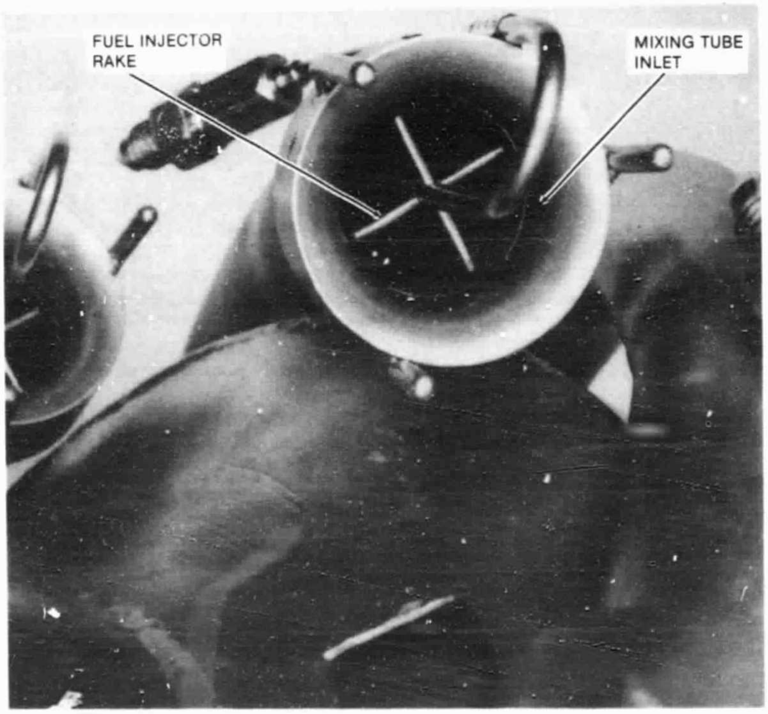

Figure 4. JIC Combustor Fuel Injector for Premixed Operation

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

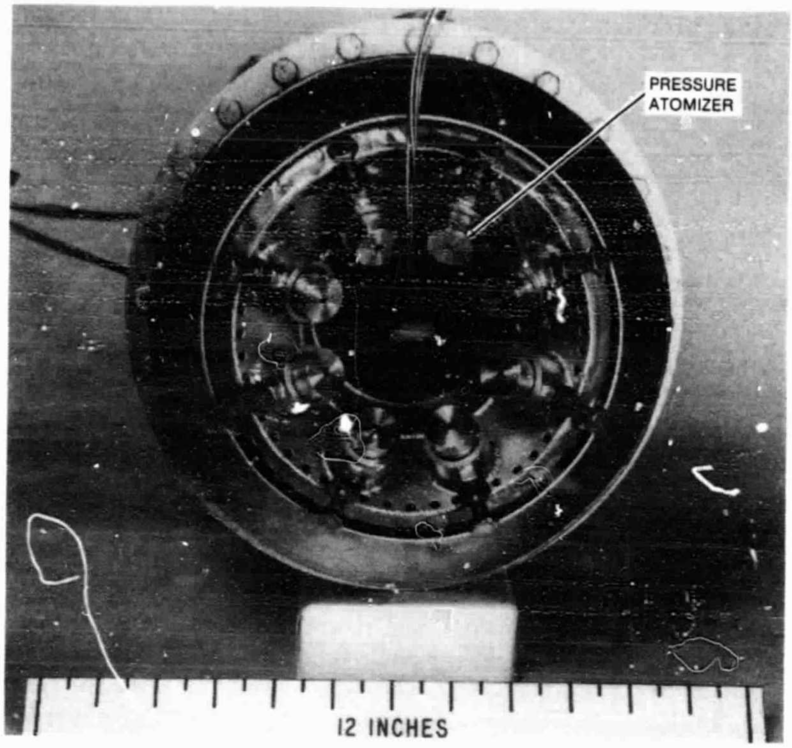

Figure 5. JIC Combustor Pressure Atomizer Installation

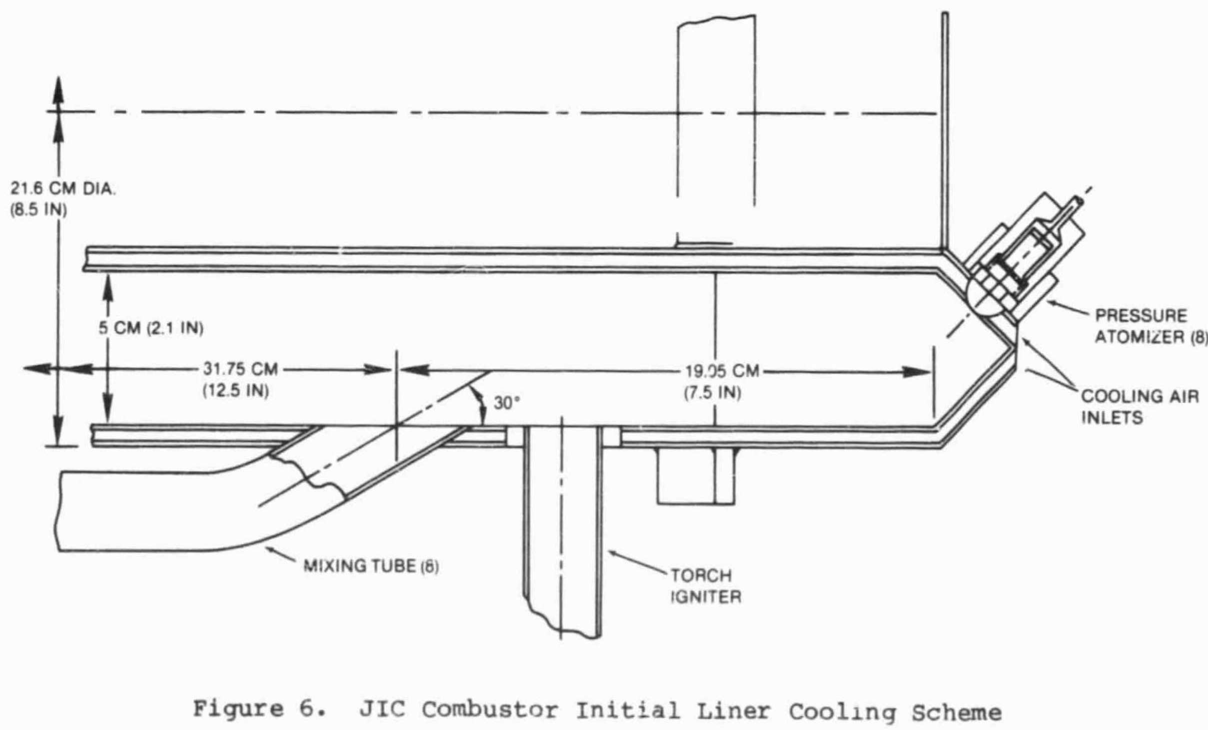

Figure 6. JIC Combustor Initial Liner Cooling Scheme

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

inner and outer cooling annulii at the dome end of the combustor, flows along the length of the combustor, and is discharged into the combustor exhaust at the rear of the liner. The test program resulted in significant modifications to this initial scheme; these will be described in subsequent sections of this report.

- Ignition System

A torch igniter was used for combustor light-o but was turned-off during normal running.

3.1.2 Vortex Air Blast (VAB) Combustor

A view of the assembled VAB combustor is shown in Figure 7.

In the VAB combustor, premixing for cruise operation is accomplished within an axial swirler and channel rather than within a system of mixing tubes as

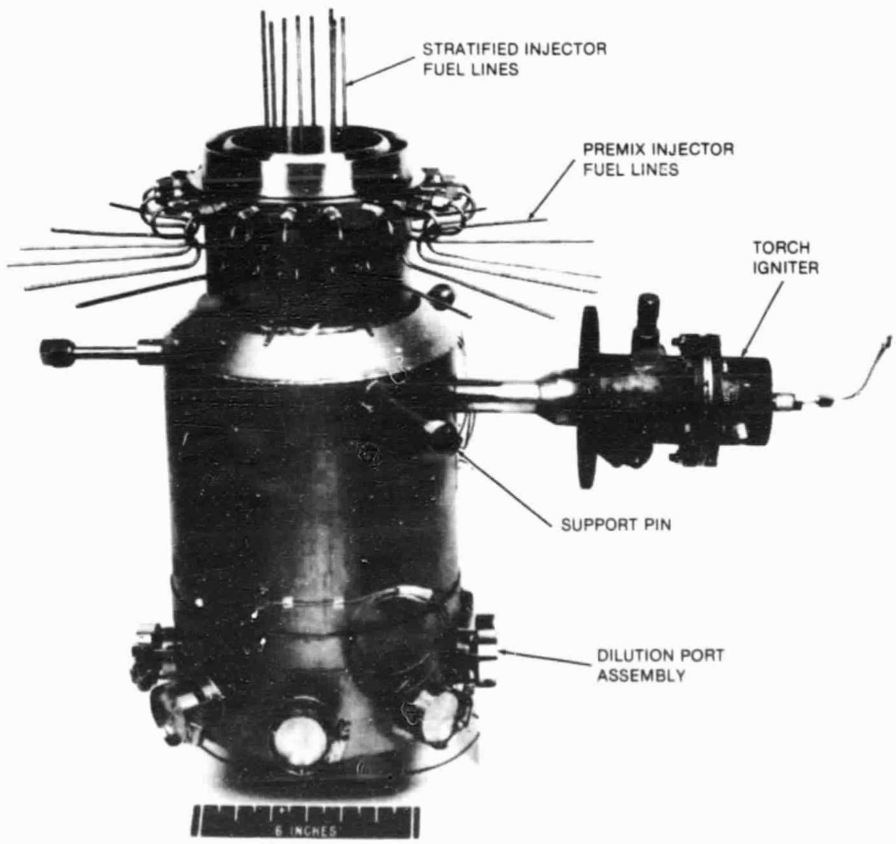

Figure 7. Small Scale Annular Vortex Air Blast (VAB) Combustor

is the case with the JIC combustor. The axial swirler for the annular VAB combustor was a significant departure from the can VAB design that utilized a radial airflow swirler. The annular channel section of the swirler discharges into the reaction zone of the combustor. 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 swirling stream. The radial static pressure gradients produced in the vortex serve to drive the reaction zone recirculation necessary for combustion stabilization.

The key elements of the design are as follows.

- <u>Fuel Preparation</u>

  The fuel and reaction zone airflow are premixed in an axial flow swirler and channel. A view of the swirler inlet is shown in Figure 8. A series of 20 vanes with a pitch/chord ratio of approximately unity are arranged around the swirler channel inlet with an outlet blade angle of 60 degrees. The vaned swirler section is followed by an annular channel that discharges into the combustor reaction zone.

- <u>Fuel Injection</u>

  As in the JIC combustor, two fuel injection systems are incorporated in the VAB combustor; one for cruise, the other for idle operation.

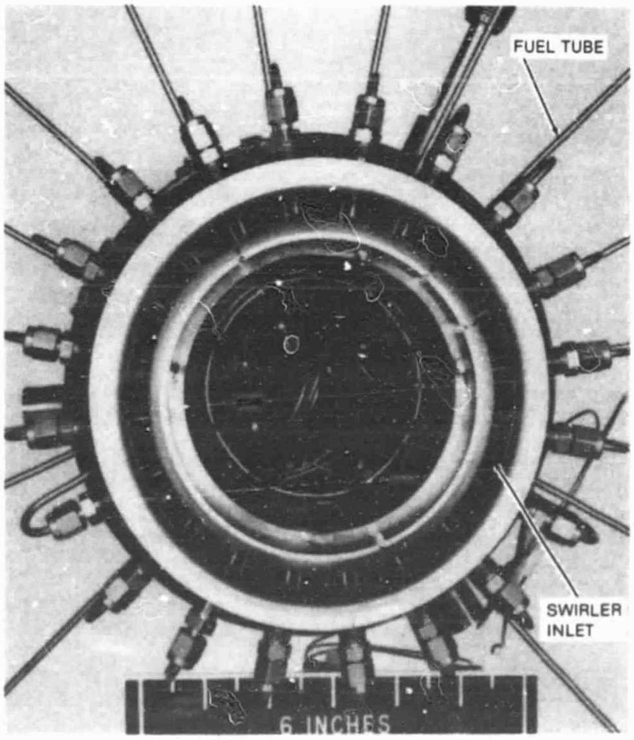

Figure 8. VAB Combustor Swirler Inlet

The cruise fuel injection system consists of a single-point, air-blast fuel injector mounted slightly upstream of the throat section in each of the 20 vane channels as shown in Figure 9. The fuel injection point is positioned a radial distance of 3.2 mm (0.125 in.) from the inner surface of the swirler.

For idle operation, a series of six air-blast fuel injection orifices can be used. These are positioned on the swirler channel inner surface near to the downstream lip as shown in Figure 10.

- Variable Geometry

Provisions are made in the design for both variable reaction zone and dilution zone geometry. The variable dilution system can be seen in Figure 11 and is the same translating plug and port concept that is utilized in the JIC combustor. Reaction zone airflow control can be obtained by changeout of the removable swirl vane ring assembly.

- Wall Cooling System

As with the JIC combustor, the initial design for the VAB cooling scheme was a simple convective scheme. The test program resulted, however, in significant modifications to this original design. Air was initially admitted to the convective cooling inner and outer annulii at the upstream section of the combustor and discharged over the closed end of the inner liner and at the rear of the outer liner as shown in Figure 10. The closed end of the inner liner and the support spider are shown in Figure 12.

- Ignition System

A torch igniter protruding into the combustor reaction zone was used for the combustor light-off but was turned off during normal running. The torch igniter can be seen in Figure 7.

3.2 TEST FACILITY

3.2.1 Flow Path

A schematic of the test rig facility is shown in Figure 13. 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.

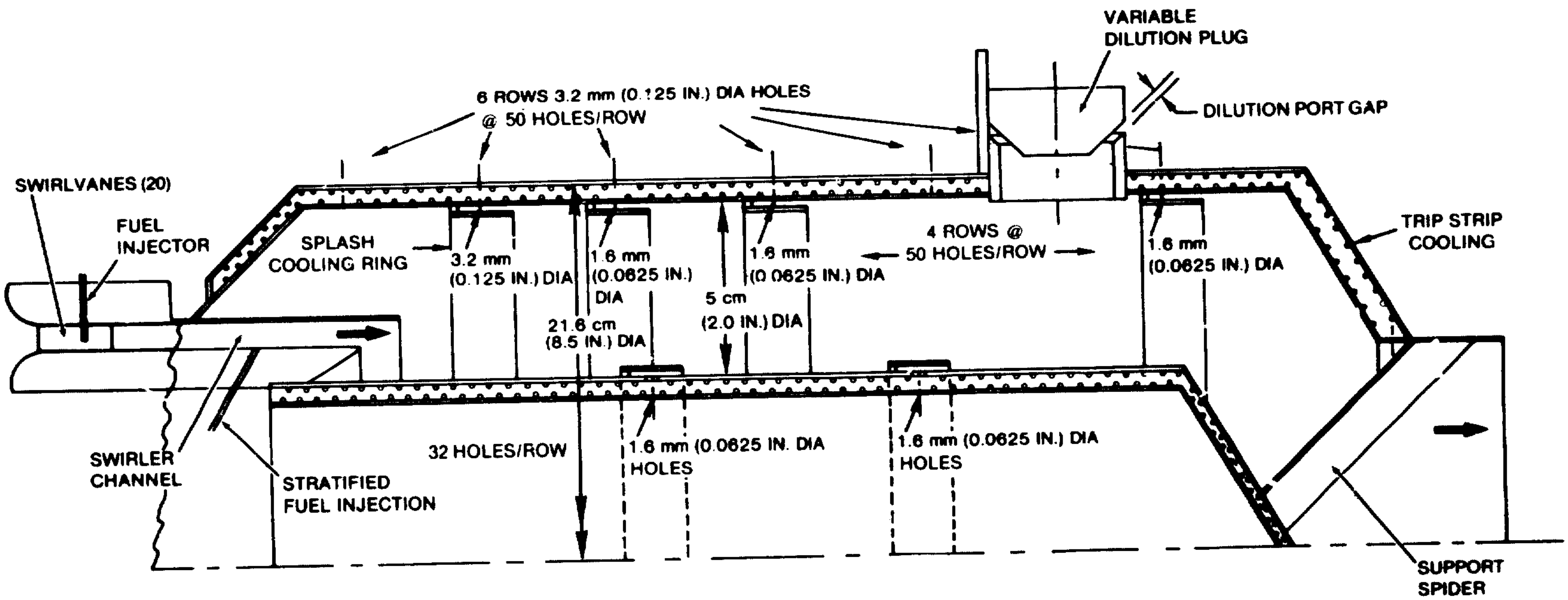

Figure 9. VAB Combustor Section

OF POOR QUALITY

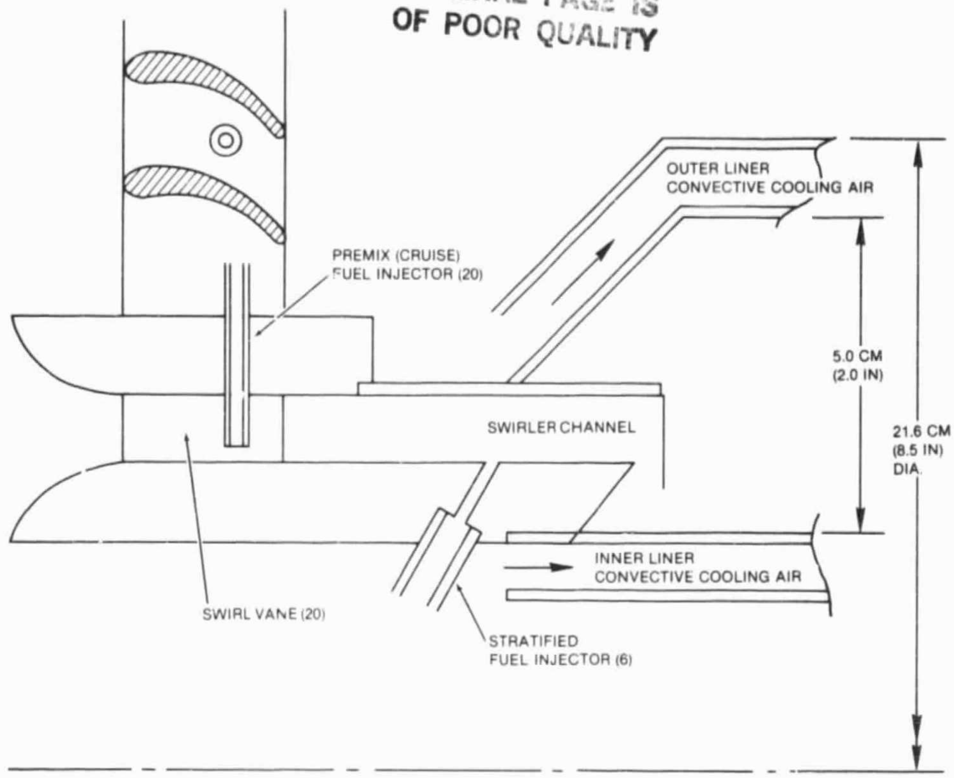

Figure 10. VAB Combustor - Fuel Injection Systems

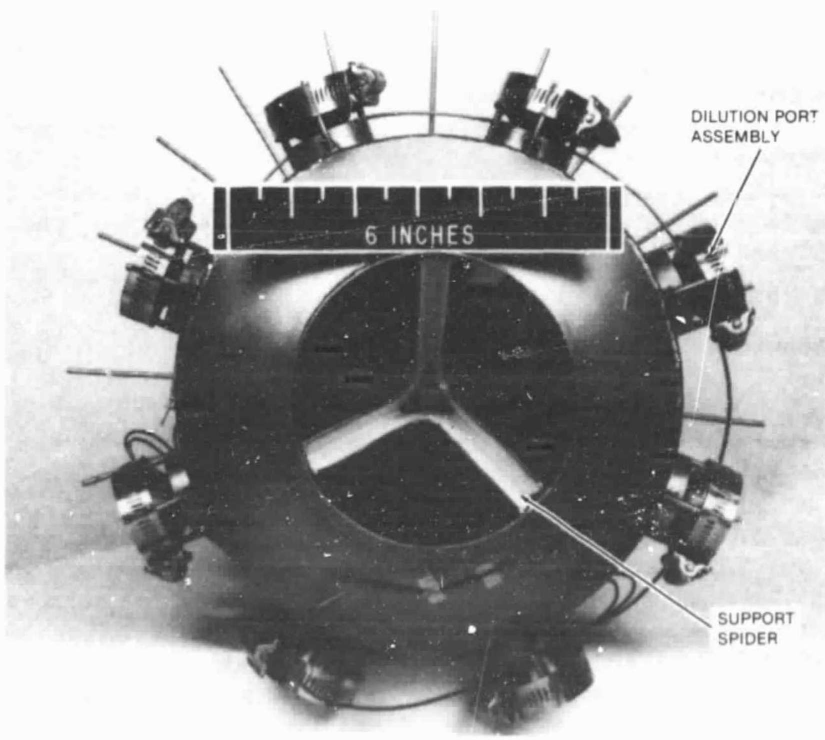

Figure 11. VAB Combustor Variable Dilution Ports

ORIGINAL PAGE IS
OF POOR QUALITY

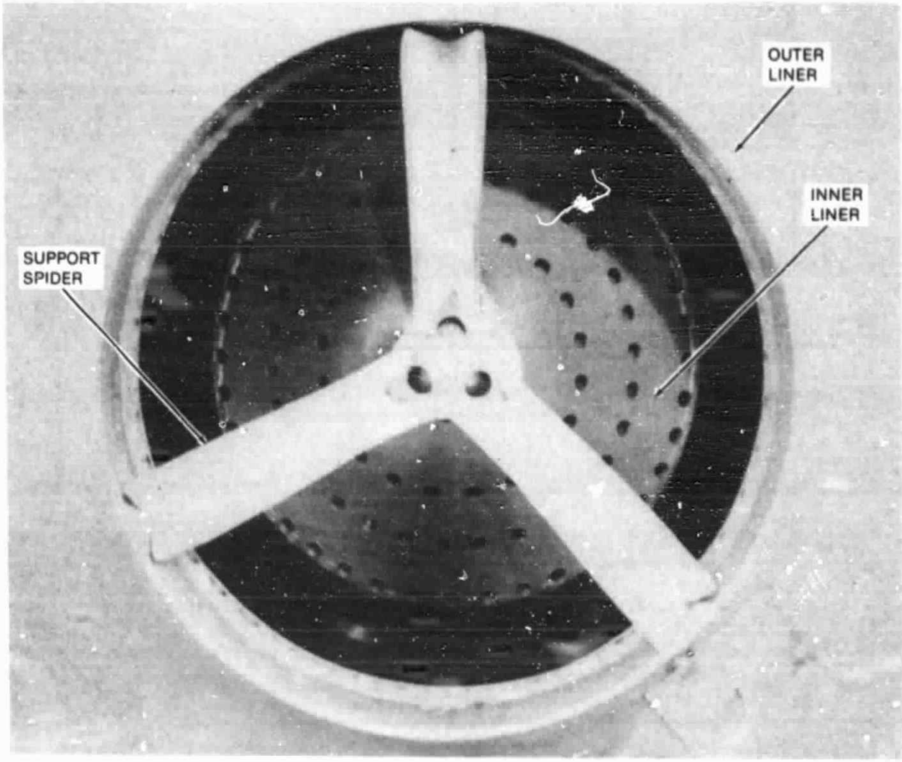

Figure 12. VAB Combustor Inner Liner and Support Spider

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.

3.2.2 Instrumentation

The various instrumentation stations are shown for reference in the rig flow path schematic of Figure 13.

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 pressure loss 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.

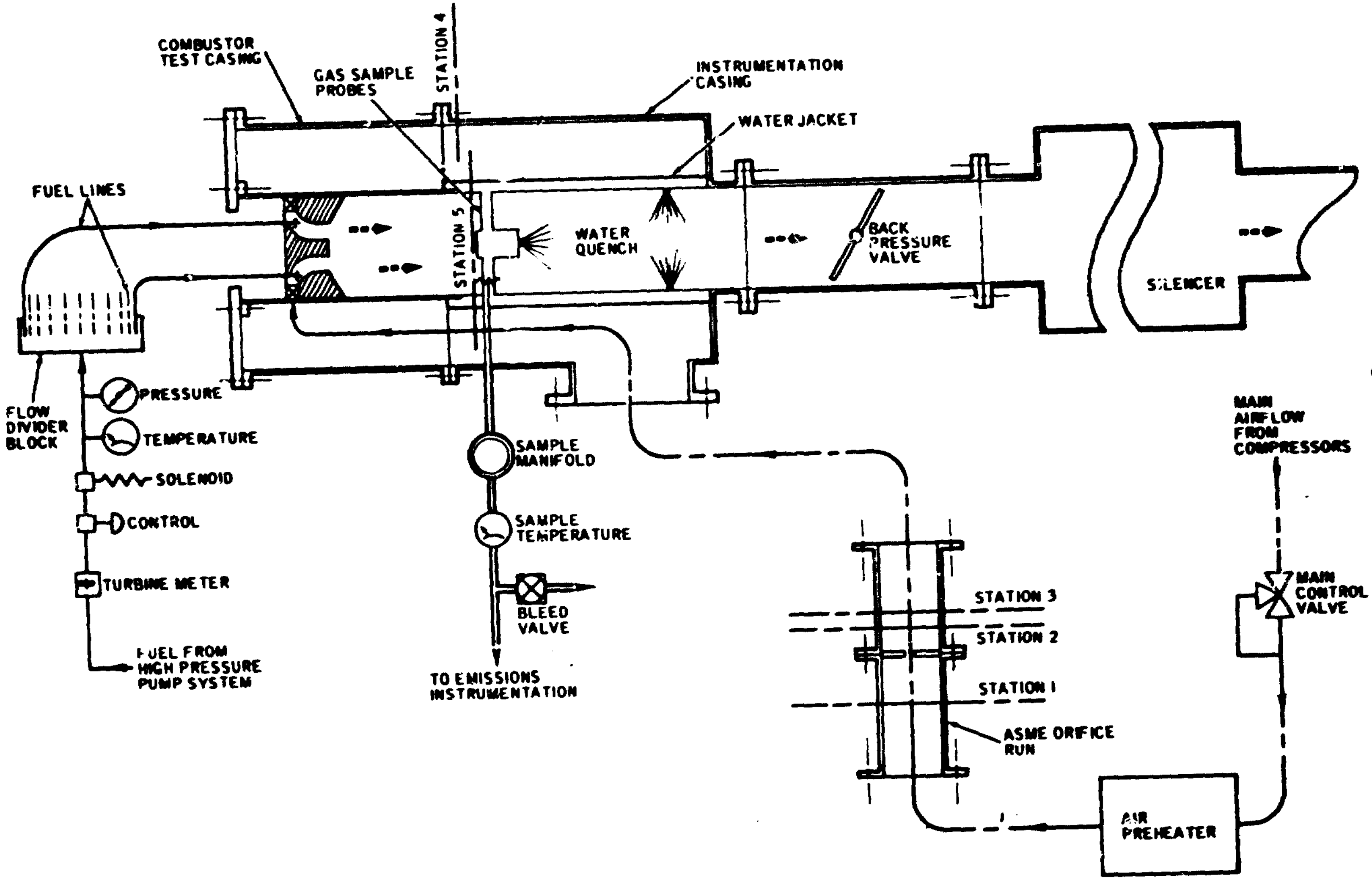

Figure 13. Test Rig Schematic

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 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 calibrated flow divider block.

The combustor inlet pressure and temperature are measured at station 4. 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 temperatures 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 three, water-cooled, diameter probes with twelve area-weighted sample points on each.

The samples from each of the probes 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 (350°F) 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 five percent as a result of the normally low-humidity conditions of the air supplied to the rig.

3.2.3 Test Procedure

The test procedure adopted during the program was to establish the required levels of combustor inlet temperature, pressure and mass flow. 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.

3.2.4 Test Conditions and Performance Goals

The test conditions and performance goals for the two combustors were identical. The combustors were characterized by testing at two discrete operating points, namely, cruise and idle.

The simulated cruise test point conditions and emissions goals for Jet-A1 fuel are shown in Table 1. The corresponding idle test point conditions and emissions goals are shown in Table 2.

Table 1

Test Conditions and Emissions Goals - Cruise

Test Conditions	Emissions Goals (g/kg fuel)
P_{in} = up to 1034.2 kPa (150 psia)	NOx - 1.0
T_{in} = 833 K (1500 R)	CO - 1.0
T_{out} = 1778 K (3200 R)	UHC - 0.5 Smoke - 15 SAE

Table 2

Test Conditions and Emissions Goals - Idle

Test Conditions	Emissions Goals (g/kg fuel)
P_{in} = up to 1034.2 kPa (150 psia)	CO - 20.0
T_{in} = 422 K (760 R)	UHC - 4.0
T_{out} = 917 K (1650 R)	

3.3 TEST RESULTS AND DISCUSSION

The following sections of the report contain a summary of the test program conducted on the small-scale JIC and VAB annular combustors.

3.3.1 VAB Combustor

The initial test runs on the small-scale, annular VAB combustor revealed excessive inner and outer liner metal temperatures. Typical NOx characteristics are shown in Figure 14 where the broken lines represent exponential extrapolations after reaching liner temperatures of 1339 K (1950°F). The results indicated that the effect of combustor inlet pressure on the NOx emissions was minimal and that the program NOx goal of 1.0 gm/kg fuel could probably be attained if the liner cooling problem could be resolved.

The initial idle point testing was conducted using the full number of premixed (cruise) fuel injectors. A series of dilution port settings was evaluated. The results are shown in Table 3.

As the dilution port gap was increased, the reaction zone equivalence ratio is increased for a constant combustor outlet temperature and the temperature at which the CO characteristic passes through the goal (20 gm/kg fuel) was decreased. Although the final test point missed the idle design point slightly, the results clearly showed that the combustor could operate at idle in a "variable-dilution only" mode without the use of fuel switching, i.e., using the same fuel injection system as for the cruise operation.

Circumferential fuel staging was attempted on the premixed fuel injectors by selectively reducing the number of injectors fueled on an equi-spaced basis. The reaction zone with zero dilution was tested with the results shown in Table 4.

ORIGINAL PAGE IS
OF POOR QUALITY

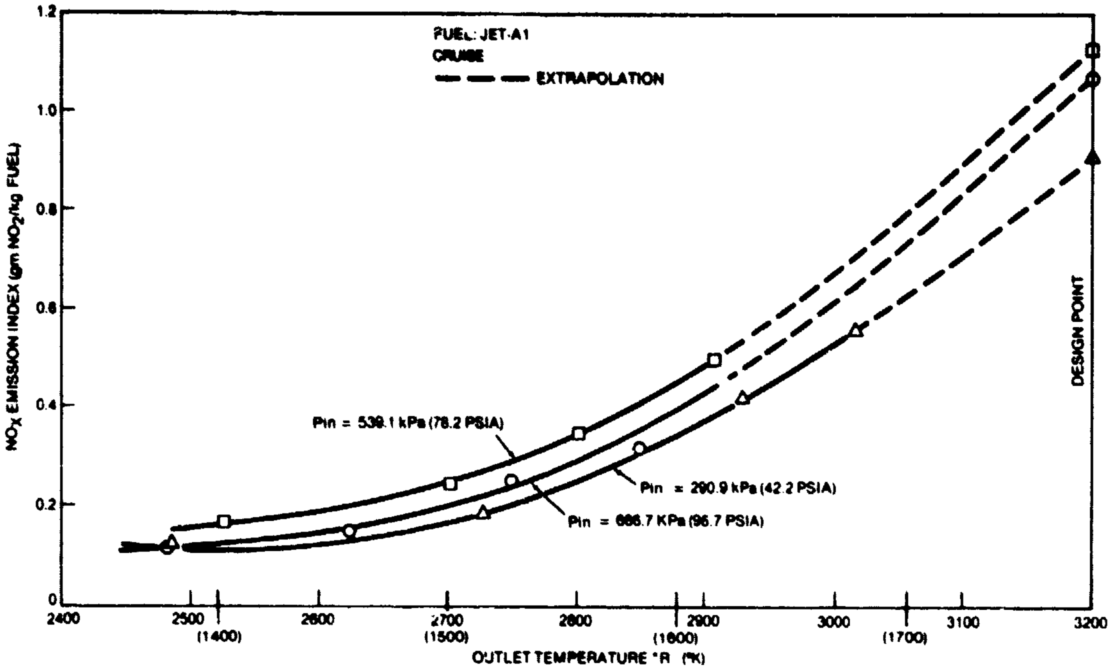

Figure 14. VAB Combustor NOx Test Results - Cruise

Table 3

VAB Test Results

Idle - 20 Premixed Fuel Injectors	
Dilution Port Gap - mm	Combustor Oulet Temperature for CO = 20 gm/kg Fuel
zero (reaction zone)	1267 K (2280°R)
2.36	1028 K (1850°R)
3.86	944 K (1700°R)

The results showed that there was little difference in the reaction zone CO (or NOx) characteristics between fuel injection at the full number of premixed fuel injectors and a much reduced number of points due to the presumably rapid mixing of fuel/air in the swirler channel. Circumferential fuel staging could therefore be made to operate in conjunction with variable-dilution at idle although there would be no positive advantage to such a system.

Fuel switching was evaluated by injecting the idle fuel at a total of eight air-blast points close to the final inner lip of the swirl channel. The reaction zone test result is shown in Table 5.

Table 4

VAB Test Results

Reaction Zone - VAB	
Idle - Premixed Fuel Injectors	
Number of Injectors	Combustor Outlet Temperature for CO = 20 gm/kg Fuel
20	1267 K (2280°R)
10	1292 K (2325°R)
4	1306 K (2350°R)

The tests showed that with a stratified type of fuel injection the combustor possessed excellent flame stability at the idle inlet conditions. No distinct flame-out point was found with combustion occurring down to essentially zero fuel flow. Inspection of the combustor after test showed a sooty region in the volume between the inner lip and the swirler channel inner lip; a portion of the idle fuel flow was apparently entrained into the eddy in this zone and acted as a pilot flame.

Although the flame stability was excellent, the stratified fuel injection gave a higher CO characteristic. This can be seen from Table 5 where the limiting CO temperature with stratified fuel injection is higher than for the premixed fuel injection.

Several developmental modifications were applied to the VAB combustor in an effort to improve the liner temperature situation. These included axial corrugated fins in the convective cooling annulii, progressive addition of cooling air to the cooling annulii, and 'trip strips' to augment the convective heat transfer in the cooling annulli. Some improvement in the liner cooling situation was made with each modification although none were successful in allowing operation of the combustor at the cruise design outlet temperature of 1778 K (3200°R).

Table 5

VAB Test Results

Reaction Zone - VAB - Idle	
Fuel Injection	Combustor Outlet Temperature for CO = 20 gm/kg Fuel
Premixed (20)	1267 K (2280°R)
Swirl Channel Inner Lip (8)	1350 K (2430°R)

The final successful liner cooling scheme for the VAB combustor is shown in Figure 15. The design incorporates selective film cooling of the inner and outer liners in addition to retaining the augmented 'trip strip' convective cooling scheme previously tested.

The combustor was retested at the cruise condition resulting in the characteristic shown in Figure 16. The liner cooling modifications allowed operation of the combustor at the design outlet temperature of 1778 K (3200°R) with a NOx emissions level of 3.7 gm/kg fuel. The corresponding CO and UHC levels were found to be 0.5 gm/kg fuel and 0.2 gm/kg fuel, respectively, both within the program goal. The test was conducted at a pressure of 517 kPa (75 psia) with no evidence of autoignition.

Cold flow tests conducted prior to the cruise test had shown that the addition of the film cooling system to the inner and outer liners had resulted in a further 18 percent of the total airflow being utilized for liner cooling. The increase in cooling air results in a concommitant decrease in primary (swirler) air flow which in turn causes higher primary reaction zone temperatures and hence NOx emissions.

A retest of the combustor at the idle conditions revealed that the addition of the film cooling air had resulted in a deterioration in the stability characteristics. At the same dilution port gap as previously tested, the CO goal of 20 gm/kg fuel was exceeded at the design point outlet temperature of 917 K (1650°R). This can be seen in Figure 17. It is thought that the stability deterioration occurred mainly because the inner liner film cooling arrangement injects cooling air in a direction opposite to the bulk recirculation flow thus tending to reduce recirculation rates.

As a demonstration of the tradeoff between design point NOx levels and the total cooling flow a final test was conducted on the small-scale VAB combustor where the film cooling airflow was reduced from the original level. As anticipated, due to the reduction of cooling air flow, the maximum outlet gas temperature was limited to 1611 K (2900°R) by the liner metal temperatures encountered. As a comparison the NOx emission level at this temperature was

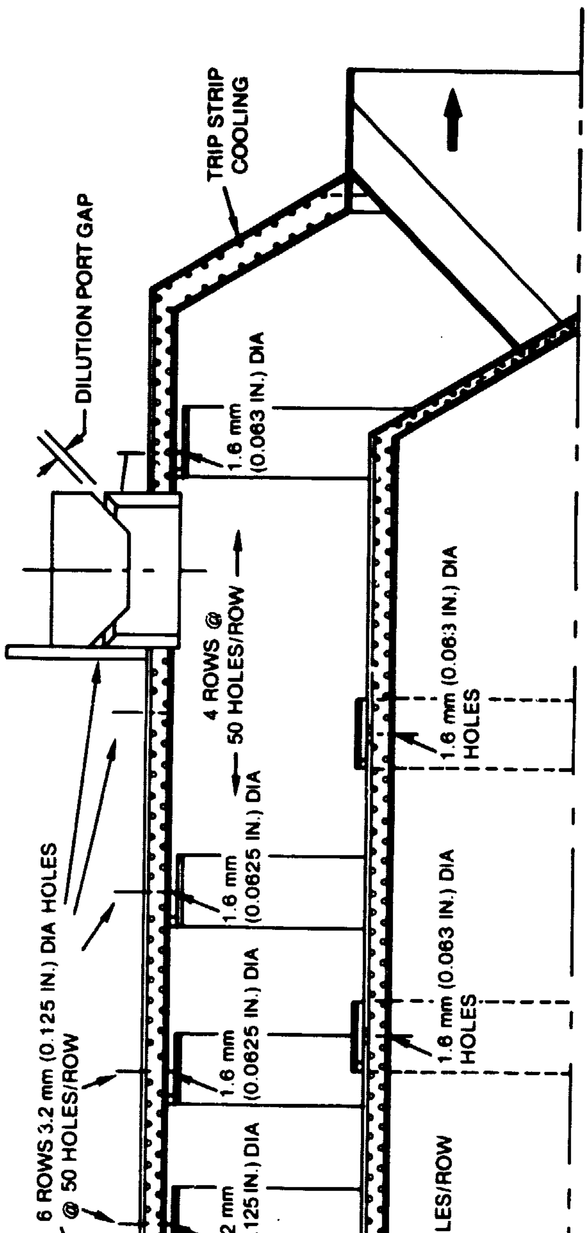

Figure 15. Final VAB Combustor Cooling Scheme

ORIGINAL PAGE IS
OF POOR QUALITY

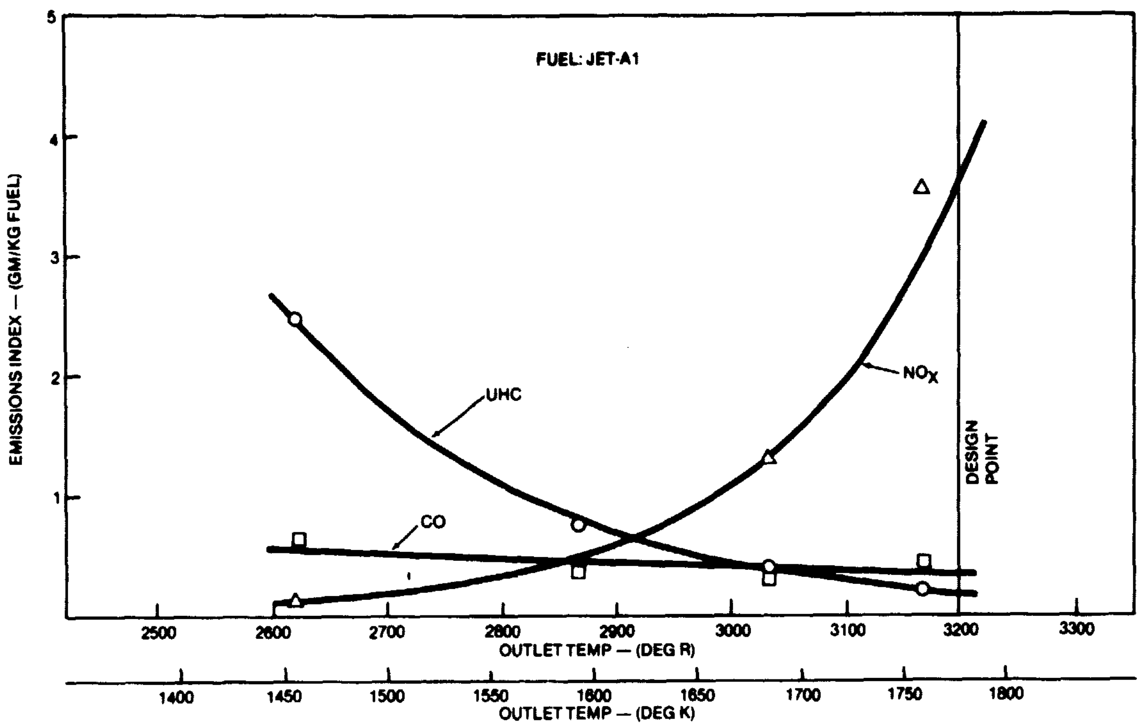

Figure 16. VAB Combustor Cruise Test Results - Final Cooling Configuration

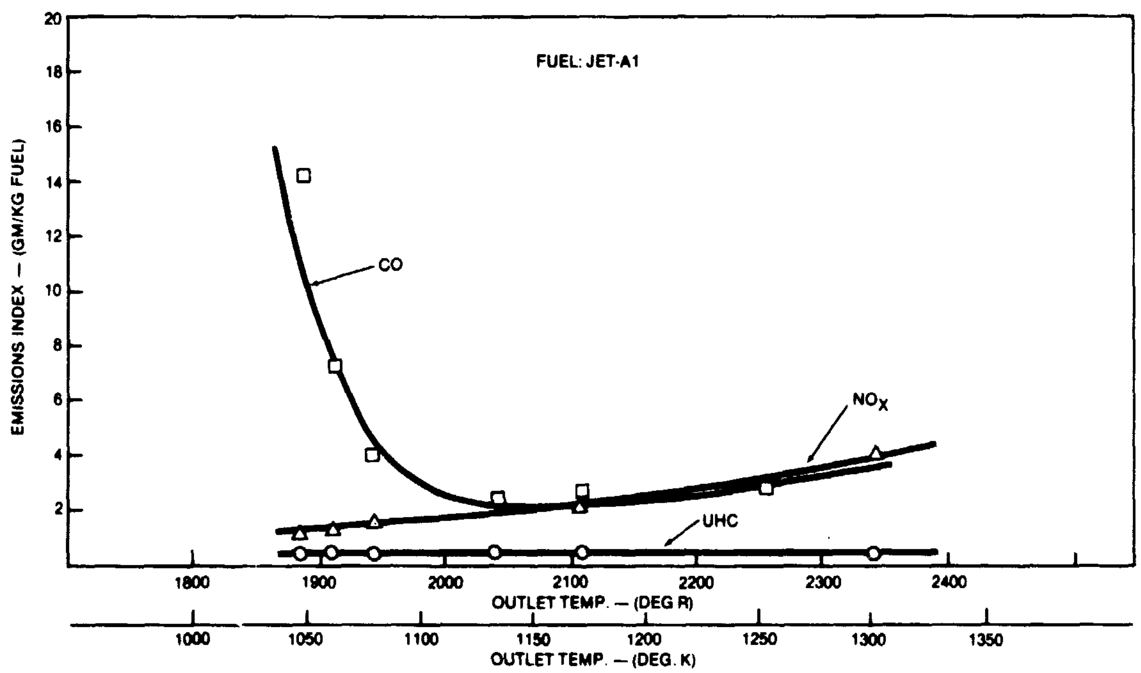

Figure 17. VAB Cooling Idle Test Results - Final Cooling Configuration

0.35 gm/kg fuel compared to a level of 0.6 gm/kg fuel at the same temperature prior to the reduction in film cooling air flow.

At this point in the test program, it was decided that sufficient design and operational test data were available for the selection of the full-size combustor design and no further testing of the small-scale VAB combustor was performed.

3.3.2 JIC Combustor

Because testing of the JIC combustor was started after some test results from the VAB combustor were available, a liner cooling problem was anticipated on the JIC and an interim modification to the cooling system was adopted before the initial tests took place. This consisted of a progressive addition of the convective cooling air along the length of the inner and outer annulii rather than admitting the total airflow at the combustor dome.

The resulting cruise NOx characteristic at a combustor inlet pressure of (50.7 psia) is shown in Figure 18 showing an extrapolated level of 3.0 gm/kg fuel at the design point cruise outlet temperature of 1778 K (3200°F). Test data could not be obtained above combustor outlet temperatures above 1700 K (2600°F) due to excessive inner liner metal temperatures.

Operation was possible at the idle test point with the dilution ports opened using the premix-type cruise injection system but the CO and UHC emissions were far in excess of the program goals.

The development modifications to the JIC combustor were concentrated around the resolution of the liner temperature problem. No completely satisfactory solution was arrived at due to schedule constraints. The final configuration is shown in Figure 19 where splash cooling rings were installed on the inner liner in the area where maximum liner metal temperatures had been observed near to the mixing tube impingement point.

The cruise test point result for this configuration is shown in Figure 20. Although data were obtained up to the design point outlet temperature of 1778 K (3200°R) liner temperatures were still marginal and the NOx emission level is seen to be 12.2 gm/kg fuel. Subsequent inspection of the combustor disclosed reaction zone warpage which would have resulted in the mixing tube operating at a higher equivalence ratio than the design level which might have partially accounted for the high NOx levels.

The corresponding idle test point conditions are shown in Figure 21 which were obtained with the dilution ports open and using the dome-mounted pressure atomizers.

It can be seen that both the CO and UHC levels are below the goals of 20 gm/kg fuel and 4 gm/kg fuel, respectively. No smoke was observed at the design idle temperature of 1172 K (1650°R) and no carbon deposits were found in the combustor.

ORIGINAL PAGE IS
OF POOR QUALITY

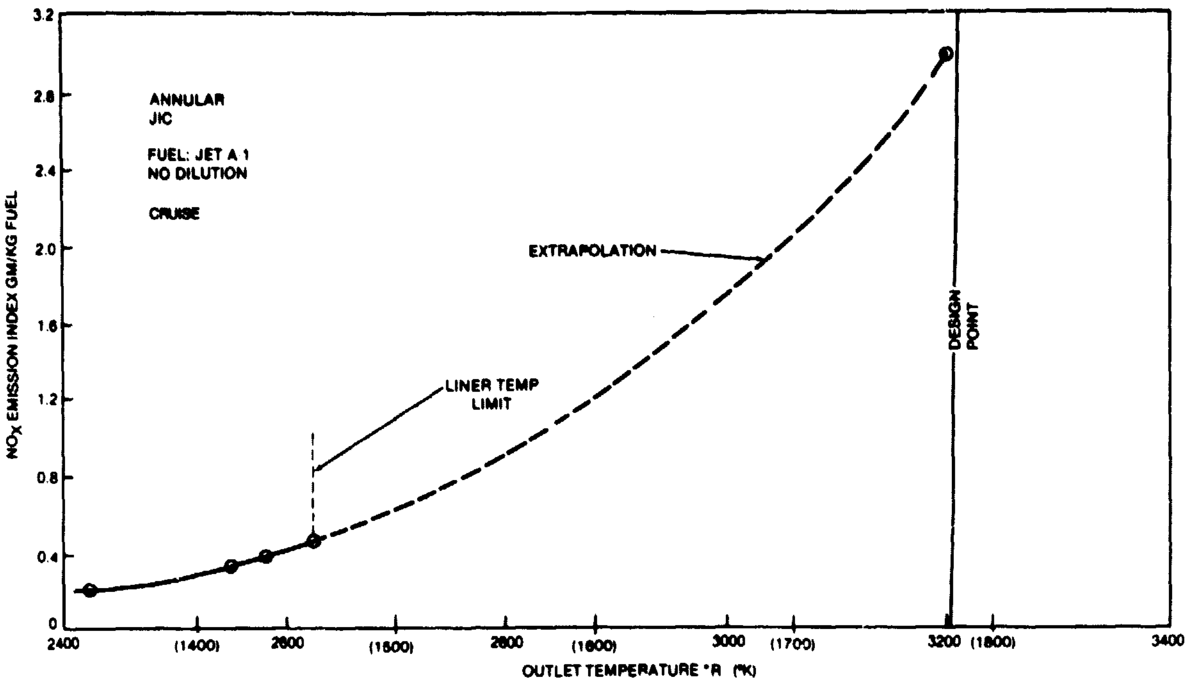

Figure 18. JIC Combustor - Cruise Test Results

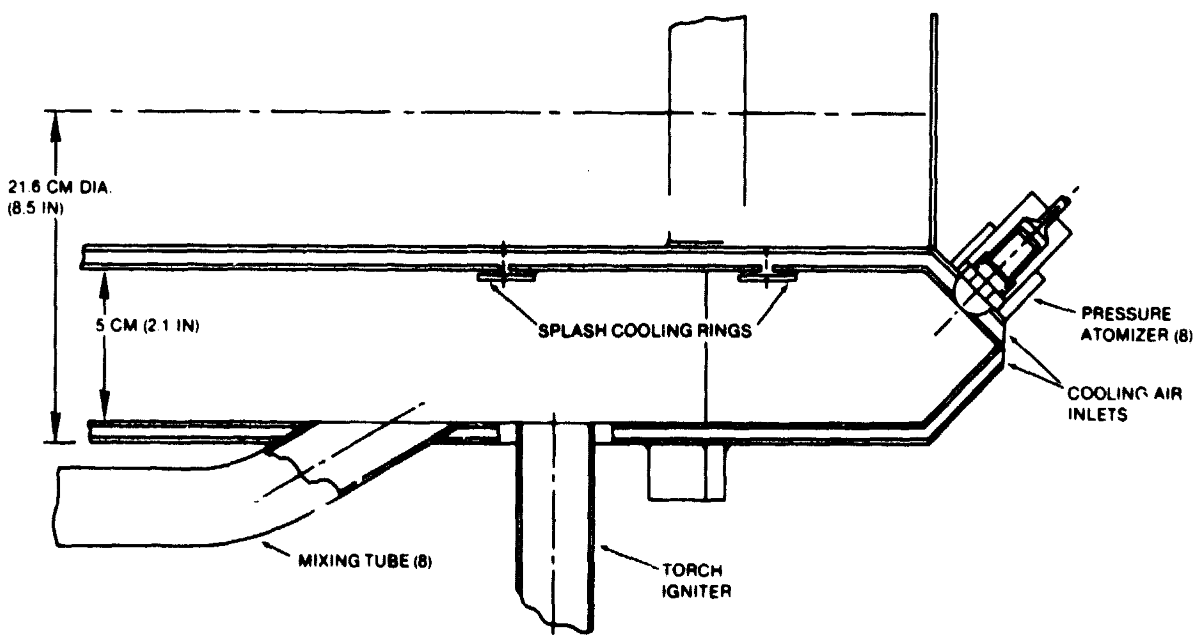

Figure 19. JIC Combustor Final Liner Cooling Scheme

ORIGINAL PAGE IS
OF POOR QUALITY

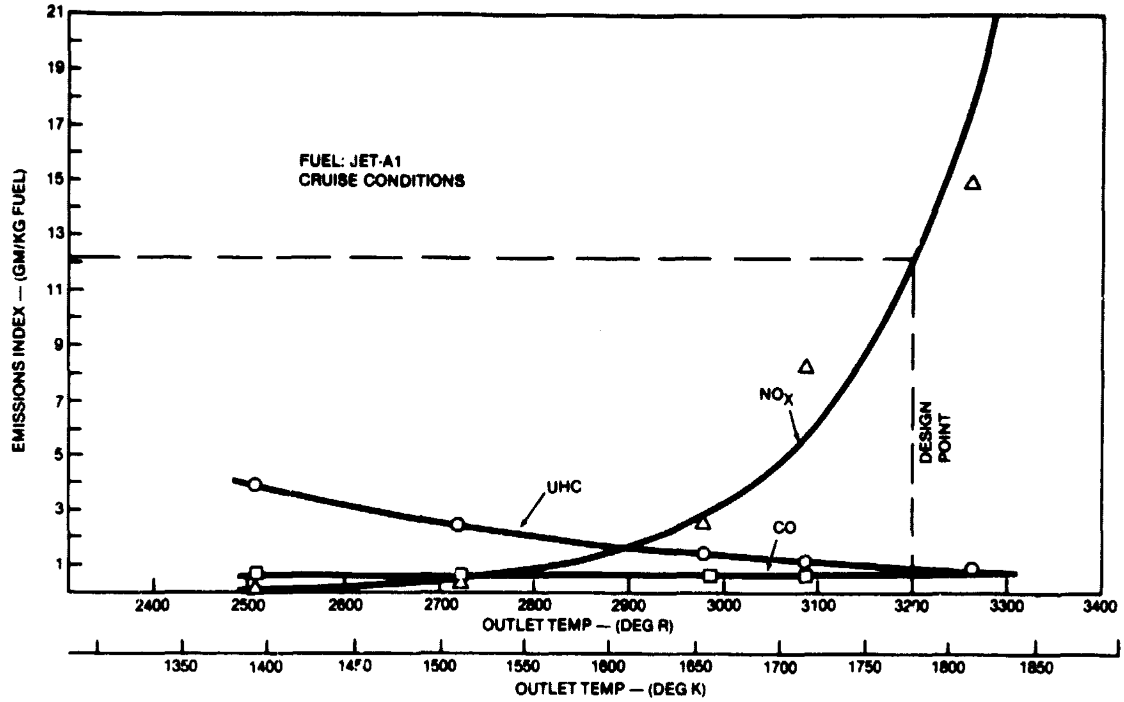

Figure 20. JIC Combustor Cruise Tests at Design Outlet Temperature - Final Cooling Scheme

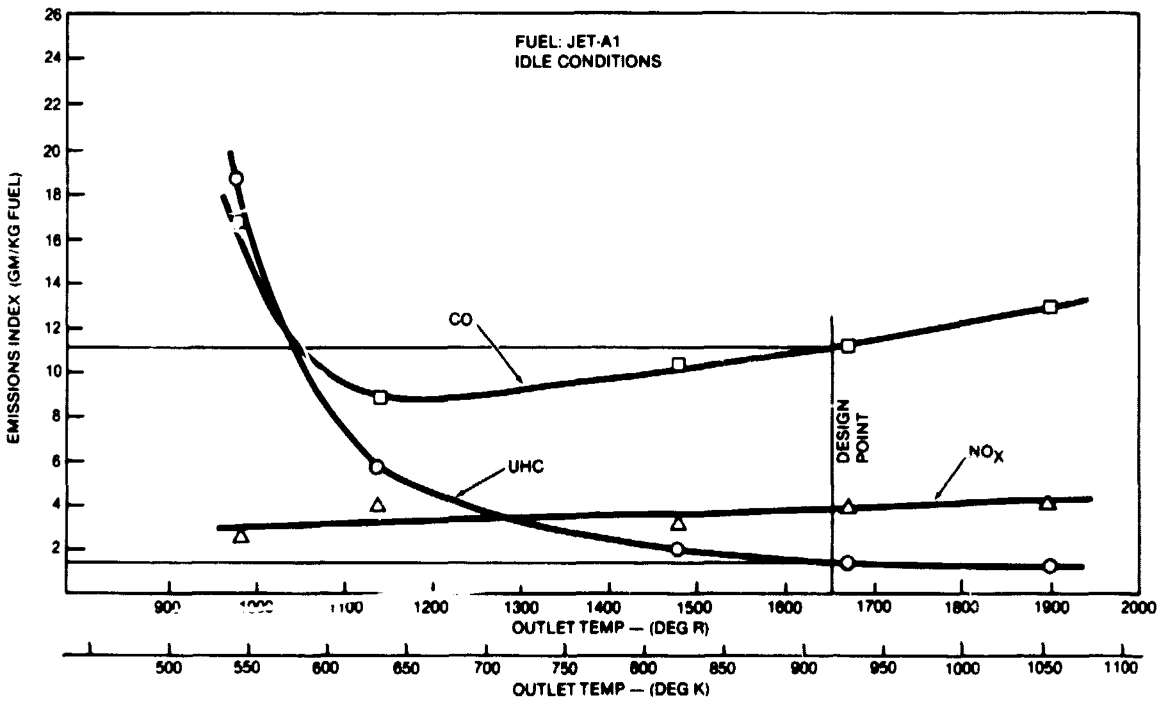

Figure 21. JIC Combustor Idle Test - Final Cooling Scheme

3.4 CONCEPT SELECTION FOR FULL-SIZE ANNULAR COMBUSTOR

At the completion of the small-scale annular combustor test phase the results of the JIC and VAB combustors were compared in order to select a preferred concept for the full-size combustor design.

The comparison resulted in the selection of the VAB concept for the full-size annular design for the following reasons:

- NOx Emissions

  Although both the JIC and VAB combustors experienced identical wall cooling problems, the VAB combustor demonstrated the potential of a cruise NOx level close to the program goal if the wall cooling could be minimized. In contrast, the NOx emissions of the JIC combustor were an order of magnitude higher at approximately 12.0 gm/kg fuel. In addition, the VAB combustor test results showed that the NOx emissions were relatively insensitive to combustor inlet pressure.

- Fuel Switching

  The VAB combustor demonstrated the ability to run satisfactorily at both the cruise and idle test points using the same fuel injection system. The JIC combustor required the use of an alternate, dome-mounted set of pressure atomizers in order to operate at the idle condition. The use of fuel switching represents an undesirable increase in the level of complexity associated with the fuel and control systems.

- Packaging

  Although not related to the test results, an examination of the final JIC and VAB small-scale annular combustor configurations showed that the VAB combustor was more amenable to packaging within conventional axial-flow aircraft gas turbine envelope constraints than the JIC combustor which is inherently a reverse flow configuration.

4
TEST PROGRAM - FULL SCALE ANNULAR VAB COMBUSTOR

4.1 COMBUSTOR CONCEPT

The combustor concept selected for the full-size experimental investigations was the Vortex Air Blast (VAB) system. The design was based on physical and operational constraints, background experience from Solar's previous test programs on this type of combustor, and with the results of the preliminary small-scale annular combustor investigations.

As a cost-effectiveness measure, Solar's earlier programs were conducted with reverse-flow can combustor configurations. The full-size VAB combustor was designed as an axisymmetric axial-flow annular system in keeping with current practice in advanced aircraft gas turbine combustion systems.

A section through the VAB combustor installed in the rig facility is shown in Figure 22 where the key features of the design can be seen. The general design strategy was to provide a combustor with a variable dilution system where at the cruise condition the dilution ports would be closed and the reaction zone equivalence ratio minimized. At the idle condition the dilution ports would be fully opened to obtain the necessary stability.

4.1.1 Swirl Stabilization

Solar's previous small-scale VAB can combustor designs were based on a radial inflow swirler to provide combustion stabilization. The full-size VAB unit retains the feature of swirl stabilization but an axial swirler, rather than a radial inflow design, is adopted. This feature results in a more effective integration of the combustor with the inlet flow. A front view of the combustor showing the swirler inlet is shown in Figure 23. The swirler consists of forty vanes set at an outlet angle of 60 degrees with a pitch/chord ratio of approximately unity.

4.1.2 Fuel Injection

The fuel injection system was the subject of much of the experimental effort and the initial configuration is shown in Figure 24. A radial air-blast fuel injector rake is installed in each of the forty swirl vane channels at a station slightly upstream of the channel throat. A view of a typical fuel injector rake is shown in Figure 25. Each rake is 1.57 mm (0.062 in.) diameter

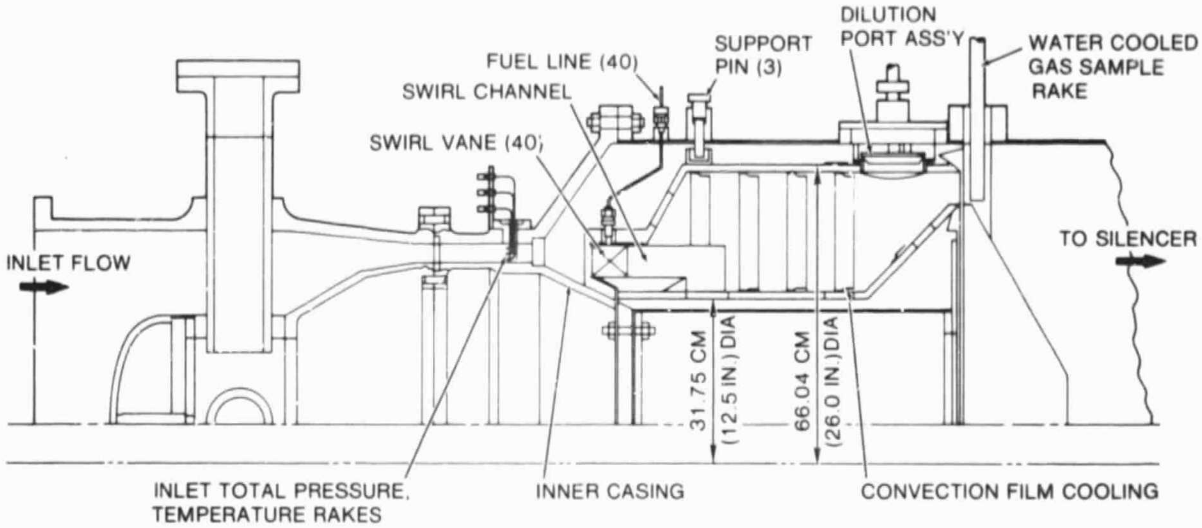

Figure 22. Full Size Annular VAB Combustor

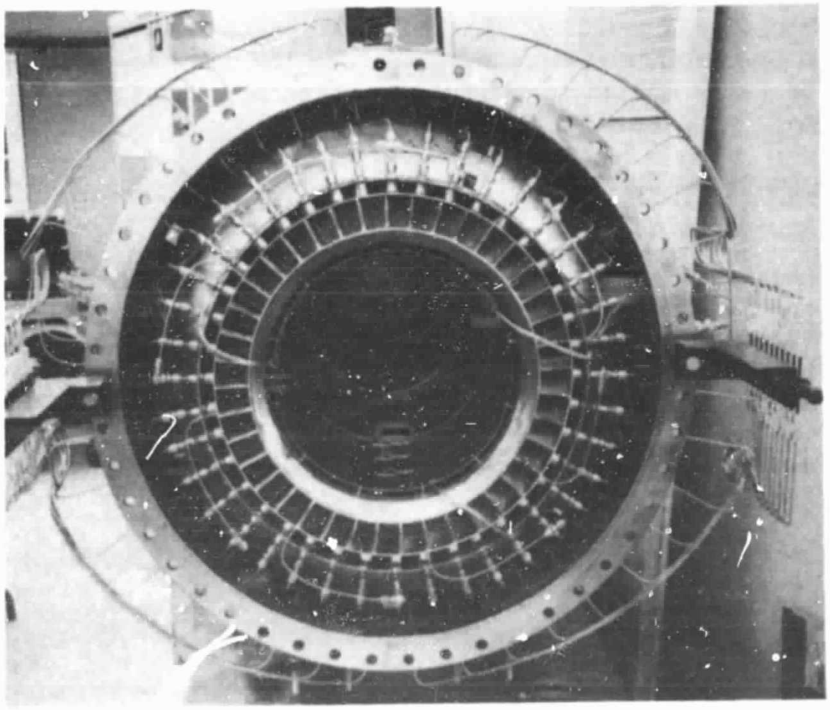

Figure 23. VAB Annular Combustor - Swirler Inlet

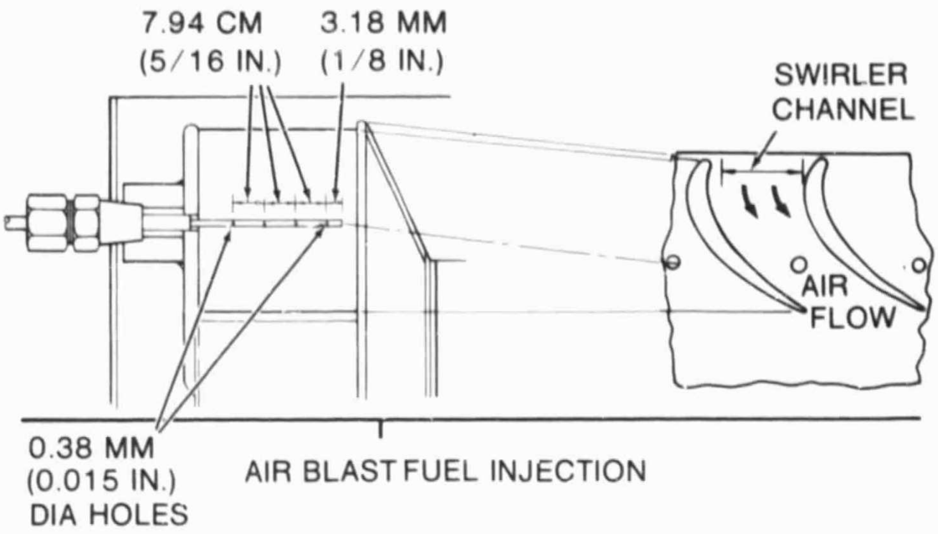

Figure 24. VAB Combustor Fuel Injection Position

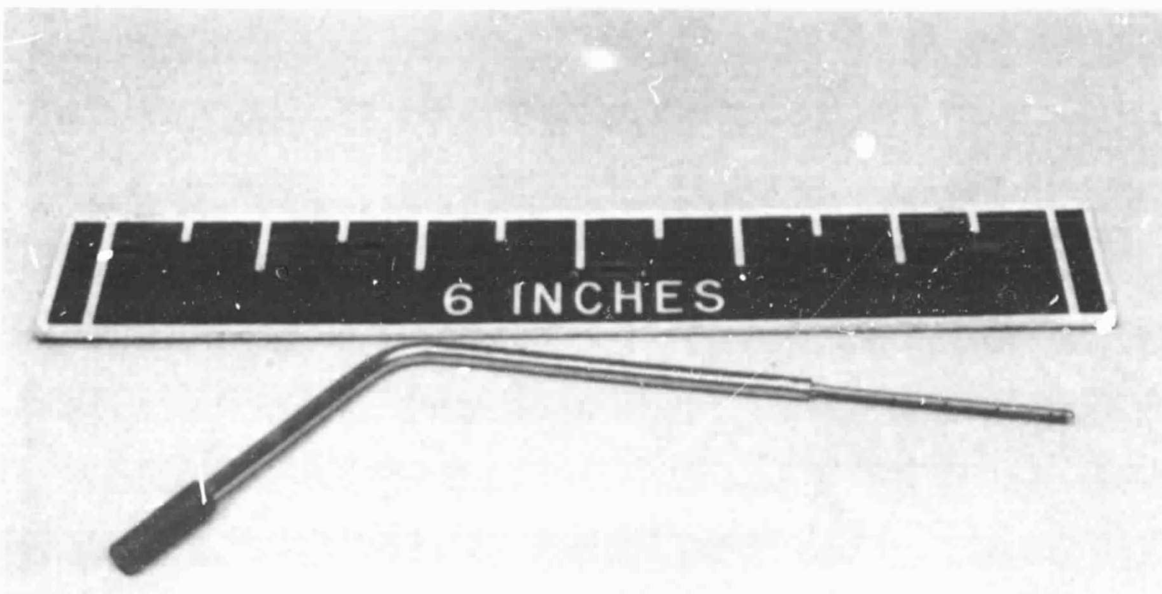

Figure 25. Fuel Injection Rake

with four fuel injection orifices 0.3 mm (0.012 in.) diameter positioned along the rake. Adequate injector-to-injector patternation is ensured by a system of external flow divider blocks.

4.1.3 Swirl Channel

The fuel is air-blast atomized slightly upstream of the vane channel throats then vaporizes and mixes with the reaction airflow in an annular swirl channel downstream of the vortex generator. The swirl channel discharges into the reaction zone of the combustor where the radial static pressure gradients of the near-homogeneous fuel/air stream serve to drive the reaction zone recirculation necessary for flame stabilization.

4.1.4 Dilution System

The dilution system consists of a series of eight variable-geometry ports situated around the outer combustor liner. The port design is based on the translating plug and seat arrangement shown in Figure 26. The dilution port assemblies function as the axial and radial locations for the combustor with the combustor forward end supported by three radial pins engaging slide blocks fastened to the combustor. The combustor support features are shown in Figure 27. No mechanism is provided for the dilution system area variation during a test run; instead, each of the dilution assemblies is adjusted

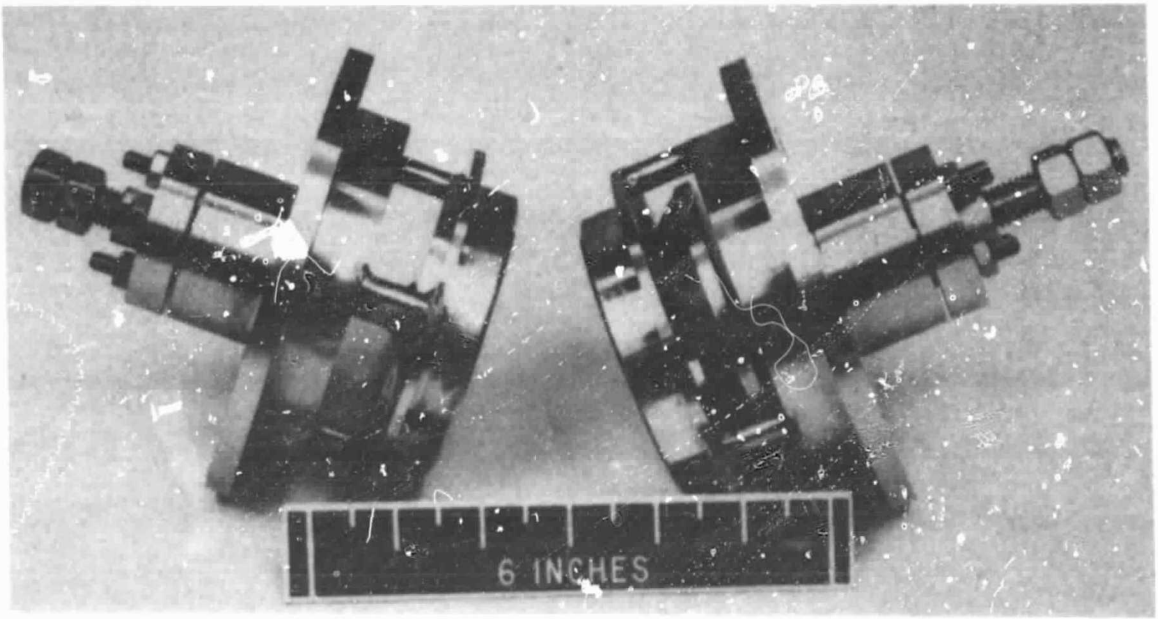

Figure 26. Variable Dilution Port Assembly

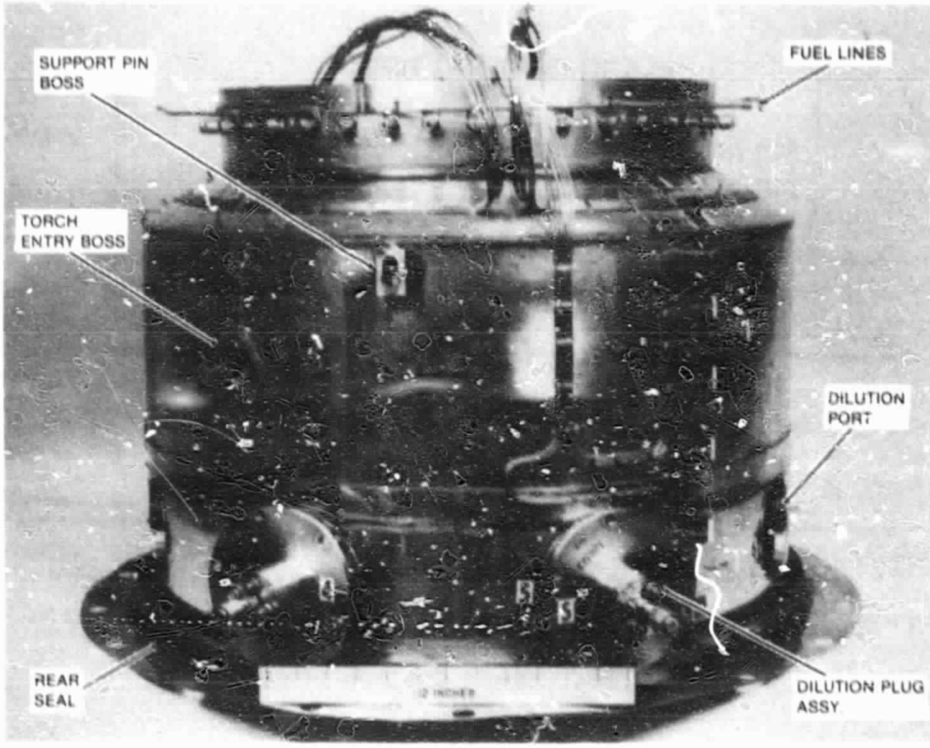

Figure 27. VAB Combustor - Outside View

prior to the beginning of each test. Accurate adjustment of the plug position can be guaranteed as the plug shaft is threaded into the outer casing housing.

4.1.5 Liner Cooling System

The inner and outer combustor liners are cooled by a combination of convective and film cooling techniques arrived at during preliminary investigations on the small-scale annular combustor. The bulk of the convective cooling air is admitted to the annulii at the forward end of the combustor. A portion is admitted through holes in the outer skins at intermediate stations along the combustor length as shown in Figure 28. A cross section through the combustor showing the position of the film cooling strips is shown in Figure 29.

4.1.6 Torch Igniter

A torch igniter is provided for light-off purposes. This is an independent unit which is turned off after ignition of the main combustor.

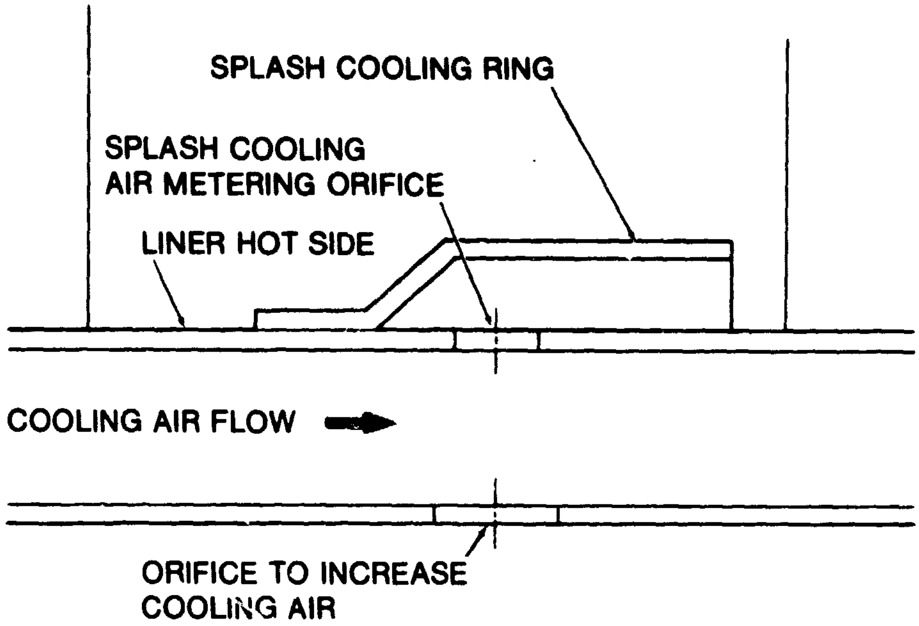

Figure 28. Liner Cooling Scheme

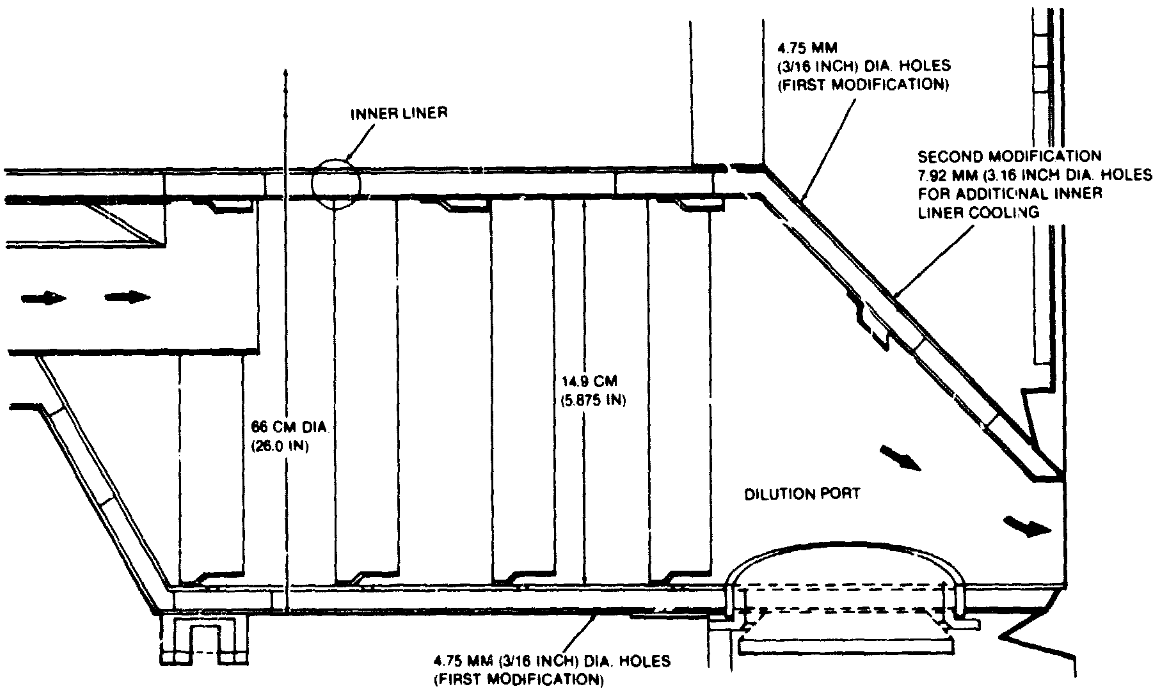

Figure 29. VAB Combustor Liner Cooling Design

4.1.7 Combustor Design Considerations

The full-size design is the result of a combination of facility limitations and operational parameters selected as representative of aircraft annular combustion system practice.

The total pressure loss selected for the system is six percent with a reference velocity of 15.2 m/sec (50 ft/sec) at the cruise condition based on the outer diameter of the combustor. Combining these requirements with Solar's atmospheric facility air mass flow restrictions produces a combustor outer diameter of 0.66 m (26.0 ins.).

The combustor swirler inlet is close-coupled to the inlet casing annular delivery flow without the use of a conventional diffuser section. The inlet flow annulus represents the exit from a final axial compressor stage and operates with a Mach number of approximately 0.3.

The overall length of the unit is constrained to fit within an existing rig facility at NASA-Lewis Research Center where the high-pressure testing is planned.

4.2 TEST FACILITIES

A schematic of the atmospheric test rig facility is shown in Figure 30. 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 sharp-edged orifice run for airflow metering purposes before entering the combustor inlet casing.

The exhaust from the combustor passes through an instrumentation section where, after emissions and temperature monitoring, the flow is quenched by direct water injection and exhausts to atmosphere through a silencer. The instrumentation section is shown in Figure 31 where the radial water-cooled gas sampling probes can be seen.

Photographs of the atmospheric test installation are shown in Figures 32 and 33.

4.2.1 Instrumentation and Test Procedure

The instrumentation test procedure adopted during the full-size investigations was identical to that adopted during the preliminary small scale annular investigation. After ignition the fuel flow to the combustor was 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.

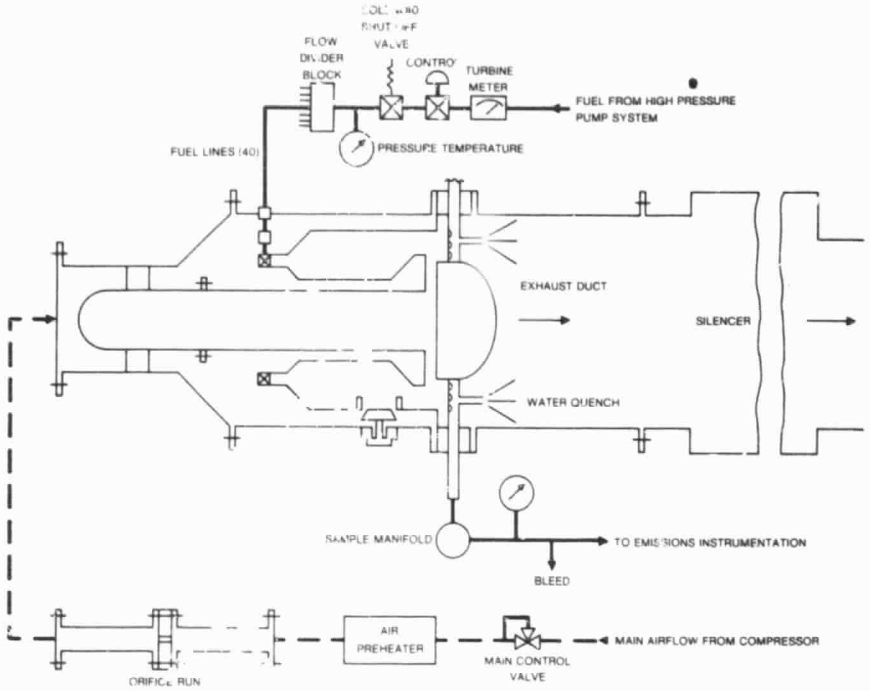

Figure 30. Test Facility Schematic

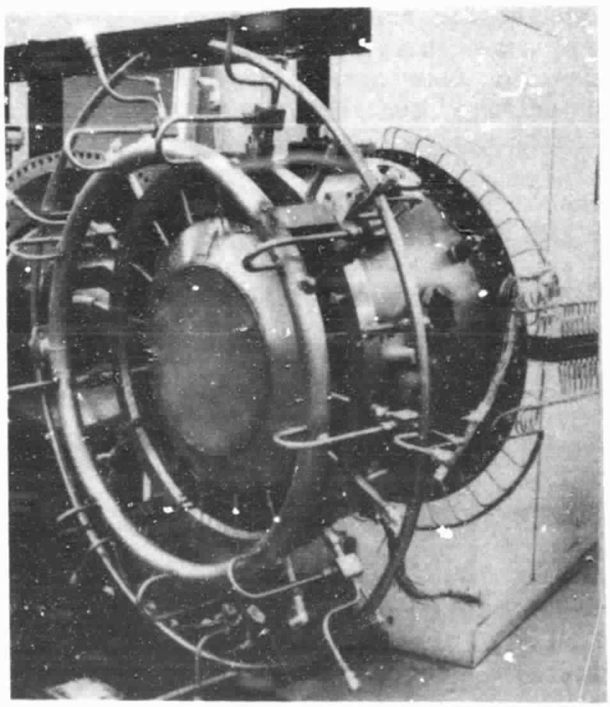

Figure 31. VAB Combustor - Instrumentation Section

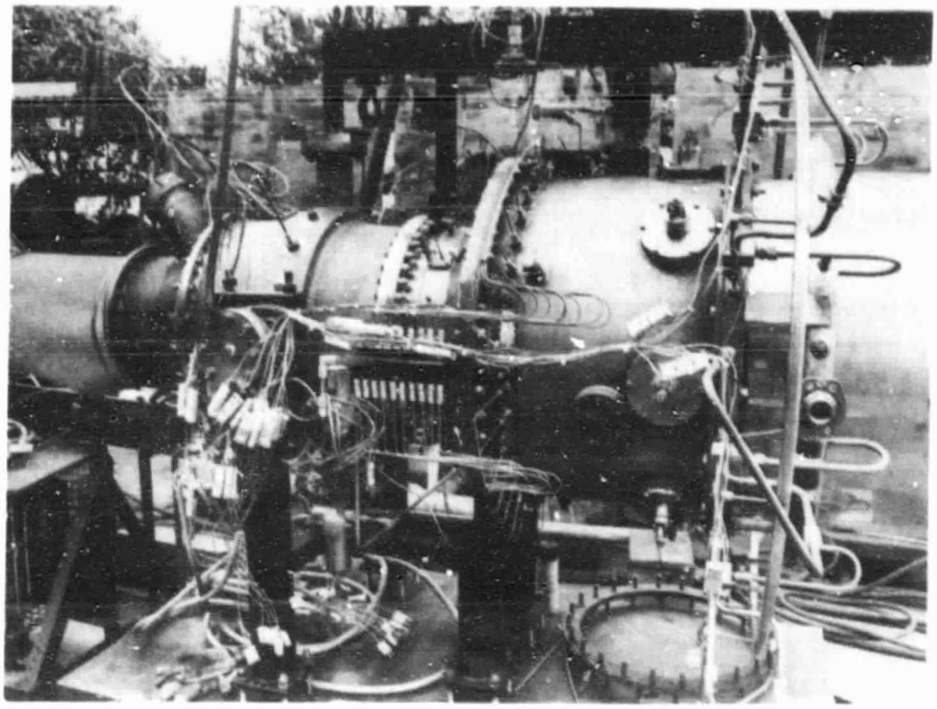

Figure 32. VAB Combustor Test Rig Installation

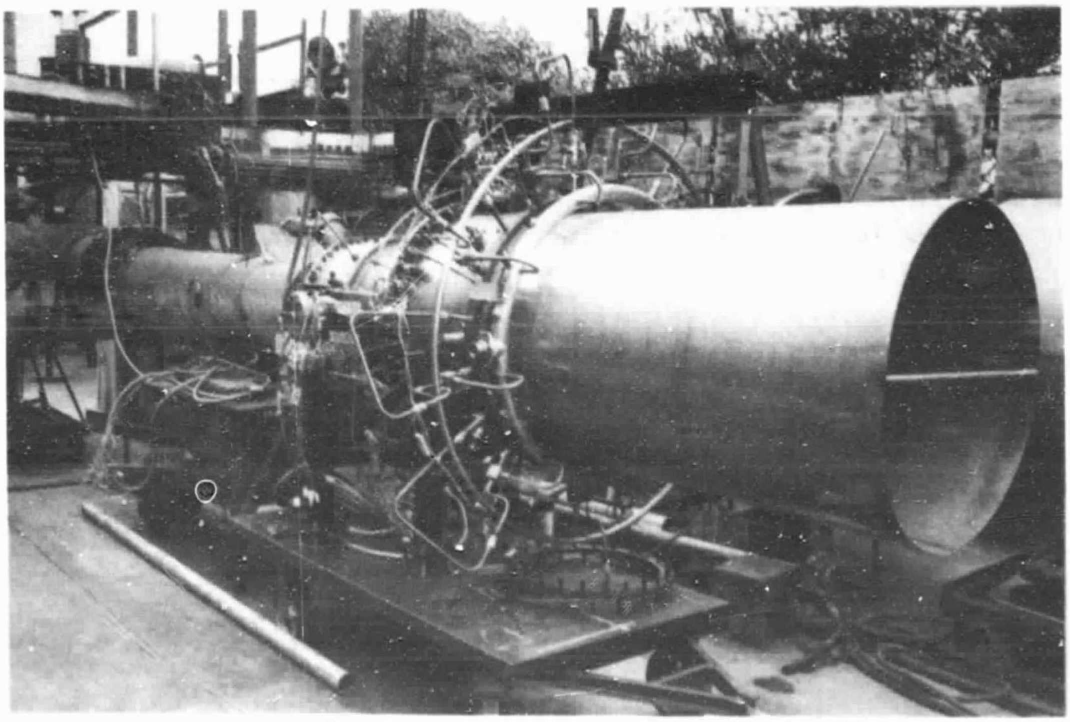

Figure 33. VAB Combustor Test Rig Installation

4.2.2 Test Conditions and Performance Goals

The test conditions and performance goals of the full-size VAB combustor were identical to those for the small-scale JIC and VAB combustors. The VAB combustor was characterized by testing at two discrete operating points, namely, cruise and idle.

4.3 TEST RESULTS AND DISCUSSION

Several previous studies and experimental programs conducted on lean premixed combustion systems (5, 6, 7, 8) have identified the specific design features that are important in achieving minimum NOx levels. The test program strategy adopted with the full-size annular combustor was to evaluate the emissions characteristics of a baseline configuration and then to evaluate the sensitivity of the emissions signatures to variations in the key design features with the objective of defining the optimum configuration for eventual high pressure testing.

The initial or baseline configuration of the full-size combustor for both cruise and idle conditions is summarized briefly below:

- Fuel Injection

  Fuel was injected slightly upstream of the swirler throat in each of the forty channels through the radial fuel rake shown in Figure 25. The fuel injection orifices were oriented such that the initial angle of fuel injection was along the channel mean flow line.

- Swirler Channel Extension

  Figure 34 shows the swirler channel extension at its original length of 8.9 cm (3.50 in.).

- Inlet Casing

  Figure 22 shows the initial configuration with the inlet casing in position. With this casing in place the incoming air was constrained to flow within an annulus with a sudden expansion section upstream of the swirler inlet.

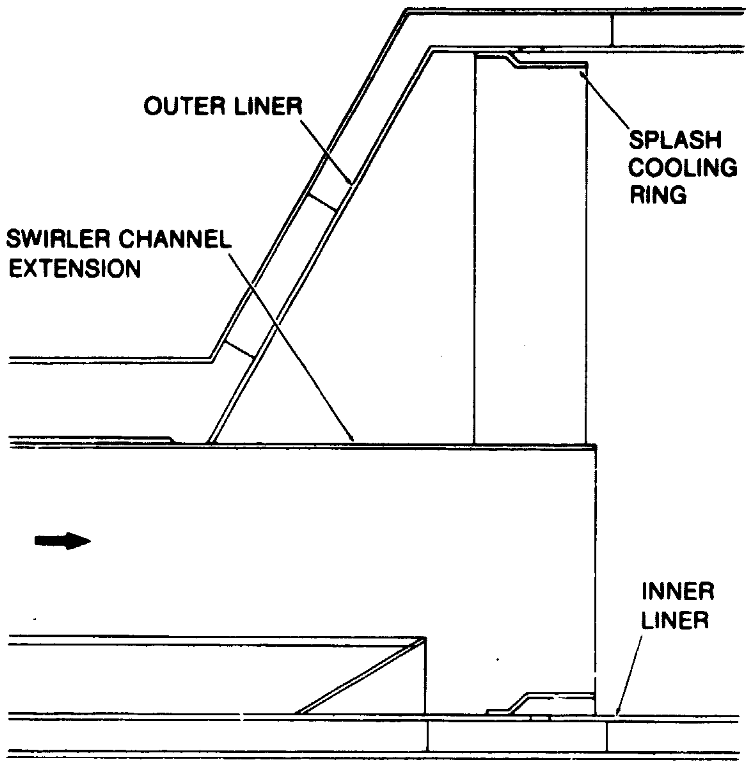

Figure 34. VAB Combustor - Baseline Swirler Channel Extension

4.3.1 Baseline Emission Characteristics

Idle Conditions

Baseline emissions characteristics at idle conditions are presented in Figure 35. The data indicate that both CO and UHC levels are well above the program goals.

Subsequent cold flow calibration tests revealed that the full-open dilution port discharge coefficient was only approximately 10 percent of the design value. Pressure traverses of the annulus between the outer casing and the combustor outer annulus showed that the reduced dilution port airflow was the result of a high loss in the area of the conical transition casing (between the simulated compressor discharge casing and the combustor outer casing) and the swirler inlet outer lip.

The effect of the reduced dilution port flow is to operate the combustor with a leaner reaction zone equivalence ratio than that designed for at the combustor outlet temperature of 916.7 K (1650°R). This resulted in considerably higher level of unburnts (CO and UHC) than anticipated.

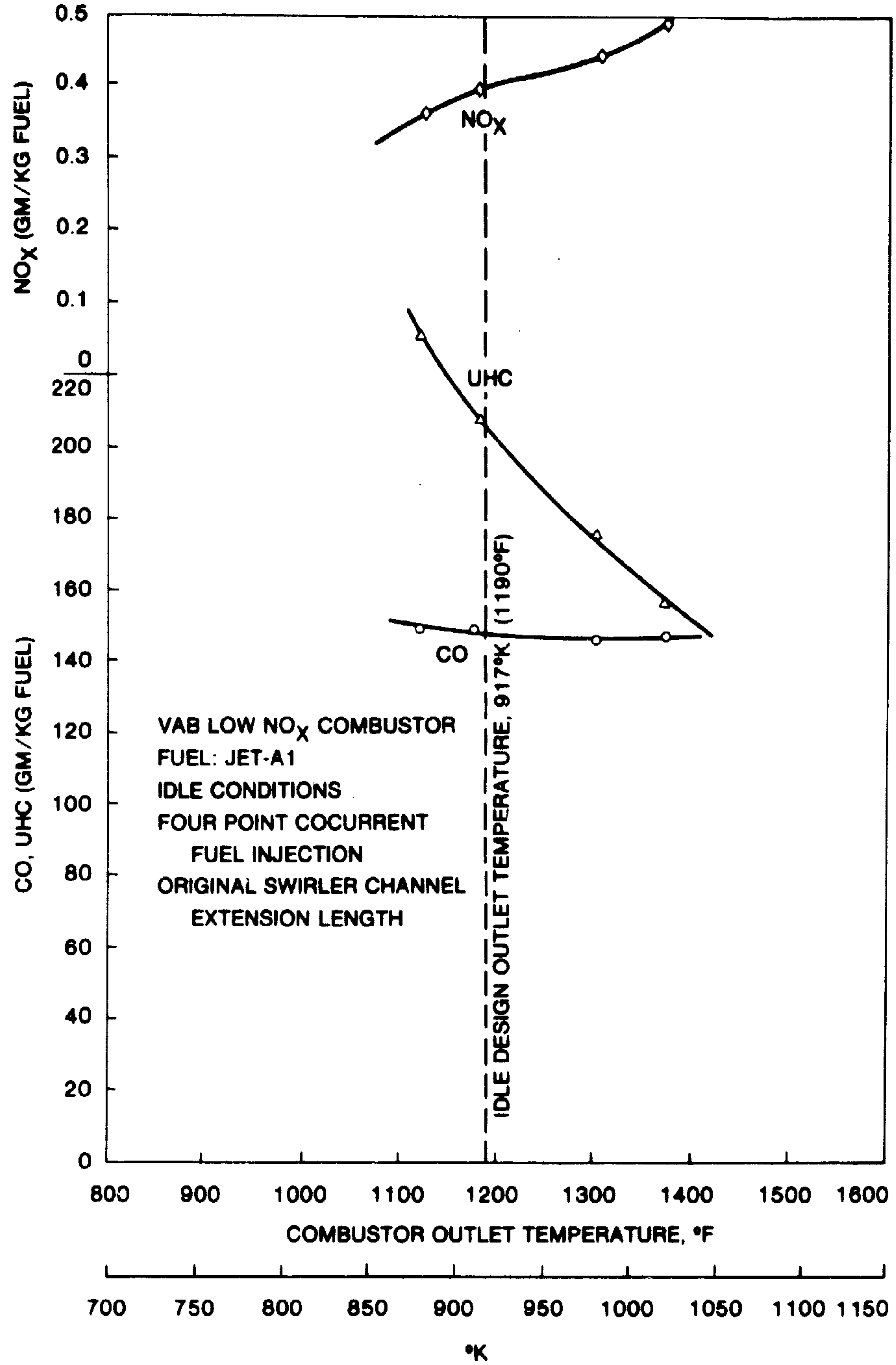

Figure 35. VAB Combustor - Baseline Configuration - Idle Test Point

No aerodynamic modifications were made to the inlet flow casings to remedy this flow problem due to the relatively greater importance of optimizing the cruise condition emissions.

Cruise Conditions

The cruise baseline emissions characteristics are presented in Figure 36. These results show that the combustor is operating with NOx levels within the 1.0 gm NO_2/kg fuel at design conditions but with CO and UHC levels much in excess of the program goals. Possible explanations for these excessive CO and UHC levels include insufficient reaction zone volume and local quenching effects caused by the film cooling scheme.

4.3.2 Effects of Fuel Injection Techniques

During the test program, four different fuel injection techniques were evaluated, namely:

1. Four-point concurrent injection
2. Single-point injection
3. Four-point counterflow injection
4. Eight-point counterflow injection

As a demonstration of the effect of initial fuel distribution on the combustor NOx emissions, the four-point fuel injector rakes were replaced by a simple single-point system as shown in Figure 37. The cruise emission results from the single-point fuel injectors are shown in Figure 38. Although no significant changes in the CO and UHC levels occurred the design point NOx increased significantly as would be expected from the reduced degree of premixing resulting from this configuration.

By rotating the four-point rakes 180 degrees, they were arranged to inject the fuel upstream into the reaction airflow. The emissions results are shown in Figure 39 where, again, no significant changes occurred to the unburnt emissions but the NOx emissions dropped approximately 20 percent at the design point. Counterflow fuel injection therefore results in decreased NOx levels due to an improved initial fuel distribution which more closely resembles a line source.

The final fuel injection system modification consisted of removing the four-point counterflow rakes and replacing them with eight-point counterflow rakes. The effects of this improvement in initial fuel distribution were small and are shown in Figures 40 and 41, representing the results of the cruise and idle test points, respectively. This final fuel injection system modification was performed with a reduced swirler channel length, the effects of which are discussed in a subsequent section.

ORIGINAL PAGE IS
OF POOR QUALITY

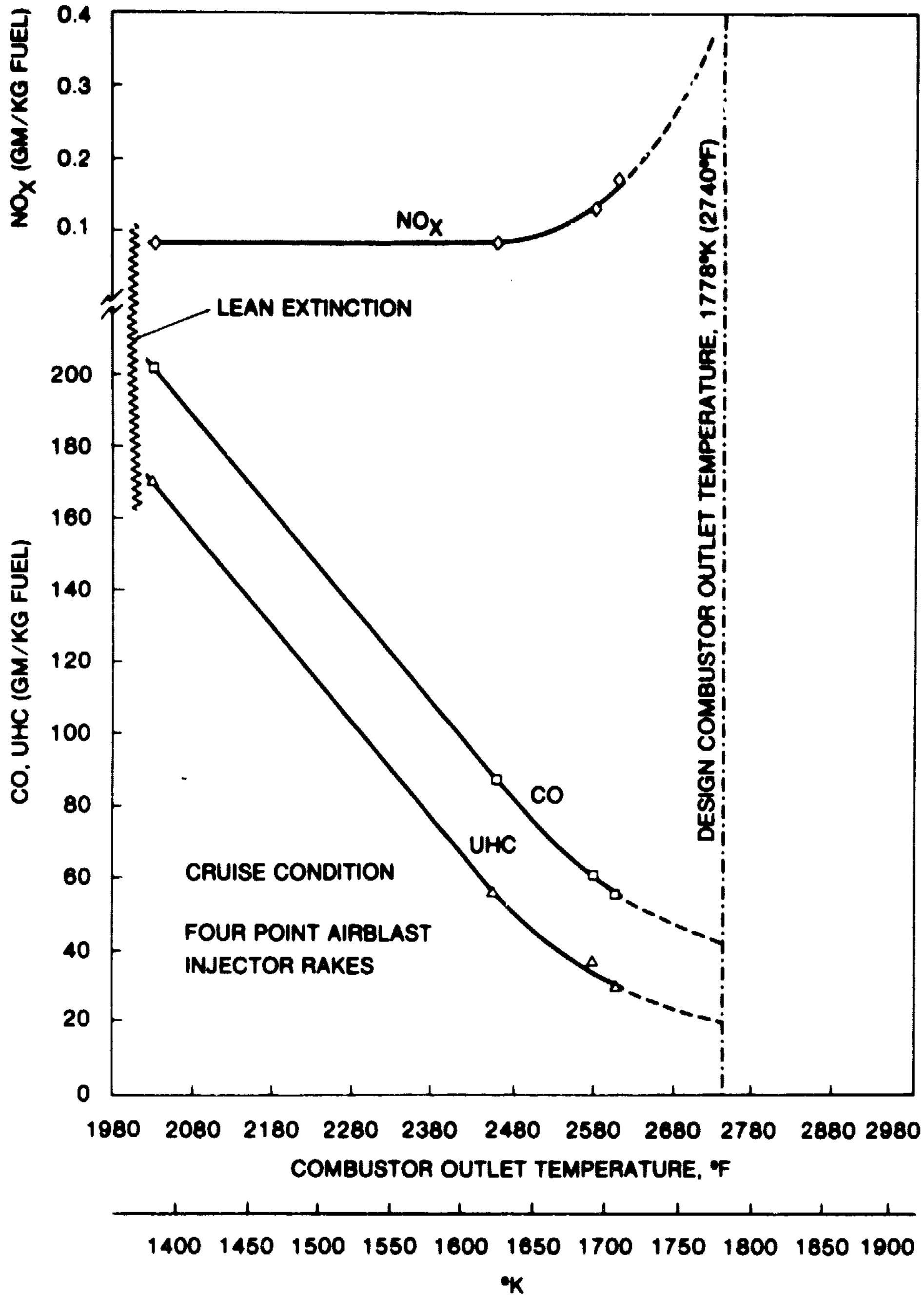

Figure 36. VAB Combustor - Baseline Configuration - Cruise Test Point

ORIGINAL PAGE IS
OF POOR QUALITY

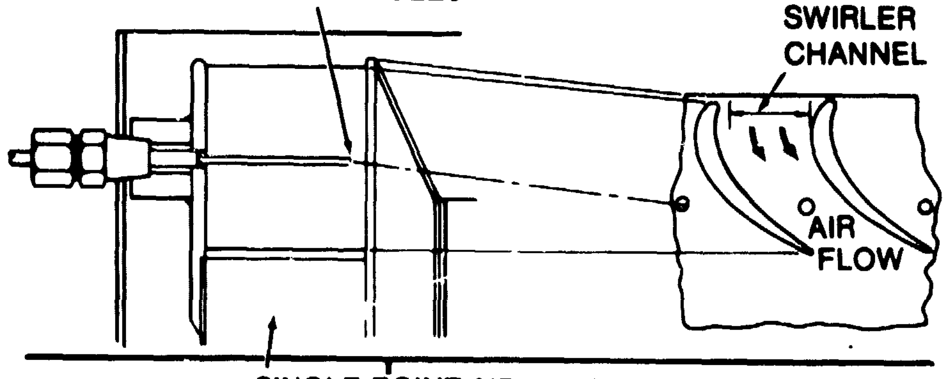

Figure 37. VAB Combustor. Single Point Fuel Injector

The effects of the various fuel injection system modifications are summarized in Table 6.

4.3.3 Inlet Flow Mismatch

The effects of the close-coupled compressor delivery flow and swirler inlet were evaluated by removing a portion of the casing as shown in Figure 42. This modification was intended to reduce the jetting into the swirler inlet and obviate any swirler separation that might be occurring. The cruise emissions results are shown in Figure 43 where it can be seen that the NOx emissions were reduced from 0.36 gm/kg fuel to 0.2 gm/kg fuel. No changes to the unburnt levels were seen.

4.3.4 Effect of Swirler Channel Length

As part of the original test plan it was intended that the swirler channel extension length would be reduced to determine the effect on the combustion characteristics. This was accomplished in two stages; 5.7 cm (2.25 in.) was removed for the first test and an additional 2.2 cm (0.875 in.) was removed for the second test, as shown in Figure 44. A summary of the emissions obtained at the cruise design point for these tests is shown in Figure 45. The reduction in the swirler channel extension length contributed significantly to a reduction in CO and UHC emissions. It had, however, the opposite effect on the NOx emissions.

ORIGINAL PAGE IS
OF POOR QUALITY

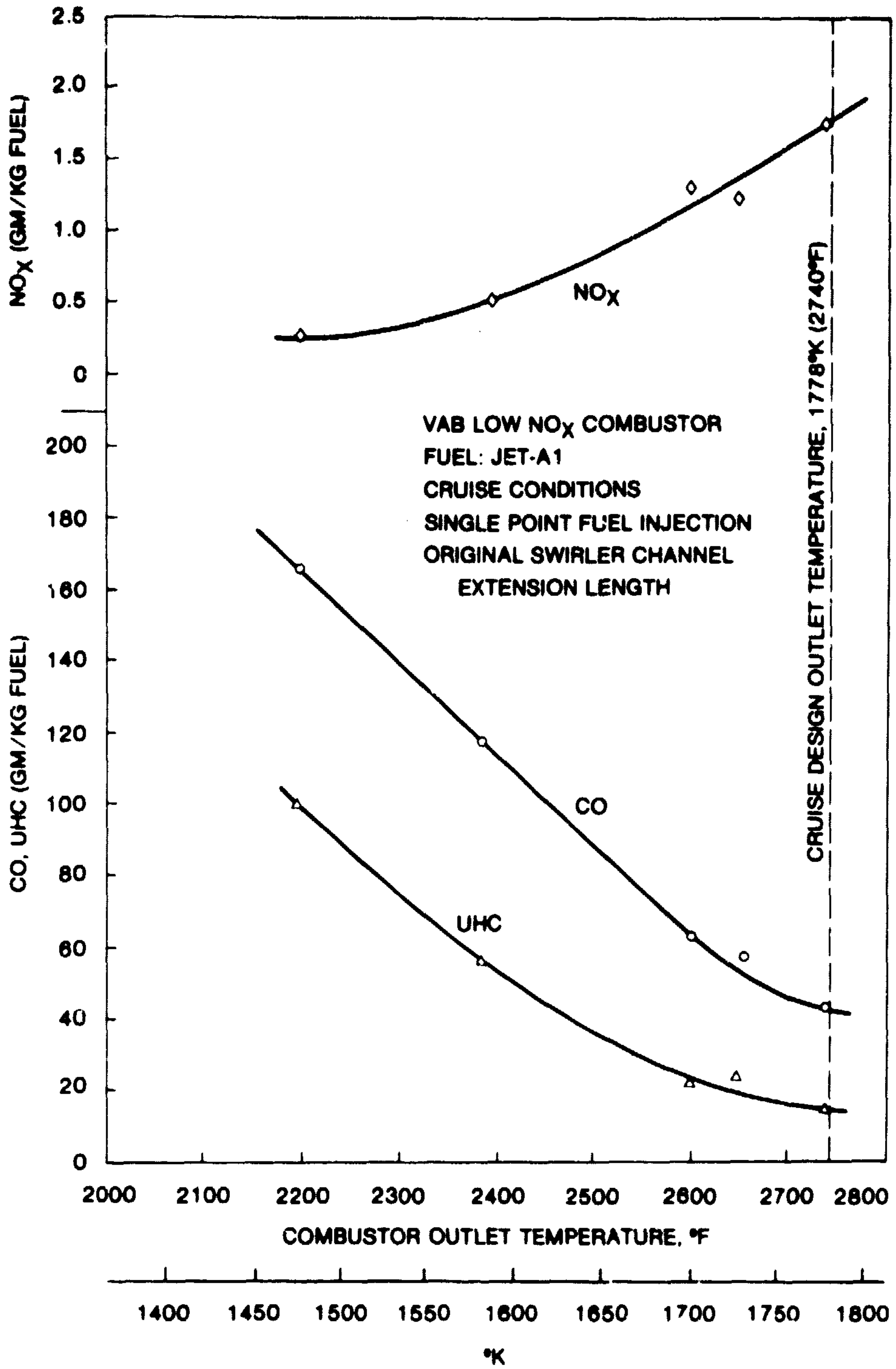

Figure 38. VAB Combustor - Baseline Configuration - Cruise Test Point Single Point Fuel Injector

ORIGINAL PAGE IS
OF POOR QUALITY

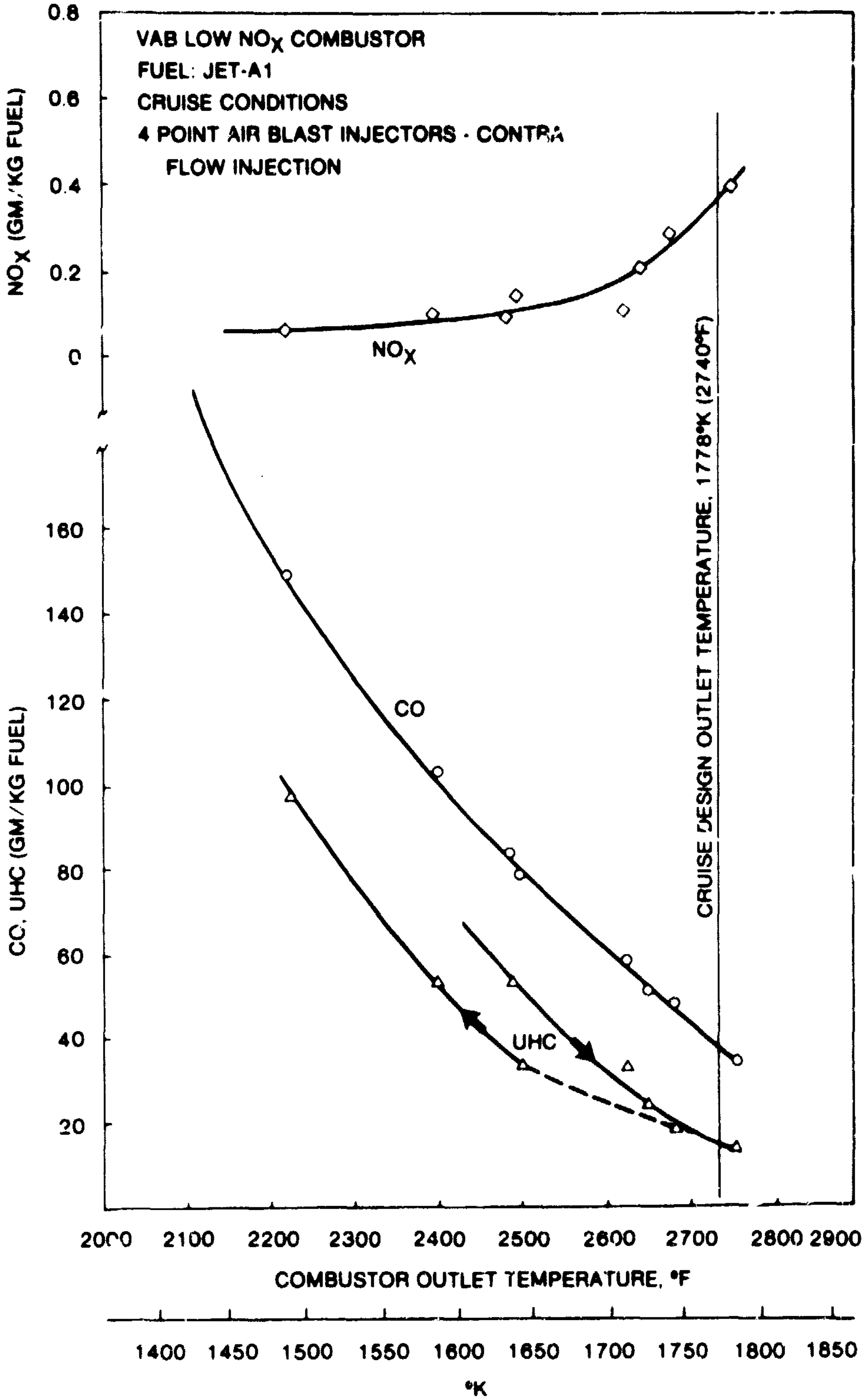

Figure 39. VAB Combustor - Baseline Configuration - Cruise Test Point Contra Flow Fuel Injection

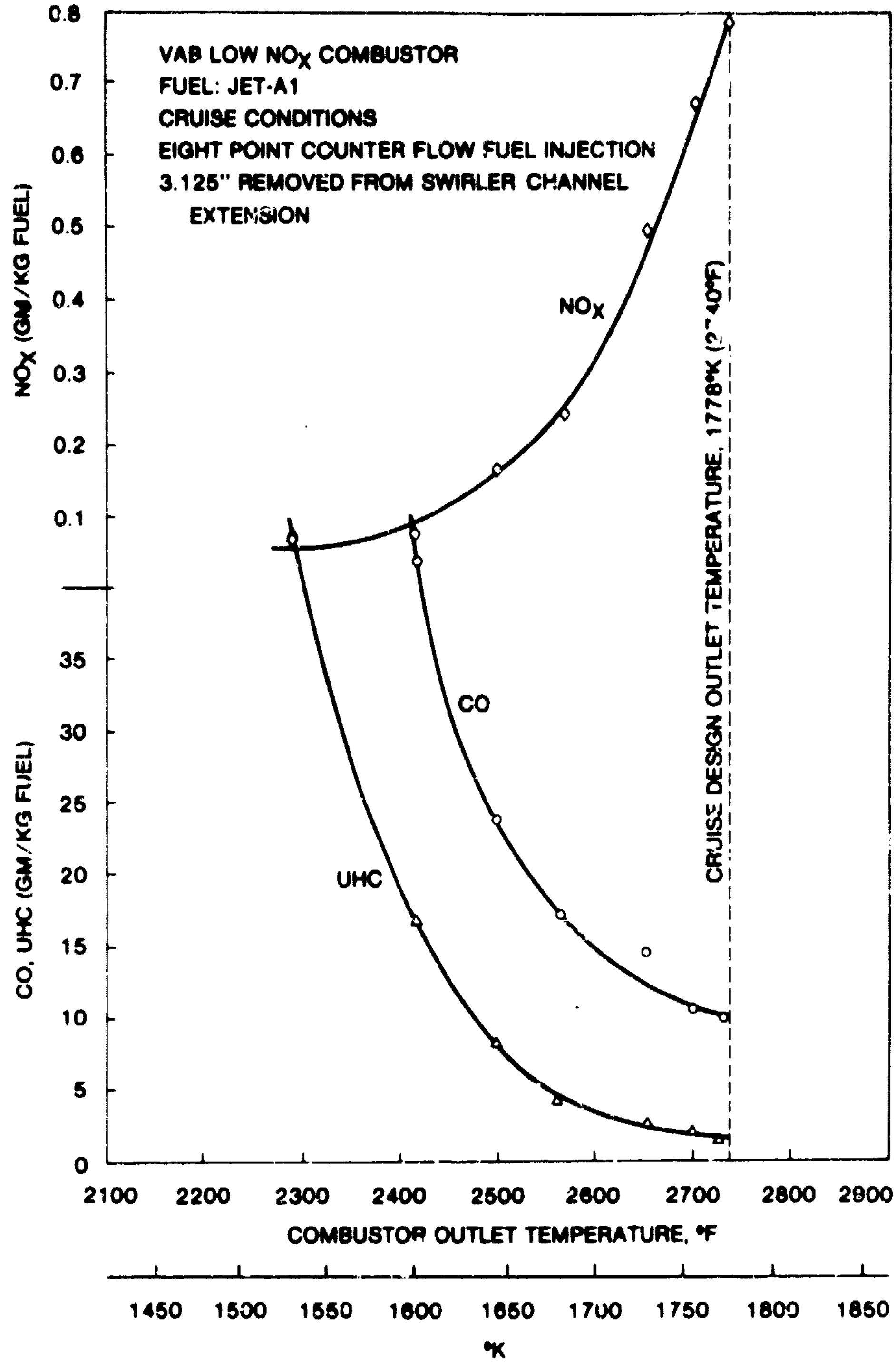

Figure 40. VAB Combustor - Cruise Test Point - Eight Point Fuel Injector Rake

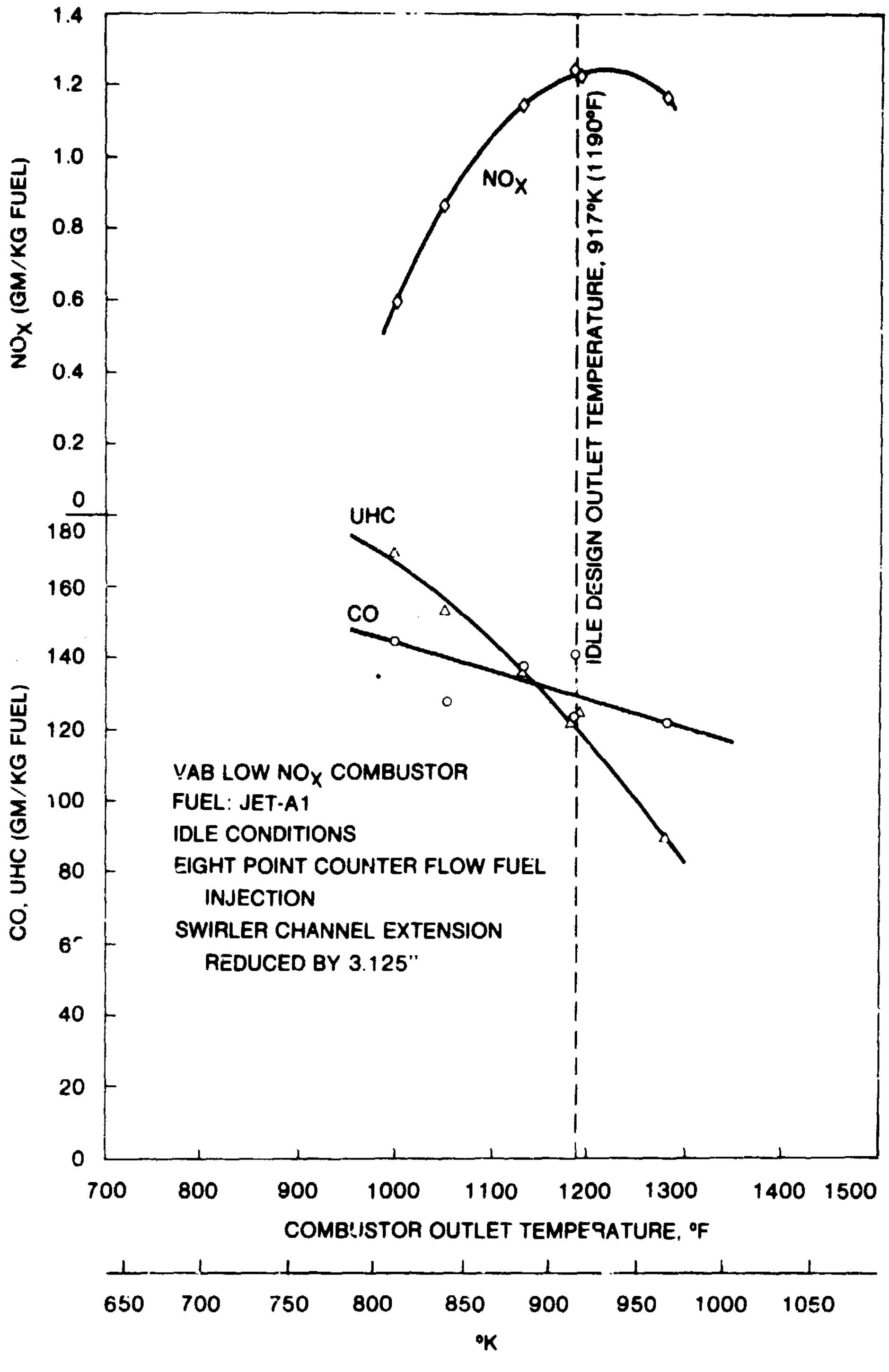

Figure 41. VAB Combustor - Idle Test Point - Eight Point Fuel Injector Rake

Table 6

Effect of Fuel Injection Mode Cruise Test Point

	Emissions at Design Combustor Outlet Temperature (grams/kg Fuel)		
	NOx	CO	UHC
Four point concurrent	0.43	41	20
Single point	1.80	43	16
Four point counterflow	0.36	39	14
Four point counterflow with reduced swirler channel length	0.67	10	2
Eight point counter-flow with reduced swirler channel length	0.84	10	2

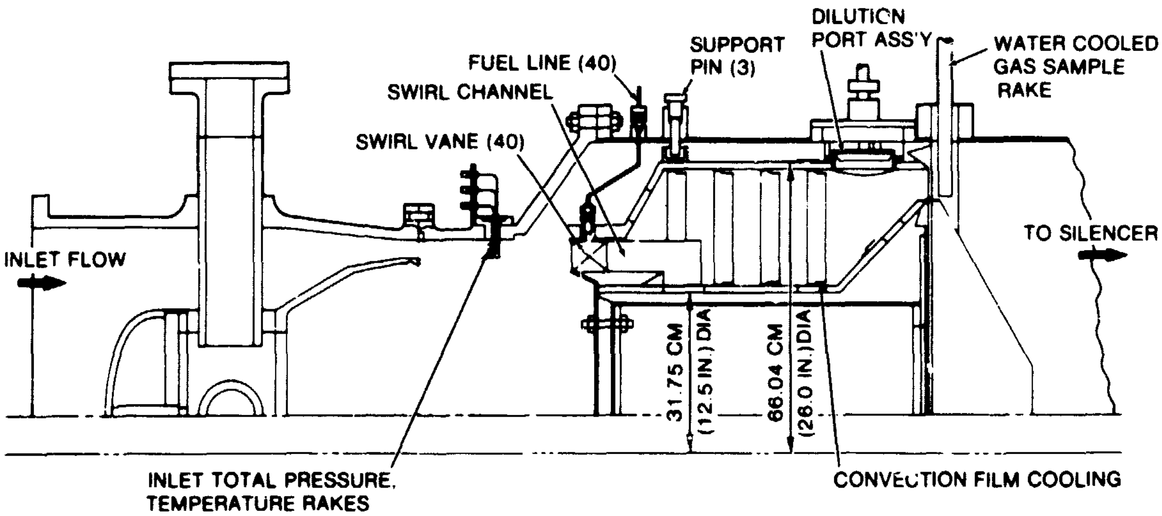

Figure 42. VAB Combustor Inlet Casing Removed

ORIGINAL PAGE IS
OF POOR QUALITY

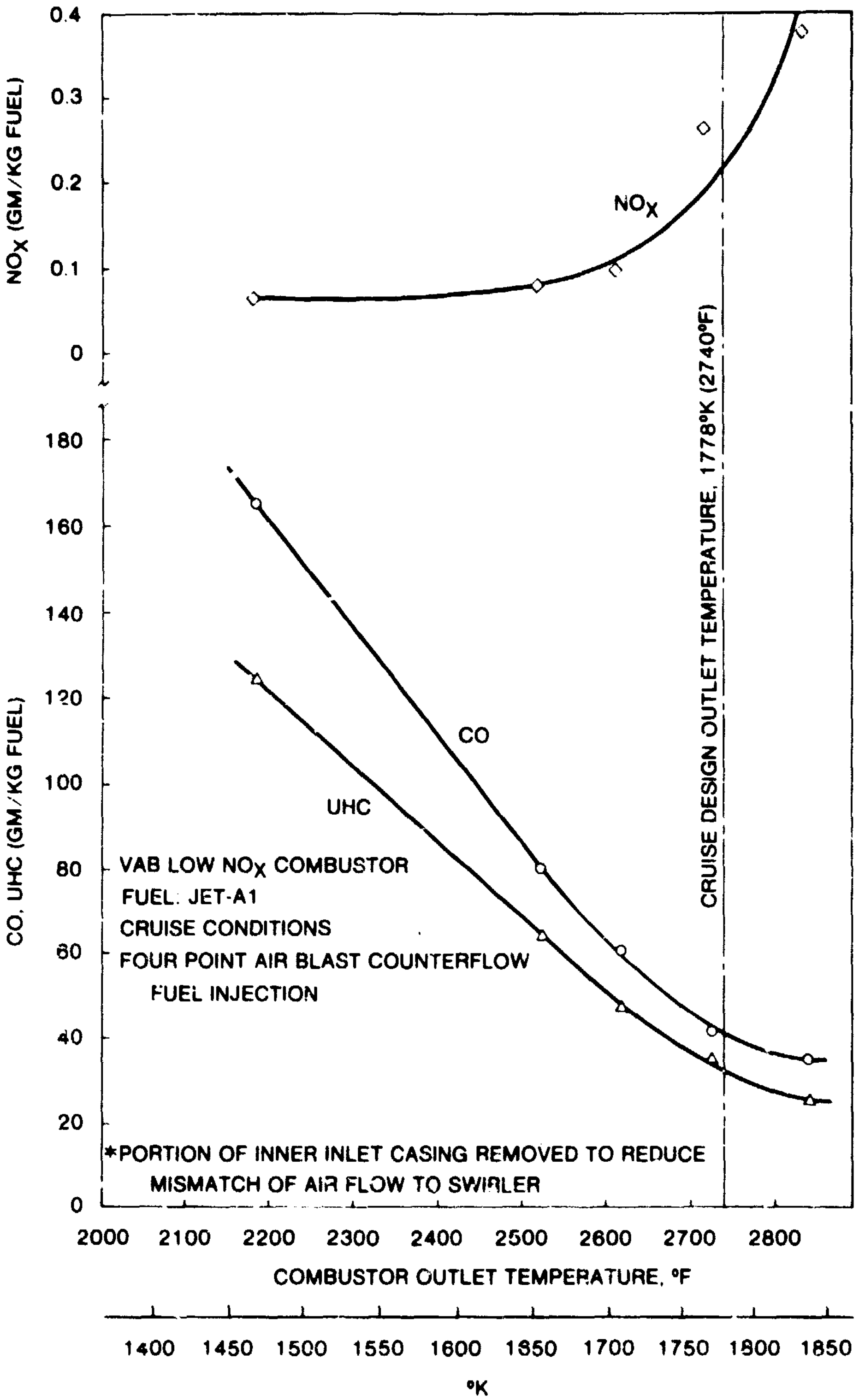

Figure 43. VAB Combustor - Cruise Test Point - Inlet Casing Removed

ORIGINAL PAGE IS
OF POOR QUALITY

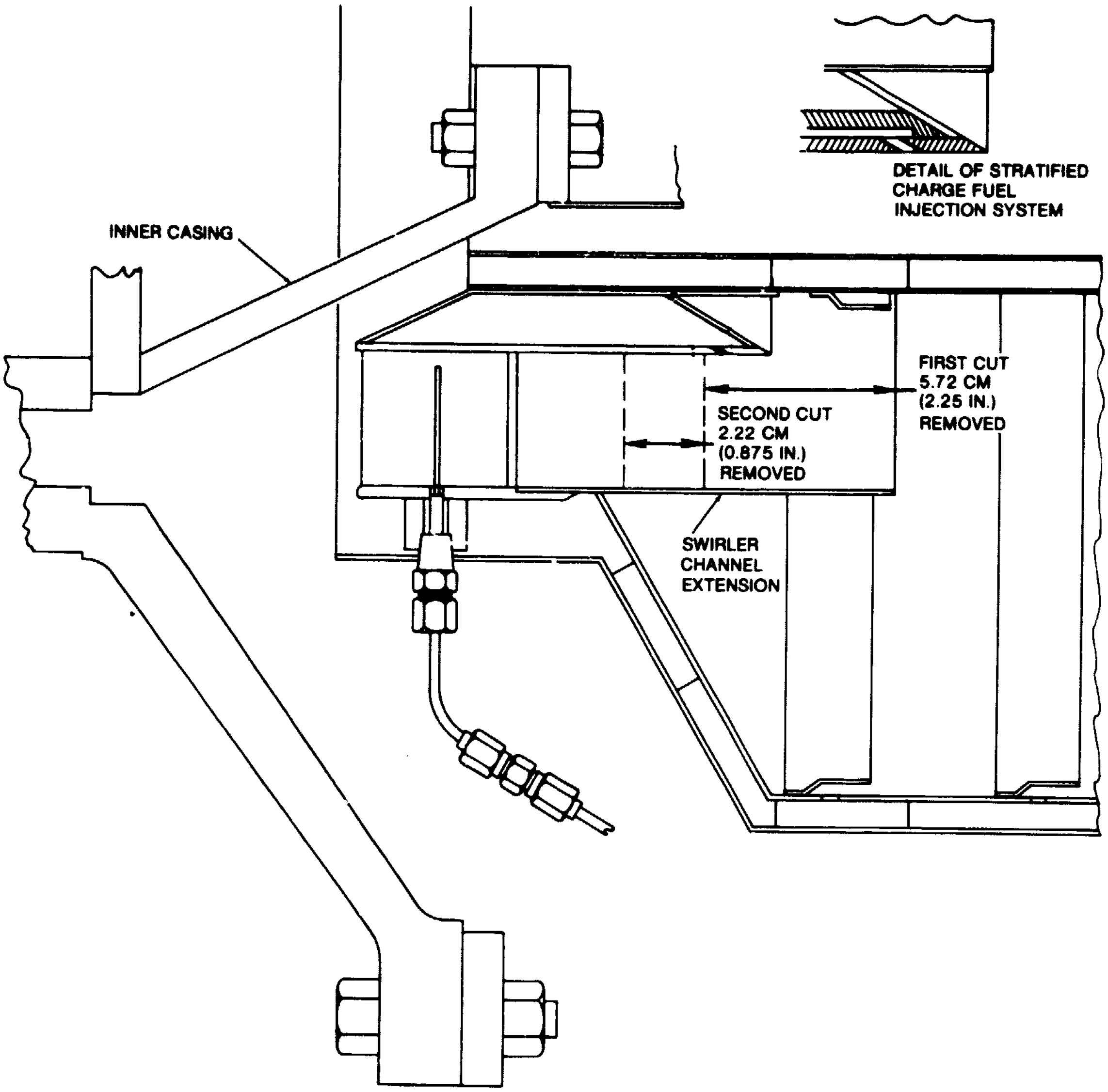

Figure 44. Detail of Swirler Channel Extension Modifications

ORIGINAL PAGE IS
OF POOR QUALITY

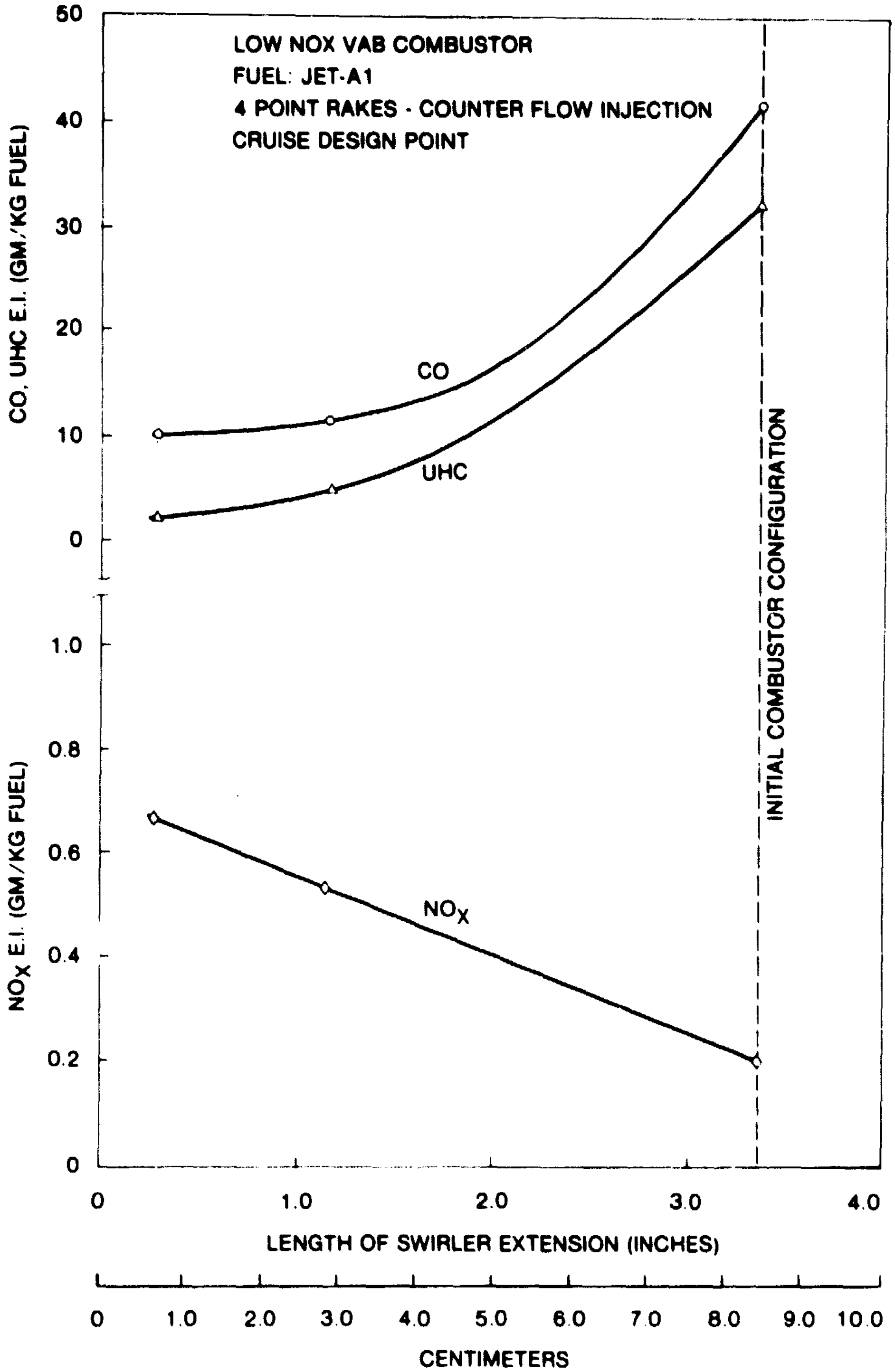

Figure 45. VAB Combustor - Cruise Test Point - Effects of Swirler Channel Length

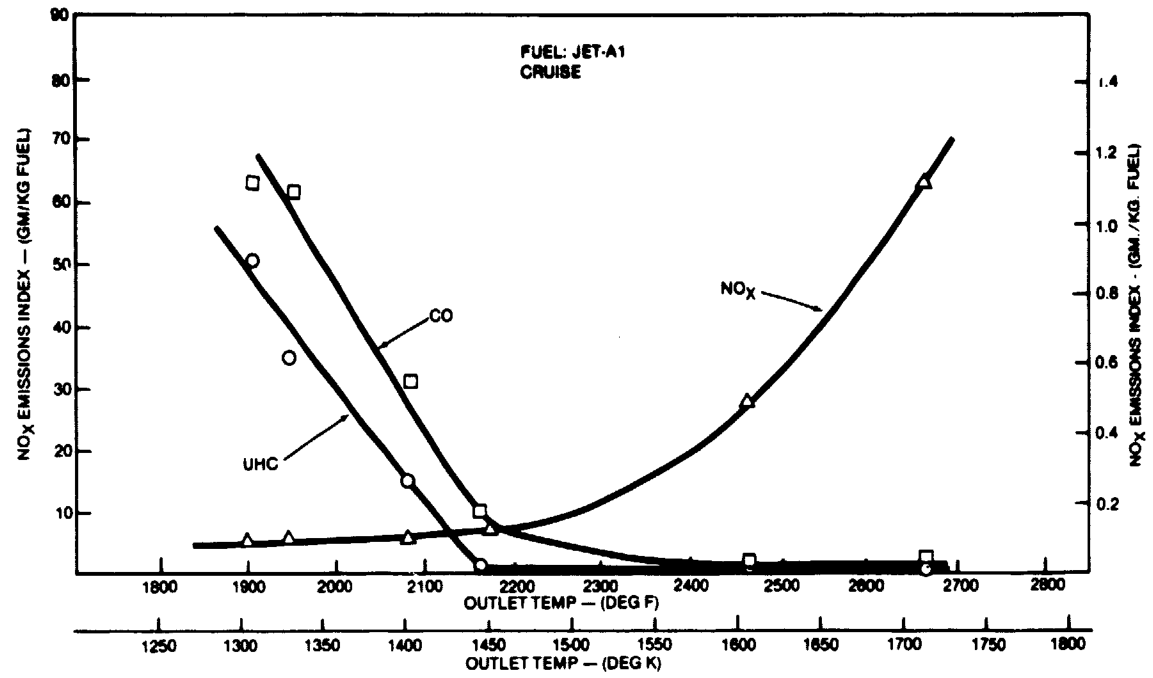

Figure 46. VAB Combustor - Cruise Test Points - Increased Reaction Zone Length

These effects are probably due to the increase in effective combustor volume that occurs as the swirler channel extension is cut back. The increased residence times result in additional reaction of CO and UHC and higher NOx levels. In addition the reduced swirler channel length results in a reduced degree of premixing which also tends to increase NOx levels.

4.3.5 Effect of Reaction Zone Length

As a demonstration of the trade-off existing between reaction zone residence time and NOx emissions, a test run was made where the length of the reaction zone was increased by adding a 30.5 cm (12.0 in.) section to the inner and outer liners between the swirler channel and the dilution ports. The cruise test result is seen in Figure 46 where it can be seen that the NOx emissions had increased from 0.66 gm/kg fuel to 1.4 gm/kg fuel previously obtained from the shorter reacton zone. At the same time, however, the CO and UHC emissions were reduced to 1.8 gm/kg and 0.2 gm/kg, respectively.

5

CONCLUSIONS

5.1 The lean premixed VAB combustor in full-size axisymmetric annular form has demonstrated the capability of operating at an atmospheric-pressure, simulated high-altitude, supersonic cruise condition with NOx emissions below 1.0 gm/kg fuel.

5.2 The CO and UHC emission goals were exceeded at the cruise condition but could be closely approached by increasing the reaction zone length in excess of the original design constraint.

5.3 Future high pressure testing of the combustor will reveal the effect of pressure on the NOx, CO and UHC emissions and the sensitivity of the VAB design to autoignition. Solar's previous investigations and the small-scale annular VAB test results contained in this report suggest that the effect of pressure on the NOx emissions of the VAB combustor can be expected to be minimal. Support for this position can be found in the work of Roffe (9).

5.4 Although the idle emission goals for CO and UHC were not met, flow test results show that this was mainly due to an aerodynamic deficiency in the design of the inlet flow casing match to the combustor. This resulted in a reduced flow to the dilution port system and a leaner idle reaction zone equivalence ratio than originally designed for.

5.5 The full size testing of the VAB combustor shows that for the full range of low emissions operation, from idle to cruise, a variable dilution port system is necessary, but that fuel-switching can be avoided and a single fuel injection system used.

REFERENCES

1. Roberts, P. B., et al, "Advanced Low NOx Combustors for Supersonic High-Altitude Aircraft Gas Turbine". 1976 ASME Gas Turbine & Fluids Engineering Conference (Paper No. 76-GT-12).

2. Roberts, P. B., et al, "Wide Range Operation of Advanced Low NOx Aircraft Gas Turbine Combustors". 1978 ASME Gas Turbine Conference (Paper No. 78-GT-128).

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

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

5. Mularz, E. J., "Lean, Premixed, Prevaporized Combustion for Aircraft Gas Turbine Engines", NASA TM 79148, June 1979.

6. Roffe, G. and Ferri, A., "Effect of Premixing Quality on Oxides of Nitrogen on Gas Turbine Combustors", NASA CR-2657, February 1976.

7. Cooper, L., "Effect of Degree of Vaporization Open Emissions for a Premixed, Prevaporized Combustion System", Premixed Prevaporized Combustor Technology Forum held at NASA-Lewis Research Center on January 9-10, 1979, CP-2078.

8. Dickan, R. A., Dodds, W. J., and Ekstedt, E. E., "Lean, Premixed Prevaporized (LPP) Combustor Conceptual Design Study", NASA CR-159629.

9. Roffe, G. and Venkatoramani, K. S., "Emission Measurements for a Lean, Premixed Propane/Air System at Pressures up to 30 Atmospheres", NASA CR-159421.

PRECEDING PAGE BLANK NOT FILMED