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# QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE)

## Double-Annular Clean Combustor Technology Development Report

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TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

## LIST OF TABLES

## LIST OF TABLES (Continued)

## LIST OF TABLES (Concluded)

# 1.0 SUMMARY

The NASA Quiet Clean Short-Haul Experimental Engine (QCSEE) Program involves the design, fabrication, and testing of experimental, high by-pass, geared turbofan engines and propulsion systems for short-haul passenger aircraft. This program includes two engine configurations; one mounted under the wing (UTW) and one other over the wing (OTW). This combustor technology development program was conducted as part of the overall QCSEE program to identify, define, and develop technology for the design of a small, compact advanced combustor, with significantly lower pollutant emission levels than those of current technology combustors suitable for use in advanced CTOL commercial aircraft engines. The efforts of this 24-month program were directed toward evaluating combustor design approaches for obtaining low carbon monoxide (CO) and unburned hydrocarbon (HC) levels, with very severe combustor inlet operating conditions at the engine ground idle power setting, as well as low oxides of nitrogen ($NO_x$) levels at high engine power settings.

This combustor program specifically involved the definition and testing of double-annular dome combustor designs, based on a concept evolved earlier in the NASA/GE Experimental Clean Combustor Program (ECCP). This concept features the use of two discrete zones within the combustor, with which the combustion process may be appropriately staged to minimize CO and HC levels at low engine power operating conditions as well as $NO_x$ and smoke levels at high engine power operating conditions. The key elements of this program included the aeromechanical design of a QCSEE-sized version of this advanced combustor design concept, the fabrication of sector versions of the combustor design, the design and fabrication of a sector combustor test rig, and the testing of various sector combustor test configurations to obtain a configuration to meet the program emissions and performance goals. These sector combustor test configurations were designed to fit within the combustor housing of the QCSEE configurations and were evaluated, at elevated pressures, in a sector test rig which exactly duplicates the combustor housing of the QCSEE configurations. In addition to detailed emission data, detailed data on the other important performance characteristics of many of the test configurations were also obtained.

Four basic versions of the double-annular dome combustor concept, involving a total of 32 test configurations, were evaluated in the sector combustor tests. They included a baseline version modeled closely after the NASA/GE ECCP double-annular dome design, a version with the location of the pilot-stage dome and main-stage dome interchanged plus an improved pilot-stage dome swirl-cup design, and a similar version except with an improved high-power main-stage dome swirl-cup design. Encouraging results were obtained with the final version which featured the pilot stage located in the inner dome and modified pilot- and main-stage swirl-cup designs. With this advanced combustor design approach, CO and HC levels at or near the program target levels were obtained. Significant reductions in $NO_x$ levels were also obtained with this advanced combustor design concept. However, large adjustments in the measured $NO_x$ values were required since the simulated

high power sector combustor inlet conditions set in the test rig were well below the actual engine conditions due to facility limitations. In addition, the other important performance characteristics of this advanced QCSEE combustor design were found to be generally satisfactory.

Based on these results, it is concluded that CO, HC, and $NO_x$ levels obtained with this double-annular dome staged combustor design concept are significantly lower than those of current technology combustors and meet the program goals for a flight engine. It is further concluded that acceptable ground ignition and altitude relight performance can also be obtained with this two-stage combustor design concept based on sector combustor test data.

## 2.0 INTRODUCTION

Various studies to define the extent of contributions of turbine-engine-powered aircraft to world-wide pollution have been conducted. In general, these studies have shown that the overall contributions of aircraft turbine engine emissions to the air pollution problems of metropolitan areas are quite small as compared to those of other contributors (Reference 1). The foremost concern associated with these engine exhaust emissions appears to be their possible impacts on the immediate areas surrounding major metropolitan airports. Because of the operating characteristics of most current turbojet and turbofan engines, the highest levels of the various objectionable exhaust constituents are typically generated at engine operating modes that occur in and around airports. Further, because large numbers of daily aircraft operations can occur in and around a given airport, the cumulative exhaust emissions resulting from these localized aircraft operations tend to be concentrated to some extent in the airport vicinity.

For these reasons, the U.S. Environmental Protection Agency (EPA) concluded that standards are needed to regulate and minimize the quantities of CO, HC, $NO_x$, and smoke emissions discharged by aircraft when operating within or near airports. Based on this finding, such standards were defined for several different categories and types of fixed-wing, commercial aircraft engines. As originally promulgated, these standards, for the most part, are to become effective in 1979 (Reference 2).

To meet these gaseous emission standards, new and advanced technology is needed for the reduction of CO and HC emission levels at ground idle operating conditions and the reduction of $NO_x$ emission levels during takeoff, climbout and cruise operations. The attainment of the required reduced exhaust emission levels in future engines primarily involves providing improved and modified main combustors for use in these engines. In most engines, major combustor design technology advances are needed to obtain the significant reductions in these gaseous emissions that are required to meet the prescribed EPA standards.

One of the programs conducted to provide these needed combustor design technology advances was the Experimental Clean Combustor Program (ECCP). This program was initiated by NASA in 1972 (Reference 3). The overall objective of this major program was to define, develop, and demonstrate technology for the design of low pollutant emission combustors for use in advanced commercial aircraft engines with high cycle pressure ratios, in the range of 20 to 35. In the NASA/GE ECCP, conducted under Contract Numbers NAS3-16830, -18551, and -19736, significant progress was made in the identification and developement of a double annular dome CF6-50 combustor design with significantly lower CO, HC, and $NO_x$ levels than those of the current production CF6-50 combustor. Emission levels approaching the stringent goals of this program were obtained with this advanced combustor configuration. Also, very low smoke levels and generally satisfactory characteristics in other important performance aspects were obtained. The technology evolved in this program is expected to be directly applicable to large turbofan engines, such as the CF6-50. However, the direct applicability of the combustor design technology evolved in the NASA/GE ECCP to smaller size engines was not evaluated in the program. Therefore as a part of the overall QCSEE program, a program involving the design, and the technology development of a smaller size double annular dome combustor was initiated, based on the advanced combustor design technology developed in the NASA/GE ECCP.

The specific objectives of this QCSEE combustor program were to define an advanced double annular dome combustor sized for use in the QCSEE configurations, based on the advanced combustor design technology developed in the NASA/GE ECCP, and to evaluate and test this design in sector combustor tests. The primary intents of those efforts were to evolve a design which meets the target CO and HC emission levels at the idle operating conditions of the QCSEE configurations and also to meet the ground start, altitude relight, and other combustor performance requirements of these engines.

The work effort of this QCSEE combustor program was initiated in May, 1976 and was completed in March 1978. This report describes the low pollution combustor concepts investigated and the test results obtained in this sector combustor technology program. In this program, data were obtained at test conditions simulating all important QCSEE operating modes from ignition to takeoff, including altitude windmilling. Due to facility limitations, the combustor test pressures used in these investigations were restricted to a maximum of 4 atmospheres. As a result of these efforts, a preferred QCSEE double annular dome combustor design was defined. This preferred combustor configuration is also described in this report.

# 3.0 PROGRAM GOALS AND PLANS

## 3.1 PROGRAM ELEMENTS

The QCSEE combustor technology development program was a multi-year effort, which was conducted as a part of the NASA QCSEE program. The primary objective of this program was to evolve advanced combustor design technology for providing significantly reduced pollutant exhaust emissions levels compared to those obtainable with current technology combustors, in the same size class as those required in the QCSEE configurations. This design technology was to expand on the advanced combustor design technology for reduced pollutant exhaust emissions levels already evolved in the NASA/GE ECCP for larger size combustors. To meet the program objectives, the program was comprised of six tasks including design, fabrication, and development testing efforts. The key elements of the program and the important milestones are shown in Figure 1.

## 3.2 PROGRAM GOALS

### Pollutant Emissions Level Goals

The specific pollutant emission goals of the QCSEE program are presented in Table I. As shown by comparing the goals with the status levels of the current QCSEE OTW configuration, when equipped with a current technology combustor, the attainment of these goals involves pollutant emission level reductions of nearly two to one for some categories. No quantitative program goals were established for $NO_x$ or smoke for this program since the major emphasis was directed at reducing the CO and HC levels at idle. However, the original overall intent of the program was to demonstrate the attainment of significant $NO_x$ level reductions as a direct consequence of the staged combustor design concept which was to be evolved in this program. The gaseous emission goals for this program are expressed in two ways: as emission indices at the engine operating mode where the peak levels of each emission are generated, and as EPA parameters by which the gaseous emission standards are defined in Reference 2.

The EPA parameter is a thrust-normalized measure of the total mass of pollutant emitted in a prescribed landing and takeoff, (LTO), cycle. The cycle conditions selected for the EPA-LTO definition were based on two QCSEE sea level static, standard day cycle representations. The first was the QCSEE-OTW sea level static standard day cycle as defined in the technical requirements. The second was a composite cycle considered to be more representative of a modern high pressure ratio, high bypass turbofan. The QCSEE UTW and OTW engines both use the existing F101 core, resulting in low pressure ratio cycle designs. With the low combustor inlet temperatures and pressures associated with this low cycle pressure ratio, the $NO_x$ emissions would not be expected to be a problem. Since the technology being developed was intended for higher pressure ratio engines, the development was carried out using the higher pressure ratio cycle.

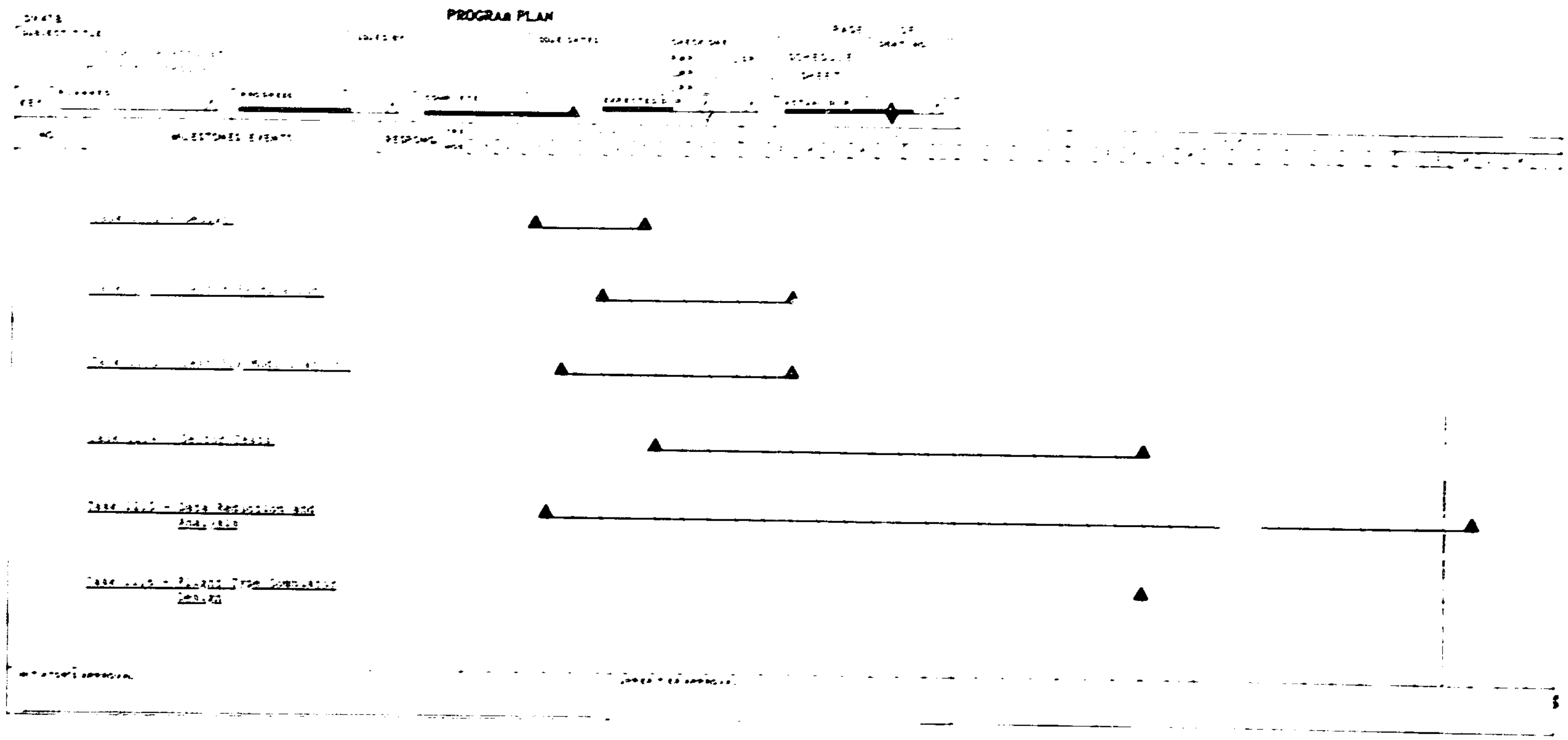



Figure 1. QCSEE Double Annular Combustor Schedule.

Table 1. Pollutant Emission Level Goals of the QCSEE Double Annular Dome Combustor Program.

- Sea Level Static Engine Operating Conditions
- Standard Day Calculations
- Aviation Kerosene Fuel
- QCSEE Double Annular Cycle (4.0% Takeoff Thrust at Idle)

A. Peak Emission Goals

| Pollutant Emission | Engine Operating Mode | Program Goal | QCSEE OTW Engine Status** |
|---|---|---|---|
| $NO_x$ (as $NO_2$) - g/kg Fuel | Takeoff | 15 | 21.5 |
| CO - g/kg Fuel | Ground Idle | 28 | 60 |
| HC (as $C_m H_{1.9m}$) - g/kg Fuel | Ground Idle | 5 | 5 |
| Smoke - (SAE SN) | Takeoff | 22 | 40 |

B. EPA Emission Parameter Goals

| Pollutant Emission | Program Goal | QCSEE OTW Engine Status** |
|---|---|---|
| $NO_x$ (as $NO_2$) lb/1000 lb Thrust - Hr | 3.0 | 4.3 |
| CO lb/1000 lb Thrust - Hr | 4.3 | 11.2 |
| HC lb/1000 lb Thrust - Hr | 0.8 | 0.94 |

* EPA 1979 Class T2 Engine Standards

**With Current Technology Combustor (Single Annular Design) and with Sectorized Burning at Idle

Table II presents a comparison between this higher pressure ratio cycle and the QCSEE-OTW low pressure ratio cycle at conditions used in performing the EPA parameter calculations. The use of this higher pressure ratio double annular cycle did result in improved combustor inlet conditions at the QCSEE ground idle power settings of 4.5% of sea level takeoff thrust. Therefore, a setting of 4.0% was selected as more representative of ground idle for this double annular cycle. The higher combustor inlet temperatures and pressures associated with this double annular cycle result in higher $NO_x$ emission levels than would be expected with the low pressure ratio cycle.

The emission goals shown in Table I are very challenging and require the development of advanced combustor design technology to obtain these very low emission levels.

### Combustor Performance Goals

The key combustor performance goals are presented in Table III. Except for combustion efficiency levels at low engine power operating modes, the current conventional design QCSEE combustor already provides performance levels equal to or better than the goals. Thus, the major challenge of this program was to develop technology for advanced combustor designs with significantly reduced pollution levels without compromising performance characteristics. The current QCSEE OTW combustor configuration has a combustion efficiency goal of 98.0 percent at the idle operating mode. The combustion efficiency goal at idle of this program was specified as 98.9 percent, to be consistent with the prescribed CO and HC emission level goals.

Table II. QCSEE Double Annular Combustor Engine Cycle.

| $F_N$% SLTO | $F_N$ kN | $W_c$ kg/s | $T_3$ K | $P_3$ Atm | $W_f$ kg/hr | $\eta_c$ | Operating Mode |
|---|---|---|---|---|---|---|---|
| 4.0 | 3.91 | 5.53 | 414 | 2.44 | 318 | 0.8933 | Idle |
| 30 | 29.4 | 19.9 | 602 | 9.94 | 957 | 0.9875 | Approach |
| 85 | 83.2 | 36.6 | 753 | 21.2 | 2833 | 0.9875 | Climb |
| 100 | 97.9 | 40.5 | 783 | 24.2 | 3412 | 0.9875 | Takeoff |
| QCSEE OTW Engine Cycle | | | | | | | |
| 4.5 | 4.1 | 5.53 | 414 | 2.44 | 318 | 0.8933 | Idle |
| 30 | 27.1 | 15.1 | 554 | 7.28 | 862 | 0.9875 | Approach |
| 85 | 76.8 | 25.8 | 686 | 14.8 | 2522 | 0.9875 | Climb |
| 100 | 90.3 | 28.4 | 726 | 17.0 | 3160 | 0.9875 | Takeoff |

Table III. Combustor Performance Goals of the QCSEE Double Annular Dome Combustor Program.

| | Operating Mode | Program Goal |
|---|---|---|
| Minimum Combustor Efficiency | Idle | 98.9% |
| | SLTO | 99.5% |
| Maximum Pressure Drop | SLTO | 5.0% |
| Altitude Relight | Windmilling | Meet QCSEE Engine Relight Envelope |

## 4.0 DOUBLE ANNULAR DOME COMBUSTOR DESIGN

The QCSEE OTW engine configuration currently uses the F101 PFRT engine combustor while the UTW engine uses the F101 PV engine combustor. A cross-sectional drawing of the F101 PFRT combustor is shown in Figure 2. Relative to those of other turbofan engine combustors, the emission characteristics of this advanced combustor design are generally quite favorable. However, in the UTW and OTW engine applications, its CO and HC emission levels - in terms of the takeoff-landing mission cycle parameter used by the EPA to define aircraft emission standards - are well in excess of the prescribed standards because of the adverse combustor operating conditions that prevail in these engines at ground idle. These adverse idle operating conditions are associated with the comparatively low cycle pressure ratios of the two QCSEE configurations.

The emission levels of the UTW and OTW engines, when equipped with the existing F101 PFRT engine combustor, are shown in Table IV.

To meet the applicable CO and HC emissions standards as defined by the EPA for the QCSEE OTW configuration, emission indices at OTW ground idle operating conditions of about 28 and 5 grams per kilogram of fuel, respectively, are required. Based on the results of tests of both the F101 PFRT engine combustor and various CF6-50 engine combustors, the use of sectorized fuel staging at idle is known to result in significant CO and HC emission level reductions. However, even with the use of this operating technique at idle and other known beneficial engine operational methods at idle, the CO and HC emission levels of the two QCSEE configurations are somewhat higher than the objective values, based on combustor component tests (Reference 4).

Based on theoretical considerations and the results of analytical studies carried out with the aid of General Electric models for predicting the CO and HC emission levels of combustors, there appears to be no fundamental barrier to meeting the target CO and HC emission levels with the QCSEE combustor conventional configuration in spite of its compact and short length design - even at the somewhat adverse idle operating conditions of the two QCSEE configurations.

These investigations have shown that the key guidelines for obtaining low CO and HC emission levels, at idle operating conditions, are:

- Provide fine fuel atomization and rapid mixing of the fuel and air within the dome swirl cups.

- Eliminate all fuel streaking from the swirl cups and prevent fuel from impinging on the dome and cooling liner surfaces.

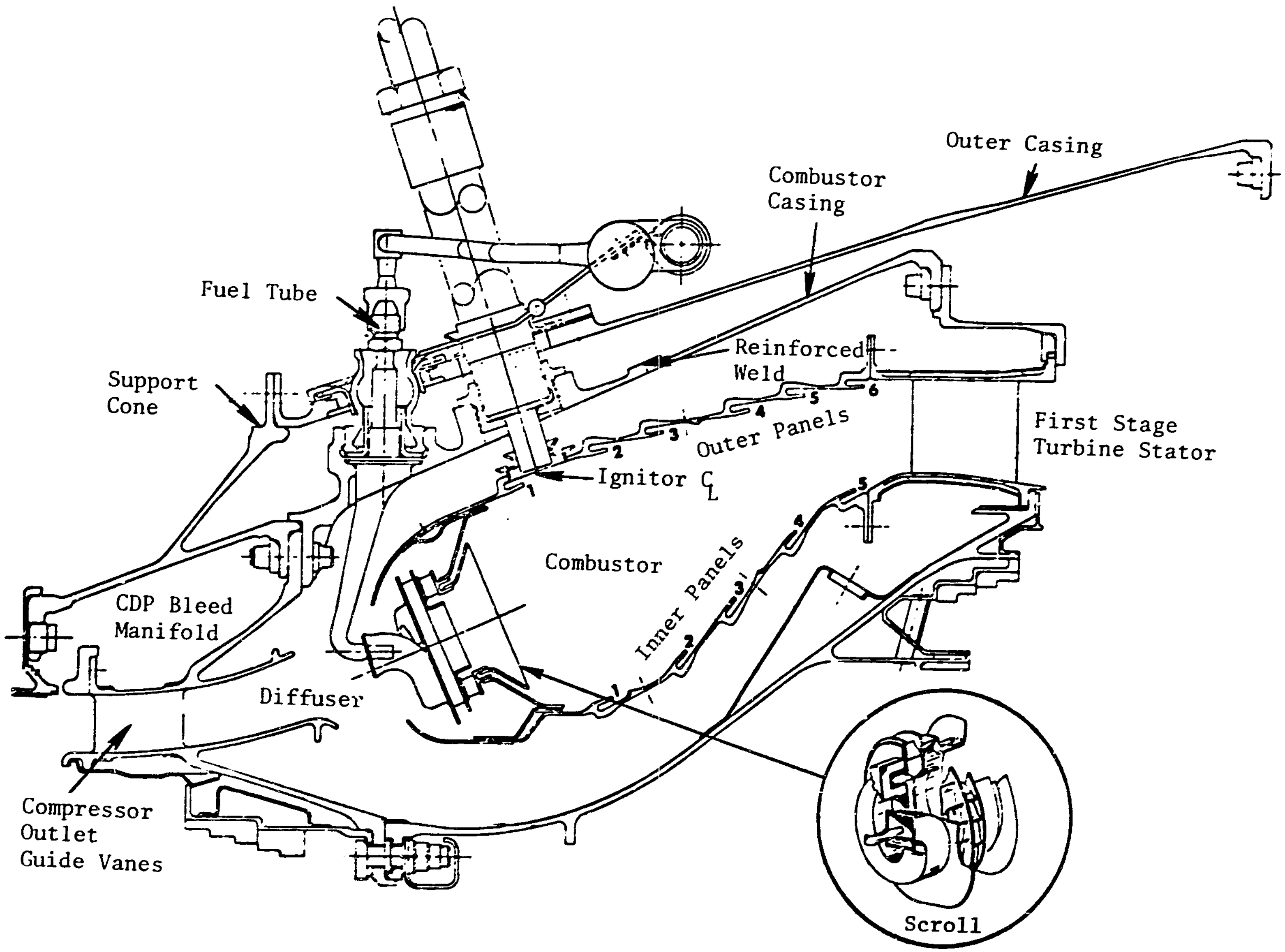



Figure 2. PFRT Combustor Cross Section.

Table IV. Summary of QCSEE Component Test Results with Conventional Combustor Compared to the EPA Standards.

| | | Constant Fan Pitch | | Constant Fan Speed | | Applicable EPA Standards |
|---|---|---|---|---|---|---|
| | | Full Burning | With Sector Burning | Full Burning | With Sector Burning | |
| UTW | $CO^*$ | 28.2 | 17.5 | 27.2 | 16.6 | 4.3 |
| | $HC^*$ | 5.9 | 1.3 | 5.8 | 1.2 | 0.8 |
| | $NO_x^*$ | 2.1 | 2.1 | 3.0 | 3.0 | 3.0 |
| | SAE - SN | 31 | - | 31 | - | 24 |
| OTW | $CO^*$ | 23.0 | 11.2 | - | - | 4.3 |
| | $HC^*$ | 5.3 | 0.9 | - | - | 0.8 |
| | $NO_x^*$ | 2.8 | 2.8 | - | - | 3.0 |
| | SAE - SN | 7 | - | - | - | 22 |

*EPA Parameter: lb per 1000 lb Thrust - hr/Cycle

- Maintain swirl cup equivalence ratios near 1.0 to promote rapid HC consumption. If fuel quenching effects are successfully eliminated, this approach - based on theoretical considerations - should result in very low residual HC emission levels.

- Rapidly dilute these near stoichiometric combustion gases, as discharged from the swirl cups, to a uniform primary combustion zone equivalence ratio in the range of 0.5 to 0.7.

- Allow sufficient residence time, in the range of 1.0 to 1.5 milliseconds, before these diluted primary zone combustion gases are further diluted. This latter guideline is based on analytically determined CO consumption rate data, obtained through the use of General Electric Analytical models developed to predict the CO emission characteristiscs of combustors.

However, these investigations have also shown that the attainment of low $NO_x$ emissions requires the use of lean and uniform fuel-air mixtures in the combustion zone at high engine power operating conditions. To meet this requirement, as well as the above described combustion zone conditions at idle operating conditions necessitates the use of some form of combustion process staging. A double annular dome combustor configuration incorporating a staged combustion approach has been developed in the NASA/GE ECCP for use in the CF6-50 engine. Based on the development efforts of this program, the Double Annular Dome combustor design concept was found to be a particularly promising design approach. With the preferred versions of this design approach, low pollutant emission levels which meet or closely approach the applicable EPA standards and otherwise acceptable performance characteristics have been obtained.

The final development version of this advanced CF6-50 combustor configuration is shown in Figure 3. Generally excellent pollutant emissions and performance characteristics were obtained with this combustor configuration in demonstrator CF6-50 engine tests conducted as part of the NASA/GE ECCP.

Based on these promising NASA/GE ECCP findings, the double annular dome combustor design concept was selected as the approach for obtaining the objective low emission levels in the QCSEE configurations and in possible future derivative QCSEE-type engines. Based on the NASA/GE ECCP results with the double annular dome CF6-50 combustor, it appears that the objective CO and HC emission levels should be attainable with a double annular dome QCSEE combustor, at the presently defined idle operating conditions of the QCSEE OTW engine, as shown in Table V. Also, $NO_x$ emissions levels well below the EPA standard should be obtainable with such an advanced combustor configuration at the operating conditions of the QCSEE UTW and OTW engines. Thus, $NO_x$ emission levels, which meet the standards, would also be expected even with versions of the QCSEE UTW and OTW engines with somewhat higher cycle pressure ratio.

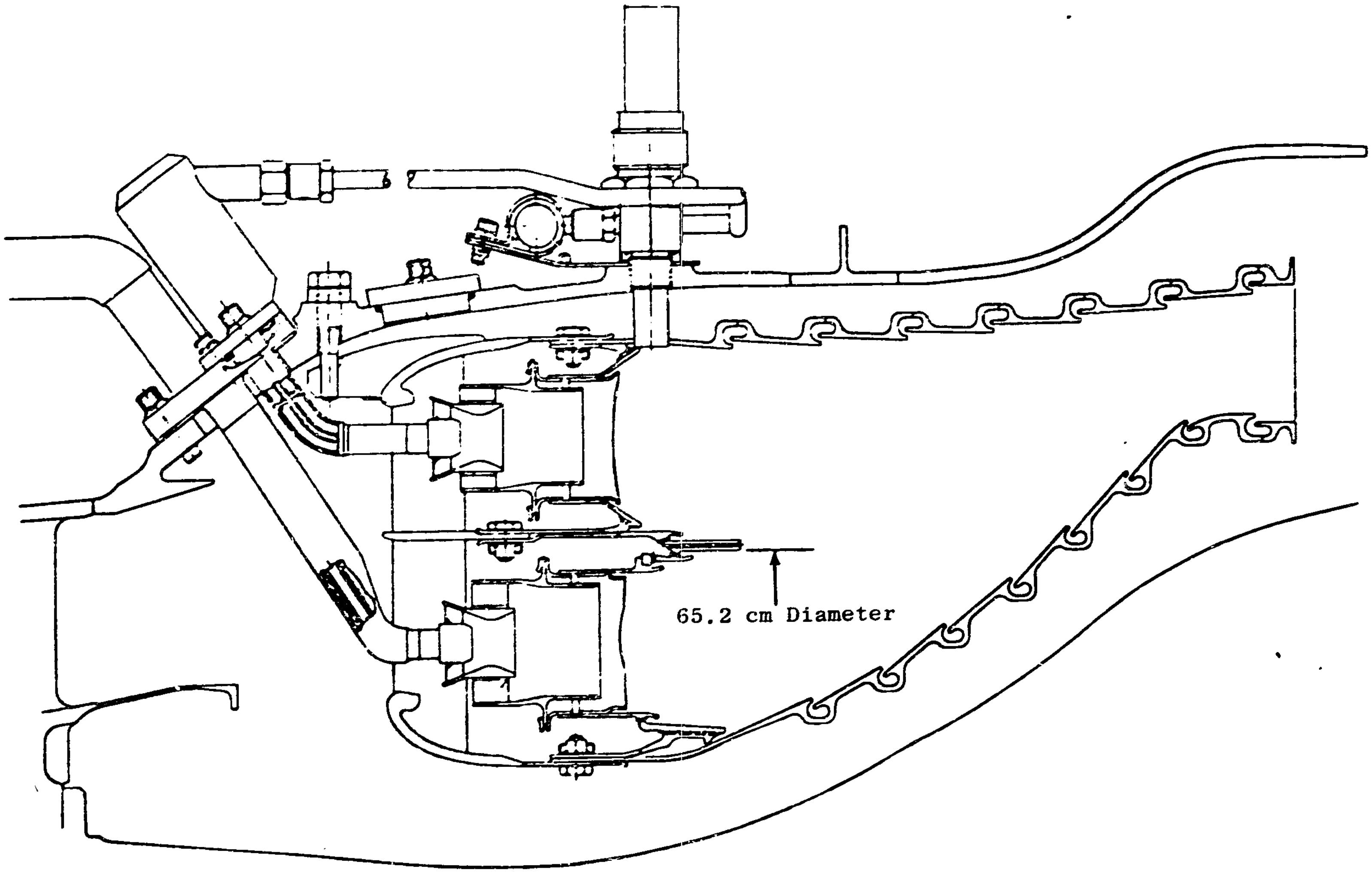



Figure 3. NASA/GE ECCP Double Annular Dome Combustor Design for CF6-50 Engine.

Table V. Combustor Operating Conditions of QCSEE OTW and CF6-50 Engines at Ground Idle and Takeoff.

| | OTW Engine | CF6-50 Engine |
|---|---|---|
| • Standard Day Ground Idle | | |
| Combustor Inlet Air Temperature, K | 415 | 429 |
| Combustor Inlet Air Pressure, Atm. | 2.5 | 2.9 |
| Combustor Fuel/Air Ratio | 0.0159 | 0.011 |
| • Standard Day Takeoff | | |
| Combustor Inlet Air Temperature, K | 726 | 821 |
| Combustor Inlet Air Pressure, Atm. | 17.0 | 29.8 |
| Combustor Fuel/Air Ratio | 0.0309 | 0.0231 |

Because the core engine of the two QCSEE configurations is considerably smaller than that of the CF6-50 engine, a considerably smaller scale version of the CF6-50 double annular dome combustor is required. The baseline design of the double annular dome QCSEE combustor is shown in Figure 4 and is a scaled-down version of the preferred CF6-50 combustor configuration, as evolved in the NASA/GE ECCP. A comparison of key aerodynamic design parameters of the baseline QCSEE double annular dome combustor, the NASA/GE ECCP CF6-50 double annular dome combustor,and the existing F101 PFRT engine combustor is presented in Table VI. As shown in this table, the combustor dome heights and the combustor airflow distribution of the baseline QCSEE double annular dome combustor design were similar to those of the preferred CF6-50 NASA/GE ECCP combustor configuration. This QCSEE configuration has been designed to fit within the existing outer combustor casing of the F101 core engine. However, a small change has been made in the inner casing contours. The inner casing diameter, aft of the step diffuser, has been decreased by up to about 0.4 inch.

The general arrangement of the QCSEE double annular dome combustor design is shown in Figure 5. The combustor consists of a dome assembly, a cowl, and modified arrays of air swirlers (20 in each annulus for a full annular combustor) which are separated by a short centerbody.

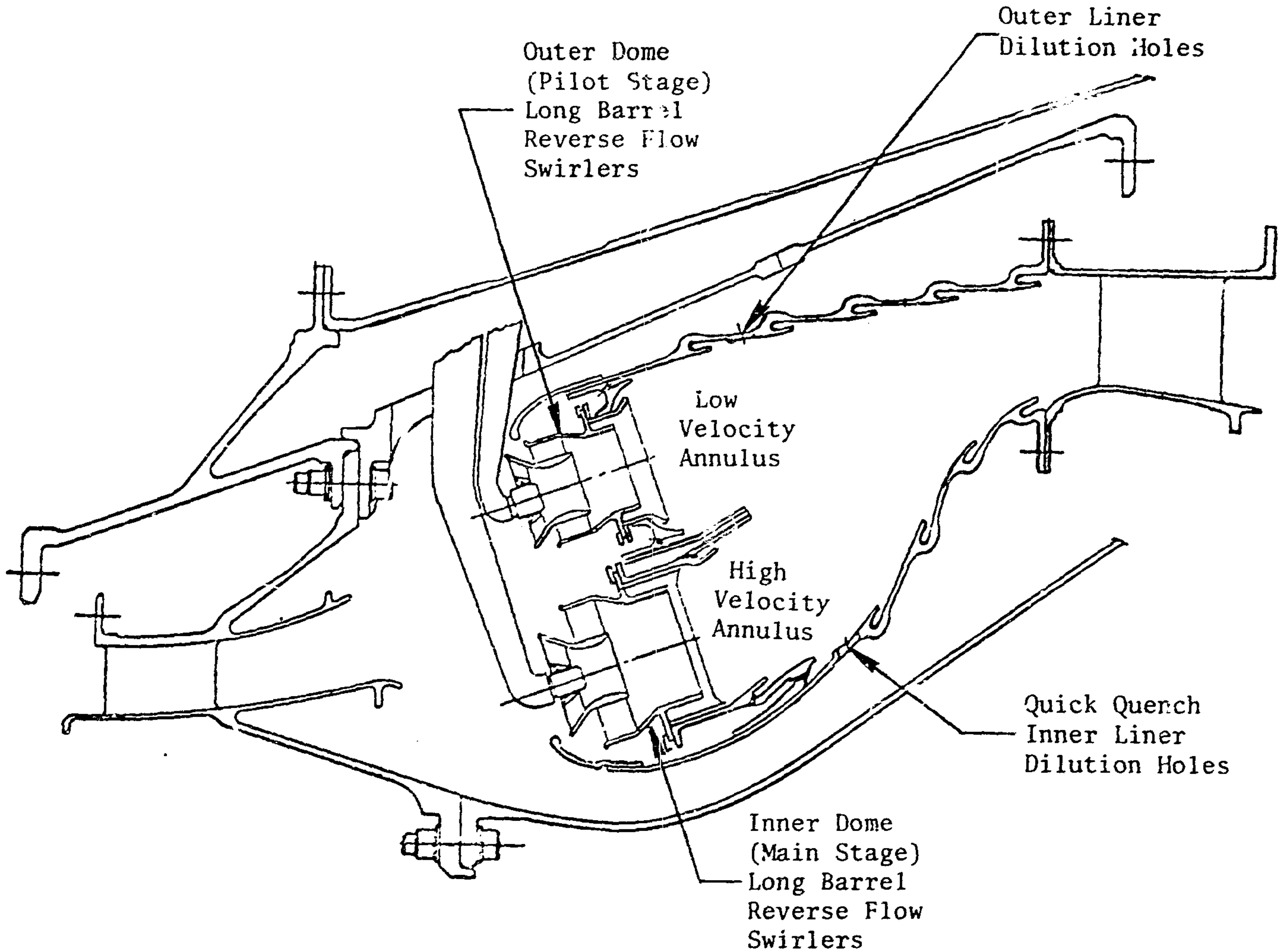



Figure 4. QCSEE Double Annular Dome Combustor Design.

Table VI. Comparison of Key Combustor Aerodynamic Design Parameters.

| Parameter | Double-Annular Dome QCSEE | Double-Annular Dome CF6-50 (NASA ECCP D-8) | F101 PFRT/ QCSEE |
|---|---|---|---|
| Combustor Operating Conditions | SLSTO of OTW Engine | SLSTO of CF6-50 Engine | SLSTO of OTW Engine |
| Combustor Length ($L_c$), cm | 19.0 | 33.3 | 20.3 |
| Dome Height ($H_D$), cm | -- | -- | 8.6 |
| Outer | 5.6 | 5.6 | -- |
| Inner | 4.6 | 5.3 | -- |
| Reference Velocity, m/s | 16.5 | 25.9 | 17.1 |
| Dome Velocity, m/s | -- | -- | 6.7 |
| Outer | 6.1 | 10.7 | -- |
| Inner | 19.8 | 35.1 | -- |
| Outer Passage Velocity, m/s | 54.3 | 42.4 | 43.3 |
| Inner Passage Velocity, m/s | 54.3 | 45.7 | 43.3 |
| Space Rate | 8.2 | 5.8 | 9.0 |
| Combustor Airflow Distribution, %: | | | |
| Dome Total | -- | -- | 34.3 |
| Dome Outer | 19.2 | 17.0 | -- |
| Dome Inner | 41.8 | 42.5 | -- |
| Centerbody | 4.2 | 4.0 | -- |
| Liner Dilution | 16.8 | 15.6 | 37.1 |
| Liner Cooling | 18.0 | 20.9 | 28.6 |
| | 100.0 | 100.0 | 100.0 |

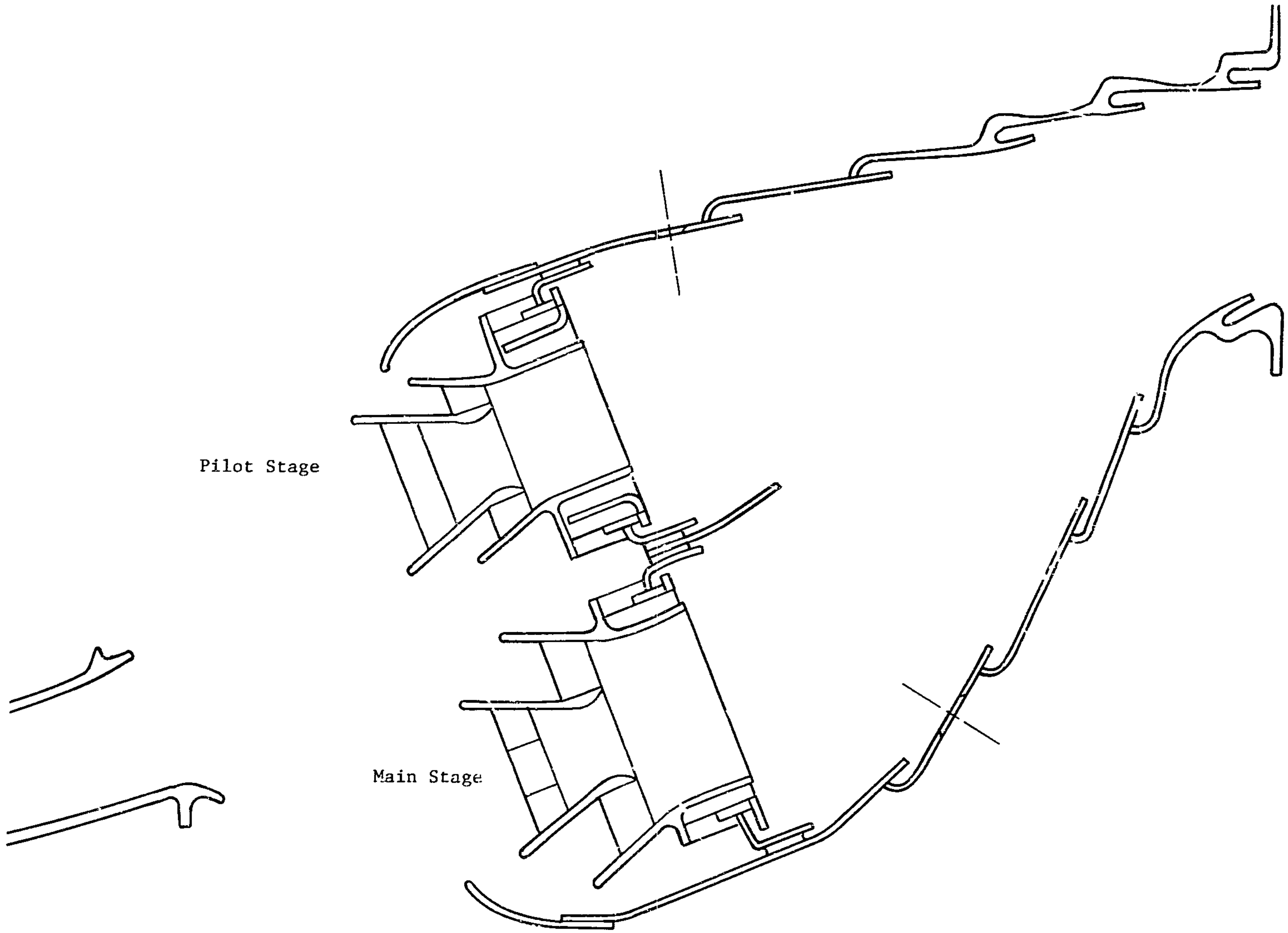



Figure 5. QCSEE Double Annular Sector Combustor.

## 5.0 DOUBLE ANNULAR SECTOR COMBUSTOR TEST CONFIGURATIONS

For the baseline combustor design, the pilot stage was located in the outer annulus. In subsequent development versions, the following six features of the baseline design were varied:

1. Centerbody geometry
2. Airflow distribution
3. Pilot stage annulus axial and radial location
4. Air swirler geometry
5. Dilution hole location
6. Intermediate and high power fueling modes

Key design features of each test configuration are illustrated in Figure 6. The combustor flow area/airflow distributions for each configuration are summarized in Table VII.

Three different secondary swirler configurations were used in the pilot stage development. These configurations are shown in Figures 7 through 9. The key development feature was the introduction of the radial secondary swirler and a wide angle swirl cup sleeve insert plus the elimination of the mixing barrel in Configuration 12. The main stage swirl cup configurations are also shown in Figures 7 and 9. As with the pilot stage, the key development feature was the introduction of the radial secondary swirler. The fuel injector assemblies used are shown in Figure 10. Simplex pressure-atomizing fuel nozzles were used in both the pilot and main stage to obtain the excellent fuel atomization required at the very severe combustor inlet conditions at QCSEE OTW ground idle operation. A number of different fueling modes were investigated in the sector. The fueling modes explored are summarized in Table VIII.

In addition to evaluating the emission levels of the double annular combustor, the altitude relight performance and combustor exit temperature profiles were also evaluated. These tests were conducted in identical sector combustor test rigs.

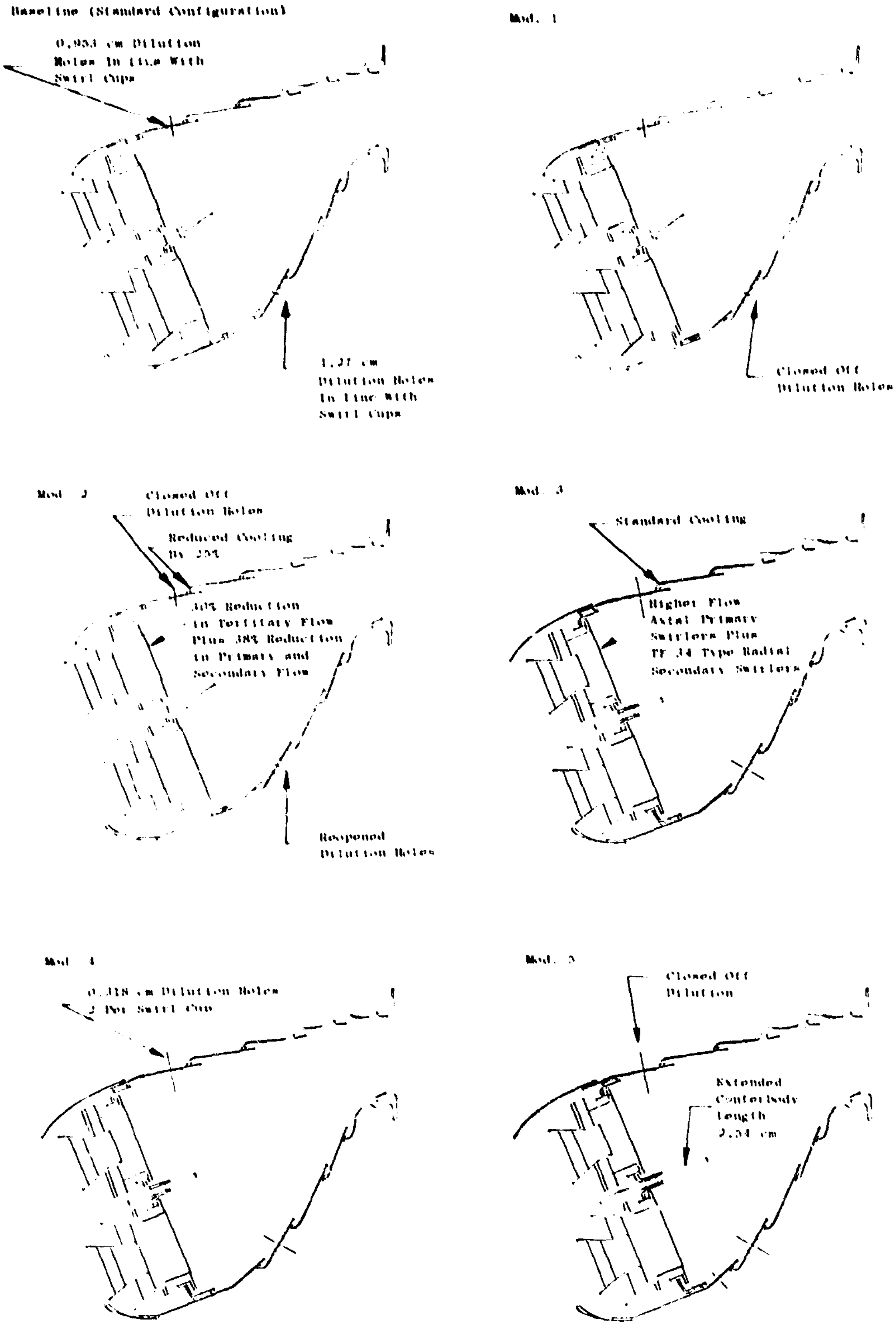



Figure 6. Key Design Features of Test Configurations.

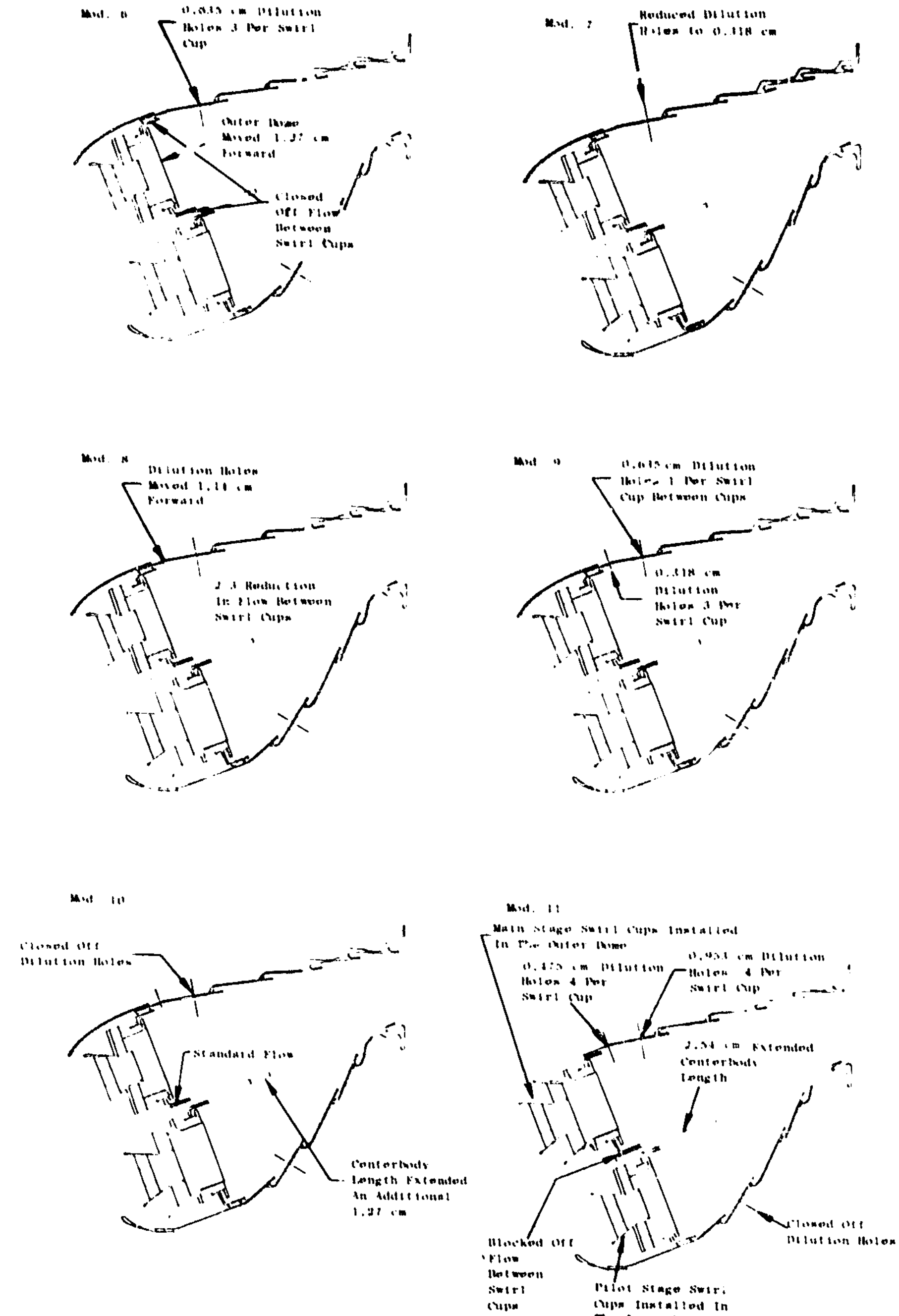



Figure 6. Key Design Features of Test Configurations (Continued).

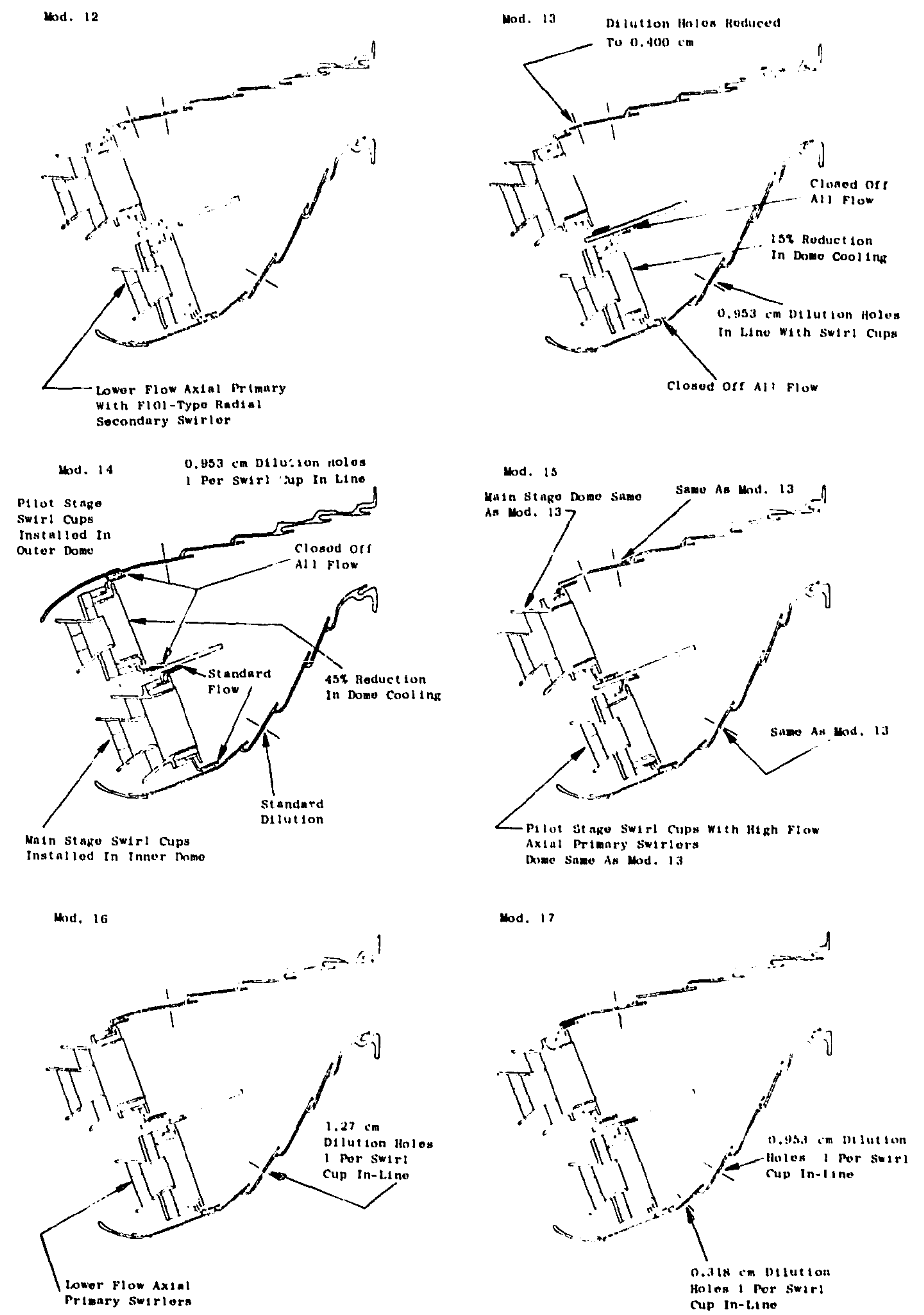
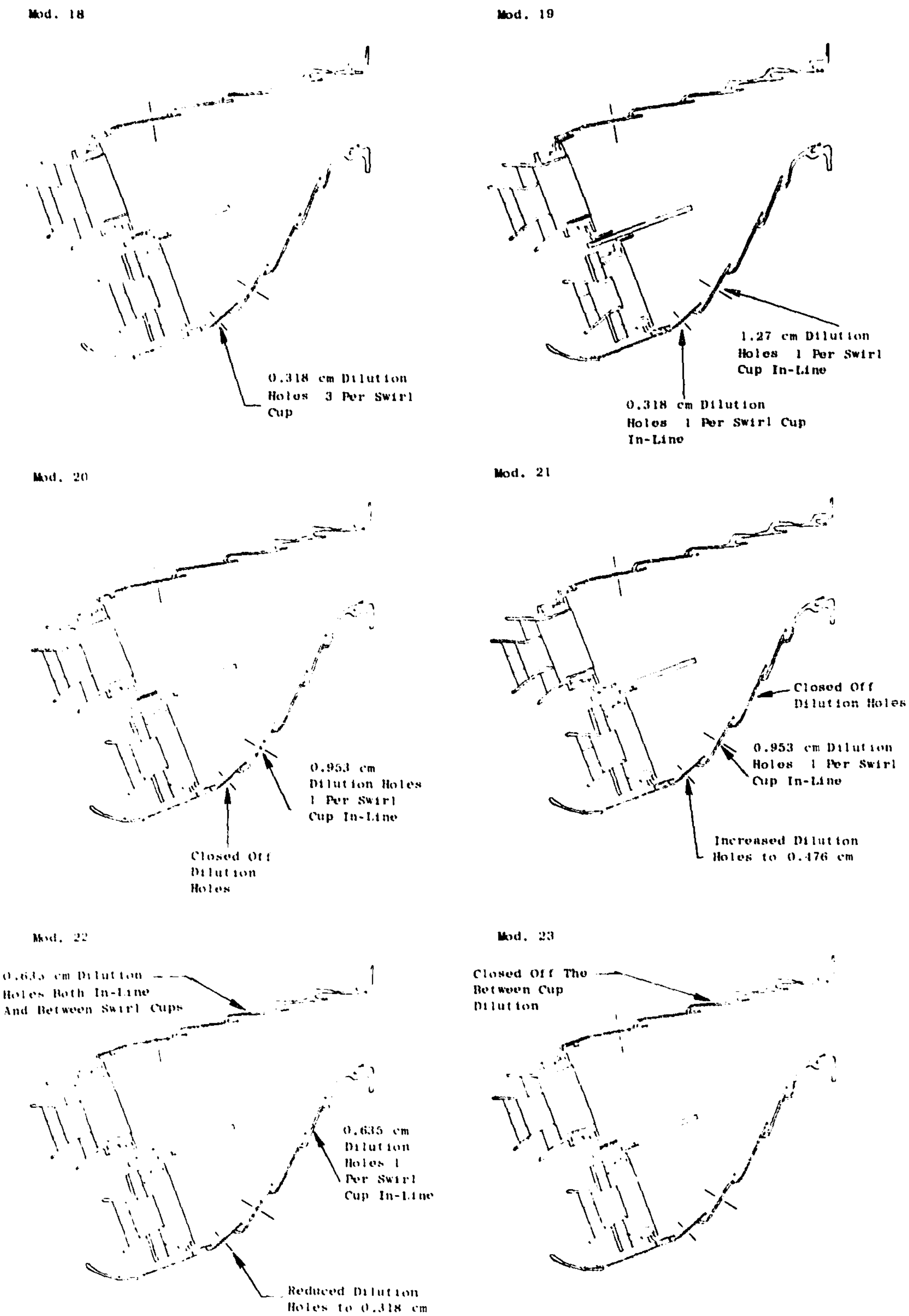



Figure 6. Key Design Features of Test Configurations (Continued).

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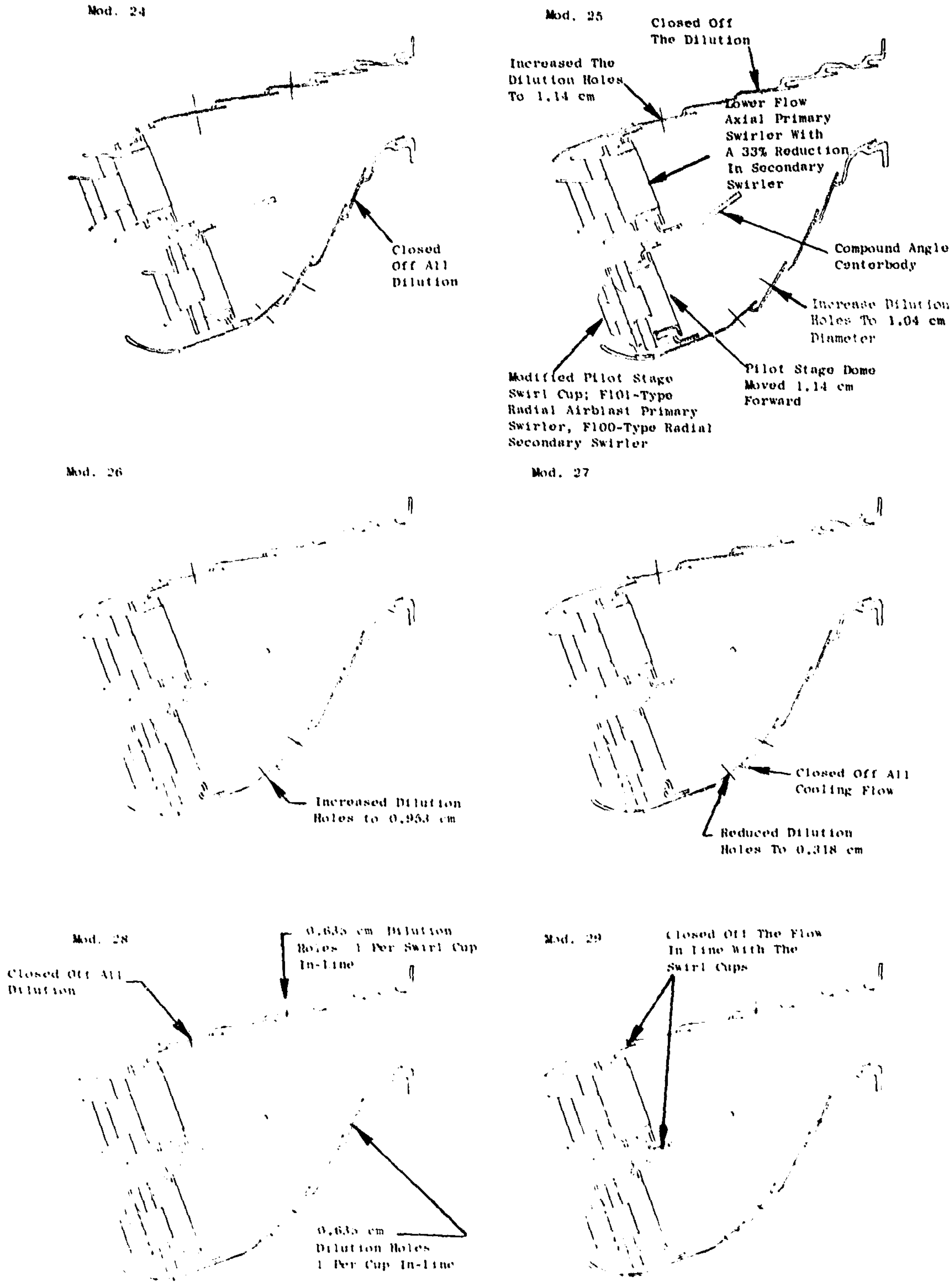



Figure 6. Key Design Features of Test Configurations (Continued).

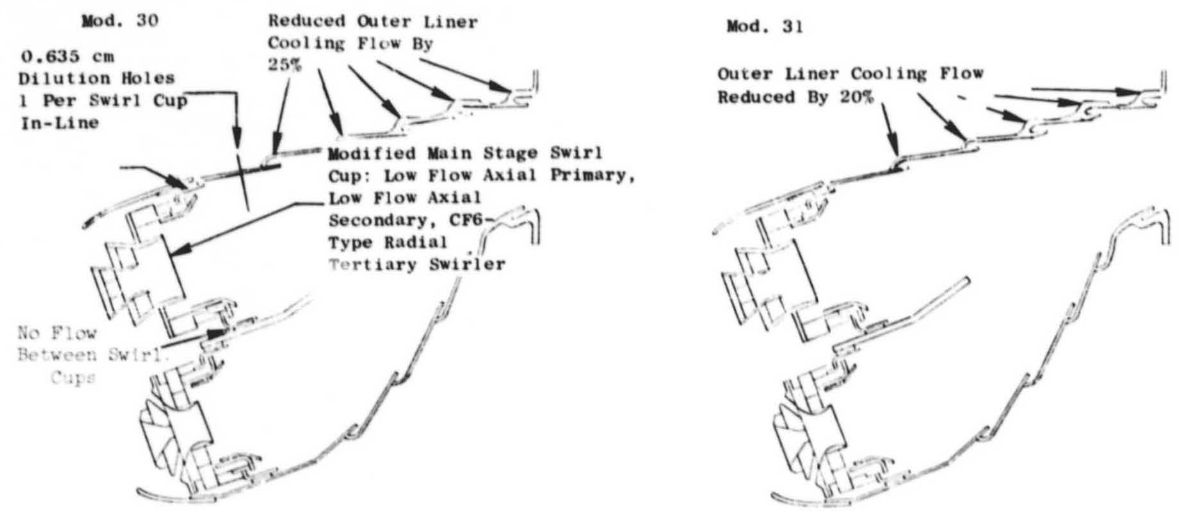
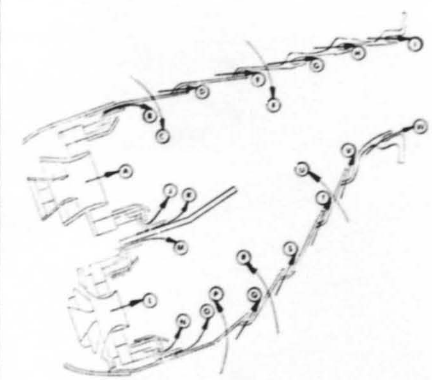



Figure 6. Key Design Features of Test Configurations (Concluded).

Table VII. Measured Flow Distributions for QCSEE Double Annular Sector Combustor.

| Configurations | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Airflows Expressed in Percent of Combustor Airflow | | | | | | | | | | | | | | | | | | | | | |
| Baseline | 14.34 | 3.50 | 4.75 | 3.50 | 2.68 | 0.00 | 1.58 | 1.52 | 0.85 | 3.38 | 2.07 | 33.56 | 2.10 | 2.26 | 2.43 | 0.00 | 2.83 | 8.03 | 2.74 | 2.80 | 0.00 | 3.21 | 1.86 |
| Mod-1 | 15.65 | 3.82 | 4.25 | 2.69 | 1.89 | 0.00 | 1.23 | 1.72 | 1.20 | 3.69 | 2.26 | 36.59 | 2.30 | 2.47 | 2.65 | 0.00 | 3.43 | 0.00 | 3.17 | 3.51 | 0.00 | 4.49 | 2.91 |
| Mod-2 | 9.22 | 3.53 | 0.00 | 3.59 | 3.75 | 0.00 | 2.24 | 2.04 | 1.08 | 3.41 | 2.09 | 34.12 | 2.14 | 2.30 | 2.47 | 0.00 | 3.70 | 10.55 | 3.65 | 3.71 | 0.00 | 4.12 | 2.29 |
| Mod-3 | 10.46 | 3.71 | 0.00 | 4.01 | 3.20 | 0.00 | 2.00 | 2.00 | 1.19 | 3.58 | 2.20 | 35.26 | 2.21 | 2.38 | 2.55 | 0.00 | 3.17 | 8.91 | 3.26 | 3.42 | 0.00 | 4.06 | 2.45 |
| Mod-4 | 11.10 | 3.94 | 0.64 | 3.82 | 3.00 | 0.00 | 1.80 | 1.64 | 0.87 | 3.80 | 2.33 | 37.42 | 2.35 | 2.52 | 2.71 | 0.00 | 2.85 | 8.10 | 2.91 | 2.98 | 0.00 | 3.34 | 1.88 |
| Mod-5 | 11.51 | 4.08 | 0.00 | 4.80 | 3.51 | 0.00 | 1.94 | 1.45 | 0.39 | 3.94 | 2.42 | 37.48 | 2.35 | 2.53 | 2.71 | 0.00 | 2.95 | 8.58 | 2.89 | 2.80 | 0.00 | 2.66 | 1.03 |
| Mod-6 | 10.90 | 2.42 | 3.81 | 3.82 | 3.00 | 0.00 | 1.83 | 1.80 | 1.03 | 3.74 | 1.32 | 36.00 | 2.26 | 2.43 | 2.61 | 0.00 | 2.89 | 8.13 | 3.00 | 3.14 | 0.00 | 3.70 | 2.22 |
| Mod-7 | 11.47 | 2.54 | 0.96 | 3.83 | 3.01 | 0.00 | 1.81 | 1.67 | 0.90 | 3.93 | 1.21 | 37.94 | 2.39 | [illegible] | 2.74 | 0.00 | 2.93 | 8.29 | 3.04 | 3.14 | 0.00 | 3.59 | 2.07 |
| Mod-8 | 11.32 | 2.51 | 1.00 | 3.87 | 2.98 | 0.00 | 1.78 | 1.72 | 0.98 | 3.88 | 1.58 | 37.71 | 2.37 | 2.54 | 2.73 | 0.00 | 3.01 | 8.52 | 2.89 | 3.00 | 0.00 | 3.52 | 2.11 |
| Mod-9 | 11.05 | 2.45 | 2.22 | 3.81 | 2.99 | 0.00 | 1.79 | 1.67 | 0.85 | 3.79 | 1.55 | 37.51 | 2.35 | 2.53 | 2.72 | 0.00 | 3.07 | 8.77 | 2.91 | 2.94 | 0.00 | 3.27 | 1.83 |
| Mod-10 | 11.92 | 2.64 | 1.07 | 4.33 | 3.43 | 0.00 | 2.06 | 1.85 | 0.97 | 4.08 | 2.50 | 36.13 | 2.27 | 2.44 | 2.61 | 0.00 | 2.72 | 7.65 | 2.80 | 2.93 | 0.00 | 3.48 | 2.10 |
| Mod-11 | 37.94 | 2.51 | 11.54 | 3.68 | 3.01 | 0.00 | 1.92 | 1.88 | 1.10 | 3.88 | 1.19 | 11.01 | 2.31 | 2.49 | [illegible] | 0.00 | 2.74 | 0.00 | 2.37 | 2.50 | 0.00 | 3.19 | 2.07 |
| Mod-12 | 35.34 | 2.34 | 13.34 | 4.03 | 3.16 | 0.00 | 1.97 | 2.01 | 1.21 | 3.67 | 1.11 | 12.24 | 2.14 | 2.30 | 2.47 | 0.00 | 2.44 | 0.00 | 2.21 | 2.45 | 0.00 | 3.35 | 2.28 |
| Mod-13 | 34.10 | 2.26 | 11.97 | 4.50 | 3.73 | 0.00 | 2.56 | 2.91 | 1.91 | 3.49 | 1.07 | 11.92 | 0.00 | 2.25 | 0.00 | 0.00 | 1.97 | 2.04 | 2.11 | 2.94 | 0.00 | 4.91 | 3.68 |
| Mod-14 | 13.16 | 0.00 | 2.47 | 3.75 | 3.01 | 0.00 | 1.98 | 2.18 | 1.39 | 2.03 | 0.00 | 36.10 | 2.26 | 2.43 | 2.61 | 0.00 | 3.27 | 9.04 | 3.34 | 3.59 | 0.00 | 4.52 | 2.88 |
| Mod-15 | 36.72 | 2.43 | 10.70 | 1.96 | 3.29 | 0.00 | 2.12 | 2.06 | 1.20 | 3.76 | 1.15 | 14.81 | 0.00 | 2.06 | 0.00 | 0.00 | 2.56 | 2.41 | 2.48 | 2.67 | 0.00 | 3.42 | 2.21 |
| Mod-16 | 39.84 | 2.64 | 8.70 | 3.32 | 2.79 | 0.00 | 1.87 | 1.96 | 1.22 | 4.08 | 1.25 | 13.91 | 0.00 | 2.21 | 0.00 | 0.00 | 2.51 | 3.70 | 2.04 | 2.31 | 0.00 | 3.33 | 2.35 |
| Mod-17 | 38.33 | 2.53 | 10.36 | 3.80 | 3.14 | 0.00 | 2.02 | 1.97 | 1.16 | 3.92 | 1.20 | 13.46 | 0.00 | 2.14 | 0.00 | 0.24 | 2.66 | 2.16 | 2.58 | 2.74 | 0.00 | 3.42 | 2.17 |
| Mod-18 | 38.80 | 2.57 | 9.82 | 3.66 | 3.05 | 0.00 | 1.97 | 1.89 | 1.10 | 3.97 | 1.22 | 13.65 | 0.00 | 3.97 | 0.00 | 0.72 | 2.67 | 2.16 | 2.57 | 2.71 | 0.00 | 3.30 | 2.05 |
| Mod-19 | 36.77 | 2.43 | 10.54 | 3.88 | 3.20 | 0.00 | 2.09 | 2.12 | 1.29 | 3.76 | 1.15 | 12.85 | 0.00 | 2.04 | 0.00 | 0.24 | 2.53 | 3.68 | 2.47 | 2.75 | 0.00 | 3.72 | 2.51 |
| Mod-20 | | | | | | | | | | | | | | | | | | | | | | | |
| Mod-21 | 37.87 | 2.51 | 10.09 | 3.77 | 3.13 | 0.00 | 2.09 | 2.20 | 1.38 | 3.87 | 1.19 | 13.37 | 0.00 | 2.12 | 0.00 | 0.61 | 2.36 | 1.84 | 2.34 | 2.71 | 0.00 | 3.86 | 2.68 |
| Mod-22 | 41.30 | 2.73 | 2.97 | 4.48 | 3.54 | 0.00 | 2.12 | 1.87 | 0.95 | 4.23 | 1.29 | 13.94 | 0.00 | 2.21 | 0.00 | 0.28 | 3.16 | 2.53 | 3.00 | 3.03 | 1.13 | 3.36 | 1.87 |
| Mod-23 | 42.36 | 2.80 | 1.40 | 4.27 | 3.40 | 0.00 | 2.04 | 1.76 | 0.86 | 4.33 | 1.33 | 14.35 | 0.00 | 2.28 | 0.00 | 0.30 | 3.25 | 2.59 | 3.18 | 3.18 | 1.15 | 3.40 | 1.79 |
| Mod-24 | 40.95 | 2.71 | 1.50 | 4.34 | 3.32 | 0.00 | 1.97 | 1.89 | 1.06 | 4.20 | 1.29 | 14.97 | 0.00 | 2.38 | 0.00 | 0.35 | 3.51 | 2.78 | 3.39 | 3.48 | 0.00 | 3.88 | 2.03 |
| Mod-25 | 20.30 | 3.16 | 14.20 | 3.77 | 3.31 | 0.00 | 1.93 | 2.01 | 0.91 | 3.63 | 3.47 | 20.67 | 0.00 | 2.33 | 0.00 | 0.31 | 3.35 | 3.84 | 3.25 | 3.39 | 0.00 | 4.18 | 1.99 |
| Mod-26 | 21.43 | 4.36 | 14.39 | 3.83 | 3.28 | 0.00 | 2.02 | 2.16 | 1.13 | 3.34 | 3.67 | 19.78 | 0.00 | 2.23 | 0.00 | 0.28 | 2.87 | 3.38 | 2.70 | 2.95 | 0.00 | 3.86 | 2.35 |
| Mod-27 | 20.86 | 4.25 | 15.55 | 4.20 | 3.63 | 0.00 | 2.26 | 2.43 | 1.09 | 3.25 | 3.57 | 18.65 | 0.00 | 2.10 | 0.00 | 0.34 | 0.00 | 4.23 | 3.48 | 3.54 | 0.00 | 4.39 | 2.18 |
| Mod-28 | 25.97 | 5.29 | 0.00 | 4.60 | 3.81 | 1.48 | 2.21 | 2.21 | 1.05 | 4.04 | 4.44 | 22.20 | 0.00 | 2.50 | 0.00 | 0.35 | 0.00 | 4.35 | 3.54 | 3.62 | 1.63 | 4.51 | 2.21 |
| Mod-29 | 27.03 | 1.57 | 0.00 | 5.49 | 4.40 | 1.71 | 2.66 | 2.78 | 1.16 | 4.21 | 2.31 | 22.60 | 0.00 | 2.55 | 0.00 | 0.38 | 0.00 | 4.64 | 3.81 | 3.88 | 1.75 | 4.82 | 2.26 |
| Mod-30 | 31.91 | 2.14 | 1.49 | 3.68 | 2.95 | 1.53 | 1.79 | 1.89 | 0.91 | 3.90 | 2.14 | 24.57 | 0.00 | 2.77 | 0.00 | 0.34 | 0.00 | 4.35 | 3.59 | 3.65 | 1.66 | 4.53 | 2.37 |
| Mod-31 | 31.67 | 0.00 | 1.46 | 3.89 | 3.12 | 1.50 | 1.90 | 2.01 | 0.97 | 3.87 | 2.12 | 24.38 | 0.00 | 2.75 | 0.00 | 0.37 | 0.00 | 4.42 | 3.56 | 3.62 | 1.55 | 4.49 | 2.35 |
| | WSCA | WDROA | WAD1 | WA1 | WA2 | WAD3 | | | | WDCA | WDR1A | WSCB | WDROB | WDCB | WDR1B | WBD1 | WB1 | WBD2 | WB2 | WB3 | WBD4 | | |



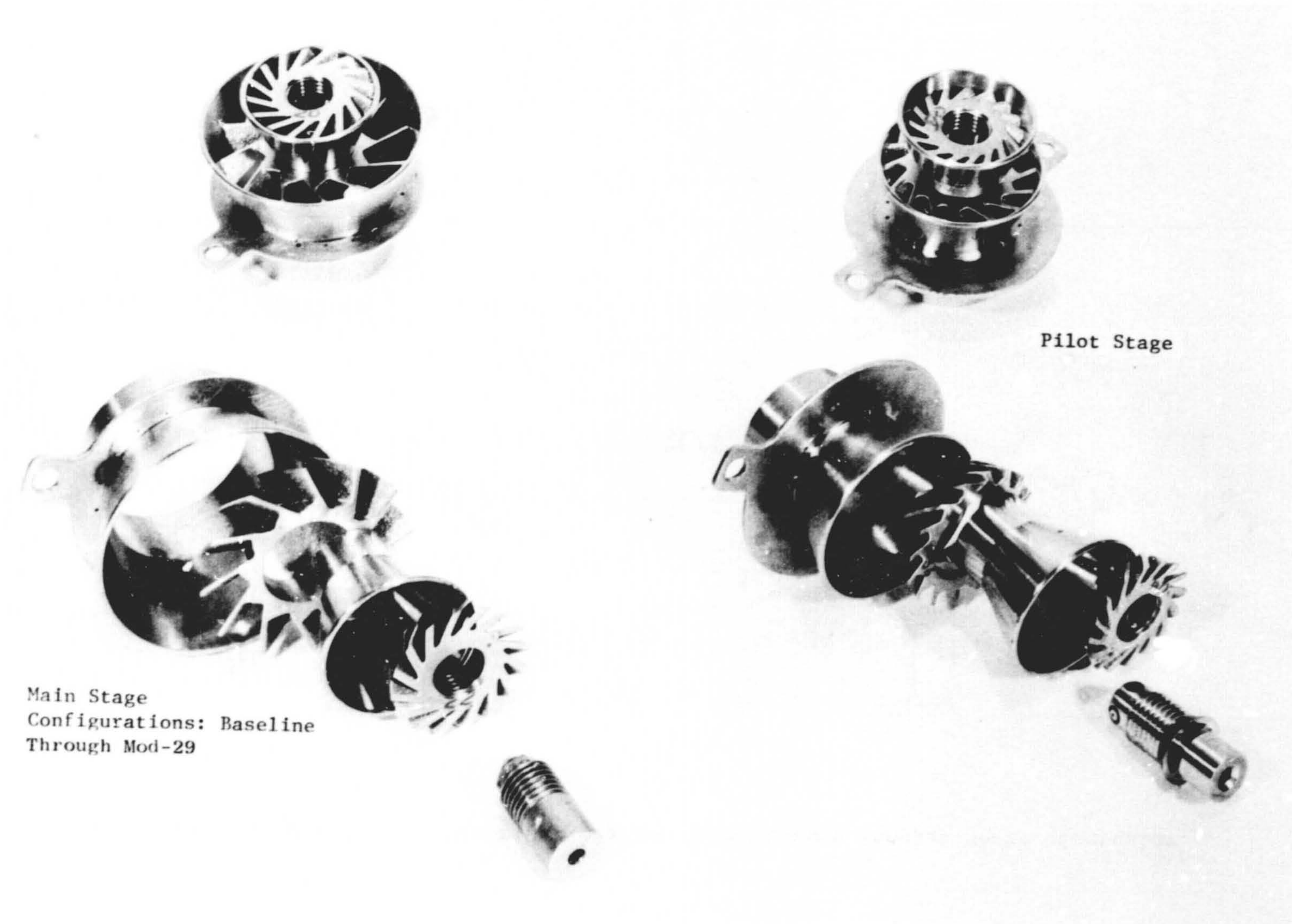



Figure 7. Baseline Design Swirl Cup Hardware.

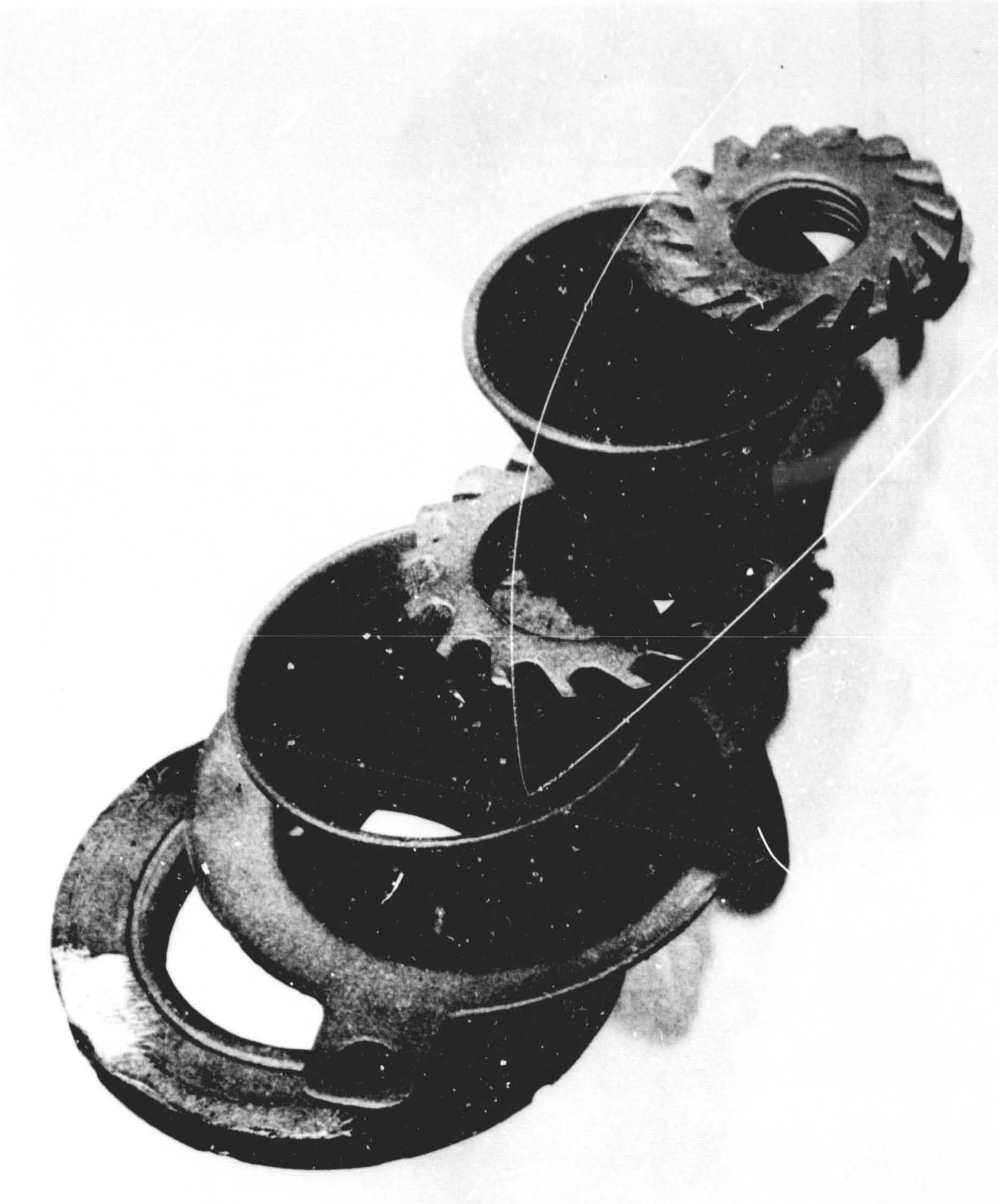


Figure 8. Baseline Test Configuration Pilot Stage Swirl Cup Hardware.

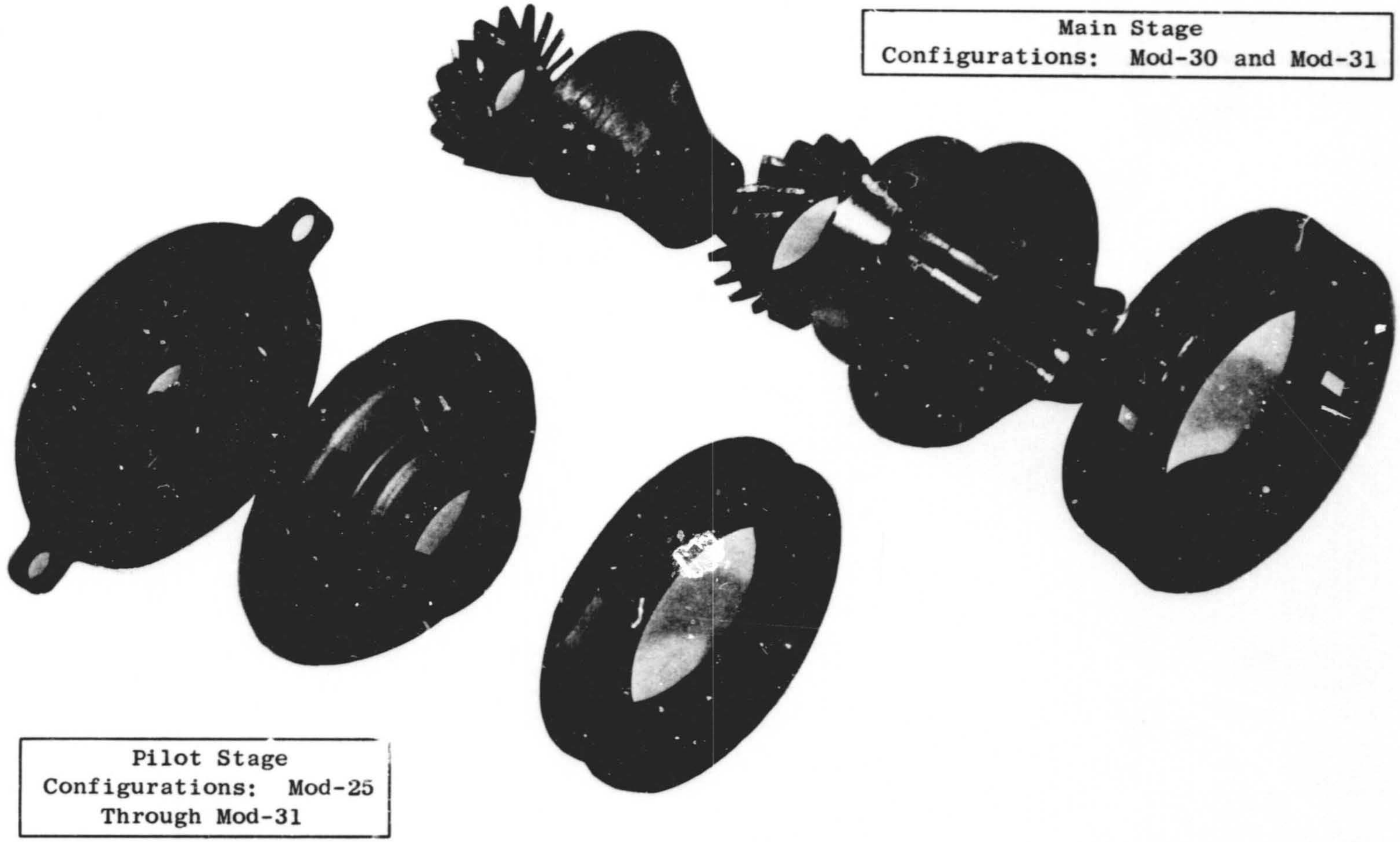
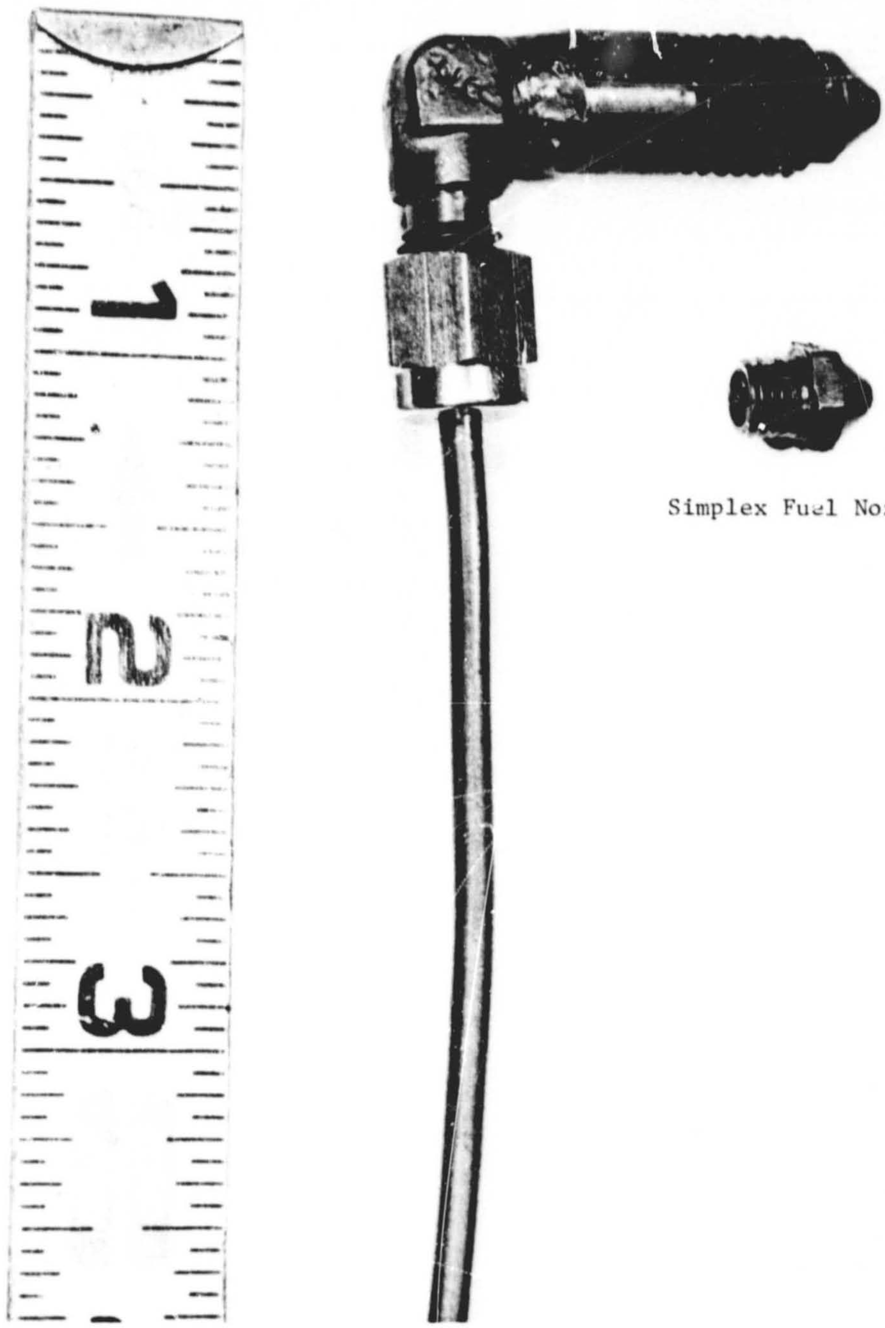



Figure 9. Final Test Configuration Swirl Cup Hardware.



Simplex Fuel Nozzle

Figure 10. Fuel Injection Hardware.

Table VIII. QCSEE Double Annular Dome Sector Combustor Pilot and Main Stage Fueling Modes.

| • QCSEE Design Cycle Operating Conditions | | |
|---|---|---|
| Operating Condition | Pilot Fuel / Total Fuel | Comments |
| Idle | 1.00 | All configurations |
| Approach | 1.00 | Baseline, Mods. 15, 17, 19, 31 |
| | 0.60 | Mod. 31 Only |
| | 0.50 | Baseline, Mods. 17, 31 |
| | 0.40 | Mod. 31 Only |
| | 0.30 | Mods. 17, 31 |
| | 0.20 | Baseline, Mod. 17 |
| | 0.00 | Mod. 31 Only |
| Climb | 0.50 | Mod. 31 Only |
| | 0.40 | Mod. 31 Only |
| | 0.30 | Mod. 31 Only |
| | 0.20 | Mod. 17 Only |
| Cruise | 0.40 | Mod. 31 Only |
| | 0.30 | Mod. 31 Only |
| | 0.20 | Mod. 17 Only |
| Takeoff | 0.50 | Mod. 31 Only |
| | 0.45 | Mod..31 Only |
| | 0.40 | Mod. 31 Only |
| | 0.30 | Mod. 31 Only |
| | 0.20 | Baseline, Mod. 17 |
| | 0.15 | Baseline |
| | 0.10 | Baseline |
| | 0.00 | Baseline |

# 6.0 DEVELOPMENT TEST METHODS

## 6.1 TEST RIG

The QCSEE double annular dome combustor evaluations were conducted in a sector combustor test rig. This sector combustor test rig duplicates the aerodynamic combustor flowpath and envelope dimensions of the QCSEE engine configurations. The test rig consists of an inlet plenum chamber, an inlet diffuser section, a housing for the sector combustor, and an instrumentation section attached to the exit of the combustor housing. The test rig was designed to house a five-swirl cup 90° sector combustor operating at up to four atmospheres pressure and 700 K temperature combustor inlet conditions. A schematic illustration and photograph of the test rig are presented in Figures 11 and 12.

The inlet plenum section of the test rig is attached to the test facility air supply. Inside of the inlet plenum, the flow is straightened by a single screen before it enters into a sector diffuser passage, simulating the compressor discharge of the QCSEE configurations. The diffuser section is a standard QCSEE diffuser design for a conventional combustor design and does not necessarily represent a double annular diffuser design. The combustor housing section consists of a 90° sector of a standard QCSEE combustor casing. Fuel tubes from the five inner and outer annulus fuel injectors are led out of the casing through five equally spaced fuel injector ports. Fuel is supplied to all 10 injectors through a double fuel manifold system. One manifold supplies the inner annulus fuel injectors, and the other supplies the outer annulus fuel injectors. Each system can be operated independently. The instrumentation section is equipped with installation ports to house fixed rake assemblies for obtaining measurements of combustor exit temperaturees and pressures. Gas samples for emissions measurements are also obtained with rakes mounted in these ports.

The test rig instrumentation consists of various pressure probes and thermocouples, plus the fixed rake gas sampling system. Pressure measurements include the diffuser exit total and static pressures, to measure the sector combustor inlet pressures; dome upstream total and static pressures plus downstream static pressures, to measure the combustor dome pressure drops of both the inner and outer annulus; and liner static pressures, to measure the inner and outer passage pressure losses. Total pressures at the sector combustor exit were measured by the probe located in the fixed rake gas sampling system. Temperature measurements included two diffuser exit air thermocouples to measure the sector combustor inlet temperature, four outer liner, four inner liner, and two centerbdy skin thermocouples to measure combustor metal temperatures. Sector combustor exhaust temperatures were measured using five fixed chromel alumel thermocouple rakes in place of the gas sampling rakes. Each of these thermocouple rakes has five individual thermocouples equally spaced at the leading edge of the rake. Several thermocouples were also located in the instrumentation section to measure the temperature of the exhaust gases entering the exhaust section of the facility to monitor the facility operation.

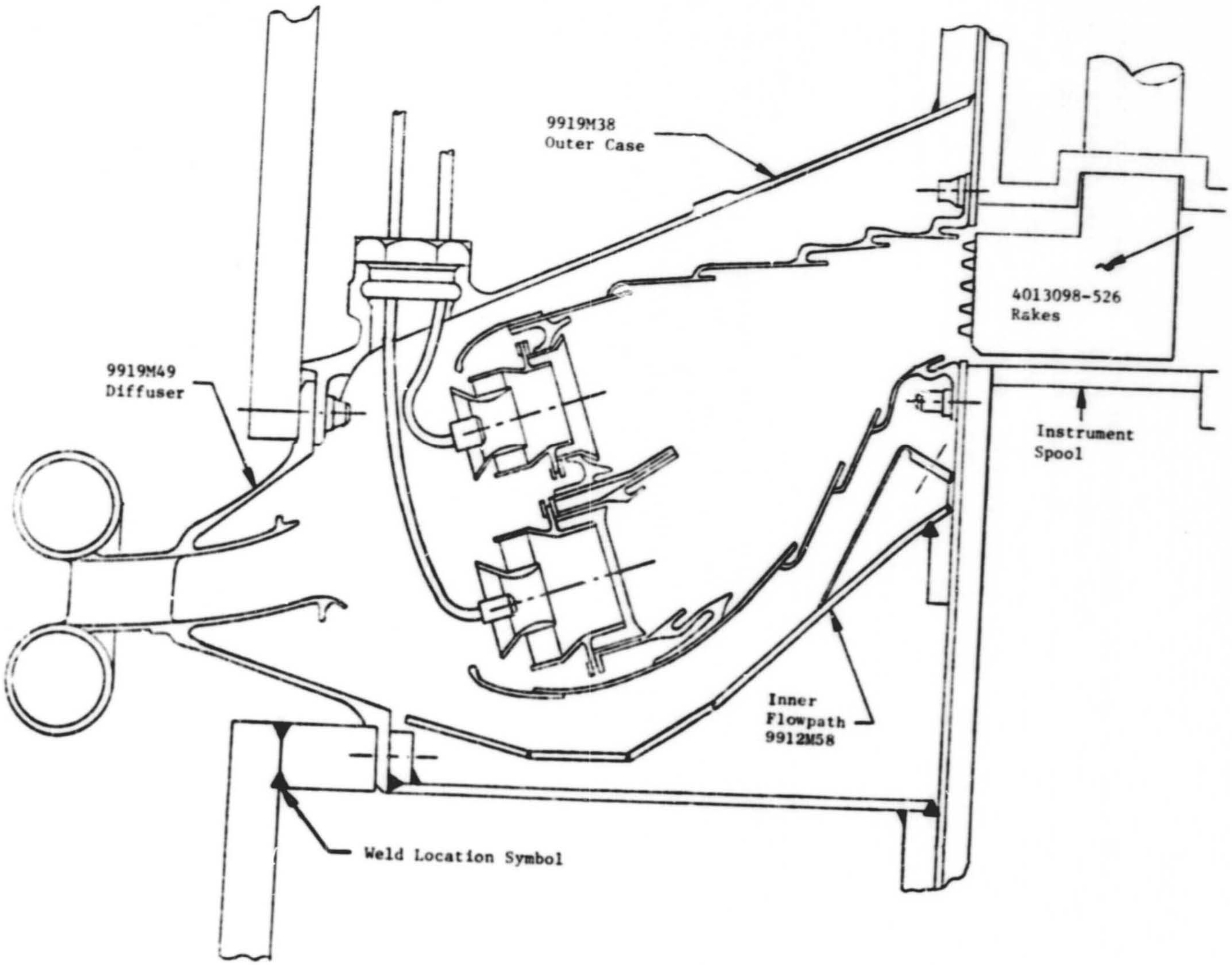



Figure 11. Schematic of Sector Combustor Test Rig.

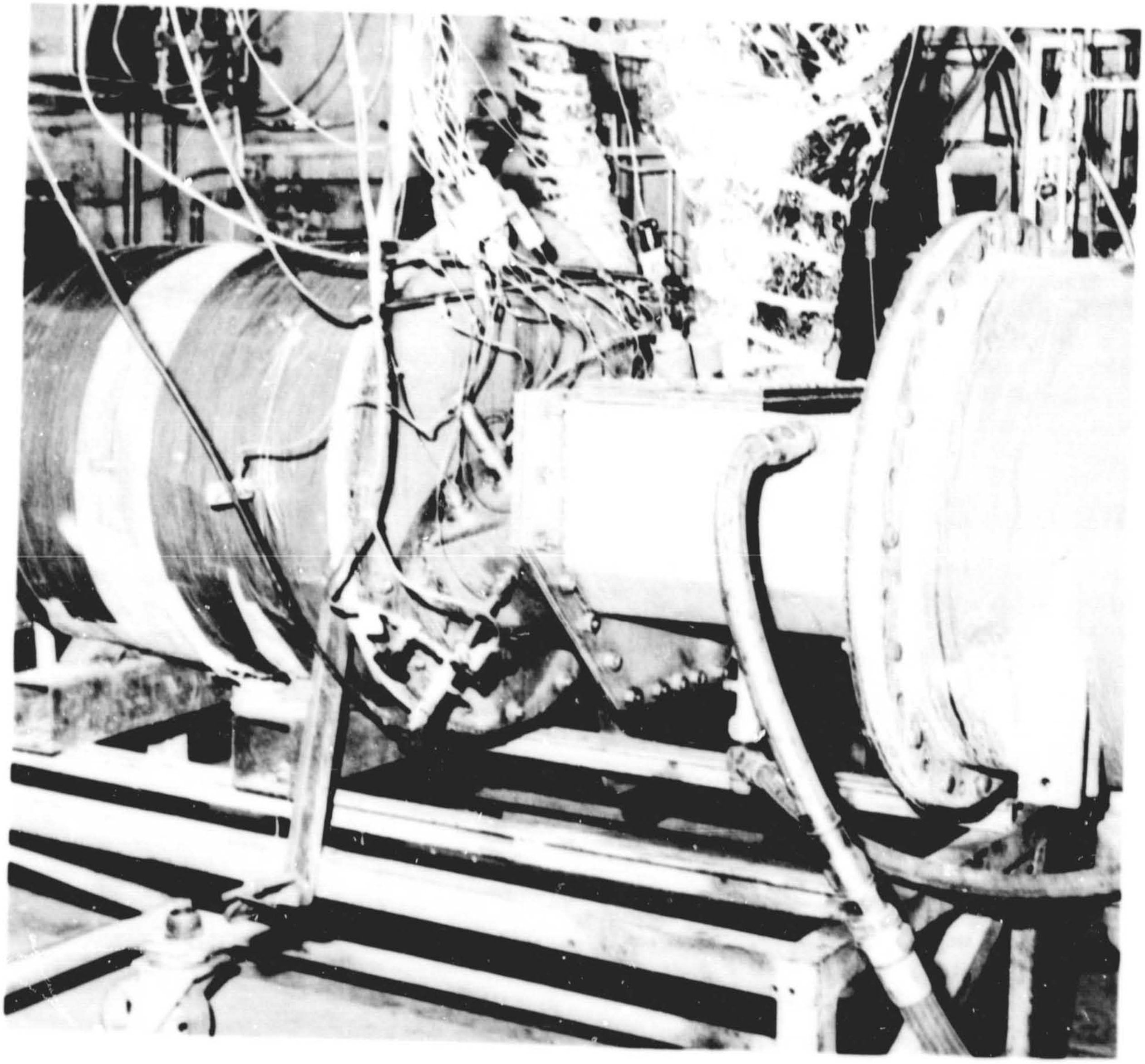


Figure 12. Photograph of Sector Combustor Test Rig.

Sector combustor exhaust gas samples were obtained by extracting samples from the exhaust flow through four gas sampling rakes located in the instrumentation section of the test rig as shown in Figure 13. Each rake has five sampling elements spaced along the leading edge of the rake. These rakes are stationary and the elements can be individually sampled or manifolded together to provide an average radial sample. All five sampling elements of each rake have quick-quenching probe tips. In this rake design, both water cooling of the rake body and steam heating of the sampling lines within the rake are used. A photograph of one of these type of rakes is shown in Figure 14. A schematic of a typical rake sampling element is presented in Figure 15. The tips of each of the sampling elements were designed to quench the chemical reactions of the extracted gas sample as soon as the sample enters the rake. The quenching is necessary to eliminate the possibility of further chemical reactions within the sampling lines. Water cooling of the rake body is necessary to maintain mechanical integrity associated with the high temperature environment created by the combustion exhaust gases. Steam heating of the sampling lines within the rakes is necessary to prevent the condensation of hydrocarbon compounds and water vapor within the sampling lines. An illustration of the locations of the various instrumentation within the test rig is presented in Figure 16.

## 6.2 TEST FACILITIES

All emissions and exit temperature profile development tests of the QCSEE double annular dome sector combustor were performed in the Advanced Combustion Laboratory facility located at the General Electric Evendale Plant. This facility, shown in Figure 17, is equipped with the inlet ducting, exhaust ducting, controls, and instrumentation necessary for conducting sector combustor tests. The range of operating conditions obtainable in this facility is limited because of the airflow and heater capacity currently available. Airflow levels up to 2.8 kg/s can be supplied to the facility from a large compressor, plus an additional 1.8 kg/s can be supplied by the shop air system. Combustor inlet air temperatures above ambient are obtained using the facility liquid fueled, shop-air-supplied indirect-air preheater. The preheater has the capability to heat 1.35 kg/s airflow to 700 K. The Jet A fuel used in all of the QCSEE double annular dome combustor tests was supplied to the sector combustor test rig by a pipeline from storage tanks located adjacent to the facility. Instrumentation cooling and exhaust gas quenching was accomplished using the facility domestic water supply with pressure boost where necessary.

A portion of the altitude ignition evaluations was performed in the Advanced Combustion Laboratory facility due to a lack of availability of the Altitude Test facility normally used for this purpose. Simulated altitude conditions can be achieved in this facility using the steam ejector exhaust system. This system gives the facility the capability to reduce test rig pressures to 0.30 atmospheres. However, the facility does not have cold air or cold fuel capability. Thus, the altitude ignition testing performed in this facility was conducted at ambient air and fuel temperatures.

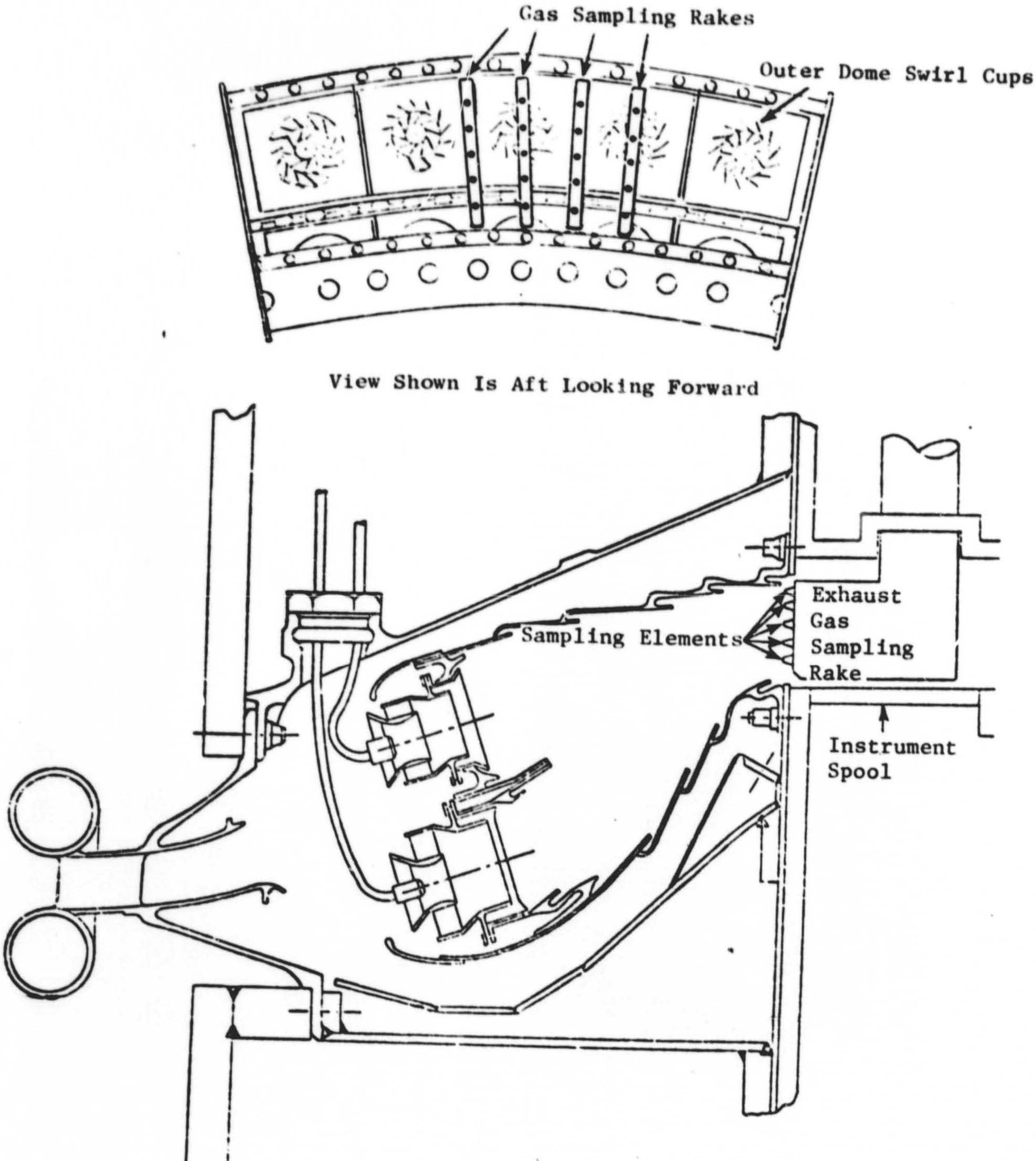



Figure 13. Schematic of Gas Sampling Hardware Location Within the Test Rig.

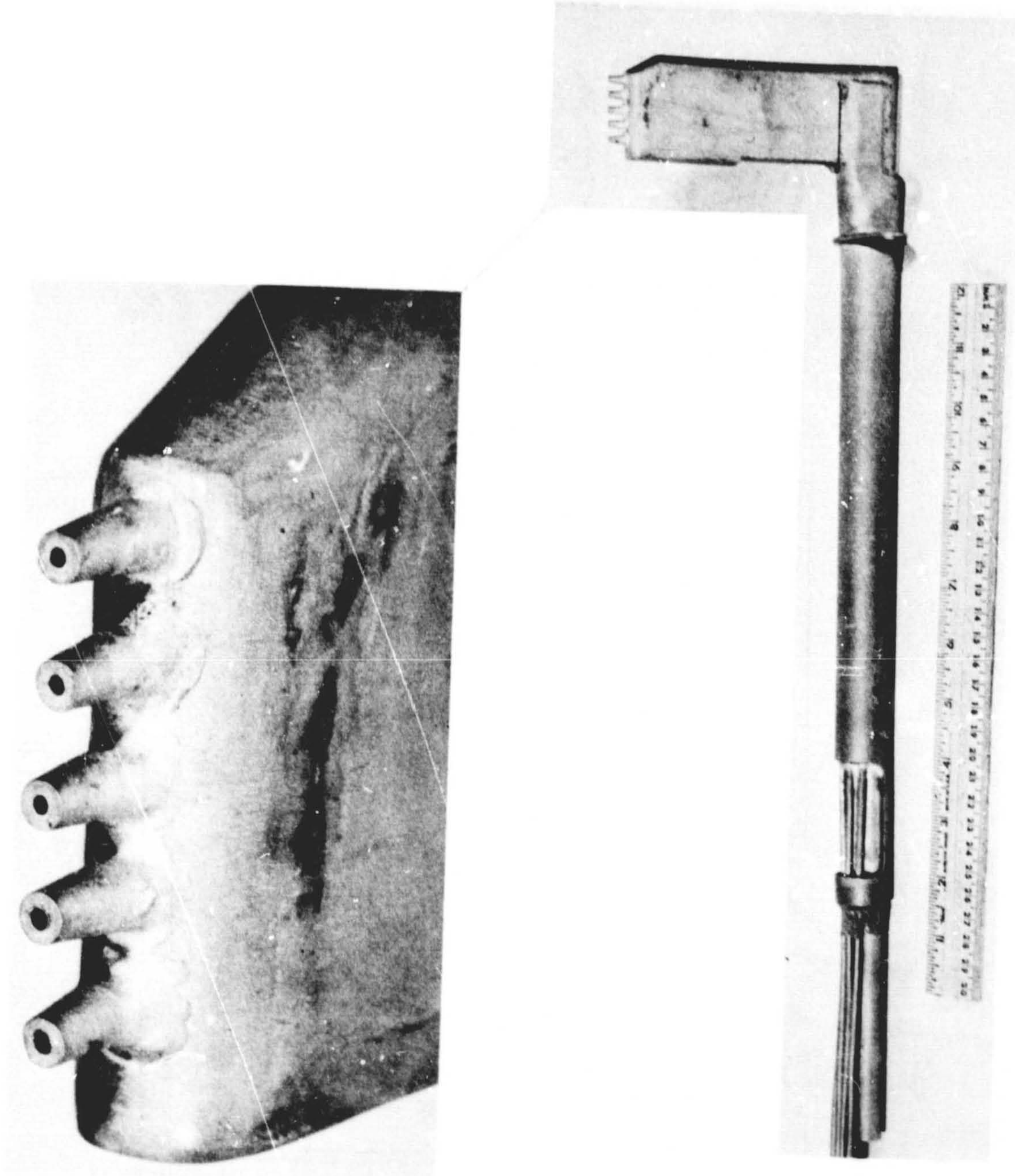


Figure 14. Gas Sample Rake Quick-Quenching Probe Tips.

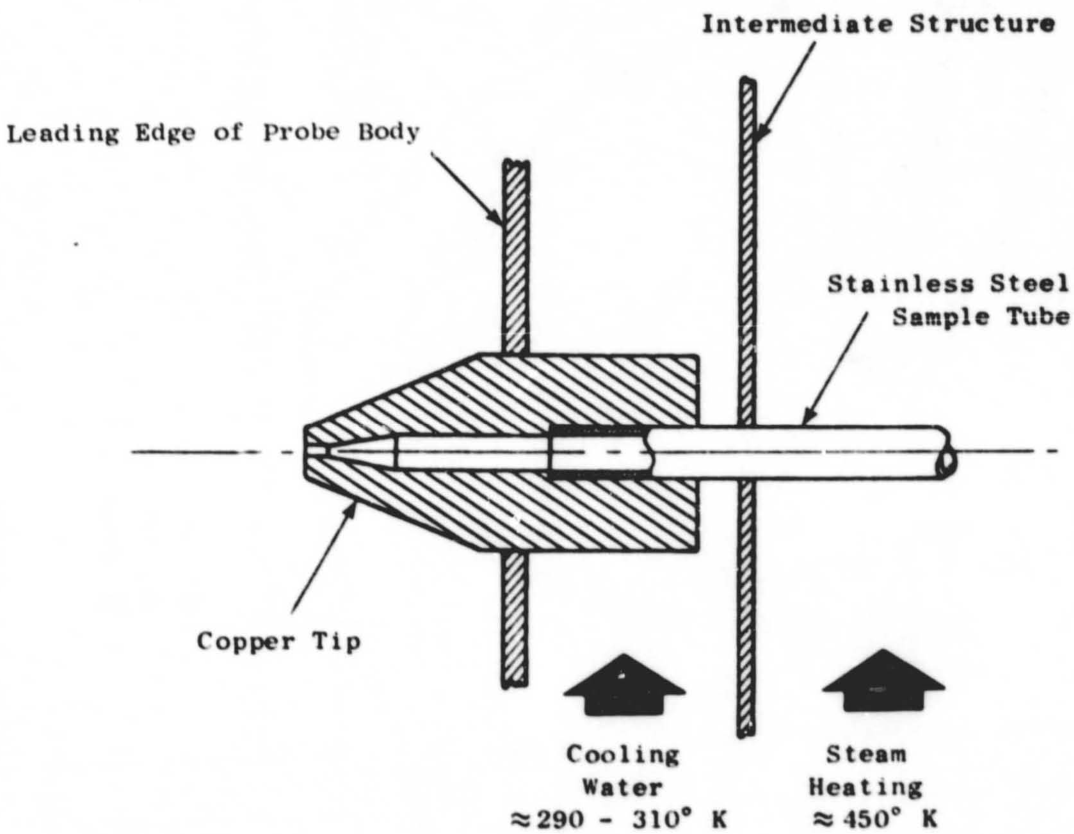



Figure 15. Steam-Heated, Water-Cooled Gas Sampling Rake.

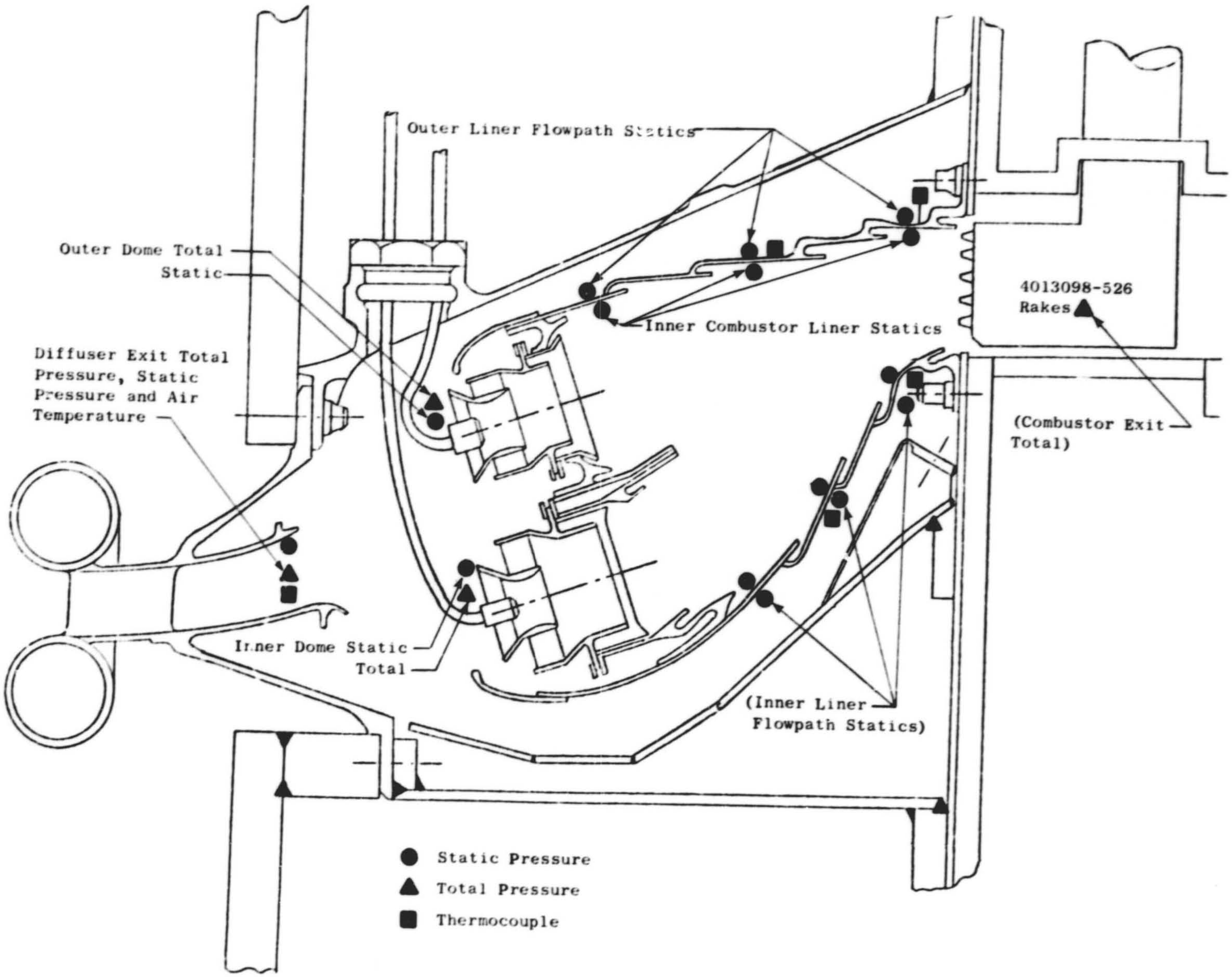



Figure 16. Schematic of Test Rig Instrumentation.

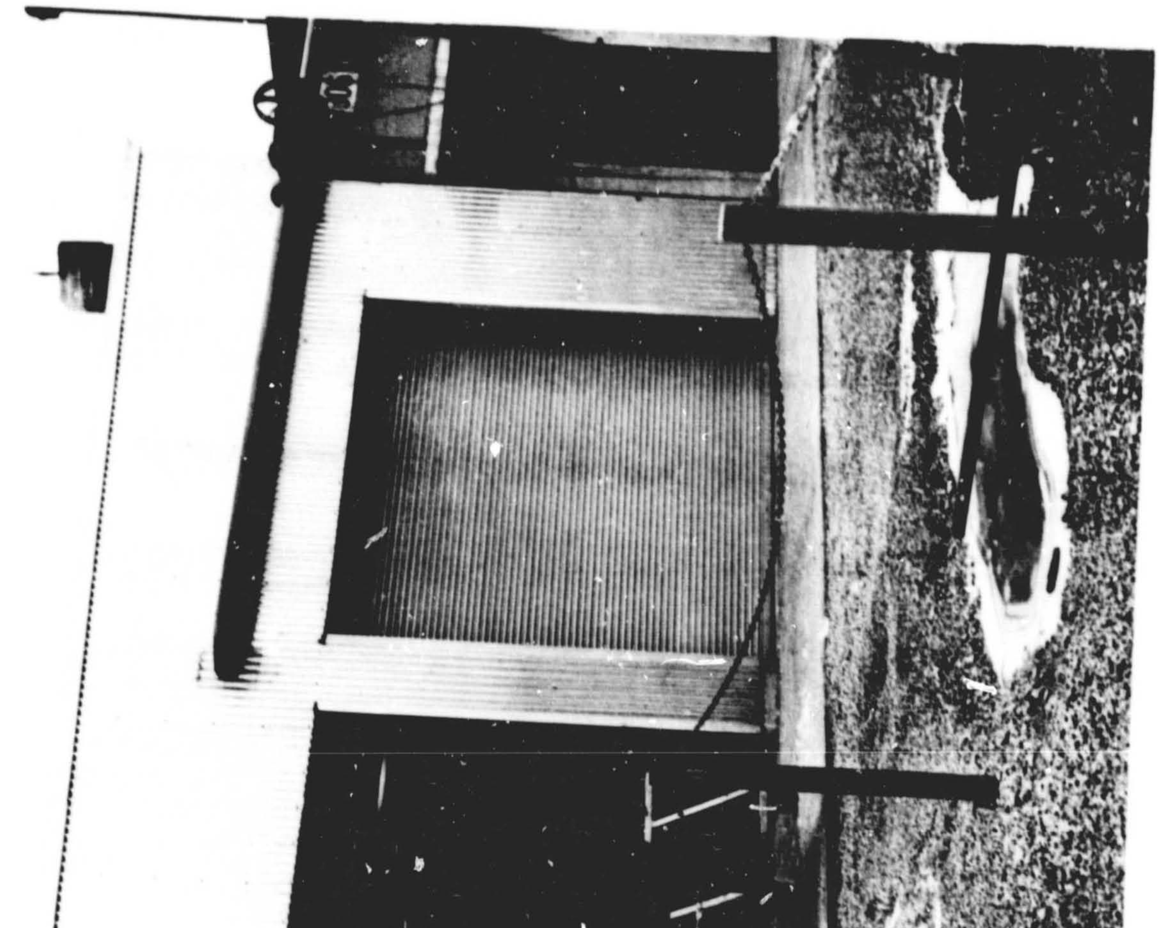


Figure 17. External View, Advanced Combustion Laboratory.

Test conditions were monitored using the facility equipped instrumentation. Airflows were monitored by manometer readings of pressure drops across standard ASME thin-plate orifice meters in the air supply lines. Fuel flows were metered by turbine-type flowmeters whose signals are input to electronic frequency meters. Test rig pressures were also monitored by manometer readings. Test rig temperatures were indicated by self-balancing potentiometer recording instruments. All configurations tested in this facility were installed and operated by skilled laboratory technicians under the direct supervision of Engineering.

To measure emissions, the facility is equipped with a CAROL (Contaminants Are Read On Line) gas analysis system. This system consists of the following instruments:

- Beckman Model 402 Total Hydrocarbon Analyzer (Flame Ionization Detector).
- Beckman Model 315-A Carbon Monoxide and Carbon Dioxide Analyzer (NDIR).
- Beckman Model 915 NO Analyzer (Chemiluminescence with converter, trap required).

Extracted exhaust gas samples were transmitted into this analysis equipment and the measured emissions levels were recorded on strip charts. An adequate supply of bottled calibration gases for the CAROL system was maintained throughout the emissions testing. A qualified technician calibrated and operated the CAROL system throughout the duration of data acquisition for each emissions test.

Additional testing was performed in another test facility. Specifically, most of the altitude ignition evaluations were performed in the Altitude Ignition facility located at General Electric's Evendale Plant. This facility, shown in Figure 18, is designed to accommodate sector combustors operating at reduced pressures, and reduced air and fuel temperatures simulating altitude conditions. This facility has an airflow capacity of 18 kg/s with the capability of achieving test rig conditions of 0.10 atmosphere at 219 K with 0.45 kg/s airflow. The facility also has a fuel temperature capability down to 244 K.

Test conditions were monitored in this facility using similar instrumentation to that used in the Combustion Laboratory facility. Thermocouples (Chromel Alumel) located directly downstream of the swirl cups were used for indicating ignition. All test configurations evaluated in this facility were installed and operated by qualified technicians under Engineering supervision.

In addition to the above-described development testing, various pilot and main stage swirl cups designs were evaluated as part of the emissions development testing of the QCSEE double annular sector combustor. These swirl cup

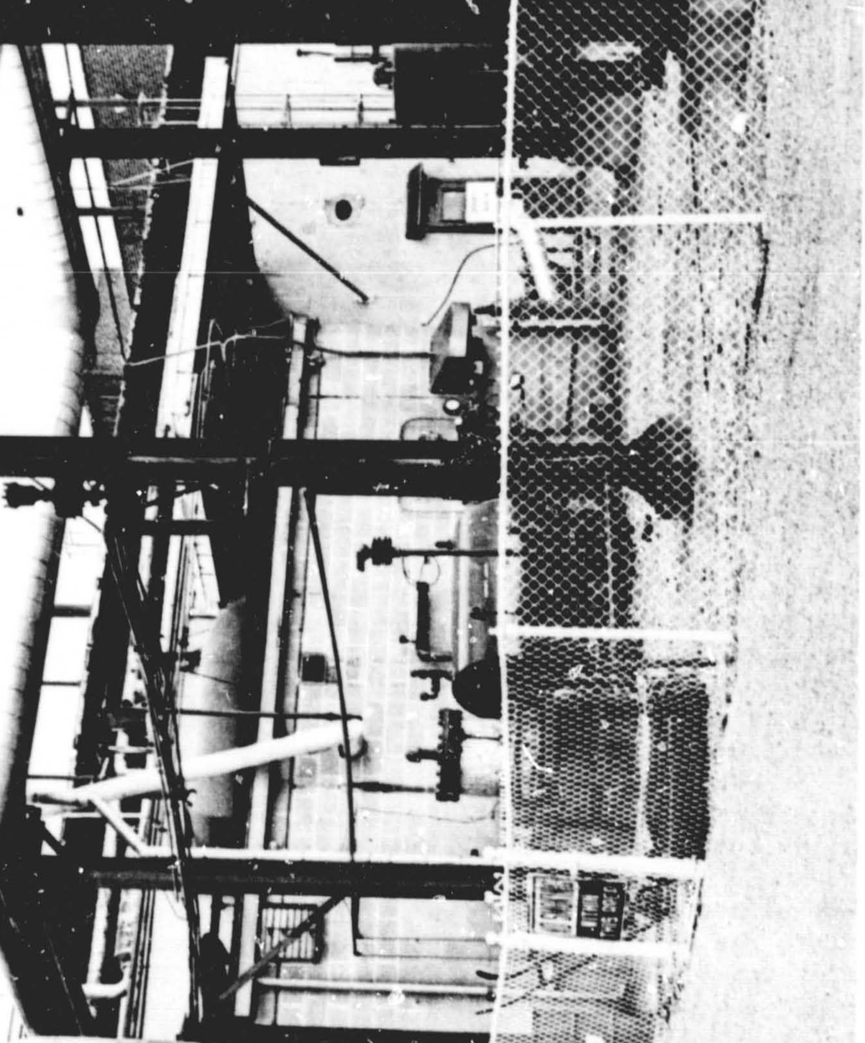


Figure 18. Small-Scale Combustor Test Facility.

designs evolved from extensive investigations in the Fuel Spray Visualization Test Facility shown in Figure 19. Tests were performed in this facility to provide a definition of swirl cup performance characteristics such as spray angle, droplet size and distribution, and spray uniformity. The facility simulates engine operating conditions at ambient temperatures and pressures by maintaining the proper relationships between air and fuel flows.

In this facility, a single swirl cup of a selected design, is mounted in a small plenum and positioned above a transparent fuel collection chamber. A metered flow of shop air and fuel simulation fluid is supplied to the plenum. Fuel spray issuing from the swirl cup is visually observed and photographed against a black background. A flash tube attached to and coordinated with a camera shutter is used for illumination of the fuel spray. The photographs of the fuel spray are used for comparative purposes in evaluating the swirl cups tested and selecting designs for evaluation in the sector combustor tests.

## 6.3 TEST PROCEDURES

### Sector Combustor Emission Tests

The double annular dome sector combustor test conditions selected represented actual as well as simulated operating conditions for the selected double annular cycle in addition to test conditions which represented the current QCSEE OTW in design cycle. However, the most important test points selected for evaluation were the QCSEE OTW standard day idle and a simulated sea level takeoff for the high pressure ratio design cycle since these operating conditions have the greatest impact on the program emissions goals. Other test points of particular interest were the EPA defined approach (30% power) and climbout (85% power) operating modes, and standard day cruise conditions. A summary of the combustor operating conditions tested to evaluate the selected engine cycle conditions is summarized in Table IX.

Combustor inlet temperature, pressure, and reference velocity of the QCSEE configurations were exactly duplicated for ground idle conditions. However, at the higher power conditions, the inlet temperatures, pressures, and airflows were reduced to be consistent with the facility limits. The airflow rates and fuel flow rates of Table IX were adjusted from the actual cycle conditions to simulate the true combustor reference velocity and fuel-air ratios. At many test conditions, data were obtained over a range of combustor fuel-air ratios. At some fuel-air ratios, the effect of varying the fuel flow splits between combustor stages was also examined.

Test points were usually run in the order of increasing combustor inlet temperature for safety considerations and to expedite testing. The majority of testing was conducted at low power settings. First, the fixed combustor instrumentation was recorded, and then the combustor exit plane detailed pollutant emission data were recorded. The normal test procedure was to obtain emission data from all the sampling probes simultaneously at the combustor exit plane. At test points of particular interest, however, individual samples from each gas sampling rake were obtained.

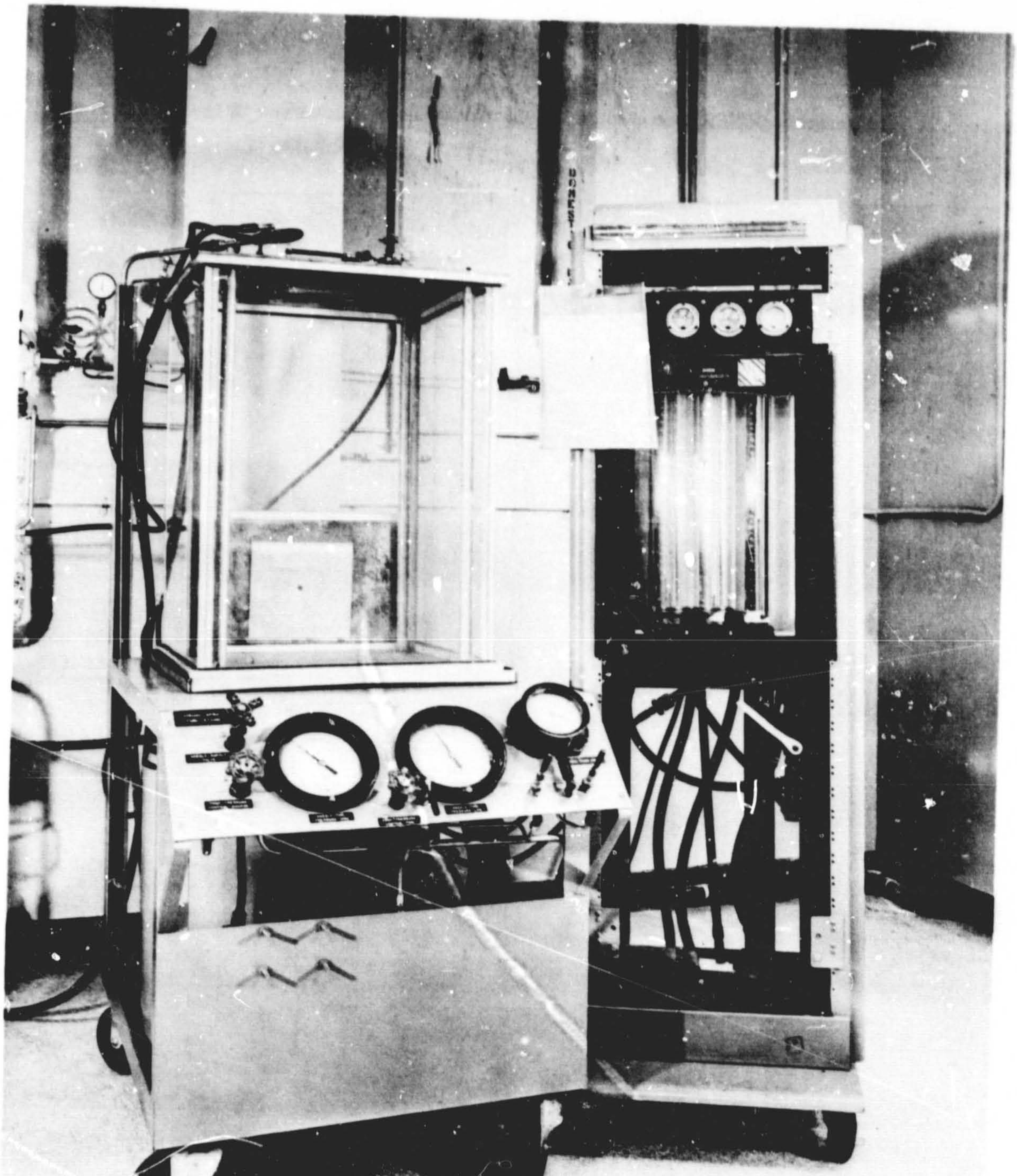


Figure 19. Fuel Injector Spray Visualization Test Facility.

Table IX. Proposed QCSEE Double Annular Combustor Baseline Emissions Test Plan.

| | Cycle Condition | $P_3$ Atm. | $T_3$ K | $W_c$ Kg/s | $f_{36}$ | $\frac{W_f \text{ pilot}}{W_f \text{ total}}$ | Gas Sampling Mode | Number Samples | Estimated Time To Set Cond. (Minutes) | Estimated Time At Cond. (Minutes) | Estimated Total Time (Minutes) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | OTW Idle (3%) | 2.06 | 397 | 4.53 | 0.018 | 1.0 | G | 1 | 60 | 5 | 65 | |
| 2-7 | UTW Idle (4.5%) | 2.26 | 425 | 5.02 | 0.009<br>0.013<br>0.0177<br>0.020<br>0.025<br>0.032 | 1.0 | G | 6 | 20 | 30 | 50 | * Key test conditions to be evaluated<br>G = All rakes ganged (1 sample)<br>I, B = In-line rake sample and between cup (Rake Sample (2 samples)<br>Ind. = Each individual rake sampled (4 samples) |
| 8-13 | CF6-50 Idle | 2.91 | 429 | 6.56 | 0.011<br>0.013<br>0.016<br>0.020<br>0.025<br>0.032 | 1.0 | G | 6 | 20 | 30 | 50 | Identifies fuel-air effect at idle<br>Identifies rake circumferential variation |
| 14-19 | DA Idle | 2.44 | 414 | 5.25 | 0.009<br>0.013<br>0.016<br>0.020<br>0.025<br>0.032 | 1.0 | G, Ind. | 9 | 20 | 45 | 65 | |
| 20 | | 2.44 | 414 | 6.88 | 0.016 | 1.0 | G | 1 | 20 | 5 | 25 | Increased residence time |
| 21 | | 2.44 | 414 | 4.16 | 0.016 | 1.0 | G | 1 | 20 | 5 | 25 | Decreased residence time |
| 22 | | 2.44 | 394 | 5.79 | 0.016 | 1.0 | G | 1 | 20 | 5 | 25 | Decreased inlet temperature |
| 23 | | 2.19 | 429 | 5.34 | 0.016 | 1.0 | G | 1 | 20 | 5 | 25 | Increased inlet temperature |
| 24 | | 2.19 | 414 | 4.98 | 0.016 | 1.0 | G | 1 | 20 | 5 | 25 | Decreased inlet pressure |
| 25 | OTW Approach (30%) | 4.08 | 554 | 8.43 | 0.0159 | 1.0 | G | 1 | 60 | 5 | 65 | |
| 26 | DA Approach (30%) | 4.08 | 602 | 8.16 | 0.0133 | 1.0 | G, I and B | 3 | 30 | 15 | 45 | |
| 27 | | | | | | 0.50 | G | 1 | 5 | 5 | 10 | Identified whether staging is preferable at approach |
| 28 | | | | | | 0.30 | G | 1 | 5 | 5 | 10 | |
| 29 | | | | | | 0.20 | G, I and B | | 5 | 15 | 20 | |
| 30 | OTW Climb | 3.4 | 686 | 5.93 | 0.027 | 0.20 | G | 1 | 120 | 5 | 125 | |
| 31 | DA Climb | | 753 | 5.8 | 0.021 | 0.20 | G | 1 | 30 | 5 | 35 | |
| 32 | OTW Takeoff | | 726 | 5.66 | 0.031 | 0.20 | G | 1 | 20 | 5 | 25 | |
| 33 | DA Cruise | | 762 | 5.71 | 0.024 | 0.20 | G | 1 | 20 | 5 | 25 | |
| 34 | DA Takeoff | | 783 | 5.66 | 0.023 | 0 | G, I and B | 3 | 20 | 15 | 35 | |
| 35 | | | | | | 0.10 | G | 1 | 10 | 5 | 15 | Identifies optimum staging at takeoff |
| 36 | | | | | | 0.15 | G | 1 | 5 | 5 | 10 | |
| 37 | | | | | | 0.20 | G, Ind. | 5 | 5 | 30 | 30 | |
| 38 | | | | | | 0.25 | G | 1 | 5 | 5 | 10 | |
| 39 | | 3.4 | 783 | 5.66 | 0.017 | 0.20 | G | 1 | 5 | 5 | 10 | Identifies fuel-air effect at takeoff |
| 40 | | | | | 0.029 | 0.20 | G | 1 | 5 | 5 | 10 | |
| 41 | | 3.4 | 783 | 4.3 | 0.023 | 0.20 | G | 1 | 20 | 5 | 25 | Decreased residence time |
| 42 | | | 783 | 7.11 | 0.023 | 0.20 | G | 1 | 20 | 5 | 25 | Increased residence time |
| 43 | | | 783 | 6.16 | 0.023 | 0.20 | G | 1 | 40 | 5 | 45 | Decreased inlet temperatures |

### Sector Combustor Ground Start Tests

In addition to elevated pressure tests, the ground start ignition characteristics of several configurations were also evaluated. To determine the sea level ignition characteristics, the combustor was operated at atmospheric conditions. Successful ignition was indicated by a thermocouple at the combustor exit plane. The initial tests were conducted with a hydrogen torch to determine the ignition capability fo the design. In these tests, only the lean stability is considered of significance. A combustor airflow within the range of starting airflows of QCSEE was set with ambient temperature inlet air. The fuel flow was slowly increased and ignition attempted. The fuel flow was recorded where at least one cup was lit. Sufficient fuel was supplied to assure all cups were lit then the fuel flow was decreased and the conditions where lean extinction occurred were recorded. This process was repeated several times until sufficient data repeatability was achieved. A second, third, and sometimes, fourth combustor airflow was then set and the entire procedure was repeated.

### Sector Combustor Altitude Relight Tests

The altitude relight test procedures consisted of determining combustor ignition and blowout limits over a range of test conditions selected from the CFM56 engine altitude windmilling map, shown in Figure 20. Windmilling characteristics for the QCSEE configuration were not available, therefore, CFM56 windmilling characteristics were considered to provide the best approximation for the expected QCSEE windmilling characteristics. Some of the tests were conducted with ambient temperature fuel and inlet air. The more promising sector combustor configurations were then evaluated with both cold air and fuel. Ignition attempts were usually made at the engine minimum fuel flow rate of 136.2 kg/hr. When the ignition attempt was unsuccessful, the process was repeated at higher fuel flow rates. When the attempt was successful, pressure extinction and lean extinction limits were measured. The procedure was then repeated at progressively more severe simulated windmilling conditions to map the relight capabilities of three selected configurations.

### Sector Combustor Profile and Pattern Factor Tests

As part of the final evaluation of the preferred sector combustor configuration, a series of combustor exit temperature surveys were conducted. These exit temperature surveys were obtained with five multielement thermocouple rakes located in fixed positions at the exit plane of the combustor, as shown in Figure 21. Test conditions were set to simulate operation at idle and approach with only the pilot stage fueled. For the preferred sector combustor configuration, the pilot stage was located on the inner dome annulus. Sea level takeoff combustor inlet conditions were simulated with both stages fueled. The measured temperatures from the individual thermocouple elements were recorded for various fuel-air ratios and pilot-to-total fuel flow ratios. Based on the measured values of the thermocouples, corrected for radiation losses, a pattern factor and profile factor were calculated.

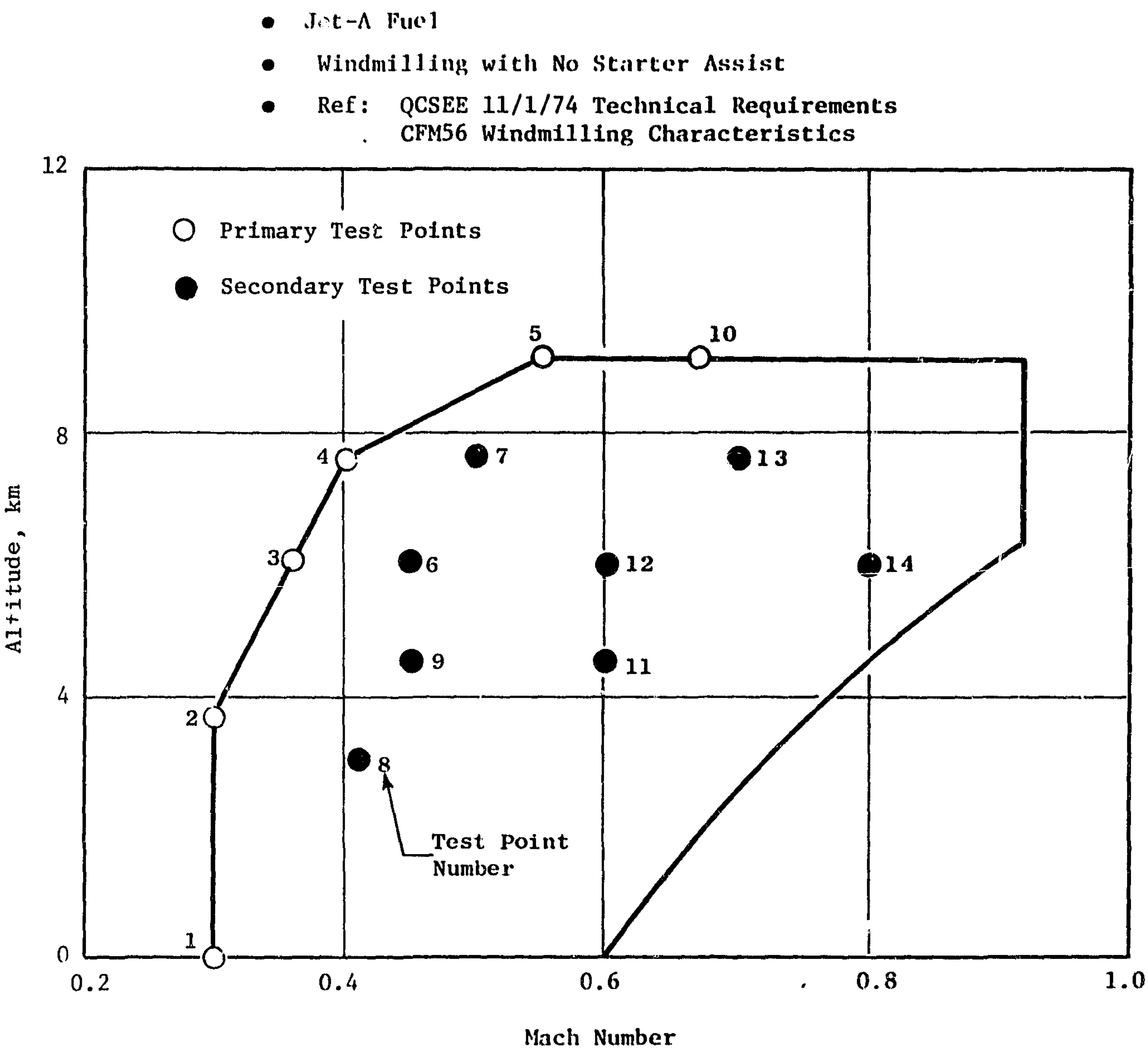



Figure 20. QCSEE Double Annular Combustor Altitude Ignition Envelope.

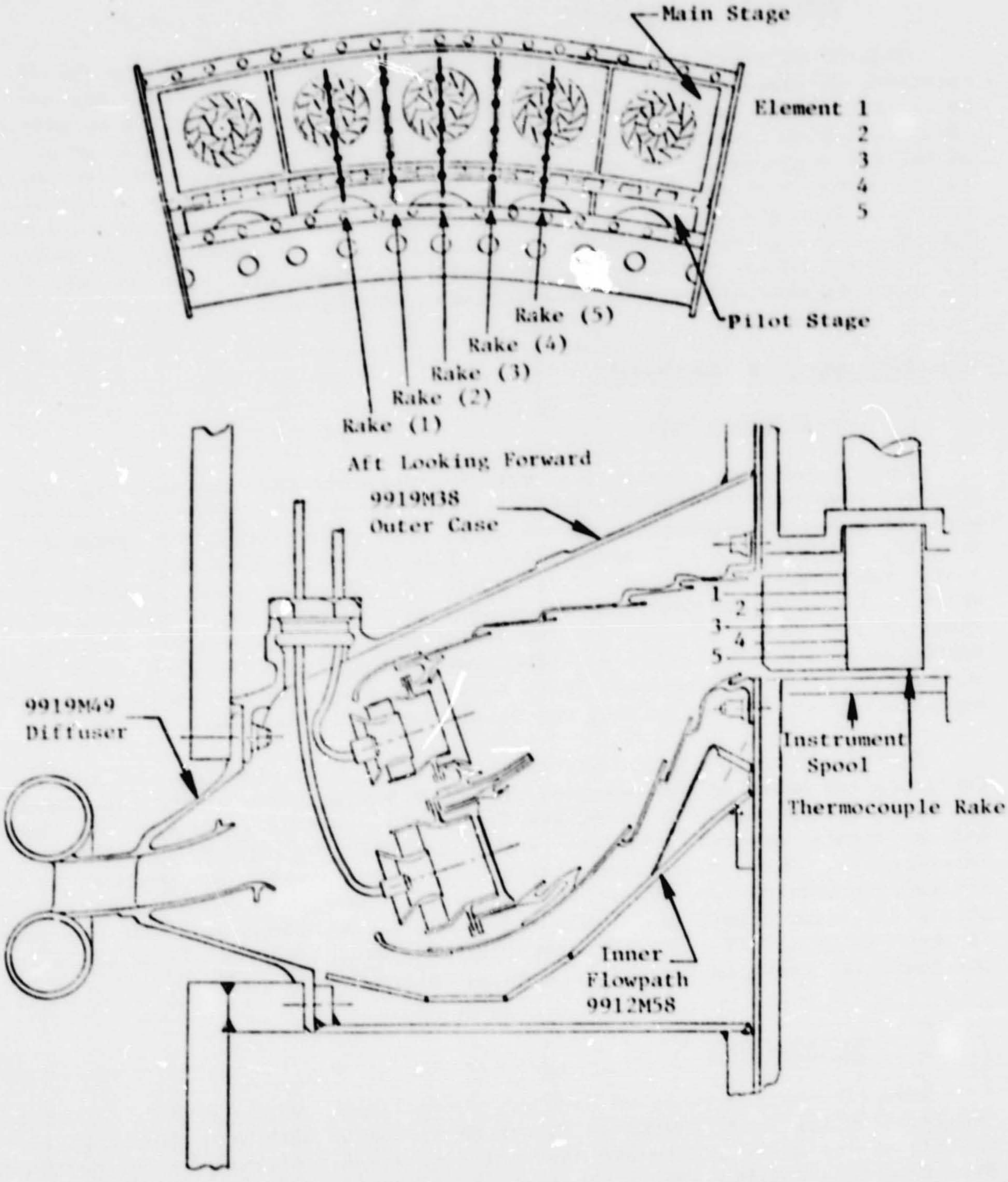



Figure 21. Schematic of Exit Temperature Hardware Location Within the Test Rig.

### Single Swirl Cup Tests

Individual swirl cup tests were conducted in parallel with the sector combustor development tests to evaluate and develop the fuel spray characteristics. These tests were conducted at conditions corresponding to ambient combustor inlet conditions using a calibration fluid (MIL-F-7044II) which has properties very similar to Jet A. In these tests the pressure drop across the swirl cup was duplicated for conditions corresponding to a range of combustor operation from ground idle to sea level takeoff. At each test condition the fuel flow was varied to duplicate fuel-to-air momentum ratios and the swirl cup fuel-air ratios evaluated in the sector combustor tests and the fuel spray was visually observed as well as recorded on photographs.

## 6.4 DATA ANALYSIS PROCEDURES

### Performance Data

Sector combustor performance data were obtained from the test rig pressure and temperature instrumentation. Data from this instrumentation along with the measured emissions data was input into a data reduction computer program, "CAROLB". This program reduced the instrumentation data to the combustor performance parameters of interest. A summary of these parameters are shown in Table X; the method by which they were measured or calculated is also shown in this table. Values for the performance parameters along with the appropriate emissions levels are tabulated in Appendix A for each sector combustor test run. Air and fuel flows have been converted to equivalent annular combustor levels by multiplying the sector levels by four (4).

Sector combustor airflow distributions were calculated for each test configuration based on the measured combustor pressure instrumentation data, and known sector combustor effective flow areas. The pressure data was input into a computer program, "QCSEE1", which performed the airflow distribution calculations. These calculated airflow distributions were instrumental in determining what sector combustor configuration changes were necessary to obtain the reduced emission levels. A sample of the output from this program is shown in Figure 22. Airflow distributions calculated for all of the sector combustor test configurations were shown previously in Table VII.

### Emission Data

Reduction of the emission data was accomplished using two data reduction programs, "CALIB" and "CAROLB". At the beginning of each test run, a calibration of the CAROL gas sample analysis system was performed by the operator. Data from this calibration in the form of indicated instrument readings for specified pollutant concentrations in parts per million, (or in the case of $CO_2$, percent of total constituents), were input into the program "CALIB" which performed a curve fit of the calibration data and generated an output file containing the results. During a test, the measured emissions data were

Table X. Summary of Measured and Calculated Combustor Parameters for Sector Tests.

| | Symbol | Units | Measured | Calculated | Value determined From |
|---|---|---|---|---|---|
| Inlet Total Pressure | $P_{T_3}$ | Atm. | X | | Average of measurements from three total pressure probes. |
| Exit Total Pressure | $P_{T_{39}}$ | Atm. | X | | Ganged pressure reading from four exhaust gas sampling rakes (5 elements each). |
| Total Pressure Loss | $\Delta P_T/P_{T_3}$ | % | | X | $100\ (P_{T_3} - P_{T_{39}})/P_{T_3}$ |
| Combustor Airflow | $W_c$ | Kg/s | X | | Standard ASME Orifice (no bleed flow $W_3 = W_c$). |
| Reference Velocity | $V_r$ | M/S | | X | $W_c\ R\ T_{T_3}/P_{T_3}\ A_R$. |
| Pilot Fuel Flow | $W_{fp}$ | Kg/hr | X | | Turbine type flowmeter |
| Main Fuel Flow | $W_{fm}$ | Kg/hr | X | | Turbine type flowmeter. |
| Total Fuel Flow | $W_f$ | Kg/hr | | X | $(W_{fp} + W_{fm})$. |
| Overall Metered Fuel/Air | f/a | | | X | $W_f/3600\ W_c$. |
| Outer Dome Upstream Static Pressure | $P_{s3.1_O}$ | Atm. | X | | Single static pressure probe. |
| Outer Dome Downstream Static Pressure | $P_{s3.2_O}$ | Atm. | X | | Single static pressure probe. |
| Inner Dome Upstream Static Pressure | $P_{s3.1_I}$ | Atm. | X | | Single static pressure probe. |
| Inner Dome Downstream Static Pressure | $P_{s3.2_I}$ | Atm. | X | | Single static pressure probe. |
| Outer Dome Pressure Loss | $\Delta P/P/_{OD}$ | % | | X | $100\ (P_{s3.1_O} - P_{s3.2_O})/P_{s3.1_O}$. |
| Inner Dome Pressure Loss | $\Delta P/P/_{ID}$ | % | | X | $100\ (P_{s3.1_I} - P_{s3.2_I})/P_{s3.1_I}$. |
| Inlet Air Humidity | H | g/Kg | X | | Dew point hygrometer. |
| Inlet Total Temperature | $T_{T_3}$ | K | X | | Average of measurements from three thermocouples. |
| Exit Total Temperature | $T_{T_{39}}$ | K | X | | Measurements from five combustor exit thermocouple rakes (5 elements each). |
| Exit Total Temperature | $T_{T_{39}}$ | K | | X | Combination temperature rise curves using $P_{T_3}$, $T_{T_3}$, f/a, $\eta_c$. |
| Pattern Factor | PF | | | X | $(T_{T_{39}}\ \text{max.} - T_{T_{39}}\ \text{avg.})/T_{T_{39}}\ \text{avg.} - T_{T_3})$. |
| Profile Factor | $P_rF$ | | | X | $(T_{T_{39}}\ \text{immersion average max.} - T_{T_3})/(T_{T_{39}}\ \text{avg.} - T_{T_3})$. |
| Combustion Efficiency | $\eta_c$ | % | | X | Measured exhaust gaseous emissions. |

OUTER LINER PASSAGE PRESSURES-PSIA

| PANEL0 | PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 |
|---|---|---|---|---|---|
| 50.974 | 50.999 | 51.023 | 51.048 | 51.072 | 51.089 |

INNER LINER PASSAGE PRESSURES-PSIA

| PANEL0 | PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 |
|---|---|---|---|---|---|
| 50.876 | 50.901 | 50.925 | 50.901 | 50.876 | 50.868 |

COMBUSTOR OUTER STAGE INNER FLOWPATH PRESSURES-PSIA

| PANEL0 | PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 |
|---|---|---|---|---|---|
| 48.862 | 48.739 | 48.617 | 48.567 | 48.516 | 48.676 |

COMBUSTOR INNER STAGE INNER FLOWPATH PRESSURES-PSIA

| PANEL0 | PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 |
|---|---|---|---|---|---|
| 48.911 | 48.813 | 48.715 | 48.567 | 48.420 | 48.676 |

DOME PRESSURES-PSIA

| UPSTREAM | | DOWNSTREAM | |
|---|---|---|---|
| OUTER | INNER | OUTER | INNER |
| 51.21 | 51.72 | 48.81 | 49.01 |

OUTER LINER AIRFLOWS-PPS

| PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 | DIL-0 | DIL-1 | DIL-2 | DIL-3 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|
| 0.581 | 0.485 | 0.293 | 0.306 | 0.142 | 0.21 | 0. | 0.23 | 0. | 2.25 |
| IN PERCENT OF WC | | | | | | | | | |
| 3.523 | 2.939 | 1.778 | 1.853 | 0.861 | 1.29 | 0. | 1.42 | 0. | 13.66 |

INNER LINER AIRFLOWS-PPS

| PANEL1 | PANEL2 | PANEL3 | PANEL4 | PANEL5 | DIL-0 | DIL-1 | DIL-2 | DIL-3 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|
| 0. | 0.530 | 0.536 | 0.661 | 0.343 | 0.05 | 0.65 | 0. | 0.24 | 3.01 |
| IN PERCENT OF WC | | | | | | | | | |
| 0. | 3.214 | 3.249 | 4.008 | 2.080 | 0.32 | 3.93 | 0. | 1.47 | 18.27 |

OUTER DOME AIRFLOWS-PPS

| DOME PLATE | WIGGLE | 1/2 CENTER WIGGLE | SWIRLER ASSY | TOTAL |
|---|---|---|---|---|
| 0.5382 | 0. | 0.2956 | 4.4050 | 5.24 |
| IN PERCENT WC | | | | |
| 3.262 | 0. | 1.792 | 26.697 | 31.750 |
| INNER DOME AIRFLOWS-PPS | | | | |
| 0.3792 | 0. | 0. | 3.3681 | 3.75 |
| IN PERCENT WC | | | | |
| 2.298 | 0. | 0. | 20.413 | 22.711 |

AIRFLOW SET-PPS=16.500

AIRFLOW ACCOUNTED-PPS=14.255

PERCENT OF AIRFLOW SET= 86.392

**Figure 22. Sample Output from Data Reduction Routine QCSEE 1.**

recorded on chart recorders contained within the CAROL system. The emissions data were also recorded on test log sheets. Following the completion of each test run, the emissions data along with the sector combustor performance data were input into program "CAROLB". By accessing the calibration file generated by program "CALIB", the reduction of the raw emissions data to emissions indices was performed by program "CAROLB". The equations used in these calculations were basically those contained in SAE ARP 1256 (Reference 5). In these calculations, the CO and $CO_2$ concentrations were corrected for the removal of water from the sample prior to its analysis. A fuel hydrogen-to-carbon atom ratio of 1.92, representing the Jet A fuel, was used in these calculations. Calculated combustion efficiency, sample fuel-air ratio, and an overall emission index were also obtained from the data reduction through program "CAROLB". The overall emission index represents a weighted average of the values obtained from each individual gas sampling rake, and is defined as follows:

$$EI_j \text{ (Overall)} = \frac{\sum_{i=1}^{N} (EI_j)_i * (\text{F/A Sampled})_i}{\sum_{i=1}^{N} (\text{F/A Sampled})_i}$$

The (j) subscript refers to the identity of the emissions, (CO, HC, or $NO_x$), and the (i) subscript refers to the individual rakes where (N) represents the total number of gas sampling rakes. Expressing the average of the emissions in this form reduces the influence of very lean combustion zones within the combustor where the concentrations of gaseous pollutants is low, which may result in calculated emissions indices that are quite high. These weighted average emissions values are presented in the numerous data tables and figures throughout this report. A sample of the outputs from programs "CALIB" and "CAROLB" are shown in Figures 23 and 24.

Because the sector combustor inlet pressure and airflow were derated at the simulated high power operating conditions, the measured emissions levels were adjusted to the actual engine cycle condition using the adjustment relations defined in Appendix B. These high power adjusted emissions levels are also tabulated in the tables contained in Appendix A for all configurations tested at higher power operating conditions.

CAROL CALIBRATION DATA

TEST- ACSEE D.A. MOD-31 DATE- 02/15/78
CELL- 306 RUN- 041 FUEL- JP-5

CURVE FIT FUNCTION:
CONCENTRATION=(DIVISIONS-A0)/(A1+A2*(DIVISIONS-A0))

| | | | CURVE FIT CONSTANTS | | |
|---|---|---|---|---|---|
| GAS | RANGE | FIT | A0 | A1 | A2 |
| CO | 1 | 2 | 0. | 0.0198 | -0.00042377 |
| CO2 | 1 | 2 | 0. | 3.2599 | -0.05281824 |
| HC | 6 | 2 | 0. | 0.0063 | -0.00000872 |
| NOX | 5 | 2 | 0. | 0.0819 | 0.00000495 |

CAL TIME = 700
CO,CO2,HC,NOX TRAP CODES = 2, 2, 0, 1
FUEL HYDROGEN TO CARBON RATIO = 1.92

| GAS | DIVISIONS | MEASURED CONCENTRATION | CALCULATED CONCENTRATION | PERCENT DEVIATION |
|---|---|---|---|---|
| CO | 0. | 0. | 0. | 0. |
| | 3.800 | 208.0 | 209.1 | 0.54 |
| | 13.300 | 953.0 | 940.2 | -1.34 |
| | 23.400 | 2350.0 | 2371.9 | 0.93 |
| | 0. | 0. | 0. | 0. |
| CO2 | 0. | 0. | 0. | 0. |
| | 5.800 | 1.970 | 1.964 | -0.32 |
| | 15.400 | 6.190 | 6.295 | 1.69 |
| | 18.200 | 8.030 | 7.918 | -1.40 |
| | 0. | 0. | 0. | 0. |
| HC | 0. | 0. | 0. | 0. |
| | 1.600 | 247.0 | 255.8 | 3.55 |
| | 2.900 | 471.0 | 464.4 | -1.39 |
| | 8.300 | 1380.0 | 1339.3 | -2.95 |
| | 29.800 | 4920.0 | 4958.8 | 0.79 |
| NOX | 0. | 0. | 0. | 0. |
| | 5.600 | 68.0 | 68.0 | 0. |
| | 24.000 | 286.0 | 286.0 | 0.00 |
| | 0. | 0. | 0. | 0. |
| | 0. | 0. | 0. | 0. |

| | CALCULATED CONCENTRATIONS OF: | | | |
|---|---|---|---|---|
| DIVISIONS | CO | CO2 | HC | NOX |
| 10.000 | 643.3 | 3.661 | 1617.5 | 120.9 |
| 20.000 | 1768.9 | 9.076 | 3281.4 | 239.3 |
| 30.000 | 4244.1 | 17.907 | 4993.5 | 355.3 |
| 40.000 | 14130.0 | 34.870 | 6756.1 | 469.1 |
| 50.000 | -35539.3 | 80.782 | 8571.4 | 580.6 |
| 60.000 | -10629.6 | 661.031 | 10441.9 | 689.9 |
| 70.000 | -7083.3 | -160.031 | 12370.0 | 797.0 |
| 80.000 | -5665.7 | -82.050 | 14358.4 | 902.2 |
| 90.000 | -4902.5 | -60.250 | 16410.1 | 1005.3 |
| 100.000 | -4425.6 | -49.457 | 18528.2 | 1106.5 |

**Figure 23. Sample Output from Data Reduction Routine CALIB.**

TEST - QCSEE DA MOD-31 CONT'D     DATE - 02/15/78
CELL - 306     RUN - 41     FUEL - JP-5
CAL TIME = 700     HUM = 6.5     FUEL H/C = 1.92

RDG 1 POINT 1

| P3 TOTAL | REF VEL FT/SEC | DP/P COMB | DP/P INNER DOME | DP/P OUTER DOME | FLOW FUCTION SQUARED | FUEL/AIR RATIO METERED | T3 DEG-R | AIRFLOW PPS |
|---|---|---|---|---|---|---|---|---|
| 30.79 | 45.90 | 0.047 | 0.036 | 0.037 | 74.672 | 0.0181 | 716.7 | 2.4844 |

*** METRIC ***

| N/CM**2 | M/SEC | | | | CM**4-DEG-K/SEC**2 | | DEG-K | KG/SEC |
|---|---|---|---|---|---|---|---|---|
| 44.65 | 13.99 | | | | 359.080 | | 398.2 | 1.1269 |

COMBUSTOR LINER METAL TEMPERATURES

| OUTER LINER T120 | OUTER LINER T128 | INNER LINER T122 | INNER LINER T130 | CENTER BODY T113 |
|---|---|---|---|---|
| DEG-R | | DEG-R | | DEG-R |
| -0.0 | 766.7 | -0.0 | 791.7 | -0.0 |
| DEG-K | | DEG-K | | DEG-K |
| -0.0 | 425.9 | -0.0 | 439.8 | -0.0 |

ACTUAL GAS ANALYSIS

| RAKE | TIME | CO SEMI-DRY (PPM) | CO2 SEMI-DRY (PCT) | HC WET (PPM) | NO DRY (PPM) | NOX DRY (PPM) | SMOKE NUMBER |
|---|---|---|---|---|---|---|---|
| G 0 | 1040 | 3533.0 | 5.43 | 40.6 | | 38.6 | |
| AVG | | 3533.0 | 5.43 | 40.6 | | 38.6 | |

CALCULATED EMISSIONS LEVELS

| RAKE | TIME | CO | HC | NO | NOX | F/A SAMPLE | COMB EFF |
|---|---|---|---|---|---|---|---|
| | | ******* LBS/1000 LBS FUEL ******* | | | | | |
| G 0 | 1040 | 122.5 | 0.7 | | 2.2 | 0.02729 | 97.07 |
| AVG | | 122.5 | 0.7 | | 2.2 | 0.02729 | 97.07 |
| OVERALL AVG | | 122.5 | 0.7 | | 2.2 | 0.02729 | 97.07 |

**Figure 24. Sample Output from Data Reduction Routine CAROLB.**

## 7.0 DEVELOPMENT TEST RESULTS

### 7.1 EXHAUST EMISSION RESULTS

The exhaust emission results obtained for the QCSEE double annular dome sector combustor were generally categorized into four major configuration groups: (1) the baseline series with the pilot stage in the outer annulus, (2) the pilot stage in the inner annulus series, (3) a redesigned pilot stage series, and (4) a redesigned mainstage series. Since high power emissions were investigated for only a limited number of the 32 configurations evaluated, the results at high power conditions will be discussed separately from the idle emission results. These 32 sector combustor configurations evaluated were shown previously in Figure 6.

#### Idle (CO and HC) Emissions

The baseline sector combustor configuration featured axial primary and secondary swirl cup assemblies in both the pilot and main stages. These versions of the pilot stage swirl cup design also featured a radial tertiary swirler. These swirler cup designs are shown schematically in Figure 25. The pilot stage was located in the outer dome annulus and the main stage was located in the inner dome annulus. Evaluation of the baseline configuration revealed that the measured CO and HC emission levels at the QCSEE OTW idle condition exceeded the target levels required to meet the program goals for these two emissions categories. The target levels required for the CO and HC emissions had previously been determined to be 28 g/kg fuel and 5 g/kg fuel, respectively, at 4% of sea level takeoff thrust at ground idle. Dilution and other minor airflow distribution changes were incorporated in modifications 1 and 2 to reduce the main stage quenching effects on the pilot stage at ground idle, believed to be the primary contributor to the high CO and HC emission levels. However, neither of these modifications produced any significant improvement in the measured emission levels. The next modifications to the baseline design, modifications 3 and 4, were designed to investigate a modified pilot stage swirl cup assembly featuring an axial primary swirler, radial secondary swirler, and wide angle (90°), conical sleeve insert. Results from these tests showed some reductions in both the CO and HC emission levels. However, the levels were still well above the program goals as shown in Figure 26. The next series of modifications, 5 through 10 and 14, investigated the effects of increasing the pilot stage length. This configuration change was accomplished by lengthening the centerbody in addition to moving the pilot stage dome assembly forward. The increased pilot stage length was designed to increase the primary reaction zone residence time to delay the quenching effects from the cool unfueled mainstage air. In addition to the pilot stage length increase, several dilution and cooling airflow modifications were incorporated. With the introduction of these modifications, some moderate reductions in CO and HC emission levels were obtained. The major reductions obtained for the CO and HC emission levels were attributed to the extended pilot stage length. The results for this test series are shown in Figure 27.

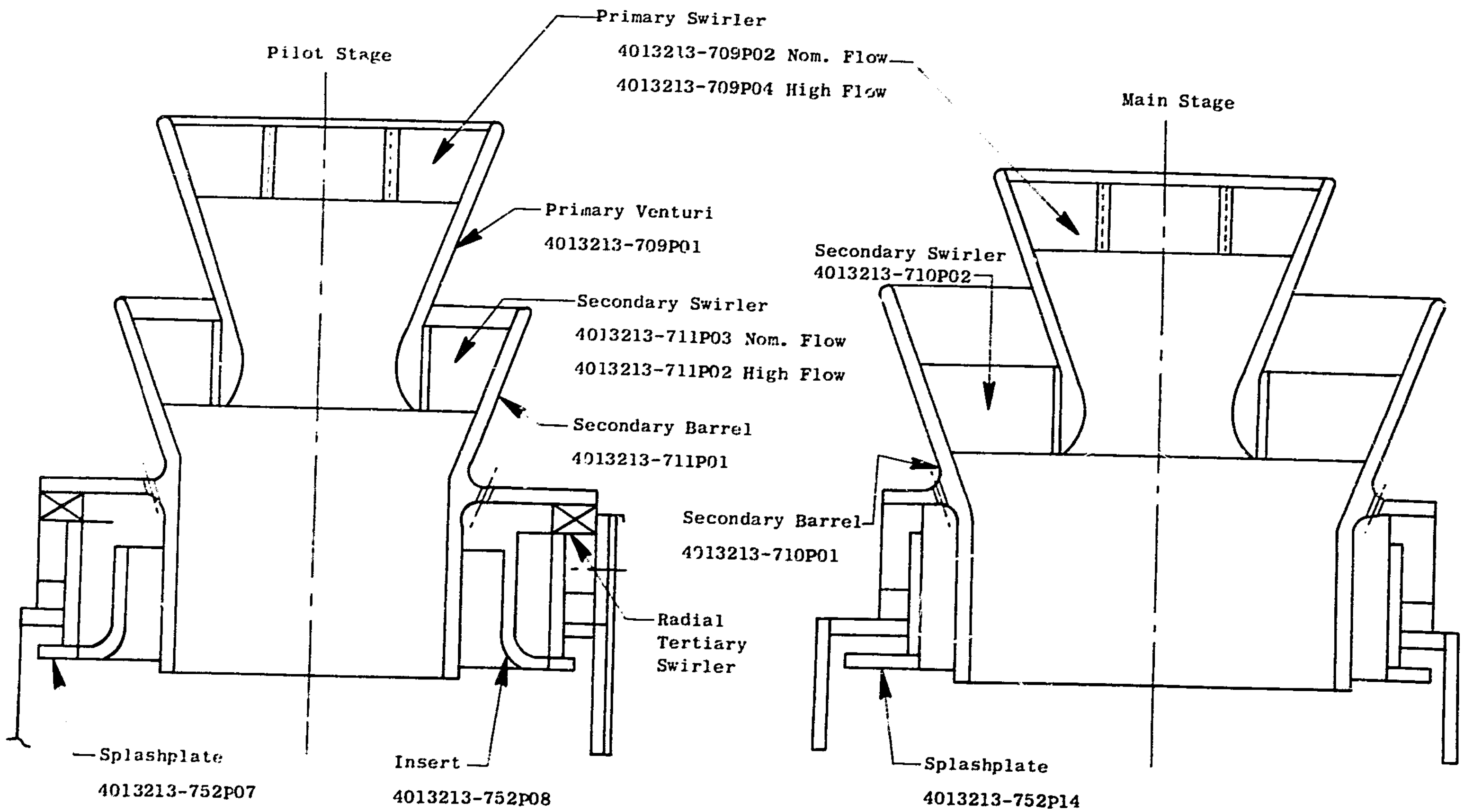



Figure 25. Schematic of Baseline Test Configuration Swirl Cup Hardware.

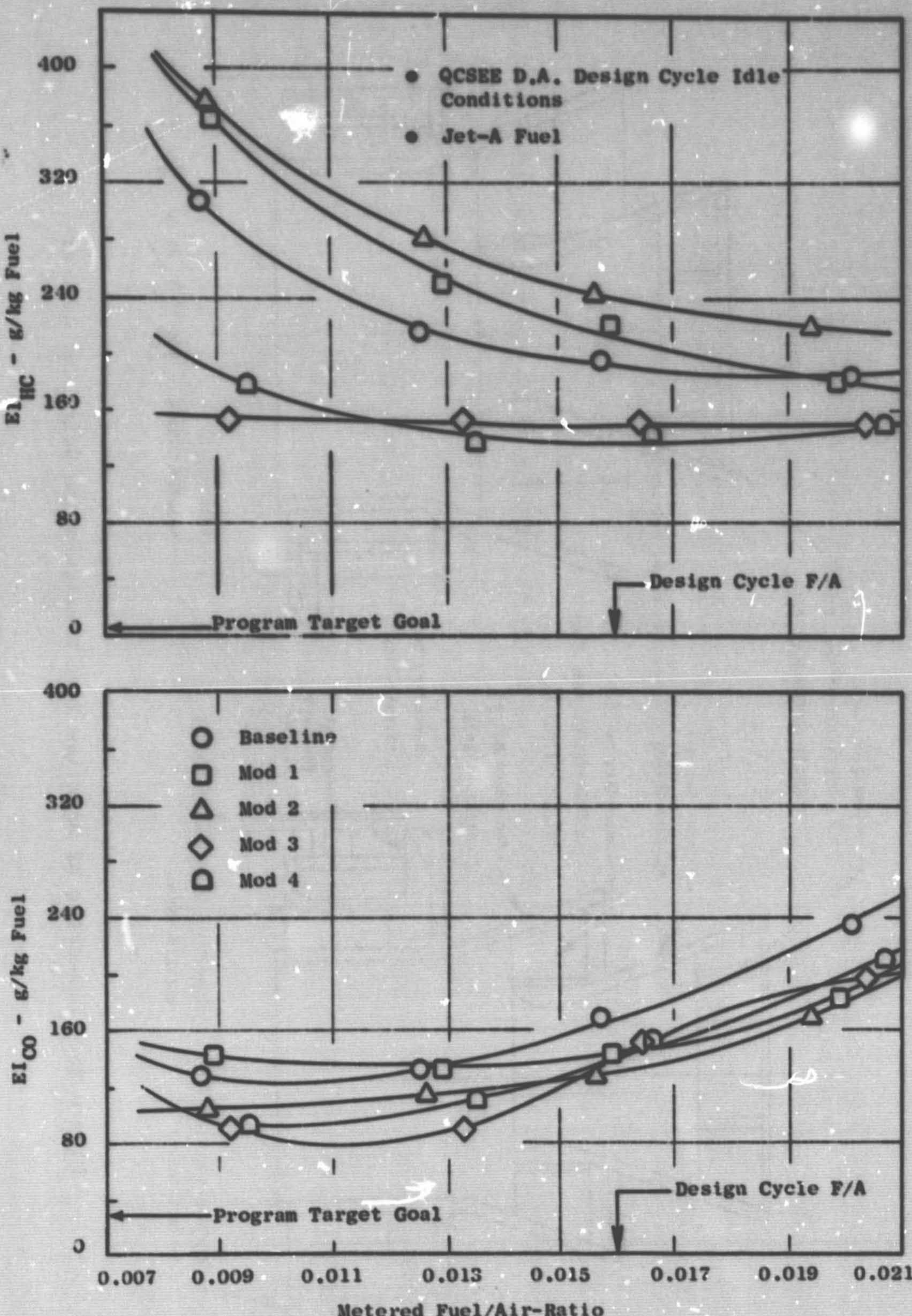



Figure 26. QCSEE Double Annular Sector Combustor Idle Emissions.

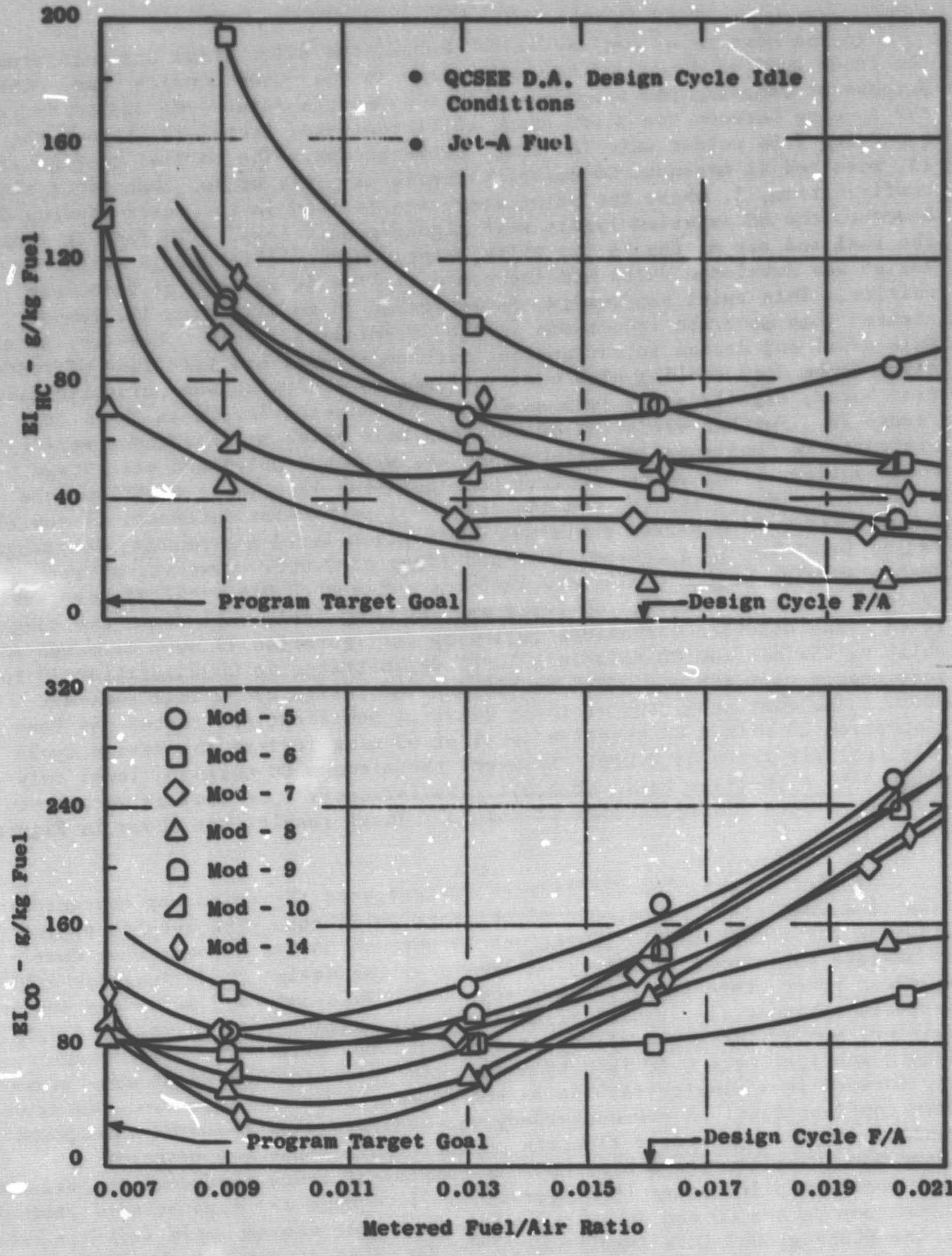



Figure 27. QCSEE Double Annular Sector Combustor Idle Emissions.

In the next major configuration change, the pilot stage was relocated in the inner annulus dome, and the main stage in the outer annulus dome. The purpose of locating the pilot stage in the inner annulus dome was to decrease the spacing between the pilot stage swirl cups and, therefore, reduce the quenching from colder unfueled zones between cups. The initial configuration, 11, resulted in measured CO emission levels slightly higher than for a similar configuration, 5, where the pilot stage was located in the outer annulus dome. However, the HC emission levels were significantly lower. To further improve the fuel and air mixing in the pilot stage, another pilot stage swirl cup design was developed which had increased airflow in the radial secondary swirler. This swirl cup design, investigated in modification 12, demonstrated some moderate reductions in the CO emission levels. However, using this swirl cup design in conjunction with additional modifications of reduced pilot stage dome cooling plus modifications to the pilot and mainstage dilution holes, significantly reduced CO and HC emission levels as shown in Figure 28. Further variation of dilution hole sizes and locations were evaluated in Configurations 15 through 24, with the pilot and main stage dome configurations unchanged from Configuration 13. These dilution hole evaluations identified two configurations of particular interest, 17 and 23. Configuration 17 achieved a minimum CO emission level approaching the program target level but at a metered fuel-air ratio of 0.009. However, at the QCSEE double annular design cycle idle fuel-air ratio of 0.016 at 4% of sea level takeoff thrust at idle the CO level was 180 g/kg fuel, well above the target level. The dilution variations following Configuration 17 were directed at shifting the minimum CO emissions level demonstrated in Configuration 17 to more nearly approach the QCSEE double annular design cycle idle fuel-air ratio. The most promising of these dilution modifications tested was Configuration 23 with a CO emission level of 93 g/kg fuel at the design cycle idle fuel-air ratio of 0.016. However, the minimum CO emission level only shifted to a fuel-air ratio of 0.011. Satisfactory HC emissions were demonstrated on both Configurations 17 and 23. These results are shown in Figure 29.

The next series of modifications investigated the emissions characteristics of a completely redesigned pilot stage swirl cup. The results of the dilution variations in Configurations 15 through 24 had demonstrated that to achieve the minimum CO emission levels at the design cycle fuel-air ratio, a leaner pilot stage swirl cup was required. This improved swirl cup design featured a higher flow radial primary swirler, higher flow radial secondary swirler, and a wide angle sleeve at the swirl cup exit. The pilot stage length was increased 0.50 inch by moving the inner annulus pilot dome assembly forward in a similar fashion as had been done on the outer annulus pilot dome configuration. A new centerbody was designed that featured a compound conical angle to provide a flowpath contour which would not restrict the inner annulus pilot stage airflow. The series of tests conducted to evaluate this modified pilot stage (Configurations 25 through 29) demonstrated further reductions in the CO and HC emission levels at the design cycle fuel-air ratio at the QCSEE ground idle conditions. The CO emission results obtained for Configuration 29 were slightly above the target goals at the design cycle idle fuel-air ratio. An illustration of the results obtained including those for Configuration 29 is shown in Figure 30.

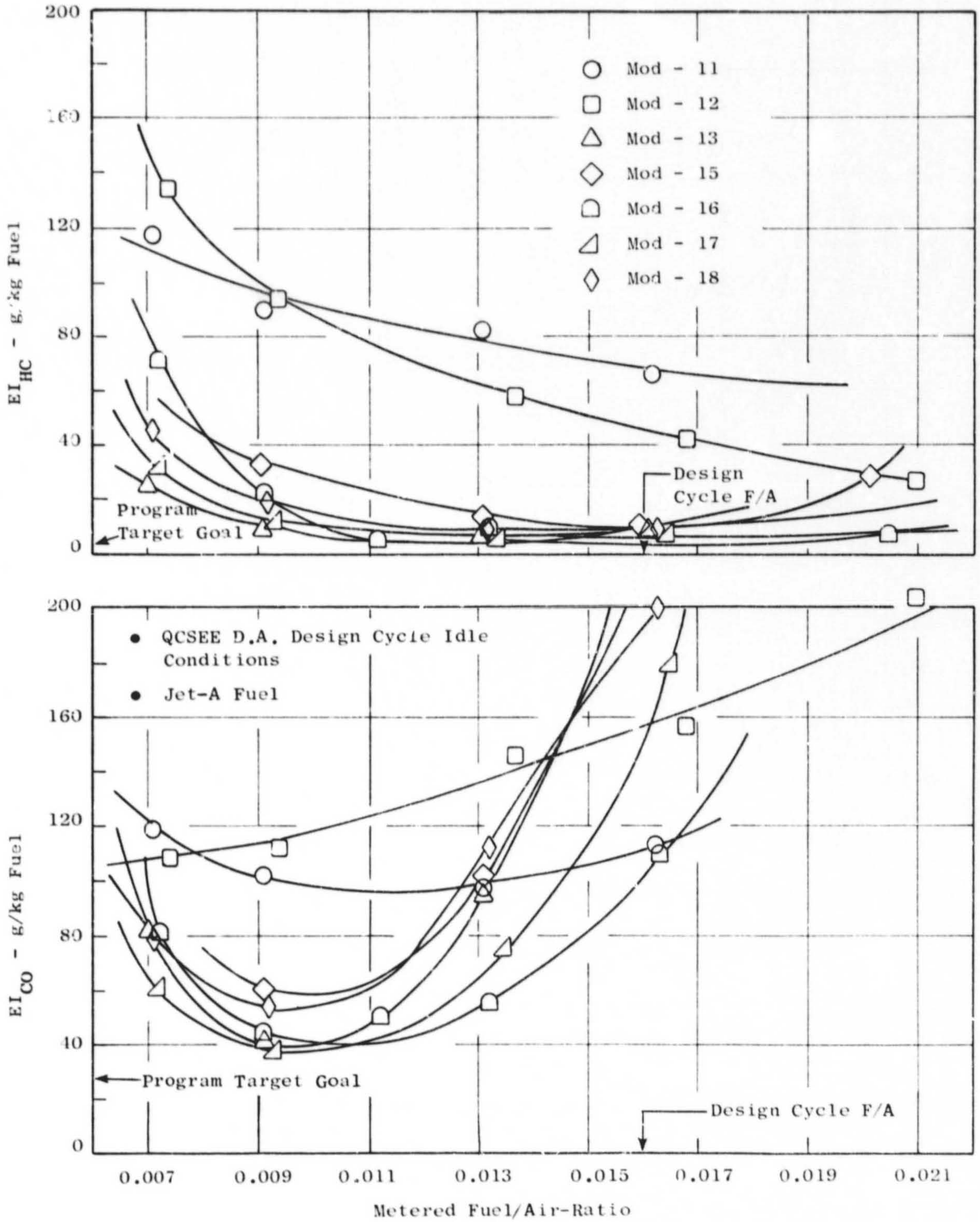



Figure 28. QCSEE Double Annular Sector Combustor Idle Emissions.

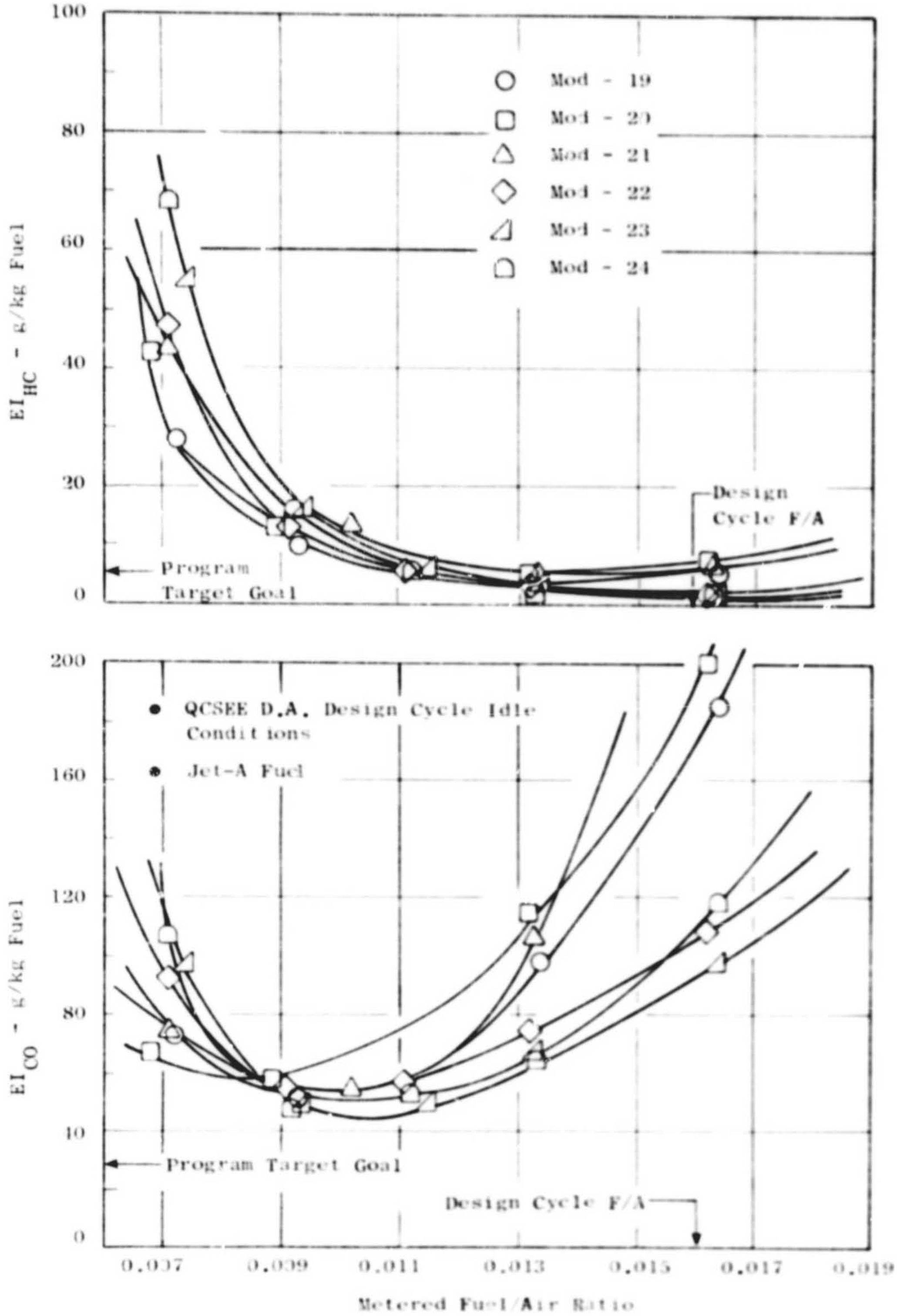



Figure 29. QCSEE Double Annular Sector Combustor Idle Emissions.

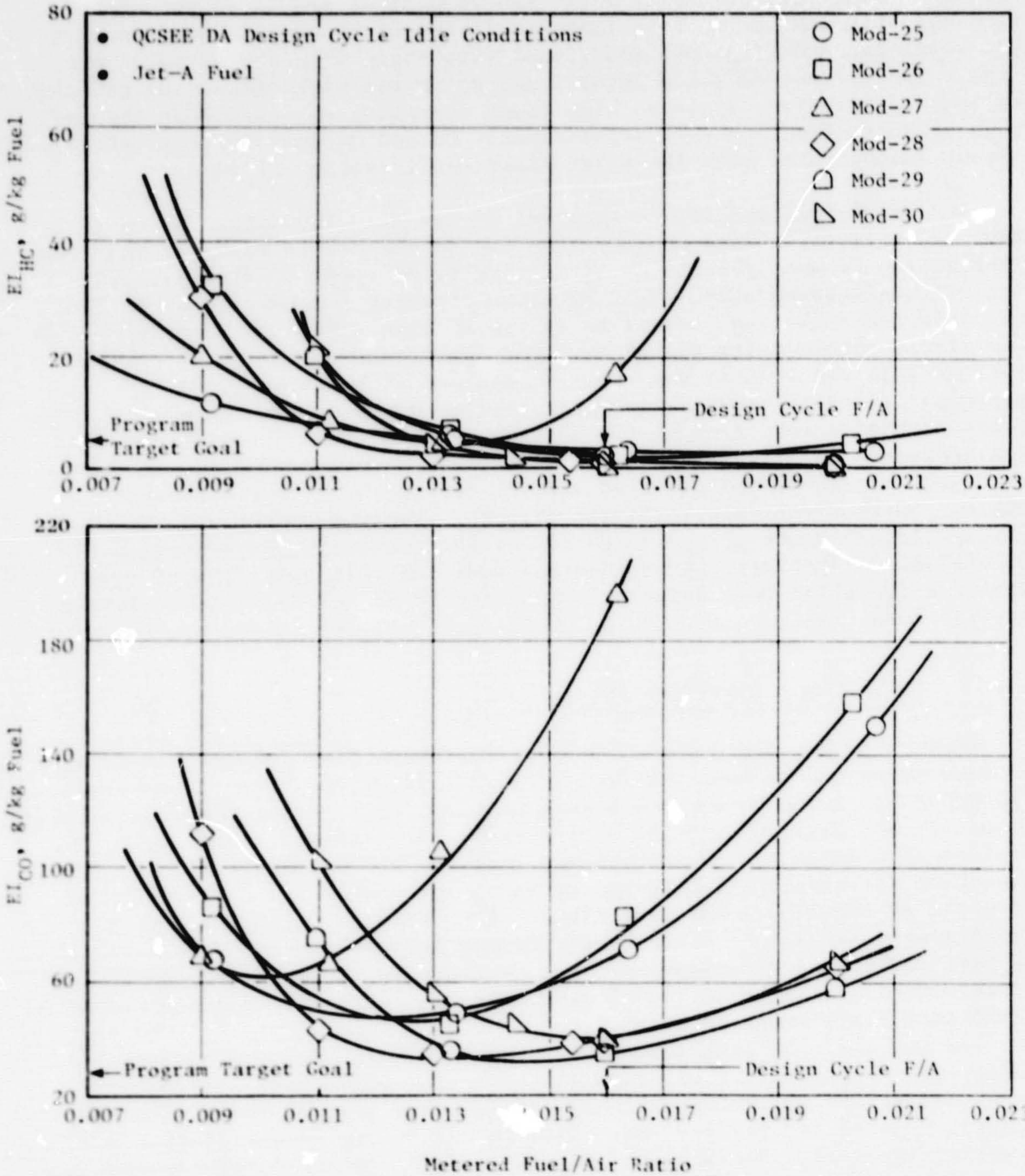



Figure 30. QCSEE Double Annular Sector Combustor Idle Emissions.

The next series of sector combustor modifications was directed at improving the main stage performance by modifying the main stage swirl cup. A new swirl cup design featuring an axial primary, axial secondary, and radial tertiary swirler was selected as the preferred configuration. The swirl cup also featured a wide angle (90°), conical sleeve insert at the swirl cup exit similar to that featured in the pilot stage. Coupled with this swirl cup modification, additional main stage dilution air was introduced. The purpose of these changes was to obtain high combustion efficiency and low $NO_x$ emission levels at high power operating conditions in the main stage without affecting the very desirable CO and HC emission characteristics already demonstrated with the pilot stage configuration at idle.

Two configurations were evaluated, 30 and 31. In Configuration 31 a minor outer liner cooling modification was introduced to readjust the flow distribution to more closely duplicate the pilot stage airflow distributions of Configuration 29. Idle emissions testing for Configuration 31 was conducted following several tests run at simulated high power operating conditions. The results showed a slight deterioration in the CO emission level at idle compared to the results obtained with Configuration 29. An investigation of the sector combustor airflow distribution revealed that due to the extensive test time at the high power conditions, significant flow area increases had developed at the mechanical joints of the sector combustor which produced pilot stage airflows different than the designed levels. Further analysis indicated that the observed increase in the CO emission levels could be accounted for by the off-design distribution of the airflow. Therefore, it was decided that the idle emissions of this final configuration were accurately represented by the CO emission levels obtained with Configuration 29, as shown in Figure 30.

High Power Emissions ($NO_x$)

Because of the large number of test configurations involved in developing the idle emissions to meet the program goals, emissions tests at simulated high power operating conditions were conducted for only the baseline, Configuration 17, and Configuration 31 sector combustor configurations. With the original main stage design in both the baseline and Configuration 17, poor combustion efficiency was observed at all pilot-to-total fuel flow ratios evaluated at the high power conditions. The efficiency decreased as the pilot-to-main stage fuel splits were reduced indicating that the source of the poor combustion efficiency was due to the main stage performance. The redesigned main stage swirl cup featured in Configuration 31 demonstrated a significant improvement in combustion efficiency in addition to providing very low $NO_x$ emission levels when adjusted to actual high power operation conditions. Based on the adjusted values at the preferred pilot to main stage fuel split, $NO_x$ emissions would satisfy the program goals. The $NO_x$ emission results for the configurations tested at high power conditions are shown in Figure 31. The adjusted CO, HC, and $NO_x$ emission levels, plus the measured combustion efficiency obtained with this final sector combustor configuration along the design cycle operating line, are shown in Figures 32 and 33.

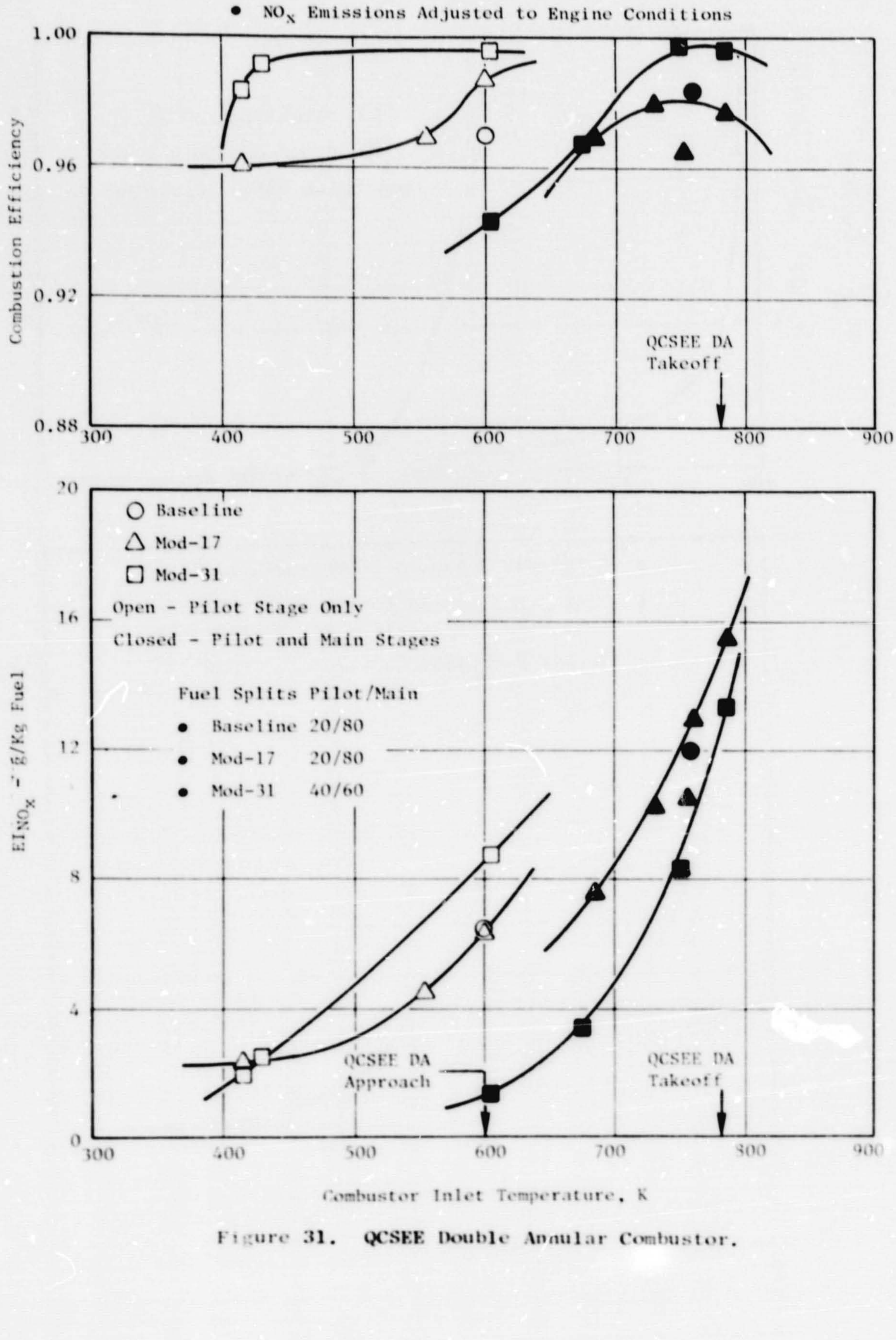



Figure 31. **QCSEE Double Annular Combustor.**

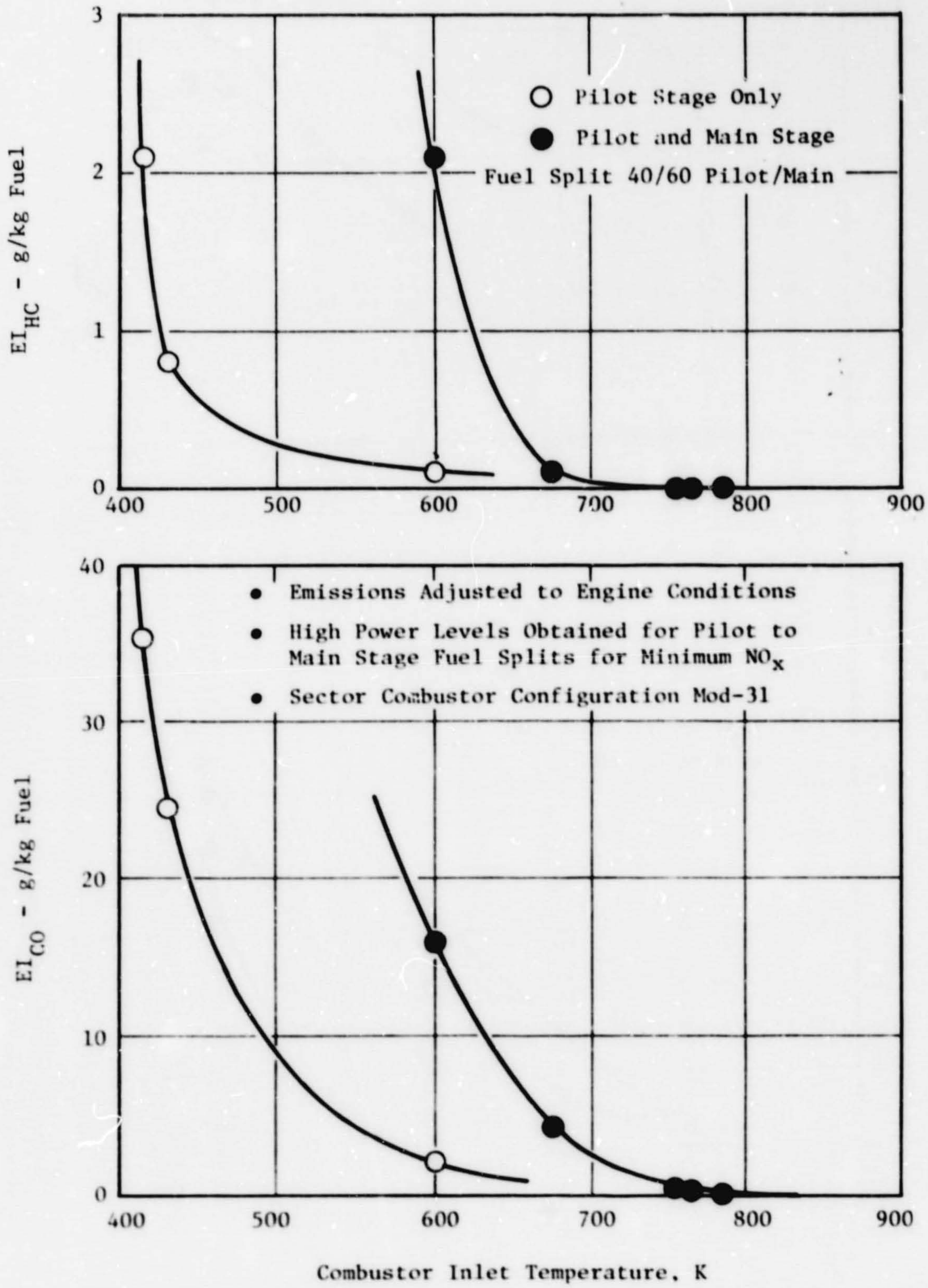



Figure 32. QCSEE Double Annular Combustor.

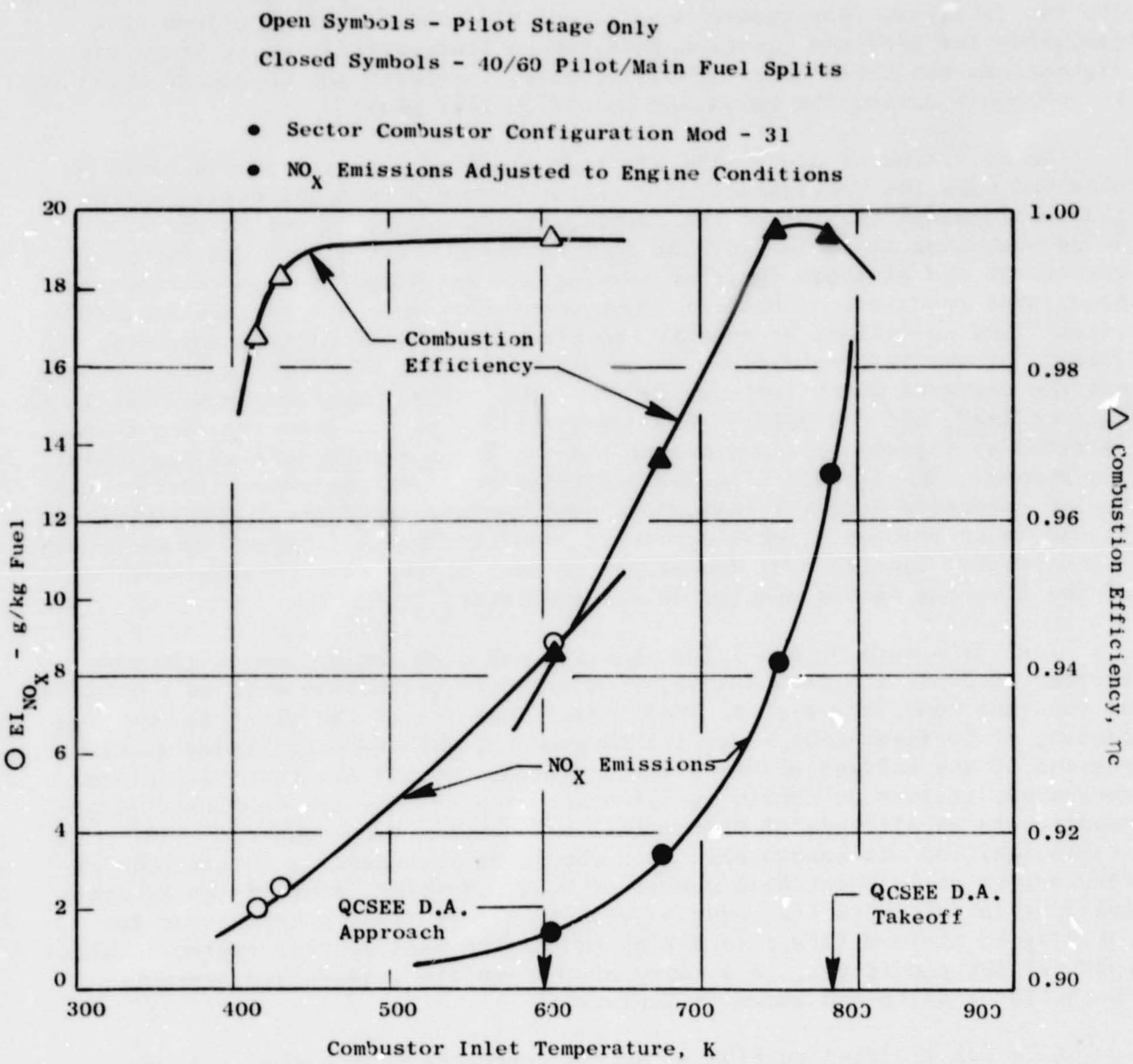



Figure 33. QCSEE Double Annular Combustor.

## 7.2 ALTITUDE IGNITION RESULTS

Altitude ignition testing was conducted to evaluate the pilot stage ignition characteristics of two key sector combustor designs of the 32 configurations investigated during the emissions reduction phase of this program. The two configurations tested were 17 and 31. These configurations were evaluated for altitude ignition performance because their pilot stage configurations exhibited considerable promise of meeting the CO and HC emissions target goals during the emissions reduction test phase.

To determine if acceptable altitude ignition characteristics could be obtained with the Configuration 17 sector combustor design, altitude ignition performance testing of this configuration was conducted in the Small Scale Combustor Altitude Ignition Test Facility. Jet A fuel was used throughout the altitude ignition testing and was supplied at cold temperatures when required. Combustor inlet conditions were set to simulate CFM56 windmilling conditions at selected points of the QCSEE relight envelope. A listing of the test conditions is provided in Table XI. The ignition system was the standard QCSEE ignition system: P/N 9101M52 exciter, P/N 4013131-400 ignitor lead, and P/N 4013163-855 spark ignitor plug. This ignition system is rated at 2 joules minimum output energy with a firing rate of two sparks per second. The ignitor plug was positioned through the inner liner of the sector combustor directly inline and just downstream of the center swirl cup in the inner annulus pilot stage dome. Ignition was determined by monitoring thermocouples located just downstream of each of the center three swirl cups of the five-cup double annular sector combustor.

Test data were obtained for ignition and lean extinction at the prescribed altitude and Mach number, plus pressure extinction data were obtained at constant combustor air and fuel flows. Results of the altitude ignition testing of Configuration 17 indicated good relight characteristics at all regions of the relight envelope investigated. Of all the test conditions evaluated, failure to obtain ignition occurred at only one condition corresponding to an altitude of 9100 meters at an inlet Mach number of 0.67. Unstable ignition was encountered at a condition representing an altitude of 7600 meters at an inlet Mach number of 0.70. However, some of the successful ignition attempts did occur at combustor fuel flows greater than the 136.2 kg/hr minimum flow rate set by the engine fuel control system at altitude relight conditions. A summary of the ignition, lean, and pressure extinction results are shown in Table XII.

Altitude ignition testing of sector combustor Configuration 31 was conducted in the Advanced Combustion Laboratory Facility at reduced pressures, but at ambient air and fuel temperatures. A full test schedule involving other development programs prohibited the use of the cold air facility for testing this configuration. The ignition system and ignitor location were identical to the Configuration 17 test. Test conditions representing the same points within the relight envelope as were tested with Configuration 17 were adjusted to reflect the ambient combustor inlet temperature. A listing of these test conditions is provided in Table XIII.

Table XI. QCSEE Double Annular Dome Altitude Ignition Test Points for Configuration 17.

- Full Annular Conditions
- Bldg. 301 Combustion Lab.
- Jet A Fuel at Prescribed Conditions
- $V_{ref} = W_c R\ T_3/P_3\ A_{ref}$

| Point | Alt. kM | Mach No. | $P_3$ Atm. | $T_3$ K | $W_c$ kg/s | $T_{fuel}$ K | $V_{ref}$ M/S | $\frac{P_3\ T_3}{V_{ref}}$ $\frac{Atm.-K}{M/S}$ | $\left(\frac{W_c}{P_3}\right)^2 T_3$ $\left(\frac{kg}{Atm.-S}\right)^2 K$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.30 | 1.02 | 294 | 0.76 | Amb. | 3.00 | 100.0 | 163.2 |
| 2 | 3.66 | 0.30 | 0.66 | 265 | 0.54 | 256 | 2.93 | 56.7 | 177.4 |
| 3 | 6.10 | 0.36 | 0.46 | 249 | 0.47 | 249 | 3.44 | 33.3 | 260.0 |
| 4 | 7.62 | 0.40 | 0.37 | 241 | 0.44 | 244 | 3.90 | 22.9 | 340.8 |
| 5 | 9.14 | 0.55 | 0.32 | 240 | 0.61 | 244 | 6.22 | 12.4 | 872.1 |
| 6 | 6.10 | 0.45 | 0.48 | 256 | 0.72 | 256 | 5.24 | 23.5 | 576.0 |
| 7 | 7.62 | 0.50 | 0.38 | 246 | 0.67 | 246 | 5.91 | 15.8 | 764.7 |
| 8 | 3.05 | 0.41 | 0.71 | 278 | 0.92 | Amb. | 4.91 | 40.2 | 466.8 |
| 9 | 4.57 | 0.45 | 0.59 | 269 | 0.84 | Amb. | 5.27 | 30.1 | 545.3 |
| 10 | 9.14 | 0.67 | 0.34 | 247 | 0.81 | 247 | 8.08 | 10.4 | 1401.9 |
| 11 | 4.57 | 0.60 | 0.61 | 279 | 1.32 | Amb. | 8.20 | 20.8 | 1306.4 |
| 12 | 6.10 | 0.60 | 0.50 | 268 | 1.07 | Amb. | 7.80 | 17.2 | 1227.3 |
| 13 | 7.62 | 0.70 | 0.41 | 263 | 1.07 | 256 | 9.48 | 11.4 | 1791.2 |
| 14 | 6.10 | 0.80 | 0.56 | 283 | 1.65 | Amb. | 11.40 | 14.1 | 2491.6 |

Table XII. Configuration 17 Relight Test Summary.

| Alt. kft | Mach No. | $T^3$ K | $W_c$ kg/s | $P_{T3}$ Atm. | $\Delta P/P$ | $V_{Ref}$ M/S | $(W_c/P_s)^2T_3$ | L/O kg/hr | LBO kg/hr | PBO Atm. | $T_{Fuel}$ K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.30 | 310.0 | 0.7619 | 1.0200 | 0.005 | 3.169 | 173.0 | 130 | 93 | --- | 306 |
| 3.0 | 0.41 | 278.9 | 0.9252 | 0.7077 | 0.008 | 4.968 | 476.7 | 149 | 114 | 0.6260 | 303 |
| 3.7 | 0.30 | 265.0 | 0.5442 | 0.6668 | 0.005 | 2.956 | 176.5 | 103 | 87 | 0.5988 | 254 |
| 4.6 | 0.45 | 267.8 | 0.8526 | 0.6192 | 0.016 | 5.029 | 507.7 | 134 | 123 | 0.5784 | 288 |
| 4.6 | 0.60 | 277.8 | 1.3240 | 0.6124 | 0.021 | 8.199 | 1298.5 | 158 | 132 | 0.5852 | 304 |
| 6.1 | 0.36 | 247.8 | 0.4717 | 0.4627 | 0.009 | 3.444 | 257.5 | 114 | 89 | 0.6124 | 250 |
| 6.1 | 0.45 | 255.0 | 0.7256 | 0.4763 | 0.014 | 5.273 | 591.8 | 131 | 112 | 0.5648 | 256 |
| 6.1 | 0.60 | 270.0 | 1.0700 | 0.5035 | 0.020 | 7.833 | 1219.4 | 160* | 129 | 0.6124 | 304 |
| 6.1 | 0.80 | 258.3 | 1.6500 | 0.5648 | 0.043 | 11.490 | 2204.5 | 149 | 122 | 0.5444 | 306 |
| 7.6 | 0.40 | 241.1 | 0.4535 | 0.3743 | 0.011 | 3.992 | 353.9 | 141 | 121 | 0.6737 | 246 |
| 7.6 | 0.50 | 247.2 | 0.6712 | 0.3743 | 0.032 | 6.035 | 794.9 | 171 | 102 | 0.6260 | 246 |
| 7.6 | 0.70 | 263.3 | 1.0700 | 0.4083 | 0.048 | 9.418 | 1808.3 | 196* | --- | --- | 254 |
| 9.1 | 0.55 | 241.7 | 0.6168 | 0.3198 | 0.023 | 6.339 | 899.1 | 161 | 136 | 0.6805 | 244 |
| 9.1 | 0.67 | 246.1 | 0.8163 | 0.3402 | 0.049 | 8.107 | 1416.9 | --- | --- | --- | 248 |

*Note: Unstable Ignition

Table XIII. QCSEE Double Annular Dome Altitude Ignition Test Points Configuration 31.

- Full Annular Conditions
- Bldg. 306 Combustion Lab.
- Jet A Fuel at Ambient Temperature
- $V_{ref} = W_c R\ T_3/P_3\ A_{ref}$

| Point | Alt. kM | Mach No. | $P_3$ Atm. | $T_3$ K | $V_{ref}$ M/S | $W_c$ kg/s | $\frac{P_3\ T_3}{V_{ref}}$ $\frac{\text{Atm.-K}}{\text{M/S}}$ | $(\frac{W_c}{P_3})^2\ T_3$ $(\frac{\text{kg}}{\text{Atm.-S}})^2$ K |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.30 | 1.02 | 283 | 2.89 | 0.78 | 99.9 | 165.5 |
| 2 | 3.66 | 0.30 | 0.66 | | 3.01 | 0.53 | 62.1 | 182.5 |
| 3 | 6.10 | 0.36 | 0.46 | | 3.56 | 0.44 | 36.6 | 422.8 |
| 4 | 7.62 | 0.40 | 0.37 | | 4.20 | 0.42 | 25.2 | 364.7 |
| 5 | 9.14 | 0.55 | 0.32 | | 6.64 | 0.56 | 13.5 | 866.7 |
| 6 | 6.10 | 0.45 | 0.48 | | 5.48 | 0.69 | 24.5 | 584.8 |
| 7 | 7.62 | 0.50 | 0.38 | | 6.30 | 0.63 | 17.1 | 777.9 |
| 8 | 3.05 | 0.41 | 0.71 | | 4.84 | 0.91 | 41.3 | 464.9 |
| 9 | 4.57 | 0.45 | 0.59 | | 5.39 | 0.83 | 30.7 | 560.1 |
| 10 | 9.14 | 0.67 | 0.34 | | 8.56 | 0.76 | 11.1 | 1414.0 |
| 11 | 4.57 | 0.60 | 0.61 | | 8.19 | 1.32 | 21.1 | 1325.2 |
| 12 | 6.10 | 0.60 | 0.50 | | 7.92 | 1.05 | 17.9 | 1248.0 |
| 13 | 7.62 | 0.70 | 0.41 | | 9.75 | 1.05 | 11.8 | 1856.1 |
| 14 | 6.10 | 0.80 | 0.56 | | 11.18 | 1.66 | 14.2 | 2486.7 |

Test results obtained in the altitude ignition evaluation of Configuration 31 indicated good ignition characeristics over the portions of the relight envelope tested. Ignition was observed at all test points. However, at two conditions, (9100 meters at 0.55 inlet Mach number and 7600 meters at 0.709 inlet Mach number), unstable ignition occurred. A summary of these test results is provided in Table XIV. Illustrations and comparisons of these results with those of Configuration 17 are shown in Figure 34. This figure indicates that both sector combustor configurations demonstrated similar altitude ignition characteristics. Lean extinction characteristics at altitude of Configuration 31 were somewhat improved over those of Configuration 17. This result is explained by the superior air and fuel mixing characteristics of the Configuration 31 pilot stage swirl cup design as compared with the pilot stage swirl cup design featured in Configuration 17.

## 7.3 GROUND START AND LEAN STABILITY RESULTS

Ground start ignition and lean extinction test results were obtained for the pilot stage designs featured in the baseline, 17, and 31 sector combustor configurations. Ground start ignition testing was performed at ambient combustor inlet pressure and temperature using the same standard QCSEE ignition system that was used for the altitude ignition testing. Lean extinction testing was also performed at ambient combustor inlet conditions with the exception of the baseline sector combustor configuration which was tested at ambient inlet temperature, but at an inlet pressure of 1.40 atmospheres.

The results of the ground start ignition and lean extinction testing are shown in Figure 35. No ground start ignition testing was performed on the baseline configuration. As indicated in this figure, Configurations 17 and 31 demonstrated similar ground start ignition characteristics. For both of these configurations, ground ignition fuel flow rates exceeded the QCSEE control main fuel minimum flow rate of 136 kg/hr at startup conditions above core speeds of 2000 rpm. The pilot stage design feature in Configuration 31 had a swirl cup design that provided a lean well-mixed combustion zone compared to the pilot stage featured in Configuration 17 which was much richer but not as well mixed. The improved quality of the Configuration 31 pilot stage swirl cup design appears to offset the leaner fuel stoichiometry producing ground start ignition results similar to the results obtained for Configuration 17. The lean extinction characteristics of Configuration 31 are considerably improved over the lean extinction characteristics obtained for both the baseline and Configuration 17. For a fixed set of combustor inlet conditions, the Configuration 31 pilot stage remained burning at fuel flow rates 50% less than for the Configuration 17 pilot stage design. Also, shown in Figure 35 are the ground start ignition and lean extinction results for the NASA/GE ECCP final design configuration. The results for this CF6-50 double annular configuration exhibit similar trends as the results demonstrated with the QCSEE Double Annular Sector Combustor configurations.

## Table XIV. Configuration 31 Relight Test Summary.

| Alt. km | Mach No. | $T_3$ K | $W_c$ kg/s | Outer $PT_3$ Atm. | Inner $PT_3$ Atm. | Outer $\Delta P/P$ | Inner $\Delta P/P$ | $V_{Ref}$ m/s | $(W_c/P_3)^2T_3$ | 1-Cup L/O kg/hr | Propagation L/O kg/hr | LBO kg/hr | PBO Atm. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.30 | 288 | 0.7129 | 1.0210 | 1.0190 | 0.0031 | 0.0029 | 2.740 | 140.4 | 114.3 | 132.4 | 50.8 | 0.5437 |
| 3.0 | 0.41 | 286 | 0.9542 | 0.7186 | 0.7152 | 0.0096 | 0.0098 | 5.209 | 504.3 | 136.1 | 168.7 | 79.8 | 0.5444 |
| 3.7 | 0.30 | 288 | 0.5551 | 0.6682 | 0.6648 | 0.0048 | 0.0044 | 3.270 | 198.8 | 108.8 | 139.7 | ~18.1 | 0.4614 |
| 4.6 | 0.45 | 288 | 0.8816 | 0.5886 | 0.5866 | 0.0138 | 0.0130 | 5.910 | 646.1 | 145.1 | 172.3 | 81.6 | 0.4491 |
| 4.6 | 0.60 | 283 | 1.3090 | 0.6117 | 0.6117 | 0.0257 | 0.0245 | 8.241 | 1296.0 | 145.1 | 195.9 | 139.7 | 0.5784 |
| 6.1 | 0.36 | 284 | 0.4717 | 0.4648 | 0.4661 | 0.0037 | 0.0050 | 3.944 | 292.5 | 117.9 | 154.2 | ~18.1 | 0.3743 |
| 6.1 | 0.45 | 286 | 0.7492 | 0.4811 | 0.4777 | 0.0194 | 0.0165 | 6.120 | 693.6 | 136.1 | 157.8 | 63.5 | 0.3334 |
| 6.1 | 0.60 | 282 | 1.1220 | 0.5117 | 0.5131 | 0.0235 | 0.0239 | 8.461 | 1355.8 | 136.1 | 194.1 | 63.5 | 0.4614 |
| 6.1 | 0.80 | 279 | 1.1420 | 0.5750 | 0.5716 | 0.0239 | 0.0215 | 7.613 | 1100.5 | 132.4 | 172.3 | 92.5 | 0.5103 |
| 7.6 | 0.40 | 288 | 0.4354 | 0.3811 | 0.3845 | 0.0026 | 0.0051 | 4.480 | 375.9 | 123.4 | 152.4 | ~18.1 | 0.3062 |
| 7.6 | 0.50 | 289 | 0.6512 | 0.3811 | 0.3811 | 0.0168 | 0.0168 | 6.730 | 843.8 | 143.3 | 188.7 | ~18.1 | 0.3470 |
| 7.6 | 0.70 | 284 | 1.0720 | 0.4042 | 0.4042 | 0.0383 | 0.0377 | 10.350 | 1997.6 | 157.8* | --- | --- | --- |
| 9.1 | 0.55 | 286 | 0.5968 | 0.3239 | 0.3212 | 0.0288 | 0.0237 | 7.275 | 971.0 | 137.9** | --- | --- | --- |
| 9.1 | 0.67 | 289 | 0.7728 | 0.3341 | 0.3314 | 0.0309 | 0.0302 | 9.125 | 1546.2 | 136.1** | --- | --- | --- |

- Fuel at Ambient Temperature (286.7 K)
- Note:
  - *Single cup in front of ignitor fired, however no propagation occurred.
  - **Single cup in front of ignitor fired, however could not be maintained without ignitor assist.
  - Test Point 6.1 km at 0.80 was run at wrong airflow. Airflow should have been 1.655 kg/s instead of 1.142 kg/s.

- Mod - 17 Tested at Low Pressure with Cold Air and Fuel Temperatures
- Mod - 31 Tested at Low Pressure with Ambient Air and Fuel Temperatures
- Jet-A Fuel
- Fuel Flows Indicated in kg/hr

Top Figures: Mod - 31 Results

Fuel Flow at Ignition/Fuel Flow at Propagation

Bottom Figure: Mod - 17 Results

Fuel Flow at Ignition

- UI - Unstable Ignition (At Fuel Flow)
- NI - No Ignition

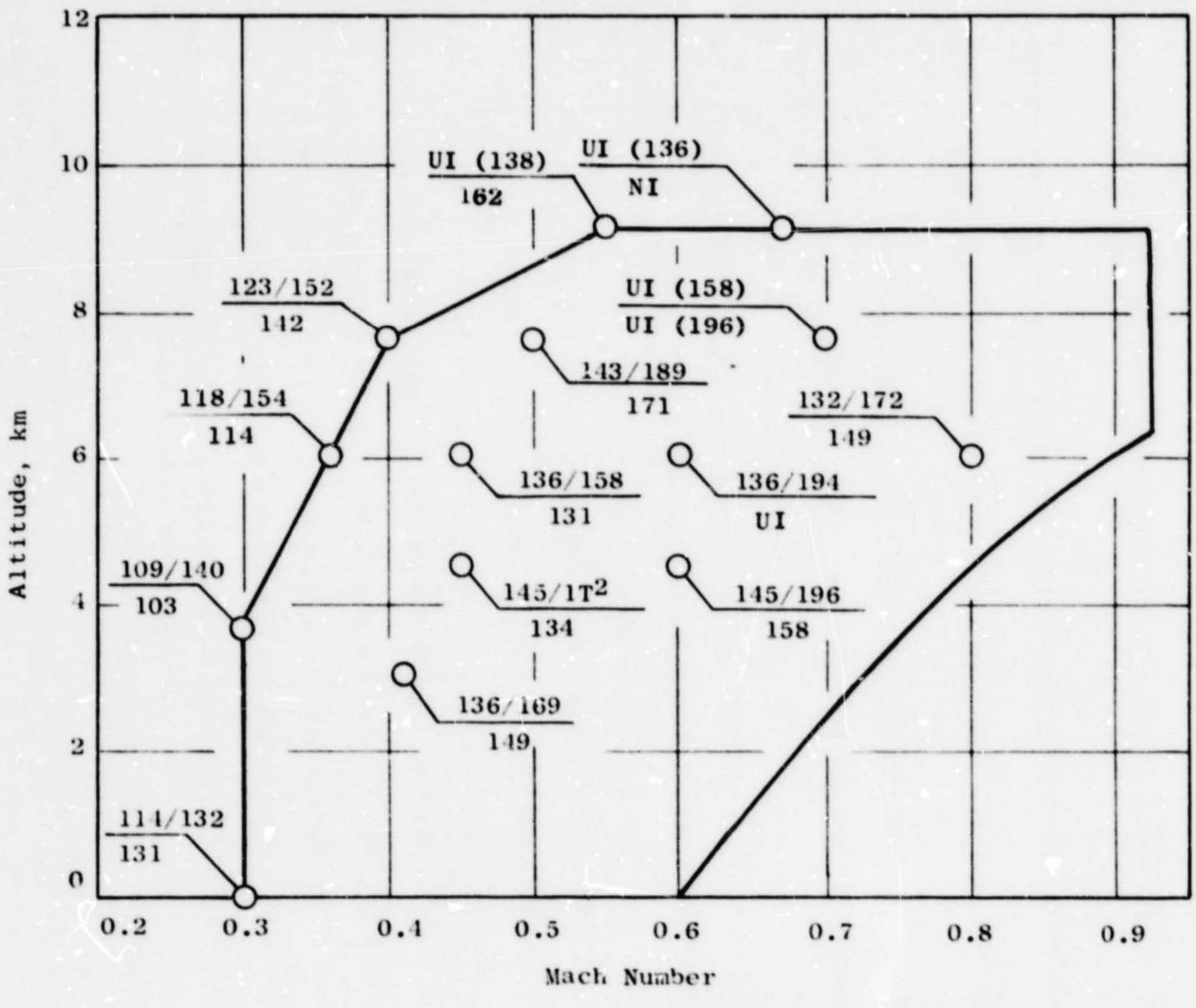



Figure 34. QCSEE Double Annular Sector Combustor Comparison of Altitude Ignition Characteristics of Configurations 17 and 31.

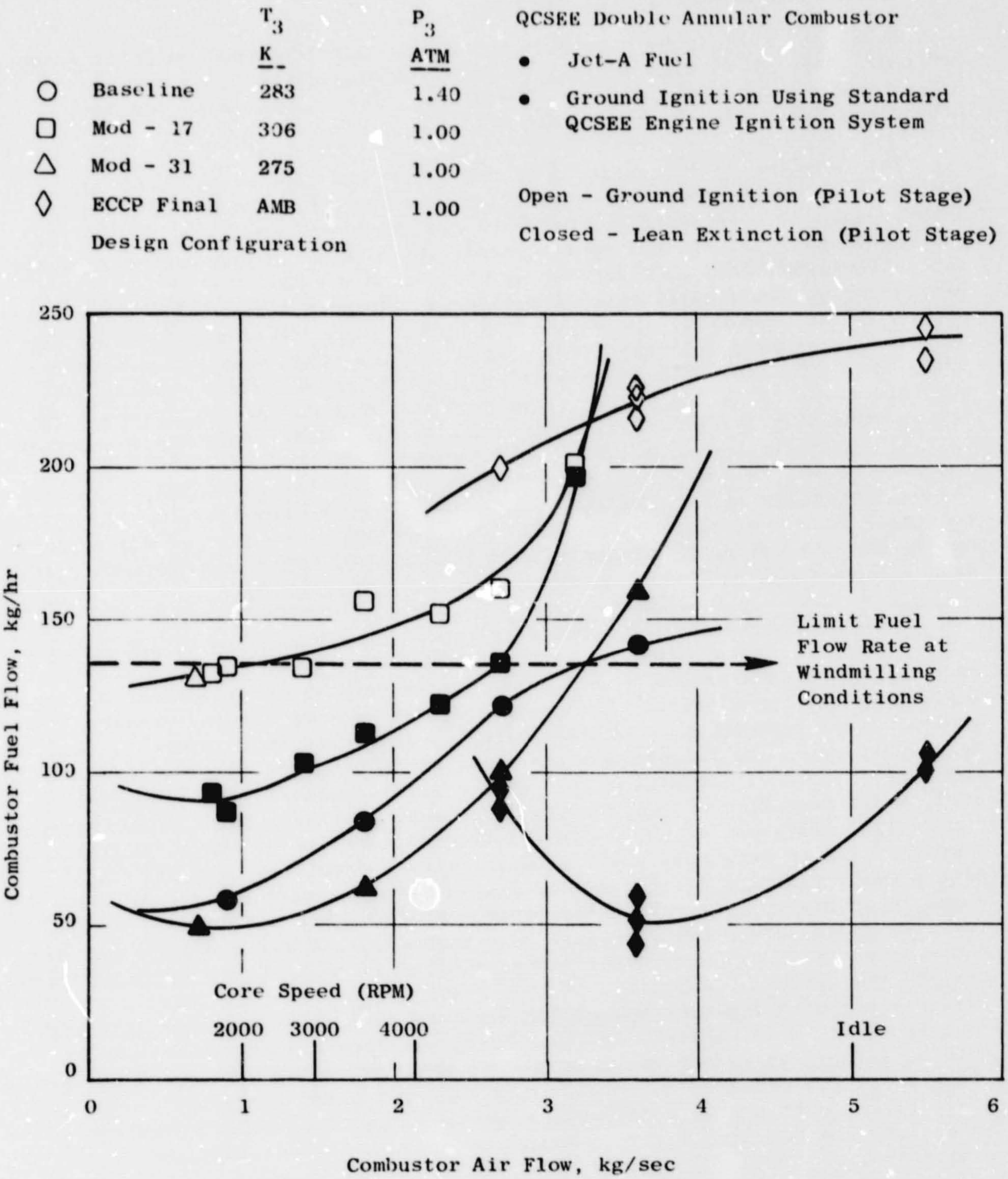



Figure 35. Ground Ignition and Lean Extinction Results.

## 7.4 SWIRL CUP FUEL SPRAY TEST RESULTS

Swirl cup fuel spray component tests were performed on the pilot stage and main stage swirl cups designs featured in the baseline, 3, 25, and 30 sector combustor configurations. These tests were conduced in the Fuel Laboratory Spray Visualization Test Facility.

The baseline configuration featured pilot and main stage swirl cup designs with counterrotating axial primary and axial secondary swirlers. A photograph of this swirl cup hardware was shown previously in Figure 18. Results of the initial fuel spray visualization tests of the baseline swirl cup designs indicated poor fuel spray dispersion and atomization quality for the pilot stage swirl cup. A fuel spray included cone angle of approximately 43° was observed. Surveys of the pilot stage swirl cup flow pattern with a tuft of yarn indicated very little recirculation downstream of the swirl cup exit. The main stage swirl cup demonstrated better atomization than did the pilot stage swirl cup when tested at the same conditions. The better atomizing characteristics of the main stage swirl cup were attributed to the higher airflows. However, observations indicated that still further improvement was needed. Tuft surveys downstream of the secondary barrel of the main stage swirl cup revealed a very narrow recirculation zone of considerable strength. The observed included fuel spray cone angle was approximately 48°. A schematic of the pilot and main stage swirl cup designs along with the observed fuel spray results is shown in Figure 36.

Based on the findings of these fuel spray investigations of the baseline sector combustor pilot stage swirl cup design, several minor modifications were incorporated into the swirl cup design and subsequently evaluated for fuel spray characteristics. This swirl cup development testing produced several swirl cup designs which exhibited considerable improvement in fuel spray dispersion and atomization characteristics over the baseline design hardware. Table XV contains a list of the swirl cup configurations evaluated, and a summary of their results. The most promising pilot stage swirl cup design configuration which evolved from this series of tests featured a reduced length secondary venturi barrel with a chamfered trailing edge, plus a small radial tertiary swirler counterrotating with respect to the axial secondary swirler. Velocity profile measurements made of the swirl cup flow field, are shown in Figure 37. However, this swirl cup design still had poor recirculation characteristics, similar to some of the other modified designs evaluated. A schematic of this preferred pilot stage swirl cup design along with a photograph of the observed fuel spray is shown in Figure 38. Since the main emphasis of the program was directed at reductions in idle emissions, no effort was made at this time to improve the baseline main stage swirl cup design. Therefore, this modified pilot stage swirl cup design along with the original main stage swirl cup design were incorporated into the baseline sector combustor configuration for idle emissions evaluation.

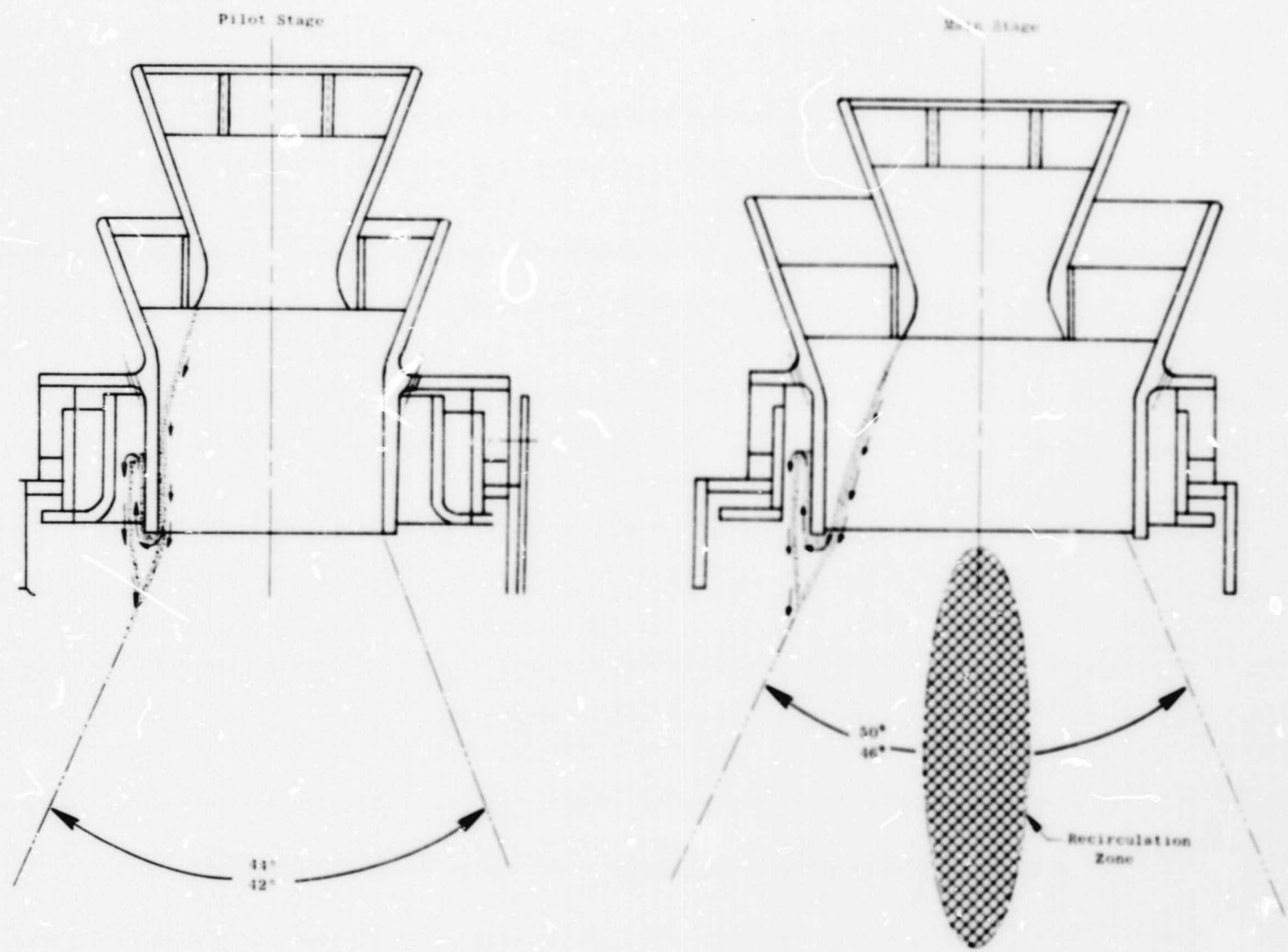



Figure 36. Baseline Pilot and Main Stage Swirl Cups.

Table XV. Summary of Baseline Pilot Stage Swirl Cup Investigation.

| Configuration / Design Objective | Primary / Axial | % Wc / 4.2 | Secondary / Axial | % Wc / 4.3 | Tertiary | % Wc | Spray Angle / 43° | Stable Spray / Yes | Recirculation Zone (Inches H2O ΔP) / Yes | Spray Quality / Good/ No Drool | Sleeve / No | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | | 3.7 | | 6.7 | --- | --- | 43° | | No | Poor/ Drools | No | None |
| No. 1 | | | | 9.2 | --- | --- | 49° | | No | Coarse/ Drools | 101P06 | Shorten Secondary |
| No. 2 | | | | 6.7 | --- | --- | 45° | | Yes | Good/ No Drool | No | Shorten Secondary Barrel and Move Flange |
| No. 3 | | | | 6.7 | --- | --- | 60° | | Yes (-1.9) | Good/ Drools | 202P07 | Shorten Secondary Barrel |
| No. 4 | | | | 9.2 | --- | --- | 43° | | (-4.8) | Good/ Drools | 172 Cylinder | Shorten Secondary Barrel |
| No. 5 | | | | 6.7 | Radial | 4.6 | 42° | | (-6.1) | Good/ No Drool | No | Extended Venturi |
| No. 6 Preferred Design | | | | 6.7 | Radial | 4.6 | 50° | | (-3.5) | Good/ No Drool | No | None |
| No. 7 | | 5.4 | | 9.2 | Radial | 4.6 | 42° | | (-3.8) | Good/ No Drool | No | Extended Venturi and Shorten Secondary Barrel |

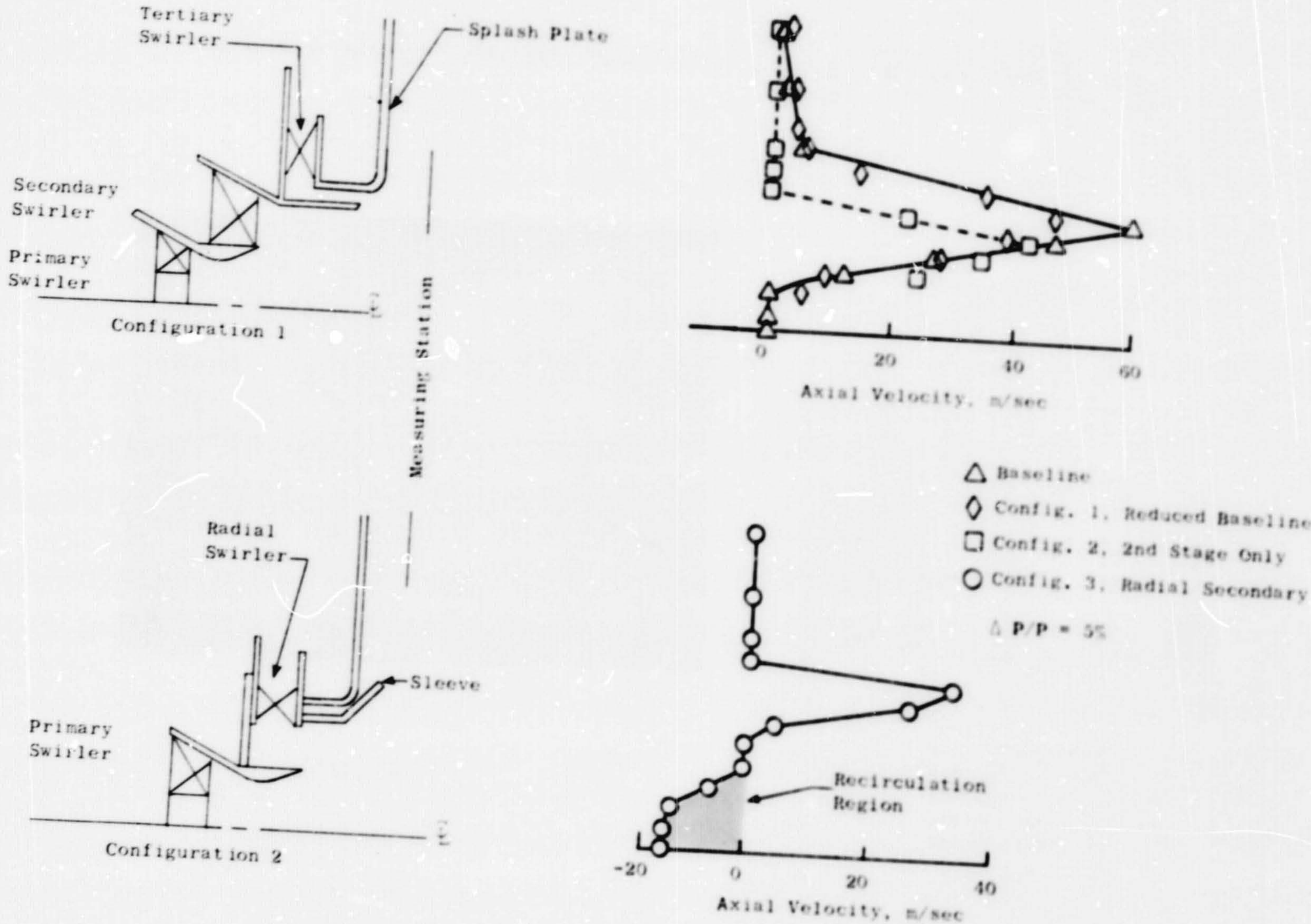
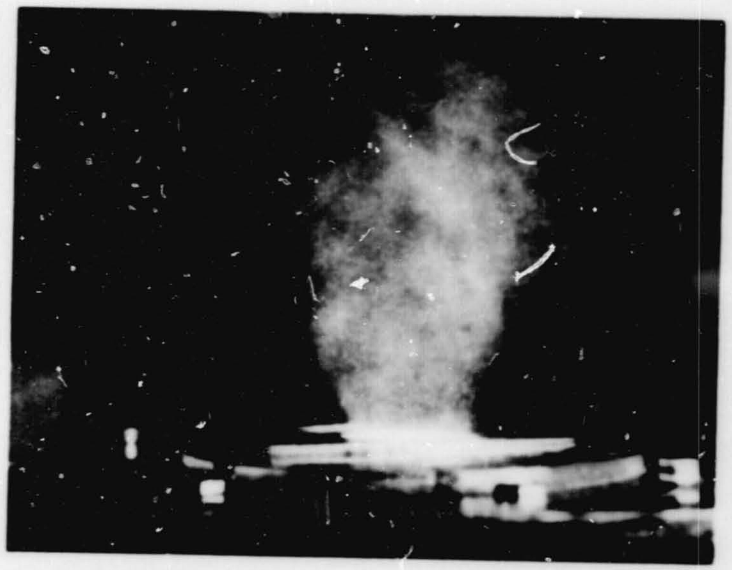



Figure 37. Swirl Cup Airflow Fields.



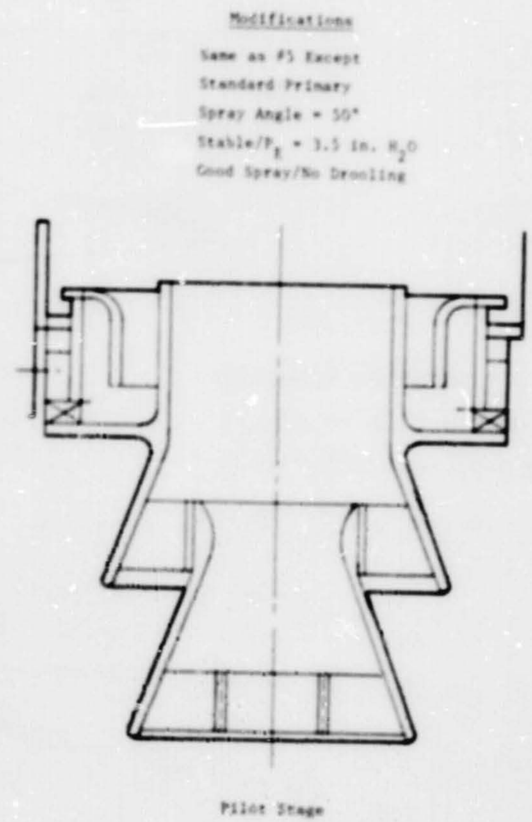



Figure 38. Baseline Test Configuration Pilot Stage Swirl Cup Design.

A series of velocity profile investigations were performed on modified configurations of the baseline sector combustor pilot stage swirl cup design, in addition to a new swirl cup design configuration featuring a small radial secondary swirler and an axial primary swirler. The intent of these investigations was to evolve a swirl cup design with improved recirculation characteristics compared to the existing baseline sector combustor pilot stage swirl cup design. A description of the designs evaluated is contained in Table XVI. Results of the velocity profile investigations using a wedge probe shown in Figure 37, reveal that the recirculation characteristics demonstrated by the radial secondary design (Configuration 3), were superior to the baseline and modified versions of the baseline design. Further evaluation of Configuration 3 was conducted in the fuel spray visualization stand and revealed that this swirl cup design had acceptable fuel spray characteristics. This radial secondary swirl cup design was then incorporated into the pilot stage dome of sector combustor Configurations 3 through 24.

For sector combustor Configuration 25, modifications to the pilot stage swirl cup design were made to increase the pilot stage airflow in an attempt to shift the fuel-air ratio at which the minimum CO emission levels occurred closer to the design cycle idle fuel-air ratio of 0.016. Several swirl cup designs were evaluated in the visual fuel spray facility. Of these, the preferred design featured an F101-type radial primary swirler, an F100-type radial secondary swirler, plus a wide angle (90°), conical sleeve insert. A schematic of this pilot stage swirl cup design is shown along with a photograph of the observed fuel spray in Figure 39. This pilot stage swirl cup design was incorporated in sector combustor Configurations 25 through 31. In sector combustor Configuration 29, the pilot stage emission levels at 4.0% of sea level takeoff thrust at idle when equipped with this design exceed slightly the program target goal for CO emissions.

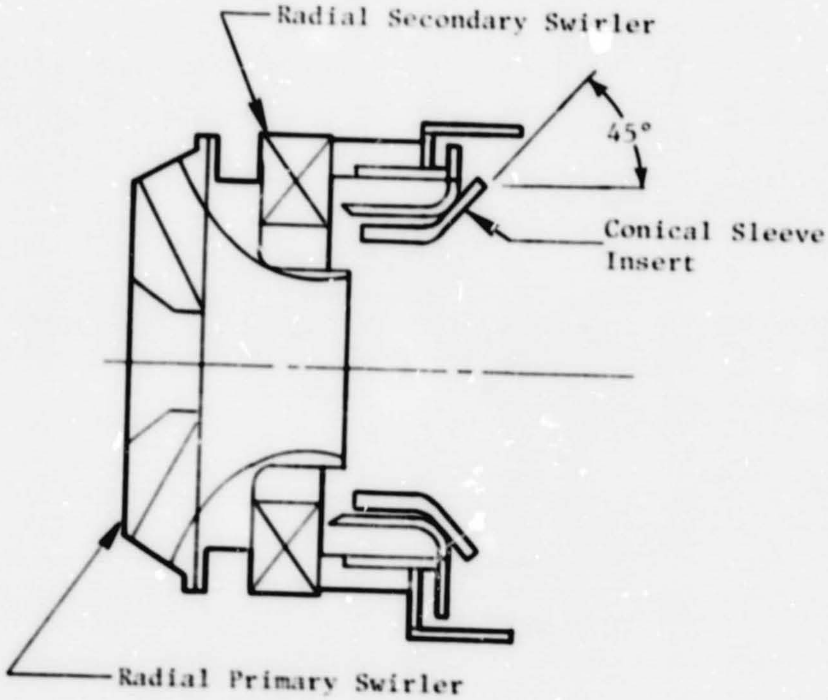
The sector combustor swirl cup development was then directed at improving the main stage combustion performance. Eighteen swirl cup design modifications were evaluated in the fuel spray facility. Several of these swirl cup designs which had demonstrated good fuel spray characteristics underwent velocity profile measurements to determine the size and strength of the recirculation zones downstream of the swirl cup. The swirl cup design which evolved with the best overall performance featured an axial primary swirler, a counterrotating axial secondary swirler, a counterrotating CF6-type radial tertiary swirler, plus a wide angle (90°) conical sleeve insert. A schematic of this main stage swirl-cup design is shown along with a photograph of the observed fuel spray in Figure 40. The measured swirl-cup flow field velocity profile is shown in Figure 41. This main stage swirl-cup design was incorporated in sector combustor Configuration 31, which demonstrated $NO_x$ emission levels which satisfied the program goals.

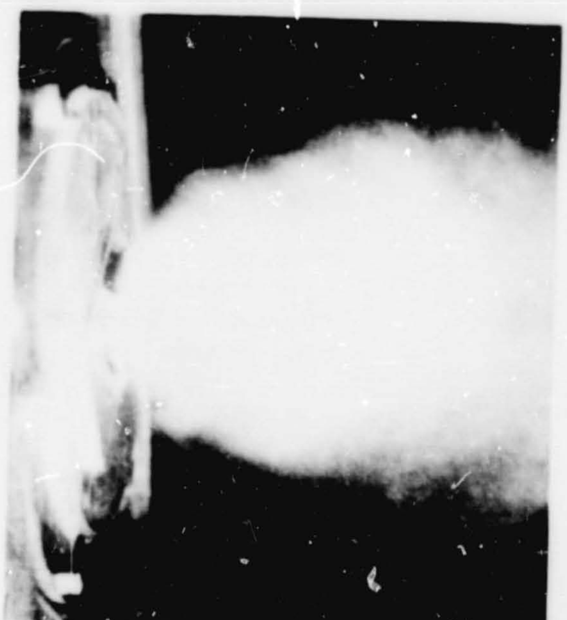
## 7.5 SWIRL-CUP CARBONING TESTS

The original program plan included a swirl-cup carboning proof test as part of the overall development program. However, this element of the program was eliminated early in the test program. Extensive carboning testing

Table XVI. Summary of Modified Pilot Stage Swirl Cup Designs.

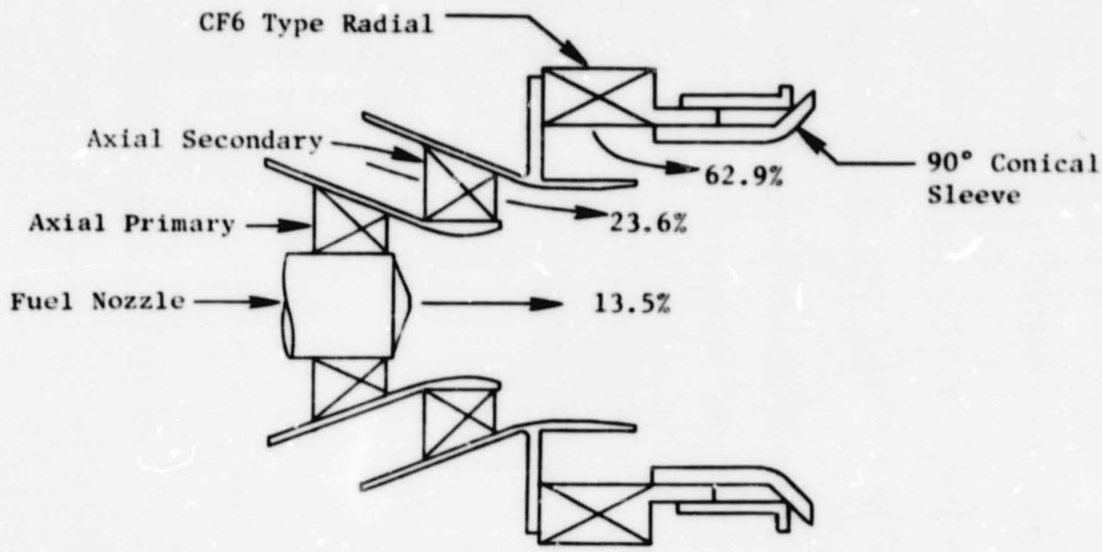
| Swirl Cup Configuration | Primary Swirler | Secondary Swirler | Tertiary Swirler |
|---|---|---|---|
| Baseline | Axial | Axial | Axial |
| Configuration No. 1 | Reduced Flow Axial | Reduced Flow Axial | Reduced Flow Radial |
| Configuration No. 2 | Same as No. 1 | Same as No. 1 | None |
| Configuration No. 3 | Higher Flow Axial | Radial | None |

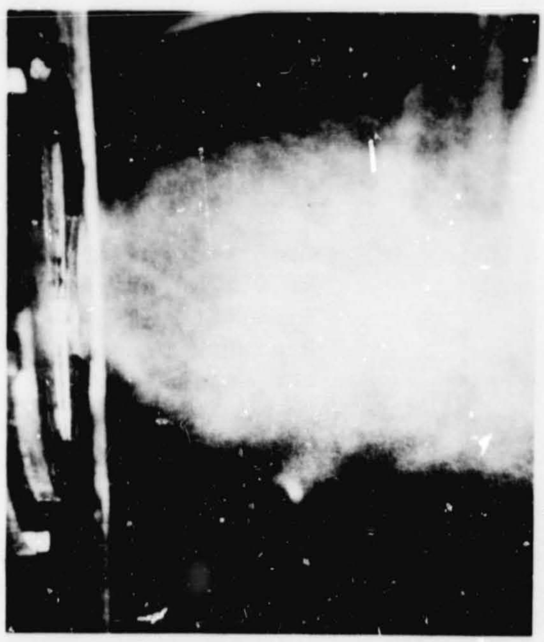


Observed Fuel Spray at 9.1 kg/hr Fuel Flow Rate with 5% Pressure Drop Across the Cup.

Figure 39. Modified Pilot Stage Swirl Cup Design Featured in Configurations 25-31.



Observed Fuel Spray at 9.1 kg/hr Fuel Flow with 5% Pressure Drop Across Cup

Figure 40. Modified Main Stage Swirl Cup Design Featured in Configurations 30 and 31.

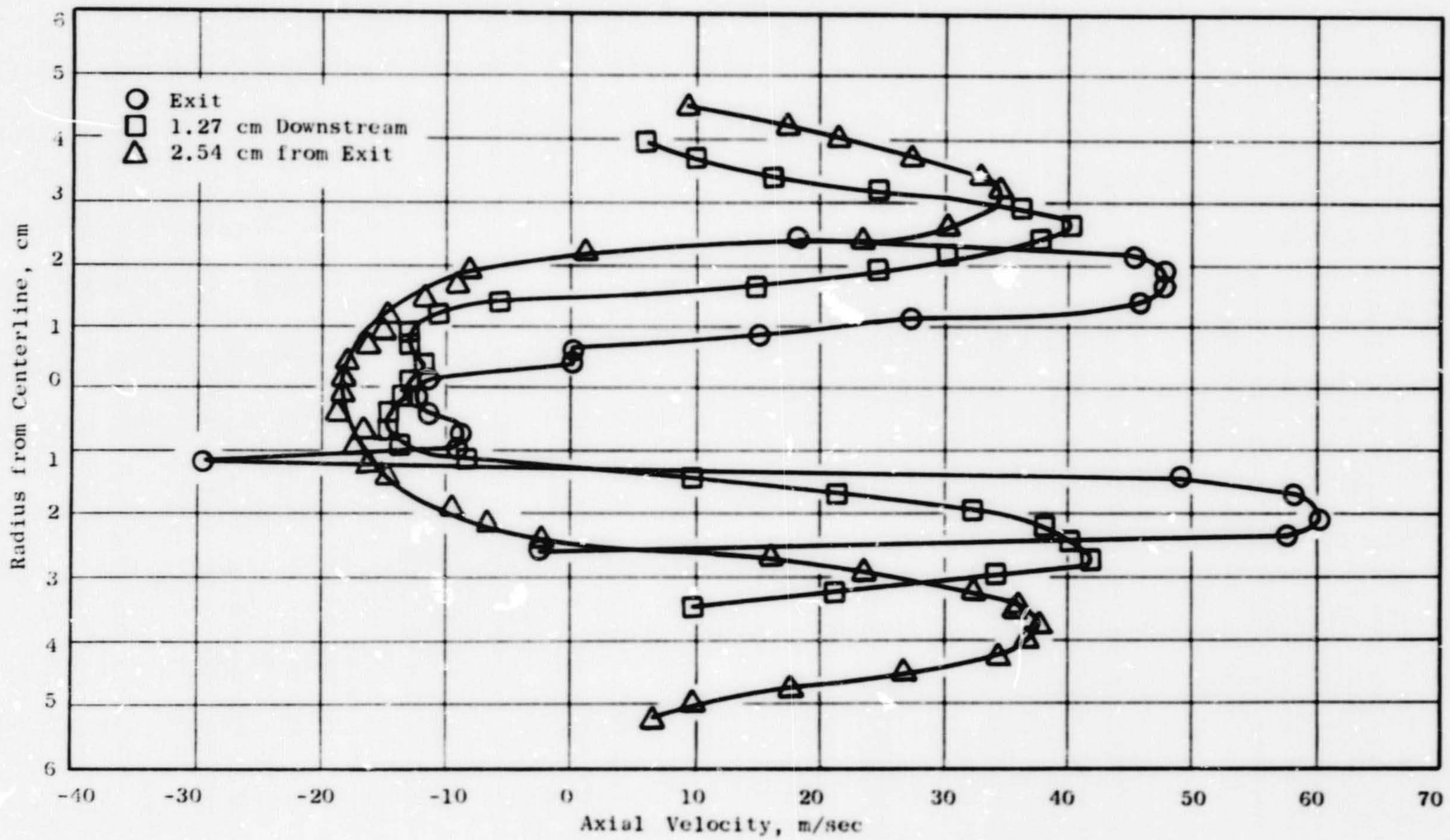



Figure 41. Velocity Profile of Configuration 30 Main Stage Swirl-Cup.

has been conducted at General Electric as an integral part of combustor development programs for new combustor designs. More recently in the NASA/GE ECCP, swirl-cup designs have been evolved demonstrating carbon-free operation using heavy distillate-type fuel. The use of the heavy distillate fuel imposes more severe conditions than would be expeced with Jet A fuel. From the results of the NASA/GE ECCP, criteria have been formulated based on swirl-cup geometry parameters to obtain a swirl-cup design which will operate without harmful, carbon deposit buildups. These design criteria are shown in Figure 42.

The swirl-cup design of the QCSEE double-annular dome combustor is very similar to that evolved in the NASA/GE double-annular dome combustor design. Therefore, with the extensive experience acquired in developing carbon-free, swirl-cup designs in these earlier programs, and the use of available design criteria to select the proper swirl-cup parameters for the QCSEE swirl-cup design for carbon-free operation, it was decided that swirl-cup carboning demonstration tests would not be required.

## 7.6 EXIT TEMPERATURE PROFILE RESULTS

Exit temperature profile characteristics of the QCSEE double-annular dome sector combustor were obtained from tests of Configuration 31 at conditions representing design cycle idle, (4% of sea level takeoff thrust), approach, and sea level takeoff. Testing was conducted in the Advanced Combustion Laboratory Facility. Therefore, the approach and sea level takeoff conditions were derated because of facility and test rig limitations.

The exit temperature profile characteristics of the double-annular dome sector combustor demonstrated radial temperature gradients peaked strongly inward at the idle and approach conditions when only the inner annulus pilot stage was fueled. This profile characteristic was also observed in tests performed earlier during the NASA/GE ECCP double-annular dome combustor program. However, the profile was peaked outward in this design due to the pilot stage being located in the outer annulus dome. The severity of the QCSEE double-annular dome combustor profile gradient was greatest in the between cup regions, and was found to be strongly influenced by the pilot to main stage fuel flow split. Significant reductions in the profile gradients were observed by increasing the fuel flow to the main stage, while correspondingly decreasing the fuel flow to the pilot stage to maintain the overall fuel-air ratio. At the approach operating conditions, a minimum radial profile gradient, peaked toward the inner liner, of 167 K was obtained at a pilot to main stage fuel flow split of 50/50. At sea level takeoff operating conditions, a uniform temperature profile was obtained while operating the sector combustor at a 30/70 pilot to main stage fuel flow split. The averge radial temperature profiles and calculated pattern and profile factors for Configuration 31 are shown in Figures 43, 44 and 45.

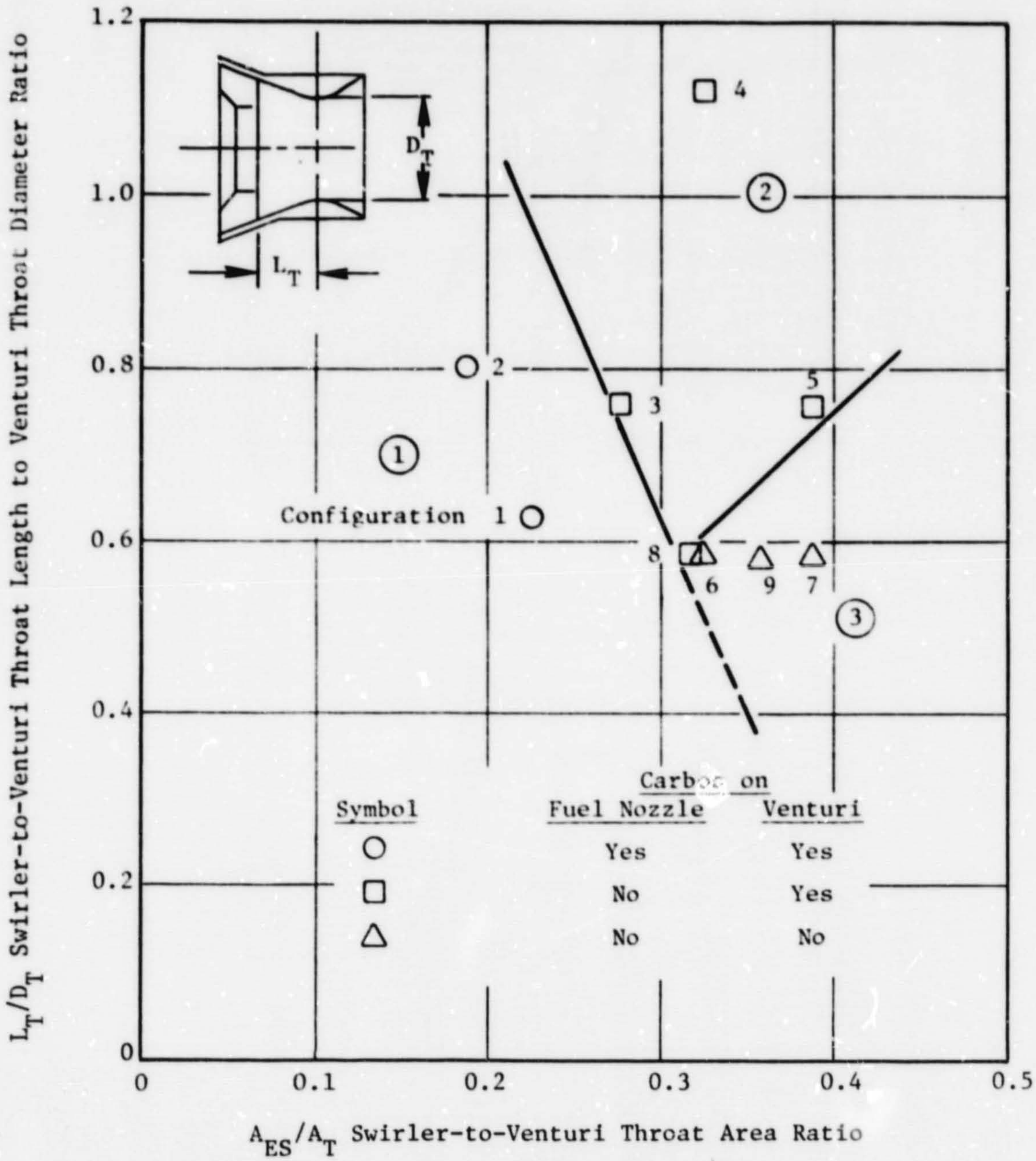
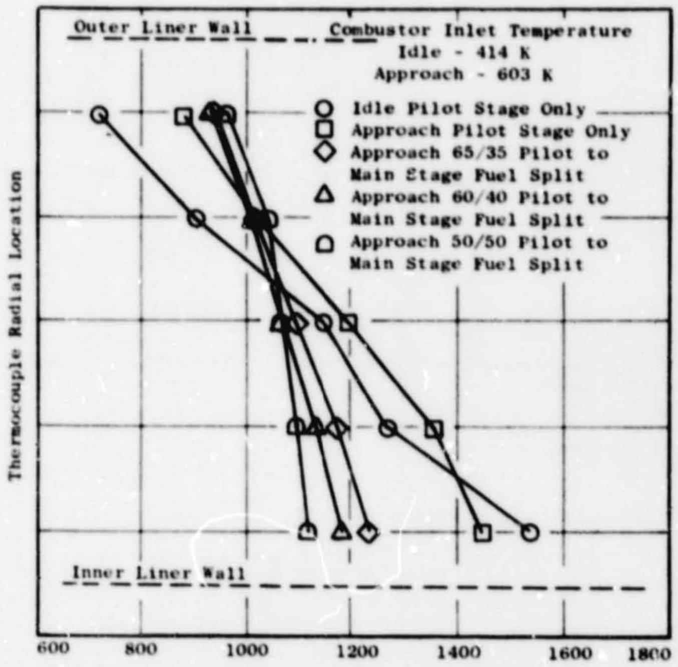



Figure 42. Swirl Cup Carboning Criteria.



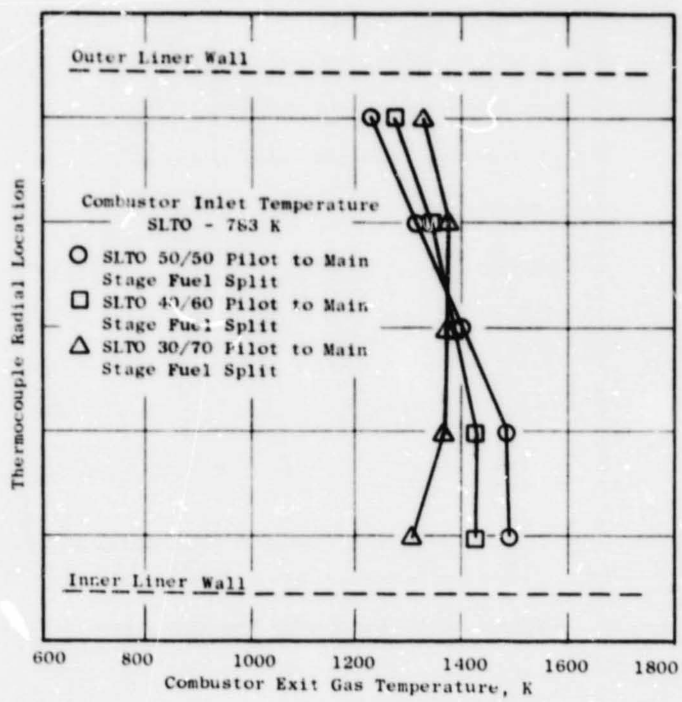




Figure 43. QCSEE Double Annular Sector Combustor, Exit Temperature Profile Test - Configuration 31.

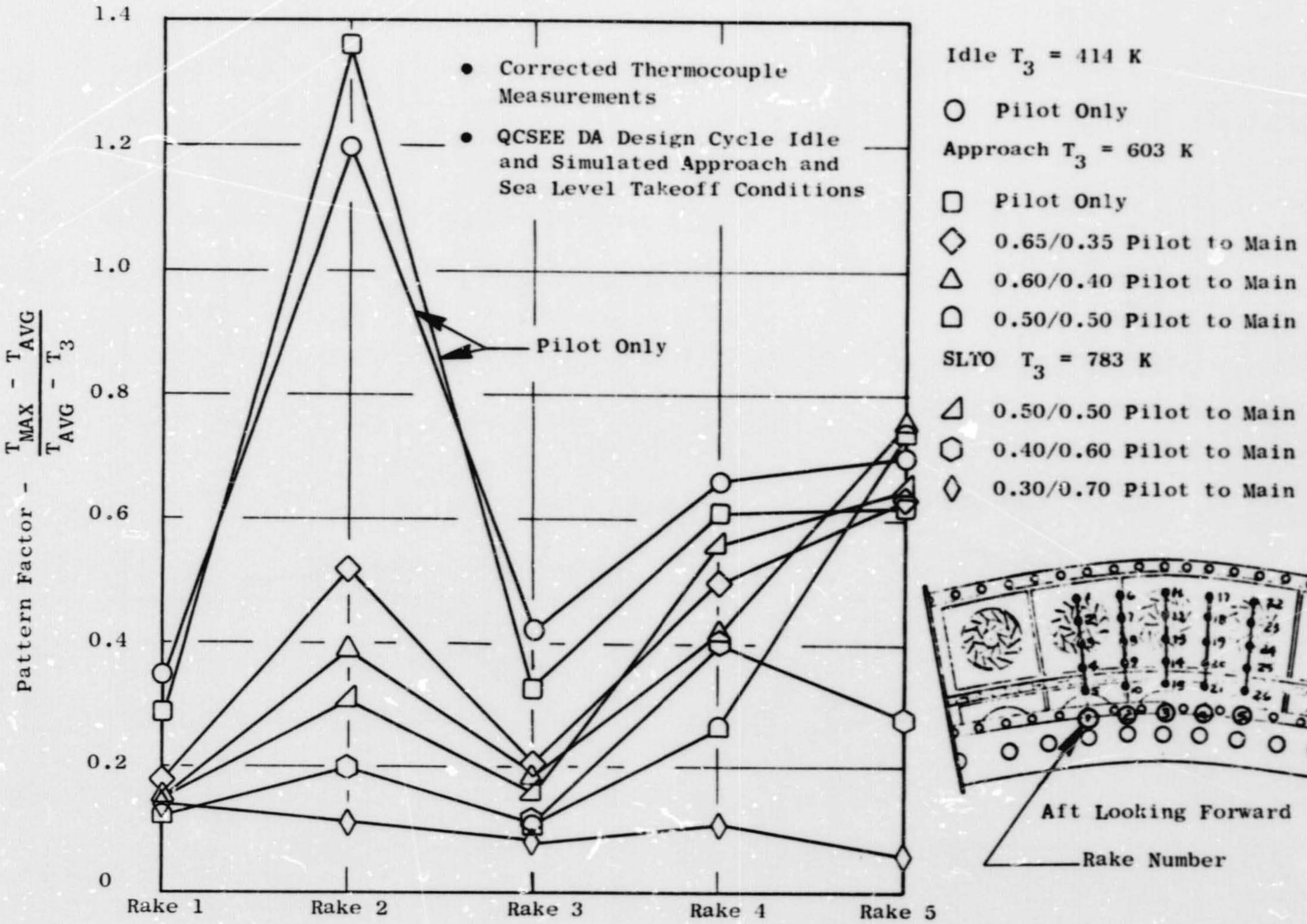



Figure 44. QCSEE Double Annular Sector Combustor, Exit Temperature Profile Test - Configuration 31.

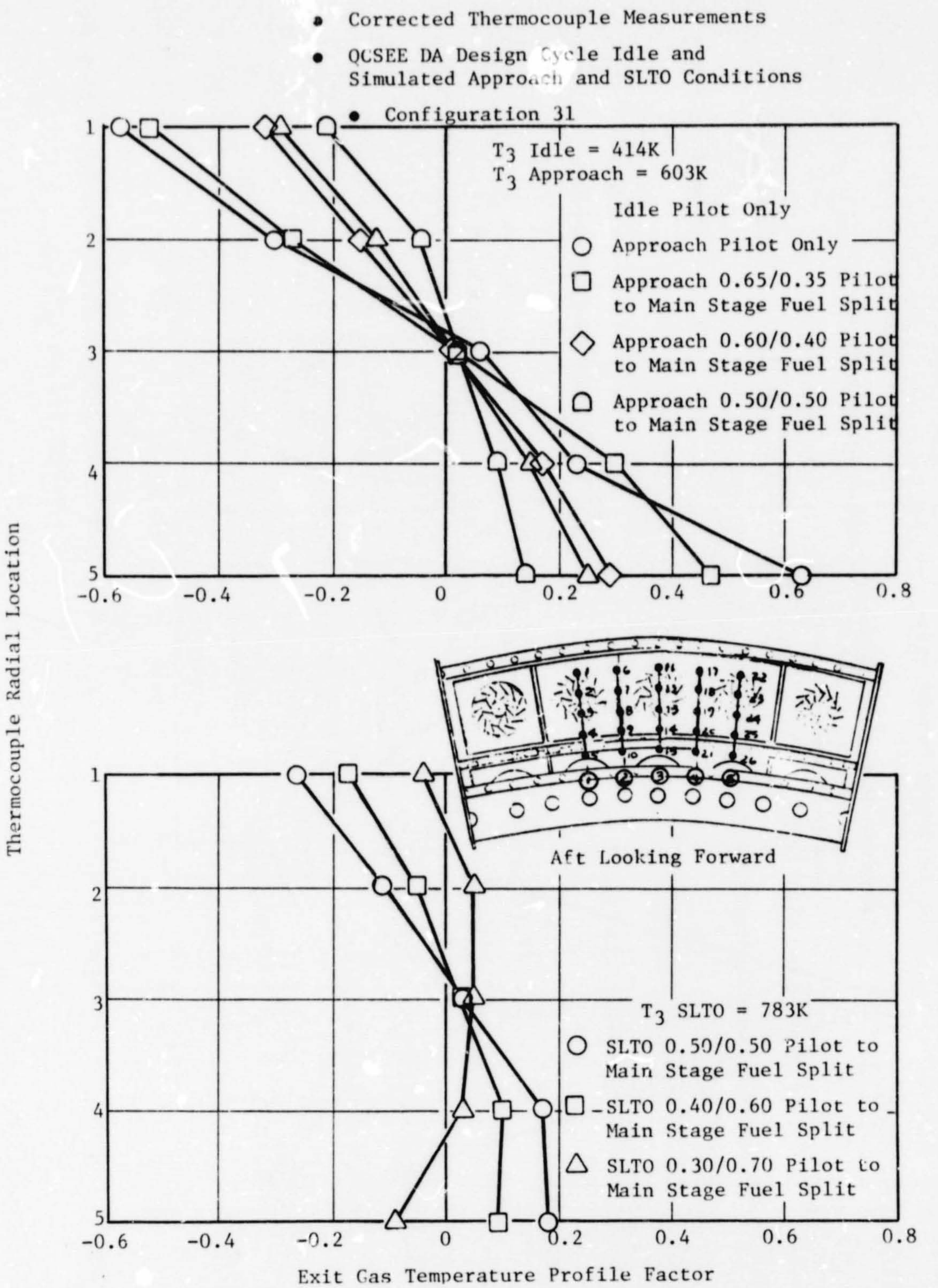



Figure 45. QCSEE Double Annular Sector Combustor Exit Temperature Profile Test.



C-2

## 7.7 LINER METAL TEMPERATURE RESULTS

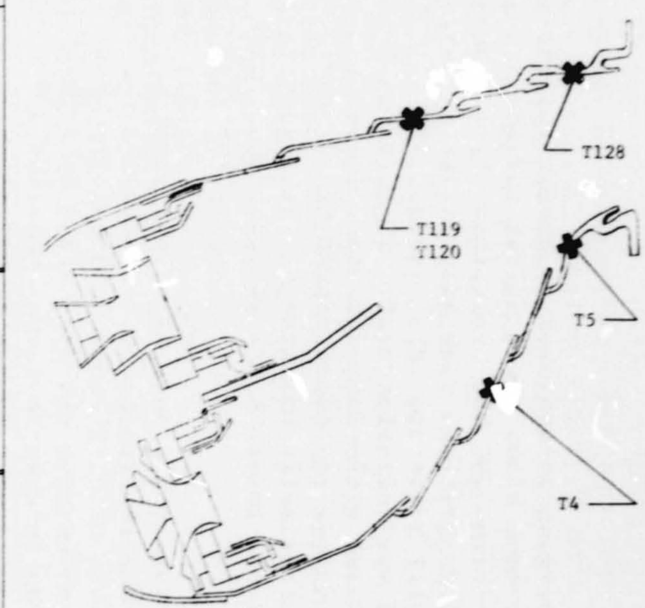
Liner metal temperatures were measured using Chromel-Alumel thermocouples located at several points on the cold side of the inner and outer liners. These thermocouples were monitored throughout the emissions testing phase of the program. For the majority of the configurations tested, only the idle conditions were set. However, for the baseline, 17, and 31 sector combustor configurations, simulated high power conditions were run. Thermocouple data from these test runs provided an indication of the liner metal temperature variation from idle to takeoff and for various pilot to main stage fuel splits at the approach and takeoff conditions. The highest indicated metal temperatures were on the inner liner panel No. 2. Because of the severe curvature of the inner liner flowpath, this panel is directly in-line with the inner annulus hot combustion gases subjecting the panel to a more severe heating condition. A summary of the indicated liner temperatures for these three sector combustor configurations is shown in Table XVII. An illustration of the location of the thermocouples is shown in the figure at the right of the table.

## 7.8 SECTOR COMBUSTOR PRESSURE DROP RESULTS

The outer dome, inner dome, and total combustor pressure drops were measured using the instrumentation installed on the sector combustor, and in the test rig. The values of these pressure drops are tabulated in Appendix A for all test conditions at which the 32 sector combustor configurations were evaluated. In general, the measured pressure drops ranged from 3% to 6%. However, there were a considerable number of measured pressure drops outside of this range, and there was often considerable variation in the measured total combustor pressure drop within a test point series in which only the overall fuel-air ratio was changed. These uncharacteristically low or high measured pressure drops, plus the observed variations, were attributed to a problem in accurately measuring the sector combustor exit total pressure. In Figure 46, the total sector combustor pressure drop corrected to the QCSEE double-annular design cycle sea level takeoff condition is plotted against the calculated sector combustor exit temperature to measured inlet temperature ratio, $(T_{3.9}/T_3)$, for the baseline, 17 and 31 sector combustor configurations. This figure indicates that an increase in the measured combustor pressure drop occurred between the baseline configuration and Configuration 31. Some increase in the measured combustor pressure drop occurs when operating the combustor with both the pilot and main stages fueled as compared to operating with only the pilot stage fueled.

# Table XVII. Liner Metal Temperatures (Corrected).

| | Pilot/Main | $T_3$ | Temperature, Kelvin | | | | | Condition |
|---|---|---|---|---|---|---|---|---|
| | | | $T_{119}$ | $T_{120}$ | $T_{128}$ | $T_4$ | $T_5$ | |
| Idle | 100/0 | 420 | --- | 490 | 492 | 431 | 445 | (Baseline) |
| Approach | 100/0 | 600 | --- | 706 | 599 | 604 | 640 | |
| | 50/50 | 606 | --- | 699 | 611 | 611 | 659 | |
| | 20/80 | 603 | --- | 665 | 600 | 598 | 638 | |
| Takeoff | 0/100 | 749 | --- | 805 | 797 | 985 | 814 | |
| | 10/90 | 757 | --- | 858 | 800 | 976 | 852 | |
| | 15/85 | 757 | --- | 879 | 799 | 974 | 852 | |
| | 20/80 | 759 | --- | 894 | 801 | 969 | 870 | |
| Idle | 100/10 | 416 | --- | 434 | --- | 535 | --- | (Mod-17) |
| Approach | 100/0 | 598 | --- | 619 | --- | 733 | --- | |
| | 50/50 | 597 | --- | 603 | --- | 683 | --- | |
| | 30/70 | 603 | --- | 614 | --- | 662 | --- | |
| | 20/80 | 597 | --- | 597 | --- | 632 | --- | |
| Takeoff | 20/80 | 782 | --- | 941 | --- | 879 | --- | |
| Idle | 100/0 | 417 | 434 | 438 | 486 | 552 | 457 | (Mod-31) |
| Approach | 100/0 | 605 | 628 | 633 | --- | 768 | 645 | |
| | 65/35 | 603 | 629 | 647 | --- | 723 | 629 | |
| | 60/40 | 601 | 632 | 647 | --- | 707 | 632 | |
| | 50/50 | 601 | 633 | 648 | --- | 682 | 629 | |
| Takeoff | 50/50 | 790 | 864 | 888 | 815 | 985 | 856 | |
| | 40/60 | 789 | 867 | 893 | 812 | 961 | 850 | |
| | 30/70 | 786 | 865 | 884 | 797 | 923 | 840 | |
| | 20/80 | 783 | 866 | 888 | 800 | 920 | 824 | |



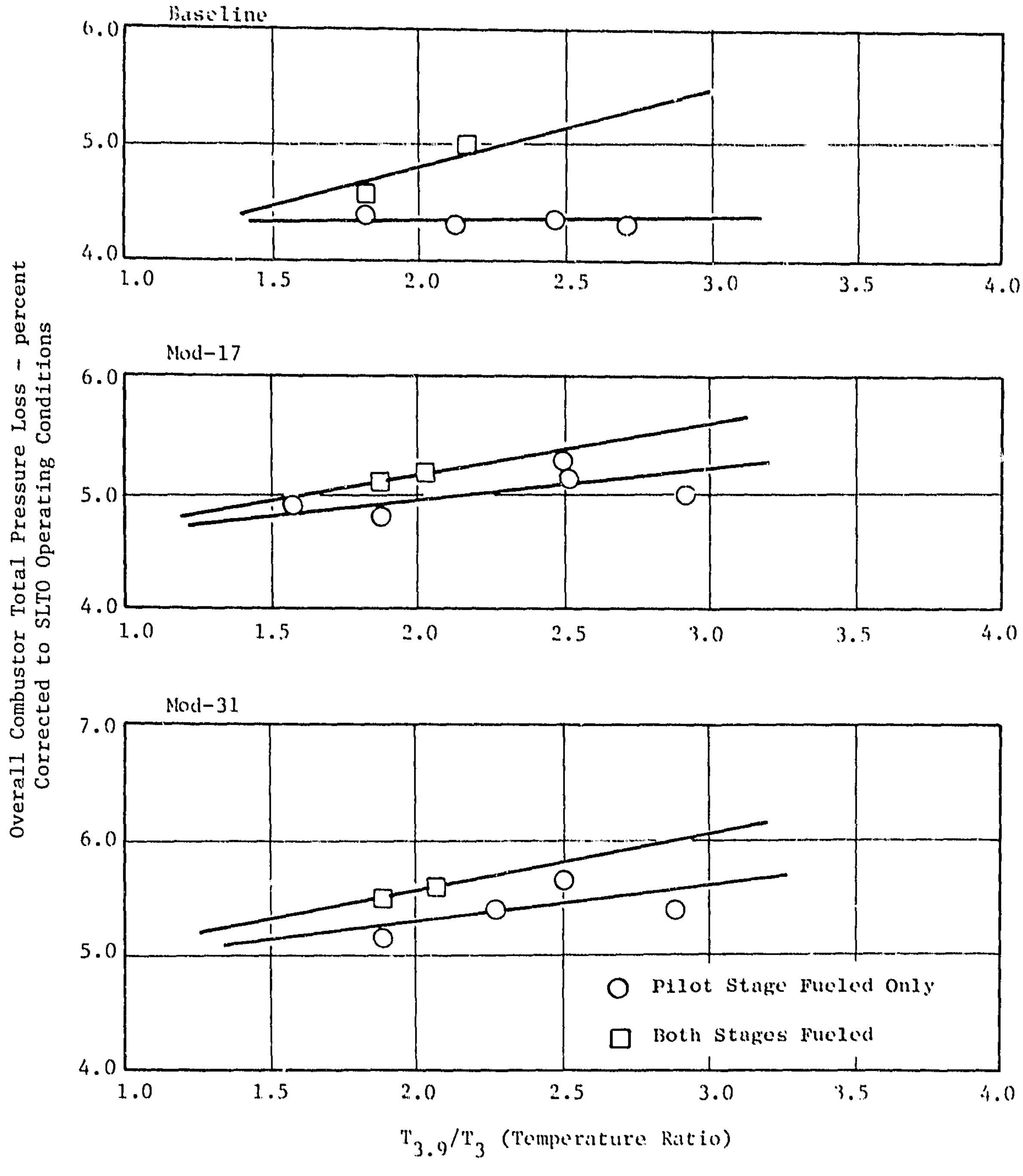



Figure 46. QCSEE Double Annular Sector Combustor.

## 8.0 FLIGHT TYPE COMBUSTOR

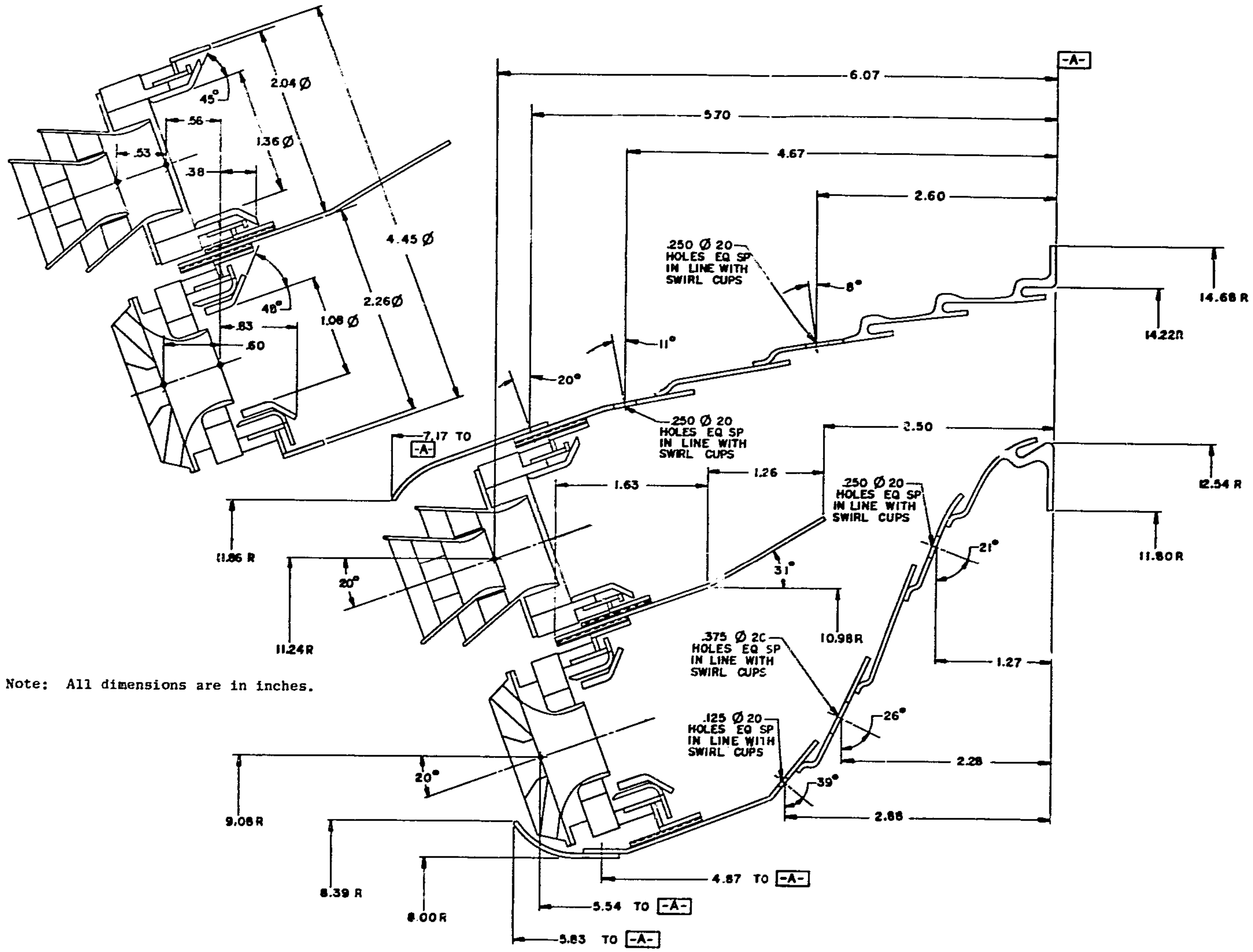
The QCSEE double-annular combustor development program was directed primarily at evolving a combustor design which could demonstrate CO and HC emissions levels at ground idle conditions, and $NO_x$ emission levels at high power conditions required to satisfy the very challenging EPA standards applicable to the QCSEE UTW and OTW engines. The preferred flight-type combustor design selected was Configuration 31. This selection was based upon the emissions results of this sector combustor technology development program in which Configurations 29 and 31 had demonstrated the applicable EPA standards for the three emissions categories. A detailed illustration of this final QCSEE double-annular sector combustor design defining the key features and dimensions is shown in Figure 47.

The EPA emissions standards are based upon a representative landing-takeoff cycle (EPA-LTO) which includes idle, approach, climbout, and sea level takeoff engine operation conditions (Reference 2). In order to evaluate the development progress in terms of satisfying the program emissions goals, it is necessary to investigate the emission levels at each of the prescribed EPA-LTO cycle conditions to determine the impact of a particular combustor modification on the CO, HC, and $NO_x$ emission levels.

The key emission results, in terms of emission indices, for the selected double-annular dome combustor configuration at standard day idle, approach, climbout, and sea level takeoff operating conditions are summarized in Table XVIII. Generally, at each operating condition, except idle, a range of fuel flow splits between the pilot and main stage domes was investigated to determine the fuel flow split that produced the lowest emissions levels. The data in Table XVIII are shown for the high pressure ratio engine cycle definition since this cycle is considered more representative of the operating characteristics of a modern version of QCSEE, when equipped with a double-annular combustor.

Emission results, in terms of the EPA parameter, for this selected combustor design are summarized for the high pressure ratio (double annular) engine cycle, and for the lower pressure ratio (QCSEE OTW) engine cycle in Table XIX. Figure 48 shows that for the high pressure ratio flight type engine cycle, the selected double-annular dome combustor design evolved as part of this program will meet the applicable EPA standards for all three emission categories with a ground idle thrust power setting of 4.5% of SLTO thrust with the pilot stage only operating at the approach condition.

While significantly reduced emissions and promising performance characteristics have been obtained in this double-annular dome combustor design, it must be recognized that this advanced combustor design is considerably more complex than current technlogy combustor designs. One of the areas not explored with the staged combustor involves crossfiring between stages, which in the case of a double annular dome combustor design, must proceed




Note: All dimensions are in inches.

Figure 47. QCSEE Double Annular Sector Combustor Final Configuration.

Table XVIII. Emissions Results for QCSEE Double Annular Combustor Final Configuration at EPA L-O-T Cycle Conditions QCSEE Double-Annular Engine Cycle.

| EPA Landing and Takeoff Cycle Condition | $EI_{CO}$ g/kg Fuel | $EI_{HC}$ g/kg Fuel | $EI_{NO_x}$ g/kg Fuel |
|---|---|---|---|
| Idle: | | | |
| 4% | 34.5 | 2.0 | 2.0 |
| 4.5% | 23.0 | 0.7 | 2.5 |
| 6.0% | 16.0 | 0.5 | 3.0 |
| Approach: | | | |
| Pilot Only | 1.9 | 0.1 | 8.8 |
| 60/40 Pilot/Main | 16.2 | 2.1 | 1.4 |
| Climbout: | 0.5 | 0 | 10.0 |
| Takeoff | 0.5 | 0 | 14.0 |

Table XIX. QCSEE Double Annular Combustor Final Configuration EPA Parameter Results.

| QCSEE Double Annular Engine Cycle | Lbs/1000 Lbs - thrust - Hr | | |
|---|---|---|---|
| | EPAP CO | EPAP HC | EPAP $NO_x$ |
| 4% Idle: | | | |
| Pilot Only at Approach | 5.6 | 0.32 | 3.0 |
| 60/40 (Pilot/Main) at Approach | 6.7 | 0.48 | 2.4 |
| 4.5% Idle: | | | |
| Pilot Only at Approach | 4.3 | 0.13 | 3.0 |
| 60/40 (Pilot/Main) at Approach | 5.4 | 0.29 | 2.5 |
| 6% Idle: | | | |
| Pilot Only at Approach | 3.3 | 0.10 | 3.0 |
| 60/40 (Pilot/Main) at Approach | 4.3 | 0.25 | 2.4 |
| QCSEE OTW Engine Cycle | | | |
| 4.5% Idle: | | | |
| Pilot Only at Approach | 6.3 | 0.25 | 2.4 |
| 1979 Standards | 4.3 | 0.8 | 3.0 |

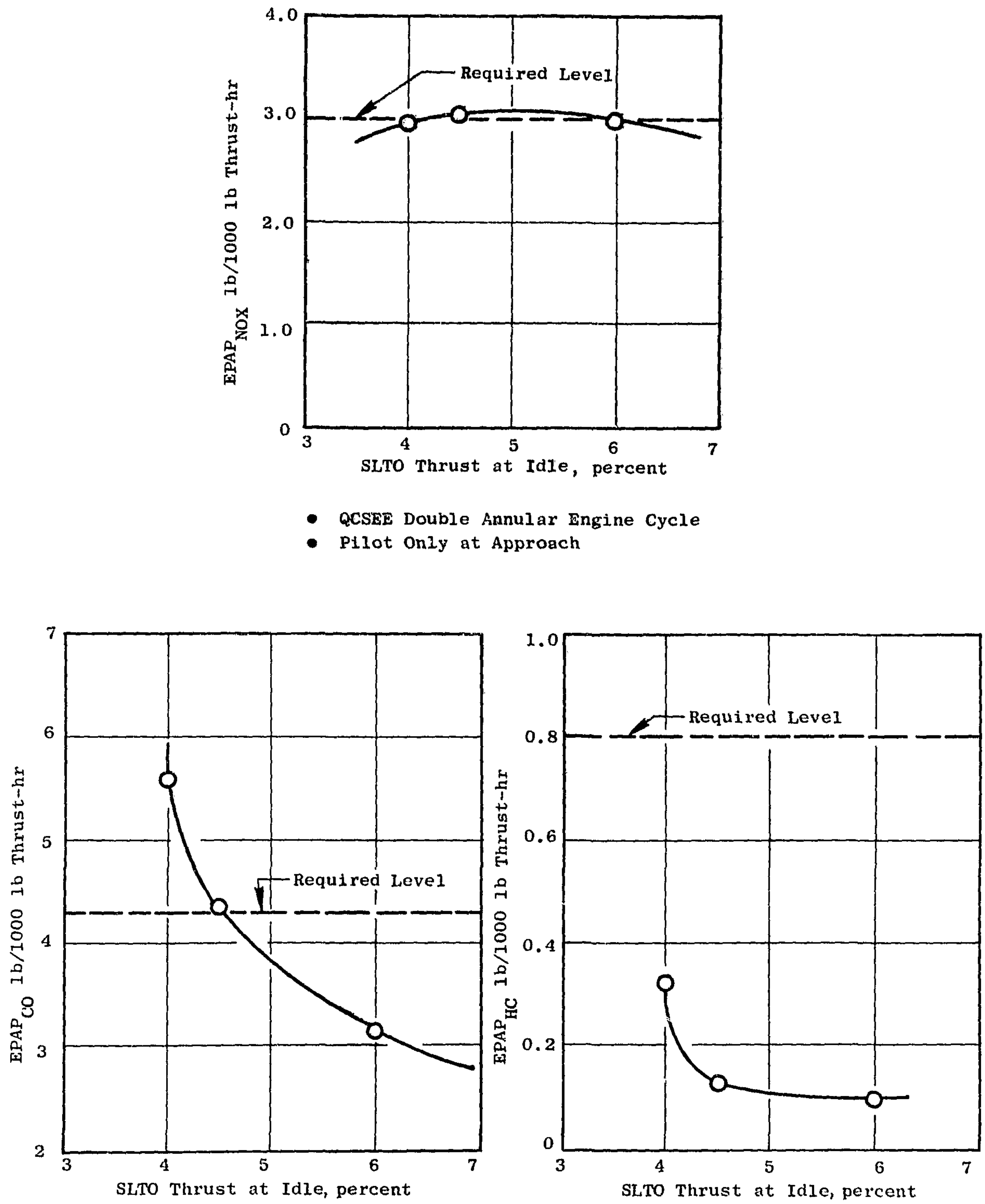



Figure 48. EPAP Results for QCSEE Double Annular Sector Combustor, Final Configuration.

smoothly and rapidly during engine acceleration and deceleration. Therefore, any further development efforts could be directed at defining the preferred means of staging the combustion process and to defining the engine fuel control and supply requirements needed to operate the combustor.

## 9.0 CONCLUSIONS

The design and development of a QCSEE-sized double-annular dome combustor has provided important additional design technology for the evolution of small size advanced combustors which will meet very stringent emissions requirements at very severe combustor inlet conditions. As a result of this sector combustor technology development test program, key design features were identified which resulted in substantial reductions in CO and HC emission levels at ground idle operating conditions, compared to the levels obtained with a conventional combustor design. In addition, based on the sector combustor test results, it is expected that this double-annular, two-stage combustor approach will provide very low $NO_x$ emission levels at high power operating conditions. With the final combustor design evolved in this program, CO, HC, and $NO_x$ emissions levels were obtained which met the program goals. It was also determined in the technology development tests of this combustor design that high combustor efficiency could be obtained over wide ranges of combustor operating conditions when the proper fuel staging conditions were selected. As part of this test program, the combustor performance characteristics were evaluated and found, in general, to be satisfactory. Altitude ignition performance, in particular, was found to be very promising at this stage of development of a combustor design. However, to evolve a QCSEE-sized double-annular combustor which will satisfy all of the performance and operating requirements such as pattern factor, profile factor, fuel scheduling, and combustor life, it is expected that additional full-annular, full-scale tests will be required to fully develop this double-annular dome combustor concept.

# APPENDIX A

This appendix contains summaries of the operating conditions, combustor performance data, and exhaust emissions data for each sector combustor configuration tested. Tables XX through LIII contained in this appendix are ordered chronologically from the initial baseline configuration to the final configuration. For each of the simulated engine high power operating conditions, the CO, HC, and $NO_x$ emission indices are presented two ways: as measured in the test and corrected to the actual engine cycle operating conditions using the correction procedures described in Appendix B.

Table XX. Summary of Test Results: Configuration Baseline QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 2 | 31.02 | 2.11 | 261 | 400 | 10.15 | 4.60 | 646.5 | 293.2 | 46.77 | 14.26 | | 1.0 | 0.0 | 0.0177 | 0.0177 | 72.00 | 229.6 | 226.4 | | | | | 5.00 | 3.83 | | |
| 2 | 2 | 33.50 | 2.28 | 271 | 406 | 11.28 | 5.15 | 361.3 | 163.9 | 48.79 | 14.87 | | 1.0 | 0.0 | 0.0089 | 0.0090 | 54.70 | 126.2 | 423.5 | | | | | 4.41 | 3.75 | | |
| 3 | 3 | 33.43 | 2.28 | 271 | 406 | 11.26 | 5.11 | 519.1 | 235.5 | 48.85 | 14.89 | | 1.0 | 0.0 | 0.0128 | 0.0127 | 61.60 | 127.5 | 358.7 | | | | | 4.35 | 3.79 | | |
| 4 | 4 | 33.38 | 2.27 | 272 | 407 | 11.26 | 5.11 | 709.7 | 321.9 | 48.99 | 14.93 | | 1.0 | 0.0 | 0.0175 | 0.0185 | 65.36 | 175.4 | 305.4 | | | | | 4.36 | 4.00 | | |
| 5 | 5 | 33.90 | 2.31 | 273 | 407 | 11.24 | 5.10 | 793.3 | 359.[illegible] | 48.2[illegible] | 14.70 | | 1.0 | 0.0 | 0.0196 | 0.0205 | 67.10 | 206.9 | 280.7 | | | | | 5.23 | 3.90 | | |
| 6 | 6 | 33.31 | 2.27 | 270 | 405 | 11.24 | 5.10 | 995.7 | 451.6 | 48.8[illegible] | 14.90 | | 1.0 | 0.0 | 0.0246 | 0.0235 | 63.23 | 276.7 | 303.1 | | | | | 4.14 | 3.95 | | |
| 7 | 7 | 33.48 | 2.28 | 272 | 407 | 11.24 | 5.10 | 1283.0 | 581.[illegible] | 48.76 | 14.86 | | 1.0 | 0.0 | 0.0317 | 0.0243 | 59.25 | 337.5 | 328.8 | | | | | 4.64 | 3.82 | | |
| 8 | 8 | 42.98 | 2.93 | 310 | 428 | 14.68 | 6.66 | 565.3 | 256.4 | 52.14 | 15.89 | | 1.0 | 0.0 | 0.0107 | 0.0103 | 69.67 | 111.5 | 277.3 | | | | | | 3.88 | | |
| 9 | 9 | 43.45 | 2.96 | 314 | 430 | 14.65 | 6.54 | 680.2 | 308.5 | 51.75 | 15.77 | | 1.0 | 0.0 | 0.0129 | 0.0120 | 75.59 | 111.6 | 218.0 | | | | | 4.48 | 3.88 | | |
| 10 | 10 | 43.06 | 2.93 | 316 | 431 | 14.63 | 6.64 | 837.6 | 379.9 | 52.31 | 15.94 | | 1.0 | 0.0 | 0.0159 | 0.0166 | 79.77 | 150.9 | 167.1 | | | | | 4.18 | 3.98 | | |
| 11 | 11 | 43.28 | 2.95 | 317 | 432 | 14.59 | 6.62 | 1040.1 | 471.8 | 51.96 | 15.84 | | 1.0 | 0.0 | 0.0198 | 0.0187 | 80.00 | 188.8 | 156.[illegible] | | | | | 4.10 | 3.97 | | |
| 12 | 12 | 43.20 | 2.94 | 316 | 431 | 14.61 | 6.62 | 1293.4 | 586.7 | 52.03 | 15.86 | | 1.0 | 0.0 | 0.0246 | 0.0191 | 77.60 | 227.6 | 170.9 | | | | | 3.93 | 3.88 | | |
| 13 | 13 | 43.20 | 2.94 | 320 | 433 | 14.61 | 6.62 | 1672.0 | 758.4 | 52.30 | 15.94 | | 1.0 | 0.0 | 0.0318 | 0.0226 | 66.18 | 352.3 | 256.0 | | | | | 4.27 | 3.87 | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 14 | 36.35 | 2.47 | 290 | 417 | 12.52 | 5.68 | 392.1 | 177.9 | 51.24 | 15.62 | | 1.0 | 0.0 | 0.0087 | 0.0107 | 66.12 | 127.1 | 309.1 | | | | | 4.32 | 3.95 | | |
| 2 | 15 | 36.27 | 2.47 | 287 | 415 | 12.46 | 5.65 | 560.6 | 254.3 | 50.89 | 15.51 | | 1.0 | 0.0 | 0.0125 | 0.0146 | 75.32 | 131.[illegible] | 216.1 | | | | | 5.21 | 4.10 | | |
| 3 | 16 | 35.90 | 2.44 | 297 | 420 | 12.21 | 5.54 | 690.1 | 313.0 | 51.06 | 15.56 | | 1.0 | 0.0 | 0.0157 | 0.0179 | 76.47 | 169.6 | 195.7 | | | | | | 4.00 | | |
| 4 | 17 | 35.88 | 2.44 | 287 | 415 | 12.16 | 5.52 | 880.2 | 399.2 | 50.23 | 15.31 | | 1.0 | 0.0 | 0.0201 | 0.0228 | 76.05 | 236.0 | 184.4 | | | | | 4.18 | 4.01 | | |
| 5 | 18 | 36.10 | 2.46 | 289 | 416 | 12.15 | 5.51 | 1098.1 | 498.1 | 50.01 | 15.24 | | 1.0 | 0.0 | 0.0251 | 0.0307 | 74.27 | 274.0 | 193.3 | | | | | 4.49 | 3.88 | | |
| 6 | 26 | 60.71 | 4.13 | 627 | 604 | 17.82 | 8.08 | 853.4 | 387.1 | 63.30 | 19.29 | | 1.0 | 0.0 | 0.0133 | 0.0110 | 94.95 | 59.7 | 36.6 | | | | | 4.94 | 4.13 | | |
| 7 | 27 | 60.32 | 4.11 | 632 | 607 | 17.74 | 8.05 | 1449.7 | 657.6 | 63.71 | 19.42 | | 0.5 | 0.5 | 0.0227 | 0.0247 | 97.60 | 58.7 | 10.3 | | | | | 5.54 | 4.18 | | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 26 | 60.41 | 4.11 | 620 | 600 | 17.55 | 7.96 | 846.[illegible] | 384.0 | 62.24 | 18.97 | | 1.0 | 1.0 | 0.0134 | 0.0110 | 97.09 | 60.2 | 15.0 | 4.7 | 16.0 | 1.7 | 6.5 | 4.47 | 4.11 | | |
| 2 | 27 | 60.71 | 4.13 | 631 | 606 | 17.41 | 7.90 | 846.2 | 383.8 | 62.07 | 18.92 | | 0.5 | 0.5 | 0.0135 | 0.0101 | 46.05 | 61.9 | 525.0 | 2.2 | 16.6 | 58.5 | 3.0 | 4.53 | 4.04 | | |
| 3 | 29 | 60.49 | 4.12 | 626 | 603 | 17.45 | 7.92 | 954.9 | 433.1 | 62.15 | 18.94 | | 0.2 | 0.8 | 0.0152 | 0.0110 | 30.27 | 55.0 | 684.4 | 1.2 | 14.7 | 75.6 | 1.7 | 4.59 | 4.07 | | |
| 4 | 34 | 49.85 | 3.39 | 888 | 749 | 12.64 | 5.73 | 1064.4 | 482.8 | 67.77 | 20.66 | | 0.0 | 1.0 | 0.0234 | 0.0321 | 92.97 | 30.0 | 63.3 | 6.2 | 1.6 | 0.5 | 12.8 | 5.42 | 4.26 | | |
| 5 | 35 | 49.68 | 3.38 | 902 | 757 | 12.63 | 5.73 | 1100.3 | 499.1 | 68.68 | 20.94 | | 0.1 | 0.9 | 0.0242 | 0.0305 | 96.08 | 26.9 | 32.9 | 6.0 | 1.4 | 0.2 | 12.1 | 5.09 | 3.93 | | |
| 6 | 36 | 49.61 | 3.38 | 902 | 757 | 12.66 | 5.74 | 1102.9 | 500.3 | 68.95 | 21.02 | | 0.15 | 0.85 | 0.0242 | 0.0297 | 96.85 | 21.8 | 26.4 | 6.1 | 1.1 | 0.2 | 12.3 | 4.95 | 4.25 | | |
| 7 | 37 | 49.26 | 3.35 | 906 | 759 | 12.67 | 5.75 | 1122.2 | 509.0 | 69.70 | 21.25 | | 0.2 | 0.8 | 0.0246 | 0.0244 | 98.21 | 26.3 | 11.7 | 6.0 | 1.4 | 0.1 | 12.0 | | 4.42 | | |
| 8 | 32 | 50.17 | 3.41 | 833 | 718 | 12.63 | 5.73 | 1445.8 | 655.8 | 64.57 | 19.68 | | 0.2 | 0.8 | 0.0318 | 0.0303 | 97.40 | 67.5 | 10.3 | 7.0 | 6.1 | 0.2 | 12.7 | | 3.95 | | |
| 9 | 25 | 60.32 | 4.11 | 536 | 553 | 17.87 | 8.10 | 1061.3 | 481.4 | 58.52 | 17.84 | | 1.0 | 0.0 | 0.0165 | 0.0193 | 94.32 | 124.7 | 27.7 | 3.2 | 52.8 | 6.6 | 8.2 | 4.72 | 4.03 | | |

Table XXI. Summary of Test Results: Configuration MOD-1 QCSEE Double Annular Combustor.

| | | Inlet Total Pressure | | Inlet Total Temperature | | Combustor Airflow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading | Point | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot/Total | Main/Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | Comments |
| 1 | 5 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | | |
| 2 | 6 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | | |
| 3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | | [illegible] | | |
| 4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | | [illegible] | | |
| 5 | 16 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | | [illegible] | | |
| 6 | 17 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | | [illegible] | | |
| 7 | 18 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | | [illegible] | | | | | [illegible] | [illegible] | | |

Table XXII. Summary of Test Results: Configuration MOD-2 QCSEE Double Annular Combustor.

| | | Inlet Total Pressure | | Inlet Total Temperature | | Combustor Airflow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading | Point | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | Comments |
| [illegible] | [illegible] | 36.[illegible] | 2.46 | 236 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | 29.63 | [illegible] | [illegible] | | | | | 4.76 | 3.22 | | |
| [illegible] | [illegible] | 36.[illegible] | 2.46 | 235 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 59.8 | [illegible] | [illegible] | | | | | 3.82 | 3.22 | | |
| [illegible] | [illegible] | 36.[illegible] | 2.46 | 236 | [illegible] | [illegible] | [illegible] | 628.[illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 72.48 | [illegible] | [illegible] | | | | | 4.35 | 3.22 | | |
| [illegible] | [illegible] | 36.23 | 2.47 | 235 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | 3.86 | 3.35 | | |
| [illegible] | [illegible] | 36.2[illegible] | 2.47 | 235 | [illegible] | [illegible] | [illegible] | 978.9 | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | 159.6 | 235.5 | | | | | 3.79 | 3.22 | | |
| 6 | [illegible] | 36.23 | 2.47 | 287 | [illegible] | [illegible] | [illegible] | [illegible] | 568.2 | [illegible] | [illegible] | | | | [illegible] | 0.2309 | 60.23 | 363.[illegible] | 324.[illegible] | | | | | 3.54 | 3.25 | | |

Table XXIII. Summary of Test Results: Configuration MOD-3 QCSEE Double Annular Combustor.

| | | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading | Point | psia | atm | F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot % | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Emg CO | Emg HC | Emg NOx | Total | Outer Dome | Inner Dome | Comments |
| 1 | 14 | 36.25 | 2.46 | 292 | [illegible] | [illegible] | 4.92 | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 82.53 | [illegible] | [illegible] | | | | | [illegible] | 2.86 | | |
| 2 | 15 | 36.2 | 2.46 | 285 | [illegible] | [illegible] | 4.92 | [illegible] | 235.4 | 44.23 | 13.48 | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | 2.77 | | |
| 3 | 16 | 35.96 | 2.45 | 286 | [illegible] | [illegible] | 4.89 | [illegible] | 288.9 | 44.45 | 13.53 | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | 2.87 | | |
| 4 | 17 | 36.01 | 2.45 | 286 | [illegible] | [illegible] | 4.92 | [illegible] | [illegible] | 44.47 | 13.56 | | | | [illegible] | [illegible] | [illegible] | 138.6 | [illegible] | | | | | [illegible] | [illegible] | | |
| 5 | 18 | 36.31 | 2.47 | 283 | [illegible] | [illegible] | 4.92 | [illegible] | [illegible] | [illegible] | 13.65 | | | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | 2.95 | | |
| 6 | 19 | 35.97 | 2.45 | 283 | [illegible] | [illegible] | 4.95 | 1276.4 | 578.8 | 44.45 | 13.53 | | | | 0.0328 | 0.0345 | 66.32 | [illegible] | 264.6 | | | | | [illegible] | 2.79 | | |

Table XXIV. Summary of Test Results: Configuration MOD-4 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 35.97 | 2.45 | 291 | 417 | 10.61 | 4.82 | 362.9 | 164.7 | 43.98 | 13.40 | | 1.0 | 0.0 | 0.0095 | 0.0094 | 86.19 | 91.8 | 276.6 | | | | | 2.40 | 2.89 | | |
| 2 | 15 | 36.17 | 2.42 | 288 | 415 | 10.74 | 4.87 | 522.5 | 236.7 | 44.05 | 13.43 | | ↓ | ↓ | 0.0135 | 0.0140 | 83.77 | 111.1 | 136.4 | | | | | 3.21 | 2.90 | | |
| 3 | 16 | 36.04 | 2.41 | 284 | 413 | 10.73 | 4.87 | 641.2 | 290.7 | 43.92 | 13.86 | | ↓ | ↓ | 0.0166 | 0.0176 | 82.09 | 154.5 | 143.1 | | | | | 2.88 | 2.94 | | |
| 4 | 17 | 36.15 | 2.42 | 290 | 416 | 10.79 | 4.89 | 804.0 | 364.8 | 44.45 | 13.54 | | ↓ | ↓ | 0.0207 | 0.0216 | 86.35 | 211.2 | 147.7 | | | | | 2.90 | 3.00 | | |
| 5 | 18 | 36.19 | 2.42 | 289 | 416 | 10.80 | 4.90 | 972.0 | 440.9 | 44.34 | 13.52 | | ↓ | ↓ | 0.0250 | 0.0270 | 76.30 | 339.0 | 157.9 | | | | | 3.26 | 2.95 | | |
| 6 | 19 | 36.14 | 2.42 | 288 | 415 | 10.72 | 4.86 | 1285.1 | 583.0 | 44.01 | 13.42 | | ↓ | ↓ | 0.0333 | 0.0570 | 59.94 | 1099.5 | 144.0 | | | | | 3.14 | 2.97 | | |

Table XXV. Summary of Test Results: Configuration MOD-5 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14 | 36.[illegible] | 2.41 | 285 | 414 | [illegible] | 5.04 | 360.3 | 163.3 | [illegible] | 13.87 | | [illegible] | [illegible] | [illegible] | [illegible] | 87.[illegible] | 99.8 | [illegible] | | | | | 2.46 | 3.[illegible] | | |
| 2 | 15 | 36.27 | 2.42 | 285 | 414 | [illegible] | 5.02 | 517.6 | 234.8 | 45.06 | 13.73 | | | | [illegible] | [illegible] | 95.4[illegible] | [illegible] | 68.[illegible] | | | | | 2.92 | [illegible] | | |
| 3 | 16 | 36.[illegible] | 2.42 | 285 | 415 | [illegible].96 | 4.97 | 637.5 | 289.9 | 44.47 | 13.55 | | | | 0.0162 | 0.0129 | 88.72 | [illegible]4.9 | 72.[illegible] | | | | | 2.3[illegible] | 2.91 | | |
| 4 | 17 | 36.15 | 2.42 | 286 | 414 | [illegible] | 4.99 | 796.7 | 361.4 | 45.0[illegible] | 13.7[illegible] | | | | 0.020[illegible] | 0.0163 | 83.49 | 237.[illegible] | 65.[illegible] | | | | | 2.87 | 3.04 | | |
| 5 | 18 | 36.15 | 2.42 | 287 | 415 | [illegible] | 4.99 | 994.5 | 451.9 | 45.09 | 13.74 | | | | 0.025[illegible] | 0.0193 | 76.77 | 312.2 | 161.8 | | | | | 3.14 | 3.06 | | |
| 6 | 19 | 36.[illegible] | 2.41 | 288 | 415 | 10.96 | 4.97 | 1278.4 | 579.7 | 45.09 | 13.74 | | | | 0.0324 | 0.0245 | 65.76 | 323.4 | 266.9 | | | | | 3.84 | 3.0[illegible] | | |
| 7 | 148 | 36.35 | 2.43 | 284 | 413 | 11.08 | 5.03 | 279.2 | 126.7 | 44.99 | 13.7[illegible] | | | | 0.0073 | 0.0075 | 67.62 | 84.6 | 304.[illegible] | | | | | 2.84 | 3.09 | | |

Table XXVI. Summary of Test Results: Configuration MOD-6 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14 | 35.95 | 2.44 | 288 | 415 | 11.22 | 5.09 | 363.5 | 164.9 | 46.39 | 14.11 | | 1.0 | 0.8 | 0.0090 | 0.0080 | 77.68 | 118.7 | 195.5 | | | | | 3.38 | 3.37 | | |
| 2 | 15 | 36.05 | 2.45 | 290 | 416 | 11.20 | 5.08 | 528.2 | 239.6 | 46.21 | 14.08 | | | | 0.0131 | 0.0101 | 88.23 | 80.7 | 98.8 | | | | | 3.64 | 3.44 | | |
| 3 | 16 | 36.18 | 2.46 | 285 | 414 | 11.18 | 5.07 | 648.0 | 293.9 | 45.66 | 13.92 | | | | 0.0161 | 0.0121 | 90.89 | 81.5 | 72.1 | | | | | 3.97 | 3.30 | | |
| 4 | 17 | 36.18 | 2.46 | 285 | 414 | 11.06 | 5.02 | 808.3 | 453.4 | 45.18 | 13.77 | | | | 0.0203 | 0.0146 | 92.65 | 113.6 | 53.0 | | | | | 3.41 | 3.27 | | |
| 5 | 18 | 36.42 | 2.48 | 286 | 414 | 11.20 | 5.08 | 1012.0 | 459.2 | 45.51 | 13.87 | | | | 0.0251 | 0.0168 | 92.00 | 151.2 | 44.7 | | | | | 2.97 | 3.47 | | |
| 6 | 19 | 36.08 | 2.46 | 287 | 415 | 11.16 | 5.06 | 1293.6 | 586.6 | 45.82 | 13.97 | | | | 0.0322 | 0.0215 | 87.31 | 286.6 | 60.0 | | | | | 3.15 | 3.26 | | |

Table XXVII. Summary of Test Results: Configuration MOD-7 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 35.95 | 2.40 | 286 | 414 | 11.05 | 5.01 | 354.0 | 160.6 | 45.33 | 13.82 | | 1.0 | 0.0 | 0.0089 | 0.0161 | 88.49 | 85.5 | 95.2 | | | | | 3.02 | 3.28 | | |
| 2 | 15 | 36.05 | 2.41 | 287 | 415 | 11.07 | 5.02 | 510.1 | 231.3 | 45.33 | 13.82 | | | | 0.0128 | 0.0146 | 94.53 | 88.6 | 34.0 | | | | | 2.73 | 3.28 | | |
| 3 | 16 | 36.18 | 2.42 | 287 | 415 | 11.08 | 5.03 | 630.2 | 285.8 | 45.44 | 13.85 | | | | 0.0158 | 0.0159 | 93.58 | 129.7 | 34.0 | | | | | 2.60 | 3.30 | | |
| 4 | 17 | 36.18 | 2.42 | 287 | 415 | 11.09 | 5.03 | 786.5 | 356.6 | 45.41 | 13.84 | | | | 0.0197 | [illegible] | 92.33 | 200.3 | 29.9 | | | | | 2.73 | 3.30 | | |
| 5 | 18 | 36.42 | 2.43 | 286 | 414 | 11.09 | 5.03 | 982.1 | 445.4 | 45.48 | 13.86 | | | | 0.0246 | 0.0265 | 84.17 | 392.9 | 66.6 | | | | | 3.02 | 3.31 | | |
| 6 | 19 | 36.08 | 2.41 | 286 | 414 | 11.10 | 5.03 | 1259.0 | 570.8 | 45.27 | 13.80 | | | | 0.0315 | 0.0366 | 72.63 | 562.6 | 142.3 | | | | | 3.54 | 3.31 | | |

Table XXVIII. Summary of Test Results: Configuration MOD-8 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 46.0 | 3.13 | 286 | 414 | 10.03 | 4.55 | 84.7 | 38.4 | 32.3 | 9.83 | | 1.00 | | 0.0094 | 0.0108 | 94.20 | 59.4 | 45.0 | | | | | 3.51 | 2.23 | 2.21 | Wrong $P_3$ |
| 2 | 15 | 45.9 | 3.12 | 284 | 413 | 10.08 | 4.57 | 125.7 | 56.9 | 32.4 | 9.88 | | 1.00 | | 0.0138 | 0.0171 | 95.54 | 60.5 | 28.5 | | | | | 3.21 | 2.04 | 2.02 | Wrong $P_3$ |
| 3 | 16 | 45.9 | 3.12 | 286 | 414 | 10.14 | 4.60 | 153.9 | 69.8 | 32.7 | 9.97 | | 1.00 | | 0.0169 | 0.0219 | 96.10 | 105.9 | 14.2 | | | | | 3.21 | 2.05 | 2.02 | Wrong $P_3$ |
| 4 | 17 | 45.9 | 3.12 | 286 | 414 | 10.14 | 4.60 | 193.8 | 87.9 | 32.7 | 9.97 | | 1.00 | | 0.0212 | 0.0241 | 95.02 | 145.0 | 15.8 | | | | | 3.21 | 2.15 | 2.10 | Wrong $P_3$ |
| 5 | 18 | 45.7 | 3.11 | 286 | 414 | 10.14 | 4.60 | 244.1 | 110.7 | 32.8 | 10.00 | | 1.00 | | 0.0267 | 0.0323 | 90.07 | 290.1 | 38.5 | | | | | 2.89 | 1.84 | 1.85 | Wrong $P_3$ |

Table XXIX. Summary of Test Results: Configuration MOD-9 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 36.03 | 2.45 | 285 | 414 | 11.03 | 5.00 | 357.4 | 162.1 | 45.31 | 13.81 | | | | 0.0090 | 0.0090 | 87.77 | 76.2 | 104.5 | | | | | 3.09 | 3.24 | | |
| 2 | 15 | 36.03 | 2.45 | 286 | 414 | 11.00 | 4.99 | 518.9 | 235.3 | 45.18 | 13.77 | | | | 0.0131 | 0.0135 | 91.78 | 102.0 | 58.4 | | | | | 3.09 | 3.22 | | |
| 3 | 16 | 36.03 | 2.45 | 286 | 414 | 10.97 | 4.98 | 639.9 | 290.2 | 45.06 | 13.73 | | | | 0.0162 | 0.0156 | 92.26 | 144.0 | 43.7 | | | | | 3.09 | 3.22 | | |
| 4 | 17 | 36.10 | 2.46 | 286 | 414 | 10.95 | 4.97 | 796.4 | 361.2 | 44.89 | 13.68 | | | | 0.0202 | 0.0216 | 91.0 | 238.6 | 34.4 | | | | | 3.29 | 3.15 | | |
| 5 | 18 | 36.03 | 2.45 | 286 | 414 | 10.93 | 4.96 | 995.7 | 451.6 | 44.90 | 13.68 | | | | 0.0253 | 0.0264 | 87.29 | 299.3 | 57.2 | | | | | 3.09 | 3.29 | | |
| 6 | 19 | 35.98 | 2.45 | 286 | 414 | 10.91 | 4.95 | 1276.8 | 579.1 | 44.88 | 13.68 | | | | 0.0325 | 0.0366 | 74.75 | 447.0 | 148.1 | | | | | 3.24 | 3.29 | | |
| 7 | 9 | 43.20 | 2.94 | 318 | 432 | 12.99 | 5.89 | 617.1 | 280.0 | 46.39 | 14.14 | | | | 0.0132 | 0.0132 | 94.47 | 72.6 | 38.3 | | | | | 3.21 | 4.68 | | |
| 8 | 10 | 43.20 | 2.94 | 313 | 429 | 12.99 | 5.89 | 948.9 | 430.4 | 46.09 | 14.05 | | | | 0.0203 | 0.0208 | 93.72 | 172.8 | 22.5 | | | | | 3.21 | 4.71 | | |
| 9 | 11 | 43.05 | 2.93 | 314 | 430 | 12.95 | 5.87 | 1188.9 | 539.3 | 46.18 | 14.08 | | | | 0.0255 | 0.0274 | 88.51 | 287.5 | 47.8 | | | | | 2.87 | 4.75 | | |

Table XXX. Summary of Test Results: Configuration MOD-10 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 36.0 | 2.45 | 286 | 414 | 10.96 | 4.97 | 359.2 | 162.9 | 45.06 | 13.93 | | | | 0.0091 | 0.0048 | 92.64 | 60.9 | 59.3 | | | | | 3.65 | 3.36 | | |
| 2 | 15 | 36.03 | 2.45 | 287 | 415 | 10.99 | 4.99 | 518.4 | 235.2 | 45.21 | 13.79 | | | | 0.0131 | 0.0062 | 93.14 | 82.8 | 49.4 | | | | | 3.44 | 3.35 | | |
| 3 | 16 | 36.03 | 2.45 | 288 | 415 | 10.99 | 4.99 | 637.2 | 289.0 | 45.27 | 13.80 | | | | 0.0161 | 0.0067 | 91.32 | 145.2 | 52.9 | | | | | 3.44 | 3.36 | | |
| 4 | 17 | 36.18 | 2.46 | 286 | 414 | 11.03 | 5.00 | 798.3 | 362.1 | 45.12 | 13.75 | | | | 0.0201 | 0.0087 | 89.10 | 243.5 | 52.2 | | | | | 3.83 | 3.35 | | |
| 5 | 18 | 36.03 | 2.45 | 288 | 415 | 11.76 | 5.02 | 995.5 | 451.6 | 45.55 | 13.88 | | | | 0.0250 | 0.0104 | 84.73 | 313.8 | 79.5 | | | | | 3.44 | 3.37 | | |

Table XXXI. Summary of Test Results: Configuration MOD-11 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13A | 35.97 | 2.45 | 285 | 414 | 11.16 | 5.06 | 285.4 | 129.4 | 45.86 | 13.98 | | | | 0.0071 | 0.0068 | 85.36 | 119.2 | 118.6 | | | | | 4.10 | 3.30 | 3.40 | |
| 2 | 14 | 35.99 | 2.45 | 286 | 414 | 11.16 | 5.06 | 365.7 | 165.9 | 45.89 | 13.99 | | | | 0.0091 | 0.0088 | 88.63 | 102.2 | 89.9 | | | | | 4.10 | 3.50 | 3.60 | |
| 3 | 15 | 35.99 | 2.45 | 286 | 414 | 11.16 | 5.06 | 526.5 | 238.8 | 45.89 | 13.99 | | | | 0.0131 | 0.0137 | 89.52 | 97.2 | 82.2 | | | | | 4.10 | 3.40 | 3.60 | |
| 4 | 16 | 35.99 | 2.45 | 286 | 414 | 11.14 | 5.05 | 649.8 | 294.7 | 45.80 | 13.96 | | | | 0.0162 | 0.0163 | 90.80 | 113.3 | 65.6 | | | | | 4.10 | 3.40 | 3.60 | |
| 5 | 18 | 35.97 | 2.45 | 286 | 414 | 11.14 | 5.05 | 1010.8 | 458.5 | 45.84 | 13.97 | | | | 0.0252 | 0.0254 | 91.65 | 189.3 | 47.4 | | | | | 4.10 | 3.30 | 3.60 | |
| 6 | 19 | 35.97 | 2.45 | 287 | 415 | 11.14 | 5.05 | 1295.3 | 587.7 | 45.90 | 13.99 | | | | 0.0323 | 0.0319 | 87.21 | 276.2 | 64.9 | | | | | 4.10 | 3.40 | 3.60 | |

Table XXXII. Summary of Test Results: Configuration MOD-12 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13 | 36.03 | 2.45 | 286 | 414 | 10.92 | 4.96 | 291.0 | 132.0 | 44.86 | 13.67 | | | | 0.0074 | 0.0083 | 84.68 | 168.1 | 134.4 | | | | | 4.00 | 3.30 | 3.40 | |
| 2 | 14 | 36.03 | 2.45 | 286 | 414 | 10.94 | 4.96 | 370.3 | 168.0 | 44.94 | 13.70 | | | | 0.0094 | 0.0114 | 88.03 | 111.7 | 93.6 | | | | | 4.00 | 3.30 | 3.40 | |
| 3 | 15 | 35.88 | 2.44 | 285 | 414 | 10.90 | 4.94 | 537.6 | 248.0 | 44.90 | 13.68 | | | | 0.0137 | 0.0170 | 90.76 | 146.4 | 58.4 | | | | | 3.60 | 3.30 | 3.40 | |
| 4 | 16 | 35.98 | 2.45 | 285 | 414 | 10.94 | 4.96 | 661.7 | 299.8 | 44.89 | 13.68 | | | | 0.0168 | 0.0209 | 92.18 | 157.1 | 41.6 | | | | | 3.90 | 3.20 | 3.40 | |
| 5 | 17 | 36.03 | 2.45 | 284 | 413 | 10.94 | 4.96 | 827.0 | 376.1 | 44.81 | 13.66 | | | | 0.0210 | 0.0254 | 92.64 | 204.5 | 25.9 | | | | | 4.00 | 3.10 | 3.40 | |
| 6 | 18 | 35.93 | 2.45 | 282 | 412 | 10.95 | 4.97 | 1032.6 | 468.4 | 44.85 | 13.67 | | | | 0.0262 | 0.0330 | 83.80 | 499.7 | 45.3 | | | | | 3.70 | 3.20 | 3.50 | |

Table XXXIII. Summary of Test Results: Configuration MOD-13 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 35.84 | 2.44 | 287 | 415 | 11.04 | 5.01 | 278.2 | 126.2 | 45.64 | 13.91 | | | | 0.0070 | 0.0099 | 95.54 | 81.4 | 25.6 | | | | | 11.3 | 5.50 | 5.30 | |
| 2 | 14 | 35.84 | 2.44 | 295 | 419 | 10.97 | 4.98 | 359.5 | 163.1 | 45.85 | 13.98 | | | | 0.0091 | 0.0133 | 98.09 | 40.8 | 9.6 | | | | | 11.3 | 5.30 | 5.10 | |
| 3 | 15 | 36.08 | 2.46 | 294 | 419 | 11.01 | 4.99 | 519.3 | 235.5 | 45.63 | 13.91 | | | | 0.0131 | 0.0213 | 97.17 | 96.6 | 5.8 | | | | | 11.9 | 5.10 | 4.90 | |
| 4 | 16 | 36.01 | 2.45 | 285 | 414 | 11.01 | 4.99 | 638.2 | 289.5 | 45.18 | 13.77 | | | | 0.0161 | 0.0261 | 93.23 | 248.2 | 9.8 | | | | | 11.7 | 5.60 | 5.30 | |
| 5 | 17 | 36.01 | 2.45 | 285 | 414 | 11.01 | 4.99 | 796.7 | 361.4 | 45.18 | 13.77 | | | | 0.0201 | 0.0343 | 80.69 | 390.1 | 102.1 | | | | | 11.7 | 5.40 | 5.10 | |
| 6 | 15R1 | 36.03 | 2.45 | 280 | 411 | 11.01 | 4.99 | 519.3 | 235.5 | 44.85 | 13.67 | | | | 0.0131 | 0.0140 | 95.93 | 110.3 | 14.9 | | | | | 11.8 | 5.70 | 5.50 | No fuel to Cup #3 |
| 7 | 15R2 | 36.10 | 2.46 | 287 | 415 | 11.01 | 4.33 | 519.3 | 235.5 | 45.03 | 13.74 | | | | 0.0131 | 0.0223 | 93.95 | 208.1 | 11.9 | | | | | 12.1 | 5.10 | 4.90 | No fuel to Cup #2 |
| 8 | 15R2 | 35.89 | 2.44 | 288 | 415 | 11.01 | 4.99 | 519.3 | 235.5 | 45.52 | 13.87 | | | | 0.0131 | 0.0158 | 92.59 | 237.6 | 18.7 | | | | | 11.4 | 5.20 | 5.00 | No fuel to Cup #4 |

Table XXXIV. Summary of Test Results: Configuration MOD-14 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13 | 35.90 | 2.44 | 288 | 415 | 10.58 | 4.80 | 270.4 | 122.6 | 43.70 | 13.32 | | | | 0.0071 | 0.0070 | 72.85 | 115.6 | 244.5 | | | | | 5.20 | 3.40 | 3.20 | |
| 2 | 14 | 35.97 | 2.44 | 284 | 413 | 10.57 | 4.80 | 350.2 | 158.9 | 43.37 | 13.32 | | | | 0.0092 | 0.0091 | 87.64 | 34.9 | 115.5 | | | | | 5.40 | 3.30 | 3.20 | |
| 3 | 15 | 36.12 | 2.46 | 284 | 413 | 10.56 | 4.79 | 505.4 | 229.3 | 43.13 | 13.14 | | | | 0.0133 | 0.0119 | 91.29 | 57.6 | 73.6 | | | | | 6.10 | 3.40 | 3.20 | |
| 4 | 16 | 36.05 | 2.45 | 287 | 414 | 10.58 | 4.80 | 620.6 | 281.5 | 43.47 | 13.25 | | | | 0.0163 | 0.0137 | 91.92 | 127.7 | 51.0 | | | | | 5.60 | 3.30 | 3.20 | |
| 5 | 17 | 36.10 | 2.46 | 290 | 416 | 10.56 | 4.79 | 775.3 | 351.7 | 43.50 | 13.26 | | | | 0.0204 | 0.0171 | 90.57 | 221.6 | 42.6 | | | | | 5.70 | 3.30 | 3.20 | |
| 6 | 18 | 36.05 | 2.45 | 285 | 414 | 10.56 | 4.79 | 969.1 | 439.6 | 43.27 | 13.19 | | | | 0.0255 | 0.0216 | 86.34 | 362.5 | 52.0 | | | | | 5.60 | 3.30 | 3.20 | |
| 7 | 14 | 42.56 | 2.90 | 315 | 430 | 12.42 | 5.64 | 398.1 | 180.6 | 44.88 | 13.68 | | | | 0.0089 | 0.0089 | 95.37 | 19.4 | 41.8 | | | | | 5.70 | 5.00 | 4.80 | |
| 8 | 15 | 42.73 | 2.91 | 315 | 430 | 12.46 | 5.65 | 578.6 | 262.4 | 44.82 | 13.66 | | | | 0.[illegible]29 | 0.0126 | 95.91 | 67.2 | 25.2 | | | | | 6.10 | 5.00 | 4.80 | |
| 9 | 16 | 42.63 | 2.90 | 315 | 430 | 12.46 | 5.65 | 708.7 | 321.4 | 44.92 | 13.69 | | | | 0.0158 | 0.0159 | 95.40 | 110.9 | 20.2 | | | | | 5.80 | 4.90 | 5.00 | |

Table XXXV. Summary of Test Results: Configuration MOD-15 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13 | 35.95 | 2.45 | 289 | 416 | 11.37 | 5.16 | 282.0 | 128.0 | 47.00 | 14.30 | | 1.0 | 0.0 | 0.0059 | 0.0092 | 90.32 | 122.8 | 68.1 | 1.2 | | | | 4.00 | 3.50 | 3.50 | |
| 2 | 14 | 36.05 | 2.45 | 287 | 415 | 11.20 | 5.08 | 366.8 | 166.4 | 46.01 | 14.02 | | | | 0.0091 | 0.0147 | 95.25 | 60.3 | 33.4 | 2.2 | | | | 4.30 | 3.80 | 3.70 | |
| 3 | 15 | 36.18 | 2.46 | 286 | 414 | 11.19 | 5.08 | 528.0 | 239.5 | 45.79 | 13.96 | | | | 0.0131 | 0.0220 | 96.33 | 102.7 | 12.8 | 2.4 | | | | 4.90 | 3.70 | 3.60 | |
| 4 | 16 | 36.10 | 2.46 | 290 | 416 | 11.22 | 5.08 | 646.0 | 293.0 | 46.21 | 14.09 | | | | 0.0160 | 0.0276 | 93.90 | 218.5 | 10.0 | 2.1 | | | | 4.20 | 3.80 | 3.70 | |
| 5 | 17 | 36.03 | 2.45 | 293 | 418 | 11.16 | 5.06 | 811.8 | 368.2 | 46.28 | 14.11 | | | | 0.0202 | 0.0331 | 88.01 | 395.2 | 27.6 | 1.7 | | | | 4.00 | 3.80 | 3.60 | |
| 6 | 25 | 60.10 | 4.09 | 539 | 555 | 17.13 | 7.77 | 986.9 | 447.6 | 56.50 | 17.22 | | | | 0.0160 | 0.0266 | 96.87 | 122.9 | 2.6 | 3.6 | 51.7 | 0.6 | 4.5 | 4.20 | 13.90 | 15.10 | |
| 7 | 26 | 60.37 | 4.11 | 618 | 599 | 16.02 | 7.26 | 796.7 | 360.9 | 56.73 | 17.29 | | | | 0.0138 | 0.0208 | 99.00 | 37.5 | 1.2 | 6.50 | 9.9 | 0.1 | 9.0 | 3.80 | 14.10 | 15.30 | |

Table XXXVI. Summary of Test Results: Configuration MOD-15 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor Airflow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °R | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 96.74 | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | 2.46 | 289 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 13.84 | | | | [illegible] | 0.0206 | 97.86 | 56.2 | 8.8 | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | 36.22 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | 0.0248 | 96.95 | [illegible] | 4.9 | | | | | [illegible] | [illegible] | 3.36 | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | 0.0255 | 0.0308 | 94.94 | [illegible] | 5.5 | | | | | [illegible] | [illegible] | 3.36 | |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 446.9 | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 98.32 | 49.5 | 5.2 | | | | | [illegible] | 3.56 | 3.36 | 4.5% Idle |
| | | 42.68 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 98.21 | [illegible] | [illegible] | | | | | [illegible] | [illegible] | 4.59 | 4.5% Idle |
| 8 | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | 98.78 | [illegible] | [illegible] | | | | | 3.56 | [illegible] | 4.60 | 4.5% Idle |
| 9 | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | 0.0226 | 98.25 | 63.3 | 2.8 | | | | | [illegible] | [illegible] | [illegible] | 4.5% Idle |

Table XXXVII. Summary of Test Results: Configuration MOD-17 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13 | 36.28 | 2.47 | 286 | 414 | 10.67 | 4.84 | 276.6 | 125.5 | 45.23 | 13.27 | | 1.0 | 0.0 | 0.0072 | 0.0067 | 95.39 | 60.0 | [illegible] | | | | | 4.66 | 3.30 | | |
| 2 | 14 | 36.12 | 2.46 | 286 | 414 | 10.71 | 4.86 | 358.6 | 162.6 | 43.82 | 13.35 | | 1.0 | 0.0 | 0.0093 | 0.0147 | 97.98 | 30.0 | [illegible] | | | | | 4.30 | 3.10 | | |
| 3 | 15 | 36.13 | 2.46 | 286 | 414 | 10.73 | 4.87 | 517.6 | 234.8 | 43.93 | 13.39 | | 1.0 | 0.0 | 0.0134 | 0.0223 | 97.70 | 16.6 | [illegible] | | | | | 4.22 | 3.10 | | |
| 4 | 16 | 36.07 | 2.45 | 286 | 414 | 10.70 | 4.85 | 635.6 | 288.3 | 43.97 | 13.40 | | 1.0 | 0.0 | 0.0165 | 0.0274 | 95.48 | 73.0 | 4.4 | | | | | 3.90 | 3.70 | | |
| 5 | | 42.79 | 2.91 | 317 | 431 | 12.23 | 5.55 | 321.4 | 145.8 | 44.05 | 13.43 | | 1.0 | 0.0 | 0.0073 | 0.0112 | 98.[illegible] | 33.8 | [illegible] | | | | | 3.70 | 4.30 | | 4.5% at Idle |
| 6 | | 42.52 | 2.89 | 318 | 432 | 12.23 | 5.55 | 409.5 | 185.7 | 44.39 | 13.53 | | 1.0 | 0.0 | 0.0093 | 0.0146 | 98.75 | 28.0 | 5.8 | | | | | 3.00 | 4.30 | | 4.5% at Idle |
| 7 | | 42.71 | 2.91 | 318 | 432 | 12.32 | 5.59 | 594.2 | 269.5 | 44.50 | 13.56 | | 1.0 | 0.0 | 0.0134 | 0.0223 | 98.28 | 62.0 | 2.7 | | | | | 3.50 | 4.30 | | 4.5% at Idle |
| 8 | | 42.59 | 2.90 | 315 | 430 | 12.32 | 5.58 | 730.4 | 331.3 | 44.28 | 13.50 | | 1.0 | 0.0 | 0.0165 | 0.0279 | 95.49 | 171.6 | 5.0 | | | | | 3.90 | 4.30 | | 4.5% at Idle |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 1 | 30.45 | 2.07 | 256 | 398 | 9.60 | 4.38 | 590.0 | 267.0 | 42.70 | 12.85 | | 1.0 | 0.0 | 0.0182 | 0.0269 | 93.60 | 241.2 | 8.0 | 1.2 | | | | 2.86 | 2.50 | 2.40 | — |
| 2 | 2 | 33.30 | 2.27 | 272 | 407 | 9.65 | 4.38 | 323.0 | 147.0 | 42.[illegible] | 12.85 | | 1.0 | 0.0 | 0.0093 | 0.0144 | 97.20 | 35.7 | 15.0 | 2.3 | | | | 3.00 | 3.20 | 3.10 | |
| 3 | 3 | 33.28 | 2.27 | 275 | 408 | 9.88 | 4.48 | 466.0 | 211.0 | 43.35 | 13.25 | | 1.0 | 0.0 | 0.0131 | 0.0196 | 97.27 | 58.4 | 4.4 | 2.6 | | | | 3.90 | 3.20 | 3.10 | |
| 4 | 4 | 33.60 | 2.29 | 276 | 409 | 9.96 | 4.52 | 635.0 | 288.0 | 43.30 | 13.20 | | 1.0 | 0.0 | 0.0177 | 0.0261 | 93.56 | 255.2 | 5.9 | 1.8 | | | | 3.90 | 3.20 | 3.00 | |
| 5 | 5 | 33.45 | 2.28 | 273 | 407 | 9.94 | 4.51 | 716.0 | 325.0 | 43.20 | 13.20 | | 1.0 | 0.0 | 0.0200 | 0.0288 | 90.58 | 337.9 | 15.7 | 1.5 | | | | 3.80 | 3.10 | 3.00 | |
| 6 | 6 | 33.30 | 2.27 | 275 | 408 | 9.94 | 4.51 | 898.0 | 407.0 | 43.50 | 13.30 | | 1.0 | 0.0 | 0.0251 | 0.0357 | 78.42 | 557.0 | 85.8 | 1.4 | | | | 3.00 | 3.10 | 3.00 | |
| 7 | 8 | 43.32 | 2.95 | 315 | 430 | 12.65 | 5.74 | 592.0 | 269.0 | 44.90 | 13.70 | | 1.0 | 0.0 | 0.0113 | 0.01672 | 98.50 | 55.3 | 1.6 | 4.0 | | | | 3.10 | 5.00 | 5.40 | |
| 8 | 9 | 38.14 | 2.60 | 315 | 430 | 12.67 | 5.75 | 611.0 | 277.0 | [illegible] | 13.69 | | 1.0 | 0.0 | 0.0134 | 0.01966 | 97.60 | 95.7 | 1.2 | 3.5 | | | | | 5.60 | 5.40 | |
| 9 | 10 | 42.94 | 2.92 | 311 | 428 | 12.48 | 5.66 | 755.0 | 343.0 | 44.40 | 13.60 | | 1.0 | 0.0 | 0.0167 | 0.0265 | 94.91 | 233.7 | 3.4 | 2.4 | | | | 4.00 | 5.10 | 4.90 | |
| 10 | 11 | 42.94 | 2.92 | 307 | 426 | 12.50 | 5.67 | 941.0 | 427.0 | 44.30 | 13.50 | | 1.0 | 0.0 | 0.0209 | 0.0317 | 88.24 | 396.4 | 25.1 | 1.9 | | | | 4.00 | 5.10 | 4.90 | |
| 11 | 13 | 35.48 | 2.41 | 260 | 400 | 10.65 | 4.83 | 276.0 | 125.0 | 42.90 | 13.10 | | 1.0 | 0.0 | 0.0072 | 0.01025 | 95.64 | 59.9 | 23.6 | 1.6 | | | | 4.10 | 3.50 | 3.30 | |
| 12 | 14 | 35.85 | 2.44 | 290 | 417 | 10.64 | 4.83 | 353.0 | 160.0 | 44.20 | 13.50 | | 1.0 | 0.0 | 0.0092 | 0.0135 | 97.79 | 47.8 | 10.9 | 2.7 | | | | 3.70 | 3.50 | 3.40 | |
| 13 | 15 | 36.07 | 2.45 | 285 | 414 | 10.56 | 4.79 | 513.0 | 233.0 | 43.20 | 13.20 | | 1.0 | 0.0 | 0.0135 | 0.0177 | 97.50 | 108.2 | 4.4 | 3.1 | | | | 4.10 | 3.50 | 3.40 | |
| 14 | 16 | 36.12 | 2.46 | 289 | 416 | 10.56 | 4.79 | 631.0 | 286.0 | 43.40 | 13.20 | | 1.0 | 0.0 | 0.0166 | 0.0248 | 95.72 | 168.9 | 3.4 | 2.3 | | | | 4.50 | 3.50 | 3.40 | |
| 15 | 17 | 35.47 | 2.45 | 285 | 414 | 10.55 | 4.78 | 790.0 | 358.0 | 43.30 | 13.20 | | 1.0 | 0.0 | 0.0208 | 0.0303 | 90.34 | 337.0 | 17.8 | 1.6 | | | | 4.10 | 3.50 | 3.40 | |
| 16 | 13 | 36.07 | 2.45 | 285 | 414 | 10.89 | 4.94 | 274.0 | 124.0 | 44.60 | 13.60 | | 1.0 | 0.0 | 0.0070 | 0.0098 | 95.68 | 73.9 | 25.9 | 1.9 | | | | 4.10 | 3.20 | 3.10 | |
| 17 | 14 | 35.90 | 2.44 | 286 | 415 | 10.89 | 4.94 | 357.0 | 162.0 | 45.00 | 13.70 | | 1.0 | 0.0 | 0.0091 | 0.0127 | 97.58 | 49.8 | 12.6 | 3.0 | | | | 3.90 | 3.20 | 3.10 | |
| 18 | 15 | 36.12 | 2.46 | 287 | 415 | 10.88 | 4.94 | 517.0 | 234.0 | 44.70 | 13.60 | | 1.0 | 0.0 | 0.0132 | 0.0179 | 97.22 | 90.8 | 6.6 | 3.1 | | | | 3.40 | 3.30 | 3.10 | |
| 19 | 16 | 35.90 | 2.44 | 286 | 415 | 10.89 | 4.94 | 631.0 | 286.0 | 45.00 | 13.70 | | 1.0 | 0.0 | 0.0161 | 0.0227 | 96.[illegible] | 148.3 | 4.2 | 2.6 | | | | 4.50 | 3.30 | 3.10 | |
| 20 | 17 | 36.07 | 2.45 | 286 | 415 | [illegible] | 5.04 | 792.0 | 359.0 | 45.60 | 13.90 | | 1.0 | 0.0 | 0.0198 | 0.0273 | 92.23 | 288.[illegible] | 15.4 | 1.8 | | | | 4.40 | 3.50 | 3.30 | |
| 21 | 20 | 36.07 | 2.45 | 289 | 416 | 13.52 | 6.13 | 788.0 | 358.0 | 55.70 | 17.00 | | 1.0 | 0.0 | 0.0162 | 0.0189 | 95.43 | 179.2 | 3.9 | 2.4 | | | | 5.60 | 5.20 | 4.80 | Design Cycle Idle & Increased ΔP/P |
| 22 | 21 | 35.73 | 2.43 | 284 | 413 | 8.28 | 3.75 | 474.0 | 215.0 | 34.10 | 10.40 | | 1.0 | 0.0 | 0.0159 | 0.0228 | 96.00 | 122.0 | 5.9 | 3.1 | | | | 2.50 | 1.90 | 1.80 | Design Cycle Idle & Increased ΔP/P |
| 23 | 22 | 36.22 | 2.42 | 286 | 414 | 11.37 | 5.16 | 659.0 | 299.0 | 46.40 | 14.20 | | 1.0 | 0.0 | 0.0161 | 0.0255 | 96.33 | 132.6 | 5.8 | 2.6 | | | | 4.50 | 3.70 | 3.50 | |

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Table XXXVIII. Summary of Test Results: Configuration MOD-17 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 23 | 36.22 | 2.46 | 285 | 414 | 10.58 | 4.80 | 609.0 | 276.0 | 43.20 | 13.20 | | 1.0 | 0.0 | 0.0160 | 0.0221 | 96.15 | 140.4 | 5.8 | 2.6 | | | | 4.50 | 3.10 | 3.50 | |
| 25 | 24 | 32.56 | 2.22 | 284 | 413 | 10.00 | 4.54 | 569.0 | 258.0 | 45.30 | 13.80 | | 1.0 | 0.0 | 0.0158 | 0.0208 | 95.82 | 150 | 6.6 | 2.7 | | | | 4.50 | 2.80 | 2.70 | |
| 26 | 25 | 60.11 | 4.09 | 538 | 554 | 15.94 | 7.23 | 918.0 | 416.0 | 52.50 | 16.00 | | 1.0 | 0.0 | 0.0160 | 0.0248 | 97.05 | 115.2 | 1.6 | 3.6 | 48.5 | 0.6 | 4.5 | 5.20 | | | |
| 27 | 26 | 60.14 | 4.09 | 616 | 598 | 16.08 | 7.29 | 758.0 | 344.0 | 57.10 | 17.4[illegible] | | 1.0 | 0.0 | 0.0131 | 0.0208 | 98.89 | 42.0 | 1.3 | 4.6 | 11.0 | 0.1 | 6.4 | 4.40 | | | |
| 28 | 27 | 60.26 | 4.10 | 615 | 597 | 16.05 | 7.28 | 763.0 | 346.0 | 56.80 | 17.30 | | 0.5 | 0.5 | 0.0132 | 0.0125 | 78.72 | 61.2 | 196.5 | 2.7 | 16.2 | 21.7 | 3.8 | | | | |
| 29 | 28 | 59.94 | 4.08 | 625 | 603 | 16.01 | 7.26 | 761.0 | 345.0 | 57.50 | 17.50 | | 0.3 | 0.7 | 0.0132 | 0.0092 | 64.91 | 46.3 | 340.1 | 1.9 | 12.2 | 36.7 | 2.6 | 5.60 | | | |
| 30 | 29 | 60.34 | 4.11 | 615 | 597 | 16.19 | 7.34 | 763.0 | 346.0 | 57.20 | 17.40 | | 0.2 | 0.8 | 0.0131 | 0.0076 | 48.74 | 105.7 | 488.0 | 1.0 | 28.0 | 53.6 | 1.4 | 4.60 | | | |
| 31 | 30 | 50.18 | 3.41 | 775 | 686 | 11.56 | 5.24 | 1116.0 | 506.0 | 56.50 | 17.20 | | 0.2 | 0.8 | 0.0268 | 0.0281 | 96.93 | 51.2 | 18.8 | 4.4 | 5.7 | 0.5 | 7.6 | 4.80 | 6.80 | 7.20 | |
| 32 | 33 | 40.65 | 2.77 | 910 | 761 | 8.89 | 4.03 | 755.0 | 343.0 | 59.40 | 18.10 | | 0.2 | 0.8 | 0.0236 | 0.0258 | 97.79 | 39.3 | 13.0 | 6.0 | 1.7 | 0.1 | 13.0 | | 4.40 | 4.20 | |
| 33 | 31 | 37.41 | 2.55 | 895 | 753 | 8.30 | 3.76 | 616.0 | 279.0 | 59.60 | 18.20 | | 0.2 | 0.8 | 0.0206 | 0.0225 | 96.63 | 49.2 | 22.2 | 4.8 | 2.0 | 0.1 | 10.5 | 3.80 | 3.60 | 3.70 | |
| 34 | 32 | 45.39 | 3.09 | 850 | 728 | 9.93 | 4.50 | 1122.0 | 509.0 | 56.80 | 17.30 | | 0.2 | 0.8 | 0.0314 | 0.0340 | 98.02 | 39.3 | 10.7 | 5.5 | 3.0 | 0.2 | 10.3 | 4.20 | 5.10 | 5.40 | |
| 35 | 37 | 36.73 | 2.50 | 948 | 782 | 8.03 | 3.64 | 627.0 | 285.0 | 61.10 | 18.60 | | 0.2 | 0.8 | 0.0217 | 0.0245 | 97.81 | 39.5 | 12.6 | 6.3 | 1.3 | 0 | 15.5 | 4.20 | 3.60 | 3.50 | |

Table XXXIX. Summary of Test Results: Configuration MOD-18 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 13 | 35.79 | 2.44 | 285 | 414 | 10.96 | 4.97 | 280.1 | 127.1 | 45.25 | 13.79 | | 1.0 | 0.0 | 0.0071 | 0.0100 | 99.65 | 79.5 | 45.0 | 1.5 | | | | 3.40 | 3.40 | 3.40 | |
| 2 | 14 | 35.96 | 2.45 | 287 | 414 | 10.92 | 4.95 | 361.7 | 164.1 | 45.00 | 13.72 | | | | 0.0092 | 0.0140 | 96.84 | 53.9 | 19.0 | 2.3 | | | | 3.90 | 3.40 | 3.30 | |
| 3 | 15 | 35.89 | 2.44 | 287 | 414 | 10.97 | 4.98 | 521.4 | 236.5 | 45.30 | 13.81 | | | | 0.0132 | 0.0225 | 96.58 | 112.5 | 8.0 | 2.4 | | | | 3.70 | 3.40 | 3.30 | |
| 4 | 16 | 35.89 | 2.44 | 286 | 414 | 10.92 | 4.95 | 640.7 | 290.6 | 45.02 | 13.72 | | | | 0.0163 | 0.0269 | 94.50 | 198.9 | 8.6 | 2.2 | | | | 3.70 | 3.20 | 3.40 | |
| 5 | | 42.30 | 2.88 | 313 | 429 | 12.25 | 5.56 | 322.0 | 146.0 | 44.42 | 13.54 | | | | 0.0073 | 0.0107 | 97.23 | 45.4 | 17.1 | 3.1 | | | | 2.70 | 4.40 | 4.30 | 4.5% Idle |
| 6 | | 42.42 | 2.89 | 315 | 430 | 12.25 | 5.56 | 414.7 | 188.1 | 44.41 | 13.53 | | | | 0.0094 | 0.0151 | 98.31 | 39.2 | 7.8 | 2.7 | | | | 2.70 | 4.50 | 4.30 | 4.5% Idle |
| 7 | | 42.32 | 2.88 | 314 | 430 | 12.21 | 5.54 | 597.9 | 271.1 | 44.30 | 13.50 | | | | 0.0136 | 0.0229 | 97.18 | 104.1 | 3.9 | 2.7 | | | | 2.90 | 4.40 | 4.30 | 4.5% Idle |
| 8 | | 42.42 | 2.89 | 315 | 430 | 12.21 | 5.54 | 734.2 | 333.0 | 44.25 | 13.49 | | | | 0.0167 | 0.0287 | 94.68 | 202.4 | 6.0 | 2.1 | | | | 2.90 | 4.40 | 4.30 | 4.5% Idle |

Table XL. Summary of Test Results: Configuration MOD-19 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor Airflow pps | Combustor Airflow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 36.47 | 2.48 | 286 | 414 | 11.05 | [illegible] | 286.5 | [illegible] | 44.84 | 13.67 | | 1.0 | 0.0 | 0.0072 | 0.0096 | 95.52 | 73.1 | 27.8 | 2.1 | | | | 5.80 | 4.90 | 4.70 | |
| 2 | 14 | 36.52 | 2.49 | 291 | 417 | 10.91 | 4.95 | 365.2 | 165.7 | 44.49 | 13.56 | | | | 0.0093 | 0.0125 | 97.82 | 51.7 | 9.8 | 3.2 | | | | 4.90 | 4.80 | 4.60 | |
| 3 | 15 | 36.57 | 2.49 | 286 | 414 | 10.91 | 4.95 | 526.2 | 238.7 | 44.14 | 13.45 | | | | 0.0134 | 0.0199 | 97.26 | 98.4 | 4.4 | 2.6 | | | | 4.70 | 4.80 | 4.50 | |
| 4 | 16 | 36.54 | 2.49 | 286 | 414 | 10.99 | 4.98 | 648.8 | 294.3 | 44.50 | 13.56 | | | | 0.0164 | 0.0233 | 95.15 | 185.7 | 5.6 | 2.1 | | | | 4.90 | 5.00 | 4.70 | |
| 6 | | 42.58 | 2.90 | 330 | 438 | 12.41 | 5.63 | 326.1 | 147.9 | 45.66 | 13.92 | | | | 0.0073 | 0.0113 | 98.34 | 37.0 | 6.0 | 2.6 | | | | 4.80 | 7.50 | 7.30 | 4.5% Idle |
| 7 | | 42.58 | 2.90 | 310 | 427 | 12.33 | 5.59 | 421.8 | 191.[illegible] | 44.23 | 13.48 | | | | 0.0095 | 0.0146 | 98.73 | 36.1 | 4.3 | 3.3 | | | | 3.60 | 6.80 | 6.50 | 4.5% Idle |
| 8 | | 42.56 | 2.90 | 316 | 431 | 12.48 | 5.66 | 610.8 | 277.1 | 45.12 | 13.75 | | | | 0.0136 | 0.0197 | 97.88 | 82.1 | 2.1 | 3.3 | | | | 4.70 | 7.10 | 6.8 | 4.5% Idle |
| 9 | | 42.58 | 2.90 | 316 | 431 | 12.46 | 5.65 | 744.9 | 337.9 | 45.05 | 13.73 | | | | 0.0166 | 0.0232 | 95.78 | 170.5 | 2.4 | 2.5 | | | | 5.50 | 7.10 | 6.70 | 4.5% Idle |
| 11 | 25 | 60.34 | 4.10 | 544 | 557 | 15.52 | 7.04 | 988.9 | 448.5 | 51.22 | 15.61 | | | | 0.0177 | 0.0291 | 95.81 | 159.8 | 4.6 | 3.6 | 67.3 | 1.1 | 4.5 | 4.60 | 12.20 | 11.70 | |
| 12 | 26 | 60.32 | 4.10 | 626 | 603 | 15.76 | 7.15 | 777.3 | 352.6 | 56.29 | 17.16 | | | | 0.0137 | 0.0230 | 99.29 | 28.1 | 0.5 | 5.0 | 7.4 | 0.5 | 7.0 | 4.90 | 13.00 | 13.30 | |

Table XLI. Summary of Test Results: Configuration MOD-20 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 35.94 | 2.45 | 285 | 414 | 10.83 | 4.91 | 265.0 | 120.2 | 44.51 | 13.57 | | 1.0 | 0.0 | 0.0068 | 0.0082 | 94.20 | 66.8 | 42.4 | 2.0 | | | | 3.70 | 3.10 | 3.10 | |
| 2 | 14 | 35.96 | 2.45 | 282 | 412 | 10.77 | 4.89 | 345.1 | 156.5 | 44.07 | 13.43 | | 1.0 | 0.0 | 0.0089 | 0.0125 | 97.36 | 57.9 | 12.9 | 2.6 | | | | 2.90 | 3.00 | 3.00 | |
| 3 | 15 | 36.01 | 2.45 | 290 | 416 | 10.78 | 4.89 | 512.2 | 232.4 | 44.53 | 13.57 | | 1.0 | 0.0 | 0.0132 | 0.0195 | 96.79 | 114.9 | 5.3 | 2.2 | | | | 3.30 | 3.00 | 3.00 | |
| 4 | 16 | 36.06 | 2.45 | 288 | 415 | 10.78 | 4.89 | 628.6 | 285.2 | 44.35 | 13.52 | | 1.0 | 0.0 | 0.0162 | 0.[illegible] | 94.52 | 200.9 | 7.9 | 1.8 | | | | 3.40 | 3.00 | 3.00 | |
| 5 | | 42.74 | 2.91 | 317 | 431 | 12.47 | 5.65 | 309.6 | 140.4 | 44.95 | 13.70 | | 1.0 | 0.0 | 0.0069 | 0.[illegible] | 97.14 | 49.6 | 17.1 | 3.5 | | | | 3.70 | 4.20 | 4.20 | 4.5% Idle |
| 6 | | 42.74 | 2.91 | 315 | 430 | 12.57 | 5.70 | 398.3 | 180.7 | 45.21 | 13.78 | | 1.0 | 0.0 | 0.0588 | 0.[illegible] | 98.64 | 48.5 | 8.2 | 3.5 | | | | 4.00 | 4.10 | 4.10 | 4.5% Idle |
| 7 | | 42.74 | 2.91 | 315 | 430 | 12.52 | 5.68 | 585.9 | 265.7 | 45.05 | 13.73 | | 1.0 | 0.0 | 0.0130 | 0.[illegible]79 | 97.23 | 164.7 | 3.3 | 3.3 | | | | 3.50 | 4.20 | 4.20 | 4.5% Idle |
| 8 | | 42.74 | 2.91 | 317 | 431 | 12.47 | 5.65 | 727.0 | 329.7 | 44.95 | 13.70 | | 1.0 | 0.0 | 0.0162 | 0.0218 | 95.58 | 178.1 | 2.6 | | | | | 3.60 | 4.20 | 4.20 | 4.5% Idle |

Table XLII. Summary of Test Results: Configuration MOD-21 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 35.95 | 2.45 | 285 | 414 | 10.94 | 4.96 | 279.5 | 126.8 | 44.94 | 13.70 | | 1.0 | 0.0 | 0.0071 | 0.0105 | 93.95 | 74.4 | 43.2 | | | | | 3.70 | 3.40 | 3.50 | |
| 2 | 14 | 36.18 | 2.46 | 285 | 414 | 10.91 | 4.95 | 400.5 | 181.7 | 44.54 | 13.58 | | 1.0 | 0.0 | 0.0102 | 0.0163 | 97.40 | 55.1 | 13.1 | | | | | 4.30 | 3.30 | 3.20 | |
| 3 | 15 | 36.05 | 2.45 | 287 | 415 | 10.92 | 4.95 | 522.7 | 237.1 | 44.86 | 13.67 | | 1.0 | 0.0 | 0.0133 | 0.0217 | 97.01 | 106.8 | 5.0 | | | | | 4.00 | 3.30 | 3.20 | |
| 4 | 16 | 36.00 | 2.45 | 289 | 416 | 10.91 | 4.95 | 640.0 | 290.3 | 45.00 | 13.72 | | 1.0 | 0.0 | 0.0163 | 0.0265 | 93.75 | 239.1 | 6.6 | | | | | 3.90 | 3.30 | 3.20 | |
| 6 | | 42.61 | 2.90 | 311 | 428 | 12.26 | 5.56 | 322.2 | 146.1 | 44.01 | 13.41 | | 1.0 | 0.0 | 0.0073 | 0.0112 | 97.42 | 41.4 | 16.1 | | | | | 4.00 | 4.40 | 4.30 | 4.5% Idle |
| 7 | | 43.10 | 2.93 | 317 | 431 | 12.26 | 5.56 | 414.9 | 188.2 | 43.84 | 13.36 | | 1.0 | 0.0 | 0.0094 | 0.0152 | 98.59 | 36.3 | 5.7 | | | | | 5.10 | 4.30 | 4.30 | 4.5% Idle |
| 8 | | 42.71 | 2.91 | 315 | 430 | 12.24 | 5.55 | 594.9 | 269.8 | 44.05 | 13.43 | | 1.0 | 0.0 | 0.0135 | 0.0238 | 96.89 | 127.4 | 2.6 | | | | | 4.70 | 4.30 | 4.20 | 4.5% Idle |
| 9 | | 42.56 | 2.90 | 316 | 431 | 12.23 | 5.55 | 730.8 | 331.5 | 44.23 | 13.48 | | 1.0 | 0.0 | 0.0166 | 0.0281 | 93.82 | 255.6 | 2.2 | | | | | 4.80 | 4.30 | 4.20 | 4.5% Idle |

Table XLIII. Summary of Test Results: Configuration MOD-22 QCSEE Double Annular Combustor.

| | | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reading | Point | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | Comments |
| 1 | 13 | 35.18 | 2.40 | 277 | 409 | 10.02 | 4.54 | 256.0 | 116.2 | 41.63 | 12.69 | | 1.0 | 0.0 | 0.0071 | 0.0103 | 93.50 | 91.9 | 47.1 | 1.4 | | | | --- | 3.30 | 3.00 | |
| 2 | 14 | 35.77 | 2.44 | 281 | 411 | 10.04 | 4.55 | 328.8 | 149.1 | 41.56 | 12.67 | | 1.0 | 0.0 | 0.0091 | 0.0127 | 97.40 | 55.4 | 13.1 | 3.5 | | | | 3.10 | 3.30 | 3.00 | |
| 3 | | 35.91 | 2.45 | 289 | 416 | 10.05 | 4.56 | 401.5 | 182.1 | 41.56 | 12.67 | | 1.0 | 0.0 | 0.0111 | 0.0158 | 98.14 | 57.4 | 5.2 | 3.2 | | | | 2.90 | 3.30 | 3.00 | |
| 4 | 15 | 35.79 | 2.44 | 286 | 414 | 10.05 | 4.56 | 477.4 | 216.5 | 41.53 | 12.66 | | 1.0 | 0.0 | 0.0132 | 0.0179 | 97.96 | 74.5 | 3.1 | 3.1 | | | | 3.70 | 3.20 | 2.80 | |
| 5 | 16 | 35.91 | 2.45 | 285 | 414 | 10.05 | 4.56 | 585.9 | 265.8 | 41.33 | 12.60 | | 1.0 | 0.0 | 0.0162 | 0.0222 | 97.27 | 109.0 | 1.9 | --- | | | | 2.60 | 3.30 | 2.90 | |

Table XLIV. Summary of Test Results: Configuration MOD-23 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 35.62 | 2.42 | 281 | 411 | 9.58 | 4.34 | 255.1 | 115.7 | 39.52 | 12.04 | | 1.0 | 0.0 | 0.0074 | 0.0106 | 92.25 | 96.7 | 54.9 | 1.2 | | | | 2.20 | 3.20 | 2.90 | |
| 2 | 14 | 35.72 | 2.43 | 290 | 416 | 9.58 | 4.35 | 324.4 | 147.1 | 39.92 | 12.17 | | 1.0 | 0.0 | 0.0094 | 0.0140 | 97.25 | 49.6 | 16.0 | 2.1 | | | | 2.70 | 3.20 | 2.90 | |
| 3 | 114 | 35.77 | 2.43 | 290 | 416 | 9.58 | 4.34 | 396.5 | 179.9 | 39.83 | 12.14 | | 1.0 | 0.0 | 0.0115 | 0.0181 | 98.23 | 49.4 | 6.1 | 2.7 | | | | 2.60 | 3.20 | 2.90 | |
| 4 | 15 | 36.01 | 2.45 | 286 | 414 | 9.77 | 4.07 | 468.0 | 196.0 | 40.16 | 12.24 | | 1.0 | 0.0 | 0.0133 | 0.0202 | 98.11 | 67.3 | 3.1 | 3.1 | | | | [illegible] | 3.40 | 3.10 | |
| 5 | 16 | 36.01 | 2.45 | 285 | 414 | 9.78 | 4.44 | 577.5 | 262.0 | 40.14 | 12.23 | | 1.0 | 0.0 | 0.0164 | 0.0248 | 97.55 | 97.0 | 1.9 | 2.1 | | | | 2.40 | 3.40 | 3.00 | |

Table XLV. Summary of Test Results: Configuration MOD-24 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 13 | 35.93 | 2.44 | 284 | 413 | 9.70 | 4.40 | 248.2 | 112.6 | 39.87 | 12.15 | | 1.0 | 0.0 | 0.0071 | 0.0094 | 90.67 | 106.8 | 68.4 | 1.2 | | | | 3.50 | 3.60 | 3.40 | |
| 2 | 14 | 35.88 | 2.44 | 289 | 416 | 9.71 | 4.40 | 321.6 | 146.8 | 40.20 | 12.25 | | 1.0 | 0.0 | 0.0092 | 0.0136 | 97.31 | 47.4 | 15.8 | 2.1 | | | | 3.60 | 3.70 | 3.30 | |
| 3 | 114 | 35.76 | 2.43 | 287 | 415 | 9.69 | 4.40 | 390.8 | 177.3 | 40.16 | 12.24 | | 1.0 | 0.0 | 0.0112 | 0.0167 | 98.18 | 52.8 | 5.8 | 2.8 | | | | 1.90 | 3.70 | 3.30 | |
| 4 | 15 | 35.85 | 2.43 | 285 | 414 | 9.69 | 4.40 | 464.0 | 210.5 | 40.00 | 12.19 | | 1.0 | 0.0 | 0.0133 | 0.0171 | 98.12 | 63.7 | 3.9 | 3.3 | | | | 2.60 | 3.60 | 3.30 | |
| 5 | 16 | 35.81 | 2.44 | 290 | 416 | 9.69 | 4.40 | 572.2 | 259.6 | 40.26 | 12.27 | | 1.0 | 0.0 | 0.0164 | 0.0238 | 97.03 | 118.8 | 1.9 | 2.4 | | | | 3.10 | 3.60 | 3.30 | |

Table XLVI. Summary of Test Results: Configuration MOD-25 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14 | 36.30 | 2.47 | 286 | 414 | 11.88 | 5.39 | 394.0 | 179.0 | 48.40 | 14.80 | | 1.0 | 0.0 | 0.0092 | 0.0116 | 97.27 | 66.8 | 11.7 | | | | | 3.30 | 4.14 | | |
| 2 | 15 | 36.01 | 2.45 | 286 | 414 | 11.89 | 5.39 | 574.0 | 260.0 | 48.90 | 14.90 | | 1.0 | 0.0 | 0.0134 | 0.0179 | 98.38 | 48.3 | 5.0 | | | | 3.20 | 3.30 | 4.12 | | |
| 3 | 16 | 35.94 | 2.45 | 283 | 413 | 11.90 | 5.40 | 703.0 | 319.0 | 48.90 | 14.90 | | 1.0 | 0.0 | 0.0164 | 0.0226 | 98.02 | 71.7 | 3.1 | | | | 3.20 | 3.40 | 4.10 | | |
| 4 | 17 | 35.93 | 2.45 | 286 | 414 | 11.72 | 5.31 | 873.0 | 396.0 | 48.80 | 14.90 | | 1.0 | 0.0 | 0.0207 | 0.0276 | 96.21 | 149.8 | 3.0 | | | | | 3.40 | 4.26 | | |
| 5 | 18 | 36.23 | 2.47 | 287 | [illegible] | 11.85 | 5.38 | 1097.0 | 497.0 | 48.50 | 14.80 | | 1.0 | 0.0 | 0.0257 | 0.0381 | 83.07 | 554.7 | 39.9 | | | | | 3.40 | 4.20 | | |

Table XLVII. Summary of Test Results: Configuration MOD-26 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 36.17 | 2.46 | 286 | 414 | 12.36 | 5.60 | 409.2 | 185.6 | 50.54 | 15.41 | | 1.0 | 0.0 | 0.0092 | 0.0116 | 94.76 | 85.9 | 32.4 | | | | | 4.00 | 3.40 | 3.20 | |
| 2 | 15 | 36.15 | 2.46 | 287 | 415 | 12.32 | 5.59 | 600.0 | 267.6 | 50.51 | 15.39 | | 1.0 | 0.0 | 0.0133 | 0.0177 | 98.29 | 46.9 | 6.2 | | | | | 3.90 | 3.40 | 3.30 | |
| 3 | 16 | 36.12 | 2.46 | 286 | 414 | 12.33 | 5.59 | 723.7 | 328.3 | 50.52 | 15.40 | | 1.0 | 0.0 | 0.0163 | 0.0229 | 97.83 | 82.6 | 2.4 | | | | | 3.60 | 3.40 | 3.30 | |
| 4 | 17 | 36.15 | 2.46 | 285 | 414 | 12.36 | 5.60 | 303.0 | 409.6 | 50.51 | 15.40 | | 1.0 | 0.0 | 0.0203 | 0.0278 | 95.84 | 158.3 | 4.7 | | | | | 3.70 | 3.40 | 3.30 | |
| 5 | 18 | 36.14 | 2.46 | 286 | 414 | 12.38 | 5.61 | 1127.5 | 511.4 | 50.69 | 15.45 | | 1.0 | 0.0 | 0.0253 | 0.0451 | 63.91 | 177.0 | 319.6 | | | | | 3.60 | 3.40 | 3.30 | |
| 6 | | 36.15 | 2.46 | 286 | 414 | 12.38 | 5.61 | 494.7 | 224.4 | 50.67 | 15.44 | | 1.0 | 0.0 | 0.0111 | 0.0142 | 97.77 | 54.3 | [illegible].6 | | | | | 3.40 | 3.50 | 3.40 | |
| 7 | | 36.31 | 2.47 | 285 | 414 | 14.84 | 6.73 | 486.3 | 220.6 | 60.41 | 18.41 | | 1.0 | 0.0 | 0.0091 | 0.0112 | 94.97 | 103.9 | 26.1 | | | | | 4.40 | 4.90 | 4.70 | Increased ΔP/P |
| 8 | | 36.28 | 2.4[illegible] | 287 | 415 | 14.88 | 6.75 | 594.8 | 269.8 | 60.78 | 18.52 | | 1.0 | 0.0 | 0.0111 | 0.0149 | 98.15 | 52.1 | 6.4 | | | | | 4.60 | 5.10 | 4.90 | Increased ΔP/P |
| 9 | | 36.21 | 2.46 | 287 | 415 | 14.90 | 6.76 | 702.6 | 318.7 | 60.96 | 18.58 | | 1.0 | 0.0 | 0.0131 | 0.0175 | 98.09 | 57.2 | 5.7 | | | | | 4.40 | 5.10 | 4.90 | Increased ΔP/P |

Table XLVIII. Summary of Test Results: Configuration MOD-27 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 1 | 14 | 36.01 | 2.46 | 288 | 415 | 11.83 | 5.36 | 378.9 | 171.9 | 48.72 | 14.85 | | 1.0 | 0.0 | 0.0089 | 0.0102 | 97.59 | 48.9 | 12.7 | | | | | 2.80 | 3.20 | 3.10 | |
| 2 | 15 | 35.71 | 2.43 | 286 | 414 | 11.79 | 5.35 | 466.9 | 211.8 | 48.86 | 14.89 | | 1.0 | 0.0 | 0.0110 | 0.0180 | 98.04 | 50.9 | 7.7 | | | | | 2.60 | 3.20 | 3.10 | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | Test Terminated |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | Due to Failure |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | of Splashplate |

Table XLIX. Summary of Test Results: Configuration MOD-28 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | Emission Indices g/kg Fuel HC | Emission Indices g/kg Fuel NOx | Emission Indices g/kg Fuel Eng CO | Emission Indices g/kg Fuel Eng HC | Emission Indices g/kg Fuel Eng NOx | Pressure Loss % Total | Pressure Loss % Outer Dome | Pressure Loss % Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 14 | 36.40 | 2.48 | 266 | 414 | 11.52 | 5.23 | 373.4 | 169.4 | 46.85 | 14.28 | | 1.0 | 0.0 | 0.0090 | 0.0098 | 94.38 | 112.6 | 29.9 | | | | | 4.30 | 4.80 | 4.10 | |
| 2 | 141 | 36.40 | 2.48 | 286 | 414 | 11.52 | 5.23 | 456.4 | 207.0 | 46.85 | 14.28 | | 1.0 | 0.0 | 0.0110 | 0.0117 | 98.38 | 42.5 | 6.2 | | | | | 4.30 | 4.60 | 4.10 | |
| 3 | 15 | 36.40 | 2.48 | 286 | 414 | 11.52 | 5.23 | 539.3 | 244.6 | 46.85 | 14.28 | | 1.0 | 0.0 | 0.0130 | 0.0140 | 98.93 | 34.7 | 2.6 | | | | | 4.80 | 4.50 | 4.10 | |
| 4 | 16 | 36.40 | 2.48 | 286 | 414 | 11.52 | 5.23 | 638.9 | 289.8 | 46.85 | 14.28 | | 1.0 | 0.0 | 0.0154 | 0.0155 | 98.95 | 37.8 | 1.7 | | | | | 5.10 | 4.40 | 4.00 | |
| 6 | 161 | 36.40 | 2.48 | 286 | 414 | 11.51 | 5.22 | 663.2 | 300.8 | 45.81 | 14.27 | | 1.0 | 0.0 | 0.0160 | 0.0169 | 98.97 | 39.1 | 1.2 | | | | | 5.10 | 4.50 | 4.10 | |
| 5 | 17 | 36.45 | 2.48 | 284 | 413 | 11.52 | 5.23 | 829.7 | 376.4 | 46.66 | 14.22 | | 1.0 | 0.0 | 0.0200 | 0.0205 | 98.43 | 64.8 | 0.6 | | | | | 5.00 | 4.60 | 4.10 | |
| 6 | | 42.91 | 2.92 | 315 | 430 | 12.97 | 5.88 | 430.0 | 195.0 | 46.50 | 14.20 | | 1.0 | 0.0 | 0.0092 | 0.0097 | 96.87 | 71.6 | 14.6 | [illegible].1 | | | | 4.60 | 4.50 | 3.80 | 4.5% Idle |
| 7 | | 42.96 | 2.92 | 315 | 430 | 12.99 | 5.89 | 524.0 | 237.0 | 46.50 | 14.20 | | 1.0 | 0.0 | 0.0112 | 0.0119 | 99.18 | 24.3 | 2.5 | 2.6 | | | | 4.50 | 4.50 | 3.90 | 4.5% Idle |
| 8 | | 43.01 | 2.93 | 315 | 430 | 12.99 | 5.89 | 603.0 | 274.0 | 46.40 | 14.20 | | 1.0 | 0.0 | 0.0129 | 0.0142 | 99.43 | 20.0 | 1.0 | 2.8 | | | | 4.40 | 4.30 | 3.90 | 4.5% Idle |
| 9 | | 42.91 | 2.92 | 315 | 430 | 12.99 | 5.89 | 762.0 | 346.0 | 46.50 | 14.20 | | 1.0 | 0.0 | 0.0163 | 0.0173 | 99.20 | 31.6 | 0.6 | 2.9 | | | | 4.20 | 4.20 | 3.80 | 4.5% Idle |
| 10 | | 42.91 | 2.92 | 314 | 430 | 12.99 | 5.89 | 954.0 | 433.0 | 46.50 | 14.20 | | 1.0 | 0.0 | 0.0204 | 0.0212 | 98.70 | 54.3 | 0.3 | 3.0 | | | | 4.20 | 4.10 | 3.90 | 4.5% Idle |
| 11 | 25 | 41.34 | 2.81 | 530 | 550 | 11.82 | 5.36 | 677.0 | 307.0 | 56.20 | 17.10 | | 1.0 | 0.0 | 0.0159 | 0.0171 | 99.34 | 27.4 | 0.2 | 4.8 | 6.6 | 0 | 6.8 | 5.60 | 6.20 | 5.40 | |

Table [illegible]. Summary of Test Results: Configuration [illegible] Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor Airflow pps | Combustor Airflow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Esq CO | Esq HC | Esq NOx | Pressure Loss % Total | Outer Zone | Inner Zone | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |
| | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | [illegible] |

Table LI. Summary of Test Results: Configuration MOD-39 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor Airflow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | F | K | pps | kg/s | pph | kg/s | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Avg CO | Avg HC | Avg NOx | Total | Outer Zone | Inner Zone | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | | | | [illegible] | [illegible] | [illegible] | |

Table LII. Summary of Test Results: Configuration MOD-31 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure psia | Inlet Total Pressure atm | Inlet Total Temperature °F | Inlet Total Temperature K | Combustor AirFlow pps | Combustor AirFlow kg/s | Total Fuel Flow pph | Total Fuel Flow kg/h | Reference Velocity ft/s | Reference Velocity m/s | Inlet Humidity g/kg | Fuel Split Pilot Total | Fuel Split Main Total | Fuel-Air Ratio Meter Overall | Fuel-Air Ratio Sample Overall | Sample Combustion Efficiency % | Emission Indices g/kg Fuel CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Pressure Loss % Total | Outer Dome | Inner Dome | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 30.79 | 2.10 | 257 | 398 | 9.94 | 4.51 | 647 | 294 | 45.9 | 14.0 | 6.5 | 1.0 | 0.0 | 0.0181 | 0.0273 | 97.07 | 122.5 | 0.7 | 2.2 | | | | 4.70 | 3.70 | 3.60 | |
| 2 | 2 | 33.93 | 2.31 | 275 | 408 | 11.01 | 5.00 | 523 | 237 | 47.3 | 14.4 | 6.5 | 1.0 | 0.0 | 0.0132 | 0.0199 | 98.72 | 49.5 | 1.3 | 2.4 | | | | 5.30 | 3.90 | 3.80 | |
| 3 | 3 | 33.68 | 2.29 | 274 | 408 | 11.00 | 4.99 | 709 | 322 | 47.6 | 14.5 | 7.0 | 1.0 | 0.0 | 0.0179 | 0.0270 | 97.55 | 103.0 | 0.9 | 2.3 | | | | 4.90 | 3.90 | 3.80 | |
| 4 | 4 | 33.68 | 2.29 | 272 | 407 | 10.99 | 4.98 | 799 | 363 | 47.4 | 14.4 | 7.0 | 1.0 | 0.0 | 0.0202 | 0.0299 | 96.57 | 143.2 | 0.9 | 2.1 | | | | 4.90 | 3.80 | 3.80 | |
| 5 | 15 | 36.39 | 2.48 | 285 | 414 | 12.07 | 5.47 | 573 | 260 | 49.0 | 14.9 | 7.0 | 1.0 | 0.0 | 0.0132 | 0.0189 | 98.58 | 49.9 | 2.5 | 2.3 | | | | 5.10 | 4.00 | 4.10 | |
| 6 | 16 | 36.34 | 2.47 | 285 | 414 | 12.08 | 5.48 | 639 | 290 | 49.1 | 15.0 | 7.0 | 1.0 | 0.0 | 0.0147 | 0.0217 | 98.49 | 58.0 | 1.6 | 2.5 | | | | 5.00 | 3.90 | 4.00 | |
| 7 | 17 | 36.39 | 2.48 | 286 | 414 | 12.07 | 5.47 | 704 | 319 | 49.1 | 15.0 | 8.0 | 1.0 | 0.0 | 0.0162 | 0.0239 | 98.35 | 69.1 | 0.4 | 2.3 | | | | 5.10 | 3.90 | 3.90 | |
| 8 | 18 | 36.34 | 2.48 | 286 | 414 | 12.05 | 5.47 | 881 | 400 | 49.1 | 15.0 | 9.0 | 1.0 | 0.0 | 0.0203 | 0.0298 | 96.77 | 132.4 | 1.4 | 2.2 | | | | 5.50 | 3.90 | 3.90 | |
| 9 | 13 | 52.57 | 3.58 | 538 | 554 | 16.50 | 7.48 | 915 | 415 | 62.1 | 18.9 | 2.0 | 1.0 | 0.0 | 0.0154 | 0.0197 | 99.44 | 21.5 | 0.6 | 5.7 | 7.4 | 0.1 | 7.4 | 7.10 | 4.60 | 5.30 | |
| 10 | | 29.78 | 2.03 | 750 | 672 | 8.23 | 3.73 | 489 | 222 | 66.3 | 20.2 | 4.0 | 0.3 | 0.7 | 0.0165 | 0.0202 | 73.64 | 118.4 | 236.0 | 1.3 | 6.1 | 1.7 | 2.4 | 6.60 | 4.40 | 5.00 | Intermediate Power Condition |
| 11 | 30 | 50.90 | 3.46 | 779 | 688 | 13.34 | 6.05 | 1282 | 581 | 64.4 | 19.6 | 1.5 | 0.4 | 0.6 | 0.0267 | 0.0280 | 99.44 | 12.5 | 2.7 | 7.0 | 8.3 | 1.4 | 12.0 | 5.20 | 3.80 | 4.30 | |
| 12 | 30 | 50.61 | 3.44 | 774 | 685 | 13.18 | 5.98 | 1277 | 579 | 63.8 | 19.4 | 4.0 | 0.3 | 0.7 | 0.0269 | 0.0289 | 99.55 | 13.2 | 1.4 | 5.7 | 8.8 | 0.7 | 9.7 | 5.50 | 3.70 | 4.30 | |
| 13 | 32 | 50.85 | 3.46 | 849 | 727 | 13.17 | 5.97 | 1400 | 634 | 67.3 | 20.5 | 4.0 | 0.3 | 0.7 | 0.0295 | 0.0327 | 99.55 | 15.2 | 0.9 | 7.4 | 1.4 | 0 | 13.3 | 5.60 | 3.50 | 4.10 | |
| 14 | 32 | 50.85 | 3.46 | 849 | 727 | 12.53 | 5.68 | 1400 | 634 | 64.0 | 19.5 | 3.0 | 0.2 | 0.8 | 0.0310 | 0.0332 | 99.62 | 15.0 | 0.3 | 5.8 | 1.4 | 0 | 10.5 | 5.60 | 3.50 | 4.10 | |
| 15 | 31 | 50.75 | 3.45 | 894 | 752 | 12.90 | 5.85 | 984 | 445 | 68.3 | 20.8 | 5.0 | 0.6 | 0.4 | 0.0212 | 0.0262 | 99.20 | 31.3 | 0.7 | 9.3 | 2.0 | 0.1 | 16.4 | 5.60 | 4.10 | 4.50 | |
| 16 | 31 | 50.85 | 3.46 | 895 | 753 | 12.88 | 5.84 | 978 | 444 | 68.1 | 20.8 | 5.0 | 0.5 | 0.5 | 0.0211 | 0.0252 | 99.54 | 18.6 | 0.3 | 8.7 | 1.2 | 0.1 | 15.3 | 5.40 | 4.00 | 4.50 | |
| 17 | 31 | 50.90 | 3.46 | 895 | 753 | 12.87 | 5.84 | 982 | 446 | 68.0 | 20.7 | 5.0 | 0.4 | 0.6 | 0.0212 | 0.0247 | 99.74 | 10.7 | 0.2 | 7.9 | 0.7 | 0 | 13.9 | 5.80 | 4.00 | 4.50 | |
| 18 | 31 | 50.80 | 3.45 | 897 | 754 | 12.81 | 5.81 | 987 | 448 | 68.0 | 20.7 | 5.0 | 0.3 | 0.7 | 0.0214 | 0.0243 | 99.80 | 8.4 | 0.2 | 6.4 | 0.5 | 0 | 11.3 | 6.00 | 4.00 | 4.60 | |
| 19 | 33 | 50.90 | 3.46 | 915 | 764 | 12.58 | 5.70 | 1096 | 497 | 67.4 | 20.5 | 5.0 | 0.4 | 0.6 | 0.0242 | 0.0274 | 99.80 | 8.1 | 0.1 | 9.2 | 0.5 | 0 | 16.5 | 5.80 | 3.80 | 4.40 | |
| 20 | 33 | 50.85 | 3.46 | 909 | 760 | 12.57 | 5.70 | 1090 | 494 | 67.1 | 20.4 | 7.0 | 0.3 | 0.7 | 0.0241 | 0.0264 | 99.80 | 8.0 | 0.1 | 7.3 | 0.5 | 0 | 13.1 | 5.90 | 3.80 | 4.50 | |
| 21 | 34 | 32.70 | 2.23 | 950 | 783 | 7.94 | 3.60 | 672 | 305 | 67.9 | 20.7 | 7.0 | 0.3 | 0.7 | 0.0235 | 0.0296 | 99.60 | 16.6 | 0.1 | 6.9 | 0.4 | 0 | 15.1 | 6.00 | 3.80 | 4.50 | |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | 26 | 47.67 | 3.24 | 615 | 597 | 14.12 | 6.40 | 671 | 304 | 63.2 | 19.3 | 3.0 | 1.0 | 0.0 | 0.0132 | 0.0150 | 99.69 | 9.6 | 0.8 | 6.5 | 1.8 | 0.1 | 8.8 | 8.40 | 4.00 | 4.20 | |
| 2 | 26 | 47.15 | 3.21 | 625 | 603 | 14.03 | 6.36 | 672 | 305 | 64.1 | 19.5 | 3.0 | 0.0 | 1.0 | 0.0133 | 0.0135 | 95.36 | 95.5 | 24.1 | 3.0 | 17.5 | 1.4 | 4.1 | 5.30 | 4.70 | 4.50 | |
| 3 | 27 | 47.52 | 3.23 | 625 | 603 | 14.02 | 6.36 | 671 | 304 | 63.5 | 19.3 | 3.0 | 0.6 | 0.4 | 0.0133 | 0.0154 | 94.42 | 87.7 | 35.4 | 1.0 | 16.3 | 2.1 | 1.4 | 6.00 | 4.10 | 4.30 | |
| 4 | 27 | 47.15 | 3.21 | 620 | 600 | 14.01 | 6.35 | 807 | 366 | 63.6 | 19.4 | 3.0 | 0.5 | 0.5 | 0.0160 | 0.0180 | 95.39 | 83.7 | 26.0 | 0 | 15.3 | 1.6 | 4.2 | 5.30 | 4.20 | 4.30 | |
| 5 | 27 | 47.01 | 3.20 | 614 | 597 | 13.97 | 6.34 | 1011 | 459 | 63.3 | 19.3 | 3.0 | 0.4 | 0.6 | 0.0201 | 0.0217 | 97.34 | 65.2 | 11.4 | 3.1 | 11.9 | 0.7 | 4.3 | 5.40 | 4.20 | 4.40 | |
| 6 | 28 | 47.03 | 3.20 | 619 | 599 | 14.03 | 6.36 | 672 | 305 | 63.9 | 19.5 | 3.0 | 0.5 | 0.5 | 0.0133 | 0.0152 | 93.87 | 111.2 | 35.4 | 1.8 | 20.4 | 2.1 | 2.4 | 5.70 | 4.20 | 4.40 | |
| 7 | 29 | 47.25 | 3.22 | 619 | 599 | 14.05 | 6.37 | 672 | 305 | 63.6 | 19.4 | 3.0 | 0.4 | 0.6 | 0.0133 | 0.0156 | 76.34 | 187.9 | 192.7 | 1.2 | 34.4 | 11.4 | 1.6 | 6.10 | 4.20 | 4.40 | |
| 8 | 34 | 32.47 | 2.21 | 949 | 783 | 8.25 | 3.74 | 665 | 302 | 71.0 | 21.6 | 3.0 | 0.5 | 0.5 | 0.0224 | 0.0261 | 99.66 | 12.0 | 0.6 | 7.0 | 0.3 | 0 | 15.2 | 5.90 | — | — | |
| 9 | 35 | 32.49 | 2.21 | 948 | 782 | 8.23 | 3.73 | 664 | 301 | 70.8 | 21.6 | 3.0 | 0.45 | 0.55 | 0.0224 | 0.0251 | 99.68 | 10.9 | 0.6 | 6.4 | 0.3 | 0 | 13.9 | 5.60 | — | — | |
| 10 | 36 | 32.39 | 2.20 | 950 | 783 | 8.22 | 3.73 | 663 | 301 | 71.0 | 21.6 | 3.0 | 0.4 | 0.6 | 0.0224 | 0.0257 | 99.74 | 9.3 | 0.5 | 6.1 | 0.4 | 0 | 13.3 | 5.60 | — | — | |

Table LIII. Summary of Test Results: Configuration MOD-31 QCSEE Double Annular Combustor.

| Reading | Point | Inlet Total Pressure | | Inlet Total Temperature | | Combustor AirFlow | | Total Fuel Flow | | Reference Velocity | | Inlet Humidity | Fuel Split | | Fuel-Air Ratio | | Sample Combustion Efficiency | Emission Indices g/kg Fuel | | | | | | Pressure Loss % | | | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | psia | atm | °F | K | pps | kg/s | pph | kg/h | ft/s | m/s | g/kg | Pilot Total | Main Total | Meter Overall | Sample Overall | % | CO | HC | NOx | Eng CO | Eng HC | Eng NOx | Total | Outer Dome | Inner Dome | |
| 11 | | 29.67 | 2.02 | 750 | 672 | 8.23 | 3.73 | 480 | 218 | 66.6 | 20.3 | 3.0 | 0.6 | 0.4 | 0.0162 | 0.0182 | 96.69 | 87.4 | 18.7 | 2.3 | 4.5 | 0.1 | 4.3 | 6.80 | - | - | Intermediate Power Condition |
| 12 | | 29.57 | 2.01 | 747 | 670 | 8.20 | 3.72 | 480 | 218 | 66.4 | 20.2 | 3.0 | 0.5 | 0.5 | 0.0163 | 0.0172 | 96.05 | 100.1 | 16.2 | 2.3 | 5.1 | 0.1 | 4.3 | 6.10 | - | - | Intermediate Power Condition |
| 13 | | 29.45 | 2.00 | 746 | 670 | 8.22 | 3.73 | 480 | 218 | 66.8 | 20.4 | 3.0 | 0.4 | 0.6 | 0.0162 | 0.0174 | 96.77 | 92.7 | 10.7 | 1.8 | 4.7 | 0.1 | 3.4 | 6.10 | - | - | Intermediate Power Condition |

## APPENDIX B

This appendix contains adjustment relationships which were used to correct the measured emissions data obtained at derated high power operating conditions to the actual QCSEE double-annular engine design cycle conditions. These relations are defined as follows:

(1) $EICO(ADJ) = EI_{CO}(MEA)\ (P_3/P_{3\ CYCLE})^{1.5} \sim$ g/kg fuel

(2) $EI_{HC}(ADJ) = EI_{HC}(MEA)\ (P_3/P_{3\ CYCLE})^{2.5} \sim$ g/kg fuel

(3) $EI_{NO_x}\ (ADJ) = EI_{NO_x}\ (MEA)(P_{3\ CYCLE}/P_3)^{0.37}\ EXP\ \dfrac{T_{3\ CYCLE} - T_3}{345} \sim$ g/kg fuel

These relations were developed as part of the EPA/CFM56 and NASA/GE ECCP programs and have generally provided a satisfactory method for adjusting the emissions levels to the correct combustor inlet conditions as specified in an engine cycle.

## APPENDIX C

## EPA EMISSION PARAMETER CALCULATION PROCEDURE

This appendix presents calculation procedures which were derived to calculate EPA emission parameters using the data obtained from the sector combustor tests.

The gaseous exhaust emission standards in Reference 5 are expressed in terms of maximum allowable quantity of emission per 1000 pounds-thrust hours, for a prescribed takeoff-landing cycle:

$$EPAP_i = \frac{\sum^{j} \frac{t_j}{60} \frac{W_{f_j}}{1000} EI_{ij}}{\sum^{j} \frac{t_j}{60} \frac{F_{N_j}}{1000}} \qquad (1)$$

where

| | | |
|---|---|---|
| EI | = | Emission index (lb/1000 lb fuel) |
| EPAP | = | Emission parameter (lb/1000 lb thrust-hr) |
| $F_N$ | = | Net thrust (lb) |
| t | = | Prescribed time (minutes) |
| $W_f$ | = | Fuel flow rate (pph) |

and the subscripts are:

| | | |
|---|---|---|
| i | = | Type of emission (CO, HC, $NO_x$) |
| j | = | Prescribed power level (idle, approach, climbout, and takeoff) |

For a particular engine cycle, Equation (1) can be reduced to:

$$EPAP_i = \sum^{j} (C_j)(EI_{ij}) \qquad (2)$$

where:

$$C_j = \frac{\frac{t_j}{60} \frac{W_{f_j}}{1000}}{\frac{t_j}{60} \frac{F_{N_j}}{1000}} \qquad (3)$$

The coefficients (Cj) for the QCSEE double-annular engine design cycle are derived in Table L. Equation (2) can be expressed in the following form:

$$EPAP_i = (EPAP_{i,STD}) \sum^{j} \frac{EI_{ij}}{\left(\frac{EPAP_{i,STD}}{C_j}\right)} \qquad (4)$$

where $EPAP_i(STD)$ is the standard for each type of gaseous emission. For the QCSEE double annular, Equation (4) becomes:

$$(5a)\ EPAP_{CO} = 4.3\ [(EI_{CO}(IDLE)/23.941) + (EI_{CO}(APPROACH)/53.885) + (EI_{CO}(CLIMB)/33.102) + (EI_{CO}(TAKEOFF)/86.345)]$$

$$(5b)\ EPAP_{HC} = 0.8\ [(EI_{HC}(IDLE)/4.454) + (EI_{HC}(APPROACH)/10.025) + (EI_{HC}(CLIMB)/6.158) + (EI_{HC}(TAKEOFF)/16.064)]$$

$$(5c)\ EPAP_{NO_x} = 3.0\ [(EI_{NO_x}\ (IDLE)/16.704) + (EI_{NO_x}\ (APPROACH/37.594 + (EI_{NO_x}\ (CLIMB)/23.095) + (EI_{NO_x}\ (TAKEOFF)/60.241)]$$

Table LIV. EPAP Coefficients for QCSEE Double Annular Engine Cycle.

| (Class T2 Engine) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Power Level | t Minutes | $F_n$ lbf | $W_f$ ppm | $C_j$ lbm/lbf-hr | CO $\left(\frac{4.3}{C_j}\right)$ | HC $\left(\frac{0.8}{C_j}\right)$ | $NO_x$ $\left(\frac{3.0}{C_j}\right)$ |
| Idle | 26 | 880 | 731 | 0.1796 | 23.941 | 4.454 | 16.704 |
| Approach | 4 | 6,600 | 2110 | 0.0798 | 53.885 | 10.025 | 37.594 |
| Climb | 2.2 | 18,700 | 6246 | 0.1299 | 33.102 | 6.158 | 23.095 |
| Takeoff | 0.7 | 22,000 | 7523 | 0.0498 | 86.345 | 16.064 | 60.241 |

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