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COMPONENT DEVELOPMENT & INTEGRATION

SINGLE-ANNULAR COMBUSTOR TECHNOLOGY REPORT

June 1980

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16. Abstract

This effort was directed at determining the feasibility of meeting or closely approaching the emissions goals established for the Energy Efficient Engine (E^3) Project with an advanced-design, single-annular combustor. A total of nine sector-combustor configurations and one full-annular-combustor configuration were evaluated in this development program.

Acceptable levels of carbon monoxide and hydrocarbon emissions were obtained with several of the sector-combustor configurations tested, and several of the configurations tested demonstrated reduced levels of nitrogen oxides compared to conventional, single-annular designs. However, none of the configurations tested demonstrated nitrogen oxide emission levels that meet the goal of the E^3 Project.

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FOREWORD

This report describes effort performed by the General Electric Company for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-20643, as part of the Energy Efficient Engine Project. Mr. Neal T. Saunders is the NASA Energy Efficient Engine Project Manger, Mr. Lawrence E. Macioce is NASA Assistant Project Manager responsible for this contract. Mr. Daniel J. Gauntner is the NASA Project Engineer responsible for managing the effort associated with the Combustor effort reported herein.

The Manager of the Energy Efficient Engine Project for the General Electric Company is Mr. M.C. Hemsworth. This report was prepared by Mr. D. Burrus with the assistance of Messrs. P.E. Sabla and D.W. Bahr.

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1.0 SUMMARY

The Energy Efficient Engine (E^3) alternate combustor effort was conducted as part of the overall E^3 combustor technology development. The main-line combustor-technology effort is directed at designing and developing a complex, double-annular configuration. The main objective of this alternate-combustor effort was to determine the feasibility of meeting the emissions goals established for the E^3 Project with an advanced, single-annular combustor design.

The key elements of this effort included the design of a baseline, single-annular, sector-combustor test configuration; fabrication of variations of the baseline configuration (including one full-annular design version); and development testing of the various sector and full-annular combustor test configurations. The baseline combustor test configuration was evolved from a current production-engine combustor. Design modifications were made to provide simulation of a short, advanced, single-annular combustor design suitable for the E^3 application. Nine sector-combustor configurations and one full-annular combustor test configuration were evaluated. Data were obtained on emissions levels, component temperatures, and important performance characteristics of each test configuration.

Acceptable levels of CO and HC emissions were obtained with several of the test configurations investigated. The final sector-combustor test configuration demonstrated CO and HC emissions levels, at 4% and 6% ground idle operating conditions, that meet the E^3 Project goals with margin. However, none of the configurations demonstrated NO_x emission levels that meet the E^3 Project goals; therefore, all future combustor-technology effort under the E^3 Project will be directed toward a double-annular configuration. This approach offers greater promise for meeting all of the E^3 emission goals.

2.0 INTRODUCTION

The General Electric Company is currently engaged in the Energy Efficient Engine (E^3) Project under Contract NAS3-20643 to NASA Lewis Research Center. The purpose of the E^3 Project is to develop and demonstrate the technology for obtaining higher thermodynamic and propulsive efficiencies in advanced, environmentally acceptable, turbofan engines for possible use in future commercial transport aircraft. The Project involves technology development for engine components, including the design of an advanced, low-emissions combustor. The primary selected approach is a double-annular-dome combustor design evolved from technology developed in the NASA/GE Experimental Clean Combustor Program (ECCP) (Reference 1) and the NASA/GE Quiet, Clean, Short-Haul, Experimental Engine (QCSEE) Program (Reference 2). The double-annular-dome combustor designs evolved from these programs demonstrated substantial reductions in gaseous exhaust emissions when compared to current, conventional, single-annular combustor designs. As a supporting technology effort to the E^3 Project, an alternate-combustor test effort was conducted to evaluate the feasibility of meeting or closely approaching the E^3 emissions goals with an advanced, single-annular combustor design. Successful development of a single-annular combustor offers promise of a simpler configuration that should be cheaper, more durable, and more reliable than the double-annular design.

The emissions goals for the E^3 Project are identical to the emissions standards currently defined by the Environmental Protection Agency (EPA) for Class T2 [rated thrust greater or equal to 89 kN, (20,000 lbf), subsonic applications] aircraft turbine engines newly certified after January 1, 1981 (Reference 3). The intent of these standards is to limit the quantities of engine exhaust emissions within and around airport facilites. The E^3 alternate-combustor technology effort was initiated at the onset of the E^3 Project and was conducted in parallel with the aeromechanical design of the double-annular combustor.

The alternate-combustor test effort included the evaluation of nine sector-combustor configurations and one full-annular combustor. All configurations tested were derived from design modifications to the current F101 PV (Product Verification), single-annular combustor design. These modifications were designed to simulate in the basic F101 PV combustor the aerothermodynamic characteristics for an E^3 single-annular design believed to be beneficial in the reduction of engine exhaust emissions. This supporting technology task, the E^3 alternate-combustor effort, was initiated in January 1978 and completed in April 1979. This report presents a description of the sector combustor and full-annular combustor test configurations, the test rigs and facilities in which the vehicles were tested, and the data-acquisition and reduction methods employed. Results of the test effort are presented in plots and tabulations of emissions indices and combustor performance parameters. Comparisons of the emissions data to E^3 Project goals are presented in the form of EPA parameter numbers (EPAP's).

3.0 PROJECT PLANS AND GOALS

3.1 PROJECT ELEMENTS

The E^3 alternate-combustor effort was comprised of four basic tasks. These tasks were combustor design, fabrication of test hardware, development testing efforts, and data analysis and reporting. The key elements and significant milestones of this effort are shown in Figure 1.

3.2 PROJECT GOALS

Emissions Goals - The specific pollutant emissions goals for the E^3 single-annular combustor design are the same as for the double-annular combustor design. They are expressed in the form of the EPA parameter for the gaseous exhaust emissions, and SAE smoke number for smoke emissions, in Table I. The EPA parameter (EPAP) is a thrust-normalized measure of the total mass of pollutants emitted in a prescribed landing and takeoff cycle. E^3 goals are identical to the emissions standards for carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO_x), and smoke as defined by the EPA for (Class T2) subsonic-aircraft turbine engines newly certified after January 1, 1981.

As shown in Table I, by comparing the E^3 emissions goals to the EPA standards for engines newly manufactured after January 1, 1981, significant reductions in CO and HC emissions are required. Although the E^3 goal for NO_x emissions is identical to the EPA standard for newly manufactured engines, these levels have yet to be demonstrated with current-technology combustor designs. Significant reductions in CO and NO_x emissions have been achieved in prior emissions-reduction efforts employing such advanced concepts as the NASA/GE ECCP CF6-50 double-annular combustor design. However,

Table I. E^3 Combustor Emissions Goals.

		E^3 Goals	CF6-50C Goals
• Carbon Monoxide (CO)	Pounds Per	3.0	4.3
• Hydrocarbons (HC)	1000 Pound Thrust-	0.4	0.8
• Nitrogen Oxides (NO_x)	Hours Per Cycle	3.0	3.0
• SAE Smoke Number		20.0	20.0

Note: E^3 goals are identical to EPA 1981 standards for newly certified engines; CF6-50C goals are identical to EPA 1981 standards for newly manufactured engines.

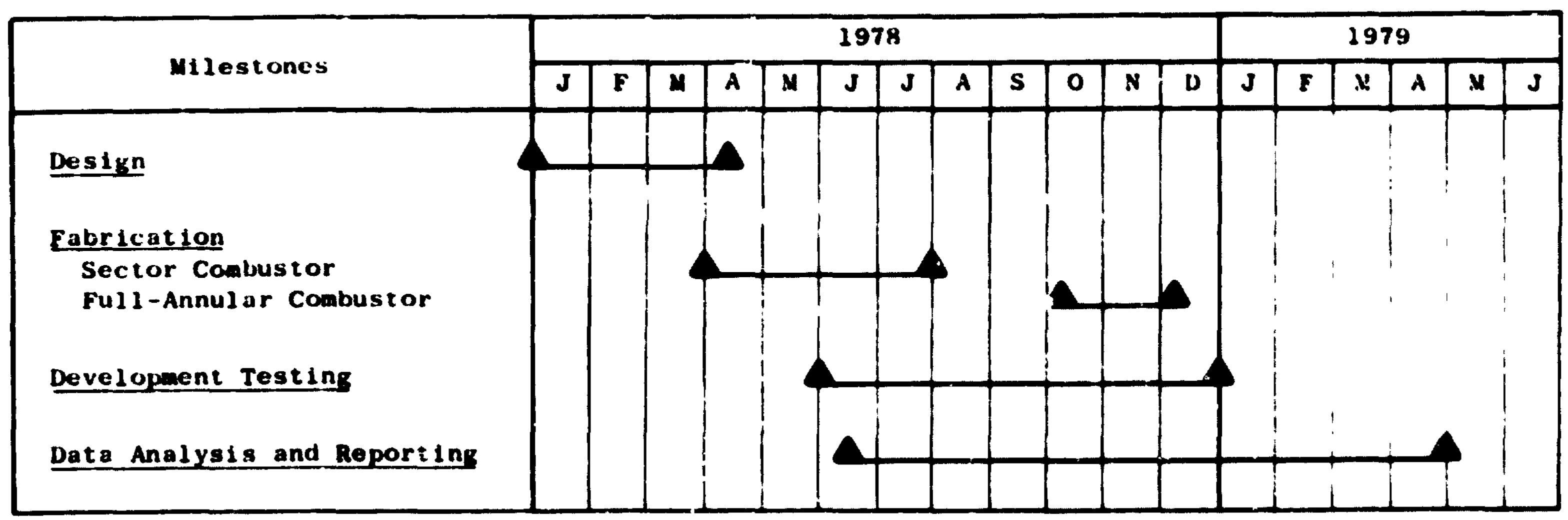


Figure 1. Project Milestone Schedule.

even this advanced design failed to demonstrate NO_x emissions that would satisfy the 1981 standard. Therefore, the E^3 emissions goals for all three gaseous exhaust emissions are very challenging and will require an even more advanced combustor design.

Performance Goals - The key combustor performance goals for the E^3 Project are presented in Table II. Most of the current, conventional, combustor designs developed by General Electric already provide performance levels generally equal to or better than the goals established for the E^3 combustor. Thus, the major challenge of the E^3 alternate combustor effort was to develop an advanced, single-annular combustor design with significantly reduced pollution levels without compromising the performance characteristics.

Table II. E^3 Combustor Key Performance Goals.

• Combustor Efficiency at SLTO	99.5% (Min.)
• Total Pressure Drop at SLTO	5.0% (Max.)
• Exit Temperature Pattern Factor at SLTO	0.250 (Max.)
• Exit Temperature Profile Factor at SLTO	0.125 (Max.)
• Altitude Relight Capability	9.1 km (30,000 ft) (Min.)
• Ground Idle Thrust (% of SLTO)	6.0 (Max.)

4.0 SINGLE-ANNULAR COMBUSTOR DESIGN

4.1 PROPOSED COMBUSTOR DESIGN

Extensive development efforts carried out by NASA and General Electric have shown that the applicable CO and HC emissions standards can be met in modern turbofan engines with conventional, single-annular combustors. However, to meet the NO_x emission goal and the CO and HC emissions goals in a fixed-geometry, single-annular combustor is a major challenge. Extensive investigations to determine the NO_x emission characteristics of various types and sizes of modern combustors have been conducted at General Electric. Some typical results of these investigations are presented in Figure 2. As shown, none of the current, conventional designs meet the E^3 Project goals for NO_x emissions.

The engine families represented in Figure 2 are equipped with single-annular combustors that are short and compact with high volumetric heat-release rates. Within a family (CF6, CFM56, etc.), each engine is equipped with the same combustor. Since the specific fuel consumption (sfc) characteristics of each engine are similar, it is possible to compare the effects of engine cycle conditions and combustor size on the NO_x EPAP levels.

As shown in Figure 2, the NO_x EPAP's of each family are directly related to engine cycle pressure ratio. It is also observed that, at the same cycle pressure ratio, the NO_x EPAP's of the smaller engines are lower than for the larger engines. This is because the combustors have been sized using essentially a constant velocity parameter as a scaling factor. Therefore, as engine size is increased the combustor size must accordingly be increased to maintain the velocity parameter value. As shown in Figure 3, combustor residence time is directly related to combustor size. The NO_x emission indices relationship to residence time is also shown in Figure 3; therefore, these results indicate that the NO_x EPAP values of these engine families are directly associated with the size of the combustors.

These findings suggest the possibility of obtaining low NO_x EPAP values with a very short, compact, single-annular combustor design. It should be noted that if the engine families presented in Figure 2 had the improved sfc characteristics of the E^3 cycle proportionally lower NO_x EPAP values would be obtained. A preliminary design of such a combustor, proposed for the E^3 application, is presented in Figure 4.

The proposed E^3 single-annular combustor design depicted in Figure 4 is considerably shorter and more compact than would be the case with a version of the F101 PV combustor directly scaled-up to the E^3 size. Since the F101 PV combustor is considered to be an advanced, short-length combustor design, any scaled versions of this combustor with shorter lengths and higher volumetric heat-release rates would involve further advances in combustor design technology. Some of the key aerothermodynamic design parameters of the proposed

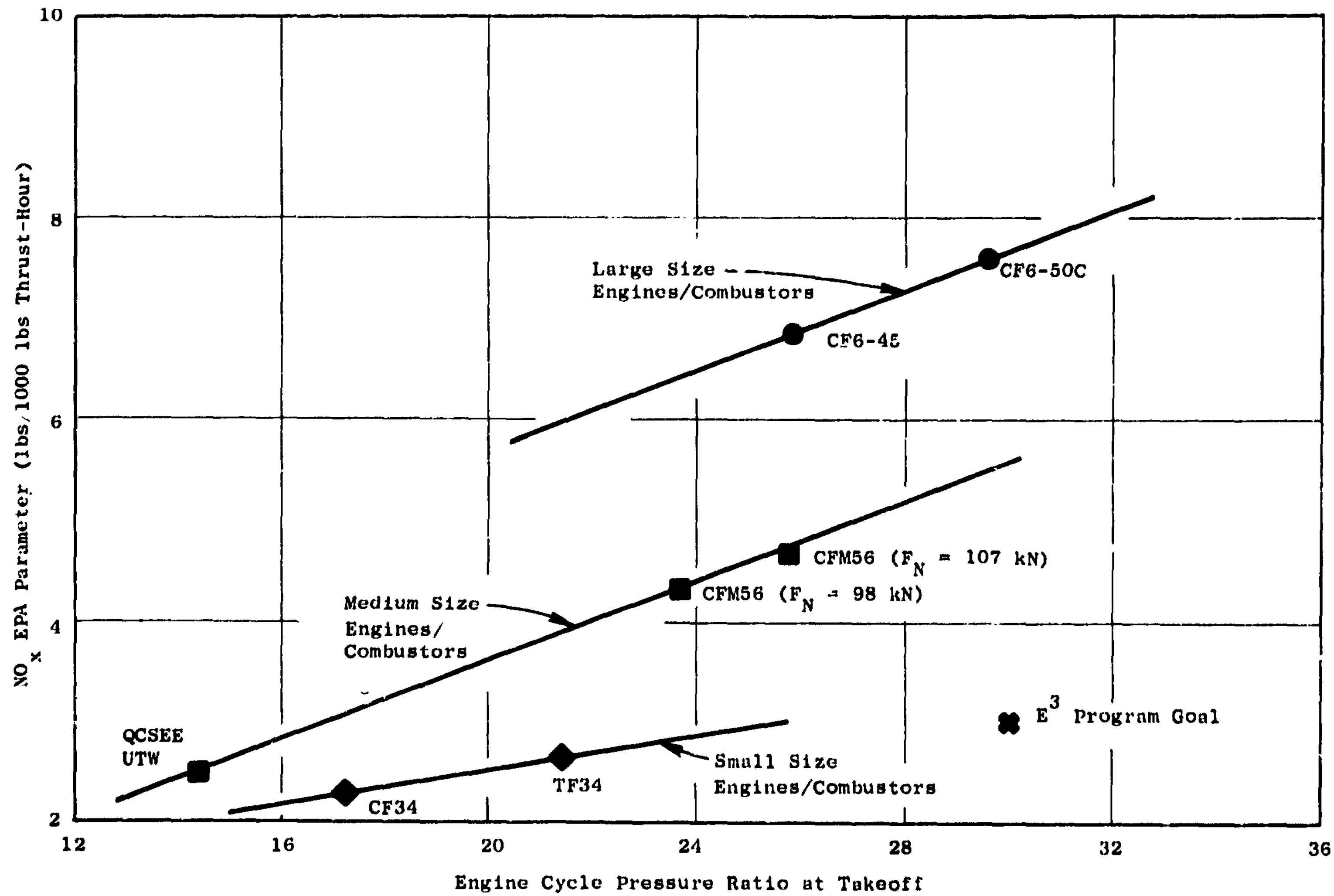


Figure 2. NO_x Levels of Modern Turbofan Engines.

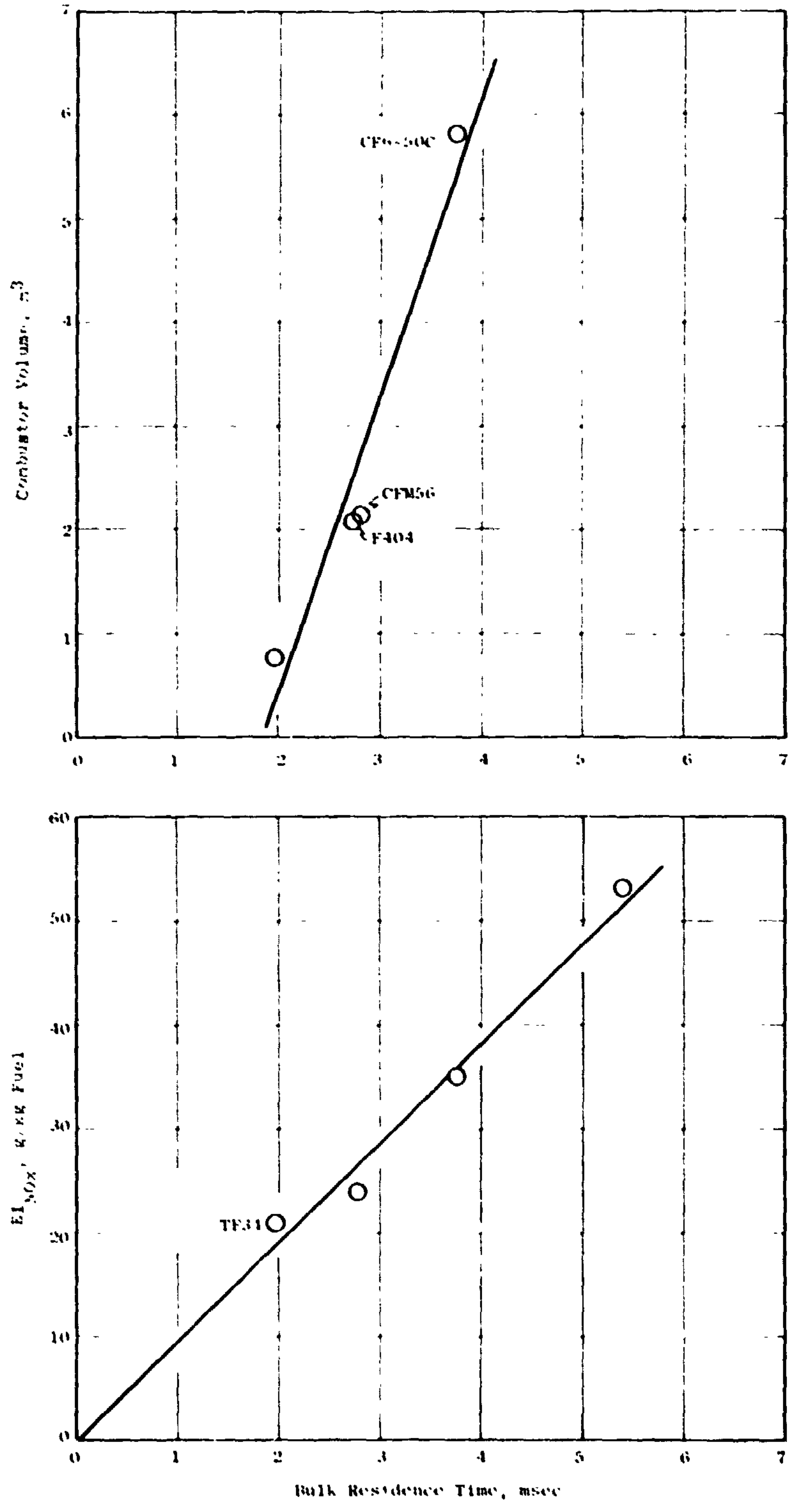
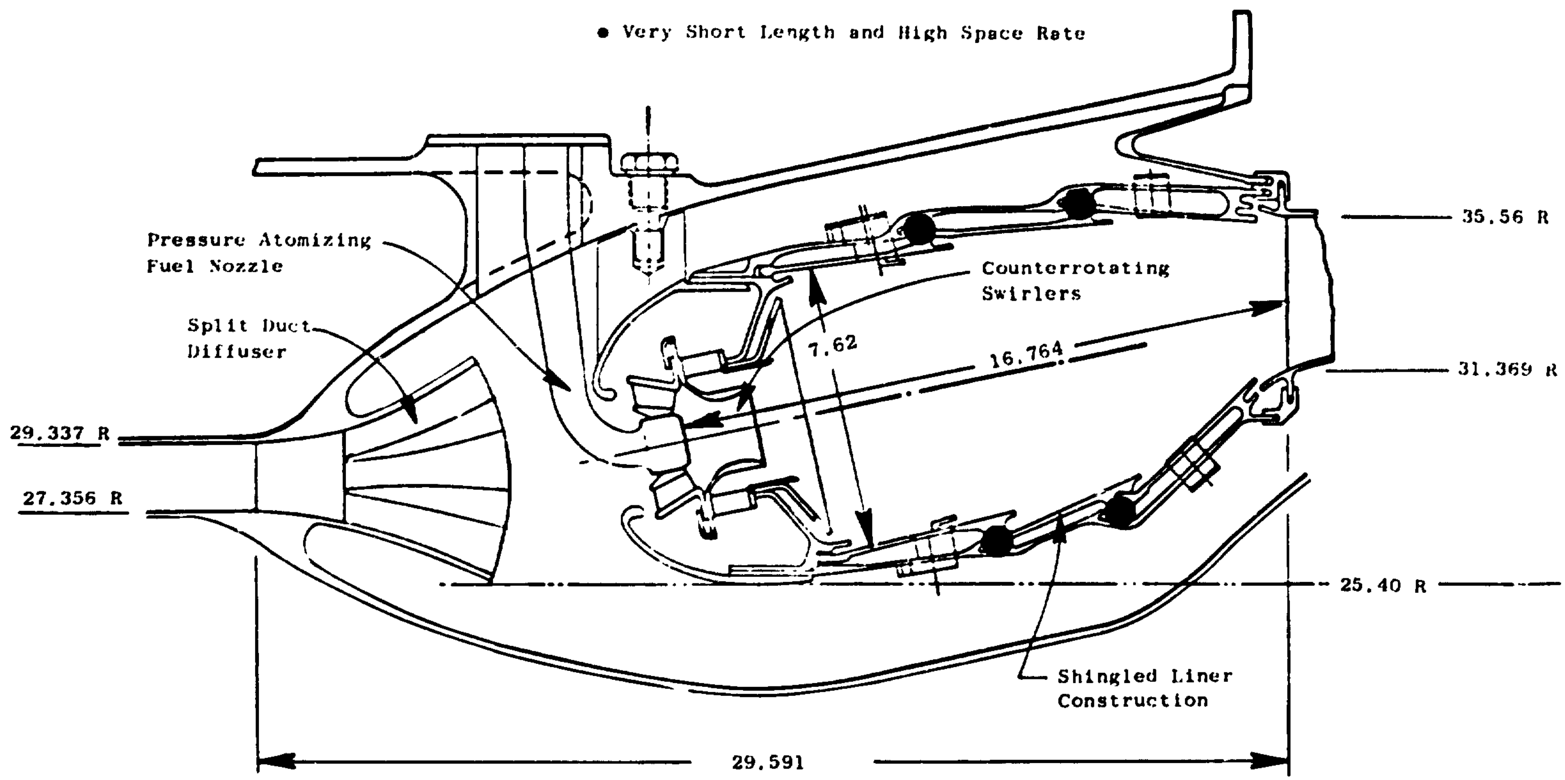


Figure 3. Combustor Bulk Residence Time Variations.



Note: Dimensions in cm

Figure 4. Proposed E^3 Alternate Combustor Design.

short, compact, E^3 single-annular combustor are compared with those of the F101 PV engine combustor and a directly scaled-up version of the F101 PV engine combustor in Table III.

Table III. E^3 Singular-Annular Combustor Design Parameters.

Parameter	Directly Scaled-up F101 PV Design	E^3 Proposed Design	F101 PV Design
Combustor (Burning) Length, cm	22.6	16.8	21.1
in.	8.9	6.6	8.3
Dome Height, cm	9.4	7.9	8.6
in.	3.7	3.1	3.4
Length/Height Ratio	2.4	2.2	2.4
Number of Fuel Injectors	30	30	20
Reference Velocity, m/sec	18.9	21.5	18.9
ft/sec	62.0	70.5	62.0
Dome Velocity (Cold), m/sec	7.6	9.8	7.6
ft/sec	25.0	32.2	25.0
Space Rate, kW/m^3-Pa	0.80	1.06	0.82
$Btu/hr-ft^3$-atm	7.8×10^6	10.3×10^6	8.0×10^6

Using General Electric data on the emissions characteristics of existing single-annular combustor designs and the data obtained from various General Electric/NASA emissions-reduction programs, detailed design studies were conducted to define a preliminary combustor airflow distribution that would provide the optimum combination of low CO, HC, and NO_x EPAP values. As a result of these studies, a preferred combustor airflow distribution was generated and is presented in Table IV.

4.2 BASELINE TEST COMBUSTOR DESIGN

Trade studies were conducted on several existing General Electric combustor designs to define a short, compact, single-annular combustor satisfactory for the E^3 application. Based upon the relative similarity of the key design features of the F101 PV combustor and the proposed E^3 single-annular combustor design, in addition to the availability of combustor hardware and test rigs, the F101 PV engine combustor was chosen for this supporting technology program. A cross section of the current F101 PV engine combustor design is presented in Figure 5.

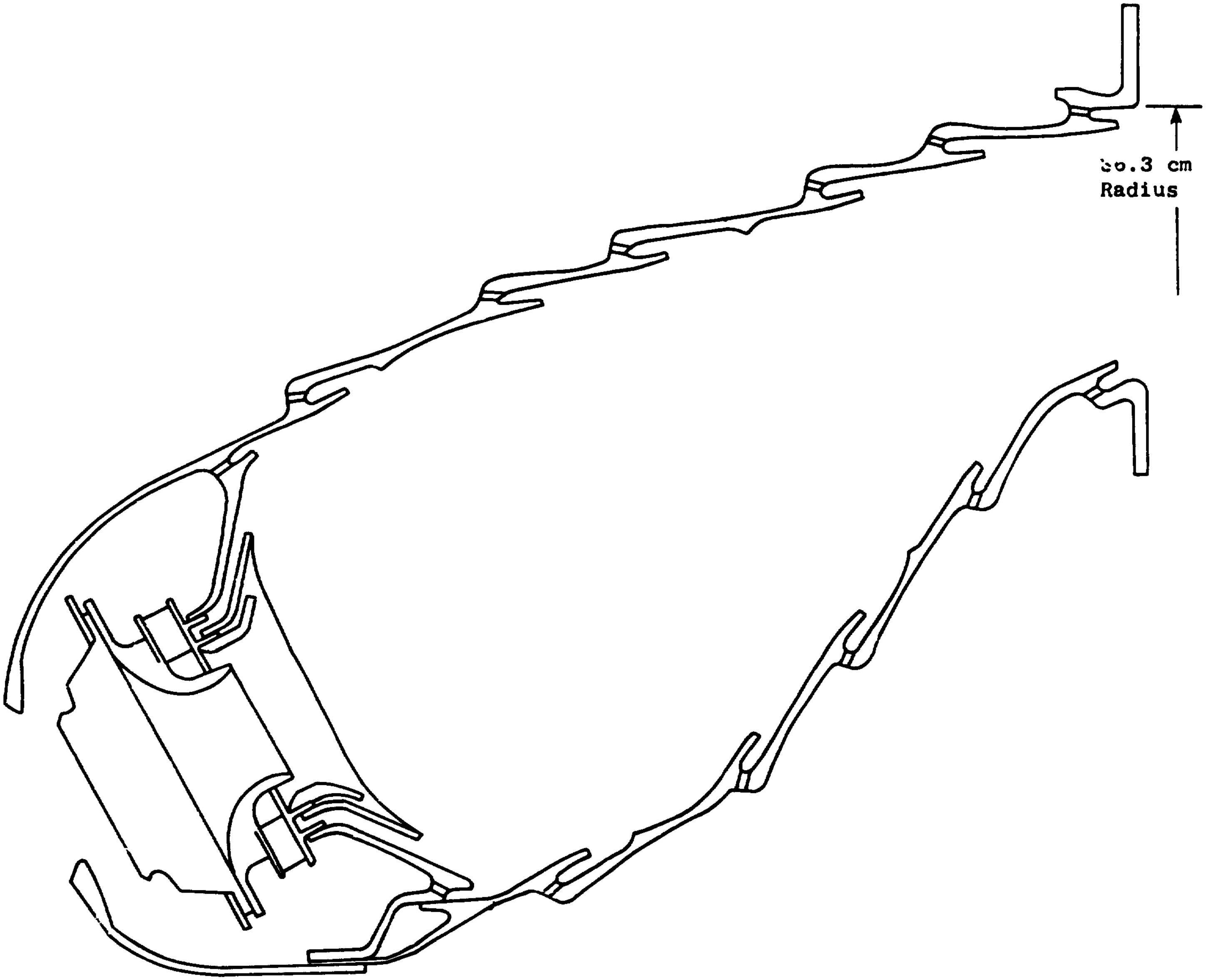


Figure 5. Current F101 PV Engine Combustor Cross Section.

Table IV. Proposed E^3 Single-Annular Combustor Airflow Distribution.

Item	Percent of Total Combustor Airflow	
Dome:		
Swirl Cup	13.00	
Cooling	12.00	
Total		25.00
Outer Liner:		
Dilution		
Primary	13.00	
Secondary	12.40	
Cooling	12.00	
Total		37.40
Inner Liner:		
Dilution		
Primary	13.00	
Secondary	14.40	
Cooling	10.20	
Total		37.60

Simulation of the proposed E^3 single-annular design in the F101 PV combustor was achieved by redistributing the airflow in the existing F101 PV combustor to closely duplicate the airflow distribution shown in Table IV. Because the F101 PV combustor and the proposed E^3 combustor designs lacked complete similarity, duplication of all combustor flows was not possible. Thus, the airflows in the primary zone of the E^3/F101 simulation combustor were selected to be closely matched while the liner-cooling and secondary dilution flows were not. The design modifications that were made to the existing F101 PV engine combustor to obtain the desired airflow distribution are presented schematically in Figure 6. This design represents the baseline E^3/F101 combustor test configuration. A comparison of the airflow distributions of the current F101 PV combustor, the baseline E^3/F101 combustor, and the proposed E^3 single-annular combustor is presented in Figure 7.

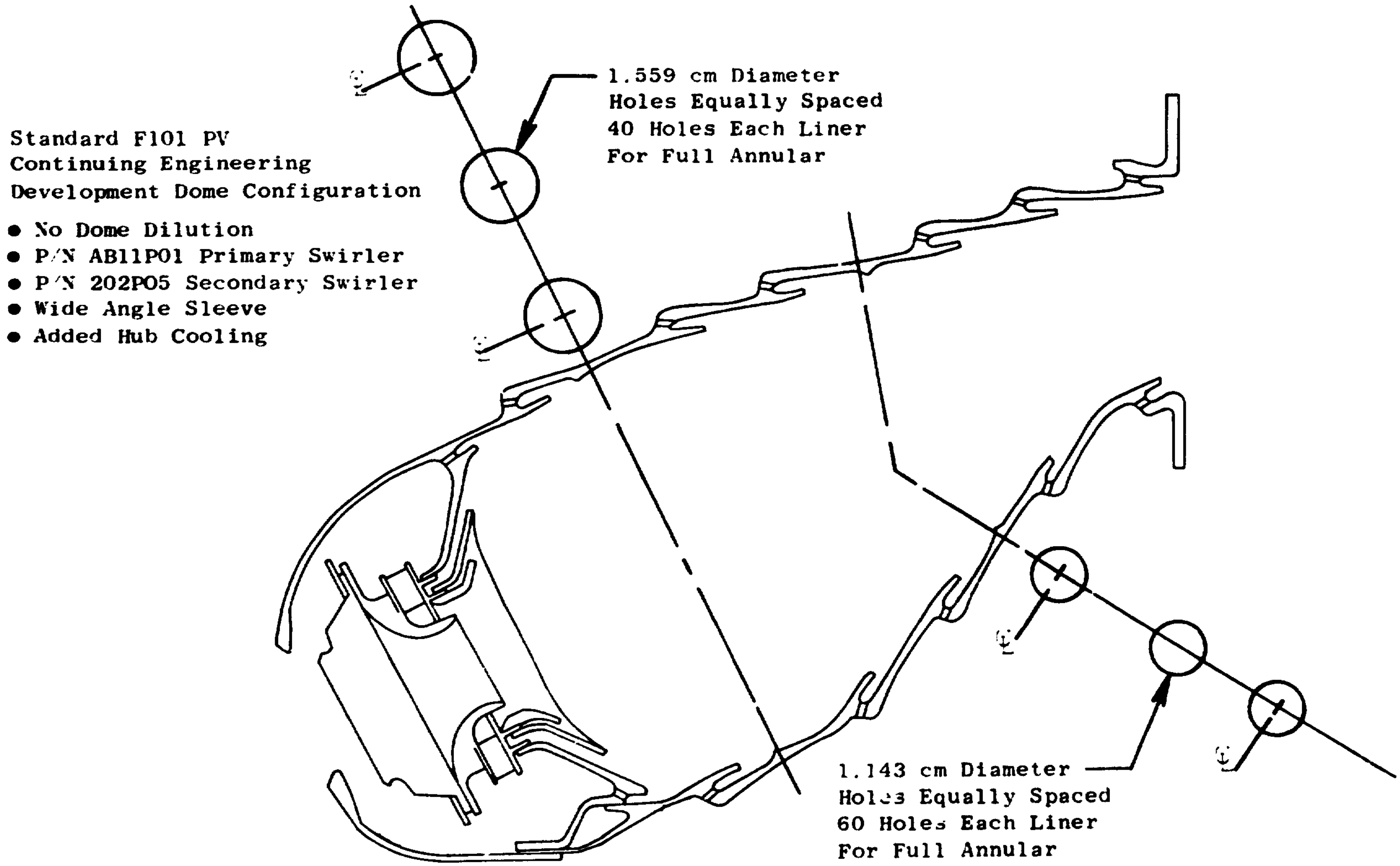


Figure 6. E^3 Single-Annular Combustor Simulation.

Item	Flows in % W_c		
	Current F101 PV (CED)	Baseline E^3/F101 PV (CED)	Proposed E^3 Single-Annular
A	25.9	21.8	20.0
B	7.3	10.7	9.6
C	16.5	23.6	25.4
D	5.0	4.2	4.9
E	18.2	23.6	27.4

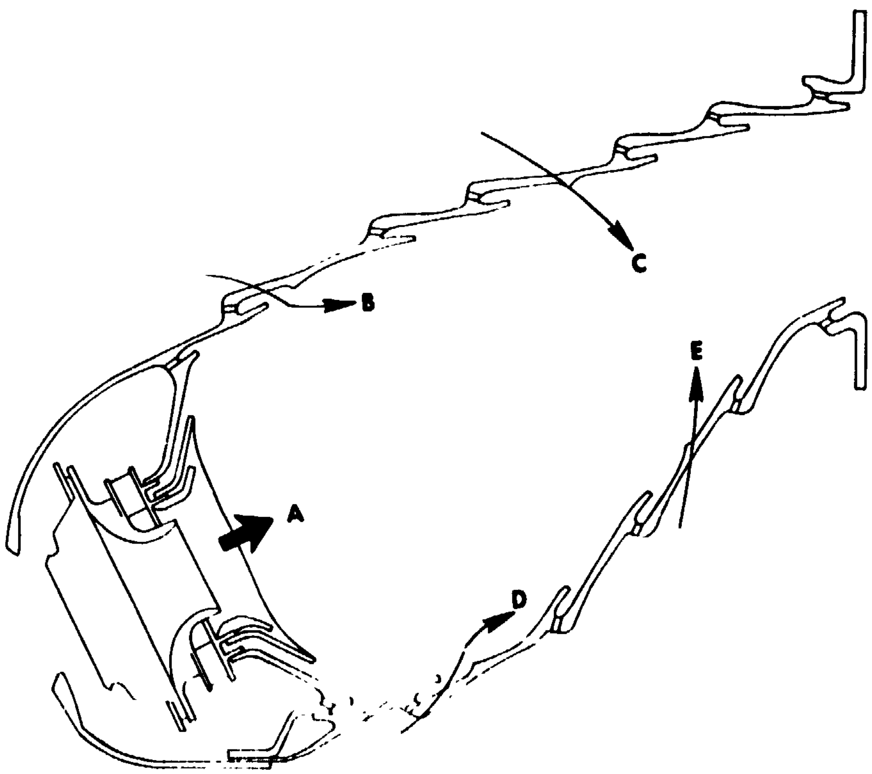


Figure 7. Airflow Distribution Comparison.

5.0 COMBUSTOR TEST CONFIGURATIONS

5.1 SECTOR-COMBUSTOR TEST CONFIGURATIONS

Nine sector-combustor configurations and one full-annular combustor configuration were evaluated in the E^3 alternate combustor effort. Each sector-combustor configuration was a five-swirl-cup, 90° section of a 20-swirl-cup, 360° (full-annular) combustor.

The nine sector-combustor test configurations included the standard F101 PV CED (Continuing Engineering Development) combustor configuration (Configuration SA-00), the baseline E^3/F101 combustor configuration (Configuration SA-01), and seven configurations representing various design modifications to the baseline E^3/F101 design (Configurations SA-02 through SA-08). Sector-combustor configurations SA-04 through SA-08 featured impingement cooling on the forward sections of the inner and outer liners as a means of achieving significant reductions in low-power CO emissions. A photograph of the baseline E^3/F101 sector combustor prior to testing is shown in Figure 8. Illustrations of the sector-combustor configurations tested are shown in Figure 9. The specific modifications incorporated in each configuration are described in these figures.

Standard F101 engine fuel injectors were used for Configuration SA-00 testing. The other sector configurations used fuel injector assemblies featuring simplex-type, pressure-atomizing fuel nozzles. This type of fuel nozzle was selected for the excellent fuel atomization it provides; a photograph of the hardware is shown in Figure 10.

5.2 FULL-ANNULAR COMBUSTOR TEST CONFIGURATION

The E^3/F101 full-annular combustor design was similar to sector-combustor Configuration SA-07. This configuration was selected because Configuration SA-07 had demonstrated acceptable liner temperatures and relatively low projected NO_x emission levels at sea level takeoff; both are important characteristics for a full-annular combustor test conducted at elevated pressures. The full-annular combustor configuration also featured modified forward panels on the inner and outer liners. This modification involved the elimination of the forward cooling-ring slot of the inner and outer liners. An illustration of this full-annular combustor configuration with a description of the modifications featured is presented in Figure 9. Photographs of this full-annular combustor configuration with and without the impingement-cooling shield attached are shown in Figures 11 and 12.

The fuel injection assemblies used for testing the full-annular combustor consisted of fabricated, simplex-type, fuel nozzles mounted in standard F101 combustor test rig nozzle holder assemblies. The simplex nozzles were fabricated from F101 nozzle bodies, with 1.4-mm diameter orifices, and fuel-metering inserts from the CF6-50 NASA/GE ECCP simplex high-flow fuel nozzles.

Figure 8. Sector-Combustor Test Hardware.

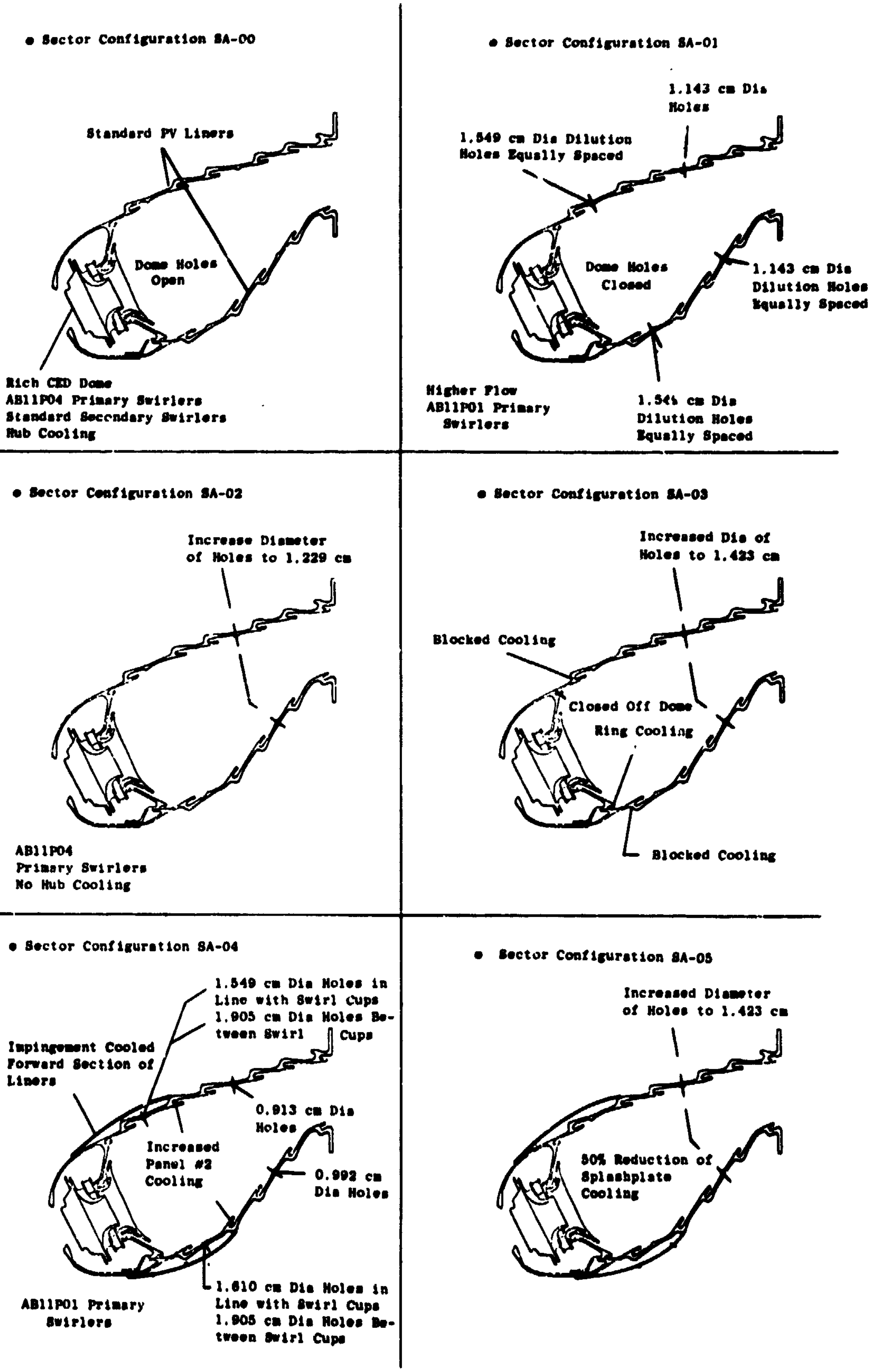


Figure 9. Combustor Test Configurations.

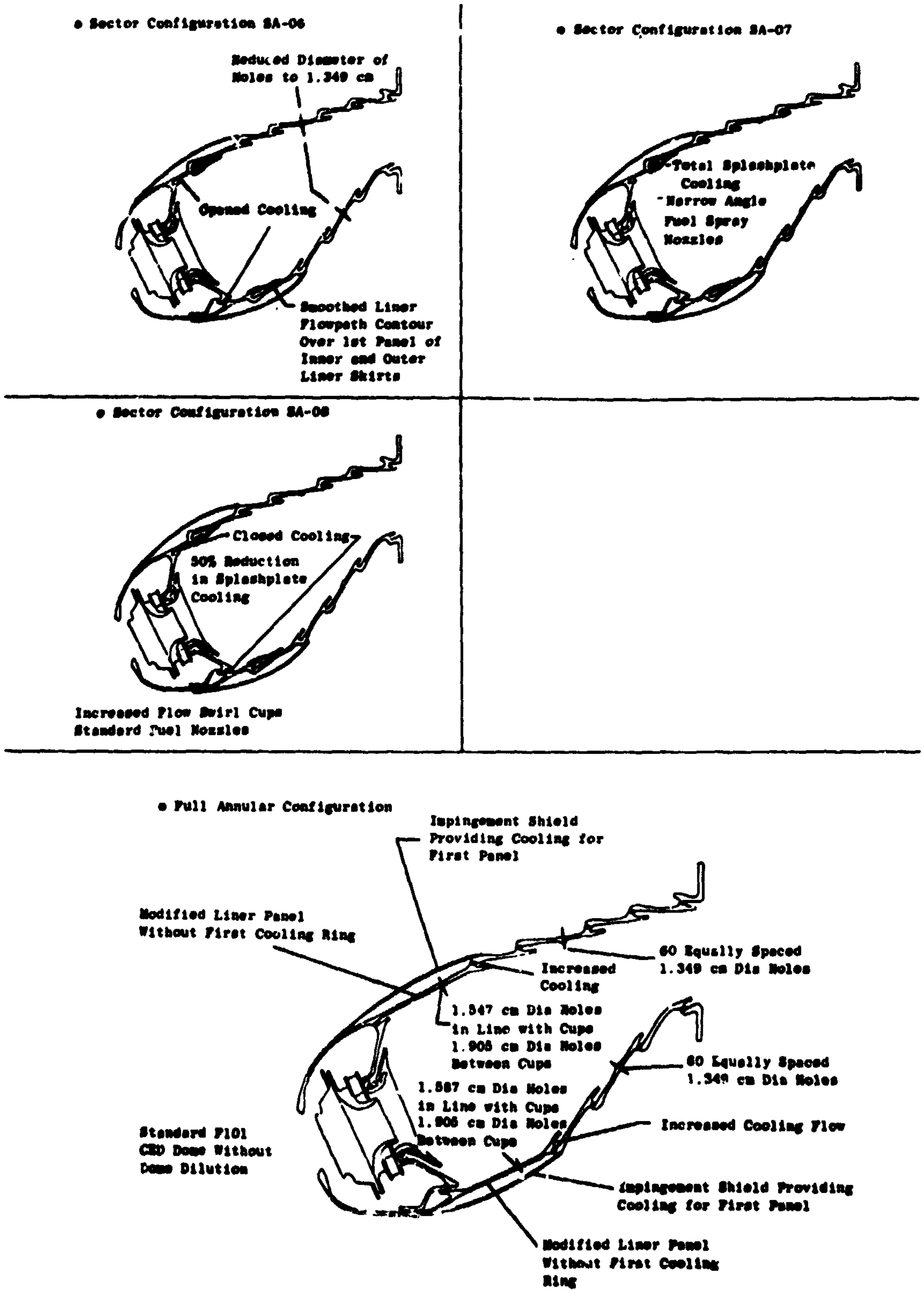


Figure 9. Combustor Test Configurations (Concluded).

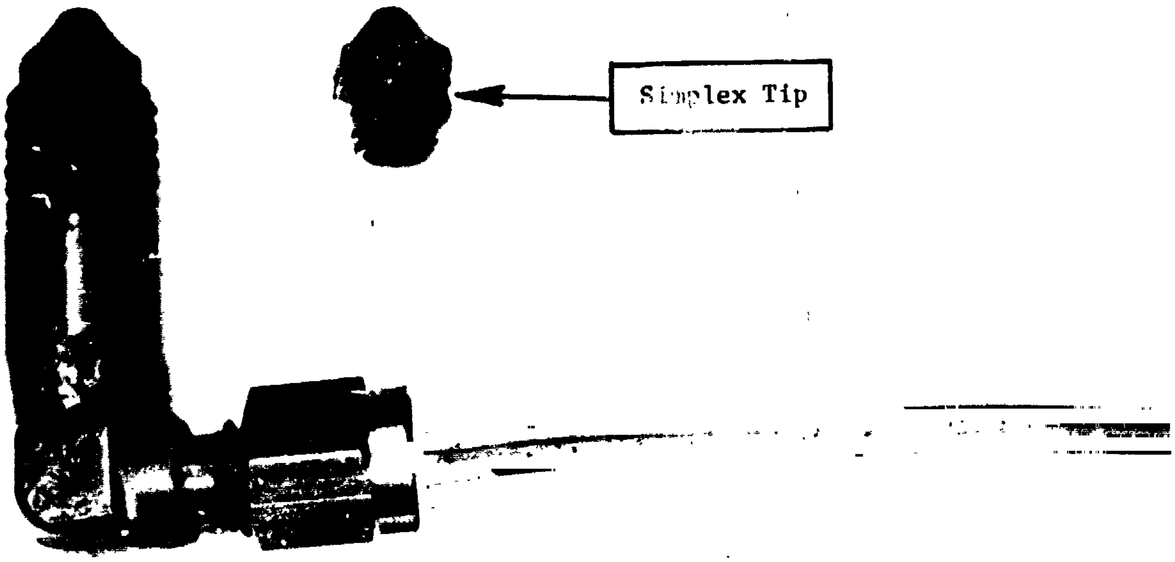


Figure 10. Fuel Injector Hardware.

Figure 11. Full-Annular Combustor Hardware with Impingement Shields.

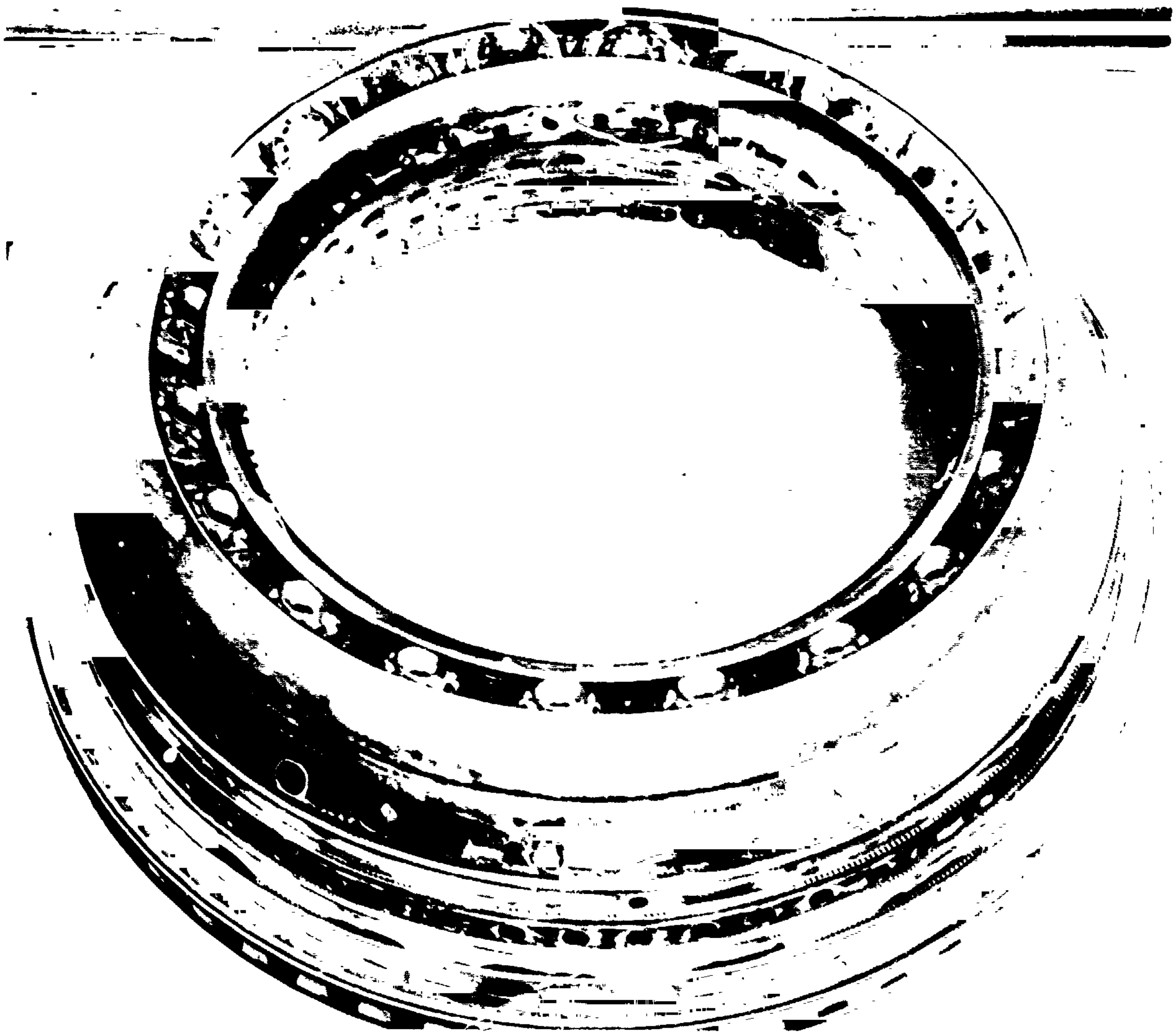


Figure 12. Full-Annular Combustor Hardware without Impingement Shields.

The fabrication of the nozzles was necessary to provide a complete set of simplex-type fuel injector assembles with the capability of operation over the entire range of fuel flows that would be encountered during the test. An illustration of this fabricated fuel injection assembly is presented in Figure 13.

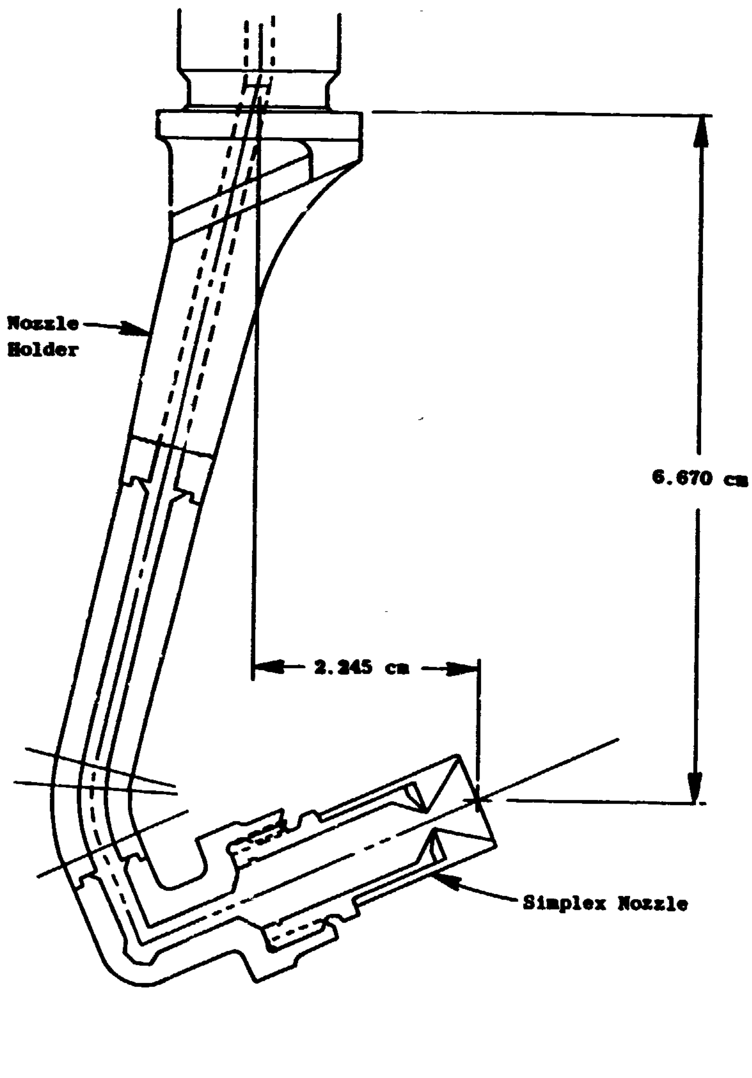


Figure 13. Schematic of Full-Annular Combustor Fuel Injector Hardware.

6.0 DEVELOPMENT TEST METHODS

6.1 SECTOR-COMBUSTOR TEST RIG

Evaluations of the nine sector-combustor configurations were conducted in a test rig that duplicated the aerodynamic flowpath and envelope dimensions of the F101 PV engine combustor. The sector test rig consisted 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 with the capability to operate at inlet conditions up to 0.405 MPa (four atmospheres) pressure and 800 K temperature. A schematic illustration and a photograph of the sector combustor test rig are presented in Figures 14 and 15.

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 the sector diffuser passage simulating the compressor discharge of the F101 engine. The diffuser section is a standard F101 diffuser design. The combustor housing section consists of a 90° sector of a standard F101 combustor casing. Fuel tubes from the five fuel injectors are led out of the casing through five equally spaced injector ports. Fuel is supplied to all five injectors through a manifold system. The instrumentation section is equipped with installation ports to house fixed rake assemblies for obtaining measurements of combustor exit temperatures and pressures. Gas samples for emissions measurements are obtained by means of rakes mounted in these ports.

The test rig instrumentation consisted of various pressure probes and thermocouples plus the fixed-rake, gas-sampling system. Pressure measurements included 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 drop), and liner static pressures (to measure the inner- and outer-passage pressure losses). Total pressures at the sector-combustor exit were measured by the probes located in the fixed-rake, gas-sampling system.

Temperature measurements included diffuser-exit air thermocouples, to measure the sector-combustor-inlet gas temperature, and numerous skin thermocouples to measure sector-combustor metal temperatures. Several thermocouples were located in the instrumentation section to measure the temperature of the gases entering the exhaust section of the facility.

Sector-combustor exhaust-gas samples were extracted through two rakes located in the instrumentation section of the test rig shown in Figure 15. Each rake has five sampling elements spaced along the leading edge. These rakes are stationary, and the elements can be individually sampled or manifolded together to provide a radial-average sample. All five sampling elements of each rake have quick-quenching probe tips. Both water cooling of

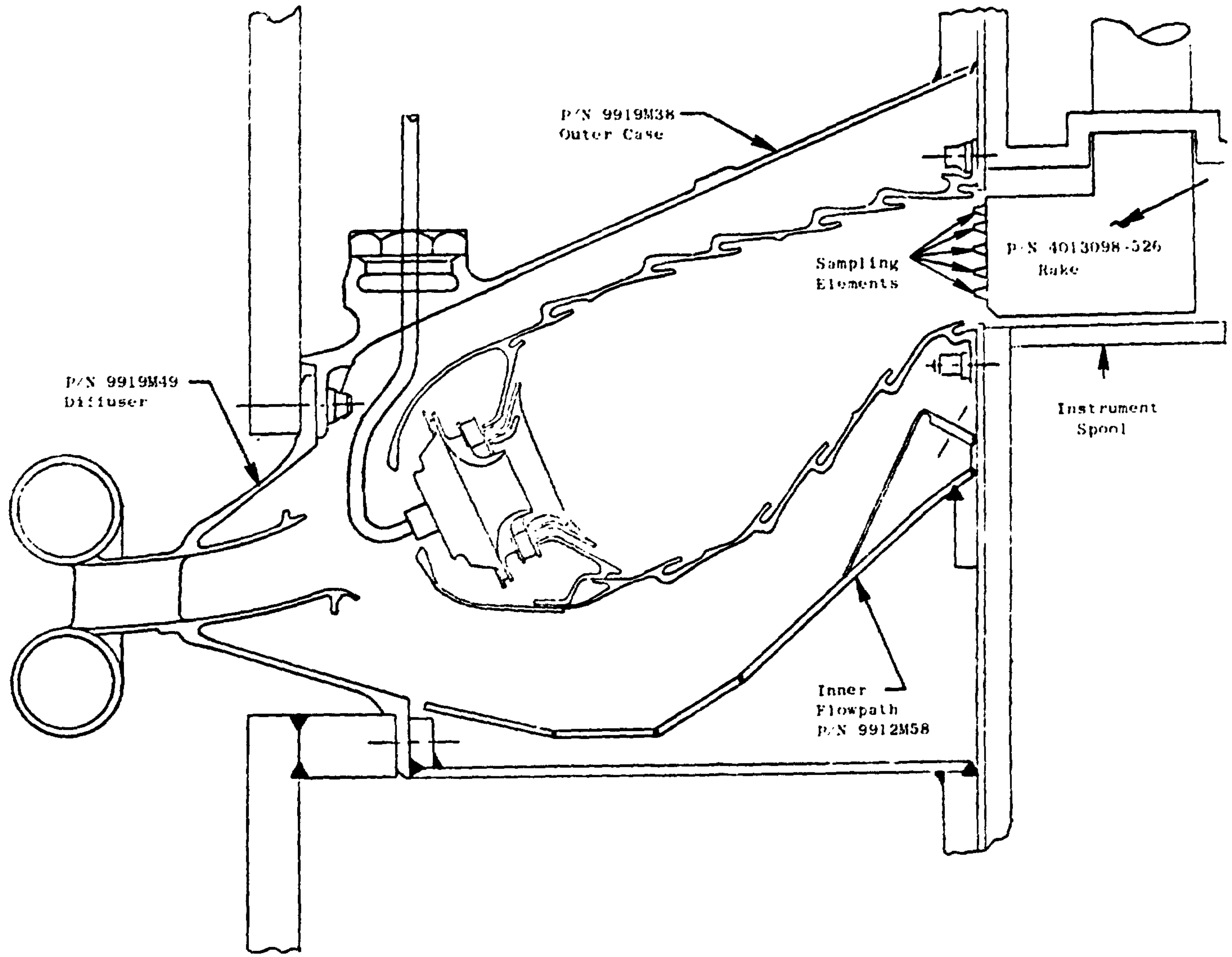


Figure 14. Schematic of E^3/F101 Sector-Combustor Test Rig.

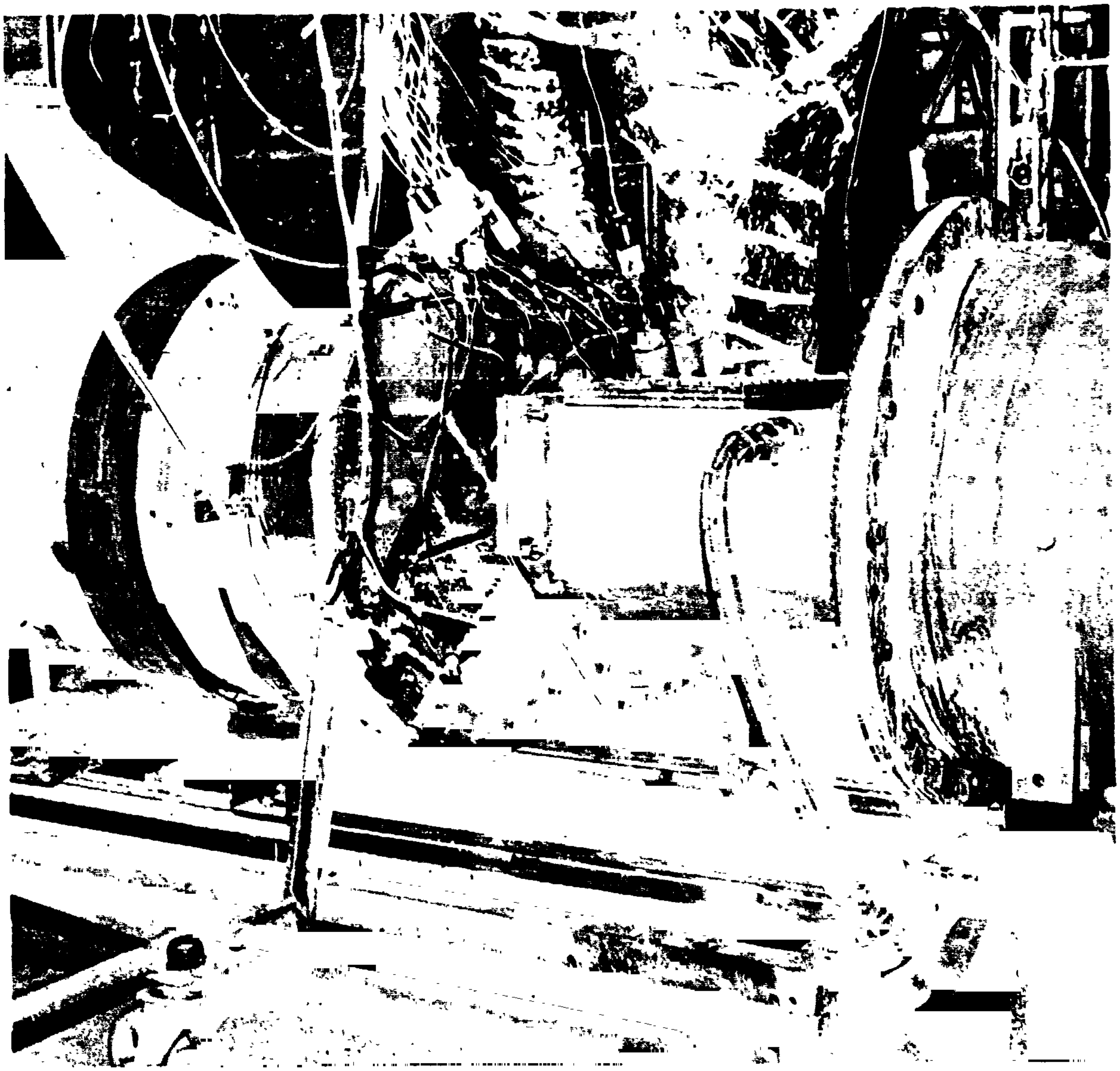


Figure 15. E^3/F101 Sector-Combustor Test Rig.

the rake body and steam heating of the sampling lines within the rake are used. A photograph of one of these rakes is shown in Figure 16. A schematic of a typical rake sampling element is presented in Figure 17. The tip of the sampling elements is designed to quench the chemical reactions of the extracted gas sample, as soon as the sample enters the rake, to eliminate further chemical reactions within the sampling lines. Water cooling of the rake body is necessary to maintain mechanical integrity in the high-temperature environment created by the combustion exhaust gases. Steam heating of the sampling lines within the rake 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 18.

6.2 SECTOR-COMBUSTOR TEST FACILITIES

All developmental emissions testing of the E^3/F101 single-annular sector combustor was performed in the Advanced Combustion Laboratory facility located at the General Electric Evendale plant. This facility is equipped with the inlet ducting, exhaust ducting, 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/sec can be supplied to the facility from a large compressor, plus an additional 1.8 kg/sec 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 preheater. The preheater has the capability to heat 1.35 kg/sec airflow to 800 K. The Jet A type fuel used in all of the E^3/F101 single-annular 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 were accomplished using the facility domestic water supply with pressure boost where necessary.

Test conditions were monitored using the facility 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 with signals 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 I (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)

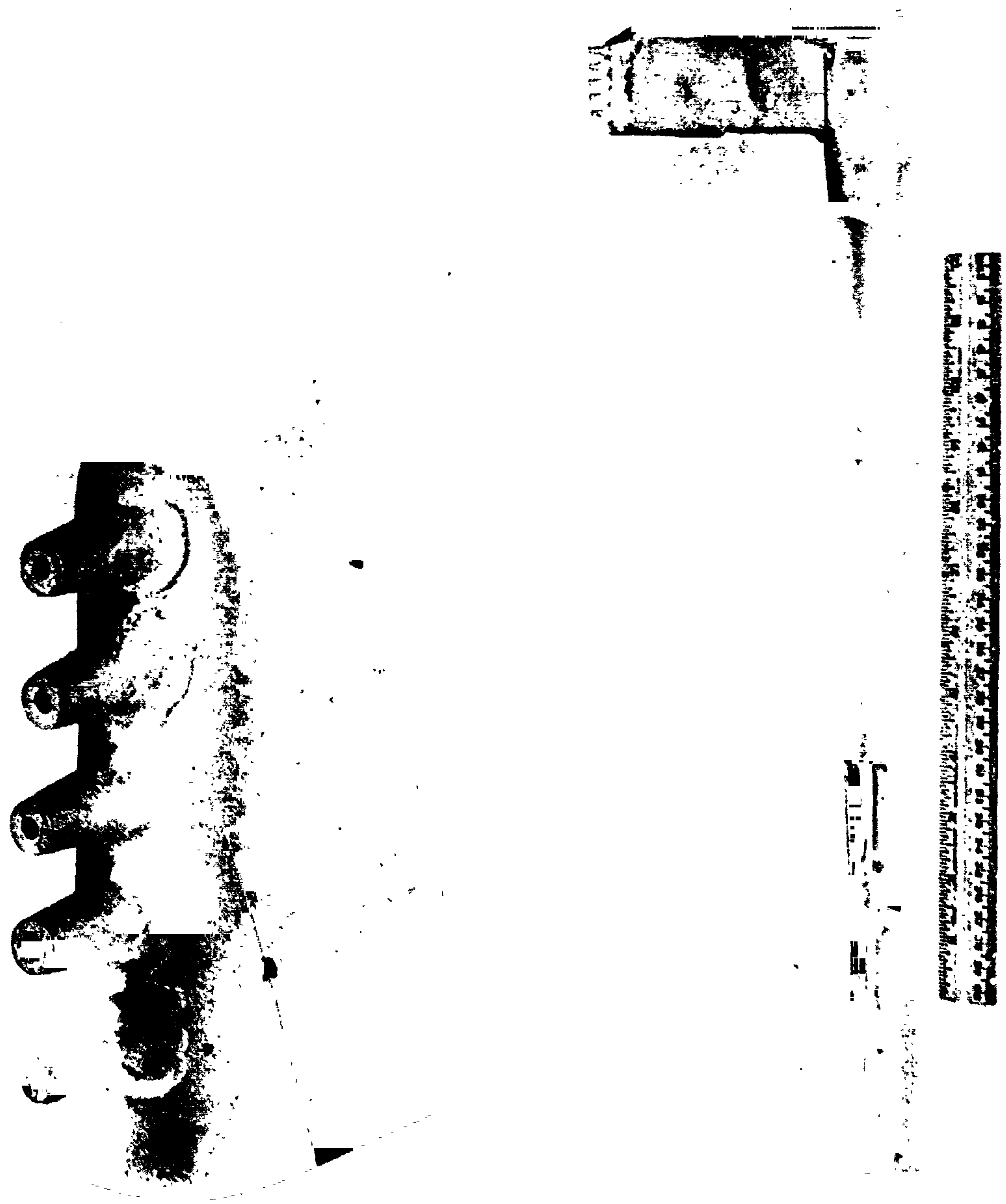


Figure 16. Quick-Quench, Gas-Sampling Rake.

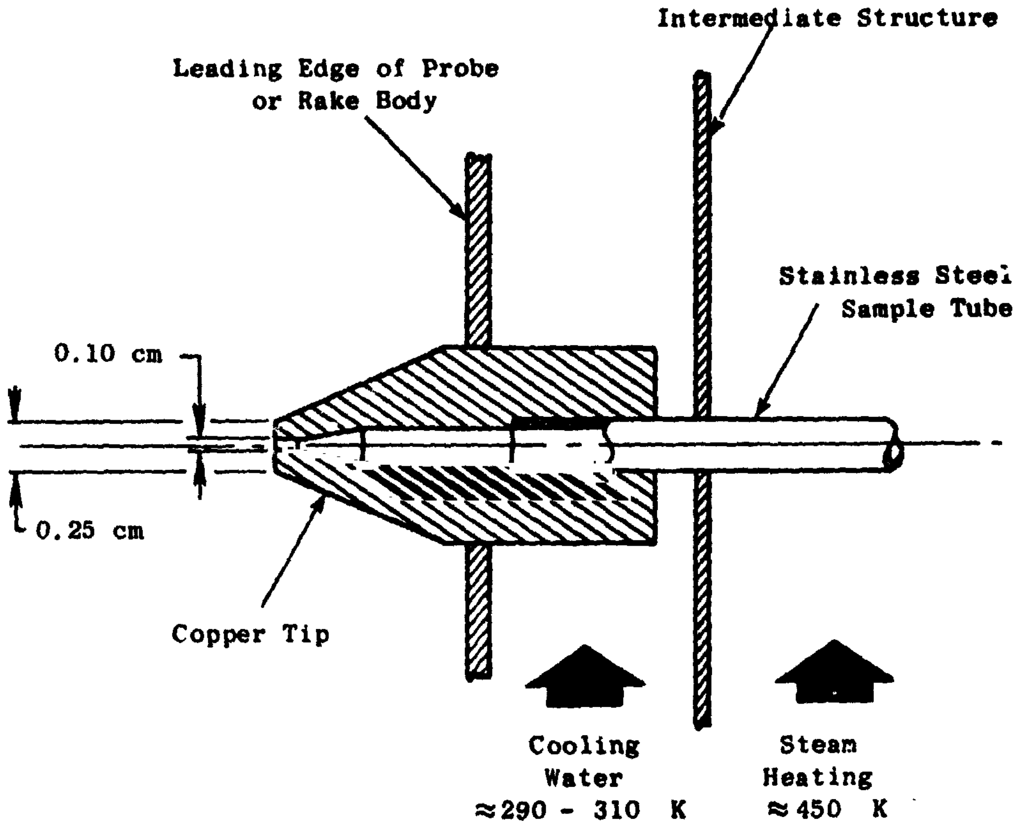


Figure 17. Gas-Sampling Probe Tip Cross Section.

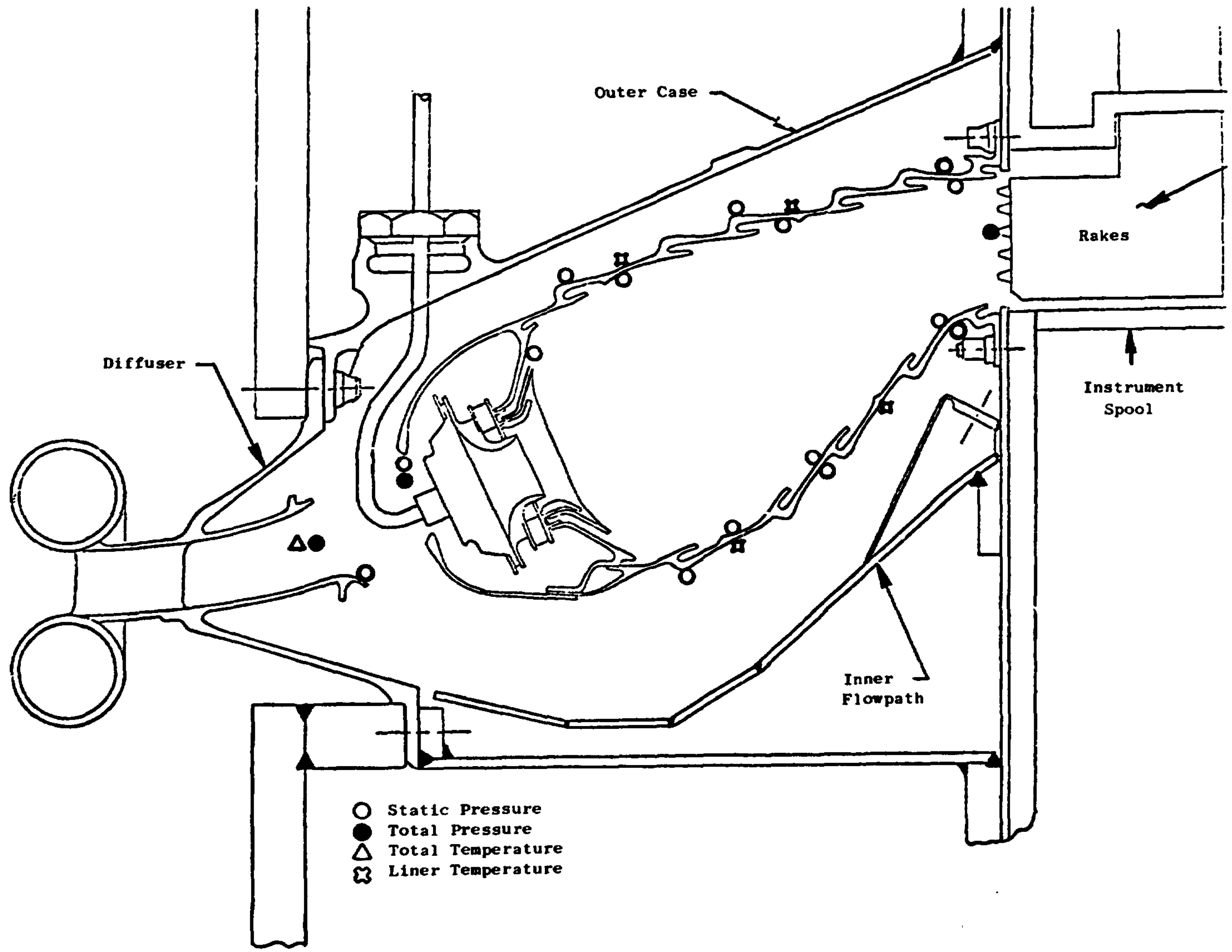


Figure 18. Sector-Combustor Test Rig Instrumentation.

- Beckman Model 915 NO_x Analyzer (Chemiluminescence with Converter, Water 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 testing. A qualified technician calibrated and operated the CAROL system throughout the duration of data acquisition for each emissions test.

6.3 SECTOR-COMBUSTOR TEST PROCEDURES

The sector-combustor tests were directed at identifying combustor features designed to obtain low emissions of carbon monoxide and unburned hydrocarbons. Test conditions were designed to simulate the E^3 combustor cold-dome velocity; this is believed to be a controlling factor in the CO and HC emissions characteristics.

A substantial data base exists that confirms a dependence of NO_x emissions on combustor bulk residence time. A similar dependence of CO emissions on combustor bulk residence time at low-power operating conditions has not been established. In general the CO emissions tend to be most affected by the dome airflow conditions, in particular the cooling and swirl-cup airflows. Therefore, the parameter selected for simulation in the E^3/F101 sector tests was the combustor cold-dome velocity. A more representive parameter might be the hot-dome velocity since a similar parameter has been used on other, conventional, single-annular combustors to identify CO emission trends. However, since fuel/air ratios directly affect the gas temperature, the dome velocity becomes a test variable.

The E^3 Flight Propulsion System (FPS) baseline operating cycle was established using initial engine component performance estimates. This cycle defined combustor operating conditions during the initial portion of the alternate combustor effort. Later, however, revised estimates of the engine high pressure compressor performance indicated a significant reduction in compressor efficiency at the low-power operating conditions. This led to a redefition of the E^3 operating cycle in July 1978. The revised cycle provided the combustor operating conditions used during most of the baseline testing. A comparison of the combustor operating conditions for the baseline and the revised cycle is shown in Table V. It is observed from this table that the revision of the E^3 operating cycle produced significant changes in the combustor operating conditions at the low-power points; however, no changes occurred at the higher power points.

Sector-combustor Configurations SA-00 through SA-02 were evaluated at inlet conditions corresponding to 4%, 6%, and 100% of sea level takeoff thrust for the E^3 FPS baseline cycle. Configurations SA-03 and SA-04 were evaluated at 4% and 6% of sea level takeoff thrust for the FPS baseline cycle plus 4%, 6%, and 100% of sea level takeoff thrust for the July 1978 revised E^3

Table V. Comparison of Combustor Operating Conditions.

Condition	F_n	FPS Baseline Cycle				July 1978 Cycle			
		P_3, atm	T_3, K	$\dot{W}_c$, kg/sec	f/a	P_3, atm	T_3, K	$\dot{W}_c$, kg/sec	f/a
Ground Idle									
	4%	3.16	448	7.7	0.0117	3.12	478	7.0	0.0158
	6%	3.96	485	9.5	0.0120	3.93	508	9.0	0.0143
Approach	30%	11.67	633	25.6	0.0139	11.67	633	25.6	0.0139
Climb	85%	25.91	782	49.1	0.0223	25.91	782	49.1	0.0223
Sea Level Takeoff	100%	29.8	814	54.9	0.0244	29.8	814	54.9	0.0244

cycle. Configurations SA-05 through SA-08 were evaluated at 4%, 6%, 30%, and 100% of sea level takeoff thrust for only the July 1978 revised cycle. Because of the limited capabilities of the small-scale testing facility, the combustor operating conditions at 6% thrust and above were derated.

At many test conditions, data were obtained over a range of combustor fuel/air ratios. A list of the sector-combustor test points and corresponding operating conditions based on the E^3 FPS baseline and E^3 revised (July 1978) cycles is shown in Tables VI and VII.

Test points were usually run in 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 data were recorded, and then the combustor exit-plane detailed pollutant emission data were recorded with the sampling probes manifolded at the combustor exit plane. At test points of particular interest, however, individual samples from each gas-sampling rake were obtained.

6.4 SECTOR-COMBUSTOR 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, were input to a data-reduction computer program "E3CAROL." This program reduced the instrumentation data to the combustor performance parameters of interest. A summary of these parameters is shown in Table VIII. The method by which they were measured or calculated is also shown in this table. For comparative purposes, 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.

Sector-combustor airflow distributions were calculated for each test configuration based on the pressure-instrumentation data and estimated effective flow areas. The pressure data were input to a computer program, "E3FDM," which performed the airflow-distribution calculations. These calculated airflow distributions were used to indicate sector-combustor configuration changes to obtain reduced emission levels. A sample of the output from this program is shown in Figure 19.

Emissions Data - Reduction of the emissions data was accomplished using two data-reduction programs: "CALIB" and "E3CAROL." At the beginning of each test run, a calibration of the CAROL gas-sample-analysis system was performed by the technician. 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) was input to 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

- Building 306 Facility
- Jet A Fuel
- Air and Fuel Flows are for 90° Sector

Table VI. Sector-Combustor Test Points for E^3 FPS Baseline Cycle.

Test Point	Operating Condition	T_3, K	P_3, Atm	$\dot{W}_c$, kg/sec	f/a	$\dot{W}_f$, kg/hr
1	4% Base	448	3.16	2.24	0.0090	72.4
2	4% Base	448	3.16	2.24	0.0117	94.2
3	4% Base	448	3.16	2.24	0.0160	128.8
4	4% Base	448	3.16	2.24	0.0200	161.0
5	4% Growth	472	3.40	2.48	0.0090	80.2
6	4% Growth	472	3.40	2.48	0.0117	107.9
7	4% Growth	472	3.40	2.48	0.0160	142.6
8	4% Growth	472	3.40	2.48	0.0200	178.3
9*	6% Base	485	3.40	2.39	0.0090	77.3
10*	6% Base	485	3.40	2.39	0.0120	103.0
11*	6% Base	485	3.40	2.39	0.0160	137.4
12*	6% Base	485	3.40	2.39	0.0200	171.8
13*	6% Growth	511	3.15	2.27	0.0090	73.5
14*	6% Growth	511	3.15	2.27	0.0121	98.8
15*	6% Growth	511	3.15	2.27	0.0160	130.6
16*	6% Growth	511	3.15	2.27	0.0200	163.3
17*	SLTO Base	783	2.50	1.36	0.0244	119.5

Table VII. Sector-Combustor Test Points for E^3 July 1978 Cycle.

Test Point	Operating Condition	T_3, K	P_3, Atm	$\dot{W}_c$, kg/sec	$\dot{W}_c/P_3$	f/a	$\dot{W}_f$, kg/hr
1	4% Idle	478	3.12	1.94	16.55	0.0080	55
2	4% Idle	478	3.12	1.94	16.55	0.0120	83
3	4% Idle	478	3.12	1.94	16.55	0.0158	109
4	4% Idle	478	3.12	1.94	16.55	0.0200	139
5	4% Idle	478	3.12	1.94	16.55	0.0240	166
6*	6% Idle	508	3.54	2.24	16.85	0.0080	64
7	6% Idle	508	3.54	2.24	16.85	0.0110	88
8	6% Idle	508	3.54	2.24	16.85	0.0143	115
9	6% Idle	508	3.54	2.24	16.85	0.0180	144
10	6% Idle	508	3.54	2.24	16.85	0.0210	168
11*	10%	545	3.54	2.30	17.32	0.0080	66
12	10%	545	3.54	2.30	17.32	0.0123	102
13	10%	545	3.54	2.30	17.32	0.0160	132
14	10%	545	3.54	2.30	17.32	0.0200	166
15	10%	545	3.54	2.30	17.32	0.0240	199
16*	30% APP	633	3.03	1.81	15.97	0.0139	91
17*	100% SLTO	783	2.68	1.36	13.54	0.0244	120

*Conditions derated to facility limit.

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

Parameter	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 two exhaust-gas-sampling rakes (five elements each).
Total Pressure Loss	$\Delta P_T/P_{T_3}$	%		x	$100\left(P_{T_3} - P_{T_{39}}\right)/P_{T_3}$.
Combustor Airflow	W_c	kg/sec	x		Standard ASME orifice (no bleed flow ∴ $W_3 = W_c$).
Reference Velocity	V_r	m/sec		x	$W_c R T_{T_3}/P_{T_3} A_R$.
Total Fuel Flow	W_f	kg/hr		x	Turbine-type flowmeter.
Overall Metered Fuel/Air	f/a			x	$W_f/3600\ W_c$.
Sample Fuel/Air	f/a_s			x	$f/a_s = 0.4514\ [\%\ (CO + CO_2 + HC)]/[(1.0 - 0.98\ (\%\ CO) - 0.49\ (\%\ CO_2)]$.
Upstream Static Pressure	$P_{s_{3.1_0}}$	Atm	x		Single static pressure probe.
Downstream Static Pressure	$P_{s_{3.2_0}}$	Atm	x		Single static pressure probe.
Dome Pressure Loss	ΔP/P/OD	%		x	$100\left(P_{s_{3.1_0}} - P_{s_{3.2_0}}\right)/P_{s_{3.1_0}}$.
Inlet Total Temperature	T_{T_3}	K	x		Average of measurements from three thermocouples.
Combustion Efficiency	η_c	%		x	Measured exhaust gaseous emissions ($\eta_c = 1 - 0.0002334\ EI_{CO} - 0.001\ EI_{HC}$).

AIRFLOW DISTRIBUTION ANALYSIS FOR E3 SECTOR COMBUSTOR

OUTER LINER PASSAGE PRESSURES-PSIA

PANEL1(O)	PANEL1(I)	PANEL2	PANEL3	PANEL4	PANEL5
44.113	43.070	44.137	44.604	44.800	44.097

OUTER FLOWPATH PRESSURES-PSIA

PANEL1	PANEL2	PANEL3	PANEL4	PANEL5
42.835	42.786	42.737	42.516	42.295

INNER LINER PASSAGE PRESSURES-PSIA

PANEL1(O)	PANEL1(I)	PANEL2	PANEL3	PANEL4
43.867	43.474	43.916	44.358	44.702

INNER FLOWPATH PRESSURES-PSIA

PANEL1	PANEL2	PANEL3	PANEL4
42.835	42.614	42.393	41.951

DOME PRESSURES-PSIA

UPSTREAM	DOWNSTREAM
45.783	42.811

OUTER LINER AIRFLOWS-PPS

RING1	RING2	RING3	RING4	RING5	RING6	DIL-1	DIL-2	DIL-3	DIL-4
0.	0.433	0.478	0.326	0.309	0.193	1.871	0.	2.848	0.

IN PERCENT OF WC

0.	2.52	2.78	1.90	1.80	1.13	10.90	0.	16.58	0.

INNER LINER AIRFLOWS-PPS

RING1	RING2	RING3	RING4	RING5	DIL-1	DIL-2	DIL-3	DIL-4
0.	0.359	0.503	0.573	0.411	1.808	0.	2.785	0.

IN PERCENT OF WC

0.	2.09	2.93	3.34	2.40	10.53	0.	16.22	0.

DOME AIRFLOWS-PPS

COOLING	DILUTION	SWRLCP	OUTER RING	INNER RING
0.781	0.	3.492	0.	0.

IN PERCENT WC

4.55	0.	20.34	0.	0.

AIRFLOW SET-PPS=17.033

AIRFLOW ACCOUNTED-PPS=17.172

PERCENT OF AIRFLOW SET=100.817

Figure 19. Sample Output from Program E3FDM.

were 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 "E3CAROL." By accessing the calibration file generated by program "CALIB," the reduction of the raw emissions data to emissions indices was performed by program "E3CAROL." The equations used in these calculations were those contained in SAE ARP 1256 (Reference 4) and shown below.

$$EI_{CO} = \frac{2.801\ [CO]}{\left(12.01 + 1.008 \left[\frac{H}{C}\right]\right)\left(\frac{[CO]}{10^4} + [CO_2] + \frac{[HC]}{10^4}\right)} \quad \text{g/kg Fuel}$$

$$EI_{HC} = \frac{0.100\ [HC]}{\left(\frac{[CO]}{10^4} + [CO_2] + \frac{[HC]}{10^4}\right)} \quad \text{g/kg Fuel}$$

$$EI_{NO_x} = \frac{4.601\ [NO_x]}{\left(12.01 + 1.008 \left[\frac{H}{C}\right]\right)\left(\frac{[CO]}{10^4} + [CO_2] + \frac{[HC]}{10^4}\right)} \quad \text{g/kg Fuel}$$

In these equations the concentrations of CO, HC, and NO_x are in parts per million; CO_2 is in percent of total constituents. In the calculations, the CO and CO_2 concentrations were corrected for the removal of water from the sample prior to analysis. A fuel hydrogen-to-carbon atom ratio of 1.92, representing 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 "E3CAROL." 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 are 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 "E3CAROL" are shown in Figures 20 and 21.

Because the sector-combustor inlet pressure and airflow were derated at the simulated high-power operating conditions, the measured emissions levels

CAROL CALIBRATION DATA

TEST- E3 EMISSIONS   DATE- 12/12/78
CELL- 306   RUN- 11   FUEL- JET A

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

GAS	RANGE	FIT	A0	A1	A2
			CURVE FIT CONSTANTS		
CO	3	2	0.	0.0749	-0.00030294
CO2	3	2	0.	17.3272	-0.05416094
HC	3	1	0.	0.3216	0.
NOX	3	2	0.	0.6514	0.00178117

CAL TIME = 1330
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.
	16.100	233.0	230.0	-1.27
	30.000	446.7 PPM	456.1 PPM	2.10
	55.000	953.0	944.9	-0.85
	0.	3195.0	0.	0.
CO2	0.	0.	0.	0.
	37.700	2.480	2.466	-0.55
	57.000	3.960 %	4.003 %	1.08
	80.000	6.190	6.157	-0.54
	0.	10.600	0.	0.
HC	0.	0.	0.	0.
	86.200	268.0	268.0	0.
	0.	699.0 PPM	0. PPM	0.
	0.	1240.0	0.	0.
	0.	4920.0	0.	0.
NOX	0.	0.	0.	0.
	20.500	29.8	29.8 PPM	-0.00
	50.400	68.0 PPM	68.0	0.00
	0.	287.0	0.	0.
	0.	0.	0.	0.

CALCULATED CONCENTRATIONS OF:

DIVISIONS	CO -PPM	CO2 -%	HC -PPM	NOX -PPM
10.000	139.2	0.596	31.1	14.9
20.000	290.7	1.231	62.2	29.1
30.000	456.1	1.911	93.3	42.6
40.000	637.5	2.638	124.4	55.4
50.000	837.2	3.420	155.5	67.5
60.000	1058.3	4.262	186.5	79.1
70.000	1304.4	5.171	217.5	90.2
80.000	1579.9	6.157	248.7	100.8
90.000	1890.5	7.227	279.8	110.9
100.000	2243.2	8.395	310.9	120.6

Figure 20. Sample Output from Program CALIB.

TEST - E3 SA-08 DATE - 12/7/78
CELL - 306 RUN - 10 FUEL - JET A
CAL TIME = 1750 FUEL H/C = 1.92

RDG 8 POINT 8

P3	REF VEL	DP/P	DP/P	FLOW FCTN	FUEL/AIR RATIO	T3	AIRFLOW
TOTAL	FT/SEC	COMB	DOME	SQUARED	METERED	DEG-R	PPS
51.92	70.27	0.0747	0.0701	137.258	0.0140	913.7	5.0311

*** METRIC ***

ATM	M/SEC			CM**4-DEG-K/SEC**2		DEG-K	KG/SEC
3.570	21.418			660.039		507.6	2.2821

ACTUAL GAS ANALYSIS

RAKE	TIME	CO SEMI-DRY (PPM)	CO2 SEMI-DRY (PCT)	HC WET (PPM)	NO DRY (PPM)	NOX DRY (PPM)	SMOKE NUMBER
GX 0	2020	415.2	3.04	12.5		35.8	
A 1	2020	449.1	3.12	12.5		36.5	
B 2	2020	373.8	2.93	10.9		35.1	
AVG		411.4	3.02	11.7		35.8	

CALCULATED EMISSIONS LEVELS

RAKE	TIME	CO	HC	NO	NOX	F/A	COMB
		******* LBS/1000 LBS FUEL *******				SAMPLE	EFF
GX 0	2020	27.0	0.4		3.8	0.01466	99.33
A 1	2020	28.5	0.4		3.8	0.01503	99.29
B 2	2020	25.3	0.4		3.9	0.01412	99.37
AVE		26.9	0.4		3.8	0.01457	99.33
OVERALL AVG		27.0	0.4		3.8	0.01457	99.33

EMISSIONS ADJUSTED TO ENGINE CYCLE CONDITIONS

EICO	EIHC	EINOX	COMB. EFF.
******* LBS/1000 LBS FUEL *******			
22.95	0.30	4.01	0.9943

Figure 21. Sample Output from Program E3CAROL.

were adjusted to the actual engine cycle conditions. The adjusted emissions levels are tabulated in Appendix A for all configurations tested at higher power operating conditions; adjustment relations are defined in Appendix B.

6.5 FULL-ANNULAR COMBUSTOR TEST RIG

The E^3/F101 full-annular combustor evaluations were conducted with an existing F101 full-annular combustor test rig. This test rig exactly duplicates the aerodynamic combustor flowpath and envelope dimensions of the F101 engine. The test rig consists of an inlet plenum chamber, an inlet diffuser section, and a housing for the combustor. Included as part of this rig is an exit-plane, fixed-rake assembly for obtaining measurements of combustor outlet temperatures and pressures and extracting gas samples.

A photograph of the test rig is presented in Figure 22. The combustor test rig is basically a cylindrical pressure vessel designed for high-temperature service and fitted with inlet and exit flanges. The rig is equipped with ports and bosses to accommodate fuel nozzles/injectors, igniters, and borescope inspection. These ports are located exactly as in the engine design. The rig is also equipped with provisions to extract both turbine cooling air and customer bleed air. These provisions also duplicate those in the engine.

The air inlet connection of the test rig consists of an 81.3-cm diameter pipe flange, of special design, bolted to the air-supply plenum of the test cell. In the supply plenum, the flow is mixed and then straightened by grates and screens. Within the test rig, a bullet-nosed centerbody directs the entering airflow into an annular passage. This annular passage simulates the compressor-discharge passage of the engine. The inner and outer walls are formed to the contour of the engine diffuser, and the gap is spanned by streamlined outlet guide vanes similar to those in the engine. Aft of the step diffuser, the centerbody forms the inner wall of the combustor housing. The outer wall is provided with ten 1.1-cm diameter bleed ports, through which a portion of the airflow can be extracted as turbine bleed air. Additional ports are provided on the inner wall to simulate turbine rotor cooling-air extraction. The air extracted from these sets of ports is routed through two 2.1-cm pipes, forward through the centerbody nose, then radially out of the rig.

The combustor test rig is equipped with 20 fuel injector ports spaced 18° apart. The fuel injectors used in this program were all installed through these existing ports. Fuel was supplied to the injectors through a 1.6-cm diameter tube manifold. Metering of the fuel occurred at the simplex nozzle tip. To assure a uniform fuel distribution, each of the 20 fuel injector assemblies was calibrated prior to the test. Typical calibration results are shown in Table IX. Adjustments to the circumferential locations of the fuel nozzles in the combustor were made to obtain as uniform a fuel distribution as possible. The arrangement used in the test is shown in Figure 23.

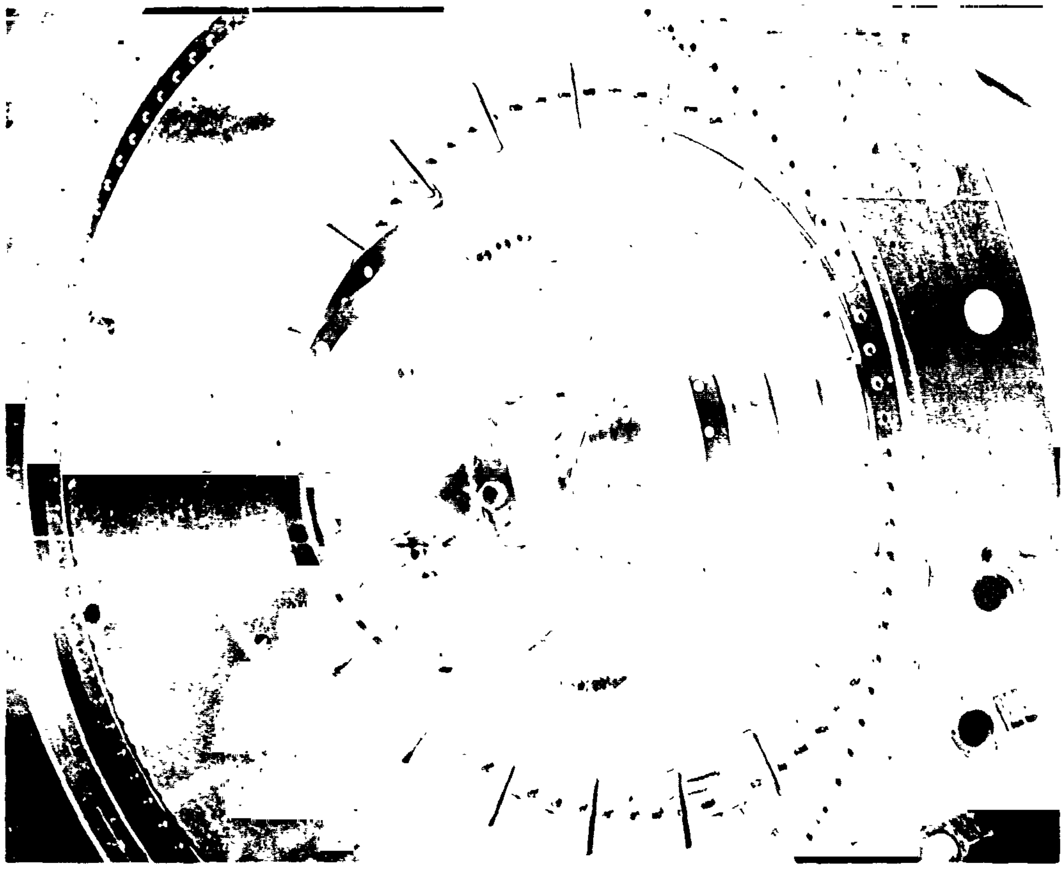


Figure 22. Full-Annular Combustor Test Rig.

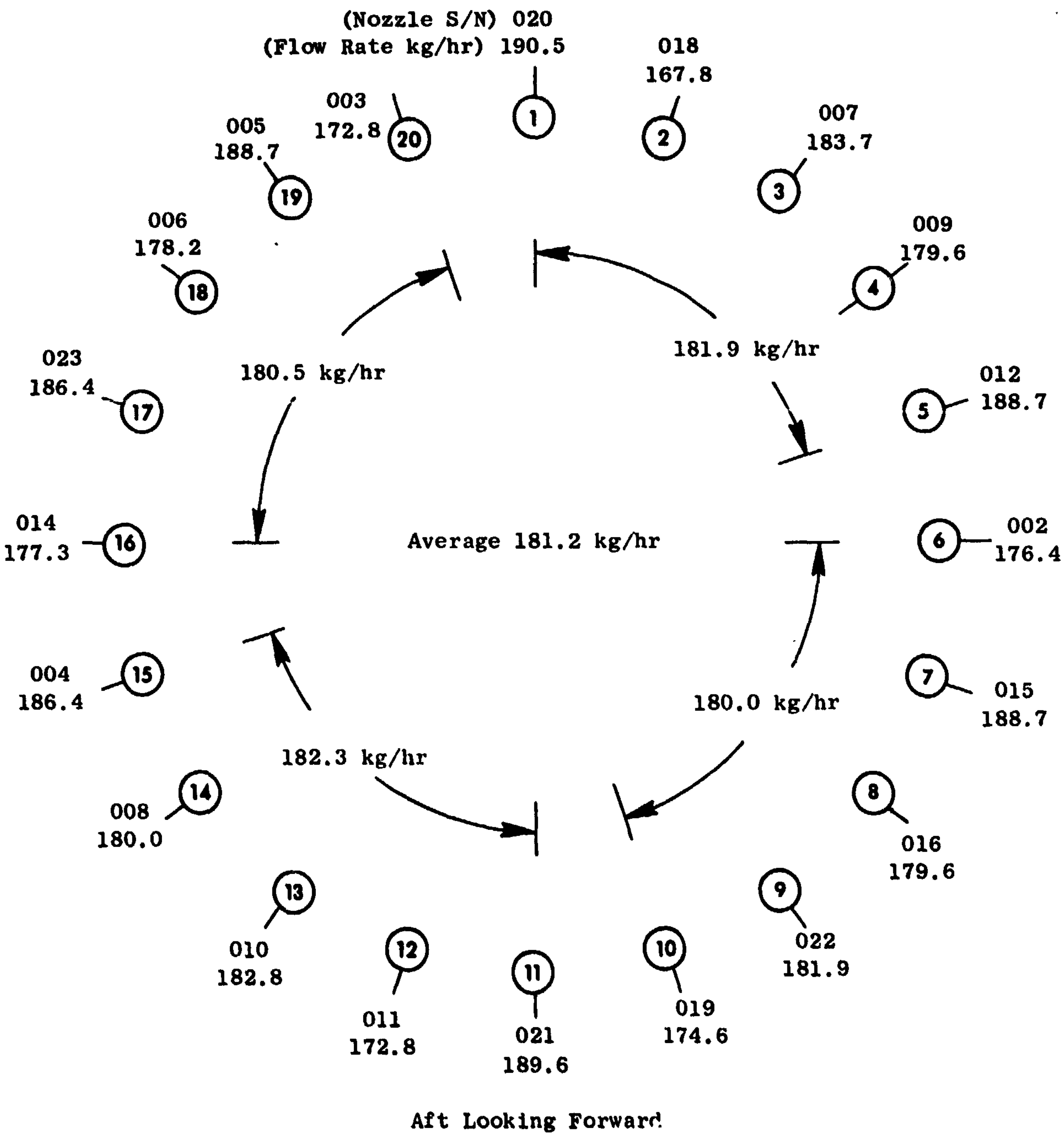


Figure 23. Full-Annular Combustor Fuel Nozzle Arrangement.

Table IX. Full-Annular Fuel Nozzle Calibrations.

Nozzle Tip Serial Number	Flow Rate - kg/hr at ΔP of		Spray Quality at 6.80 Atm
	6.80 Atm	40.83 Atm	
016	71.2	179.6	Satisfactory
022	73.1	181.9	Satisfactory
008	71.0	180.0	Satisfactory
005	76.1	188.7	Satisfactory
013 (Spare)	75.4	188.7	Satisfactory
007	74.1	183.7	Satisfactory
003	70.3	172.8	Satisfactory
015	74.7	188.7	Satisfactory
020	75.7	190.5	Satisfactory
006	71.0	178.2	Satisfactory
021	74.8	189.6	Satisfactory
011	69.5	172.8	Satisfactory
014	70.8	177.3	Satisfactory
002	69.8	176.4	Satisfactory
023	74.7	186.4	Satisfactory
010	72.2	182.8	Satisfactory
018	68.1	167.8	Satisfactory
004	77.3	186.4	Satisfactory
009	71.7	179.6	Satisfactory
019	70.4	174.6	Satisfactory
012	76.0	188.8	Satisfactory

The exhaust end of this combustor test rig is provided with a large-diameter flange to which an instrumentation spool section can be joined. The instrumentation spool section used in this program consisted of an existing, short-flanged pipe with a ring incorporating mounting pads for gas-sampling rakes at specific circumferential locations. This instrumentation spool also contains water-spray rings to cool the combustion gases downstream of the measurement plane. A photograph of the instrumentation spool section with the rakes installed is presented in Figure 24.

The full-annular combustor test rig instrumentation consisted of numerous pressure probes and thermocouples plus the fixed-rake, gas-sampling system. Pressure measurements included the diffuser exit total and static pressures, dome upstream and downstream static pressures, liner wall static pressures, and total pressures at the combustor exit. Temperature measurements included diffuser-discharge air thermocouples to measure the combustor inlet temperature and numerous skin thermocouples to measure the combustor liner temperatures. Other pressure and temperature instrumentation monitored the test rig and facility.

Figure 24. Full-Annular Combustor Instrumentation Spool.

Combustor exhaust-gas samples were extracted through a fixed array of sampling rakes mounted at specific circumferential locations in the instrumentation spool. A total of six rakes was used for obtaining gas samples; two of these were also used for obtaining smoke samples. Two additional rakes were mounted in the instrumentation spool to measure the combustor exit total pressures. The gas-sampling rakes employed were identical to the sampling rakes used throughout the sector-combustor testing and are shown in Figures 16 and 17. All five sampling elements of each rake were manifolded to provide a single gas sample from each of the six rakes used. This array of six sampling rakes was connected to the gas-analysis system in a manner that allowed analysis of a single "ganged" sample obtained simultaneously from all six rakes. A schematic of the rake locations and piping is shown in Figure 25. A summary of the rig instrumentation employed for this test is presented in Table X. An illustration of the locations of the combustor instrumentation is shown in Figure 26.

Table X. Combustor/Rig Instrumentation.

Parameter	Instrumentation
Total Airflow	Standard ASME Orifice
Fuel Flow	Turbine Flow Meters
Fuel Injector Pressure Drop	Pressure Tap in the Fuel Manifold
Fuel Temperature	Thermocouple in Fuel Manifold
Diffuser Inlet Total Pressure	2 One-Element, Fixed-Impact Rakes
Diffuser Inlet Total Temperature	6 Thermocouples on 2 Three-Element Rakes
Combustor Exit Emissions Levels	6 Five-Element Impact Rakes
Combustor Exit Total Pressure	2 Single-Element Rakes
Combustor Metal Temperature	26 Thermocouples on Liners
Inlet Air Humidity Level	Dew Point Hygrometer
Combustor Passage Static Pressure	5 Wall Taps in Each Passage (10 Total)
Combustor Dome Pressure Drop	4 Pressure Taps

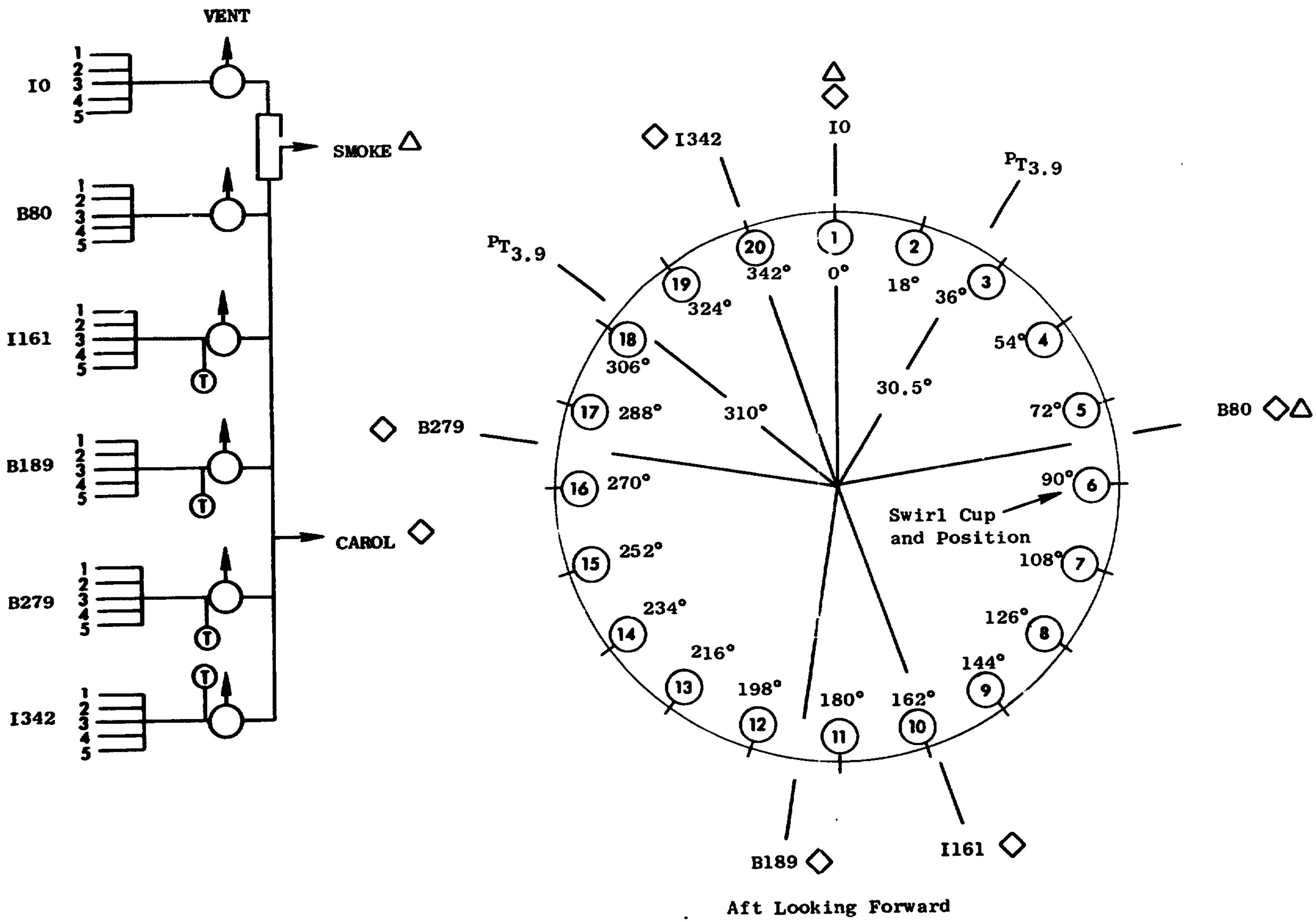


Figure 25. Schematic of Instrumentation Spool Rake Locations and Sample-Line Hook-up.

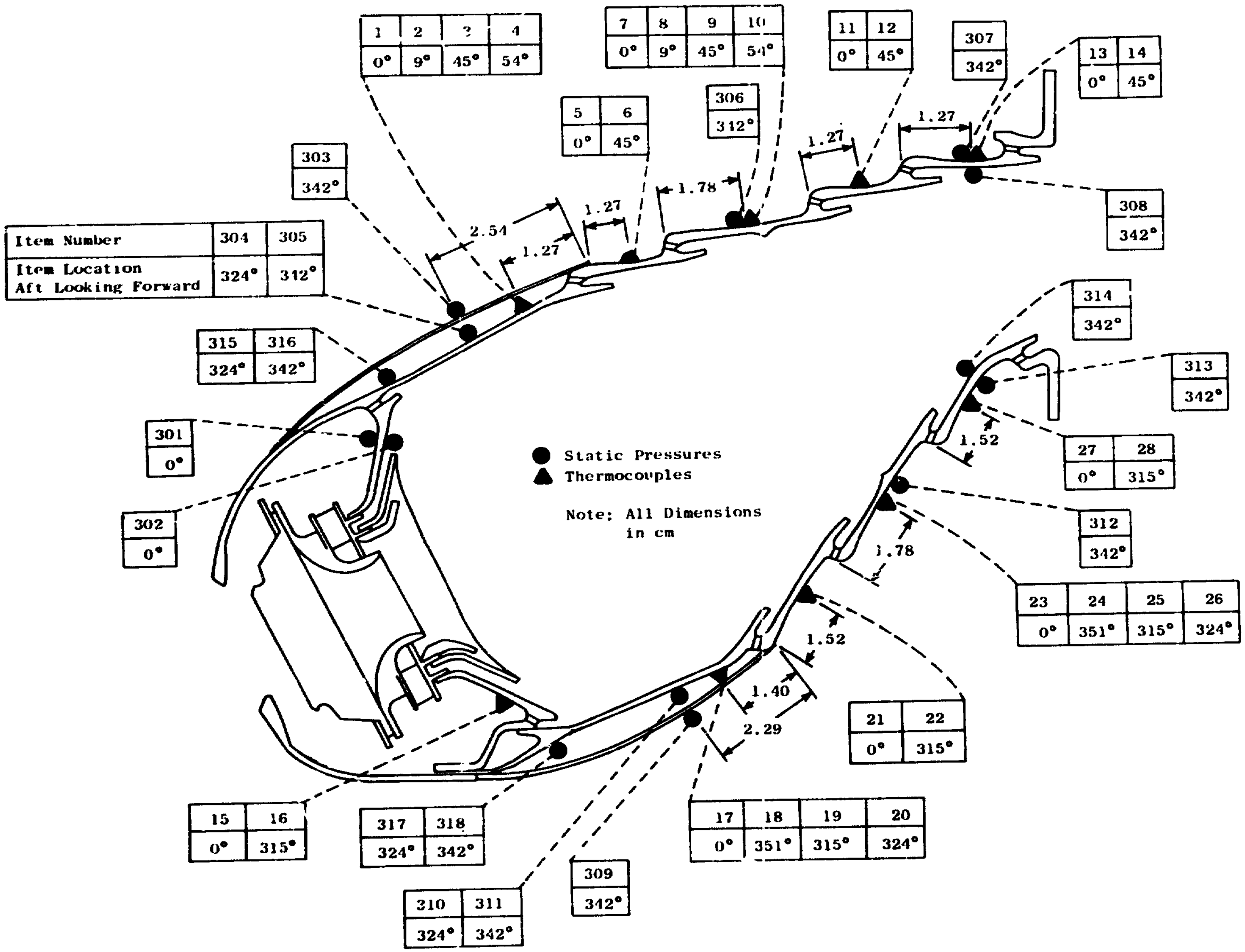


Figure 26. Full-Annular Combustor Instrumentation Location.

6.6 FULL-ANNULAR COMBUSTOR TEST FACILITY

The E^3/F101 full-annular combustor component test evaluation was performed in Test Cell A3 at the General Electric Evendale Plant. This facility is fully equipped with the inlet ducting, exhaust ducting, controls, and instrumentation required for conducting full-scale combustor component tests over wide ranges of operating conditions. A view of the interior of the cell is shown in Figure 27. The cell is a rectangular chamber with reinforced-concrete blast walls on three sides and a lightweight roof. The installed ventilation and safety equipment is designed specifically for tests involving combustible fluids. This cell contains the necessary air piping to accommodate two test vehicles.

In operating this test cell, utilization is maximized by mounting the test rigs on portable dollies with quick-change connections so that buildup operations are accomplished in another area, and the test vehicle occupies the cell only for the duration of actual testing. This concept allows the installation of a typical test vehicle in about four hours. The turnaround time from the completion of a test with one vehicle to the start of a test with another is, therefore, only about eight hours. Instrumentation reliability is improved since the sensors are prewired to multiple quick-connect panels and checked out in the favorable environment of the vehicle build-up area.

The control consoles and data-recording equipment are located in an adjacent control room. This room is insulated to muffle test noise and facilitate communication and is environmentally controlled for the benefit of the electronic equipment.

Air is supplied to this test cell from a central air-supply system. This system has a nominal capacity of 45 kg/sec of continuing airflow at a delivery pressure of up to 2 MPa (20 atm). The system may also be used for exhaust suction to simulate altitude up to 8.9 km (29,000 ft), with flow rates reduced in proportion to density.

Auxiliary equipment in the air-distribution network provides for further conditioning of the delivered air when required. This conditioning includes 10-micron filtration, drying to a 233 K dewpoint, and temperature control. Cold air, down to 217 K, can be provided by piping connections to a turbo-refrigeration unit. Warm air, up to 450 K can be supplied directly by bypassing the aftercooler. Further heating, up to 922 K, is accomplished with a gas-fired heat exchanger. The gas-fired, indirect, air heater is designed to accept 36 kg/sec of air from the central air-supply system at 450 K and 0.96 MPa (9.5 atm) pressure and to discharge the air unvitiated at 922 K and 0.84 MPa (8.3 atm). The heater is capable of accommodating higher flows and higher pressures at reduced outlet temperatures. The heater is a refractory-lined shell, 8.2 m in diameter and 13.7 m tall, containing a conical radiating furnace baffle and a heat exchanger.

Figure 27. Interior View of Test Cell A3 Facility.

Combustors being tested in this cell can be exhausted directly to the atmosphere or can be connected to the facility exhaust system for pressure control. When connected to the facility exhaust system, the combustor pressure can be regulated from the upper limit, imposed by the pressure or flow capacity of the air-supply system, down to about 20 kPa (0.2 atm). Exhaust suction is provided either by the centrifugal compressors of the air-supply system or by a two-stage, steam-ejector system with an interstage condenser.

Liquid fuels are supplied to Cell A3 from two large (114 m^3), aboveground tanks. Each tank is provided with a centrifugal pump to transfer fuel through 10.2-cm pipelines. The high-pressure fuel pumps, located in Cell A3, boost the fuel pressure as high as 8.37 MPa (82.6 atm). The available fuel pressures and flows with these pumps were more than adequate for this test program; there was ample margin for metering and control.

The data-processing equipment permanently installed in Cell A3 includes a 900-channel digital data-acquisition system, strip-chart recorders for continuous recording of up to 24 test parameters, and displays of 22 pressures, 24 temperatures, and 4 fuel flows for use by the operators in controlling test parameters, plus a small analog computer that is generally programmed to calculate airflows and fuel/air ratios. Portable equipment includes a teletype terminal for the time-sharing computers. The valves used to regulate fuel flows, airflows, combustor air temperatures, and combustor air pressures are remotely operated from the control room by means of pneumatic controls.

Throughout a combustor test, data are recorded by the digital data-acquisition system in the test cell. This apparatus scans each of the measured parameters in sequence, controls the position of pressure scanning valves when required, converts the amplified d.c. signal of the measurement to digital form, and records the value on a perforated paper tape suitable for input to the time-sharing computer through the teletype terminal. During each scan, the overall voltage accuracy is checked against a precision potentiometer that has been calibrated in a standards laboratory. The digital voltmeter and low-level amplifier are of sufficient quality that voltages are accurate to 0.02% of full-scale in the 0 to 10-millivolt range.

All connections between data sensors and readout instrumentation, and all programming of the sequencing and control circuitry, are accomplished through interchangeable program boards. Thus, each test setup includes a prewired, preprogrammed, front panel to aid rapid changeover from one circuit configuration to the next.

To measure emissions, the facility is equipped with a CAROL II gas-analysis system along with a standard GE filter-stain type smoke console. Current analysis instruments in the CAROL II system are:

- Beckman Model 402 total hydrocarbon analyzer (flame ionization detector)

- Beckman Model 315-B carbon monoxide and carbon dioxide analyzer (NDIR)

- Beckman Model 951-H NO_x analyzer (chemiluminescence with converter, water trap required)

Output from these analyzers is recorded on strip-chart paper, on hand-logged data-acquisition sheets, and is input directly into the facility data-acquisition and processing equipment. Smoke samples are submitted to the General Electric Instrumentation Data Reduction Facility, following the completion of a test, for processing. A schematic of the Cell A3 facility data-acquisition installation setup is shown in Figure 28.

6.7 FULL-ANNULAR COMBUSTOR TEST PROCEDURES

The E^3/F101 full-annular testing was directed at evaluating the NO_x emission characteristics. Therefore, test conditions for the full-annular combustor were designed to simulate the combustor bulk residence times of the proposed E^3 alternate combustor in an F101 combustor test vehicle operating at the E^3 cycle conditions.

The full-annular combustor was evaluated at inlet conditions corresponding to 4%, 6%, 30%, 85%, and 100% of sea level takeoff thrust plus several intermediate power conditions for the revised E^3 July 1978 operating cycle. Data were also obtained at 4% of sea level takeoff thrust for the E^3 FPS baseline operating cycle. The combustor inlet conditions at the 85% and 100% power settings were derated to avoid exceeding the test facility capabilities. At the low-power conditions, data were obtained over a range of combustor fuel/air ratios. At the E^3 July 1978 cycle conditions for 4%, 6%, and sea level takeoff, several test points representing variations in the combustor bulk residence time were also evaluated. A list of test points and corresponding operating conditions for the full-annular combustor test is presented in Table XI.

The test points were run in order of increasing combustor inlet temperature for safety considerations and to expedite testing. As test conditions were changed, the combustor pressure drop and the various combustor metal temperatures were monitored on multichannel strip-chart recorders to ensure that the established transient safety limits were not exceeded. When each test condition was set and stabilized, the data were recorded in two phases. First the fixed combustor instrumentation (inlet air pressure and temperature, airflow, fuel flow, metal temperatures, exit pressure, etc.) was recorded. Then a recording of the pollutant-emissions data at numerous positions in the combustor exit plane was made.

Smoke-emission levels were also measured at selected test points of interest. At those conditions where smoke data were acquired, samples were extracted from the combustor exit plane with two gas-sampling rakes. These two

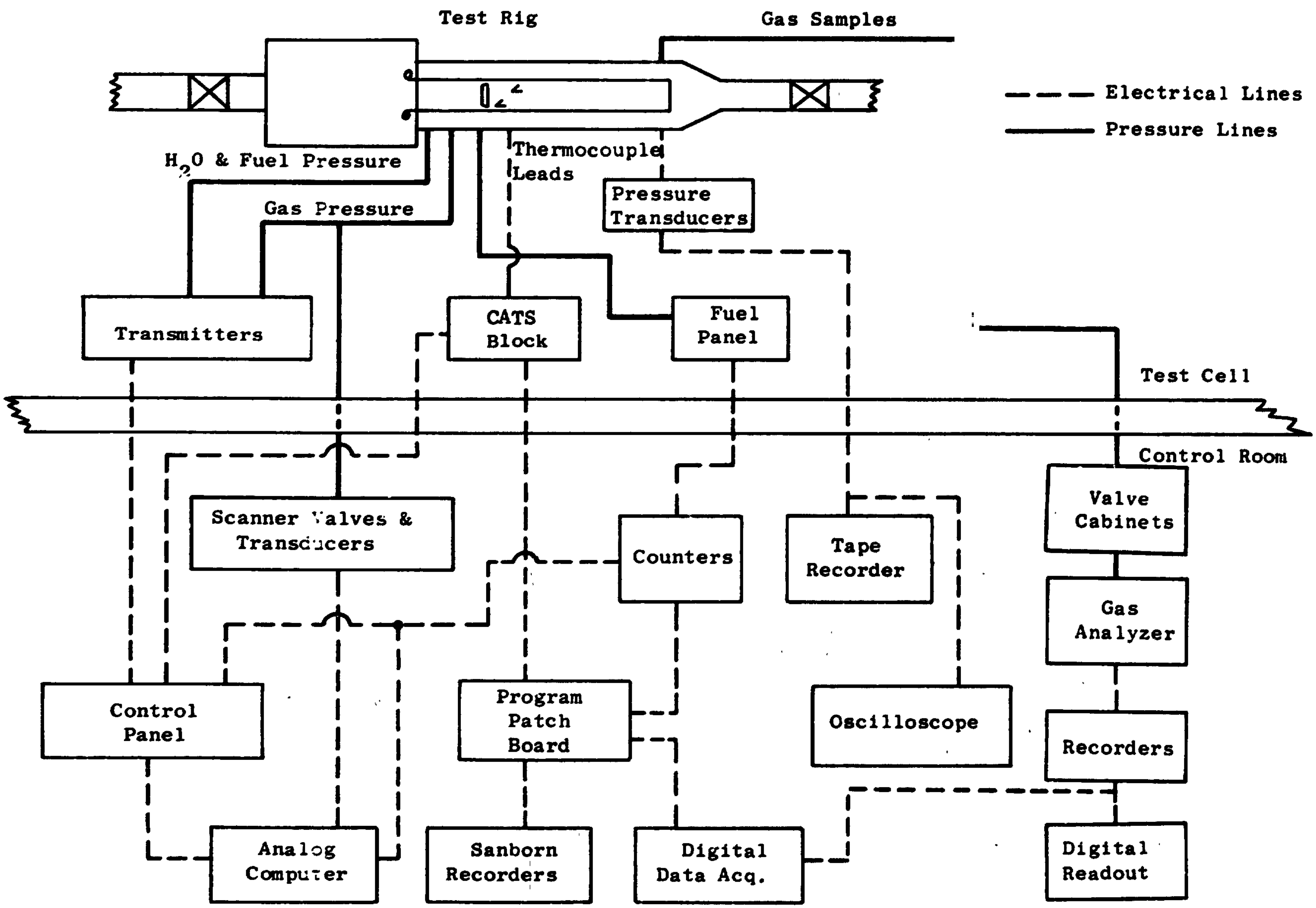


Figure 28. Test Facility Data-Acquisition Schematic.

Table XI. Full-Annular Combustor Test Schedule.

Point	Operating Condition	T_3, K	P_3, Atm	W_c, kg/sec	f/a	t, msec	Sample Conditions
1	4% Ground Idle	448	3.16	9.30	0.0090	2.69	G
2	(FPS Cycle)	↓	↓	↓	0.0016	↓	I, S
3		↓	↓	↓	0.0160	↓	G
4		↓	↓	↓	0.0200	↓	G
5		↓	↓	↓	0.0250	↓	G
6	4% Ground Idle	478	3.12	8.45	0.0090	2.48	G
7	(July 1978 Cycle)	↓	↓	↓	0.0120	↓	G
8		↓	↓	↓	0.0158	↓	I, S
9		↓	↓	↓	0.0200	↓	G
10		↓	↓	↓	0.0250	↓	G
11		↓	↓	9.38	0.0160*	2.39	G
12		↓	↓	9.91	0.0247*	2.27	G
13	6% Ground Idle	508	3.93	10.87	0.0090	2.46	G
14	(July 1978 Cycle)	↓	↓	↓	0.0120	↓	G
15		↓	↓	↓	0.0143	↓	I, S
16		↓	↓	↓	0.0200	↓	G
17		↓	↓	↓	0.0250	↓	G
18		↓	↓	12.12	0.0245*	2.39	G
19		↓	↓	12.79	0.0246*	2.27	G
20	30% Approach	633	11.68	30.69	0.0100	2.35	G
21		↓	↓	↓	0.0139	↓	I, S
22		↓	↓	↓	0.0160	↓	G
23	85% Climbout	782	16.33	37.26	0.0223	2.00	I, S
24	100% Sea Level	814	16.33	36.24	0.0244	1.96	I, S
25	Takeoff	↓	15.88	↓	↓	1.90	G
26		↓	15.17	↓	↓	1.80	G
A	Intermediate	478	3.12	8.45	0.0158		G
B		533	5.15	14.06	0.0125		G
C		589	8.34	22.3	0.0125		G
D		672	15.10	37.5	0.0156		G
E		728	16.33	39.5	0.0188		G
F		797	16.33	36.8	0.0235		G

*NOTE: Fuel/air ratio set to correspond to fuel/air ratio at which the minimum CO emissions occurred during the test condition series.

S - Smoke sample taken
G - Ganged emissions sample taken
I - Individual emissions samples taken

sampling rakes were manifolded to provide a single sample to the smoke-measurement console. At least three smoke spots were taken at each test condition, and the SAE Smoke Number for this operating point was determined from the average of the three spots judged most uniform from the samples taken.

6.8 FULL-ANNULAR COMBUSTOR DATA-ANALYSIS PROCEDURE

Measured combustor performance and emissions data obtained at each test point were directly input to the Cell A3 facility data-acquisition equipment where it was converted to digital output. This digital output was then input to a computer for reduction of the data to engineering units and emissions indices. The reduced data from the computer were printed at a terminal site located in the facility control room. Total time for the complete acquisition and processing of data at each test point was generally accomplished in 10 minutes or less.

Values for the various measured and calculated performance parameters along with the appropriate measured and adjusted emission levels for each test point are tabulated in Appendix A. Because the combustor inlet conditions were derated at the 85% and 100% power settings, the measured emissions levels were adjusted to the actual engine cycle conditions using adjustment relations defined in Appendix B.

7.0 DEVELOPMENT TEST RESULTS

7.1 SECTOR-COMBUSTOR IDLE EMISSIONS

Idle emissions characteristics of the sector-combustor test configurations were evaluated at conditions that provided a simulation of the cold dome velocity of the proposed E^3 single-annular combustor design. Test conditions above 4% ground idle thrust were derated to avoid exceeding the sector-combustor test rig and facility capabilities. Gaseous exhaust emissions measured at these derated test conditions were adjusted to the actual E^3 cycle conditions by employing the relations defined in Appendix B.

The discussion of sector-combustor idle emissions is in two parts. The first part will present the results of those sector-combustor test configurations evaluated at the E^3 FPS baseline cycle conditions (SA-00, SA-01, and SA-02). The second part will present the results of those test configurations evaluated at the E^3 July 1978 cycle conditions (SA-03 through SA-08). Prior to completion of the sector-combustor testing program, a third engine-operating cycle was defined and issued in October 1978. A comparison of the combustor operating conditions for the FPS baseline, July 1978, and the October 1978 E^3 cycles is presented in Table XII. To maintain the continuity of the test program, the July 1978 cycle was retained for the remainder of the test program as the basis for test conditions. Because of the complexity of adjustment to a common cycle, the emissions data are presented at the cycle conditions at which the sector-combustor configurations were tested. However, to provide a convenient basis of comparison, emissions results in the form of the EPA parameter are presented in terms of the October 1978 cycle.

At the start of the test program, emissions data were obtained on a standard F101 PV sector-combustor configuration (SA-00). The geometry and airflow distribution of this standard F101 PV combustor design were quite different than the proposed E^3 combustor design. Therefore, this configuration did not provide a close simulation of the E^3 single-annular combustor cold-dome velocity. This test was conducted to obtain reference emissions data for a conventional, single-annular combustor design operating at the E^3 cycle conditions. The CO and HC emissions levels obtained at ground idle for this sector-combustor test exceeded the goals as shown in Figure 29.

The baseline E^3/F101 single-annular, sector-combustor configuration (SA-01) was designed to provide a close simulation of the proposed E^3 single-annular combustor primary-zone airflow distribution and cold-dome velocity using a modified F101 PV sector combustor. These modifications were previously described and illustrated in Figure 6 of Section 4.0. HC emission results obtained with this baseline configuration were significantly reduced as shown in Figure 29. However, only a slight reduction in CO emission was observed; the CO emission levels remained well above program goals.

Table XII. Combustor Operating Conditions for E^3 FPS, July 1978, and October 1978 Cycles.

Conditions		FPS				July 1978				October 1978			
		P3, Atm	T3, K	$\dot{W}c$, kg/sec	f/a	P3, Atm	T3, K	$\dot{W}c$, kg/sec	f/a	P3, Atm	T3, K	$\dot{W}c$, kg/sec	f/a
Ground Idle	4%	3.16	448	7.7	0.0117	3.12	478	7.0	0.0158	3.35	487	7.6	0.0154
	6%	3.96	485	9.5	0.0120	3.93	508	9.0	0.0143	4.22	517	9.7	0.0140
Approach	30%	11.67	633	25.6	0.0139	11.67	633	25.6	0.0139	11.90	637	26.1	0.0141
Climb	85%	25.91	782	49.1	0.0223	25.91	782	49.1	0.0223	25.95	782	49.5	0.0224
Sea Level Takeoff	100%	29.80	814	54.9	0.0244	29.80	814	54.9	0.0244	29.80	814	55.2	0.0245

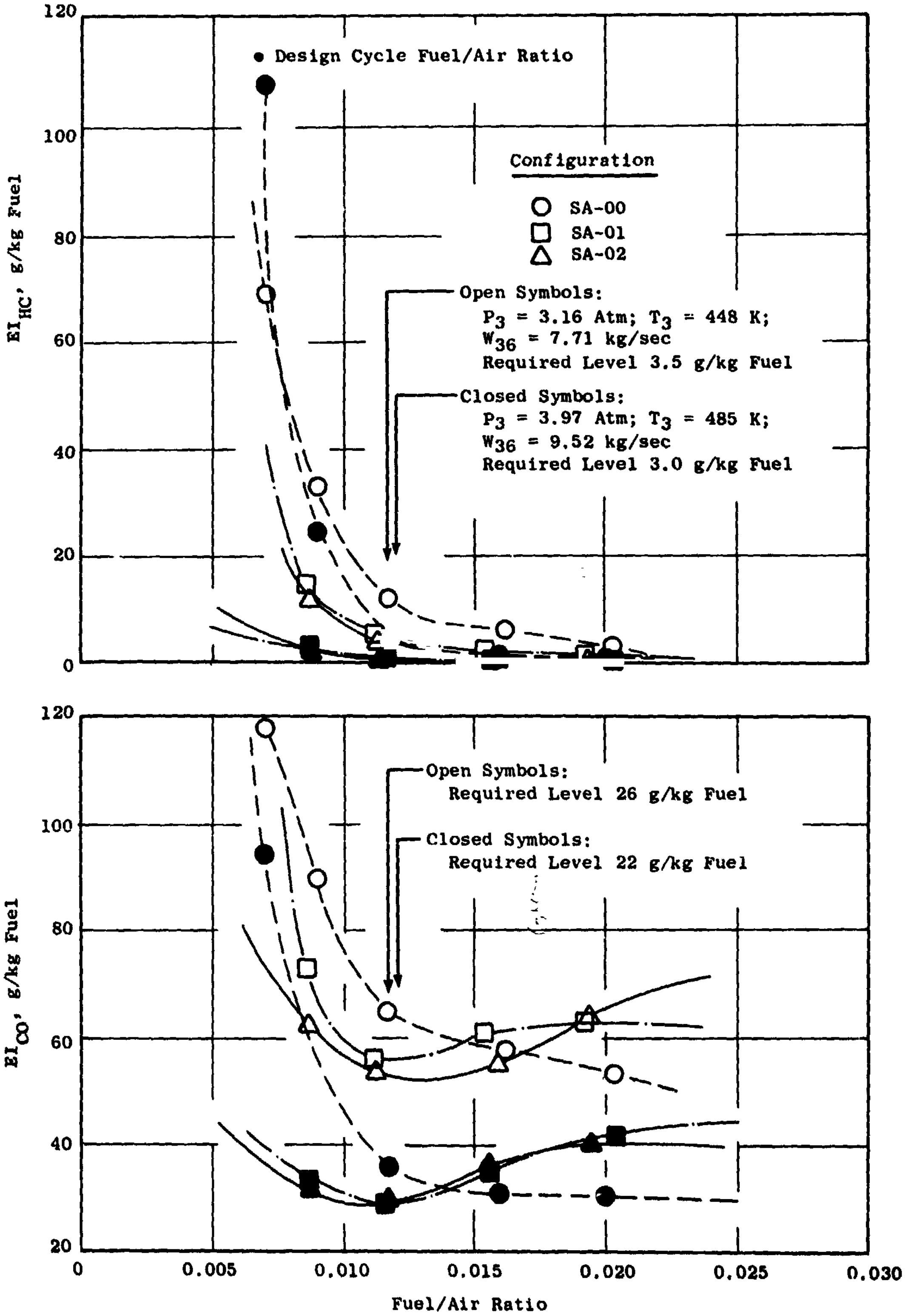


Figure 29. Sector-Combustor Configurations SA-00, SA-01, and SA-02: CO and HC Emissions Results.

The next configuration modification (SA-02) featured a reduced-flow primary swirler and elimination of the cooling flow in the swirl-cup sleeve insert. These changes were designed to enrich the combustor dome stoichiometry and increase the primary-combustion-zone residence time by the elimination of air in the vicinity of the swirl cup. As shown in Figures 29 and 30, this sector-combustor configuration demonstrated no significant change in the CO or HC emission levels from Configuration SA-01. The benefit of the increased primary-zone residence time in reducing the CO emissions was offset by the adverse effect of the excessively rich dome stoichiometry.

Sector-combustor Configuration SA-03 featured elimination of the inner and outer dome ring cooling flows and elimination of the first-panel cooling flow of the inner and outer liners. To maintain the same total combustor flow area, the secondary dilution area was increased to offset the forward cooling-flow areas that were eliminated. Previous experience has shown that the secondary dilution has little, if any, impact on measured CO and HC emissions levels. Blocking these cooling flows in the dome region was intended to eliminate quenching effects on the primary-combustion-zone reaction. These quenching effects are believed to contribute significantly to the production of large quantities of CO and HC emissions in the combustor dome. As expected, results from this test configuration indicated significant reductions in CO and HC emissions levels (Figure 31). The CO emission levels were still above the program goals at the design-cycle operating conditions. However, levels approaching or satisfying these goals were achieved at a fuel/air ratio of 0.009; this is less than the design-cycle fuel/air ratio of 0.0158. The HC emission levels achieved with Configuration SA-03 were well below the required levels.

Sector-combustor Configuration SA-04 involved substantial design modifications, including: the addition of impingement cooling to the forward section of the inner and outer liners, increased primary-swirler airflow, increased primary dilution airflow, and reduced secondary dilution airflow. Cooling airflows for the second panel both of the inner and of the outer liner were also increased. The increased liner cooling was adopted along with the impingement-cooling concept because of the excessively high inner and outer liner forward-panel temperatures encountered during the test of Configuration SA-03. The increased swirl-cup and primary dilution flows were adopted to provide better mixing for reduced CO emissions and to lean the combustor primary reaction zone, thus, moving the minimum CO emission levels to the design-cycle fuel/air ratio. The secondary dilution airflow was reduced to maintain the total combustor flow area. As observed in Figures 31 and 32, a slight reduction in CO emission levels and a slight increase in HC emission levels were obtained for Configuration SA-04. The less-than-anticipated reduction in CO emission levels resulted from the decrease in residence time offsetting the benefits of the better mixing conditions. However, the minimum CO emission levels occurred at a fuel/air ratio that more nearly approached the design value than was obtained with Configuration SA-03. Although HC emission levels increased, they remained well below the E^3 goals.

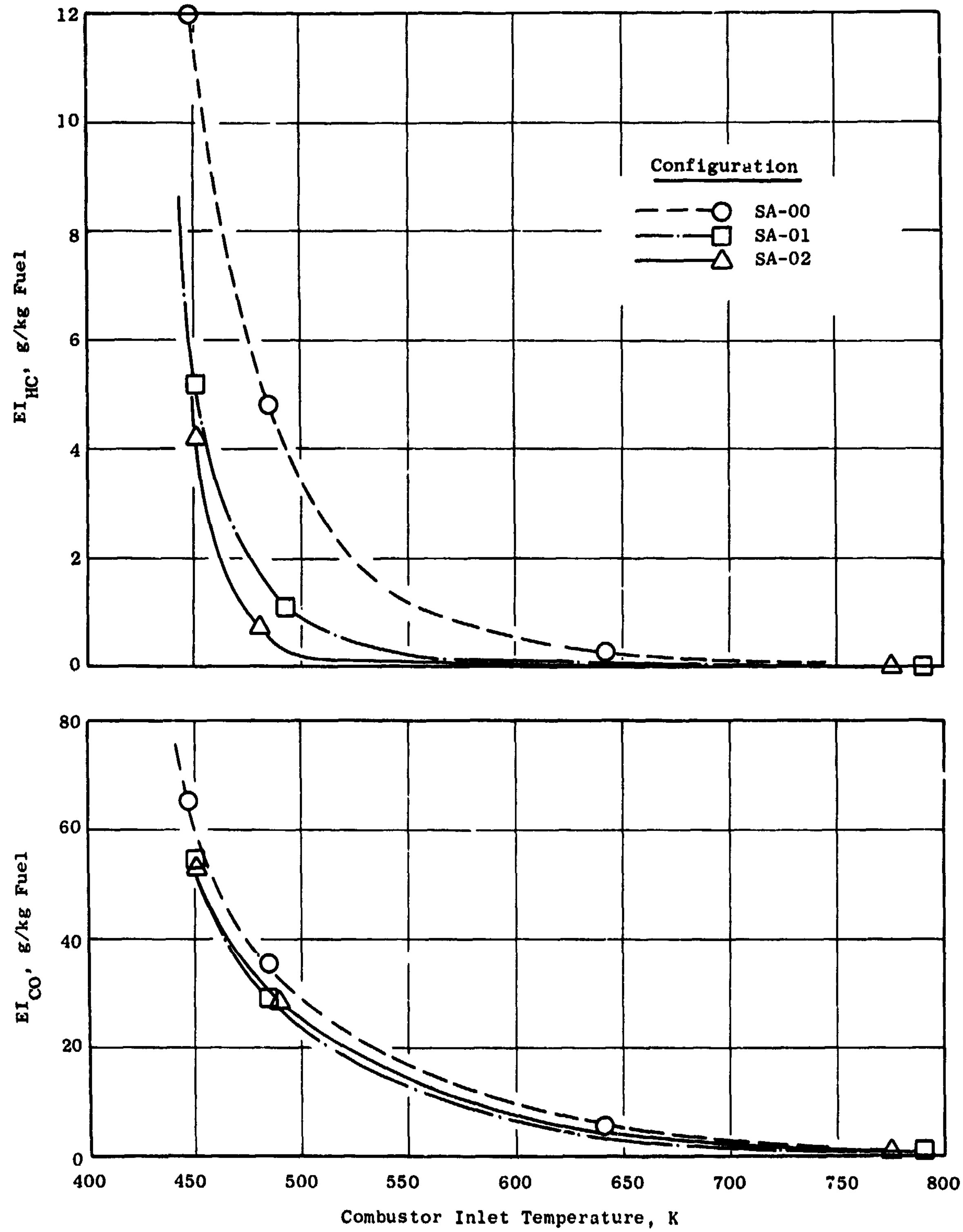


Figure 30. Sector-Combustor Configurations SA-00, SA-01, and SA-02: CO and HC Emissions Results Along the Design-Cycle Operating Line.

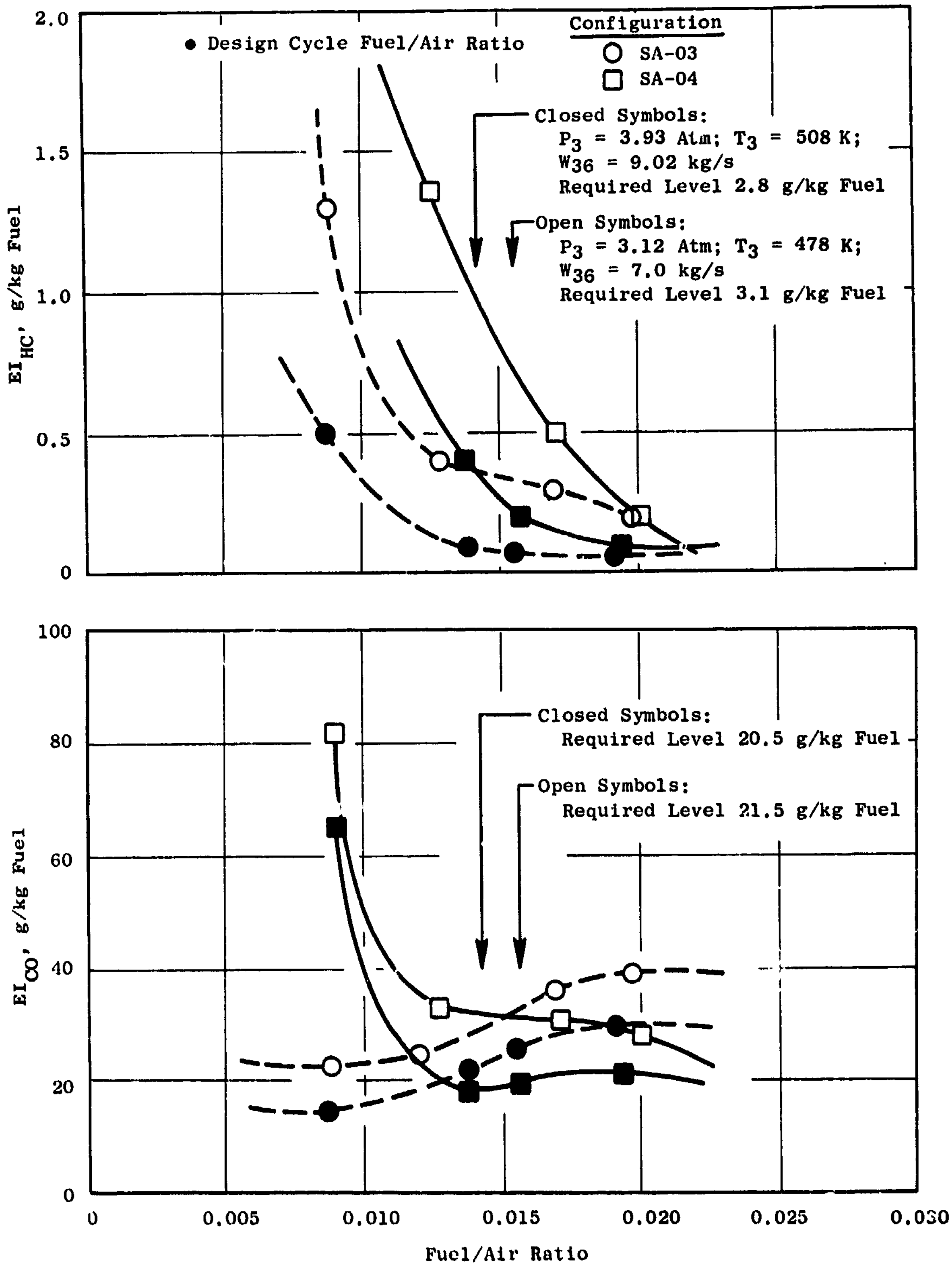


Figure 31. Sector-Combustor Configurations SA-03 and SA-04: CO and HC Emissions Results.

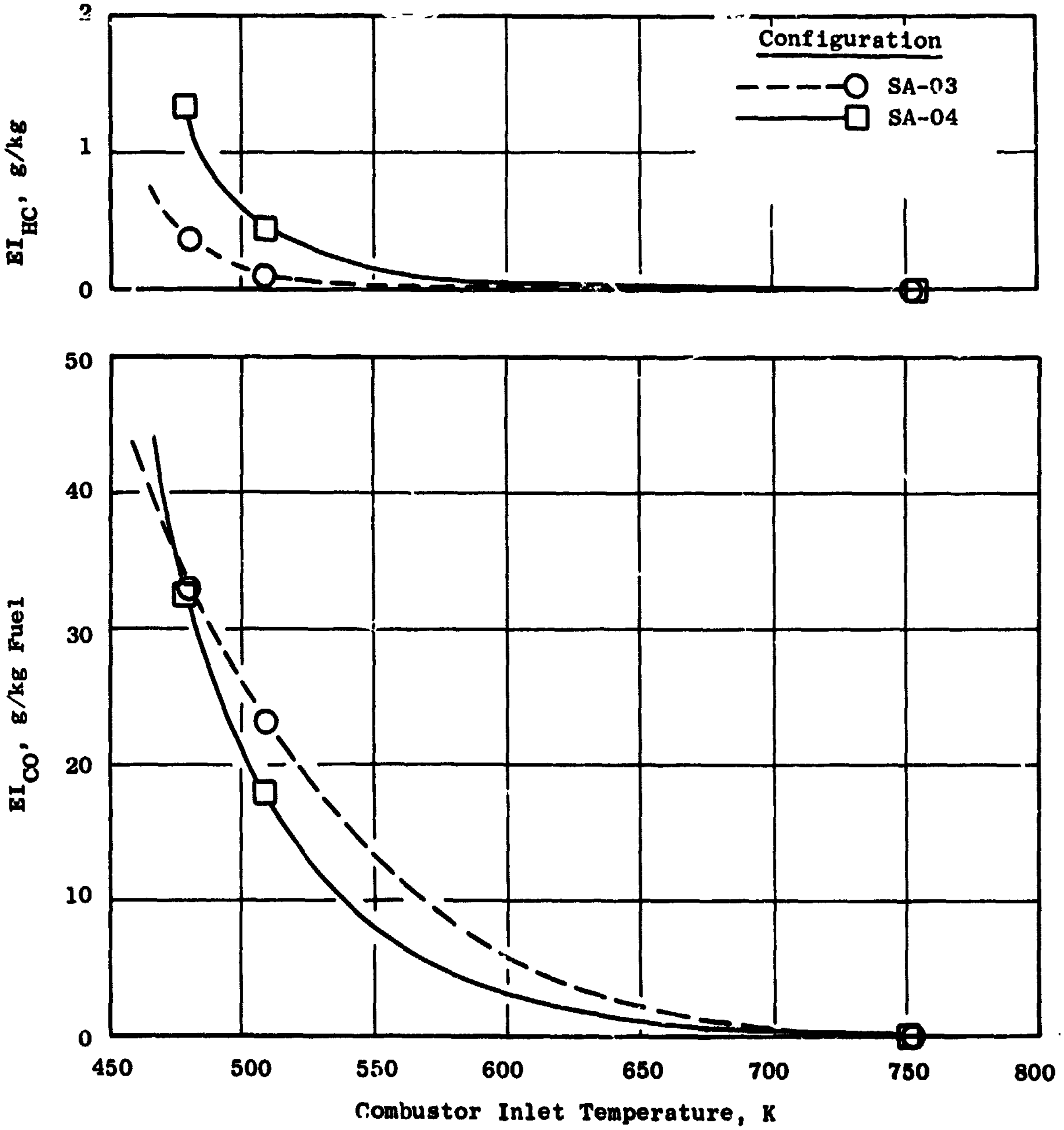


Figure 32. Sector-Combustor Configurations SA-03 and SA-04: CO and HC Emissions Results Along the Design-Cycle Operating Line.

A 50% reduction in dome splash-plate cooling flow and an increase in secondary dilution flow were incorporated in sector-combustor Configuration SA-05. The reduction in the dome splash-plate cooling was adopted to further reduce quenching effects from dome cooling flows. The corresponding increase in secondary dilution flow was incorporated to maintain the total combustor flow area. The CO and HC emissions levels obtained for Configuration SA-05 were similar to the levels previously obtained for Configuration SA-03. The combination of the increased swirl cup flow and the reduction in the splash-plate cooling flow produced a dome flow level and stoichiometry similar to that of Configuration SA-03. This, coupled with the similar (high) liner temperature, produced the observed similarity in the CO and HC emissions results.

The inner and outer dome ring-cooling flows were reintroduced in Configuration SA-06 to reduce the excessively high inner and outer liner forward-panel temperatures encountered during the test of Configuration SA-05. Total combustor flow area was maintained by a decrease in secondary dilution. The interior flowpath contour was smoothed by using a thin strip of sheet metal to eliminate the step created by the first-panel cooling overhang of the inner and outer liners. Results from testing of this configuration showed significant increases in the CO and HC emissions levels at 4% idle. Smaller increases were observed at 6% idle. These results demonstrate the sensitivity of the CO and HC emissions to the dome cooling-airflow levels. Despite the increases in CO and HC emissions, the HC emission levels remained below the program target goals.

In sector-combustor Configuration SA-07, the splash-plate cooling air eliminated in Configurations SA-05 and SA-06 was reintroduced. Fuel nozzles with narrower fuel-spray angles were also introduced. These changes were made to evaluate in sector form a combustor configuration similar to that planned for the high-pressure, full-annular combustor test. With this configuration, further increases in the CO emission levels were obtained with little change in the HC emission levels.

The final sector-combustor test Configuration (SA-08) incorporated all of the desirable features evolved earlier to obtain low CO and HC emissions levels at the design-cycle fuel/air ratio. Based upon previous test results, these changes, in general, were expected to produce excessively high liner temperatures. However, this test configuration was intended to demonstrate CO and HC emissions levels that would satisfy the program goals at the design-cycle fuel/air ratio. With this configuration, CO emission levels of 26.0 g/kg fuel and 12.5 g/kg fuel, respectively, were obtained at 4% and 6% thrust at idle. These represent the lowest CO emission levels obtained for any of the nine sector-combustor configurations evaluated in the sector test program. CO emission levels which would satisfy the goals at 4% thrust at ground idle were obtained at a fuel/air ratio of 0.010 to 0.012 which is about 25% below the design-cycle fuel/air ratio. The HC emission levels for this configuration were well below the program goals. The CO and HC emissions levels achieved with sector-combustor Configurations SA-05 through SA-08 are illustrated in Figures 33 and 34.

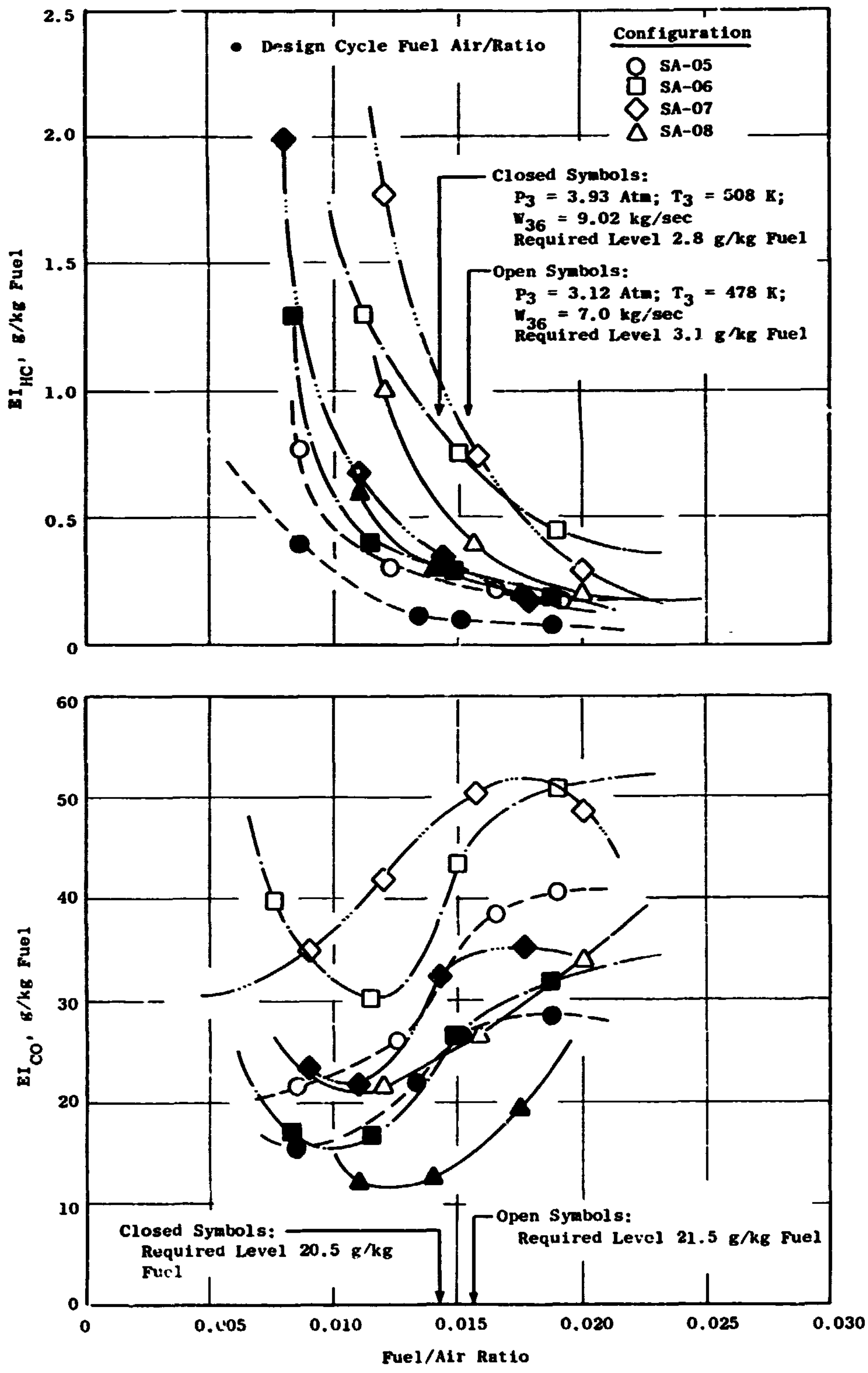


Figure 33. Sector-Combustor Configurations SA-05, SA-06, SA-07, and SA-08: CO and HC Emissions Results.

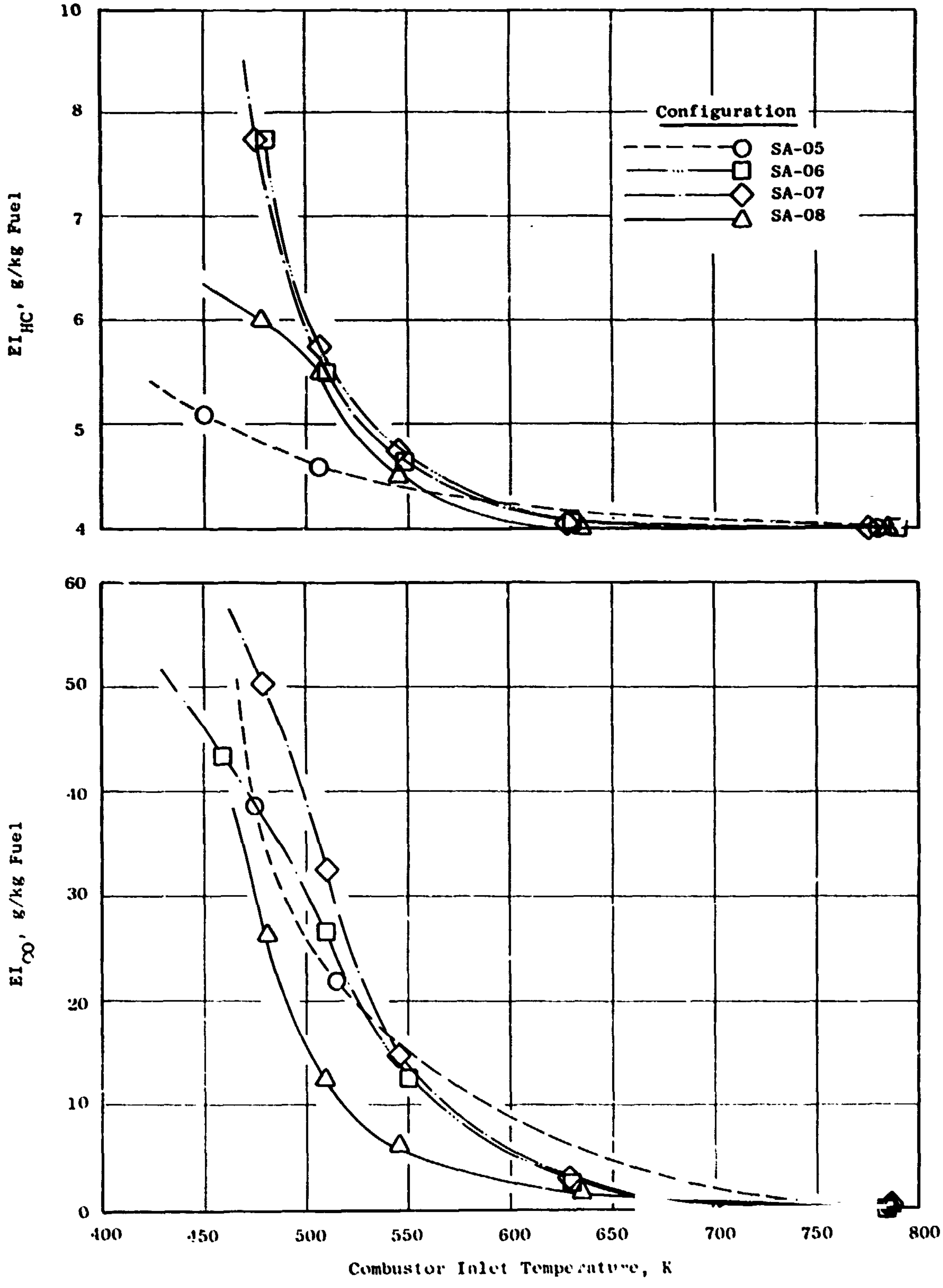


Figure 34. Sector-Combustor Configurations SA-05, SA-06, SA-07, and SA-08: CO and HC Emissions Results Along the Design-Cycle Operating Line.

7.2 SECTOR-COMBUSTOR NO_x EMISSIONS

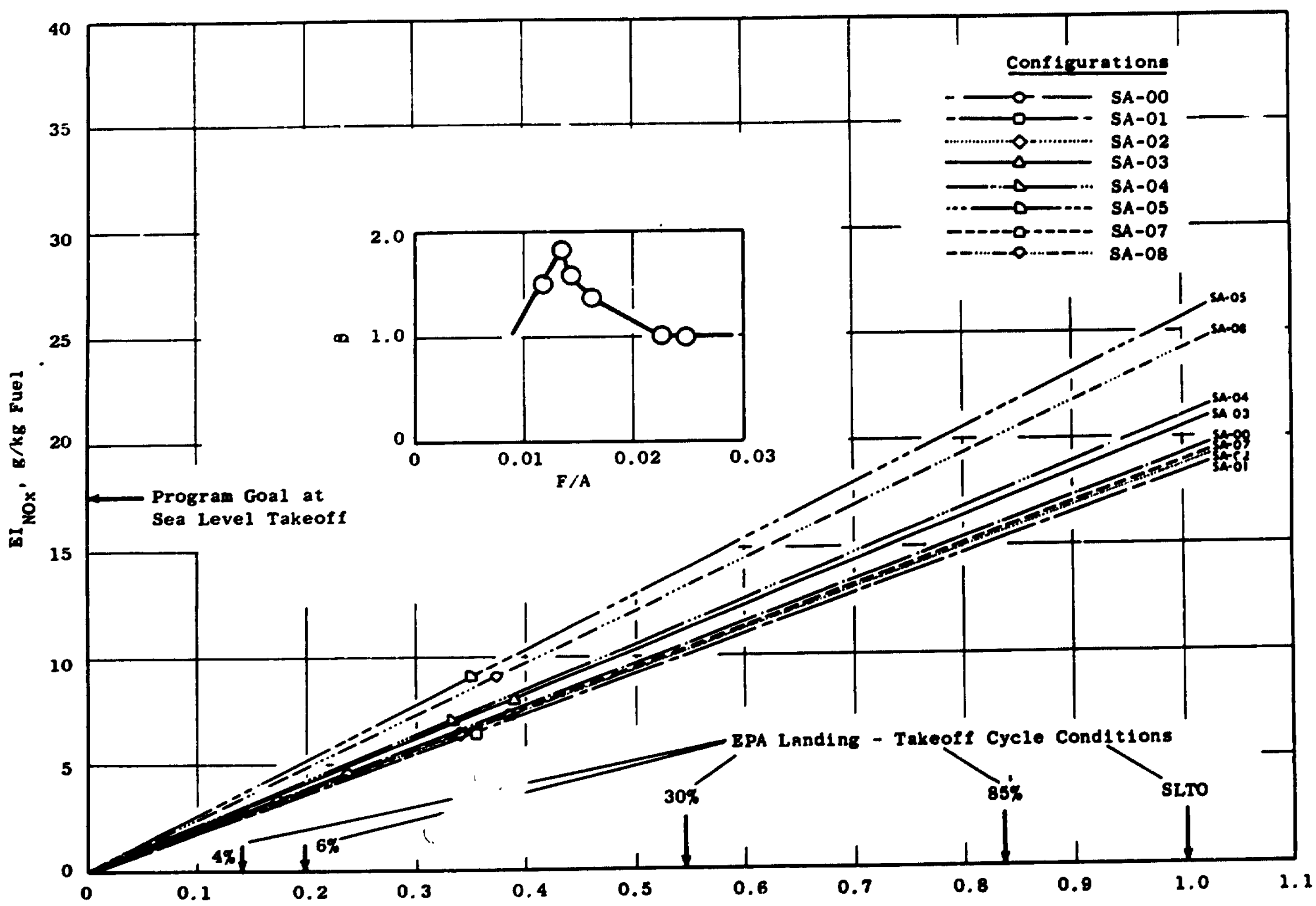
With the exception of Configuration SA-06, NO_x emission data were obtained on all sector-combustor configurations at simulated sea level takeoff conditions. NO_x emission data for Configuration SA-06 were not obtained because the NO_x analyzer was unavailable at the time of the test.

Because of test rig and facility limitations, the sector-combustor inlet pressure, airflow, and temperature test conditions at simulated sea level takeoff were derated. Measured NO_x emission levels obtained for each configuration at these derated-high-power conditions were then adjusted to the actual E^3 cycle conditions.

Because the sector-combustor test conditions were designed to simulate the proposed E^3 single-annular combustor cold dome velocity, further adjustment to the measured NO_x emission data was required to simulate E^3 single-annular combustor bulk residence time. Geometric dissimilarities between the proposed E^3 single-annular combustor design and the E^3/F101 single-annular combustor test vehicle prevented simulation of both the cold dome velocity and bulk residence time with one set of test conditions. Insufficient test time and funding prevented evaluating each sector-combustor configuration at conditions which would simulate both the cold dome velocity and bulk residence time. Since it is believed that the bulk residence time is a significant controlling factor in NO_x emission characteristics, it was decided that the adjustment of the sector-combustor emission data for bulk residence time was necessary for a more meaningful representation of the expected NO_x emissions for a single-annular combustor. The relationship employed to provide these required adjustments to the NO_x emission data is discussed in Appendix B. The adjustment procedure provides a linear relation with measured NO_x emission data along the engine cycle operating line and permits extrapolation of NO_x emission data, measured at derated test conditions, to the actual engine cycle sea level takeoff conditions.

NO_x emission levels from eight of the nine sector-combustor configurations are plotted against this adjustment relation for the E^3 October 1978 cycle conditions in Figure 35. In order to meet the E^3 goal for NO_x emissions, it was determined that a NO_x emission level of 17.5 g/kg fuel was required at the E^3 sea level takeoff condition. As observed from Figure 35, none of the sector-combustor configurations tested met with the target level for NO_x emissions at sea level takeoff.

A summary of the sector-combustor test results in terms of the October 1978 E^3 cycle is presented in Table XIII It is observed from the table that, with the exception of Configuration SA-07, all of the sector-combustor configurations tested demonstrated CO emission levels that satisfy the program goals at 6% ground idle thrust. This is due to the higher combustor-inlet pressures and temperatures associated with the October 1978 cycle. However, only Configuration SA-08 demonstrated CO emission levels that satisfy the program goals at 4% ground idle thrust. All of the sector-combustor configurations tested demonstrated HC emission levels which satisfy the program goals



$$\text{Severity Parameter (S)} = \left(\frac{2.124 \times 10^4 \, P_3 \, (1 - \Delta P/P_3)/RT_4 \, W_c}{2 \times 10^{-3}}\right)\left(\frac{P_3}{3.02}\right)^{0.37} \beta(F/A) \, \text{Exp}\left(\frac{T_3 - 815}{192}\right)$$

Figure 35. Sector-Combustor NO_x Emissions Results.

with margin at 4% and 6% ground idle thrust. However, none of the configurations tested demonstrated NO_x emission levels which satisfy the program goals at simulated sea level takeoff. In general, those configurations which demonstrated low CO emission levels also demonstrated higher NO_x emission levels.

Table XIII. Summary of Sector-Combustor Emissions.

- October 1978 Cycle
- CO and HC Emissions for Simulated Cold-Dome Velocity.
- NO_x Emissions for Simulated Bulk Residence Time.

	Emissions Index, g/kg Fuel				
	CO		HC		NO_x
Configuration	4%	6%	4%	6%	SLTO
SA-00	28.5	17.4	1.4	0.3	19.2
SA-01	29.4	18.6	0.5	0.5	18.3
SA-02	32.6	18.4	0.3	0.2	18.7
SA-03	26.2	18.7	0.3	0.1	20.3
SA-04	25.1	13.5	0.9	0.4	20.7
SA-05	25.8	17.6	0.2	0.2	25.6
SA-06	34.7	19.5	0.5	0.2	N/A
SA-07	39.6	24.3	0.5	0.2	18.8
SA-08	17.5	8.6	0.3	0.2	24.2
Full Annular	36.6	24.4	1.3	0.4	21.7
Goals	20.0	19.2	2.8	2.7	17.5

7.3 SECTOR-COMBUSTOR PERFORMANCE

Sector-combustor performance data were obtained from the test rig pressure and temperature instrumentation at each test point investigated. The data were used to determine combustor pressure drops, airflow distributions, and liner temperature distributions.

Measured overall combustor pressure drops for all nine sector-combustor configurations evaluated are plotted against the square of the combustor inlet flow function parameter in Figure 36. As observed from this figure, all of the configurations evaluated exceeded the E^3 performance goals for a pressure drop of 5% at sea level takeoff. For Configurations SA-01 through SA-08, the excessive combustor pressure drops were determined to be the result of excessive losses in the standard F101 diffuser system when operating at higher than design airflow conditions. These high-flow conditions were

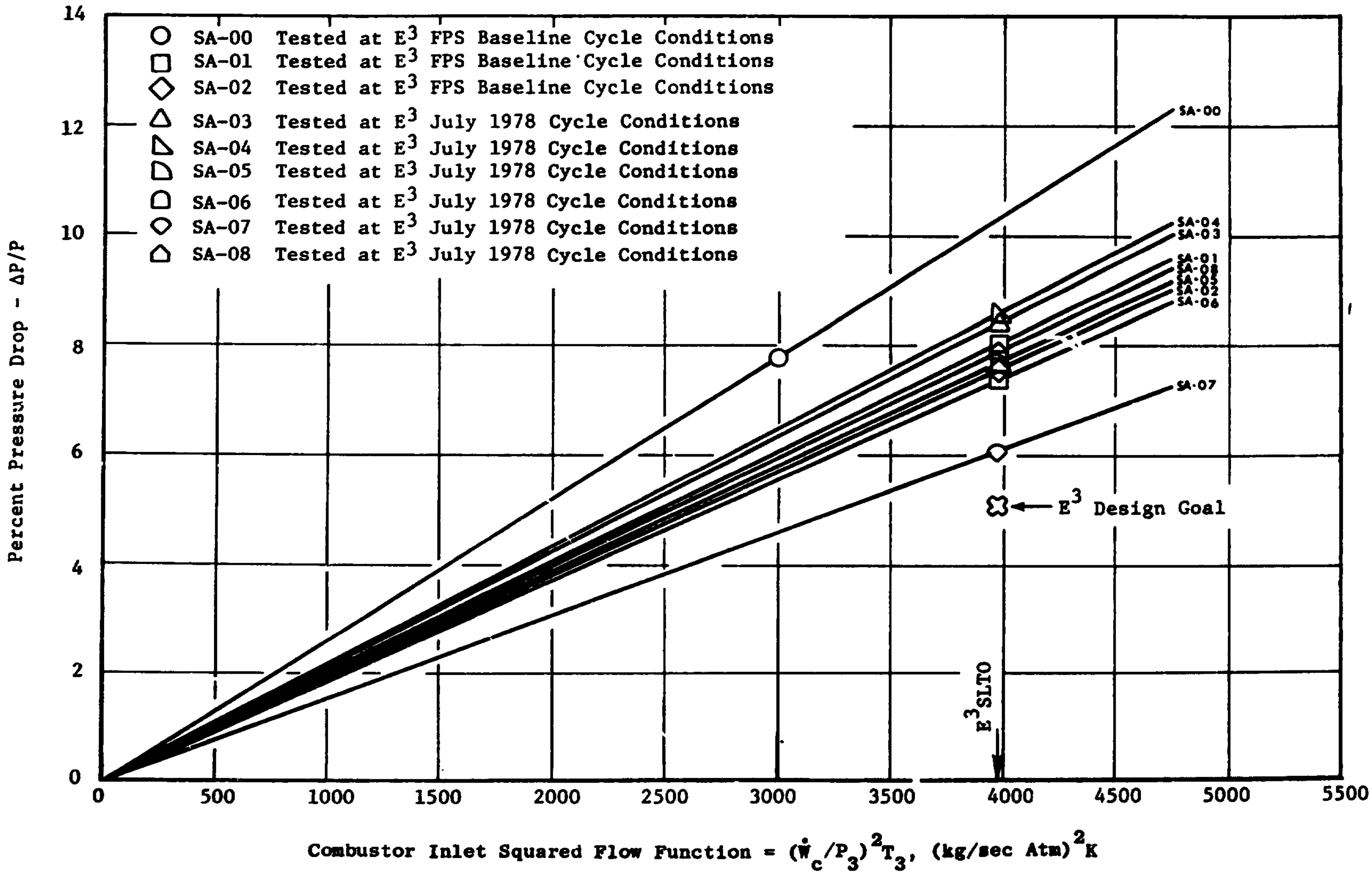


Figure 36. Sector-Combustor Overall Pressure Drops.

required to simulate the proposed E^3 single-annular cold dome velocity in the F101 PV combustor test vehicle. In the case of Configuration SA-00, the excessive overall combustor losses were attributed not only to the high diffuser-system losses but also to the combustor pressure losses chargeable to the smaller total combustor flow area of the standard F101 PV combustor.

With the exception of Configuration SA-00, estimated airflow distributions were calculated for each sector-combustor test configuration using measured static pressures obtained at various points along the cold and hot surfaces of the combustor liner and estimated effective flow areas. Configuration SA-00 did not have sufficient pressure instrumentation to provide an estimate of the airflow distribution. A summary of the estimated effective flow areas and corresponding airflow distributions for each configuration is shown in Table XIV.

For Configurations SA-01 through SA-03, eight skin thermocouples were located on the cold surfaces of the inner and outer liners as shown in Figure 37(a). As shown in Figure 37(b), a total of 22 liner skin thermocouples were used for Configurations SA-04 through SA-08; these configurations featured impingement cooling on the forward section of the liners. Configuration SA-00 was not instrumented with liner thermocouples. Indicated liner temperatures were recorded at each test point for Configurations SA-01 through SA-08; the temperature distributions obtained at simulated sea level takeoff conditions are presented in Table XV. Since the sector-combustor test conditions at the sea level takeoff conditions were derated due to facility and test rig limitations, liner temperatures approximately 8.5% higher than those presented in Table XV are anticipated at the actual engine operating conditions.

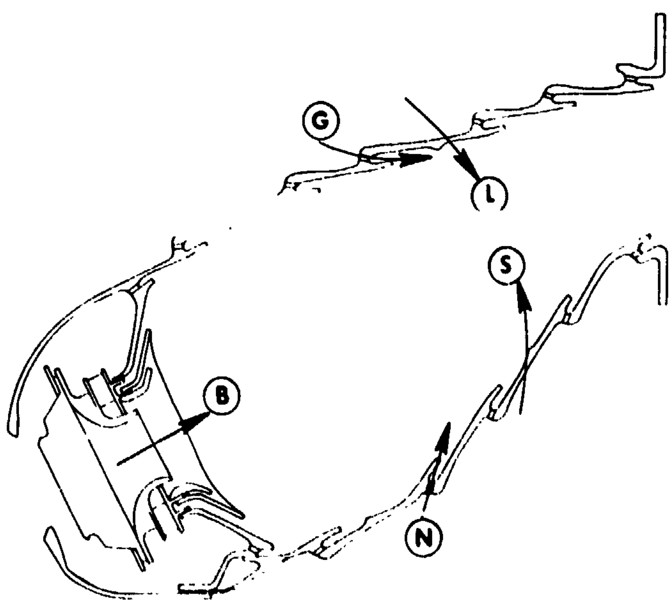
7.4 FULL-ANNULAR COMBUSTOR IDLE EMISSIONS

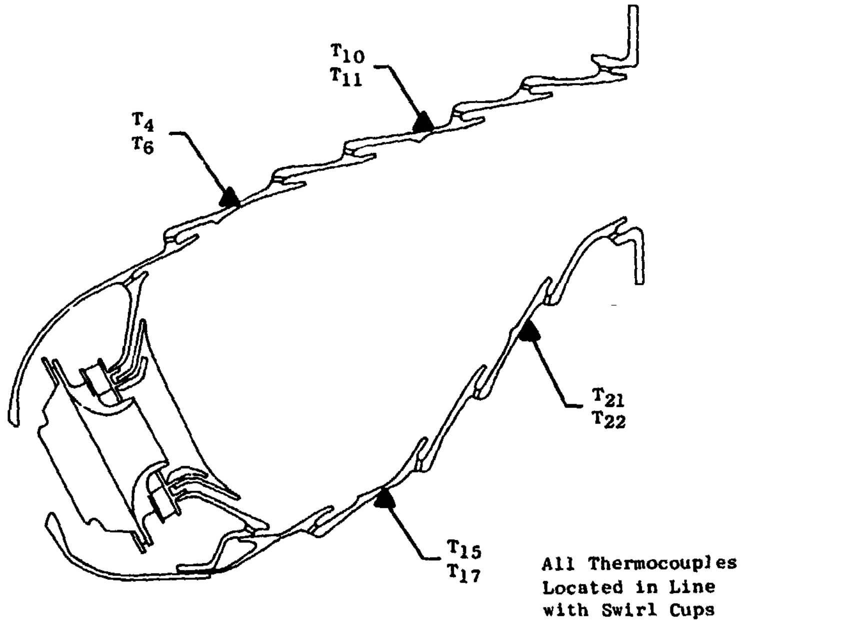
The primary purpose of the full-annular combustor test was the investigation of NO_x and smoke emissions at high pressure. Therefore, the test conditions used in this evaluation simulated only the E^3 single-annular combustor bulk residence time. As part of this test, low-power emissions data were also investigated. Measured CO and HC emissions levels obtained at the ground idle conditions investigated are plotted against the metered combustor overall fuel/air ratio in Figure 38. As shown in the figure, the HC emission levels obtained with this combustor configuration satisfied the program target levels for the three ground idle conditions tested. However, the CO emission levels were significantly above the program target levels. As indicated by the shape of the CO emission curves, little if any reduction in CO emission levels would be obtained by sectorized burning at idle. Sectorized burning is accomplished by supplying fuel to only a portion of the total, full-annular, swirl-cup array. The intent of the sectorized-burning concept is to reduce idle emissions by enrichment of the primary combustion zone in the fueled regions of the combustor while maintaining the overall cycle design fuel/air ratio. Correlation of data is made on the basis of an effective primary-zone fuel/air ratio defined as the overall fuel/air ratio times the reciprocal of the fraction of the total swirl cups fueled. The CO and HC emissions characteristics of this full-annular design for the combustor-inlet

Table XIV. Sector-Combustor Estimated Flow Areas and Airflow Distribution.

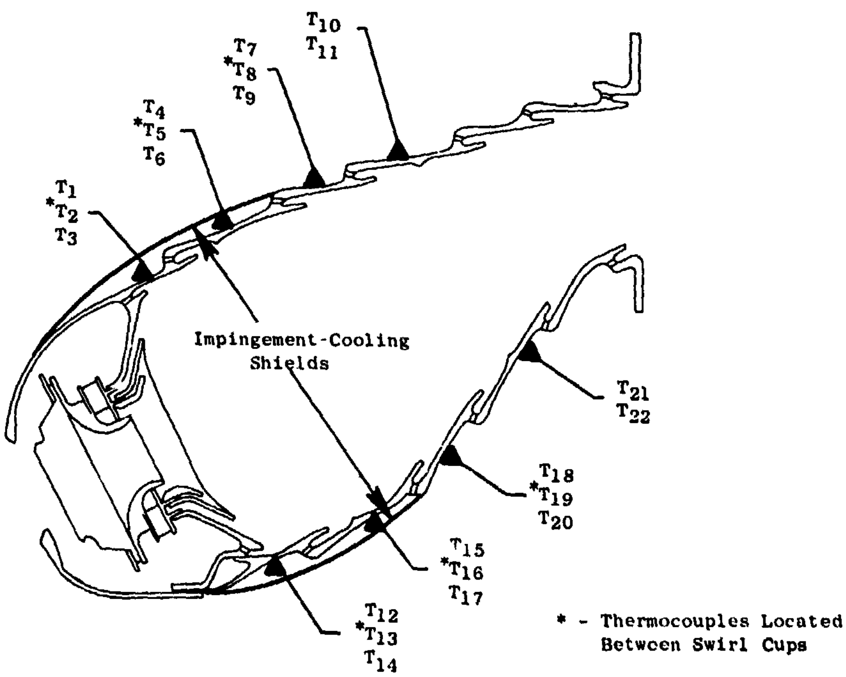
Configuration		Ⓖ	Ⓑ	Ⓝ	Ⓛ	Ⓢ	Total
SA-00	Ae	52.89	66.69	50.08	44.89	50.76	265.31
	%Wc	← Insufficient Data Available →					
SA-01	Ae	47.42	68.26	47.75	89.48	86.71	339.62
	%Wc	13.69	24.50	14.44	23.47	24.31	
SA-02	Ae	47.42	54.32	47.75	96.45	93.68	339.62
	%Wc	13.83	19.28	14.36	26.15	26.38	
SA-03	Ae	29.62	54.32	32.58	114.06	108.90	339.48
	%Wc	9.07	19.40	9.68	31.81	30.02	
SA-04	Ae	32.65	62.39	34.19	80.97	90.84	301.04
	%Wc	11.44	26.19	12.13	22.93	27.31	
SA-05	Ae	32.15	50.78	34.19	110.19	121.68	349.49
	%Wc	9.35	18.53	10.82	28.43	32.85	
SA-06	Ae	39.10	50.78	40.84	109.68	110.26	350.66
	%Wc	12.36	19.62	13.50	28.01	26.52	
SA-07	Ae	39.10	62.39	40.84	109.68	110.26	362.27
	%Wc	118.20	23.21	12.93	26.38	25.67	
SA-08	Ae	32.65	63.16	34.19	107.23	110.58	347.81
	%Wc	10.13	24.89	10.76	27.48	26.75	

Note: Flow Areas are cm^2 in Terms of a 360° (Full-Annular) Combustor.





(a) Configurations SA-01 Through SA-03



(b) Configurations SA-04 Through SA-08

Figure 37. Sector-Combustor Liner Thermocouple Locations.

Table XV. Summary of Sector-Combustor Liner Temperatures.

- Simulated Sea Level Takeoff Conditions.
- Temperatures in Kelvin.

Sector Combustor Configuration	F/A	T_3	T(1) T(2)	T(3) T(4)	T(5) T(6)	T(7) T(8)	T(9) T(10)	T(11) T(12)	T(13) T(14)	T(15) T(16)	T(17) T(18)	T(19) T(20)	T(21) T(22)
SA-01	.0240	787	* *	* 877	* 892	* *	* 943	946 *	* *	856 *	852 *	* *	965 944
SA-02	.0234	775	* *	* 878	* 916	* *	* 991	1006 *	* *	861 *	854 *	* *	982 953
SA-03	.0239	794	* *	* 1208	* 1260	* *	* 1260	1104 *	* *	1155 *	1116 *	* *	1097 1025
SA-04	.0232	752	823 867	--- 963	1138 1021	632 830	1041 889	917 869	891 843	1117 975	--- 930	904 ---	839 822
SA-05	.0143	784	856 808	--- 1063	1248 ---	--- ---	1090 892	--- 1015	--- 876	1276 1081	790 957	941 ---	862 858
SA-06	.0244	790	852 900	888 1054	1187 1129	--- 816	1046 931	969 ---	--- 934	881 865	847 971	936 936	876 842
SA-07	.0244	787	849 875	860 1009	--- ---	--- ---	--- 914	953 841	--- ---	840 840	831 938	932 916	880 841
SA-08	.0240	785	937 1110	1004 1268	1201 1278	999 996	1000 ---	1013 1104	1002 1107	1230 1024	1168 1065	1024 1037	--- 1056

(*) No thermocouples available.
(-) Thermocouples available but inoperative

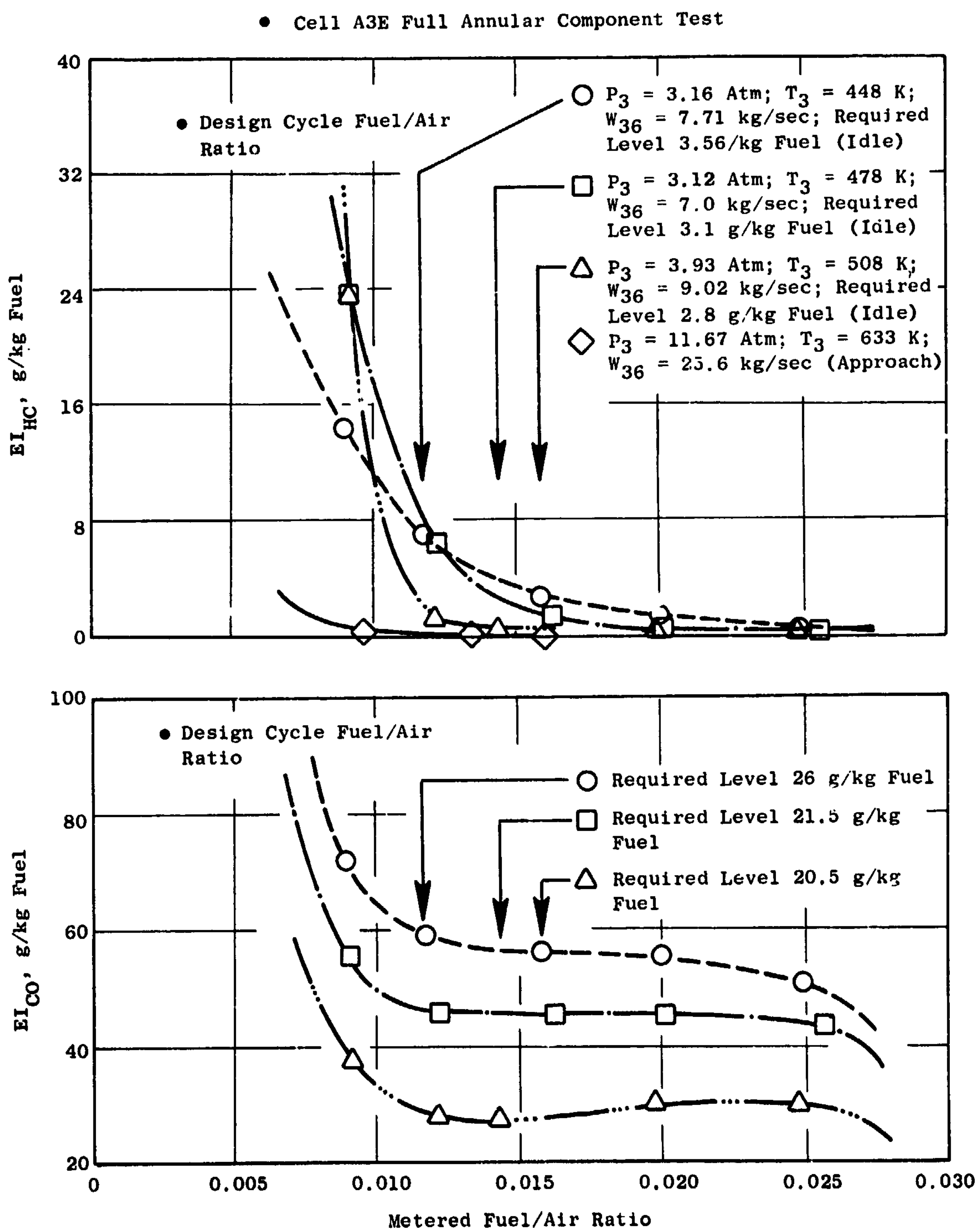


Figure 38. CO and HC Emissions Versus Fuel/Air Raio for the Full-Annular Combustor Test Configuration.

temperature corresponding to the E^3 cycle operating conditions are shown in Figure 39. Combustor operating conditions at 85% of sea level takeoff thrust and above were derated to avoid exceeding the test facility high-pressure capabilities. Therefore, the CO and HC emissions levels measured at high-power test conditions were adjusted to the actual cycle conditions using the adjustment relations discussed in Appendix B.

7.5 FULL-ANNULAR COMBUSTOR NO_x EMISSIONS

NO_x emission levels measured in the full-annular combustor configuration are plotted against the NO_x adjustment parameter in Figure 40. The parameter is similar to that used in adjusting the NO_x emission data obtained from the sector-test configurations, but an added term provides an adjustment for the inlet-air humidity. As part of the data acquisition during the full-annular combustor test, the inlet-air humidity was measured with a hygrometer and recorded at each test point. A hygrometer was not available during the sector-combustor testing effort; hence, the humidity was not accounted for in the adjustment of the sector-combustor NO_x emissions data. The impact of the inlet-air humidity on measured NO_x emission levels is generally less than 7%. As observed from Figure 40, an NO_x emission level of 21.7 g/kg fuel is estimated for the full-annular combustor configuration at the sea level takeoff conditions. This is approximately 24% above the a 17.5 g/kg fuel that was estimated as the level required to satisfy the E^3 project goal. Because there are essentially no differences between engine operating cycles at the sea level takeoff condition, the NO_x emission level obtained from this figure at sea level takeoff would be representative for all the engine cycles which evolved during the test program. In Figure 41 the effect of bulk residence time on the measured NO_x emission levels at sea level takeoff conditions is shown. It is observed from this data that a 10% reduction in combustor bulk residence time resulted in a 6% reduction in the measured NO_x emission levels.

The CO and HC emissions data obtained with the full-annular combustor were adjusted to the E^3 October 1978 cycle at simulated cold-dome velocity conditions. These adjusted CO and HC emissions levels, along with the sea level takeoff NO_x emission level, were compared to the program goals and to the levels obtained with the nine sector-combustor configurations in Table XIII (Section 7.2). As observed from this table, the full-annular combustor demonstrated CO and NO_x emissions levels that exceeded the project goals, but the HC emission levels satisfied the goals with margin.

7.6 SMOKE EMISSIONS

Combustor smoke data were obtained at the design-cycle combustor fuel/air ratio at each of the key operating conditions set. The smoke data are plotted against a correlating parameter in Figure 42. This smoke-correlating parameter was developed for use in adjusting F101/CFM56 component and engine smoke data measured at off-design combustor inlet conditions to the actual design-cycle operating conditions. As observed from this figure, the smoke data do not correlate well with this parameter. During the data processing of the

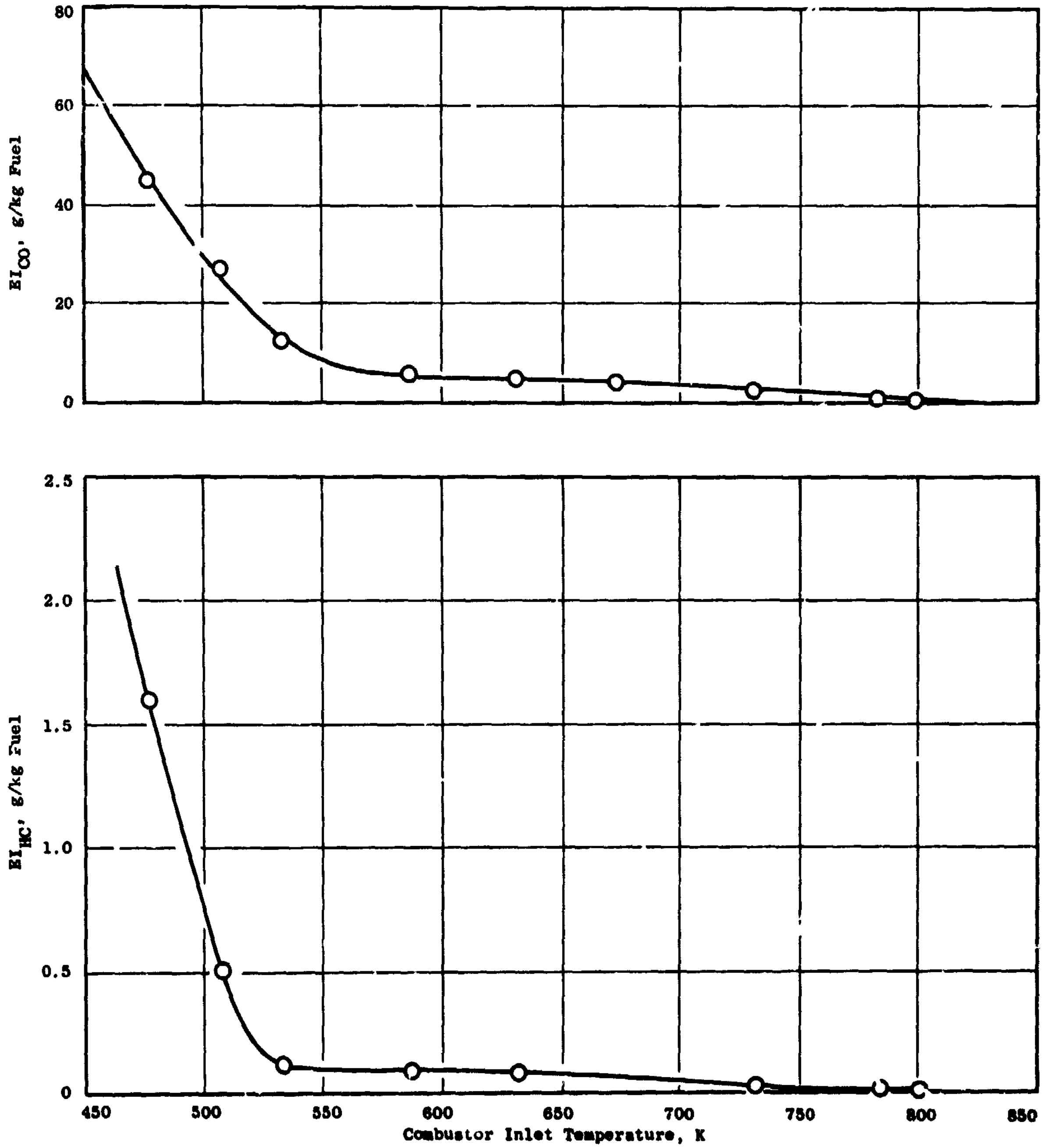
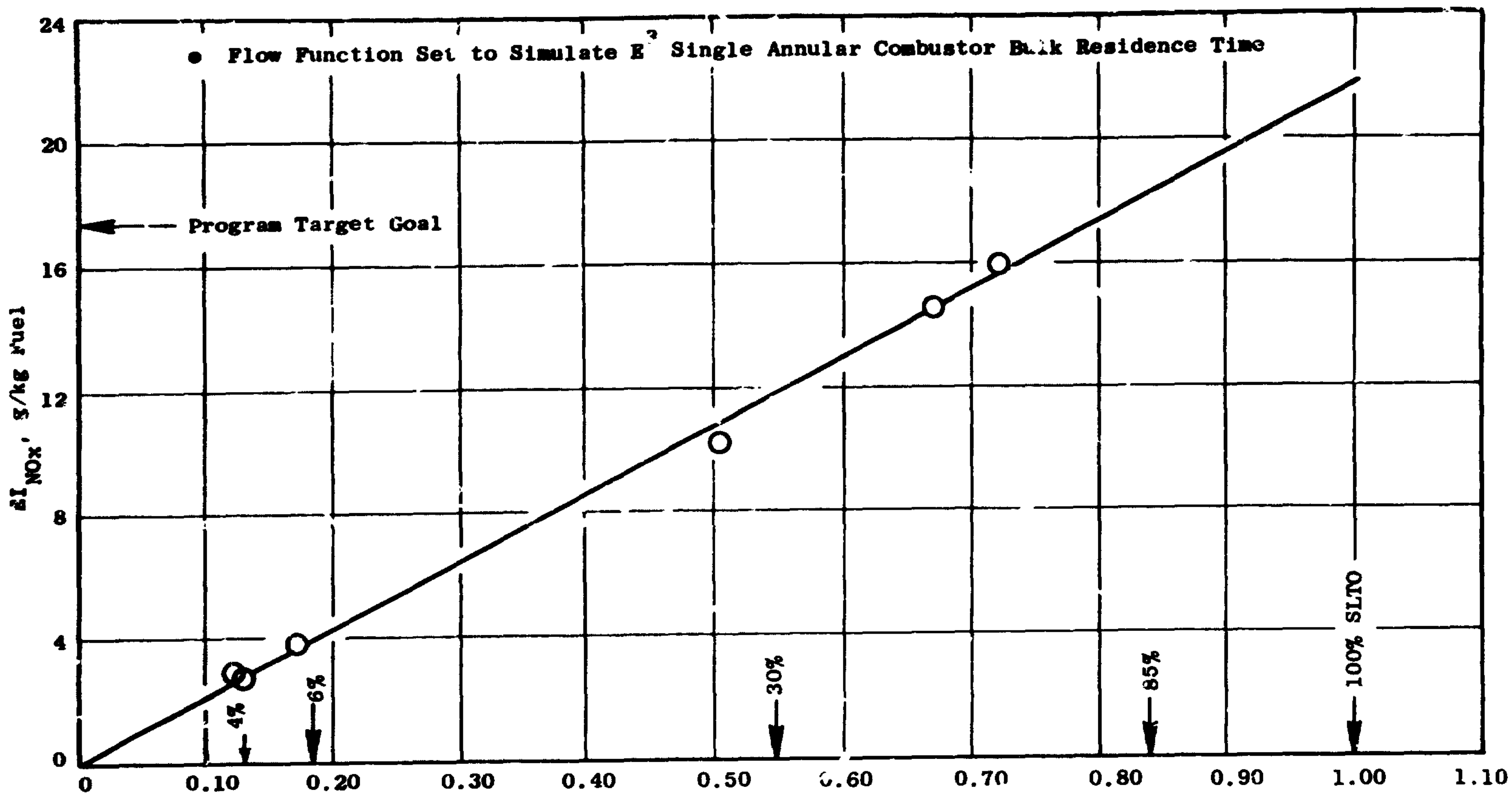


Figure 39. CO and HC Emissions Versus Combustor Inlet Temperature Along the Design-Cycle Operating Line for the Full-Annular Test Configuration.



$$\text{Severity Parameter (S)} = \left(\frac{2.124 \times 10^4 \, P_3 (1-\Delta P/P)/RT_4 W_c}{2.0 \times 10^{-3}}\right)\left(\frac{P_3}{3.02}\right)^{0.37} \beta(F/A) \, \text{Exp}\left(\frac{T_3 - 815}{192} + \frac{6.29 - \text{Humidity}}{53\ 19}\right)$$

Figure 40. NO_x Emissions Along the Design-Cycle Operating Line for the Full-Annular Test Configuration.

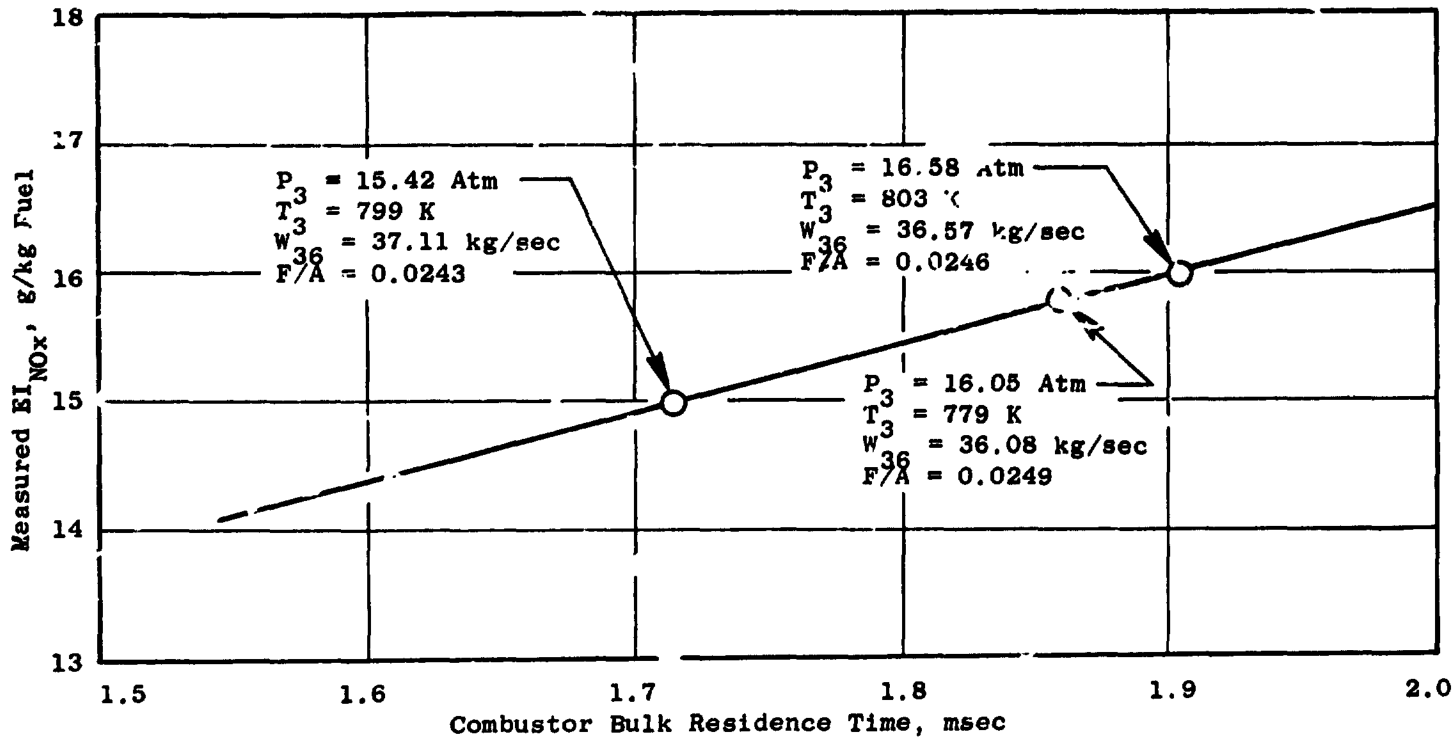


Figure 41. Full-Annular Combustor NO_x Emissions Versus Bulk Residence Time.

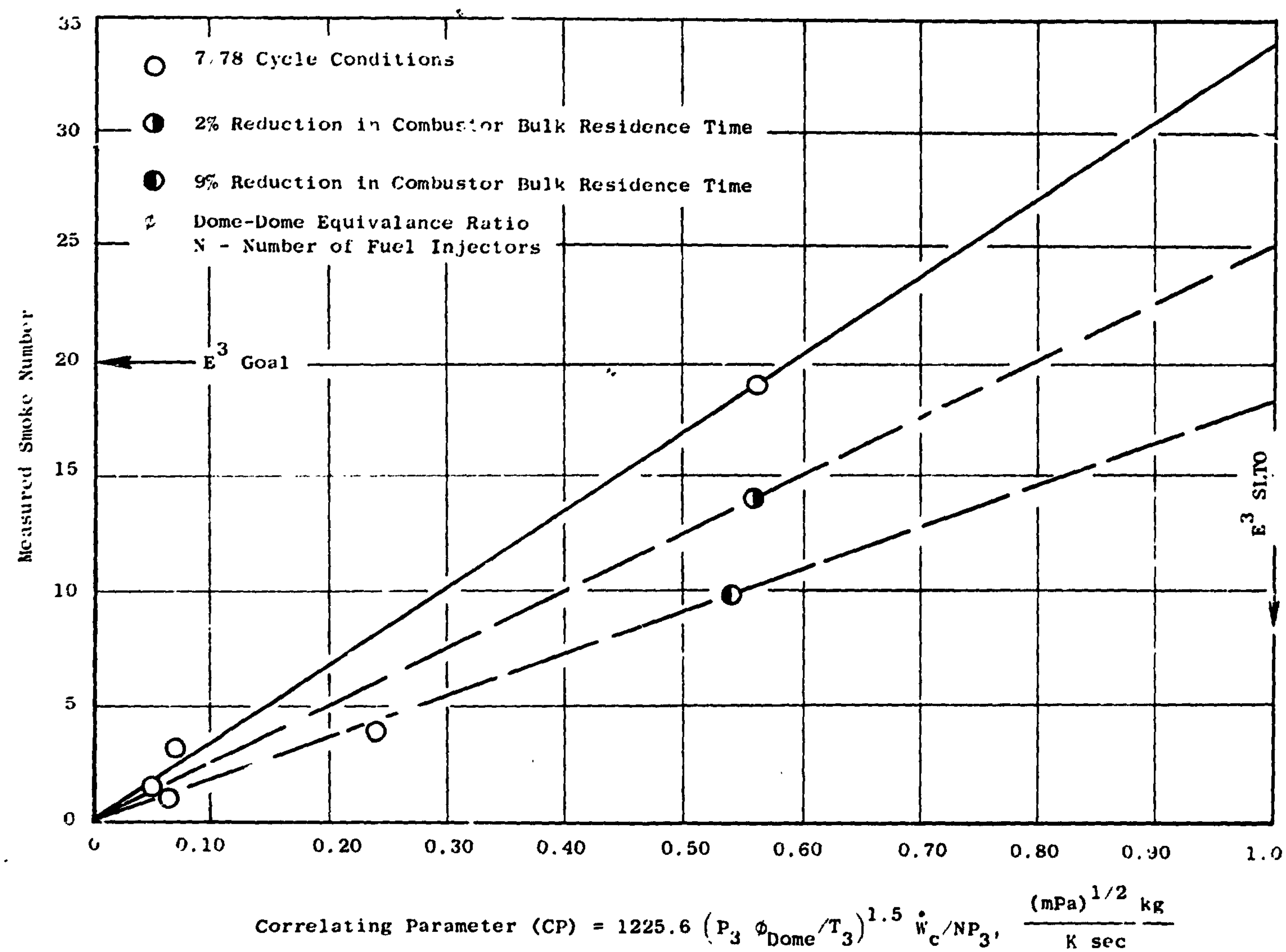


Figure 42. Smoke Number Versus F101/CFM56 Smoke-Correlation Parameter.

smoke samples, it was observed that a considerable amount of water had condensed onto the samples. This water comes from the combustion process. The GE smoke console is designed to remove most of the water from the smoke sample; however, due to excessive amounts of combustion water, and/or malfunction of the smoke console water trap, water collected in the sample line and contaminated the smoke sample. Thus, the amount of uncontaminated sample from which to obtain a smoke number was considerably less than desired. This water contamination produces some doubt as to the validity of the smoke data obtained.

7.7 FULL-ANNULAR COMBUSTOR PERFORMANCE

At each test point evaluated, data were obtained from the combustor test-rig pressure and temperature instrumentation and used to determine the combustor liner temperature distributions, the combustor pressure drops, and airflow distribution. The quantities and locations of the test-rig instrumentation are shown schematically in Figure 26 (Section 6.0).

Peak temperatures were measured for conditions along the combustor operating line on each panel of both the inner and outer combustor liners and are shown in Figure 43. At the simulated sea level takeoff condition, maximum indicated temperatures of 1150 K (1610° F) and 1100 K (1520° F) were recorded respectively on panel No. 1 of the outer liner and panel No. 2 of the inner liner. Because these temperatures were obtained at derated pressure conditions, peak liner temperatures at the actual engine cycle conditions would be approximately 5% higher. Figures 44 and 45 show the peak-temperature axial distributions, along the outer and inner liners respectively, at selected operating conditions.

Measured overall combustor and combustor-dome pressure drops are plotted against the square of the combustor inlet flow function parameter in Figure 46. At the simulated sea level takeoff condition, an overall combustor pressure drop of 8.5% was obtained. Along the revised-cycle combustor operating line, a maximum overall drop of 10% was obtained at the approach (30%) power condition. The design overall pressure drop for the E^3 combustor system at sea level takeoff is 5%. As in the case of the sector-combustor pressure drops, the high pressure drops obtained with this configuration are due to large diffuser-system pressure losses caused by the high airflow levels set for the basic F101 combustor to provide the desired low combustor bulk residence times of the proposed E^3 alternate combustor design.

Measured static pressures on the liners and dome at various power settings along the E^3 cycle combustor operating line are shown in Table X"I. Some pressure data at high power conditions were not obtained due to failure of the static pressure instrumentation.

The estimated airflow distribution for the full-annular combustor design is shown in Figure 47. In obtaining this airflow distribution, a complete reassessment was made of the combustor effective flow areas obtained from a

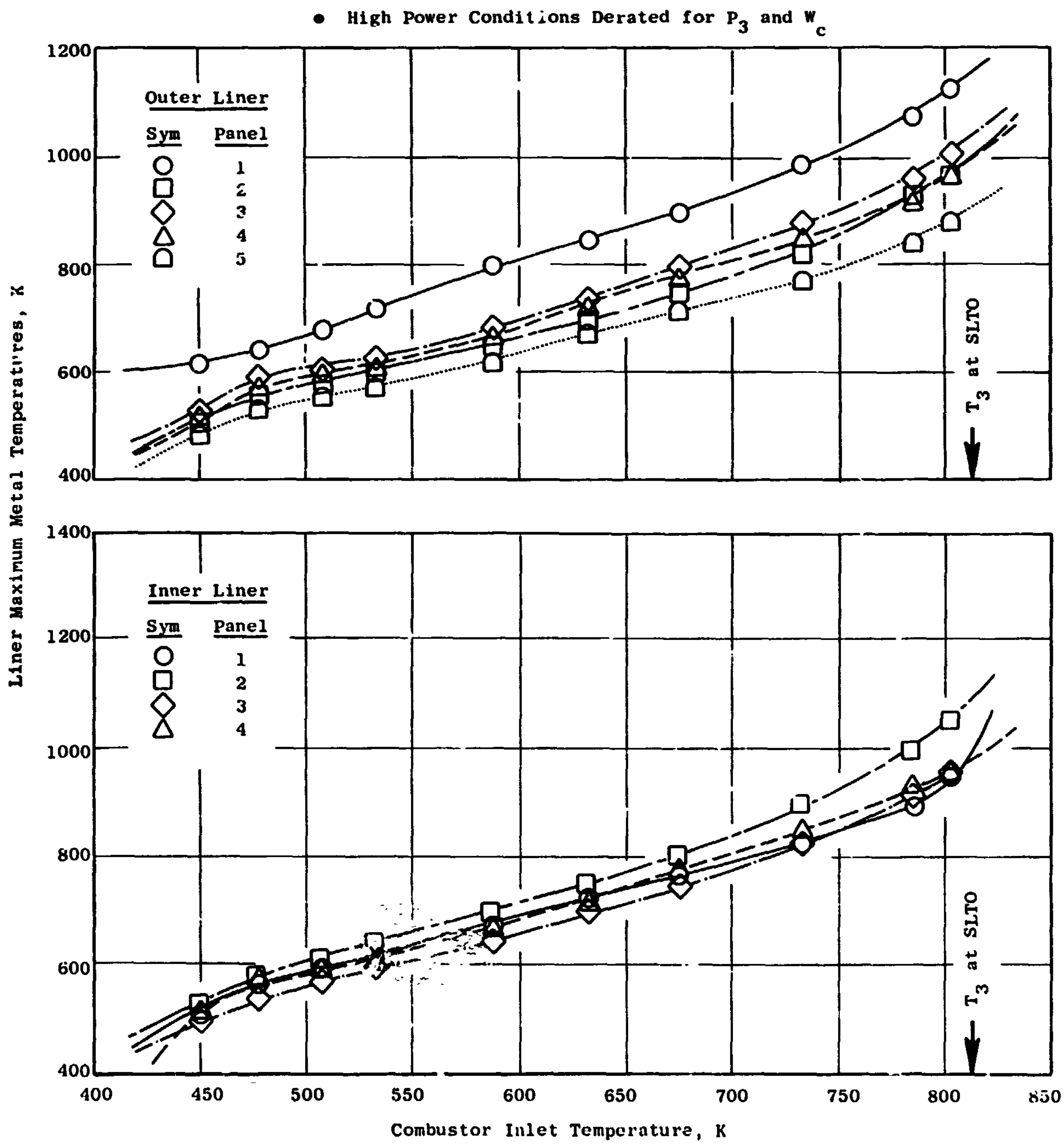


Figure 43. Peak Liner Temperatures.

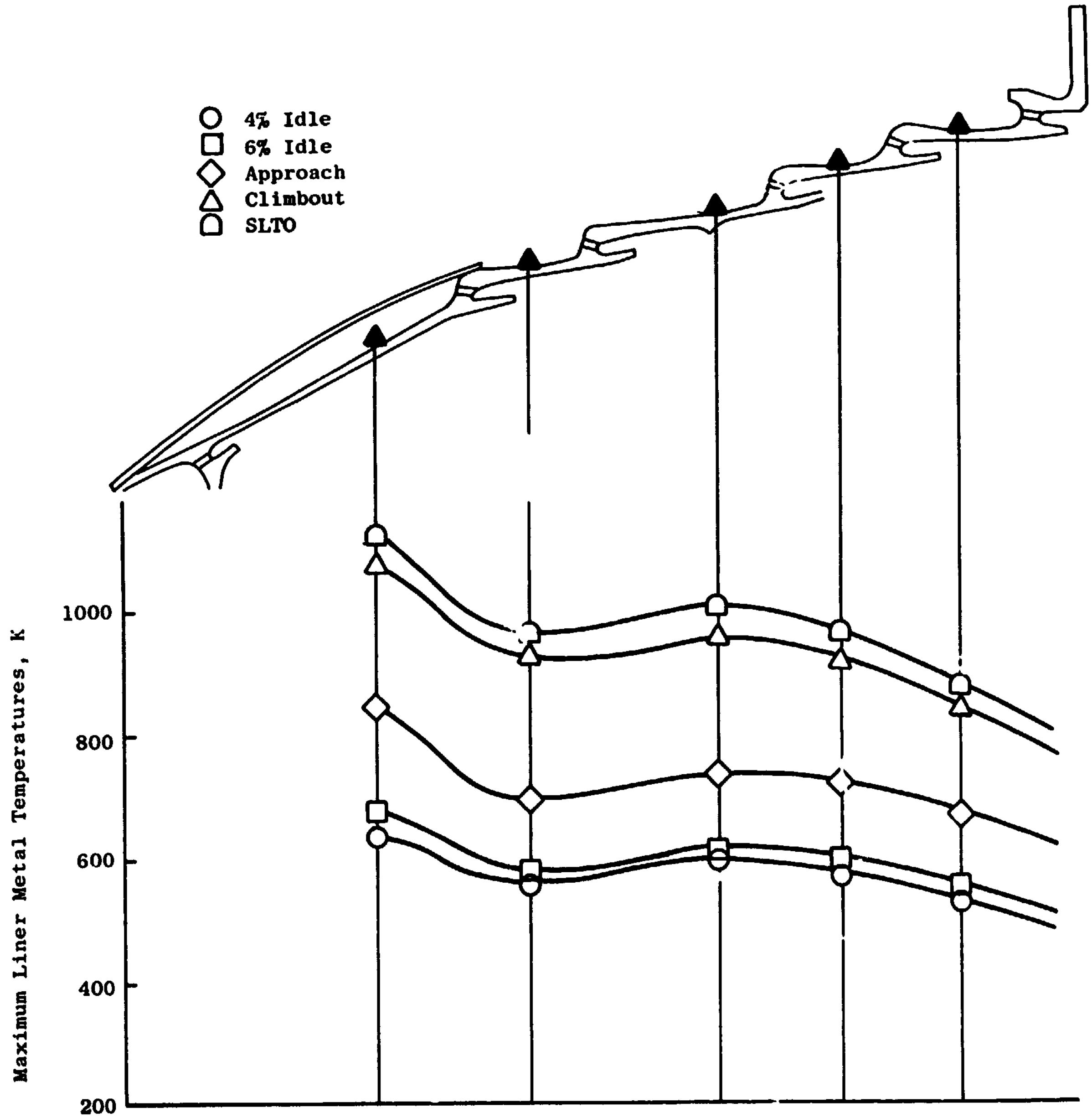


Figure 44. Outer-Liner-Temperature Axial Distribution.

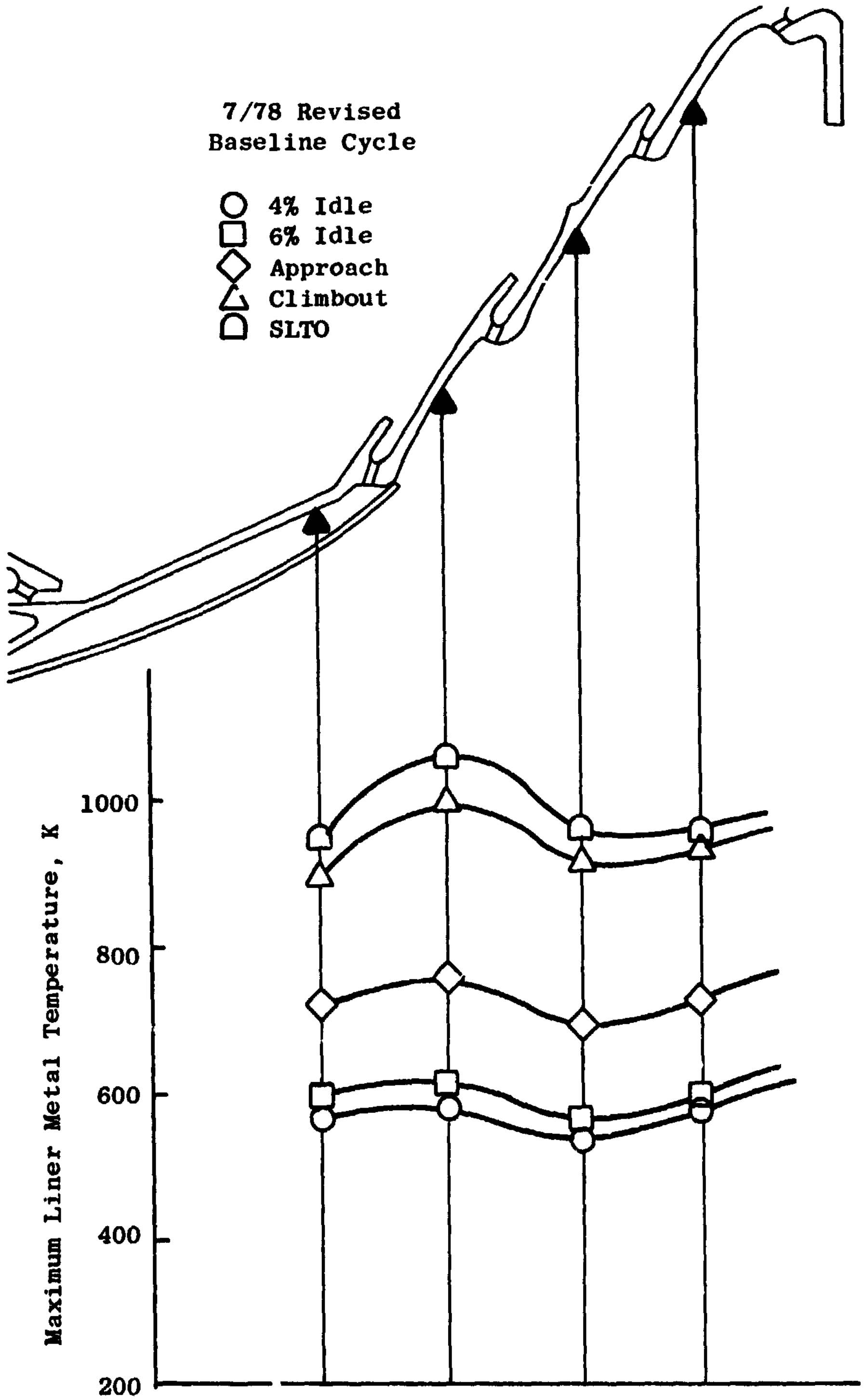


Figure 45. Inner-Liner-Temperature Axial Distribution.

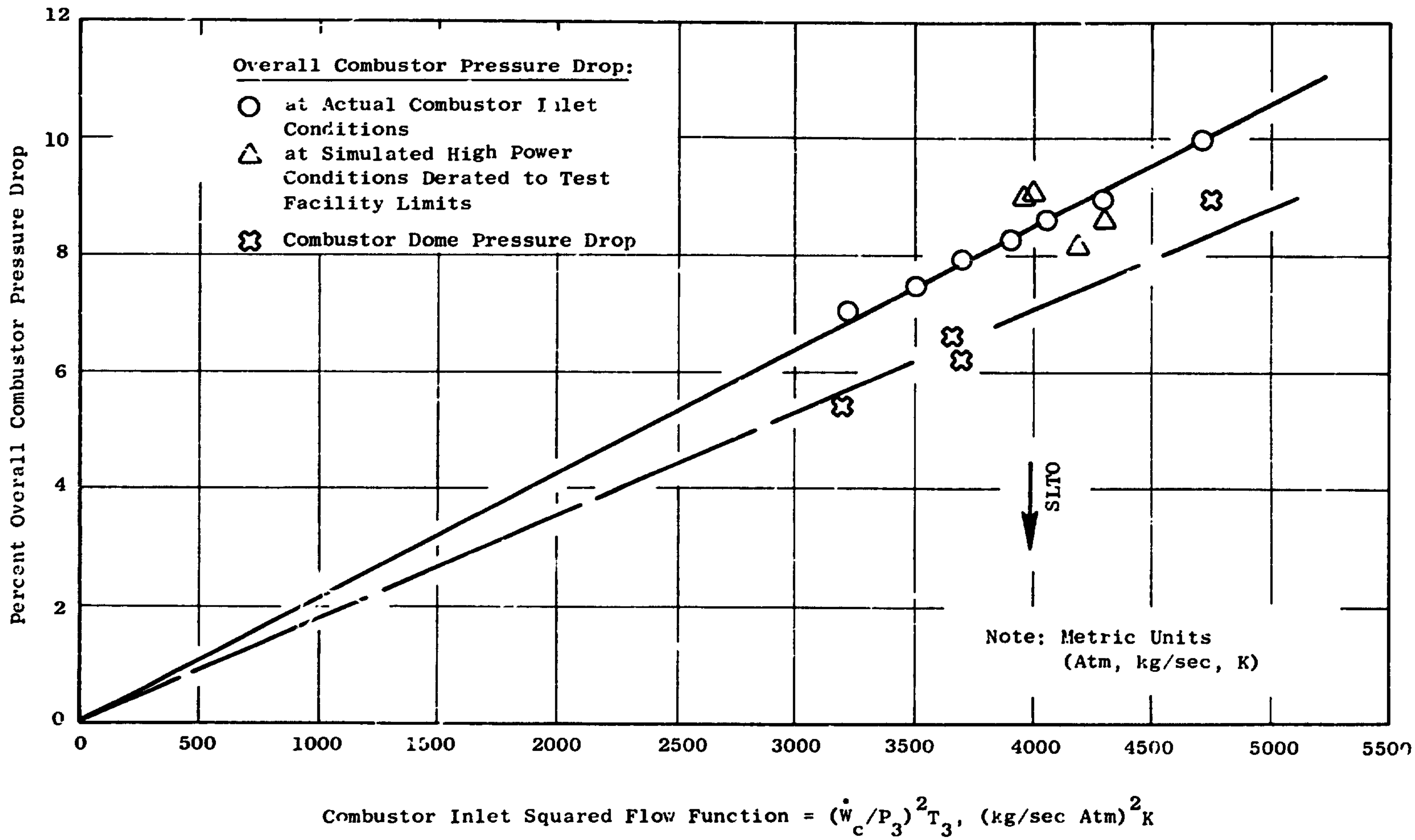


Figure 46. Full-Annular Combustor Overall Pressure Drops.

Table XVI. Measured Static Pressures for Full-Annular Test Configuration.

- Pressures are MPa

Test Condition	A	*B	C	*D	E	F	*G	*H	*I	J
4% FPS Idle	0.308	0.308	0.308	0.308	0.309	0.302	0.301	0.300	0.298	0.297
4% Revised Idle	0.305	0.306	0.307	0.307	0.307	0.301	0.300	0.300	0.299	0.299
6% Revised Idle	0.372	0.373	0.374	0.374	0.374	0.368	0.365	0.365	0.363	0.362
30% Approach	1.108	1.111	1.105	1.114	1.113	1.076	1.071	1.066	1.061	1.056
85% Climb	1.577	1.582	1.584	1.584	1.584	N/A	N/A	N/A	N/A	1.544
100% SLTO	1.578	1.582	1.585	1.585	1.584	N/A	N/A	N/A	N/A	1.543
Test Condition	**K**	**L**	**M**	***N**	**O**	**P**	**Q**	***R**	***S**	**T**
4% FPS Idle	0.322	0.302	0.312	0.312	0.313	0.314	0.302	0.300	0.298	0.298
4% Revised Idle	0.319	0.301	0.310	0.310	0.311	0.312	0.301	0.300	0.298	0.297
6% Revised Idle	0.392	0.368	0.378	0.380	0.381	0.381	0.368	0.368	0.365	0.360
30% Approach	1.182	1.076	1.122	1.124	1.127	1.133	1.076	1.071	1.064	1.059
85% Climb	1.659	N/A	1.592	1.596	1.596	1.604	N/A	N/A	N/A	1.515
100% SLTO	1.657	N/A	1.593	1.594	1.595	1.598	N/A	N/A	N/A	1.515

*Note: These pressures determined by linear extrapolation and interpolation of measured data.

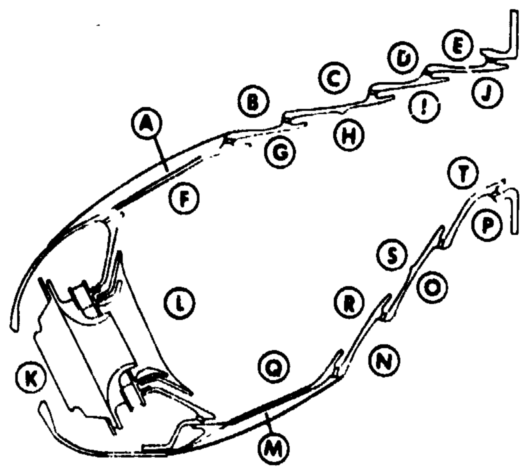
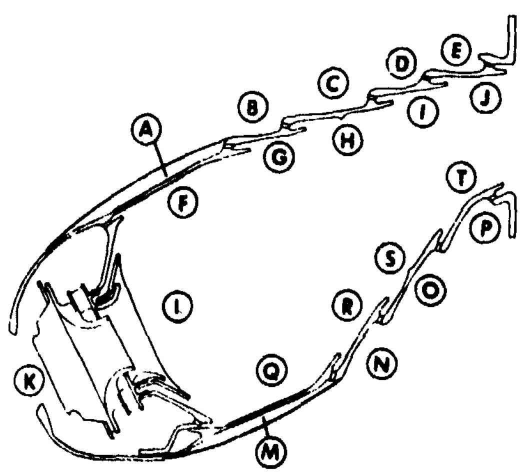


Table XVI. Measured Static Pressures for Full-Annular Test Configuration (Concluded).

- Pressures are PSIA

Test Condition	A	*B	C	*D	E	F	*G	*H	*I	J
FPS 4% Idle	44.60	44.65	44.70	44.75	44.80	43.80	43.63	43.45	43.28	43.10
Revised 4% Idle	44.30	44.40	44.50	44.50	44.50	43.70	43.58	43.45	43.33	43.20
Revised 6% Idle	54.00	54.15	54.30	54.30	54.30	53.30	53.10	52.90	52.70	52.50
30% Approach	160.70	161.20	161.70	161.60	161.50	156.10	155.35	154.60	153.85	153.10
85% Climb	228.80	229.45	229.70	229.70	229.70	N/A	N/A	N/A	N/A	224.00
100% SLTO	228.90	229.40	229.90	229.85	229.80	N/A	N/A	N/A	N/A	223.80
Test Condition	**K**	**L**	**M**	***N**	**O**	**P**	**Q**	***R**	***S**	**T**
FPS 4% Idle	46.70	43.80	45.20	45.30	45.40	45.50	43.80	43.50	43.30	43.00
Revised 4% Idle	46.20	43.70	44.90	45.0	45.10	45.20	43.70	43.50	43.30	43.10
Revised 6% Idle	56.90	53.30	54.90	55.05	55.20	55.30	53.30	53.31	52.90	52.20
30% Approach	171.40	156.10	162.80	163.10	163.40	164.30	156.10	155.30	154.40	153.60
85% Climb	240.60	N/A	230.90	231.40	231.90	232.60	N/A	N/A	N/A	219.80
100% SLTO	240.30	N/A	231.00	231.15	231.30	231.70	N/A	N/A	N/A	219.80

*Note: These pressures determined by linear extrapolation and interpolation of measured data.



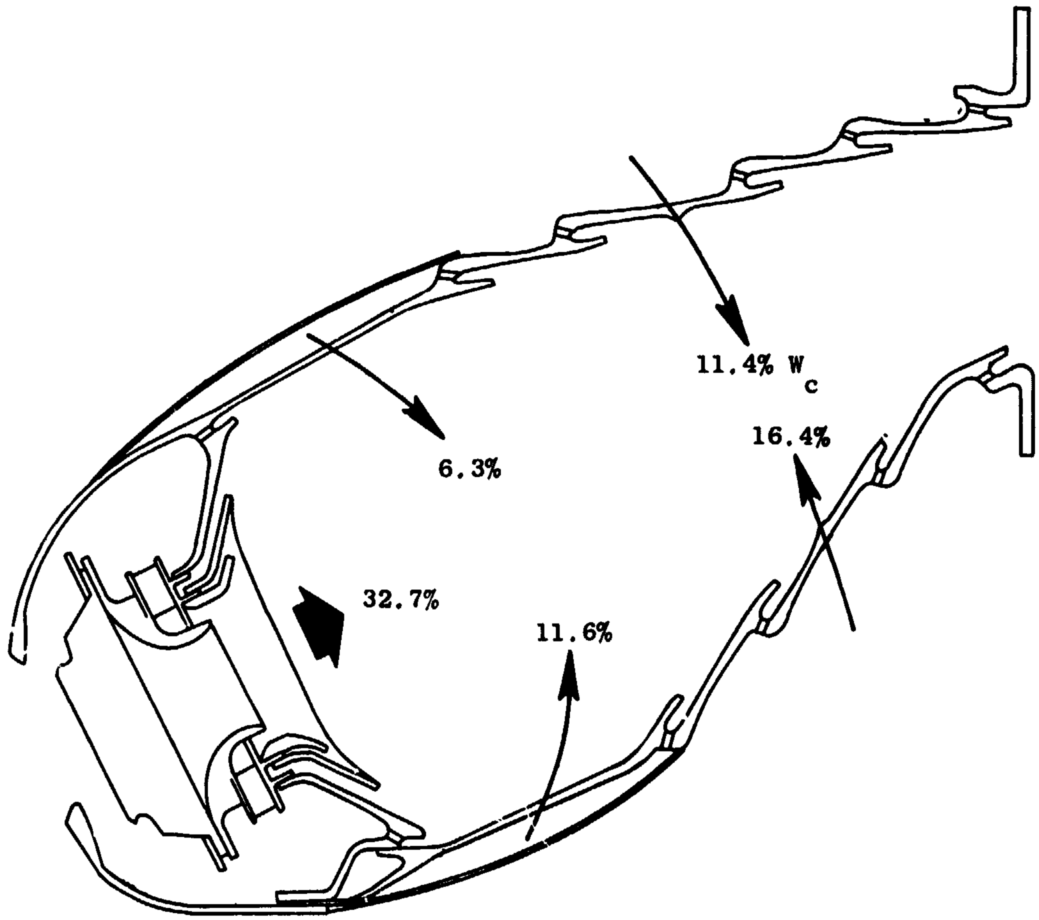


Figure 47. Estimated Airflow Distribution for the Full-Annular Combustor Test Configuration.

posttest combustor flow check. Effective areas measured on the flow-calibration stand produced a total combustor effective area of 335.5 cm^2 (52 $in.^2$). The pressure-drop data measured during the test indicated that the combustor had a total effective area of 260 cm^2 (40 $in.^2$). An analytical investigation of this discrepancy indicated that the discharge coefficients of the various combustor cooling and dilution holes were significantly less for the conditions existing in the test rig than those measured at the near-static conditions on the flow-calibration stand. This decrease in the discharge coefficients is related to high pressure losses in the diffuser and high liner-passage velocities associated with operating the basic F101 diffuser/combustor system at the high airflow conditions required to simulate the proposed E^3 alternate combustor bulk residence times. A recalculation of the individual combustor areas using discharge coefficients determined at the test-rig conditions produced a total combustor effective flow area of 265 cm^2 (41.0 $in.^2$), confirming the measured combustor pressure drop data.

7.8 EPA PARAMETER

The emissions goals for the E^3 Project are expressed in the form of the EPA parameter (EPAP). These goals are the emissions standards currently defined by the EPA for Class T2 aircraft engines newly certified after January 1, 1981. The EPA emissions standards are based upon a representative landing/takeoff cycle (EPA-LTO) that includes idle, approach, climbout, and sea level takeoff engine operating conditions (Reference 3). The EPA parameter is defined in equation form as:

$$EPAP_i = \frac{\sum^{j} (EI_i)_j \, (WF)_j \, (Time)_j}{\sum^{j} (F_N)_j \, (Time)_j}$$

where i is the category of gaseous emission (CO, HC, or NO_x), EI is the emission index, W_F is the fuel-flow rate, Time is in hours at each power level, F_N is the corresponding thrust, and j is the prescribed power level (idle, 30%, 85%, and SLTO). Units of EPAP are defined as pounds of emissions per 1000 pounds thrust-hour-cycle. In order to evaluate the development program in terms of satisfying the program emission goals, it was necessary to investigate the emission levels at each of the prescribed EPA-LTO cycle conditions to determine the impact of a particular combustor design modification on the CO, HC, and NO_x emissions levels.

EPAP numbers for the full-annular combustor configuration were generated for the October 1978 cycle at 4%, 6%, and 7% of sea level takeoff thrust at ground idle. The results of these EPAP calculations, shown in Figure 48, indicate that this single-annular combustor design should meet the E^3 Project goals for CO emissions at approximately 6.5% of sea level takeoff thrust at ground idle. However, reductions in NO_x emissions on the order of 25% are needed to satisfy the E^3 Project goal at the same operating conditions. Emissions results presented in the form of the EPA parameter, along with

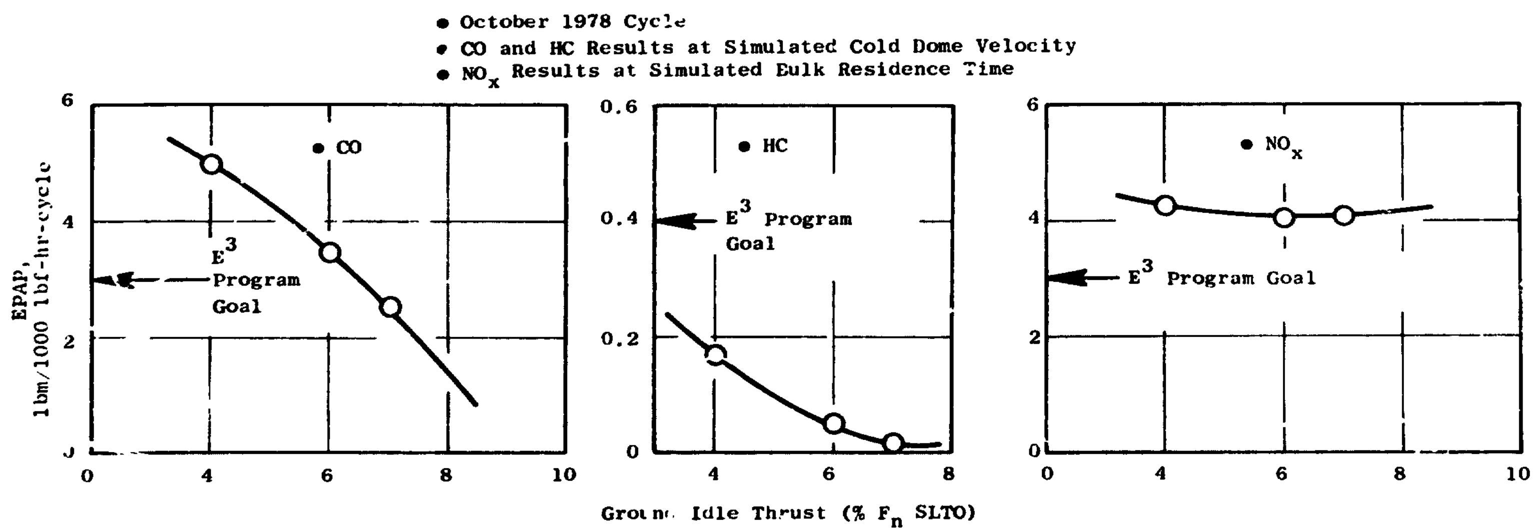


Figure 48. CO, HC, and NO_x EPAP Numbers Versus Percent of Power at Idle.

several key combustor-performance results, are summarized for each of the nine sector-combustor configurations and the full-annular combustor configuration in Table XVII for the October 1978 E^3 cycle. In this table, the CO and HC emissions results are representative of simulated cold-dome velocity; the NO_x emissions results are representative of simulated combustor bulk residence time.

7.9 DESIGN ASSESSMENT

The alternate combustor task assessed the feasibility and practicality of using a single-annular combustor design in the E^3 application. This assessment was based on the test results reported herein and on a trade study which evaluated the relative performance and product applicability of the single-annular and double-annular combustor designs.

The double-annular combustor concept was selected for the E^3 application because it is expected to meet all of the objectives of the E^3 Project. The single-annular combustor design (while less complex, lighter, and less expensive) will not, based on results of this study, meet the E^3 emissions goals, especially for the oxides of nitrogen.

Cross sections of the double-annular and single-annular combustor designs proposed for the E^3 application are shown in Figure 49. Both designs use split-duct diffusers, pressure-atomizing fuel nozzles, counterrotating swirl cups, and impingement-plus-film-cooled shingle liners. The centerbody and the dual-fuel-nozzle system give the double-annular design added complexity. In addition, the double-annular design requires staging of combustion in the two domes to obtain the very low emissions required to meet the E^3 Project goals.

Quantitative or qualitative estimates of the combustor characteristics and performance parameters of both designs are compared in Table XVIII. In general, these comparisons indicate that the single-annular combustor should meet the E^3 Project objectives except for emissions, would weigh less, cost less, be less expensive to maintain (based on production price), and give adequate performance. Furthermore, the single-annular design would provide more desirable combustor-exit-temperature distribution during low-power operation and be more resistant to gumming in the fuel system because of the continuous supply of fuel to the fuel nozzles during operation. In addition, the absence of a centerbody provides additional combustor airflow for combustion purposes or exit-temperature-profile control. However, the double-annular design should meet all of the E^3 Project objectives and would give better performance for some of the operating requirements. This better performance would result because the two stages of the double-annular combustor can be adjusted over wider ranges of stoichiometries at the various engine cycle conditions.

The main impetus for the double-annular approach in the E^3 Project is to demonstrate the ability to meet the emissions goals; these are equivalent to the emissions standards specified by the EPA (Reference 3) for Newly Certified Engines (NCE) after 1981. The results of the alternate combustor task,

Table XVII. Summary of Emissions and Performance Results for the E^3 Single-Annular Combustor Test Configurations.

- October, 1978 Baseline Cycle
- CO and HC Emissions at Simulated Cold-Dome Velocity
- NO_x Emissions at Simulated Bulk Residence Time

Combustor Configuration	4% Idle			6% Idle			EPAP HC 4%	EPAP HC 6%	EPAP NO_x 4%	EPAP NO_x 6%	Max. Liner Temp. SLTO - K	Pressure Loss SLTO - %
	EPAP CO	EPAP Min. CO	F/A at Min. CO	EPAP CO	EPAP Min. CO	F/A at Min. CO						
SA-00	4.34	4.21	.020	2.90	2.74	[illegible]	0.20	0.05	3.66	3.52	N/A	N/A
SA-01	4.36	3.99	.012	2.98	2.74	.012	0.08	0.07	3.44	3.35	965	8.0
SA-02	[illegible]	3.92	.013	2.99	2.59	.012	0.05	0.03	3.57	3.44	1006	7.5
SA-03	[illegible]	2.87	.010	3.06	[illegible]	.008	0.04	0.02	3.87	3.72	1260	8.3
SA-04	[illegible]	3.30	.020	2.17	2.17	.014	0.12	0.06	3.94	3.79	1138	8.4
SA-05	[illegible]	2.78	.009	2.88	2.33	.009	0.03	0.02	4.88	4.69	1276	7.6
SA-06	[illegible]	3.47	.011	3.06	2.48	.011	0.06	0.03	N/A	N/A	1187	7.3
SA-07	[illegible]	4.62	.008	3.75	2.70	.011	0.06	[illegible]	3.56	3.42	1009	6.0
SA-08	[illegible]	2.46	.011	1.40	1.30	.012	0.04	0.02	4.61	4.43	1278	7.8
Full Annular	[illegible]			[illegible]			0.17	0.05	4.23	4.03	1150	8.5
Goals	[illegible]	3.0		3.0	[illegible]		[illegible]	0.40	3.0	3.0	1150	5.0

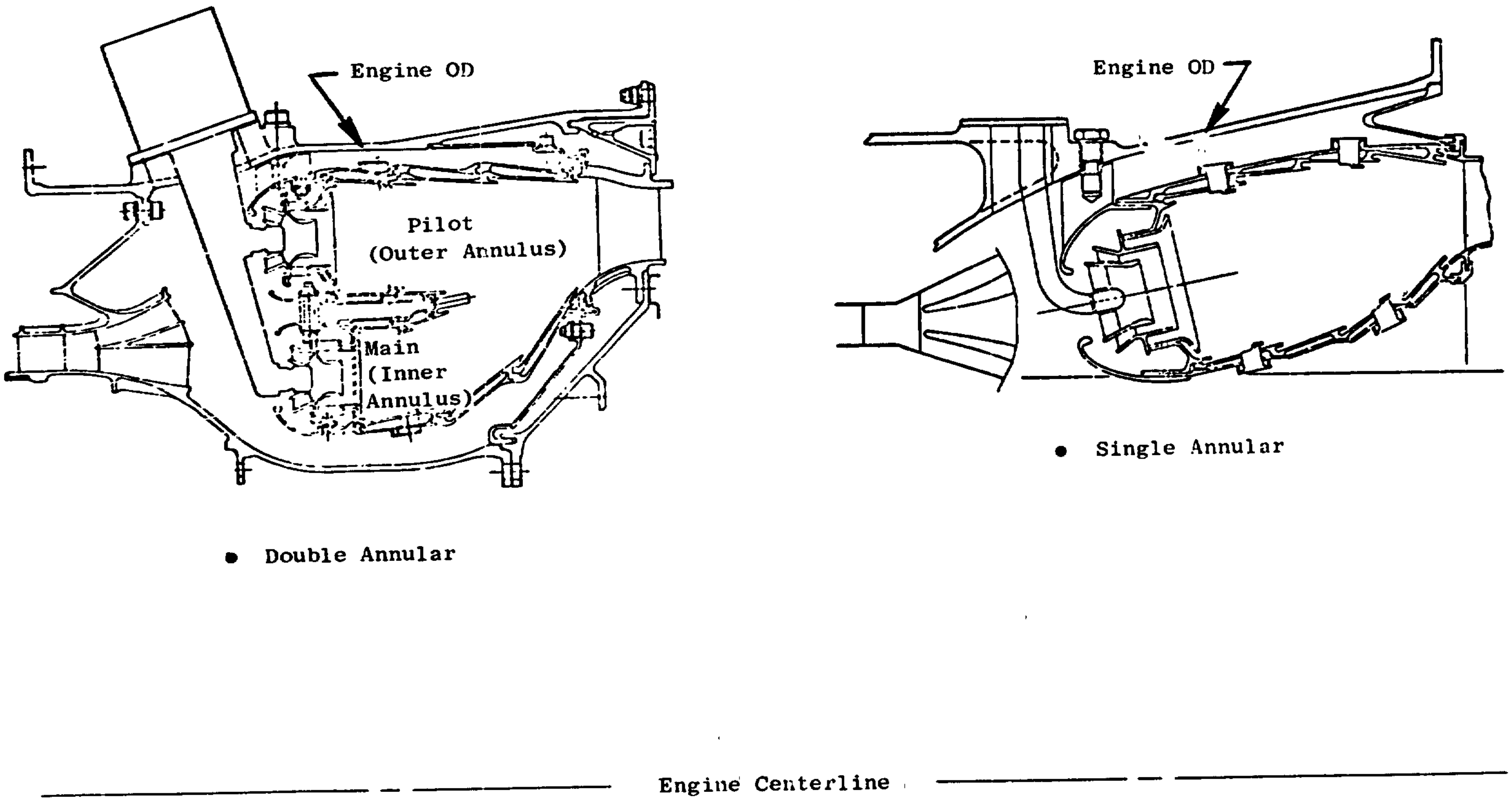


Figure 49. Double-Annular and Single-Annular Combustor Comparison.

C-2

Table XVIII. Combustor Design Assessment.

Estimated Characteristics	Single-Annular	Double-Annular	Comments
Weight, kg	-31.8	Base	ΔDOC = -0.4% Benefit for Single-Annular Combustor
Price, Production	-$40,000	Base	
Maintenance Cost per Engine Flight Hour	-$1.90	Base	
Pattern Factor	0.25	0.25	
Efficiency, SLTO	99.9%	99.9%	
Pressure Drop, ΔP/P, Max.	5%	5%	
Life			
Centerbody	Better	Base	Film/Impingement Cooling and Shingle Liner Allow Both Designs to Meet Objective of 9,000 Cycles
Dome	Base	Better	
Liner	Better	Base	
Altitude Relight	Base	Base	E^3 Performance Estimated From Other Engine Programs
Cold Day Ignition	Base	Better	
Decel Transient	Base	Better	
Idle Stability	Base	Base	
Broad-Specification Fuel	Base	Better	Double-Annular Combustor Has More Parts
Complexity	Better	Base	
Reliability	Better	Base	
Emissions (6% FN SLTO)			Single-Annular Combustor Based on Reported E^3 Test Results. Double-Annular Combustor Estimates Based on ECCP and QCSEE Program Results. Values include margin.
CO (lbm per 1000 lbf Thrust per hr-Cycle)	4.2*	2.4	
HC (lbm per 1000 lbf Thrust per hr-Cycle)	0.2	0.2	
NOx (lbm per 1000 lbf Thrust per hr-Cycle)	3.7*	3.1	
Smoke (SN)	19	19	

* Note: Reflects Single-Annular Combustor Results (Reference Figure 50) Which Most Nearly Approach E^3 Project Goals.

as shown in Figure 50, indicate that a single-annular design will not meet the 1981 CO and NO_x standards, particularly when the margin required for engine-to-engine variability is taken into account. However, the projected emissions levels for the double-annular combustor are expected to meet these goals, as shown in Figure 50.

The assessment of the combustor designs also considered the fact that the EPA has issued a Notice of Proposed Rule Making (Reference 5) which would delay the effective date for NCE standards to 1984 and would increase the NO_x standard. Again, the double-annular combustor is the only design, of the two discussed herein, which will meet the proposed standards. The proposed 1984 standards, adjusted for an idle thrust setting of 6% SLTO, are also shown on Figure 50.

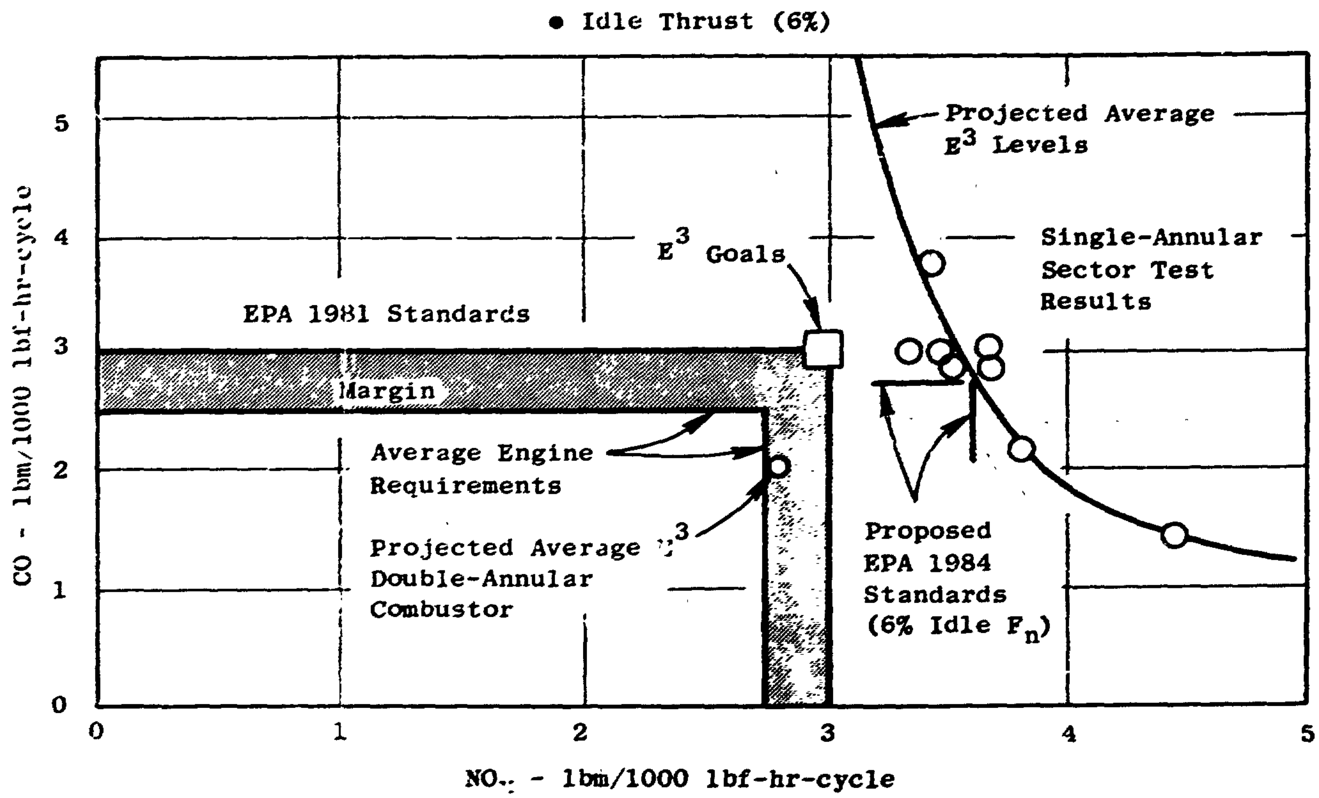


Figure 50. Projected CO/NO_x Emissions Trade-Off.

8.0 CONCLUDING REMARKS

The E^3 Single Annular Alternate Combustor Project provided important design technology for the evolution of short, single-annular, combustor designs required to satisfy the very stringent emissions requirements of the E^3 combustor system. As a result of this development test program, several key design features were identified which resulted in significant reductions in CO and HC emissions, at ground-idle operating conditions, to levels which would satisfy the E^3 Project goals for these two emissions categories. These features included impingement cooling of the forward sections of the combustor liners, reduced dome-cooling flows, and increased swirl-cup flows. However, additional development effort will be required to evolve a single-annular combustor design that will simultaneously demonstrate NO_x emission levels within the project goals.

As part of this testing program, several combustor performance parameters were evaluated. Results determined that the overall combustor total pressure drops, and combustor liner temperatures in general, exceed the E^3 combustor system requirements. However, neither of these observed performance shortcomings represents a significant design barrier.

APPENDIX A - DEVELOPMENT TEST DATA

This appendix contains summaries of the operating conditions, combustor performance data, and exhaust emissions data for each of the nine sector-combustor configurations and the one full-annular combustor configuration tested. For each of the simulated high engine power operating conditions, the CO, HC, and NO_x emissions indices are presented two ways: (1) measured test data and (2) corrected to the E^3 baseline cycle combustor inlet conditions, at which the configurations were evaluated, using the adjustment procedures described in Appendix B.

Summary of Test Results: Configuration SA-00

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.17	448	6.97	25.5	N/A	16.1	0.0071	0.0077	90.37	118.4	68.7	N/A				6.25	N/A
2	2	3.19	449	6.97	32.7	N/A	16.0	0.0091	0.0100	94.64	89.5	32.7	N/A				6.06	N/A
3	3	3.17	448	6.99	42.1	N/A	16.1	0.0117	0.0129	97.26	65.6	12.1	N/A				4.74	N/A
4	4	3.20	450	6.95	58.3	N/A	16.0	0.0162	0.0182	98.08	57.7	5.8	N/A				8.46	N/A
5	5	3.19	450	6.93	73.0	N/A	16.0	0.0203	0.0227	98.42	53.6	3.2	N/A				5.99	N/A
6	6	3.17	448	8.53	25.5	N/A	19.7	0.0071	0.0078	85.85	143.7	102.9	N/A				8.96	N/A
7	7	3.17	449	8.54	32.7	N/A	19.8	0.0091	0.0099	93.50	108.9	39.6	N/A				8.96	N/A
8	8	3.23	448	8.77	41.0	N/A	20.2	0.0114	0.0116	96.50	90.5	13.9	N/A				9.45	N/A
9	9	3.23	448	8.71	56.8	N/A	20.1	0.0158	0.0159	97.56	81.0	5.5	N/A				9.68	N/A
10	10	3.25	448	8.73	71.2	N/A	19.9	0.0198	0.0198	98.00	71.4	3.3	N/A				9.81	N/A
11	11	4.05	486	8.73	25.2	N/A	17.4	0.0070	0.0074	86.99	94.7	108.0	N/A				6.01	N/A
12	12	4.05	483	8.73	32.4	N/A	17.3	0.0090	0.0094	95.97	69.0	24.2	N/A				6.01	N/A
13	13	4.05	486	8.73	42.4	N/A	17.4	0.0118	0.0123	98.70	35.4	4.8	N/A				6.17	N/A
14	14	4.05	485	8.71	57.6	N/A	17.3	0.0160	0.0164	99.11	31.0	1.7	N/A				6.35	N/A
15	15	4.06	487	8.73	71.6	N/A	17.3	0.0199	0.0220	99.18	30.7	1.0	N/A				6.67	N/A
16	19	4.07	487	10.63	57.6	N/A	21.1	0.0160	0.0190	97.12	39.0	19.7	N/A				10.58	N/A
17	20	4.04	485	10.57	72.3	N/A	21.1	0.0201	0.0226	97.96	42.7	10.5	N/A				10.09	N/A
18	18	4.05	485	10.53	43.2	N/A	21.1	0.0120	0.0132	97.20	42.9	18.0	N/A				9.44	N/A
19	17	4.06	484	10.53	32.7	N/A	21.0	0.0091	0.0100	95.29	68.7	31.1	N/A				10.28	N/A
20	21	3.23	642	5.54	86.7	N/A	18.3	0.0241	0.0268	99.38	20.6	1.4	N/A				7.71	N/A
21	22	2.53	648	5.57	86.0	N/A	23.7	0.0239	0.0264	99.28	27.8	0.7	N/A				9.59	N/A

Summary of Test Results: Configuration SA-1

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.17	450	2.145	66.4	N/A	21.85	0.0086	0.0077	96.83	72.9	14.7	2.5				7.53	6.59
2	2	3.17	450	2.122	85.6	N/A	21.74	0.0112	0.0105	98.17	55.8	5.2	3.0				7.53	6.53
3	3	3.18	449	2.118	117.0	N/A	21.70	0.0154	0.0144	98.36	60.4	2.3	3.1				7.38	6.38
4	4	3.18	449	2.113	146.0	N/A	21.64	0.0192	0.0175	98.40	62.3	1.4	3.9				7.38	6.33
5	9	3.42	488	2.231	69.9	N/A	23.14	0.0087	0.0081	98.55	41.2	4.8	2.9	33.1	3.3	3.1	7.82	6.66
6	10	3.44	488	2.240	93.5	N/A	23.12	0.0116	0.0105	98.99	36.4	1.6	3.9	29.3	1.1	4.1	7.48	6.67
7	11	3.42	488	2.240	126.0	N/A	23.22	0.0156	0.0143	98.90	44.2	0.7	3.6	35.5	0.5	3.8	7.68	6.69
8	12	3.42	488	2.240	165.0	N/A	23.25	0.0204	0.0189	98.73	52.1	0.6	3.6	41.9	0.4	3.8	7.58	6.71
9	17	2.54	769	1.288	70.9	N/A	28.39	0.0153	0.0140	99.62	15.4	0.2	9.6	0.4	0	23.9	7.79	6.44
10	17	2.53	783	1.288	88.6	N/A	28.97	0.0191	0.0194	99.66	13.8	0.2	8.0	0.3	0	19.9	7.98	---
11	17	2.53	787	1.288	109.0	N/A	29.15	0.0235	0.0217	99.64	14.7	0.1	6.5	0.4	0	16.2	7.99	6.46

Summary of Test Results: Configuration SA-2

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg,	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.19	449	2.100	65.8	N/A	21.6	0.0087	0.0076	97.35	63.1	11.8	2.4				6.4	6.2
2	2	3.20	453	2.086	84.9	N/A	21.5	0.0113	0.0102	98.33	53.4	4.2	2.9				6.5	6.0
3	2'	3.20	450	1.705	69.4	N/A	17.4	0.0113	0.0096	98.48	45.8	4.5	3.2				4.3	4.1
4	2''	3.20	450	1.265	51.0	N/A	13.0	0.0112	0.0098	97.33	46.5	15.8	3.2				2.4	2.1
5	2'''	3.21	453	0.880	35.2	N/A	8.8	0.0111	0.0100	92.50	57.5	61.6	3.1				---	1.0
6	3	3.21	450	2.091	119.7	N/A	21.5	0.0159	0.0144	98.61	54.8	1.1	3.0				7.0	6.0
7	4	3.20	449	2.091	145.3	N/A	21.5	0.0193	0.0178	98.41	63.2	1.2	2.6				6.4	6.0
8	9	3.45	489	2.218	70.3	N/A	23.0	0.0088	0.0077	98.67	39.8	4.0	2.9	31.7	2.8	3.0	7.7	6.5
9	10	3.47	487	2.204	92.8	N/A	22.8	0.0117	0.0107	99.08	35.4	1.0	3.8	28.4	0.7	4.0	7.3	6.2
10	11	3.44	483	2.209	124.1	N/A	22.7	0.0156	0.0144	98.89	45.4	0.5	3.4	36.0	0.4	3.6	6.5	6.2
11	12	3.44	483	2.218	154.9	N/A	22.8	0.0194	0.0183	98.77	50.4	0.5	3.0	39.9	0.3	3.2	6.7	6.3
12	17	2.53	776	1.293	108.9	N/A	29.1	0.0234	0.0217	99.60	16.4	0.1	6.4	0.4	0	15.9	7.5	6.2

Summary of Test Results: Configuration SA-3

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg,	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.24	446	2.005	65.7	N/A	20.1	0.0091	0.0091	98.79	36.4	3.6	2.9				6.4	5.5
2	2	3.23	445	2.014	84.1	N/A	20.4	0.0116	0.0118	99.22	29.2	0.9	3.3				6.5	5.8
3	3	3.22	444	2.018	116.2	N/A	20.4	0.0160	0.0164	98.97	42.1	0.5	3.2				6.0	5.7
4	4	3.21	446	2.018	145.3	N/A	20.5	0.0200	0.0204	98.82	49.1	0.3	3.0				6.7	5.7
5	4	3.20	478	1.814	57.5	N/A	19.8	0.0088	0.0087	99.34	22.5	1.3	3.4				6.8	5.1
6	6	3.18	479	1.823	84.0	N/A	20.1	0.0128	0.0126	99.38	24.7	0.4	4.0				6.0	5.1
7	7	3.19	479	1.832	111.5	N/A	20.1	0.0169	0.0170	99.15	35.4	0.3	3.7				6.5	5.0
8	8	3.19	479	1.800	127.7	N/A	19.9	0.0197	0.0194	99.07	39.0	0.2	3.6				6.0	5.0
9	9	3.43	480	2.231	69.1	N/A	23.0	0.0086	0.0085	99.36	23.0	1.1	3.3	18.1	0.7	3.6	7.8	7.0
10	10	3.44	483	2.213	93.2	N/A	22.8	0.0117	0.0115	99.40	23.9	0.4	3.9	18.9	0.3	4.2	7.6	6.8
11	11	3.44	483	2.209	124.1	N/A	22.8	0.0156	0.0152	99.13	36.3	0.2	3.7	26.7	0.2	4.0	7.6	6.7
12	12	3.42	483	2.227	154.7	N/A	23.1	0.0193	0.0189	98.96	43.6	0.2	3.5	34.2	0.1	3.7	8.[illegible]	6.7
13	13	3.43	505	2.127	66.6	N/A	22.9	0.0087	0.0085	99.50	18.2	0.7	3.6	14.6	0.5	3.8	7.7	6.7
14	14	3.43	507	2.118	105.2	N/A	23.0	0.0138	0.0135	99.35	26.7	0.2	4.1	26.5	0.1	4.3	7.6	6.6
15	15	3.41	508	2.109	117.7	N/A	23.1	0.0155	0.0153	99.24	31.6	0.2	4.0	25.4	0.1	4.2	7.5	6.6
16	16	3.41	509	2.109	145.0	N/A	23.1	0.0191	0.0187	99.14	36.4	0.1	3.8	29.3	0.1	4.1	7.5	6.6
17	17	2.54	794	1.270	108.3	N/A	29.1	0.0239	0.0234	99.50	20.8	0.1	7.9	0.5	0	19.7	8.3	6.8

Summary of Test Results: Configuration SA-4

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.310	446	1.991	65.2	N/A	19.695	0.0091	0.0095	93.76	95.9	40.0	2.4	101.1	43.7	2.4	7.71	7.29
2	2	3.319	448	2.036	84.3	N/A	20.166	0.0115	0.0122	98.48	48.0	4.0	3.0	50.8	4.4	3.0	8.17	7.23
3	3	3.323	448	1.992	115.6	N/A	19.645	0.0162	0.0164	98.77	45.0	1.8	3.2	47.7	2.0	3.2	8.05	7.42
4	4	3.318	448	1.991	144.1	N/A	19.722	0.0201	0.0221	99.17	34.0	0.3	3.3	35.9	0.4	3.3	7.72	6.78
5	5	3.266	479	1.773	56.8	N/A	19.200	0.0089	0.0091	96.03	22.9	21.5	3.0	82.2	23.5	2.9	6.68	6.15
6	6	3.254	478	1.782	81.5	N/A	19.278	0.0127	0.0132	99.15	31.1	1.3	3.9	32.6	1.4	3.9	6.54	6.20
7	7	3.261	477	1.782	108.4	N/A	19.210	0.0169	0.0174	99.28	28.9	0.4	4.0	30.4	0.5	4.0	7.15	6.29
8	8	3.271	477	1.787	127.4	N/A	19.167	0.0198	0.0215	99.37	26.3	0.2	3.8	27.9	0.2	3.8	6.18	5.92
9	9	3.583	485	2.231	69.9	N/A	22.030	0.0087	0.0092	91.90	93.9	59.0	2.7	79.5	44.7	2.9	8.01	8.00
10	10	3.587	485	2.213	93.2	N/A	21.913	0.0117	0.0126	99.17	30.8	1.2	3.6	26.1	0.9	3.8	9.08	8.00
11	11	3.600	485	2.204	123.8	N/A	21.825	0.0156	0.0165	99.15	33.3	0.7	3.6	28.4	0.6	3.8	10.35	8.48
12	12	3.595	486	2.209	153.5	N/A	21.896	0.0193	0.0219	99.34	27.4	0.2	3.6	23.3	0.2	3.7	8.52	7.76
13	13	3.602	508	2.104	66.8	N/A	21.747	0.0088	0.0093	95.04	75.7	31.9	2.8	65.4	25.0	2.9	8.69	7.61
14	14	3.592	508	2.109	104.0	N/A	21.827	0.0137	0.0149	99.46	20.8	0.5	4.3	17.9	0.4	4.5	8.43	7.60
15	15	3.584	507	2.109	118.4	N/A	21.828	0.0156	0.0170	99.45	22.5	0.2	4.3	19.3	0.2	4.5	8.42	7.68
16	16	3.586	507	2.109	145.8	N/A	21.814	0.0192	0.0213	99.42	24.2	0.1	4.0	20.8	0.1	4.2	8.29	7.59
17	17	2.645	752	1.311	109.5	N/A	26.918	0.0[illegible]32	0.0252	99.74	10.5	0.1	6.9	0.27		16.9	8.41	7.36
18	18	2.649	749	1.306	86.0	N/A	26.734	0.0183	0.0197	99.76	9.6	0.1	8.0	0.25	0	19.6	8.23	7.23
19	19	2.649	745	1.288	66.8	N/A	26.312	0.0144	0.0154	99.76	9.5	0.2	8.4	0.25	0	20.6	7.84	7.24

Summary of Test Results: Configuration SA-5

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec.	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg,	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.15	448	2.150	67.3	N/A	21.474	0.0087	0.0096	98.07	31.2	2.0	3.0				7.12	6.46
2	2	3.184	447	2.145	86.5	N/A	21.122	0.0112	0.0116	99.15	31.8	1.0	3.3				7.27	6.48
3	3	3.180	446	2.145	122.0	N/A	21.125	0.0158	0.0168	98.90	45.4	0.4	3.3				7.14	6.22
4	4	3.175	446	2.145	149.8	N/A	21.155	0.0194	0.0205	98.72	49.3	1.3	3.0				7.01	6.26
10	4.5	3.142	479	1.923	47.8	N/A	20.662	0.0069	0.0073	98.79	88.0	61.6	2.8				6.24	5.68
5	5	3.143	480	1.882	65.0	N/A	20.230	0.0096	0.0099	99.42	21.4	0.8	3.5				6.70	5.15
6	6	3.099	477	1.923	85.2	N/A	20.824	0.0123	0.0131	99.36	26.3	0.3	3.9				5.39	5.60
7	7	3.141	475	1.927	113.3	N/A	20.521	0.0164	0.0174	99.08	38.3	0.2	3.6				5.99	5.54
8	8	3.160	477	1.918	131.2	N/A	20.407	0.0190	0.0203	99.05	40.1	0.2	3.4				7.85	---
11	9	3.409	486	2.376	71.9	N/A	23.788	0.0084	0.0082	99.09	28.7	2.4	2.9	22.8	1.6	3.03	8.38	7.58
12	10	3.426	483	2.358	95.1	N/A	23.444	0.0112	0.0123	99.43	22.4	0.4	3.7	18.9	0.3	3.93	8.43	7.24
13	11	3.408	483	2.345	128.3	N/A	23.530	0.0152	0.0164	99.10	37.6	0.2	3.6	29.8	0.2	3.89	8.55	7.39
14	12	3.430	485	2.336	158.9	N/A	23.441	0.0189	0.0202	99.07	39.4	0.1	3.3	31.5	0.1	3.51	8.35	7.25
19	12.9	3.402	509	2.190	56.8	N/A	23.342	0.0072	0.0070	88.68	86.3	93.1	2.5	69.1	64.2	2.6	7.19	7.11
15	13	3.418	508	2.218	68.7	N/A	23.331	0.0086	0.0093	99.49	19.1	0.6	3.4	15.4	0.4	3.61	7.22	6.90
16	14	3.417	508	2.222	106.4	N/A	23.334	0.0133	0.0141	99.35	27.1	0.2	4.5	21.8	0.1	4.76	7.79	6.76
17	15	3.422	507	2.21[illegible]	121.1	N/A	23.229	0.0152	0.0160	99.23	32.5	0.1	4.4	26.2	0.1	4.66	7.54	6.76
18	16	3.414	508	2.190	148.2	N/A	23.207	0.0188	0.0195	99.17	35.2	0.1	3.8	28.4	0.1	3.97	7.53	6.69
20	17	2.493	784	1.306	67.2	N/A	29.531	0.0143	0.0151	99.63	13.2	0.6	11.0	0.3	0	27.5	7.59	7.17
21	18	2.521	784	1.324	46.2	N/A	29.407	0.0097	0.0106	99.75	7.5	0.8	8.4	0.2	0	21.0	8.35	7.33
22	19	2.525	783	1.324	37.7	N/A	29.326	0.0079	0.0076	99.80	5.2	0.7	9.6	0.1	0	24.0	8.20	7.33

Summary of Test Results: Configuration SA-6

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature ✓	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg.	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %	Comments
1	1	3.144	479	2.005	56.[illegible]	N/A	21.54	0.0078	0.0079	98.21	39.3	8.7	N/A			N/A	6.56	6.51	
2	2	3.130	479	2.018	83.[illegible]	N/A	21.71	0.0115	0.0113	99.17	29.9	1.3	N/A			N/A	7.25	6.45	
3	3	3.121	480	2.018	109.7	N/A	21.83	0.0151	0.0144	98.91	43.5	0.8	N/A			N/A	6.98	6.46	
4	4	3.125	480	2.009	139.6	N/A	21.73	0.0193	0.0182	98.77	50.9	0.5	N/A			N/A	7.08	6.38	
5	6	3.551	504	2.113	63.9	N/A	21.25	0.0084	0.0083	99.38	19.6	1.7	N/A	16.8	1.29	N/A	6.56	5.91	
6	7	3.528	509	2.113	88.2	N/A	21.52	0.0116	0.0112	99.49	19.6	0.5	N/A	16.7	0.41	N/A	5.94	5.98	
7	8	3.553	508	2.118	114.4	N/A	21.42	0.0150	0.0144	99.25	30.7	0.4	N/A	26.4	0.2[illegible]	N/A	6.43	5.92	
8	9	3.534	508	2.113	144.[illegible]	N/A	21.50	0.0190	0.0082	99.10	37.5	0.2	N/A	32.0	[illegible]18	N/A	6.31	5.92	
9	11	3.560	553	2.249	71.7	N/A	24.66	0.0088	0.0081	99.51	15.3	1.3	N/A	8.06	0.[illegible]5	N/A	7.94	6.35	
10	12	3.535	547	2.272	102.2	N/A	24.68	0.0125	0.0119	99.48	20.7	0.4	N/A	10.8	[illegible].12	N/A	8.07	6.31	
11	13	3.530	546	2.277	132.0	N/A	24.78	0.0161	0.0154	99.22	32.4	0.2	N/A	16.8	0.07	N/A	7.73	6.27	
12	14	3.520	547	2.277	165.6	N/A	24.87	0.0202	0.0193	99.15	35.6	0.2	N/A	18.5	0.0[illegible]	N/A	7.86	6.14	
13	16	3.016	631	1.746	90.5	N/A	26.00	0.0144	0.0130	99.47	21.7	0.2	N/A	2.9	0.01	N/A	8.00	6.15	
14	17	2.693	790	1.333	119.5	N/A	27.72	0.0249	0.0215	99.61	16.2	0.1	N/A	0.44	0	N/A	7.33	5.42	

Summary of Test Results: Configuration SA-7

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg,	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
1	1	3.098	480	1.917	55.9	N/A	19.455	0.0081	0.0087	98.83	35.5	3.4	3.7				4.80	5.21
2	2	3.091	477	1.932	83.5	N/A	19.505	0.0120	0.0122	98.85	41.1	1.8	4.1				4.37	5.21
3	3	3.107	477	1.933	109.3	N/A	19.401	0.0157	0.0157	98.74	50.9	0.8	3.4				4.63	5.08
4	4	3.108	477	1.932	139.8	N/A	19.377	0.0201	0.0196	98.83	49.0	0.3	3.1				4.67	5.03
5	6	3.515	504	2.239	64.5	N/A	21.020	0.0080	0.0083	99.08	28.0	2.7	3.9	23.6	2.0	4.2	5.63	5.97
6	7	3.531	510	2.230	88.3	N/A	21.087	0.0110	0.0110	99.30	26.2	0.9	5.0	[illegible]	0.7	5.1	5.66	5.97
7	8	3.524	508	2.235	115.1	N/A	21.091	0.0143	0.0141	99.06	38.1	0.5	4.1	32.3	0.4	4.2	5.87	5.90
8	9	3.512	507	2.249	144.1	N/A	22.225	0.0178	0.0176	99.00	42.0	0.2	3.5	35.3	0.2	3.5	5.35	5.82
9	11	3.556	545	2.257	65.3	N/A	22.773	0.0080	0.0087	99.39	19.2	1.6	4.3	10.1	0.5	5.0	6.50	6.39
10	12	3.520	546	2.263	101.8	N/A	22.963	0.0125	0.0132	99.65	28.0	0.4	5.1	14.5	0.2	6.0	6.14	6.38
11	13	3.532	543	2.269	131.5	N/A	22.804	0.0161	0.0169	99.14	35.8	0.2	4.0	18.6	0.1	4.7	6.08	6.27
12	14	3.527	543	2.265	165.5	N/A	22.800	0.0203	0.0210	99.59	33.9	0.1	3.6	17.6	0.04	4.3	5.93	6.28
13	16	2.995	623	1.807	89.8	N/A	24.773	0.0138	0.0140	99.43	23.7	0.1	6.5	3.1	0	11.1	6.31	6.61
14	17	2.672	787	1.362	119.6	N/A	26.255	0.0244	0.0247	99.69	13.1	0.1	7.2	0.4	0	17.6	4.66	5.63

Summary of Test Results: Configuration SA-8

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg.	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NOx	Eng CO	Eng HC	Eng NOx	Total Pressure Loss %	Doce Pressure Loss %
1	1	3.12	482	1.939	57.2	N/A	19.65	0.0082	0.0084	91.62	97.0	61.2	2.3				6.09	6.28
2	2	3.13	478	1.955	84.5	N/A	19.53	0.0120	0.0012	99.40	21.4	1.0	3.4				6.41	6.40
3	3	3.14	478	1.932	109.2	N/A	19.30	0.0157	0.0145	99.35	26.1	0.4	4.1				6.51	6.49
4	4	3.11	478	1.941	139.8	N/A	19.53	0.0200	0.0184	99.19	34.0	0.2	3.8				6.68	6.35
5	7	3.55	508	2.272	89.2	N/A	21.31	0.0109	0.0105	99.67	13.7	0.7	3.0	11.8	0.6	3.1	7.65	7.08
6	8	3.56	507	2.289	116.2	N/A	21.37	0.0141	0.0128	99.63	14.3	0.4	4.1	12.3	0.3	4.3	7.66	7.41
7	9	3.55	507	2.296	144.6	N/A	21.46	0.0175	0.0159	99.45	22.7	0.2	4.4	19.4	0.2	4.6	8.03	7.49
8	6	3.57	508	2.285	76.5	N/A	21.34	0.0093	0.0095	97.95	41.5	10.8	2.0	35.7	8.4	2.1	7.64	6.95
1	11	3.56	546	2.344	80.2	N/A	23.72	0.0095	0.0092	98.89	28.0	4.6	2.1	14.5	1.6	2.4	7.98	8.05
2	12	3.55	545	2.344	103.8	N/A	23.73	0.0123	0.0117	99.70	11.5	0.3	3.9	5.9	0.1	4.6	8.13	8.08
3	13	3.55	547	2.346	132.6	N/A	23.86	0.0157	0.0149	99.53	19.5	0.2	5.2	10.1	0.1	6.0	8.29	8.10
4	14	3.54	544	2.348	165.7	N/A	23.76	0.0196	0.0180	99.34	27.8	0.1	4.6	14.3	0	5.5	8.18	8.11
5	16	3.06	634	1.851	91.3	N/A	25.30	0.0137	0.0128	99.72	11.5	0.1	6.1	1.5	0	10.1	8.41	7.93
6	17	2.71	785	1.390	120.1	N/A	26.52	0.0240	0.0229	99.69	12.8	0.1	9.1	0.35	0	22.1	7.76	6.97

Summary of Test Results: Full-Annular Configuration

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg	Reference Velocity m/sec	Fuel/Air Ratio: Meter Over-All	Fuel/Air Ratio: Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel: CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Zone Pressure Loss %
	1	3.204	449	9.306	163	6.6	15.683	0.0089	0.0097	96.12	72.0	14.3	2.5				8.08	N/A
	2	3.224	447	9.270	389	6.6	15.465	0.0116	0.0123	97.5	59.0	7.0	2.8				7.92	N/A
	3	3.218	449	9.302	530	6.4	15.609	0.0158	0.0160	98.1	56.4	2.7	3.0				8.09	N/A
	4	3.218	448	9.370	669	6.7	15.704	0.0199	0.0200	98.4	55.5	1.5	2.8				8.34	N/A
	5	3.231	448	9.374	840	6.9	15.645	0.0249	0.0252	98.6	50.9	0.6	2.7				8.33	N/A
	6	3.163	478	8.472	279	7.5	15.391	0.0091	0.0099	95.0	55.7	19.5	2.8				7.17	N/A
	7	3.177	478	8.404	369	7.8	15.202	0.0122	0.0129	97.9	45.6	5.3	3.1				6.92	N/A
	8	3.134	477	8.272	483	7.9	14.915	0.0162	0.0165	98.7	45.5	1.3	3.0				6.98	N/A
	9	3.156	477	8.354	594	8.3	15.192	0.0201	0.0206	98.7	45.2	0.4	2.7				7.19	N/A
	10	3.129	477	8.190	756	7.9	15.025	0.0256	0.0258	98.9	43.6	0.2	2.5				7.35	N/A
	11	3.116	476	9.215	531	8.1	16.539	0.0160	0.0161	98.4	57.6	1.2	2.7				9.31	N/A
	12	3.116	477	9.977	885	8.3	18.361	0.0247	0.0246	98.6	58.7	0.3	2.2				11.36	N/A
	13	3.939	508	10.916	357	8.3	16.928	0.0091	0.0098	95.2	37.6	24.6	3.4				8.11	N/A
	14	3.952	510	10.789	468	8.2	16.746	0.0121	0.0125	99.1	27.9	1.4	4.1				8.28	N/A
	15	3.932	508	10.898	561	8.2	16.929	0.0143	0.0145	99.3	27.4	0.5	3.9				8.29	N/A
	16	3.952	508	11.039	780	8.3	17.077	0.0197	0.0197	99.3	29.6	0.2	3.4				8.44	N/A
	17	3.952	508	10.952	976	8.3	16.944	0.0248	0.0249	99.3	29.6	0.1	3.1				8.46	N/A
	18	3.932	505	12.317	1089	8.3	19.029	0.0246	0.0247	99.1	37.5	0.1	2.8				11.00	N/A
	19	3.959	509	13.057	1149	8.2	20.209	0.0245	0.0241	99.0	41.2	0.1	2.8				12.56	N/A

Summary of Test Results: Full-Annular (Concluded)

Reading Number	Point Number	Inlet Total Pressure Atm	Inlet Total Temperature K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg,	Reference Velocity m/sec	Fuel/Air Ratio Meter Over-All	Fuel/Air Ratio Sample Over-All	Sample Combustion Efficiency %	Emission Indices lb/klb fuel CO	HC	NO_x	Eng CO	Eng HC	Eng NO_x	Total Pressure Loss %	Dome Pressure Loss %
	A	3.156	479	8.531	485	8.8	15.568	0.0158	0.0153	98.7							7.46	N/A
	B	5.095	533	14.054	631	8.6	17.696	0.0125	0.0121	99.5	12.4	0.1	5.5				8.60	N/A
	C	8.245	588	22.299	1000	8.4	19.122	0.0125	0.0129	99.7							8.97	N/A
	20	11.823	629	32.263	1107	9.1	20.643	0.0096	0.0103	99.6	6.0	0	8.9				9.81	N/A
	21	11.721	632	32.082	1545	9.0	20.815	0.0134	0.0131	99.7	4.8	0.1	10.4				9.98	N/A
	22	11.816	635	31.039	1777	9.4	20.064	0.0159	0.0159	99.8	4.9	0.1	9.5				9.14	N/A
	D	14.918	674	37.669	2117	9.3	20.485	0.0156	0.0158	99.8	4.2	0	12.6				8.59	N/A
	E	16.517	732	39.501	2647	9.5	21.048	0.0186	0.0191	99.9	4.5	0	14.1	3.5	0	15.0	8.18	N/A
	23	16.600	784	37.321	3021	6.0	21.325	0.0225	0.0222	99.9	1.7	0	15.2	0.8	0	18.1	9.09	N/A
	24	16.489	803	36.571	3243	6.22	21.418	0.0246	0.0267	99.9	1.9	0	15.8	0.8	0	19.6	8.97	N/A
	25	15.965	799	36.080	3238	6.26	20.649	0.0249	0.0258	99.9	2.1	0	14.9	0.8	0	18.7	9.31	N/A
	26	15.335	799	37.113	3240	6.24	23.274	0.0243	0.0252	99.9	2.4	0	14.2	0.9	0	18.1	10.43	N/A

APPENDIX B - EMISSIONS ADJUSTMENT FACTORS

This appendix contains the relationships that were used to adjust the measured emissions data, obtained at derated operating conditions, to the actual E^3 design-cycle conditions. The relations are defined as follows:

1. $EICO\ (Adj) = EICO\ (MEA)\ (P_3/P_3\ cycle)^{1.5}$ - g/kg fuel

2. $EIHC\ (Adj) = EIHC\ (MEA)\ (P_3/P_3\ cycle)^{2.5}$ - g/kg fuel

The NO_x emission indices are plotted versus a severity parameter that provides adjustments for pressure, temperature, fuel/air ratio, humidity, and combustor bulk residence time. A value of unity for the severity parameter represents the actual sea level takeoff conditions of the particular engine design cycle.

3. $EINO_x = f\ (s)$

4. $$S = (\tau_B/\tau_B\ cycle)(P_3/P_3\ cycle)^{0.37}\ \beta\ (f/a)\ \exp\left(\frac{T_3 - T_3\ cycle}{192}\right)$$

The variable τ_B represents the combustor bulk residence time, and β (f/a) is an adjustment for combustor fuel/air ratio. For this NO_x emission severity parameter, cycle reference variables are taken at the sea level takeoff conditions for the particular engine design cycle. Since inlet-air humidity was measured during the emissions testing of the full-annular combustor configuration, a humidity-adjustment term was included in the form of the severity parameter.

5. $$S = (\tau_B/\tau_B\ cycle)(P_3/P_3\ cycle)^{0.37}\ \beta\ (f/a)\ \exp\left(\frac{T_3 - T_3\ cycle}{192} + \frac{6.29 - Humidity}{53.19}\right)$$

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

APPENDIX C - NOMENCLATURE

Symbol		Units
A_e	Combustor effective flow area (Geometric area x flow coefficient)	cm^2
A_r	Combustor reference area	cm^2
CO	Carbon monoxide pollutant emission	
CO_2	Carbon dioxide emission	
C_p	Smoke Correlating Parameter	$\sqrt{MPa}$ kg/K (sec)
EI	Emission index	g/kg fuel
EPAP	Environmental Protection Agency emission parameter	lbm-lbf-hr-cycle
f, f_{36}	Total combustor metered fuel/air ratio	g/kg
f_s	Fuel/air ratio calculated from gas sample	g/kg
F_N, F_n	Installed Thrust	kN
H	Engine/combustor inlet-air humidity	g/kg
HC	Total unburned hydrocarbon pollutant emission	
N	Number of fuel injectors	
NO	Nitric oxide pollutant emission	
NO_x	Total oxides of nitrogen pollutant emission	
P_3, P_{T3}	Compressor discharge (combustor inlet) pressure	MPa
S	Severity Parameter	
T_3	Compressor discharge (combustor inlet) temperature	K
T_i	Combustor Metal Temperature	K
T_f	Fuel temperature	K
W_f	Fuel flow rate	kg/s

APPENDIX C - NOMENCLATURE (Concluded)

Symbol		Units
W_3	Compressor discharge total airflow rate	kg/s
W_{36}, W_c	Combustor airflow rate	kg/s
ΔP_f	Fuel manifold pressure drop	MPa
ΔP_t	Combustor total pressure drop	MPa
ϕ	Equivalence Ratio	
τ_B	Bulk Residence Time	ms

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