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# EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

## Diesel No. 2 Fuel Addendum
## Phase III Final Report



GENERAL ELECTRIC COMPANY

Prepared For

**National Aeronautics and Space Administration**

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## NOMENCLATURE

| Symbol | | Units |
|---|---|---|
| CO | Carbon monoxide pollutant emission | |
| $CO_2$ | Carbon dioxide emission | |
| EI | Emission index | g/kg fuel |
| $f_T$, $f_4$ | Total combustor metered fuel-air ratio | g/kg |
| $f_m$ | Main-stage metered fuel-air ratio | g/kg |
| $f_p$ | Pilot-stage metered fuel-air ratio | g/kg |
| $f_8$ | Engine exit metered fuel-air ratio | g/kg |
| $f_s$ | Fuel-air ratio calculated from gas sample | g/kg |
| H | Engine/combustor inlet air humidity | g/kg |
| HC | Total unburned hydrocarbon pollutant emission | |
| NO | Nitric oxide pollutant emission | |
| $NO_x$ | Total oxides of nitrogen pollutant emission | |
| $N_1$ | Low pressure (fan) rotor speed | rps |
| $N_2$ | High pressure (core engine) rotor speed | rps |
| $P_2$ | Engine inlet total pressure | MPa |
| $P_{25}$ | High pressure rotor inlet total pressure | MPa |
| $P_3$, $P_{T3}$ | Compressor discharge (combustor inlet) pressure | MPa |
| $T_2$ | Engine inlet total temperature | K |
| $T_{25}$ | High pressure rotor inlet total temperature | K |
| $T_3$ | Compressor discharge (combustor inlet) temperature | K |
| $T_{49}$ | High pressure turbine exit temperature | K |
| $T_f$ | Fuel temperature | K |
| $W_f$ | Fuel flow rate | kg/s |

| Symbol | | Units |
|---|---|---|
| $W_{FT}$ | Total fuel flow rate | kg/s |
| $W_{FP}$ | Pilot-stage fuel flow rate | kg/s |
| $W_{FM}$ | Main-stage fuel flow rate | kg/s |
| $W_2$ | Engine inlet total airflow rate | kg/s |
| $W_3$ | Compressor discharge total airflow rate | kg/s |
| $W_{36}$, $W_c$ | Combustor airflow rate | kg/s |
| $W_8$ | Core engine exit gas flow rate | kg/s |
| $\Delta P_F$ | Fuel manifold pressure drop | MPa |
| $\Delta P_T$ | Combustor total pressure drop | MPa |
| $\alpha$ | Throttle angle | degrees |
| $\delta$ | Ambient-to-standard pressure ratio (=P/0.191325) | |
| $\theta$ | Ambient-to-standard temperature ratio (=T/288.3) | |

## SECTION 1.0

## SUMMARY


The Diesel No. 2 Fuel Addendum to the Phase III Experimental Clean Combustor Program was conducted to provide a direct comparison of the performance and exhaust emissions of a CF6-50 engine equipped with an advanced, low-emission, Double Annular Combustor when fueled with Diesel No. 2 and JP-5 fuels. In the base program, an extensive series of engine tests was conducted with JP-5 fuel. In this addendum, selected engine steady-state operating conditions ranging from idle to full power were retested with Diesel No. 2 fuel. The engine results were further compared to rig data obtained in the Phase II program.

Effects of fuel type on engine/combustor performance and exhaust emissions were generally very small and in good agreement with rig results. However, at approach power level, the smoke level with Diesel No. 2 fuel was significantly higher than with JP-5 fuel and exceeded the EPA requirement. The need for some improvement in fuel-air mixing techniques and/or leaner burning techniques for use with Diesel No. 2 fuel is, therefore, indicated. At high power, smoke levels and peak metal temperatures with Diesel No. 2 and JP-5 fuels were virtually identical; this confirms the previous observation that advanced, low-emission combustors tend to be far more tolerant to fuel changes than are older engine/combustor designs. However, the Double Annular Combustor used in these tests is considerably more complex than any combustor currently in use, and additional development of this design concept is required, particularly in the areas of exit temperature distribution, engine fuel control, and exhaust emission levels before it can be considered for production engine use.

## SECTION 2.0

## INTRODUCTION

Current fuel specifications for aircraft turbines were established when there was an abundance of high-quality, domestic petroleum resources. Presently, however, the United States is highly dependent upon foreign supplies, and demand is projected to exceed petroleum availability sometime after 1985 (Reference 1). It is therefore essential that aviation turbine fuel specifications be broadened to increase the yield from available petroleum crudes and ultimately permit production from tar sands, shale, and coal. However, broadened fuel specifications may result in penalties to engine performance, exhaust emissions characteristics, and durability. These changes may, in turn, require changes in combustor/fuel-system designs and/or materials.

In 1974, NASA and other government agencies initiated a series of programs to define problems associated with the use of broadened specification fuels. The program was designed to evolve solutions to these problems and to guide the industry in establishing practical fuel specifications (Reference 2). Generally, these studies have shown that older combustion system designs are quite sensitive to fuel property variations, particularly with respect to smoke emissions, flame radiation, and resulting increases in metal temperatures (References 3, 4, and 5). However, advanced low-emission combustor designs, such as those which have been developed in Phase II of the NASA Experimental Clean Combustor Program (ECCP), appear to be more tolerant to fuel property variation (References 6 and 7). These ECCP data were obtained in component rig development tests where engine operating conditions were duplicated except for combustor pressure level at simulated high-power engine-operating conditions. This report describes results of a follow-on program in which the effects of broadened fuel specifications were further investigated in actual tests of a CF6-50 engine which was equipped with an advanced, low-emission, Double Annular Combustor.

This program was conducted as an addendum to Phase III of the NASA/GE ECCP. The overall purpose of the program was to develop and demonstrate technology for the design of advanced combustors, with significantly lower exhaust pollutant-emission levels than those of current technology combustors, for use in advanced commercial aircraft engines. Phase I of the NASA/GE ECCP was specifically directed toward screening and evaluating a large number of combustor design approaches (Reference 8). The Phase II Program (Reference 9) was directed toward further developing the two most promising design approaches from the Phase I Program and providing a combustor design for engine demonstration testing in the Phase III Program (Reference 10).

The Alternate Fuels Addendum to the Phase II Program (Reference 6) involved a test matrix of four combustor configurations and four special fuels, in addition to tests with JP-5 fuel in the basic program. The last combustor tested was the prototype for the demonstrator Double Annular design evaluated in the Phase III CF6-50 engine tests. One of the special fuels was ASTM Grade 2-D Diesel fuel. Compared to Jet-A or JP-5, this fuel has an increased final boiling point, an increased aromatic content (reduced hydrogen content), and is very similar to the Experimental Referee Broad - Specification (ERBS) fuel recommended by the NASA ad hoc panel on jet engine hydrocarbon fuels (Reference 1). Diesel No. 2 fuel was selected for further investigation in the ECCP Phase III tests.

## SECTION 3.0

## PROGRAM PLAN AND TEST FUELS

The Diesel No. 2 Fuel Addendum to Phase III of the NASA/GE ECCP consisted of:

- Performance testing and exhaust emissions testing, using Diesel No. 2 fuel, a General Electric CF6-50 engine equipped with a low-emission, Double Annular Combustor.

- Analysis and comparison of these data to previously obtained engine and rig test data which are summarized in References 6 and 10.

The engine test was conducted immediately following the basic program steady-state performance and emissions tests with JP-5 fuel. Following the Diesel No. 2 fuel tests, additional evaluations with JP-5 fuel were conducted as part of the basic program and other program addenda (References 11 and 12). Eleven engine operating conditions from the JP-5 fuel test schedule were selected for Diesel No. 2 fuel testing. These test conditions are shown in Table I. Test points were selected to provide data at the EPA emissions test power levels of idle, approach, climb-out, and takeoff. Variations in fuel split between the pilot and main stages at high-power operating conditions were investigated to determine the preferred splits with respect to exhaust emissions levels. Additional, intermediate, power levels were investigated to more clearly define the effects of combustor operating parameters on performance and on exhaust emissions. At each test point, engine performance parameters, combustor performance parameters, and exhaust emissions were measured.

Diesel No. 2 fuel with a final boiling point of 615 K and a hydrogen content of 13.2 weight percent was used in these tests. Analyses of this commercially obtained fuel are shown in Table II; properties of the JP-5 fuel are also shown for comparison.

Table I. Diesel No. 2 Fuel Test Point Schedule.

- Based on CF6-50C Rated Thrust (224.2 kN)
- No Customer Air Bleed or Power Extraction
- Double Cruciform Exhaust Gas Sampling Technique

| Test Point No. | Test Point Designation | $F_N/\delta_2$, Corrected Thrust % of Rated | $N1/\sqrt{\theta_2}$, Corrected Fan Speed, rps | $W_{fp}/W_{ft}$ Pilot-to-Total Fuel Flow Split |
|---|---|---|---|---|
| 25 | Standard Idle(1) | 3.3 | --- | 1.00 |
| 26 | Secondary Power Point | 5.0 | 16.3 | 1.00 |
| 27 | Secondary Power Point | 7.0 | 19.3 | 1.00 |
| 28 | Approach | 30.0 | 40.0 | 1.00 |
| 29 | Secondary Power Point | 45.0 | 47.3 | 0.21(2) |
| 30 | Secondary Power Point | 65.0 | 53.8 | 0.18 |
| 31 | Climb-Out | 85.0 | 59.0 | 0.18 |
| 32 | Climb-Out | 85.0 | 59.0 | 0.13 |
| 33 | Secondary Power Point | 92.0 | 60.7 | 0.13 |
| 34 | Takeoff | 100.0 | 67.8 | 0.18 |
| 35 | Takeoff | 100.0 | 67.8 | 0.13 |

(1) Standard Idle is controlled to corrected core speed: $N_2/\sqrt{\theta_2} = 106.7$ rps.
(2) Approximately minimum fuel-splitter setting attainable.

Table II. ECCP/CF6-50 Engine Test Fuel Analyses.

| Fuel Property | Test Method | JP-5 Fuel | Diesel No. 2 Fuel |
|---|---|---|---|
| Composition | | | |
| Aromatics, Vol % | ASTM D1319 | 15.4 | 30.9(1) |
| Olefins, Vol % | ASTM D1319 | 1.3 | 1.2(1) |
| Napthalenes, Vol % | ASTM D1840 | 1.6 | 9.5(1) |
| Saturates, Vol % | ASTM D1319 | 83.3 | 67.9(1) |
| Hydrogen, Wt % | ASTM D1018 | 14.0 | 12.2 |
| Sulfur, Wt % | ASTM D1266 | 0.08 | 0.19 |
| Nitrogen, Wt ppm | ASTM D3431 | 2.5 | 89.0 |
| Volatility | | | |
| Distillation Temperature, K | ASTM D86 | | |
| Initial Boiling Point | | 450 | 460 |
| 10% | | 469 | 489 |
| 20% | | 475 | 502 |
| 50% | | 489 | 533 |
| 90% | | 516 | 585 |
| Final Boiling Point | | 533 | 615 |
| % at 478K | | 25.5 | 4.5 |
| Residue, % | ASTM D86 | 1.2 | 1.1 |
| Loss, % | ASTM D86 | 0.8 | 0.9 |
| Flashpoint, K | ASTM D93 | 330 | 338 |
| Specific Gravity (288.7/288.7 K) | ASTM D1298 | 0.8104 | 0.8493 |
| Fluidity | | | |
| Viscosity at 310.9 K, $mm^2/s$ | ASTM D445 | 1.53 | 2.63 |
| Pour Point, K | ASTM D97 | --- | 250 |
| Combustion | | | |
| Net Heat of Combustion, MJ/kg | ASTM D2382 | 43.178 | 42.445 |
| Smoke Point, mm | ASTM D1322 | 24.5 | 14.0 |

(1)Gas Chromatograph.

## SECTION 4.0

## EQUIPMENT AND EXPERIMENTAL PROCEDURES

Except for the use of Diesel No. 2 fuel, equipment and procedures utilized in these addendum tests were identical to those utilized in the basic program tests. In-depth descriptions are contained in Reference 10; the following sections are brief descriptions.

### 4.1 CF6-50 ENGINE DESCRIPTION

The CF6-50 is a dual-rotor, high bypas ratio turbofan incorporating a variable stator, a high pressure ratio compressor, an annular combustor, an air-cooled core engine turbine, and a coaxial front fan with a low-pressure compressor driven by a low-pressure turbine. Major features of the engine are shown in Figure 1. The CF6-50C engine model (224 kN rated thrust) operating parameters, listed in Table III, were used as the combustor design and test conditions of this program.

CF6-50 Engine Number 455-105/7 was used for these Double Annular Combustor demonstration tests. This development engine was equipped, generally, with production engine parts; it had been previously operated to CF6-50M engine rated thrust levels of 241 kN. However, prior to the ECCP tests, the engine had deteriorated to the point that specific fuel consumption and turbine temperatures were higher than those of any high-time, in-service production engine.

### 4.2 DOUBLE ANNULAR COMBUSTION SYSTEM DESCRIPTION

In Phases I and II of the NASA/GE ECCP, four advanced combustor concepts were evaluated in CF6-50 engine-size, full-annular, combustor rig tests. The best results were obtained with the Double Annular configuration. The Double Annular Combustor, shown in Figure 2, contains two annular primary burning zones separated by a short centerbody. Thirty fuel nozzles were used each annulus. The outer annulus is the pilot stage and is always fueled. The inner annulus is the main stage and is fueled only at higher power operating conditions. The airflow distribution is highly biased to the main stage in order to reduce both idle and high-power emissions. The pilot-stage airflow is specifically sized to provide nearly stoichiometric fuel/air ratios and long residence times at idle power settings, thereby minimizing CO and HC emissions. At high-power operating conditions, most of the fuel is supplied to the main stage where the residence times are very short. Also, at high-power operating conditions, lean fuel-air ratios are maintained in both stages to minimize $NO_x$ and smoke emission levels.

The demonstrator Double Annular Combustor design used in the Phase III tests incorporated thermodynamic features identified in the Phase I and II Programs together with advanced aeromechanical features from other General Electric programs needed for high-pressure, high-temperature usage. Details

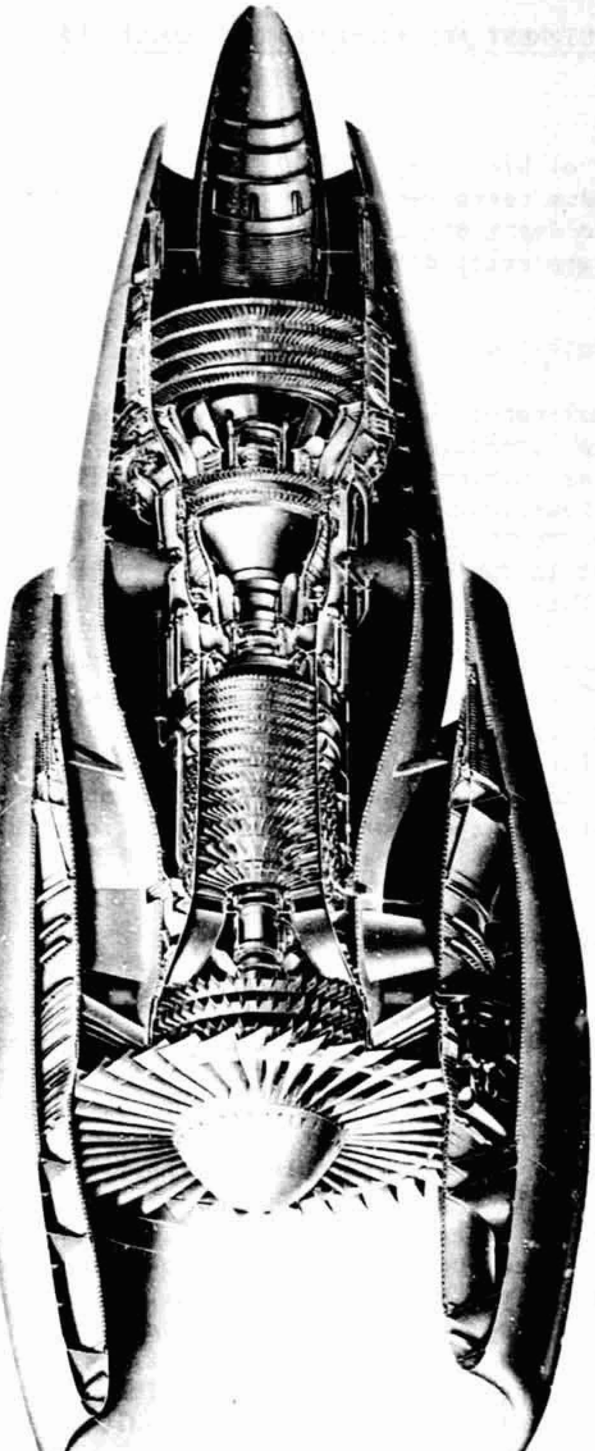


Figure 1. General Electric CF6-50 High Bypass Turbofan Engine.

# Table III. CF6-50C Production Engine Cycle Parameters.

- $T_{amb}$ = 288.2 K
- $P_{amb}$ = 0.1013 MPa
- Kerosene Fuel
- No Bleed

| Rating | | | GIDL | --- | --- | FIDL | --- | APPR | --- | --- | Climb | --- | TKOF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_1$ | Fan Speed | rps | 14.07 | --- | --- | --- | --- | 39.17 | --- | --- | 58.93 | --- | 62.52 |
| $N_2$ | Core Speed | rps | 104.7 | --- | --- | --- | --- | 143.8 | --- | --- | 164.4 | --- | 169.1 |
| $W_{ft}$ | Fuel Flow Rate (Total) | kg/s | 0.1526 | 0.1782 | 0.2130 | 0.2505 | --- | 0.6645 | --- | --- | 1.953 | --- | 2.376 |
| $T_3$ | Combustor Inlet Temperature | K | 437.4 | 463 | 489 | 514 | 579 | 631.9 | 691 | 745 | 791.9 | 807 | 826.3 |
| $P_3$ | Combustor Inlet Pressure | MPa | 0.300 | 0.374 | 0.461 | 0.561 | 0.917 | 1.197 | 1.606 | 2.117 | 2.616 | 2.785 | 2.983 |
| $W_{36}$ | Combustor Airflow Rate | kg/s | 13.93 | 17.3 | 21.3 | 25.3 | 38.6 | 48.17 | 61.0 | 76.7 | 90.81 | 95.3 | 100.6 |
| $f_4$ | Combustor Fuel-Air-Ratio | g/kg | 10.96 | 10.3 | 10.0 | 9.9 | 11.6 | 13.79 | 16.4 | 19.0 | 21.51 | 22.4 | 23.62 |
| $V_r$ | Combustor Reference Velocity (1) | m/s | 18.56 | 19.6 | 20.7 | 21.4 | 22.3 | 23.29 | 24.0 | 24.7 | 25.18 | 25.3 | 25.51 |
| $W_8$ | Core Exhaust Gas Flow Rate | kg/s | 17.55 | --- | --- | --- | --- | 61.05 | --- | --- | 115.2 | --- | 127.2 |
| $f_8$ | Core Exhaust Fuel-Air Ratio | g/kg | 8.8 | --- | --- | --- | --- | 11.0 | --- | --- | 17.3 | --- | 19.0 |
| $F_n$ | Uninstalled Net Thrust | kN | 7.42 | 11.2 | 15.7 | 21.3 | 44.8 | 67.27 | 100.9 | 195.7 | 190.5 | 206.2 | 224.2 |
| $F_n/F_r$ | Percent of Rated Thrust | % | 3.31 | 5.0 | 7.0 | 9.5 | 20.0 | 30.0 | 45.0 | 65.0 | 85.0 | 92.0 | 100 0 |

(1) Based on $A_r$ = 3729 $cm^2$ and $W_{36}/W_3$ = 0.841.

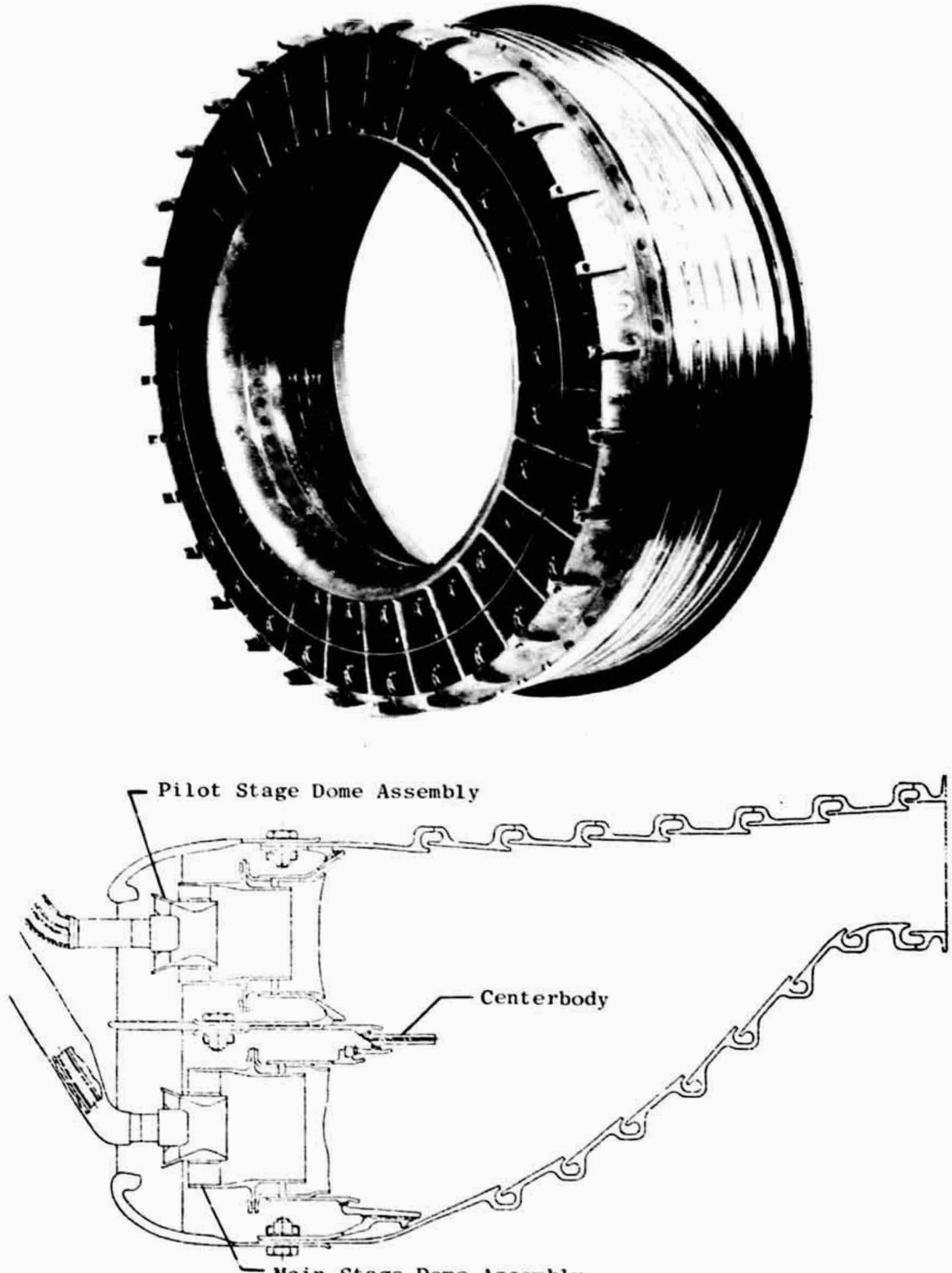



Figure 2. Engine Demonstrator Double-Annular Combustor.

of the swirl cup and dome construction are shown in Figures 3 and 4. Fuel nozzles are shown in Figure 5. Both the pilot- and main-stage fuel nozzles are installed through the existing fuel nozzle parts of the engine with the combustor installed. The main-stage fuel nozzles are connected to the existing engine fuel manifold, and the pilot-stage fuel nozzles are connected to a new fuel manifold, as shown in Figure 6. Fuel flow-split between manifolds is automatically scheduled as a function of overall fuel-flow rate and predetermined settings of the fuel-splitter control device shown in Figure 7. The main-stage cut-in point and pilot-to-total fuel-flow split after main-stage cut-in were adjusted from the engine operating panel.

## 4.3 TEST FACILITY DESCRIPTION

Tests were conducted in Cell 7 of the Development Engine Test Complex in Building 500 of the Evendale, Ohio, plant. Cell 7 is designed specifically for the development testing of large turbofan engines at sea-level static conditions. A typical installation is shown in Figure 8. The engine is suspended from a thrust measuring frame through a flight-type pylon and engine fan duct cowling. The engine is operated from an acoustically isolated control room located immediately adjacent to the test cell and on the left side, aft looking forward. The gas analysis equipment is located in a mezzanine room adjacent to the other side of the test cell and approximately in line with the engine exhaust nozzle; thus, the gas sample lines are only about 8m long.

## 4.4 ENGINE/COMBUSTOR INSTRUMENTATION

Combustor instrumentation locations are shown in Figure 9. The engine and test cell are equipped with all of the normal development test instrumentation needed to operate the engine safety and determine the overall steady-state and transient operating characteristics. In addition, the Double Annular Combustor and associated fuel supply and control system were extensively instrumented to determine the performance of the new components. A summary of key measured and calculated parameters is shown in Table IV.

A new exhaust gas sampling rake and traversing system, shown schematically in Figure 10, was utilized in these tests. The assembly installed in the test cell is shown in Figure 11. Eight sampling arms are mounted radially inward from a traverse ring which is sized to clear the CF6-50 engine fan jet. Each arm has three sampling ports which are located on centers of area of the core engine exhaust nozzle. Alternate arms are manifolded to collect 12-point mixed samples. The entire ring can be rotated for traverse sampling. The two sample lines and traverse motor controls are routed to the gas-analysis room where rake position and sample processing are selected during test.

With this rake system, three different sampling techniques were utilized in the Diesel No. 2 fuel tests:

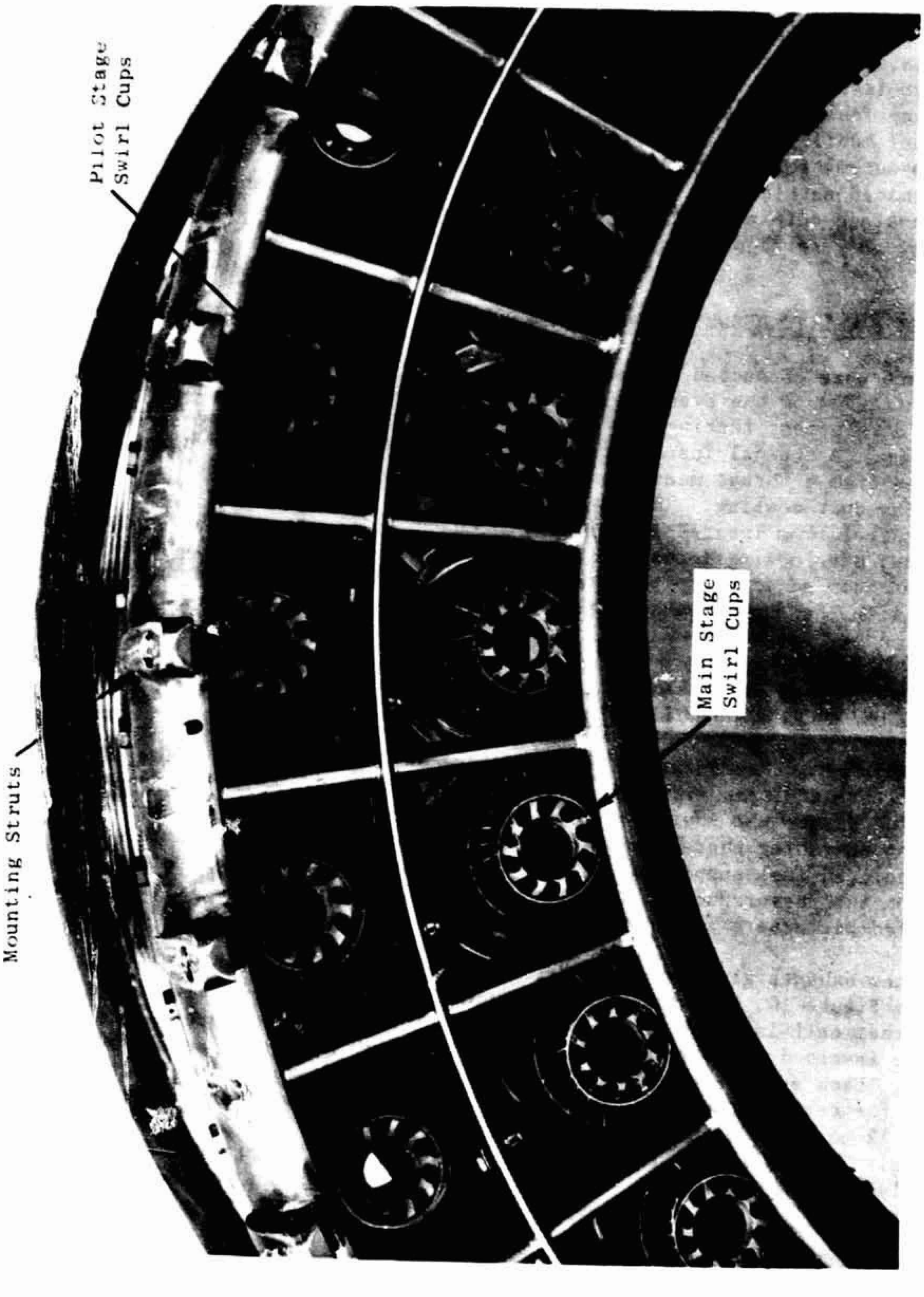



Figure 3. Demonstrator Combustor Overall Dome Details, Aft Looking Forward.

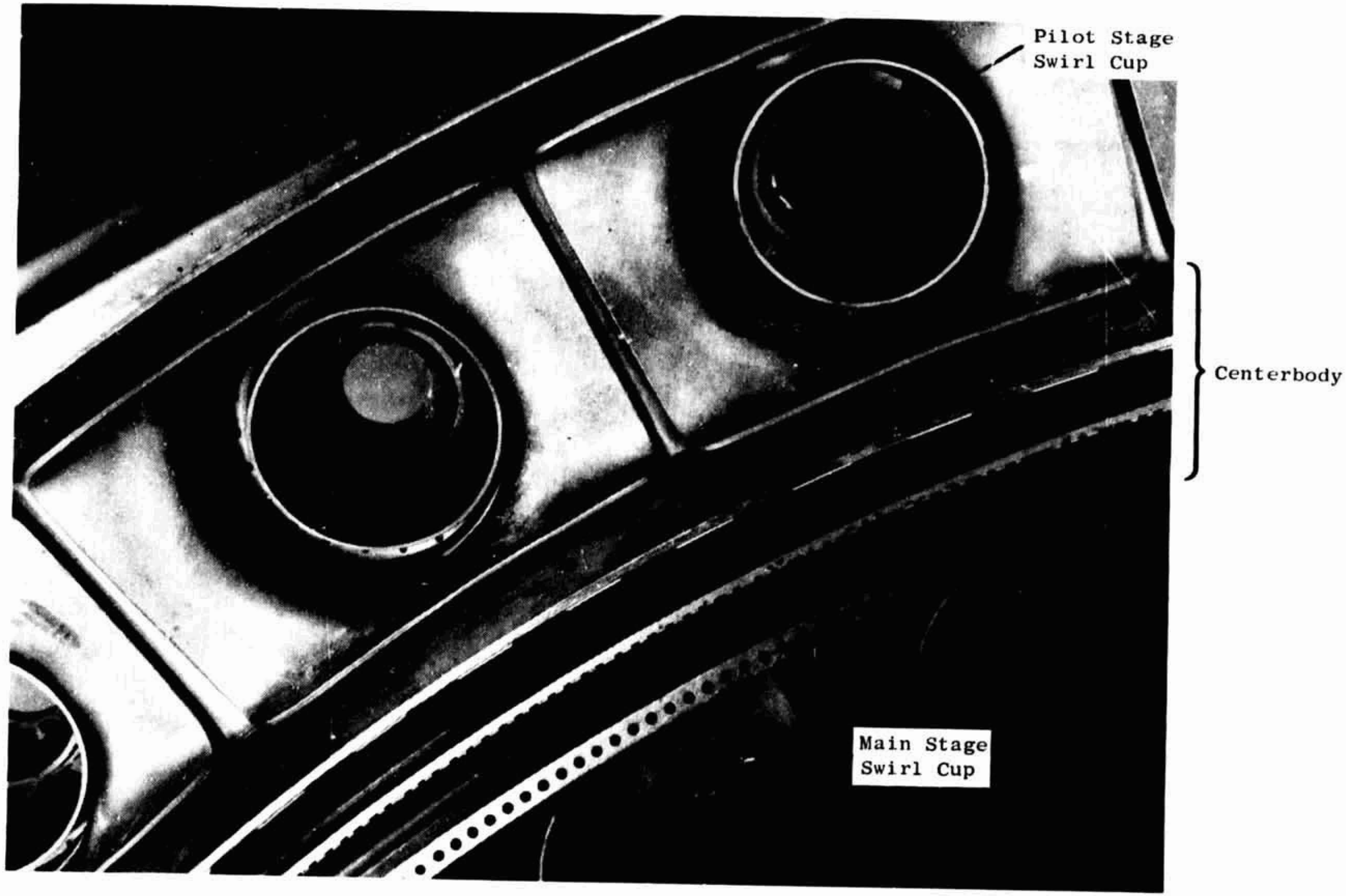
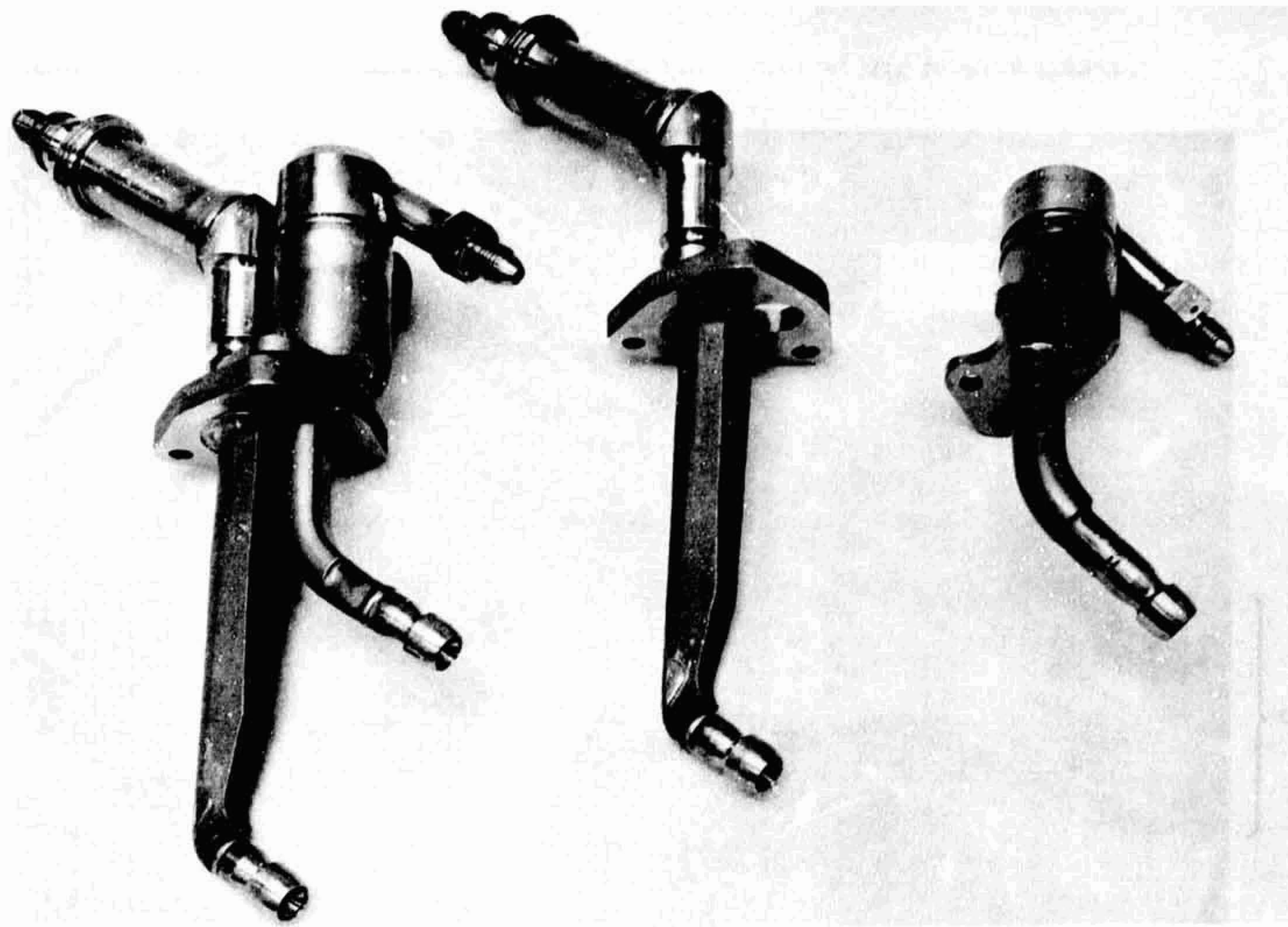



Figure 4. Demonstrator Combustor Pilot Stage Dome Details, Aft Looking Forward.



Main and Pilot Stage Assembly | Main Stage | Pilot Stage

Figure 5. Engine Fuel Nozzles.

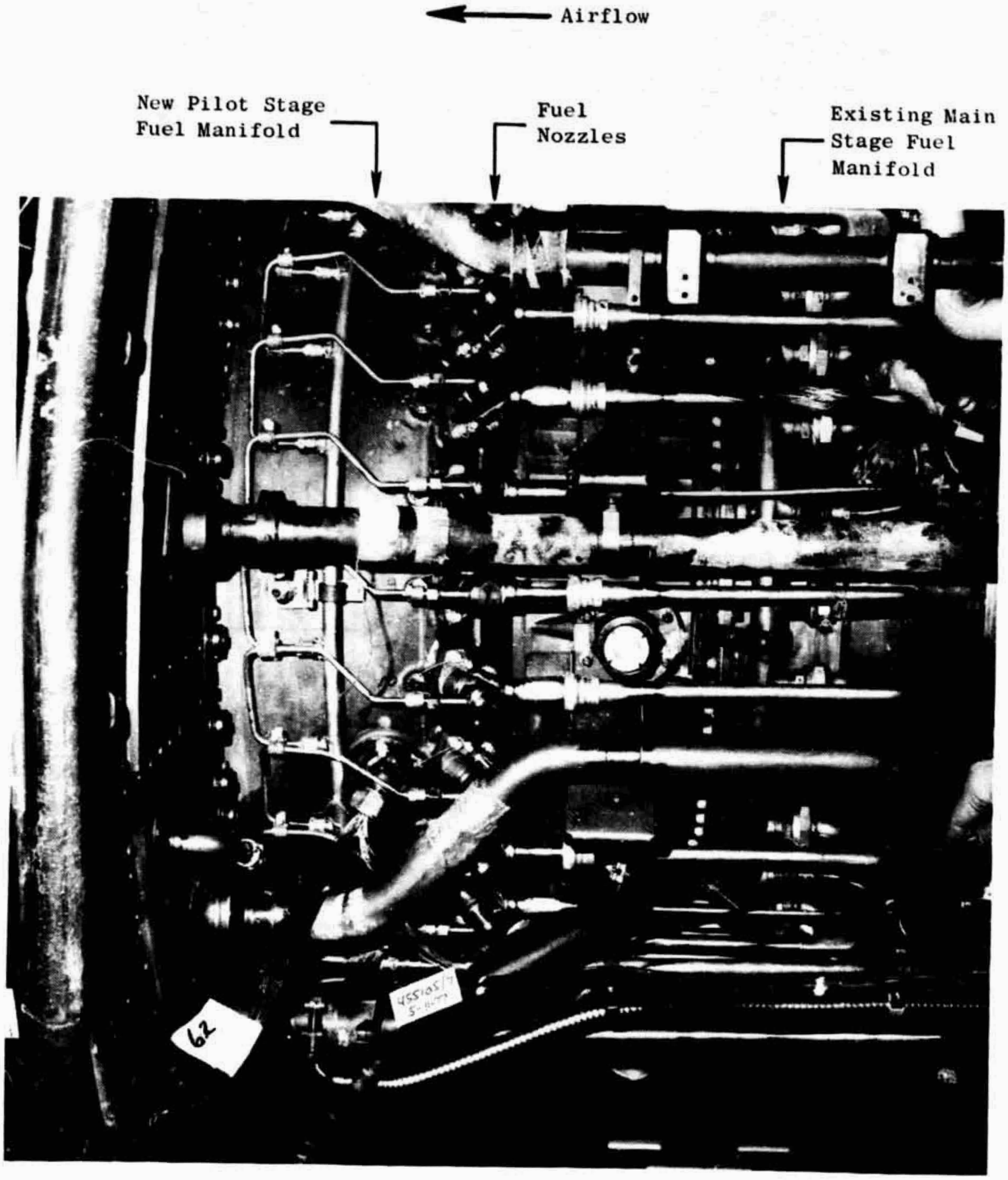



Figure 6. Engine Fuel Nozzle Manifolds.

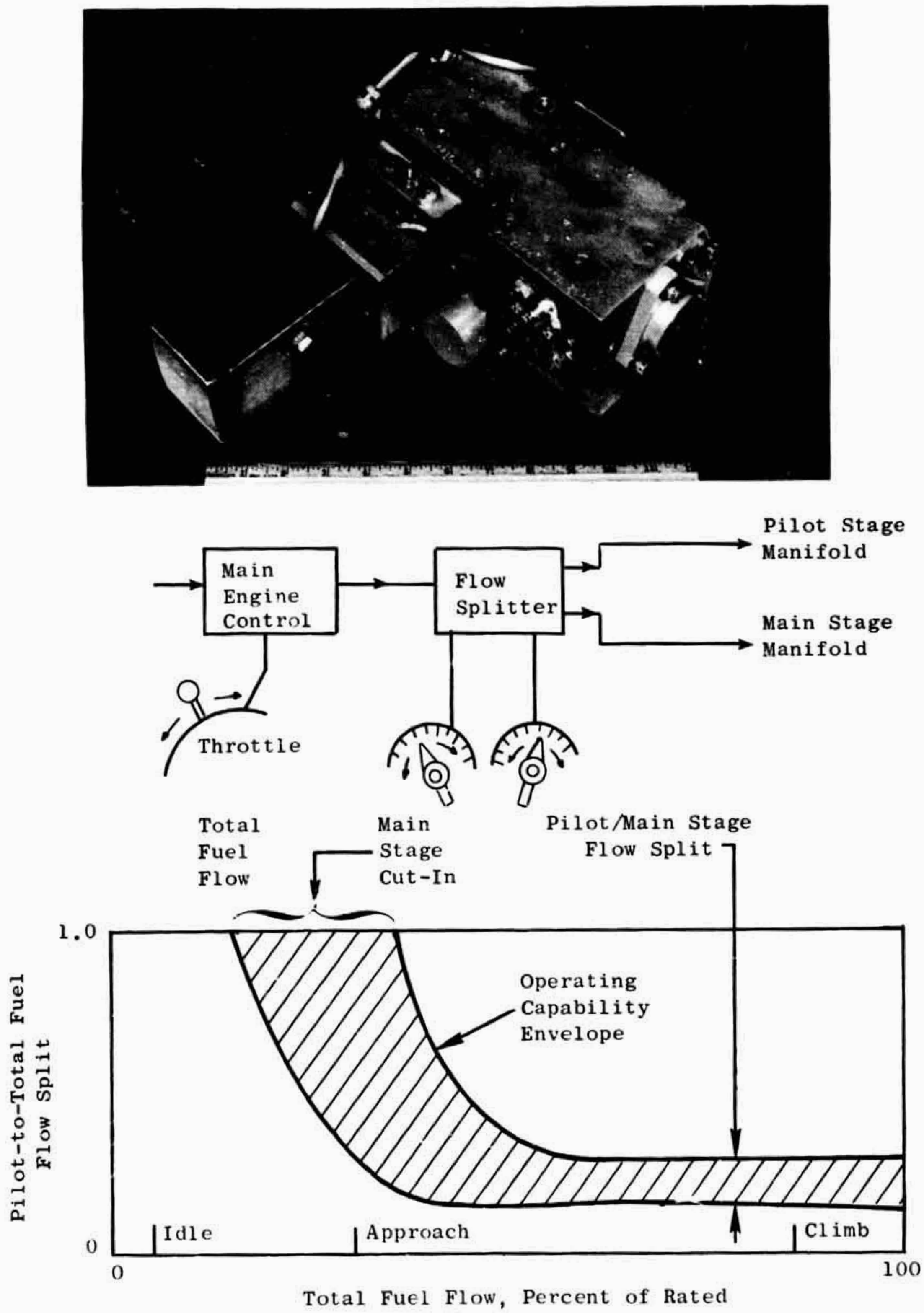



Figure 7. Demonstrator Engine Fuel-Flow Splitter.

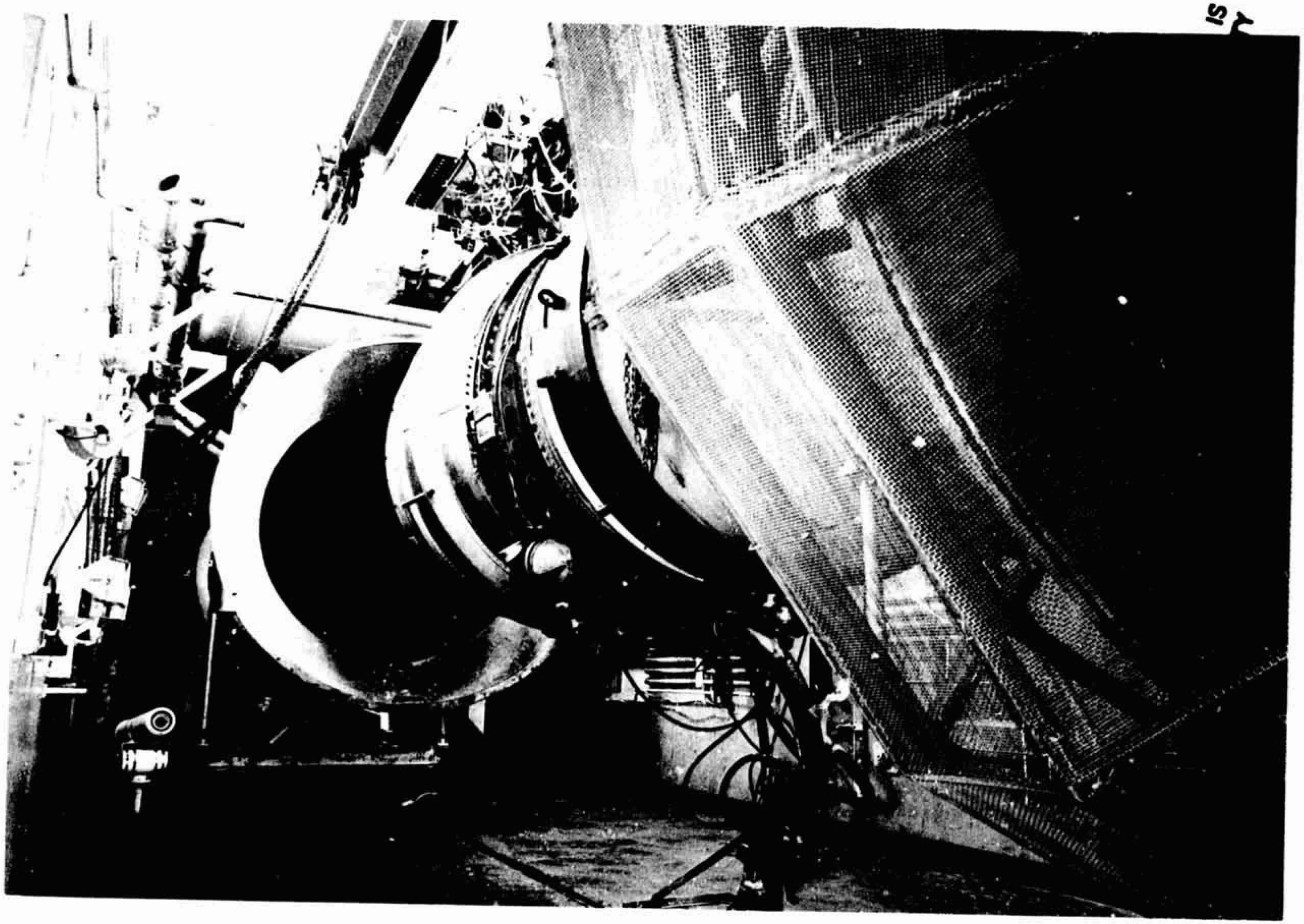


Figure 8. CF6 Engine Mounted in Development Test Cell, Forward Looking Aft.

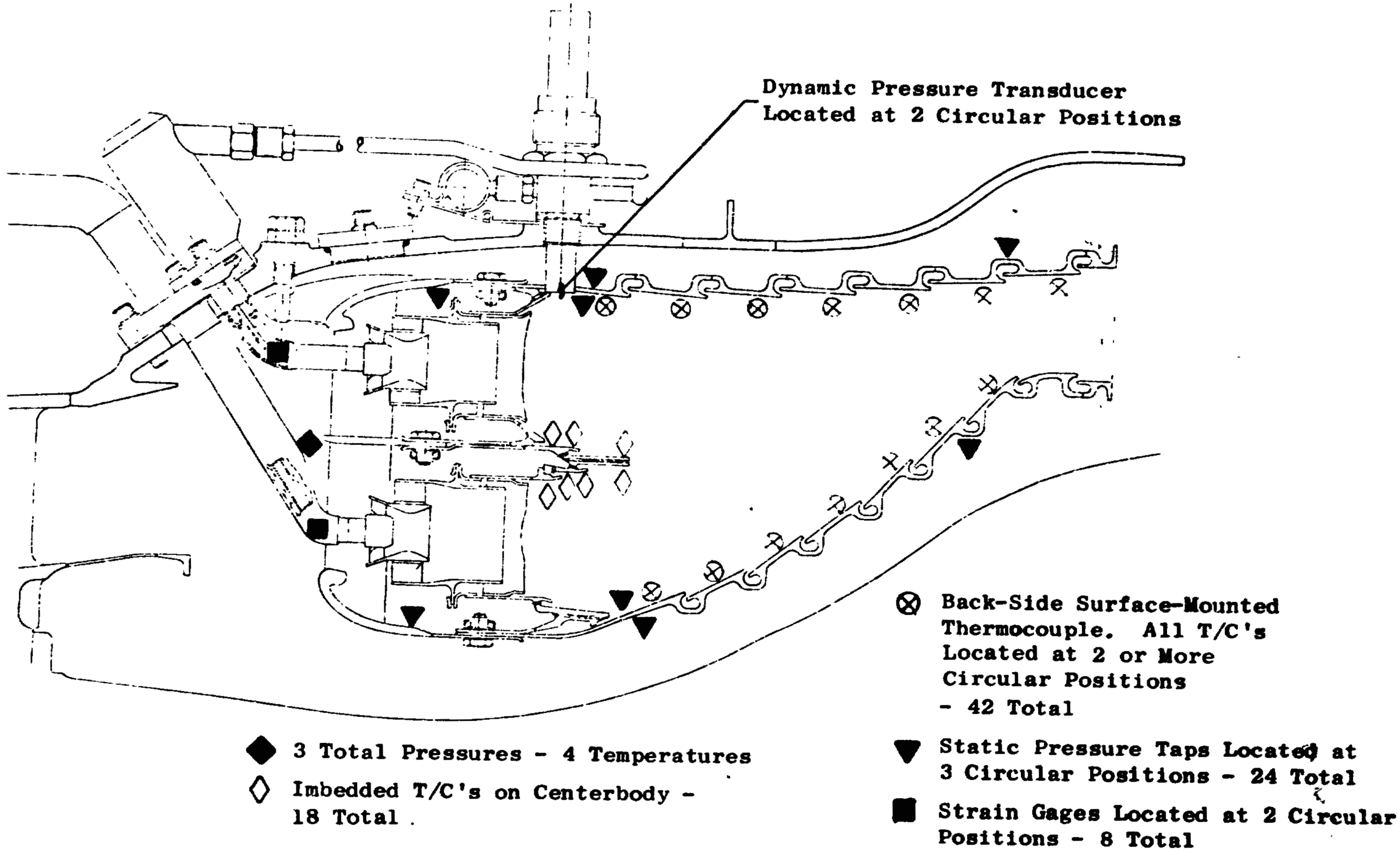



Figure 9. Combustor Instrumentation Locations, Demonstration Engine Tests.

Table IV. Summary of Key Measured and Calculated Demonstrator Engine/Combustor Performance Parameters.

| Parameter | Measured | Calculated | Symbol | Value Determined from |
|---|---|---|---|---|
| Barometer | X | | $P_o$ | Continuously recording weather station |
| Ambient Humidity | X | | $H_o$ | Continuously recording weather station |
| Engine Inlet Total Pressure | X | | $P_2$ | Inlet Bellmouth rakes, 5 rakes, 5 immersions |
| Engine Inlet Total Temperature | X | | $T_2$ | Inlet Bellmouth rakes, 5 rakes, 5 immersions |
| Thrust | X | | $F_n$ | Three calibrated load Cell 5, corrected for Tare and cell factor |
| Fuel Temperature | X | | $T_f$ | Thermocouples at 4 flow meters |
| Fuel Specific Gravity | X | X | | Calculated from pre-test sample and test temperature, and pre-test S.G. |
| Fuel Flow Rate | X | | $W_f$ | Four calibrated turbine meters (total, verification, pilot and mainstages) |
| Low Pressure Rotor (Fan) Speed | X | | $N_1$ | Two tachometers |
| High Pressure Rotor (Core) Speed | X | | $N_2$ | Two tachometers |
| High Pressure Rotor Inlet Total Temperature | X | | $T_{25}$ | |
| High Pressure Turbine Outlet Total Temperature | X | | $T_{49}$ | Eleven rakes, 5 immersions |
| High Pressure Turbine Outlet Total Pressure | X | | $P_{49}$ | Two probes |
| Total Engine Airflow Rate | X | | $W_{ai}$ | Calibrated inlet Bellmouth |
| Core Airflow Rate | | X | $W_{a8}$ | Computed from core engine energy balance |
| Engine Throttle Angle | X | | $\alpha$ | |
| Compressor Variable Stator Setting | X | | $\beta$ | |
| Combustor Inlet Total Pressure | X | | $P_{T3}$ | Three probes on combustor cowl |
| Combustor Inlet Total Temperature | X | | $T_3$ | Five immersion rakes in diffuser and 4 probes on combustor cowl |
| Combustor Static Pressure | X | | $P_{36}$ | Twenty-four combustor wall taps |
| Combustor Metal Temperature | X | | $T_m$ | Sixty surface and imbedded thermocouples |
| Combustor Vibrations | X | | | Two borescope ports mounted dynamic pressure sensors (Kulites) |
| Fuel Injector Vibrations | X | | | Eight strain gages on fuel nozzle stems |
| Fuel Manifold Pressure | X | | $P_f$ | Static tap on each manifold |
| Combustor Airflow Rate | | X | $W_{a36}$ | Computed from high pressure turbine energy balance |
| Combustor Fuel-Air Ratio | | X | $f_4$ | $= W_{ft}/W_{a36}$ |
| Fuel Nozzle Pressure Drop | | X | $\Delta P_f$ | $= P_F - P_{36\ Dome}$ |
| Combustor Total Pressure Drop | | X | $\Delta P_T/P_s$ | $= (P_{T3} - P_{36\ Dome})/P_{T3}$ |
| Combustor Reference Velocity | | X | $V_r$ | Computed from $W_{a36}$, $T_3$, $P_3$ |
| Core Engine Exhaust Fuel-Air Ratio | | X | $T_4$ | Computed from $T_3$, $f_{36}$ |
| Combustor Outlet Total Temperature | | X | $f_8$ | $= W_{ft}/W_{a8}$ |

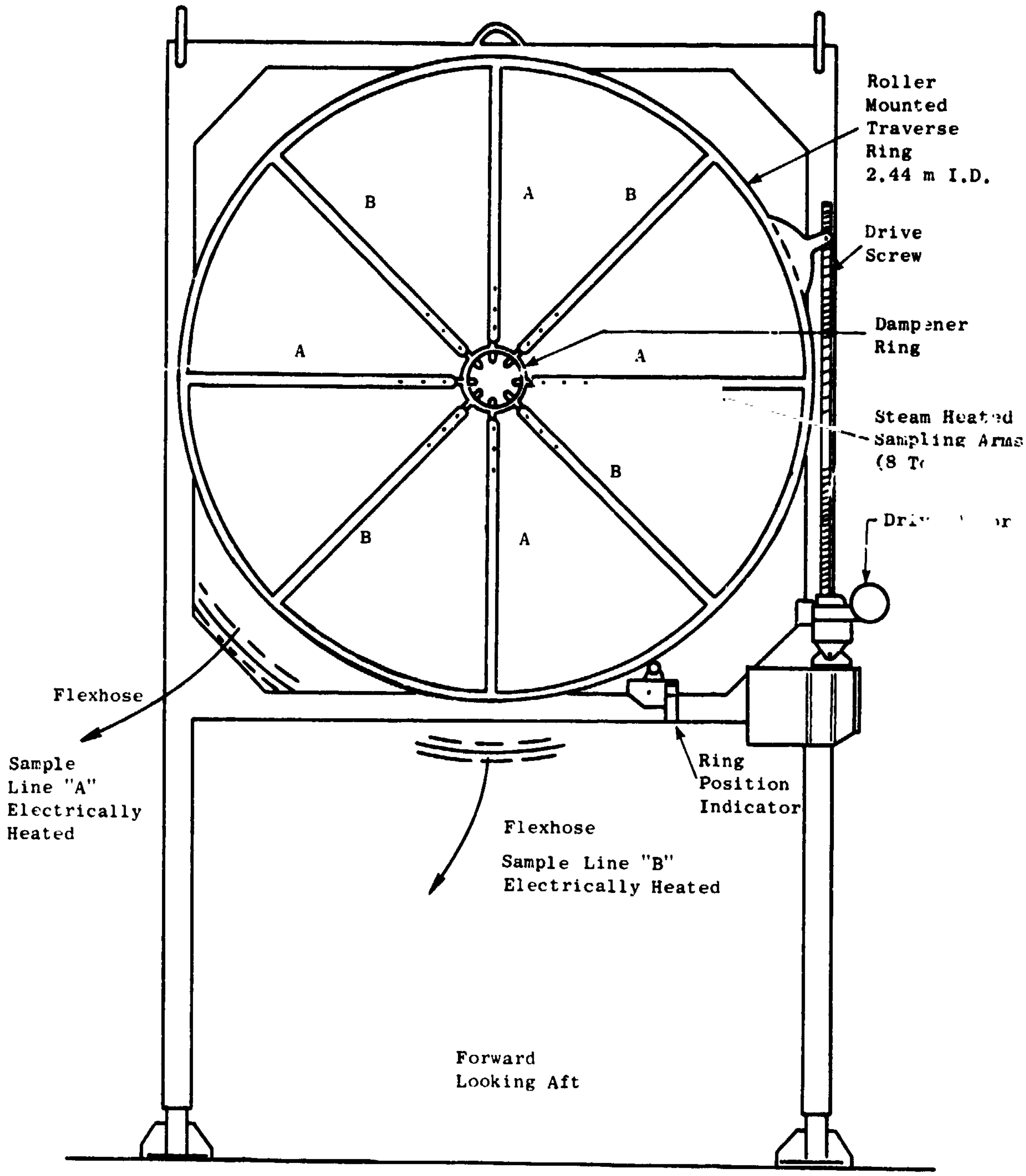



Figure 10. Exhaust Gas-Sampling and Traversing Rake Diagram.

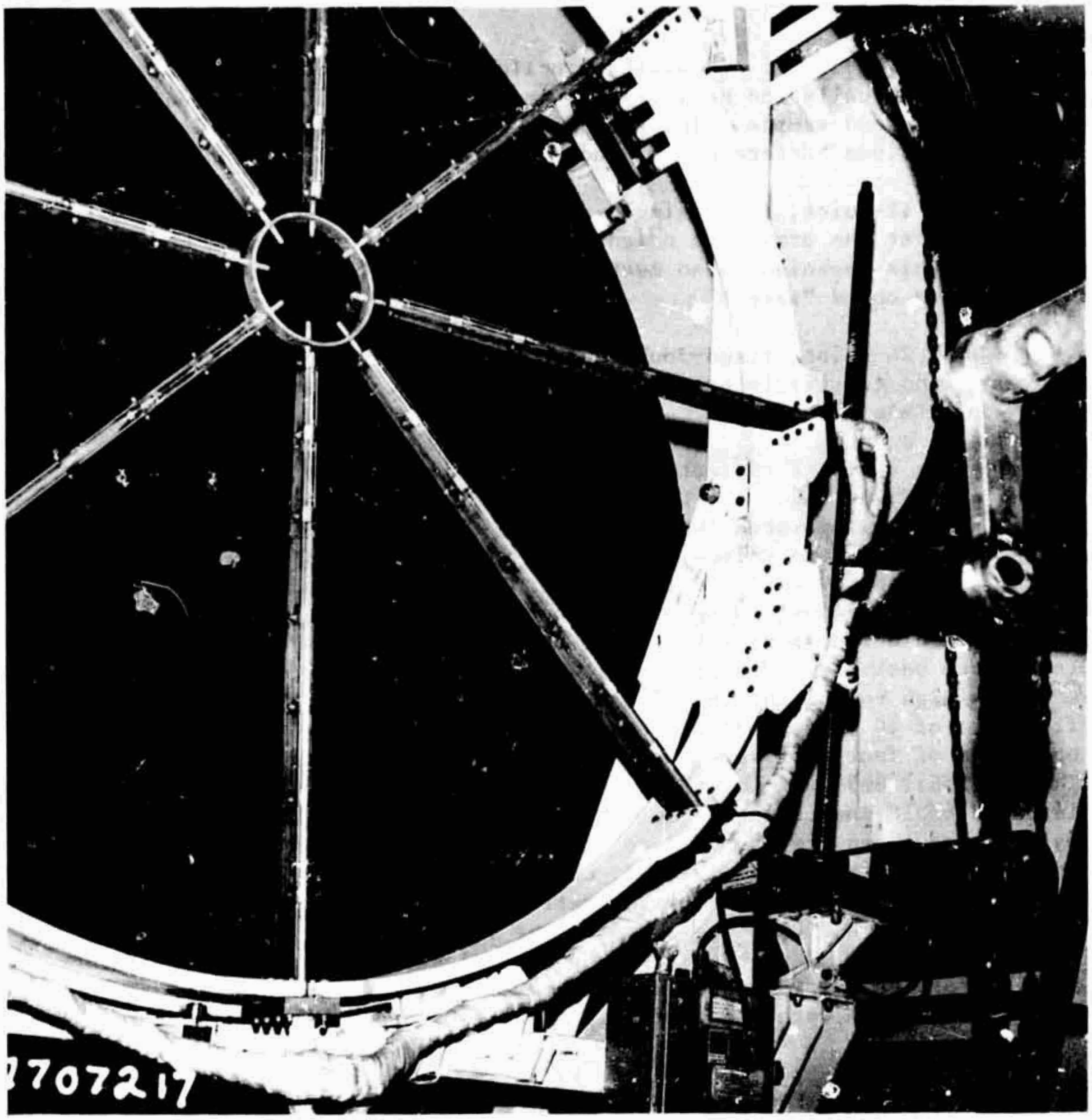



Figure 11. Exhaust Gas-Sampling and Traversing Rake System Installation.

- A 12-point, fixed-single-cruciform rake with the arms oriented vertically and horizontally and manifolded to collect and analyze a mixed sample. This technique meets the Federal Register specifications (Reference 13) and is coded "Rake A".

- A 12-point, fixed-single-cruciform rake as described above except that the arms were oriented 45° from the vertical and horizontal. This technique also meets the Federal Register specifications and is coded "Rake B".

- A 24-point, fixed-double-cruciform rake obtained by manifolding the two single-cruciform rakes together. This technique is coded "Rake D".

The gas analysis apparatus is shown in Figure 12, and a flow diagram is shown in Figure 13. The two sample lines from the rakes were connected to the sampling apparatus through a double three-way valve system. By manipulation of these valves, one line could be analyzed for smoke emissions while the other was analyzed for gaseous emissions, or one or both lines could be simultaneously analyzed for both smoke and gaseous emissions. In order to avoid fuel contamination of the system during engine starting, the rakes were back-flushed with dry air by opening valve "B" in Figure 13. To maintain high velocities in the sample lines, the dump pump vented a nominal flow rate of 20 liters per minute. The gaseous emissions analysis system consisted of four analyzers, each manufactured by Beckman Instruments, Inc. The CO (Model 865) and $CO_2$ (Model 864) analyzers were both nondispersive infrared (NDIR)instruments. To minimize water interference, the sample was passed through an ice trap before entering the NDIR instruments. The $NO_x$ analyzer was a (Model 951) heated, chemiluminescece analyzer; the HC analyzer was a (Model 402) flame-ionization detector (FID) instrument. No traps were used in the $NO_x$ and HC lines ahead of the instruments. The pumps, the flex-lines at the rakes, and the valve box were electrically heated. All other portions of the sample system were steam-traced. Temperatures throughout the sample system were monitored with fourteen Chromel-Alumel thermocouples.

## 4.5 DATA REDUCTION PROCEDURES

All key engine and combustor performance data were recorded by digital data acquisition systems to be processed through standard test data reduction programs for converting signals to engineering units and calculating prescribed averages, flow rates, and performance parameters.

The gaseous emission analysis instruments were calibrated, before and after each test run, with calibration gases which had been checked against National Bureau of Standards SRM gas standards. The calibration data and emission test data were manually logged during the test and subsequently input to a computer data reduction program where emission index, fuel-air ratio, and combustion efficiency were calculated. The equations used for these calculations were basically those contained in SAE ARP 1256 (Reference 14); the CO and $CO_2$ concentrations were corrected for removal of water

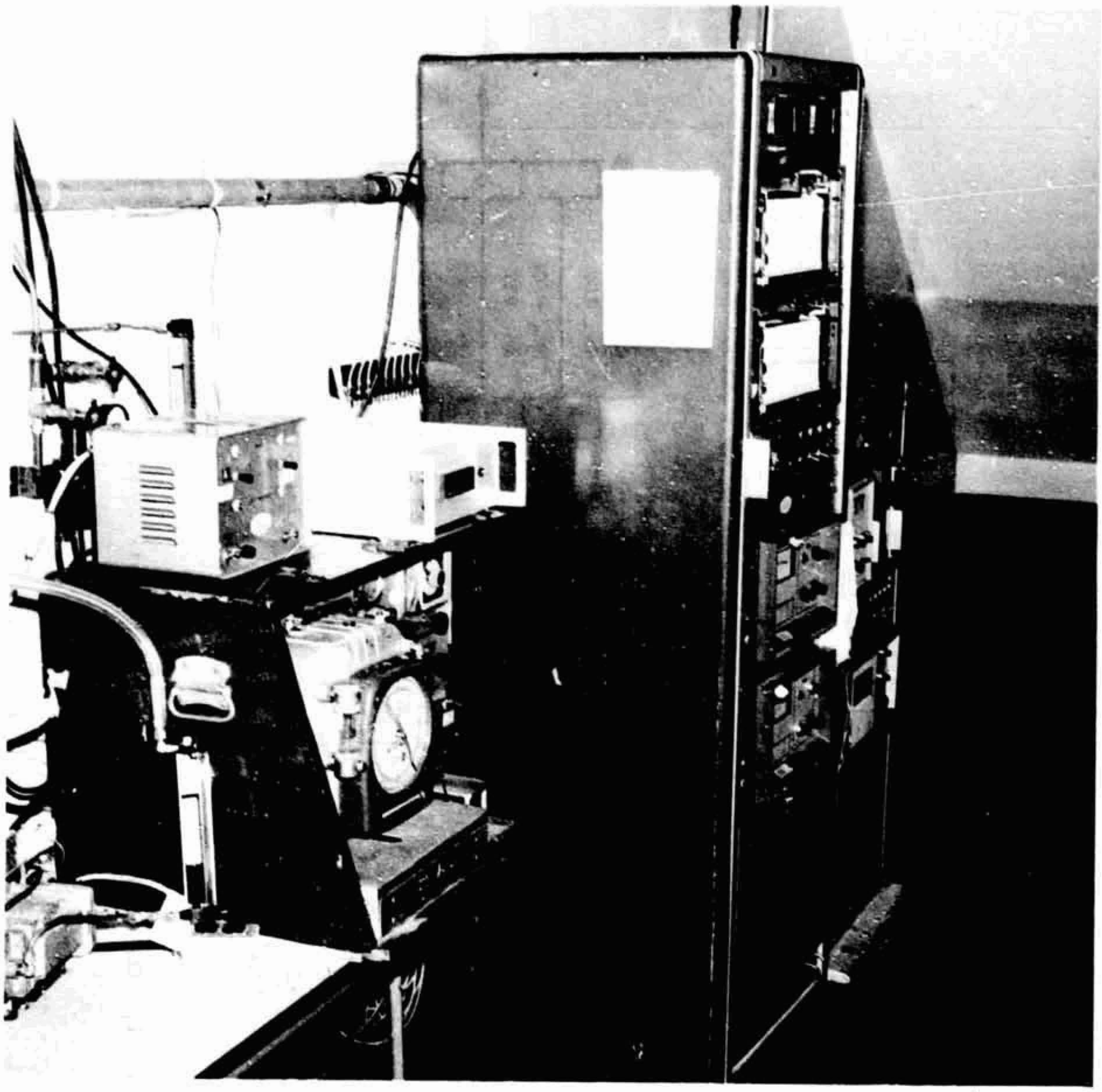


Figure 12. Exhaust Gas Analysis Apparatus.

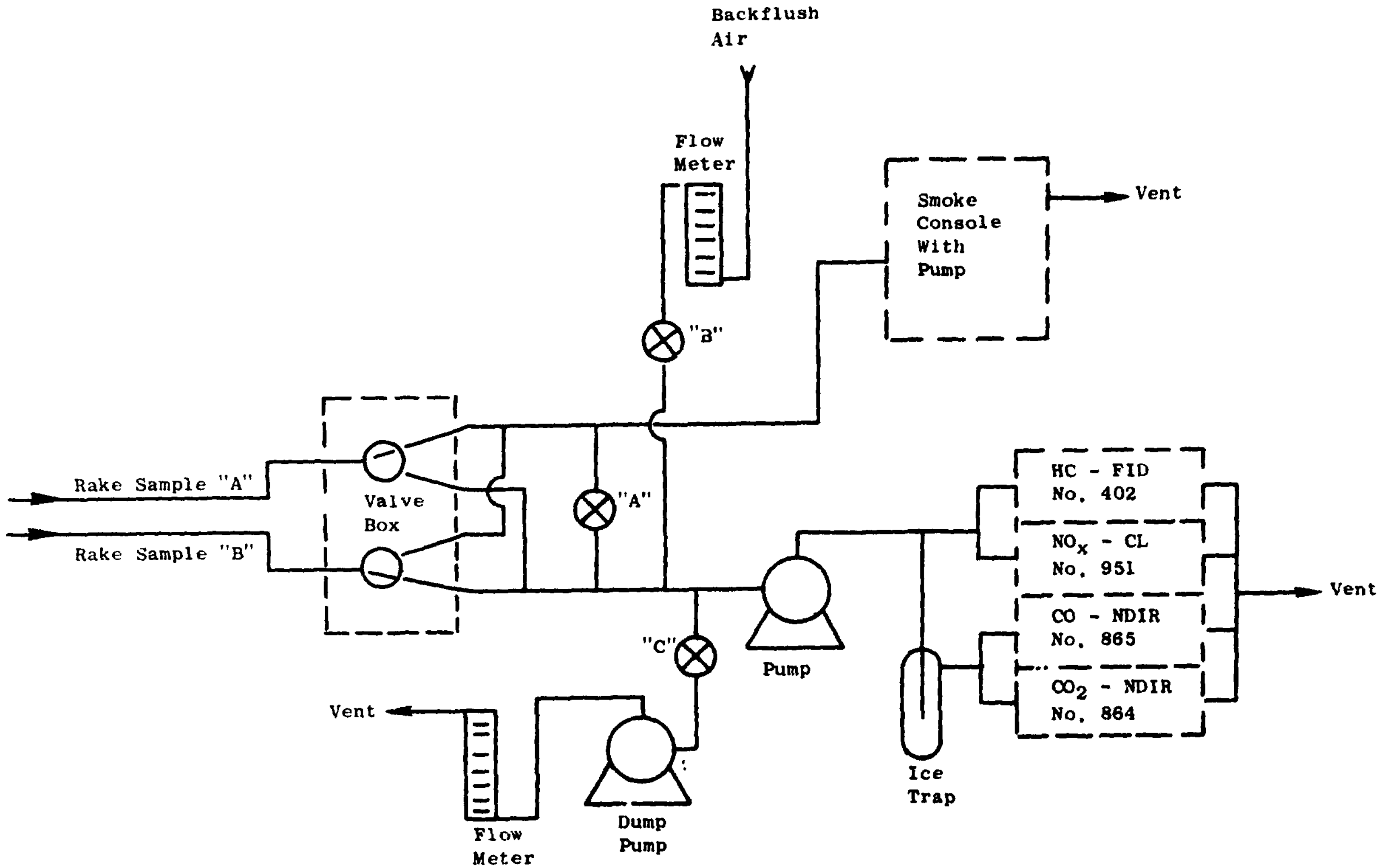



Figure 13. Emissions Sampling and Analysis System Hookup.

from the samples before analyses. Hydrocarbon emissions were assumed to have the same molecular weight as the parent fuel in the emission index calculations. For use in EPAP calculations, hydrocarbon emission levels were converted to methane molecular weight as specified in the Federal Register (Reference 13). Smoke samples were collected at four different soiling rates, bracketing the quoted soiling rate, for subsequent reflectance measurement and data curve-fitting in accordance with Reference 13.

Emissions data from these engine tests are presented two ways: (a) as measured on the demonstrator engine, and (b) as corrected to standard-day, CF6-50C production engine operating conditions. The engine data required correction for pressure, temperature, humidity, velocity, and fuel-air ratio. The engine inlet pressure, temperature, and humidity were not controlled. The engine performance, due to prior cyclic endurance testing, had deteriorated from production engine status. In particular, standard-day combustor airflow rates ($W_{36}\sqrt{\theta_2}/\delta_2$) were about 7% low, and standard-day fuel flow rates ($W_f/\theta_2\delta_2$) were about 25% high at idle and about 8% high at takeoff, relative to production engine status. Standard-day combustor fuel-air ratio ($f_4/\theta_2$) was therefore about 33% high at idle and about 14% high at takeoff, relative to production engine status.

Engine emission data correction factors used in this report are presented in Table V. These factors are based on correlations of rig test data where each of the combustor operating parameters was systematically varied and verified by correlations of engine data which are described in Reference 10. In some cases, the emissions data correction factors were quite large due to the combined effects of the hot-day ambient conditions and the deteriorated engine performance. Multipliers for correcting the measured emission levels to standard-day, production engine combustor operating conditions were approximately of the following magnitudes:

| Emission | Minimum Multiplier | Maximum Multiplier |
|---|---|---|
| CO | 0.54 (at idle) | 1.11 (at climb) |
| HC | 1.00 (except idle) | 1.75 (at idle) |
| $NO_x$ | 0.82 (at climb) | 1.05 (at idle) |
| Smoke | 0.26 (at climb) | 0.62 (at approach) |

# Table V. Emissions Correction Factors.

<u>Only Pilot Stage Fueled (Low Power)</u>

$$E_{NO_x}\ \text{corr} = \left(EI_{NO_x}\ \text{meas}\right)\left(\frac{P_3\ \text{std}}{P_3\ \text{test}}\right)^{0.2}\left(\frac{V_r\ \text{test}}{V_r\ \text{std}}\right)\left(\frac{f_p\ \text{test}}{f_p\ \text{std}}\right)^{0.3}\left\{\exp\left[\left(\frac{T_3\ \text{std} - T_3\ \text{test}}{211.1}\right) + \left(\frac{H_o\ \text{test} - 6.29}{53.2}\right)\right]\right\} \tag{1}$$

$$EI_{CO}\ \text{corr} = \left(EI_{CO}\ \text{meas}\right)\left(\frac{P_3\ \text{test}}{P_3\ \text{std}}\right)^{0.8}\left(\frac{V_r\ \text{std}}{V_r\ \text{test}}\right)\left(\frac{f_p\ \text{std}}{f_p\ \text{test}}\right)^{2.0}\left[\exp\left(\frac{T_3\ \text{test} - T_3\ \text{std}}{226.1}\right)\right] \tag{2}$$

$$EI_{HC}\ \text{corr} = \left(EO_{HC}\ \text{meas}\right)\left(\frac{P_3\ \text{test}}{P_3\ \text{std}}\right)^{2.0}\left(\frac{V_r\ \text{std}}{V_r\ \text{test}}\right)\left(\frac{f_p\ \text{test}}{f_p\ \text{std}}\right)^{1.2}\left[\exp\left(\frac{T_3\ \text{test} - T_3\ \text{std}}{71.7}\right)\right] \tag{3}$$

$$SN_{corr} = \left(SN_{meas}\right) - 11.54\ (f_p\ \text{test} - f_p\ \text{std}) \geq 0 \quad \text{JP-5 Fuel} \tag{4}$$

$$= \left(SN_{meas}\right) - 3.79\ (f_p\ \text{test} - f_p\ \text{test}) \geq 0 \quad \text{Diesel No. 2 Fuel} \tag{5}$$

<u>Both Stages Fueled (High Power)</u>

$$EI_{NO_x}\ \text{corr} = \left(EI_{NO_x}\ \text{meas}\right)\left(\frac{P_3\ \text{std}}{P_3\ \text{test}}\right)^{0.4}\left(\frac{V_r\ \text{test}}{V_r\ \text{std}}\right)\left(\frac{f_p\ \text{std}}{f_p\ \text{test}}\right)^{0.2}\left(\frac{f_m\ \text{std}}{f_m\ \text{test}}\right)^{0.2}\left\{\exp\left[\left(\frac{T_3\ \text{std} - T_3\ \text{test}}{194.4}\right) + \left(\frac{H_o\ \text{test} - 6.29}{53.2}\right)\right]\right\} \tag{6}$$

$$EI_{CO}\ \text{corr} = \left(EI_{CO}\ \text{meas}\right)\left(\frac{P_3\ \text{test}}{P_3\ \text{std}}\right)\left(\frac{V_r\ \text{std}}{V_r\ \text{test}}\right)\left(\frac{f_t\ \text{std}}{f_t\ \text{test}}\right)^{6.3}\left(\frac{f_p\ \text{test}}{f_p\ \text{std}}\right)^{1.7}\left(\frac{f_m\ \text{test}}{f_m\ \text{std}}\right)^{3.3}\left[\exp\left(\frac{T_3\ \text{test} - T_3\ \text{std}}{83.3}\right)\right] \tag{7}$$

$$EI_{HC}\ \text{corr} = \left(EI_{HC}\ \text{meas}\right)\left(\frac{EI_{CO}\ \text{corr}}{EI_{CO}\ \text{meas}}\right)^{2.4} \tag{8}$$

$$SN_{corr} = SK_{meas} - 6.25\ (f_m\ \text{test} - f_m\ \text{std}) \geq 0 \quad \text{JP-5 or Diesel No. 2 Fuel} \tag{9}$$

where:

$H_o$, $f_p$ and $f_m$ are in (g/kg)

$T_3$ is in (K)

(Others in consistent units)

## SECTION 5.0

## RESULTS AND DISCUSSION

The engine test using Diesel No. 2 fuel was run on August 2, 1977. The only change from the previous JP-5 fuel test setup was adjusting the engine main fuel control setting from 0.820 to 0.830 to account for the higher specific gravity of the Diesel No. 2 fuel. No difficulties were encountered. The engine fired on the first attempt and was run 4.8 hours. Fourteen steady-state performance and exhaust emissions data readings were obtained. At the completion of the Diesel No. 2 fuel test, a boroscope inspection of the combustor and turbine was made. No thermal distress or carbon deposits were found. Thirty-three additional hours of engine testing with JP-5 fuel were then conducted before engine teardown.

Detailed exhaust emissions data are listed in Appendix A and detailed engine/combustor performance data are listed in Appendix B. These results are summarized in Tables VI and VII and are discussed in the following sections.

### 5.1 MEASURED EXHAUST EMISSION RESULTS

Measured emission levels of CO, HC, $NO_x$, and smoke are listed in the center block of Table VI, and trends with engine/combustor operating conditions are illustrated in Figures 14 through 17. In these figures, measured emission levels are plotted against the combustor operating parameters, derived from the JP-5 data analyses in Reference 10, that were the bases for the emission correction factors shown in Table V. In each of these figures, the plotted symbols are the measured Diesel No. 2 fuel data, the solid lines are linear regression curve-fits of the Diesel No. 2 fuel data, the dashed lines are linear regression curve-fits of the JP-5 fuel data from Reference 10, and (for reference) values of the operating parameters for the CF6-50C production engine on a standard day are indicated.

CO emission levels, shown in Figure 14, were highly dependent upon engine power level and the combustor fuel staging mode. However, the Diesel No. 2 data correlate very well with the parameters derived for JP-5 fuel, and the Diesel No. 2 emission levels are only slightly higher than the JP-5 emission levels.

HC emission levels at low power, shown in Figure 15, were very low. These Diesel No. 2 data also calculate very well with the parameter derived for JP-5 fuel, but the emission levels are substantially higher, percentage-wise, these were the levels with JP-5 fuels. At high-power operating conditions, HC emission levels were at or below the measurement threshhold range.

Table VI. Summary of Diesel No. 2 Fuel Engine Emission-Test Results.

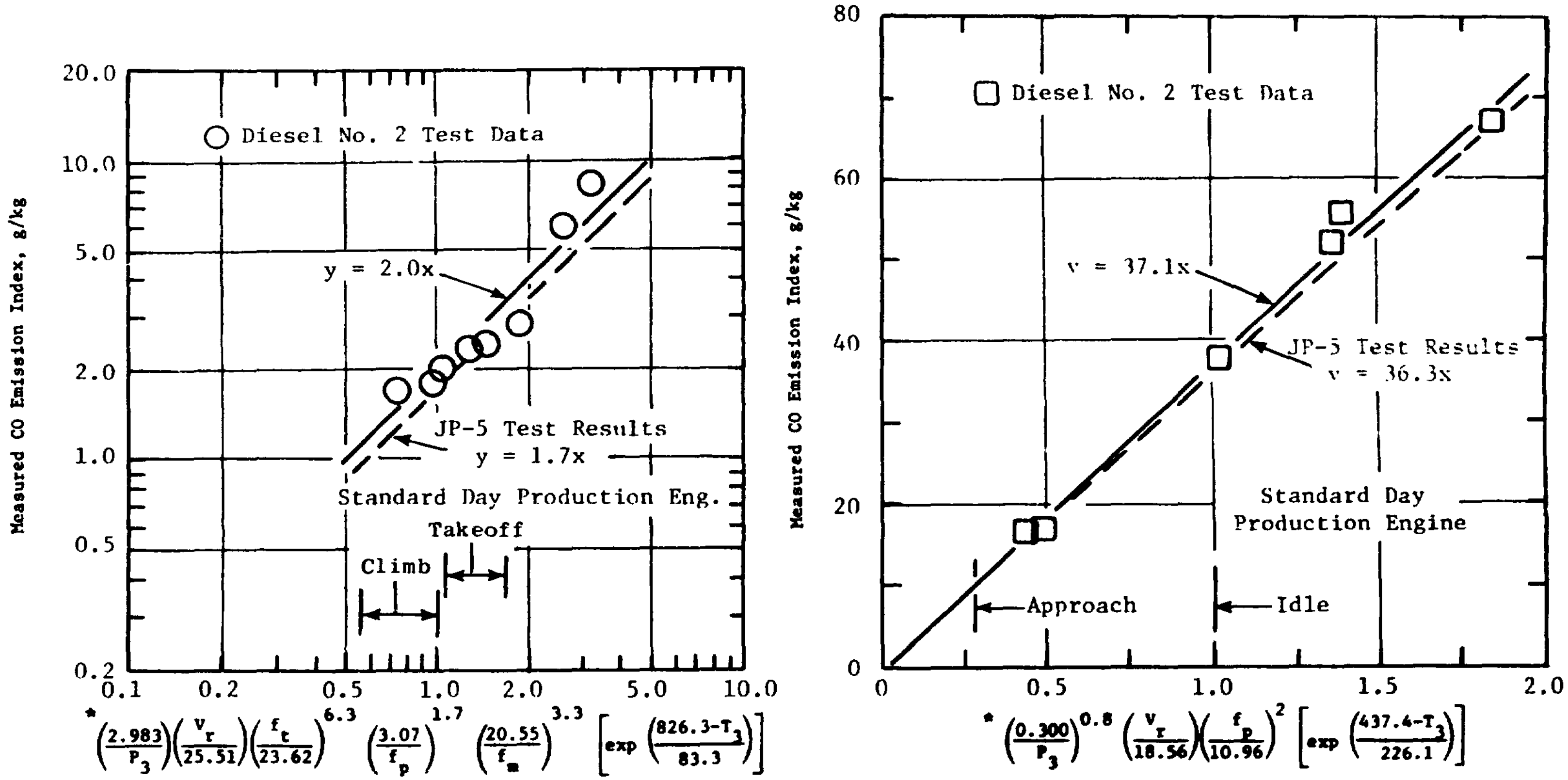
(24-Point Double Cruciform Sampling Technique Data)

| Nominal Thrust Setting, % of 224.2 kN | Reading Number | Actual Corrected Thrust, % of 224.2 kN | $\delta_2 = P_2/P_{std}$, Engine Inlet-to-Standard Pressure Ratio | $\theta_2 = T_2/T_{2std}$, Engine Inlet-to-Standard Temperature Ratio | Engine Inlet Humidity, g/kg | $W_{ft}$, Total Fuel Flow, kg/s | $Wa_{36}$, Combustor Airflow, kg/s | $P_3$, Compressor Exit Total Pressure, MPa | $T_3$, Compressor Exit Total Temperature, K | Vr Combustor Reference Velocity, m/s | $\Delta P_T/P_{t3}$, Combustor Total Pressure Drop, % | $f_4$, Combustor Fuel-Air Ratio, g/kg | $W_{fp}/W_{ft}$, Pilot-to-Total Fuel Split | $T_4$ Combustor Exit Temperature, K | Sample Fuel-Air Ratio / Metered Fuel-Air Ratio | Sample Combustion Efficiency, % | Measured Emission Indices g/kg CO | Measured Emission Indices g/kg HC | Measured Emission Indices g/kg $NO_x$ | Measured SAE Smoke Number | Corrected Emission Indices g/kg CO | Corrected Emission Indices g/kg HC | Corrected Emission Indices g/kg $NO_x$ | Corrected SAE Smoke Number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.3 | 59 | 3.48 | 0.9852 | 1.0495 | 8.29 | 0.195 | 12.76 | 0.289 | 451.9 | 18.23 | 3.14 | 15.27 | 1.00 | 1024.7 | 0.944 | 98.26 | 67.1 | 1.6 | 4.2 | 32.0 | 36.4 | 2.8 | 4.4 | 15.7 |
| 3.3 | 73 | 3.69 | 0.9823 | 1.0408 | 9.14 | 0.177 | 13.56 | 0.297 | 443.6 | 18.53 | 3.96 | 13.06 | 1.00 | 933.5 | 1.040 | 98.48 | 55.4 | 2.2 | 3.8 | 21.3 | 6 | 2.9 | 4.1 | 13.3 |
| 5.0 | 60 | 4.77 | 0.9821 | 1.0490 | 8.29 | 0.221 | 15.12 | 0.346 | 476.8 | 19.07 | 3.67 | 14.60 | 1.00 | 1022.5 | 0.935 | 98.70 | 51.7 | 0.8 | 4.9 | 26.3 | 26.4 | 1.3 | 5.2 | 10.1 |
| 7.0 | 61 | 6.64 | 0.9817 | 1.0498 | 8.57 | 0.259 | 18.32 | 0.423 | 505.5 | 20.01 | 3.87 | 14.14 | 1.00 | 1031.3 | 0.928 | 99.07 | 37.6 | 0.5 | 5.7 | 23.7 | 19.5 | 0.8 | 6.0 | 8.1 |
| 20.0 | 62 | 20.25 | 0.9784 | 1.0497 | 8.57 | 0.532 | 34.71 | 0.857 | 603.8 | 22.35 | 4.05 | 15.33 | 1.00 | 1158.2 | 0.960 | 99.61 | 16.5 | 0.1 | 9.2 | 19.0 | 10.0 | 0.2 | 9.4 | 4.9 |
| 30.0 | 63 | 30.55 | 0.9760 | 1.0490 | 8.57 | 0.769 | 43.64 | 1.133 | 651.3 | 22.94 | 4.05 | 17.62 | 1.00 | 1290.1 | 0.990 | 99.62 | 16.1 | 0 | 11.0 | 37.7 | 10.4 | 0 | 11.2 | 23.2 |
| 45.0 | 64 | 46.34 | 0.9759 | 1.0497 | 8.29 | 1.119 | 57.69 | 1.571 | 716.8 | 24.06 | 4.41 | 19.40 | 0.287 | 1387.4 | 0.989 | 99.85 | 6.0 | 0.1 | 12.3 | 1.6 | 6.4 | 0.1 | 10.6 | 1.6 |
| 45.0 | 66 | 45.97 | 0.9758 | 1.0480 | 8.29 | 1.105 | 57.96 | 1.566 | 712.8 | 24.11 | 4.17 | 19.06 | 0.208 | 1373.6 | 0.995 | 99.79 | 8.2 | 0.2 | 11.0 | 2.4 | 8.5 | 0.2 | 9.4 | 2.4 |
| 65.0 | 67 | 65.93 | 0.9730 | 1.0475 | 8.29 | 1.602 | 70.77 | 2.031 | 770.5 | 24.54 | 4.53 | 22.63 | 0.174 | 1534.6 | 0.971 | 99.93 | 2.8 | 0.1 | 16.3 | 15.6 | 2.9 | 0.1 | 14.0 | 1.3 |
| 85.0 | 68 | 89.41 | 0.9699 | 1.0460 | 9.14 | 2.242 | 84.26 | 2.546 | 825.2 | 24.96 | 4.42 | 26.60 | 0.173 | 1692.3 | 0.985 | 99.96 | 1.8 | 0 | 24.4 | 35.7 | 2.0 | 0 | 20.0 | 9.4 |
| 85.0 | 69 | 89.19 | 0.9699 | 1.0460 | 9.14 | 2.237 | 84.43 | 2.552 | 823.1 | 24.89 | 4.54 | 26.49 | 0.125 | 1686.6 | 0.978 | 99.94 | 2.4 | 0 | 24.3 | 42.4 | 2.6 | 0 | 20.1 | 15.0 |
| 92.0 | 70 | 94.10 | 0.9693 | 1.0442 | 9.14 | 2.376 | 87.21 | 2.660 | 832.4 | 24.95 | 4.54 | 27.24 | 0.125 | 1716.3 | 0.977 | 99.95 | 2.3 | 0 | 26.0 | 45.6 | 2.3 | 0 | 22.4 | 19.1 |
| 100.0 | 71 | 102.90 | 0.9682 | 1.0457 | 9.14 | 2.642 | 91.84 | 2.848 | 851.6 | 25.10 | 4.43 | 28.77 | 0.126 | 1777.0 | 0.970 | 99.95 | 2.0 | 0 | 29.2 | 50.6 | 2.0 | 0 | 25.0 | 22.5 |
| 100.0 | 72 | 102.70 | 0.9679 | 1.0413 | 9.14 | 2.626 | 92.03 | 2.848 | 847.4 | 25.03 | 4.52 | 28.54 | 0.174 | 1765.4 | 0.980 | 99.96 | 1.7 | 0 | 27.7 | 43.7 | 1.7 | 0 | 24.3 | 18.3 |

Table VII. Comparison of Exhaust Emission Levels with Diesel No. 2 and JP-5 Fuels.

| Corrected Thrust, % of Takeoff | Pilot-to-Total Fuel Flow Split | Corrected Emission Indices, g/kg | | | | | | Corrected SAE Smoke Number | |
|---|---|---|---|---|---|---|---|---|---|
| | | CO | | HC | | $NO_x$ | | | |
| | | D2 | JP-5(1) | D2 | JP-5(1) | D2 | JP-5(1) | D2 | JP-5(1) |
| 3.3 | 1.00 | 38.1 | 36.3 | 2.8 | 1.8 | 4.2 | 4.1 | 9.5 | 3.0 |
| 5.0 | 1.00 | 26.4 | 25.4 | 1.3 | 1.3 | 5.2 | 4.7 | 10.1 | 3.3 |
| 7.0 | 1.00 | 19.5 | 19.1 | 0.8 | 1.2 | 6.0 | 5.3 | 8.1 | 3.2 |
| 20.0 | 1.00 | 10.0 | 10.6 | 0.2 | 0.4 | 9.4 | 8.3 | 4.9 | 3.9 |
| 30.0 | 1.00 | 10.4 | 10.1 | 0 | 0.5 | 11.2 | 10.0 | 23.2 | 3.3 |
| 45.0 | 0.21 | 8.5 | 11.5 | 0.2 | 0.4 | 9.4 | 9.3 | 2.4 | 0.4 |
| 65.0 | 0.18 | 2.9 | 3.5 | 0.1 | 0.1 | 14.0 | 14.1 | 1.3 | 1.2 |
| 85.0 | 0.18(2) | 2.0 | 1.8 | 0 | 0.1 | 20.0 | 19.1 | 9.4 | 7.7 |
| 85.0 | 0.12 | 2.6 | 2.7 | 0 | 0 | 20.1 | 19.3 | 15.0 | 18.7 |
| 92.0 | 0.13 | 2.3 | 2.4 | 0 | 0.1 | 22.4 | 20.9 | 19.1 | 17.5 |
| 100.0 | 0.19(2) | 1.7 | 1.6 | 0 | 0 | 25.0 | 25.5 | 18.3 | 19.0 |
| 100.0 | 0.13 | 2.0 | 2.0 | 0 | 0 | 24.3 | 23.5 | 22.5 | 24.6 |

(1)JP-5 Data from Reference 10, Table XX.
(2)Preferred Split for Emissions.




a. High Power CO Test Results
(Both Stages Fueled)

* Parameter No. 7 from Table V

b. Low Power CO Test Results
(Only Pilot Stage Fueled)

* Parameter No. 2 from Table V

**Figure 14. CO Emission Characteristics with Diesel No. 2 Fuel.**

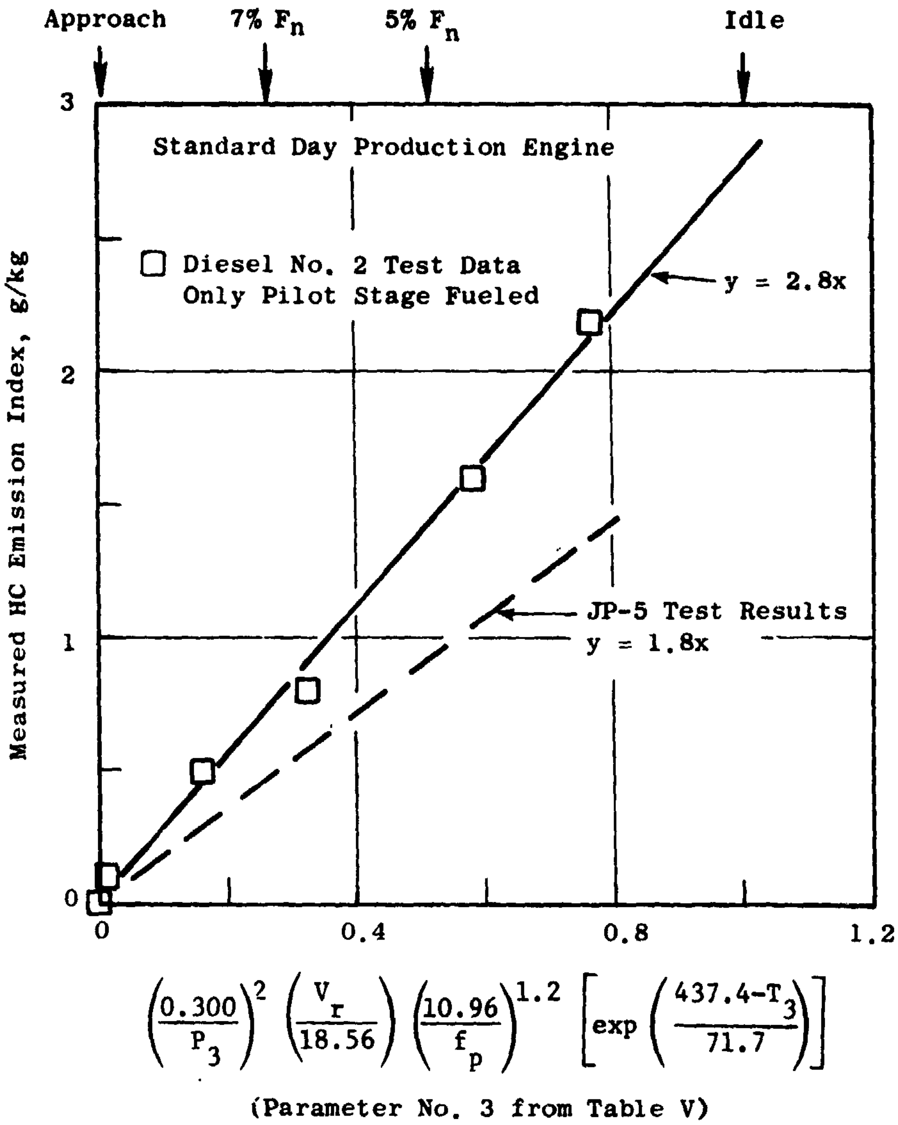
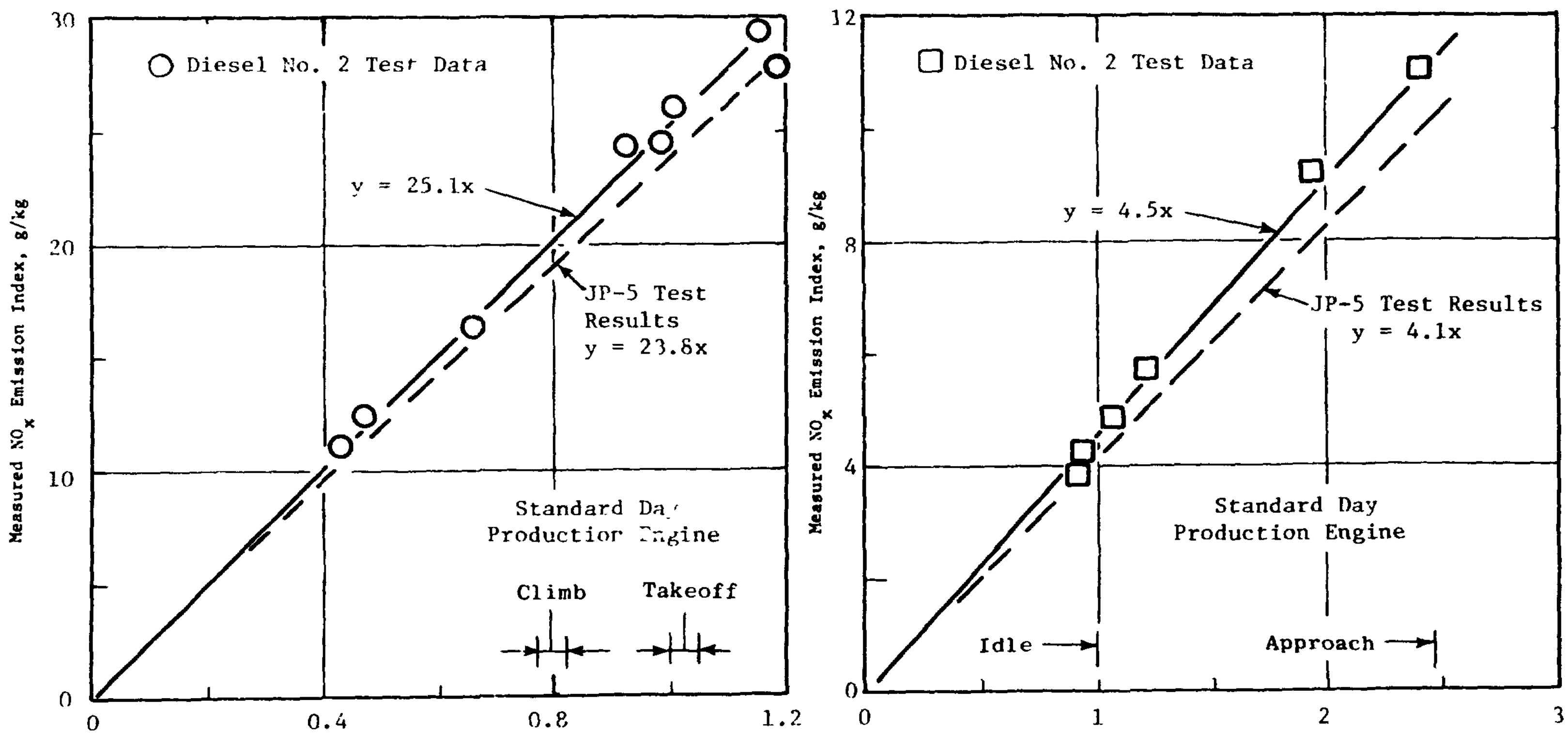



Figure 15. HC Emission Characteristics with Diesel No. 2 Fuel




$$^{*}\left(\frac{P_3}{2.983}\right)^{0.4}\left(\frac{25.51}{V_r}\left(\frac{f_p}{3.07}\right)^{0.2}\left(\frac{f_m}{20.55}\right)\left[\exp\left(\frac{T_3-826.3}{194.4}+\frac{6.29-H_2}{53.2}\right)\right]\right)$$

a. High Power $NO_x$ Test Results (Both Stages Fueled)

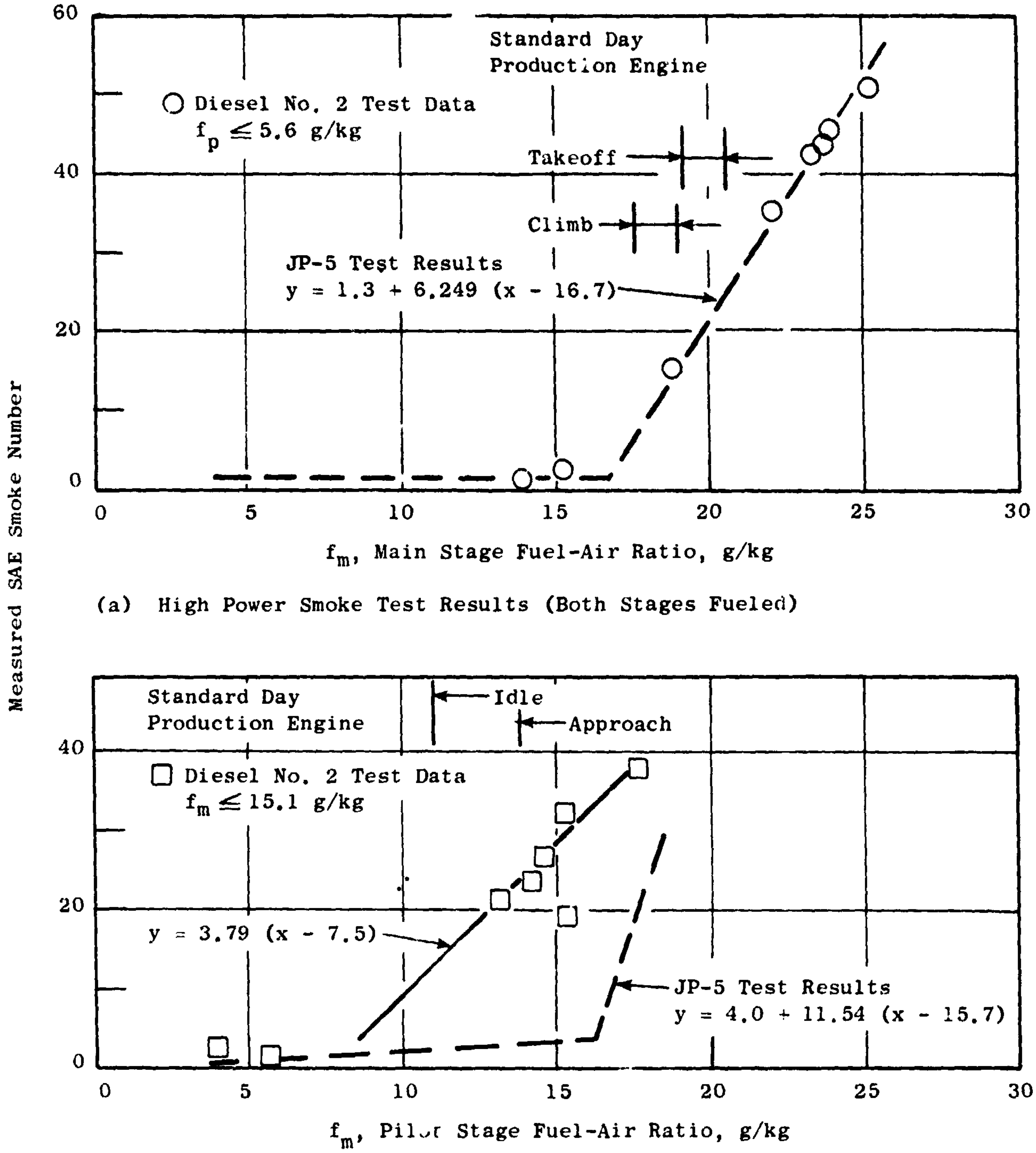
* Parameter No. 6 from Table V

$$^{*}\left(\frac{P_3}{0.300}\right)^{0.2}\left(\frac{18.58}{V_r}\right)\left(\frac{10.96}{f_p}\right)^{0.3}\left[\exp\left(\frac{T_3-437.4}{211.1}+\frac{6.29-H_o}{53.2}\right)\right]$$

b. Low Power $NO_x$ Test Results (Only Pilot Stage Fueled)

* Parameter No. 1 from Table V

**Figure 16. $NO_x$ Emission Characteristics with Diesel No. 2 Fuel.**




(a) High Power Smoke Test Results (Both Stages Fueled)



(b) Low Power Smoke Test Results (Main Stage Lean or Unfueled)

Figure 17. Smoke Emission Characteristics with Diesel No. 2 Fuel.

$NO_x$ emission levels, shown in Figure 16, were also highly dependent upon engine power level and the combustor fuel staging mode. The Diesel No. 2 data again correlate very well with the parameters derived for JP-5 fuel, and the Diesel No. 2 emission levels are slightly higher than the JP-5 emission levels.

Smoke emission levels, shown in Figure 17, also were highly dependent upon engine power level and fuel staging node. At high-power operating conditions (Figure 17a), the Diesel No. 2 fuel results were virtually identical to the JP-5 data with respect to both the effect of combustor operating conditions (main-stage fuel-air ratio) and the absolute levels. Smoke levels were very low with either fuel when main-stage fuel-air ratios were less than 17g/kg, but they increased very rapidly. At low-power operating conditions (Figure 17b), the Diesel No. 2 fuel results differed significantly from the JP-5 data, particularly with respect to the pilot-stage fuel-air ratio at which smoke levels began to increase very rapidly. For JP-5 fuel, this critical fuel-air ratio was about 16g/kg, which is higher than the standard-day, production engine pilot-stage, design-operating conditions. But with Diesel No. 2 fuel, the critical fuel-air ratio was about 8g/kg, which is well below the pilot-stage, design operating conditions.

## 5.2 CORRECTED EXHAUST EMISSION RESULTS

Emission levels of CO, HC, $NO_x$, and smoke which have been corrected to standard-day, CF6-50C production engine operating conditions, using procedures described in Section 4.5, are listed in the right-hand block of Table VI. Because of the hot-day ambient conditions and the deteriorated engine performance, the corrected emission levels of CO at low-power operating conditions and smoke at all operating conditions are significantly lower than the measured levels of these emissions.

The corrected exhaust emission levels with Diesel No. 2 and JP-5 fuels are listed in Table VII. Except for smoke level at lower engine power operating conditions, the emissions levels are nearly the same with either fuel. At approach power level, the smoke number was 23.2 with Diesel No. 2 fuel. This smoke emission level exceeds the EPA standard of 18.8 for the CF6-50C engine thrust rating.

## 5.3 PERFORMANCE RESULTS

Detailed engine and combustor performance results are presented in Appendix B. Key trends are illustrated in Figures 18 and 19.

Corrected engine specific fuel consumption and corrected combustor fuel-air ratio characteristics, shown in Figure 18, were virtually the same with Diesel No. 2 and JP-5 fuels, indicating no significant difference in combustion efficiency.

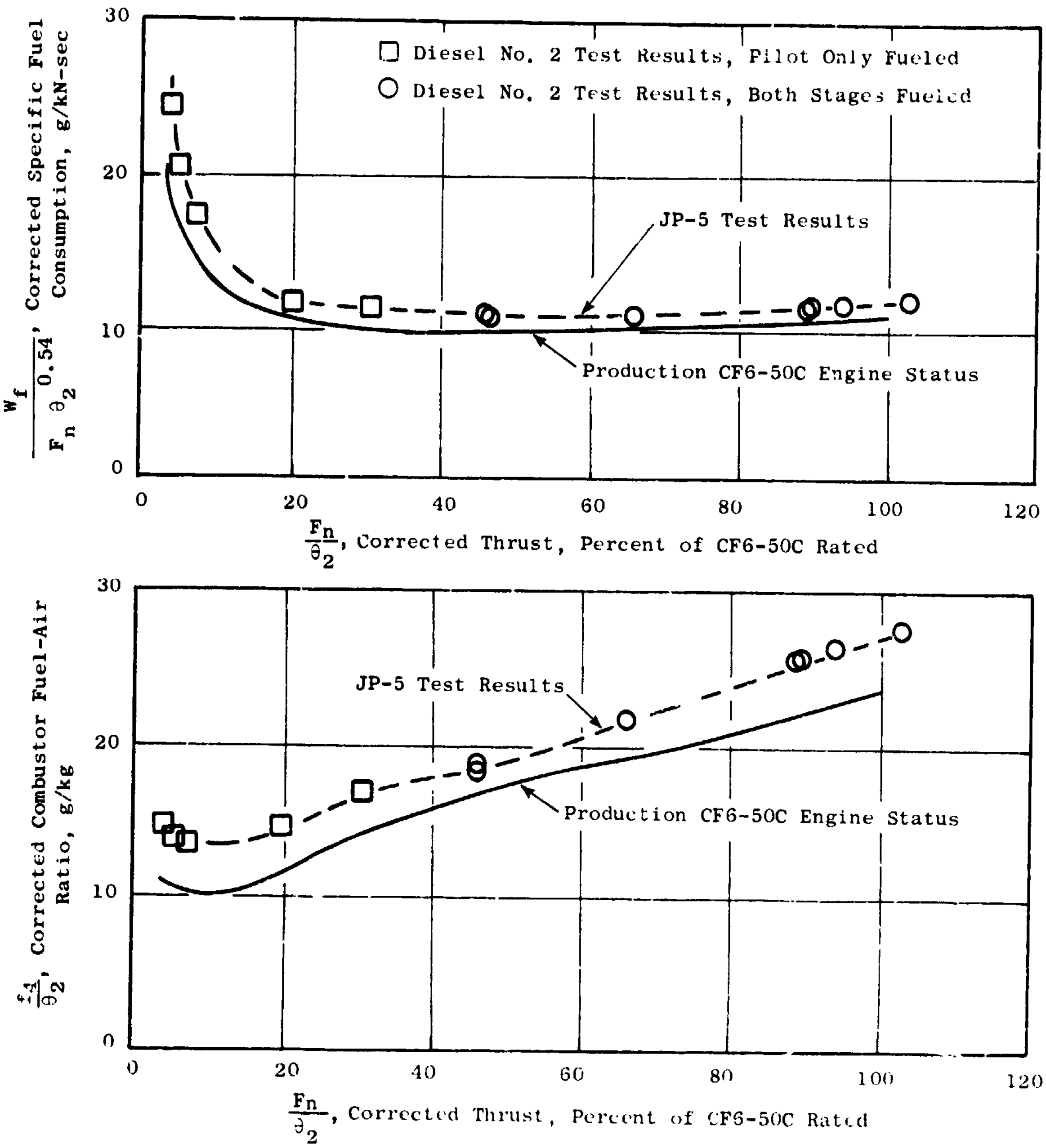



Figure 18. Engine Performance Characteristics with Diesel No. 2 Fuel.

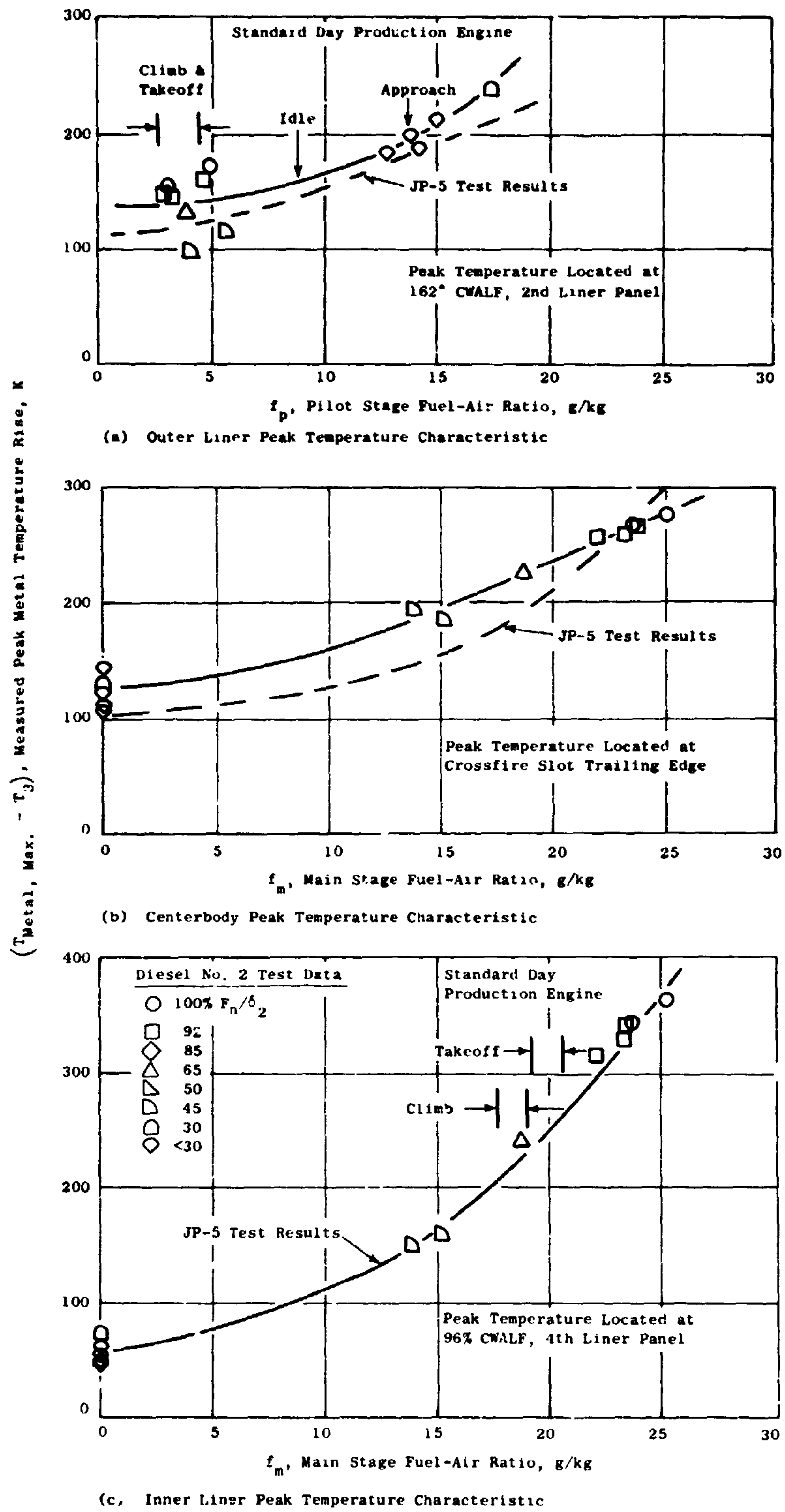



Figure 19. Combustor Metal Temperature Characteristics with Diesel No. 2 Fuel.

Peak combustor metal temperatures with Diesel No. 2 fuel occurred at the same locations and correlated with the same combustor operating parameters identified for JP-5 fuel (as shown in Figure 19). The peak outer liner and centerbody temperatures were as much as 30 K higher with Diesel No. 2 fuel than with JP-5 fuel. However, the highest metal temperatures occurred on the inner liner and were virtually identical for Diesel No. 2 and JP-5 fuels. All of the combustor metal temperatures were lower than those of current production combustors and generally within the limits considered necessary for long-life designs. A comparison of metal temperatures corrected to standard-day, production CF6-50C engine operating conditions with Diesel No. 2 and JP-5 fuels is shown in Table VIII.

## 5.4 COMPARISON OF ENGINE AND RIG TEST RESULTS

The fuel trends obtained in the engine tests are in good agreement with test rig data obtained previously and reported in Reference 6. The current engine data and previous test rig data are compared in Table IX. These data also indicate that the effects of fuel properties on exhaust emissions and liner temperature levels are somewhat greater with the production CF6-50 combustor than with the Double Annular Combustors.

Table VIII. Comparison of Combustor Metal Temperature Levels with Diesel No. 2 and JP-5 Fuels.

| Corrected Thrust, % of Takeoff | Pilot-to-Total Fuel Flow Split | Corrected Peak Metal Temperature, K | | | | |
|---|---|---|---|---|---|---|
| | | Outer Liner | | Centerbody | | Inner Liner D2 and |
| | | D2 | JP-5 (1) | D2 | JP-5 (1) | JP-5 (1) |
| 3.3 | 1.00 | 607 | 591 | 564 | 541 | 495 |
| 5.0 | 1.00 | 629 | 613 | 590 | 567 | 521 |
| 7.0 | 1.00 | 652 | 637 | 616 | 593 | 547 |
| 20.0 | 1.00 | 752 | 739 | 706 | 683 | 637 |
| 30.0 | 1.00 | 826 | 810 | 759 | 736 | 690 |
| 45.0 | 0.21 | 831 | 804 | 869 | 829 | 824 |
| 65.0 | 0.18 | 885 | 858 | 945 | 903 | 915 |
| 85.0 | 0.18 (2) | 932 | 909 | 1008 | 969 | 994 |
| 85.0 | 0.12 | 932 | 904 | 1019 | 987 | 1018 |
| 92.0 | 0.13 | 947 | 919 | 1038 | 1009 | 1045 |
| 100.0 | 0.19 (2) | 966 | 944 | 1054 | 1022 | 1056 |
| 100.0 | 0.13 | 966 | 938 | 1065 | 1044 | 1088 |

(1) JP-5 Data from Reference 10, Table XXII.
(2) Preferred Split for Emissions.

Table IX. Comparison of Fuel Effects in CF6-50 Combustor Tests.

| Combustor Type | Standard(1) Production Single Annnular | Prototype(1) Double Annular Configuration D7, 12, 13 | Demonstrator Double Annular Configuration E12 |
|---|---|---|---|
| Test Type | Full Annular Rig | Full Annular Rig | CF6-50 Engine |
| Idle Comparison(2) | | | |
| $EI_{CO}$, $D2/EI_{CO}$, JP-5 | 1.18 | 1.06 ± 0.12 | 1.05 |
| $EI_{HC}$, $D2/EI_{HC}$, JP-5 | 1.23 | 1.78 ± 0.12(4) | 1.56 |
| $EI_{NO_x}$, $D2/EI_{NO_x}$, JP-5 | 1.00 | 1.03 ± 0.03 | 1.10 |
| Smoke No. D2/Smcke No. JP-5 | 7.2 | 2.3 ± 0.7(4) | 3.2 |
| $\Delta T_{metal}$ $D2/\Delta T_{metal}$, JP-5 | 0.72 | 1.07 ± 0.02 | 1.03 |
| Takeoff Comparison(3) | | | |
| $EI_{CO}$, $D2/EI_{CO}$, JP-5 | 0.8(4) | 1.2 ± 0.1(4) | 1.2(4) |
| $EI_{HC}$, $D2/EI_{HC}$, JP-5 | 0.4(4) | 2.6 ± 2.4(4) | 1.0(4) |
| $EI_{NO_x}$, $D2/EI_{NO_x}$, JP-5 | 1.15 | 1.02 ± 0.04 | 1.05 |
| Smoke No. D2/Smoke No. JP-5 | 4.3(4) | 0.8 ± 0.3(4) | 1.0 |
| $\Delta T_{metal}$, $D2/\Delta T_{metal}$, JP-5 | 1.10 | 1.04 ± 0.08 | 1.0 |

(1) Data from Reference 6

(2) Engine Idle operating conditions exactly duplicated in test rig.

(3) Engine Takecff operating conditions exactly simulated in test rig except for pressure level (1.0 instead of 3.0 MPa).

(4) Emissions very low with both JP-5 and Diesel No. 2 fuels.

## SECTION 6.0

## CONCLUDING REMARKS

A CF6-50 engine equipped with an advanced, low-emission, Double Annular Combustor has been tested at sea level operating conditions using both JP-5 and Diesel No. 2 fuel. Exhaust emission levels and engine/combustor performance were measured in these tests. As was predicted from previous rig tests of low-emission combustor design concepts (Reference 6), fuel effects were quite moderate. CO and HC emission levels at idle were slightly higher with Diesel No. 2 fuel; this is attributed primarily to the lower volatility of this fuel. At higher power operating conditions, CO and HC levels were very low with both fuels. $NO_x$ emission levels were slightly higher with Diesel No. 2 fuel at all power levels, which is attributed to the reduced hydrogen content and, hence, higher stoichiometric flame temperature of the Diesel No. 2 fuel. At high engine power levels where both combustor stages were fueled and operated lean, smoke emission levels were not fuel dependent. However, at low power operating condtions where only the pilot stage was fueled and, hence, near stoichiometric, smoke levels were significantly higher with Diesel No. 2 fuel. The need for improved fuel atomization, improved fuel-air mixing, or leaner burning in the pilot stage with Diesel No. 2 fuel is therefore indicated from these tests. Liner metal temperature trends were very similar to the smnoke emission trend. At high-power operating conditions, peak metal temperatures occurred on the inner liner and were not fuel dependent. In contrast to these results, tests at NASA and elsewhere, with older engine combustor designs, have shown significantly increased smoke emission levels, carboning tendencies, flame radiation, and metal temperatures with Diesel fuel (References 3, 4, and 5).

While these test results are encouraging, more testing experience is still needed to identify problems which may be encountered with the use of broadened-specification fuels in commercial airline and military service. In particular, the following types of tests are recommended:

1. Relight Tests with Cold Fuel and Air - Tests in Reference 6 with ambient temperature air and fuel showed little deterioration with Diesel fuel, but generally greater effects are anticipated.

2. Fuel-Supply/Injection-System Thermal-Stability-Related Tests - No fuel-nozzle gumming or plugging was indicated in the short test reported in this document, but these problems do not normally show up until after many hours of operation. Even with current-specification fuels, the high temperature environment in which the fuel system components must operate makes the life goals difficult to meet. Therefore, any change in fuel specifications will almost surely aggravate this situation.

3. Flight-Quality Combustor/Engine Tests - The Double Annular combustor used for these tests is a very advanced design concept. It incorporates more complexity than any combustor design currently in use. Additional development of this combustor design concept is required (particularly in the areas of exit temperature distribution, engine fuel control, and exhaust emission reduction) before it can be considered for production engines. The required design changes in these important areas cold increase the sensitivity to fuel properties.

# APPENDIX A

## DETAILED EMISSION TEST RESULTS

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Table A-I. Exhaust Emission Test Results, Diesel No. 2 Fuel Engine Tests.

| Rdg | HUM G/KG | Rake(1) | EICO G/KG | EIHC G/KG | EINO G/KG | EINOX G/KG | FARS G/KG | COMEFF % | SMKNBR |
|---|---|---|---|---|---|---|---|---|---|
| 59 | 8.29 | A | 67.1 | 1.4 | 2.4 | 4.2 | 11.64 | 98.28 | 34.6 |
| 59 | 8.29 | B | 66.8 | 1.7 | 2.4 | 4.2 | 11.64 | 98.26 | 30.0 |
| 59 | 8.29 | D | 67.1 | 1.6 | 2.6 | 4.2 | 11.64 | 98.26 | 32.0 |
| 60 | 8.29 | A | 51.5 | 0.7 | 3.0 | 4.8 | 11.05 | 98.71 | 26.1 |
| 60 | 8.29 | B | 51.7 | 0.8 | 3.0 | 3.8 | 11.02 | 98.70 | 25.5 |
| 60 | 8.29 | D | 51.7 | 0.8 | 3.2 | 4.9 | 11.02 | 98.70 | 26.3 |
| 61 | 8.57 | A | 38.8 | 0.5 | 3.8 | 5.5 | 10.65 | 99.04 | 22.9 |
| 61 | 8.57 | B | 37.9 | 0.5 | 3.9 | 5.7 | 10.53 | 99.06 | 25.9 |
| 61 | 8.57 | D | 37.6 | 0.5 | 3.9 | 5.7 | 10.60 | 99.07 | 23.7 |
| 62 | 8.57 | A | 17.9 | 0.1 | 7.2 | 9.1 | 11.93 | 99.57 | 21.8 |
| 62 | 8.57 | B | 16.6 | 0.1 | 7.3 | 9.4 | 11.81 | 99.60 | 16.7 |
| 62 | 8.57 | D | 16.5 | 0.1 | 7.4 | 9.4 | 11.89 | 99.61 | 19.0 |
| 63 | 8.57 | A | 17.0 | 0 | 8.7 | 11.0 | 14.06 | 99.60 | 37.8 |
| 63 | 8.57 | B | 16.6 | 0 | 8.8 | 11.0 | 13.82 | 99.61 | 38.6 |
| 63 | 8.57 | D | 16.1 | 0 | 8.8 | 11.0 | 14.10 | 99.62 | 37.7 |
| 64 | 8.29 | A | 6.0 | 0.1 | 10.1 | 12.5 | 15.75 | 99.85 | 1.4 |
| 64 | 8.29 | B | 5.9 | 0.1 | 10.1 | 12.4 | 15.42 | 99.85 | 0.8 |
| 64 | 8.29 | D | 6.0 | 0.1 | 10.1 | 12.3 | 15.50 | 99.85 | 1.6 |
| 66 | 8.29 | A | 8.4 | 0.2 | 8.3 | 11.0 | 15.35 | 99.78 | 1.8 |
| 66 | 8.29 | B | 8.5 | 0.2 | 8.2 | 10.8 | 15.19 | 99.78 | 2.4 |
| 66 | 8.29 | D | 8.2 | 0.2 | 8.4 | 11.0 | 15.31 | 99.79 | 2.4 |
| 67 | 8.29 | A | 2.7 | 0.1 | 14.1 | 16.3 | 18.20 | 99.93 | 15.3 |
| 67 | 8.29 | B | 2.8 | 0.1 | 14.2 | 16.5 | 17.67 | 99.93 | 14.5 |
| 67 | 8.29 | D | 2.8 | 0.1 | 14.0 | 16.3 | 17.75 | 99.93 | 15.6 |
| 68 | 9.14 | A | 1.8 | 0 | 21.9 | 24.1 | 21.85 | 99.96 | 34.0 |
| 68 | 9.14 | B | 1.8 | 0 | 22.1 | 24.3 | 21.16 | 99.96 | 37.6 |
| 68 | 9.14 | D | 1.8 | 0 | 22.1 | 24.4 | 21.16 | 99.96 | 35.7 |
| 69 | 9.14 | A | 2.2 | 0 | 21.6 | 24.0 | 21.51 | 99.95 | 41.3 |
| 69 | 9.14 | B | 2.4 | 0 | 22.0 | 24.5 | 20.68 | 99.94 | 43.6 |
| 69 | 9.14 | D | 2.4 | 0 | 22.0 | 24.3 | 20.92 | 99.94 | 42.2 |
| 70 | 9.14 | A | 2.2 | 0 | 23.3 | 25.7 | 21.80 | 99.95 | 44.1 |
| 70 | 9.14 | B | 2.3 | 0 | 23.3 | 25.8 | 21.31 | 99.95 | 46.8 |
| 70 | 9.14 | D | 2.3 | 0 | 23.2 | 25.0 | 21.51 | 99.95 | 45.6 |
| 71 | 9.14 | A | 1.9 | 0 | 26.1 | 28.5 | 23.27 | 99.96 | 49.4 |
| 71 | 9.14 | B | 2.1 | 0 | 26.6 | 29.0 | 22.35 | 99.95 | 52.3 |
| 71 | 9.14 | D | 2.0 | 0 | 26.5 | 29.2 | 22.55 | 99.95 | 50.6 |
| 72 | 9.14 | A | 1.6 | 0 | 25.4 | 27.8 | 23.06 | 99.96 | 43.7 |
| 72 | 9.14 | B | 1.8 | 0 | 25.5 | 27.9 | 22.40 | 99.96 | 45.8 |
| 72 | 9.14 | D | 1.7 | 0 | 25.3 | 27.7 | 22.60 | 99.96 | 43.7 |
| 73 | 9.14 | A | 46.3 | 1.9 | 2.0 | 4.8 | 10.29 | 98.72 | 16.7 |
| 73 | 9.14 | B | 54.6 | 2.2 | 1.9 | 3.8 | 10.78 | 98.50 | 11.8 |
| 73 | 9.14 | D | 55.5 | 2.2 | 2.0 | 3.8 | 10.97 | 98.48 | 21.3 |

(1) A = 12-point single cruciform oriented at 0°-90°
B = 12-point single cruciform oriented at 45°-135°
D = 24-point double cruciform (A and B)

Table A-II. Fuel-Air Ratio Comparisons, Diesel No. 2 Fuel Engine Tests.

| Reading Number | FNPC, Corrected Thrust, % of Ratio | $FAR_8$, Metered Core Exhaust Fuel-Air Ratio, g/kg | $\frac{FAR_S}{FAR_8}$, Ratio of Sample to Metered Fuel-Air Ratio | | |
|---|---|---|---|---|---|
| | | | Double Cruciform (Rake D) | 0° - 90° Cruciform (Rake A) | 45° - 135° Cruciform (Rake B) |
| 59 | 3.5 | 12.33 | 0.944 | 0.944 | 0.944 |
| 60 | 4.8 | 11.79 | 0.935 | 0.937 | 0.935 |
| 61 | 6.6 | 11.42 | 0.928 | 0.933 | 0.922 |
| 62 | 20.2 | 12.38 | 0.960 | 0.964 | 0.954 |
| 63 | 30.6 | 14.24 | 0.990 | 0.987 | 0.971 |
| 64 | 46.3 | 15.67 | 0.989 | 1.005 | 0.984 |
| 66 | 46.0 | 15.39 | 0.995 | 0.997 | 0.987 |
| 67 | 65.9 | 18.28 | 0.971 | 0.996 | 0.967 |
| 68 | 89.4 | 21.49 | 0.985 | 1.017 | 0.985 |
| 69 | 89.2 | 21.40 | 0.978 | 1.005 | 0.966 |
| 70 | 94.1 | 22.01 | 0.977 | 0.990 | 0.968 |
| 71 | 102.9 | 23.24 | 0.970 | 1.001 | 0.962 |
| 72 | 102.7 | 23.05 | 0.980 | 1.000 | 0.972 |
| 73 | 3.7 | 10.54 | 1.041 | 0.976 | 1.023 |
| Number of Observations | | | 14 | 14 | 14 |
| Mean Value | | | 0.974 | 0.982 | 0.967 |
| Standard Deviation | | | 0.0282 | 0.0273 | 0.0248 |

# APPENDIX B

## DETAILED ENGINE/COMBUSTOR PERFORMANCE TEST RESULTS

Table B-I. Engine/Combustor Performance Results, Diesel No. 2 Fuel Tests.

a. Key Overall Performance Parameters.

| Reading Number | $\delta_2$, Engine Inlet-to-Standard Pressure Ratio, Dimensionless | $\theta_2$, Engine Inlet-to-Standard Temperature Ratio, Dimensionless | $H_o$, Engine Inlet Air Humidity, g/kg | $N_1/\sqrt{\theta_2}$, Corrected Fan Speed, rps | $N_2/\sqrt{\theta_2}$, Corrected Core Speed, rps | $F_N/\delta_2$, Corrected Installed Thrust, kN | $F_N/\delta_2$, Corrected Installed Thrust, % of 221.2 kN | $W_f/\delta_2\theta_2$, Corrected Fuel Flow, kg/s | $W_f/F_N\theta_2^{0.54}$, Corrected Specific Fuel Consumption, g/N | $P_{49}/P_2$, Engine Pressure Ratio, Dimensionless | $T_{49}/\theta_2$, Corrected High Pressure Turbine Exit Temperature, K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 59 | 0.98516 | 1.0495 | 10.571 | 14.069 | 106.43 | 7.7311 | 3.4795 | 0.19012 | 24.592 | 1.1852 | 739.79 |
| 60 | 0.98211 | 1.0490 | 8.5714 | 16.328 | 114.25 | 10.605 | 4.7731 | 0.21635 | 20.400 | 1.2523 | 717.39 |
| 61 | 0.98174 | 1.0498 | 8.5714 | 19.224 | 121.48 | 14.761 | 6.6433 | 0.25385 | 17.197 | 1.3470 | 706.17 |
| 62 | 0.97839 | 1.0497 | 8.5714 | 32.827 | 137.56 | 44.991 | 20.249 | 0.52320 | 11.629 | 2.0513 | 750.42 |
| 63 | 0.97598 | 1.0490 | 8.5714 | 39.707 | 144.09 | 67.888 | 30.554 | 0.75851 | 11.173 | 2.6109 | 817.41 |
| 64 | 0.97586 | 1.0497 | 8.5714 | 47.312 | 152.34 | 102.97 | 46.344 | 1.1034 | 10.716 | 3.4882 | 881.63 |
| 66 | 0.97579 | 1.0480 | 8.5714 | 47 428 | 152.60 | 102.14 | 45.969 | 1.0901 | 10.673 | 3.4606 | 875.02 |
| 67 | 0.97300 | 1.0475 | 8.5714 | 53.664 | 158.96 | 146.48 | 65.927 | 1.5858 | 10.826 | 4.5060 | 972.77 |
| 68 | 0.96987 | 1.0460 | 8.5714 | 59.407 | 168.05 | 198.66 | 89.410 | 2.2282 | 11.216 | 5.6932 | 1077.9 |
| 69 | 0.96993 | 1.0460 | 9.1429 | 59.394 | 167.81 | 198.18 | 89.192 | 2.2224 | 11.215 | 5.6847 | 1072.2 |
| 70 | 0.96933 | 1.0442 | 9.1429 | 60.523 | 169.66 | 209.09 | 94.103 | 2.3646 | 11.309 | 5.9321 | 1092.7 |
| 71 | 0.96821 | 1.0457 | 9.1429 | 52.510 | 172.45 | 228.62 | 102.90 | 2.6301 | 11.504 | 6.3855 | 1130.7 |
| 72 | 0.96788 | 1.0413 | 9.1429 | 62.438 | 172.27 | 228.20 | 102.70 | 2.6211 | 11.486 | 6.3714 | 1129.7 |
| 73 | 0.98233 | 1.0408 | 9.1429 | 14.068 | 104.99 | 8.1963 | 3.6889 | 0.17412 | 21.243 | 1.2149 | 697.04 |

Table B-I. Engine/Combustor Performance Results, Diesel No. 2 Fuel Tests (Continued).

b. Supplementary Overall Performance Parameters.

| Reading Number | $\delta_{25}$, Core Engine Inlet-to-Standard Pressure Ratio, Dimensionless | $\theta_{25}$, Core Engine Inlet-to-Standard Temperature Ratio, Dimensionless | $\frac{W_{25}\sqrt{\theta_{25}}}{\delta_{25}}$ High Pressure Rotor Inlet Corrected Airflow, kg/s | $T_{41}$ First Stage Turbine Rotor Inlet Temperature, K | $T_{49}$, High Pressure Turbine Exit Temperature, K | $\frac{W_2\sqrt{\theta_2}}{\delta_2}$ Total Engine Inlet Airflow, kg/s | $P_3/P_2$, Compression Ratio, Dimensionless | $T_{49}/T_{25}$, Core Engine Temperature Ratio, Dimensionless | $\alpha$, Throttle Angle, Degrees |
|---|---|---|---|---|---|---|---|---|---|
| 59 | 1.0291 | 1.0791 | 16.784 | 931.53 | 769.69 | 116.62 | 2.8974 | 2.4329 | 55.422 |
| 60 | 1.0406 | 1.0804 | 19.935 | 941.53 | 746.23 | 137.01 | 3.4731 | 2.3752 | 56.950 |
| 61 | 1.0644 | 1.0860 | 23.638 | 958.04 | 735.05 | 162.20 | 4.2538 | 2.3435 | 59.100 |
| 62 | 1.2583 | 1.1420 | 37.937 | 1089.2 | 781.00 | 283.24 | 8.6453 | 2.4255 | 63.996 |
| 63 | 1.4096 | 1.1864 | 43.448 | 1198.6 | 850.27 | 345.76 | 11.455 | 2.5583 | 67.030 |
| 64 | 1.6421 | 1.2464 | 50.035 | 1305.1 | 917.59 | 451.07 | 15.885 | 2.6259 | 74.038 |
| 66 | 1.6425 | 1.2453 | 49.729 | 1292.1 | 909.47 | 450.44 | 15.838 | 2.6161 | 74.756 |
| 67 | 1.8815 | 1.2982 | 54.711 | 1438.7 | 1010.7 | 534.28 | 20.604 | 2.7858 | 80.730 |
| 68 | 2.1409 | 1.3477 | 58.398 | 1587.8 | 1118.5 | 616.71 | 25.912 | 2.9770 | 89.694 |
| 69 | 2.1418 | 1.3476 | 58.335 | 1582.4 | 1112.6 | 617.29 | 25.968 | 2.9736 | 89.585 |
| 70 | 2.1965 | 1.3557 | 58.925 | 1609.3 | 1132.2 | 632.75 | 27.083 | 3.0102 | 91.971 |
| 71 | 2.2957 | 1.3756 | 59.948 | 1663.3 | 1173.0 | 659.37 | 29.030 | 3.0707 | 95.779 |
| 72 | 2.2913 | 1.3693 | 59.925 | 1654.1 | 1167.8 | 658.88 | 29.042 | 3.0703 | 94.925 |
| 73 | 1.0277 | 1.0704 | 17.938 | 859.60 | 720.25 | 119.08 | 2.9811 | 2.2378 | 57.059 |

Table B-I. Engine/Combustor Performance Results, Diesel No. 2 Fuel Tests (Continued).

c. Combustor Emissions Correlation Parameters.

| Reading Number | $P_3$, Compressor Exit Pressure, MPa | $T_3$, Compressor Exit Temperature, K | $W_{a36}$, Combustor Airflow, kg/s | $W_{ft}$, Total Fuel Flow, kg/s | $W_{fp}/W_{ft}$, Pilot-to-Total Fuel Split, Percent | $f_4$, Combustor Fuel-Air Ratio, g/kg | $f_8$, Core Engine Exit Fuel-Air Ratio g/kg | $\Delta P_T/P_3$, Combustor Pressure Loss, Percent | $V_r$, Combustor Reference Velocity, m/s |
|---|---|---|---|---|---|---|---|---|---|
| 59 | 0.28922 | 451.93 | 12.761 | 0.19483 | 100.0 | 15.267 | 12.333 | 3.1375 | 18.226 |
| 60 | 0.34561 | 476.80 | 15.123 | 0.22075 | 100.0 | 14.597 | 11.791 | 3.6710 | 19.069 |
| 61 | 0.42315 | 505.48 | 18.325 | 0.25902 | 100.0 | 14.135 | 11.417 | 3.8678 | 20.009 |
| 62 | 0.85706 | 603.78 | 34.708 | 0.53200 | 100.0 | 15.328 | 12.382 | 4.0513 | 22.348 |
| 63 | 1.1328 | 651.33 | 43.643 | 0.76910 | 100.0 | 17.622 | 14.235 | 4.0518 | 22.936 |
| 64 | 1.5707 | 716.75 | 57.688 | 1.1191 | 28.699 | 19.399 | 15.670 | 4.4053 | 24.062 |
| 66 | 1.5659 | 712.77 | 57.963 | 1.1046 | 20.837 | 19.057 | 15.393 | 4.1678 | 24.114 |
| 67 | 2.0313 | 770.49 | 70.769 | 1.601[illegible] | 17.416 | 22.634 | 18.283 | 4.5251 | 24.535 |
| 68 | 2.5464 | 825.25 | 84.258 | 2.2416 | 17.277 | 26.604 | 21.490 | 4.4116 | 24.958 |
| 69 | 2.5521 | 823.14 | 84.433 | 2.2366 | 12.499 | 26.490 | 21.398 | 4.5447 | 24.891 |
| 70 | 2.6600 | 832.44 | 87.209 | 2.3761 | 12.489 | 27.246 | 22.009 | 4.5424 | 24.946 |
| 71 | 2.8480 | 851.62 | 91.837 | 2.6418 | 12.618 | 28.767 | 23.237 | 4.4261 | 25.101 |
| 72 | 2.8482 | 847.44 | 92.027 | 2.6260 | 17.363 | 28.535 | 23.049 | 4.5210 | 25.027 |
| 73 | 0.29672 | 443.65 | 13.558 | 0.17699 | 100.0 | 13.055 | 10.545 | 3.9643 | 18.528 |

Table B-I. Engine/Combustor Performance Results, Diesel No. 2 Fuel Tests (Continued).

d. Combustor Heat Transfer Parameters.

| Reading Number | $P_3$, Compressor Exit Pressure, MPa | $T_3$, Compressor Exit Temperature, K | $f_4$, Combustor Fuel-Air Ratio, g/kg | $W_{fp}/W_{ft}$, Pilot-to-Total Fuel Split, Percent | $\Delta T_{mol}$, Peak Outerliner Temperature Rise, K | $\Delta T_{mcb}$, Peak Centerbody Temperature Rise, K | $\Delta T_{mil}$, Peak Inner Liner Temperature Rise, K | $f_p$, Pilot Stage Fuel-Air Ratio, g/kg | $f_m$, Main Stage Fuel-Air Ratio, g/kg |
|---|---|---|---|---|---|---|---|---|---|
| 59 | 0.28922 | 451.93 | 15.267 | 100.0 | 211.17 | 60.367 | 142.70 | 15.032 | 0 |
| 60 | 0.34561 | 476.80 | 14.597 | 100.0 | 185.80 | 49.127 | 110.51 | 14.332 | 0 |
| 61 | 0.42315 | 505.48 | 14.135 | 100.0 | 195.74 | 46.472 | 123.04 | 13.858 | 0 |
| 62 | 0.85706 | 603.78 | 15.328 | 100.0 | 211.35 | 55.076 | 108.98 | 15.136 | 0 |
| 63 | 1.1328 | 651.33 | 17.622 | 100.0 | 237.08 | 82.609 | 130.70 | 17.481 | 0 |
| 64 | 1.5707 | 716.75 | 19.399 | 28.699 | 117.21 | 150.10 | 193.72 | 5.5674 | 13.832 |
| 66 | 1.5659 | 712.77 | 19.057 | 20.837 | 98.190 | 159.84 | 186.28 | 3.9707 | 15.086 |
| 67 | 2.0313 | 770.49 | 22.634 | 17.416 | 132.34 | 241.43 | 228.33 | 3.9420 | 18.692 |
| 68 | 2.5464 | 825.25 | 26.604 | 17.277 | 160.25 | 315.71 | 255.93 | 4.5965 | 22.008 |
| 69 | 2.5521 | 823.14 | 26.490 | 12.499 | 145.73 | 329.63 | 259.71 | 3.3110 | 23.179 |
| 70 | 2.6600 | 832.44 | 27.246 | 12.489 | 148.96 | 342.26 | 265.25 | 3.4027 | 23.843 |
| 71 | 2.8480 | 851.62 | 28.767 | 12.618 | 155.79 | 363.38 | 276.19 | 3.6298 | 25.137 |
| 72 | 2.8482 | 847.44 | 28.535 | 17.363 | 170.99 | 346.25 | 267.12 | 4.9544 | 23.580 |
| 73 | 0.29672 | 443.65 | 13.055 | 100.0 | 181.74 | 49.034 | 124.31 | 12.866 | 0 |

Table B-I. Engine/Combustor Performance Results, Diesel No. 2 Fuel Tests (Concluded).

e. Combustor Fuel Nozzle Parameters.

| Reading Number | $W_{ft}$, Total Fuel Flow, kg/s | $W_{fv}$, Verification Fuel Flow, kg/s | $W_{fp}$, Pilot Stage Fuel Flow, kg/s | $W_{fm}$, Main Stage Fuel Flow, kg/s | $T_{fp}$, Pilot Stage Fuel Temperature, K | $T_{fm}$, Main Stage Fuel Temperature, K | $\gamma_{Man}$, Fuel Specific Gravity @ Manifolds, dim. | $\Delta P_{fp}$, Pilot Stage Fuel Nozzle Pressure Drop, MPa | $\Delta P_{fm}$, Main Stage Fuel Nozzle Pressure Drop, MPa |
|---|---|---|---|---|---|---|---|---|---|
| 59 | 0.19483 | 0.19437 | 0.19183 | 0 | 348.01 | 0 | 0.83834 | 1.1277 | 1.1044 |
| 60 | 0.22075 | 0.22025 | 0.21674 | 0 | 353.70 | 0 | 0.83805 | 1.1563 | 1.1104 |
| 61 | 0.25902 | 0.25860 | 0.25394 | 0 | 354.04 | 0 | 0.83707 | 1.1772 | 1.0946 |
| 62 | 0.53200 | 0.53039 | 0.52534 | 0 | 345.81 | 0 | 0.83518 | 1.3271 | 0.97516 |
| 63 | 0.76910 | 0.76659 | 0.76291 | 0 | 343.12 | 0 | 0.83443 | 1.5098 | 1.2080 |
| 64 | 1.1191 | 1.1150 | 0.32117 | 0 | 340.71 | 0 | 0.83432 | 1.1972 | 2.3644 |
| 66 | 1.1046 | 1.1013 | 0.23015 | 0.86970 | 339.98 | 342.91 | 0.83466 | 1.1375 | 2.4382 |
| 67 | 1.6018 | 1.6361 | 0.27897 | 1.3196 | 336.10 | 338.32 | 0.83558 | 1.1688 | 2.8634 |
| 68 | 2.2416 | 2.2553 | 0.38729 | 1.8276 | 331.20 | 332.30 | 0.83780 | 1.2263 | 3.4527 |
| 69 | 2.2366 | 2.2517 | 0.27956 | 1.9149 | 329.72 | 331.43 | 0.83930 | 1.1746 | 3.5912 |
| 70 | 2.3761 | 2.3764 | 0.29675 | 2.0197 | 328.81 | 330.30 | 0.83977 | 1.1887 | 3.7449 |
| 71 | 2.6418 | 2.6316 | 0.33335 | 2.2010 | 327.78 | 328.89 | 0.84028 | 1.2083 | 4.0612 |
| 72 | 2.6260 | 2.6161 | 0.45594 | 2.0749 | 327.33 | 328.08 | 0.84093 | 1.2709 | 3.8525 |
| 73 | 0.17699 | 0.17646 | 0.17443 | 0 | 362.38 | 0 | 0.84106 | 1.0583 | 1.0749 |

Table B-II. Combustor Metal Temperatures, Diesel No. 2 Fuel Test.

a. Outer Liner Forward Panels

| Reading Number | ($T_{metal}$ - $T_3$), Metal Temperature Rise, K | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TK3619-90° Panel 1 | TK3620-93° Panel 1 | TK3621-96° Panel 1 | TK3622-99° Panel 1 | TK3623-90° Panel 2 | TK3624-91.5° Panel 2 | TK3625-94.5° Panel 2 | TK3626-96° Panel 2 | TK3627-97.5° Panel 2 | TK3628-100.5° Panel 2 | TK3629-162° Panel 2 | TK3630-222° Panel 2 |
| 59 | 130.83 | 132.63 | 90.291 | 78.230 | 181.22 | 174.59 | 141.96 | 117.50 | 159.87 | 250.57 | 281.50 | 131.48 |
| 60 | 120.43 | 118.59 | 79.658 | 75.760 | 159.30 | 150.48 | 124.71 | 104.39 | 121.69 | 158.47 | 253.07 | 120.74 |
| 61 | 141.82 | 141.14 | 85.699 | 86.395 | 174.88 | 168.55 | 139.24 | 110.05 | 137.28 | 182.07 | 248.86 | 123.13 |
| 62 | 153.59 | 150.76 | 85.300 | 121.26 | 184.99 | 180.96 | 143.60 | 111.06 | 176.36 | 241.81 | 226.76 | 154.28 |
| 63 | 168.84 | 165.57 | 101.42 | 138.02 | 204.64 | 200.92 | 157.01 | 134.26 | 210.03 | 284.81 | 223.14 | 196.53 |
| 64 | 114.02 | 119.09 | 51.143 | 58.929 | 128.80 | 130.40 | 111.96 | 78.593 | 97.74 | 105.10 | 110.54 | 110.96 |
| 66 | 98.711 | 105.81 | 51.888 | 59.796 | 105.28 | 108.37 | 93.356 | 71.960 | 88.96 | 90.66 | 99.81 | 96.08 |
| 67 | 123.72 | 132.98 | 78.181 | 92.124 | 129.45 | 137.37 | 116.39 | 98.203 | 118.31 | 111.79 | 96.82 | 114.53 |
| 68 | 141.54 | 151.34 | 99.137 | 112.92 | 155.59 | 166.05 | 140.21 | 121.67 | 140.19 | 133.91 | 105.58 | 133.91 |
| 69 | 117.03 | 125.42 | 83.532 | 93.857 | 134.04 | 142.88 | 122.11 | 105.77 | 118.64 | 111.47 | 87.04 | 113.75 |
| 70 | 119.78 | 127.85 | 86.323 | 96.797 | 137.58 | 146.60 | 125.49 | 109.00 | 102.36 | 94.40 | 70.73 | 95.77 |
| 71 | 128.44 | 136.42 | 93.179 | 103.64 | 144.98 | 154.89 | 132.54 | 115.50 | 128.80 | 120.20 | 94.90 | 120.18 |
| 72 | 147.38 | 156.80 | 105.73 | 120.41 | 166.09 | 176.13 | 148.67 | 129.59 | 148.05 | 140.35 | 124.49 | 140.35 |
| 73 | 119.27 | 120.01 | 80.510 | 68.663 | 156.24 | 152.69 | 126.10 | 99.191 | 112.27 | 142.47 | 230.71 | 117.83 |

Table B-II. Combustor Metal Temperatures, Diesel No. 2 Fuel Test (Continued).

b. Outer Liner Aft Panels

| Reading Number | ($T_{metal} - T_3$), Metal Temperature Rise, K | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | TK3631-90° Panel 3 | TK3632-96° Panel 3 | TK3634-96° Panel 4 | TK3642-96° Panel 5 | TK3639-90° Panel 6 | TK3640-96° Panel 6 | TK3635-90° Panel 7 | TK3636-93° Panel 7 | TK3637-96° Panel 7 | TK3638-99° Panel 7 |
| 59 | 211.21 | 166.35 | 156.05 | 115.89 | 207.52 | 135.03 | 171.11 | 134.62 | 144.82 | 152.64 |
| 60 | 185.82 | 151.96 | 137.53 | 102.47 | 182.95 | 122.51 | 151.48 | 118.21 | 134.32 | 146.59 |
| 61 | 195.74 | 157.91 | 138.09 | 100.52 | 167.80 | 117.18 | 142.54 | 114.43 | 132.43 | 145.67 |
| 62 | 211.37 | 163.74 | 146.77 | 104.91 | 191.08 | 121 89 | 163.55 | 123.86 | 140.00 | 155.85 |
| 63 | 237.14 | 193.42 | 179.26 | 128.09 | 225.71 | 143.56 | 193.09 | 144.91 | 162.27 | 188.08 |
| 64 | 117.21 | 90.69 | 72.79 | 51.406 | 105.40 | 65.462 | 103.08 | 73.092 | 78.100 | 100.76 |
| 66 | 98.20 | 80.13 | 63.59 | 45.638 | 97.645 | 54.957 | 96.238 | 60.153 | 69.192 | 98.997 |
| 67 | 132.34 | 116.06 | 102.72 | 72.291 | 133.15 | 77.683 | 133.34 | 82.738 | 89.125 | 120.62 |
| 68 | 160.30 | 144.36 | 135.24 | 96.974 | 168.35 | 104.05 | 166.84 | 111.91 | 113.77 | 139.99 |
| 69 | 145.73 | 132.33 | 128.97 | 93.663 | 158.80 | 99.428 | 164.66 | 109.68 | 108.74 | 135.62 |
| 70 | 148.96 | 135.89 | 133.64 | 97.710 | 167.78 | 104.32 | 174.35 | 117.44 | 113.71 | 139.44 |
| 71 | 155.78 | 143.35 | 143.50 | 106.84 | 186.02 | 115.73 | 194.76 | 134.95 | 125.90 | 149.15 |
| 72 | 170.96 | 154.56 | 147.71 | 107.33 | 192.87 | 117.05 | 192.52 | 131.93 | 126.67 | 149.49 |
| 73 | 181.81 | 139.83 | 127.12 | 91.718 | 166.55 | 108.62 | 166.55 | 110.07 | 119.77 | 128.50 |

Table B-II. Combustor Metal Temperatures, Diesel No. 2 Fuel Test (Continued).

## c. Centerbody Temperatures

| Reading Number | $(T_{metal} - T_3)$, Metal Temperature Rise, K | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TK3109-57° Trailing Edge, Main Stage Side | TK3110-60° Trailing Edge, Main Stage Side | TK3112-102° Trailing Edge, Crossfire Slot | TK3114-102° Trailing Edge, Crossfire Slot, Pilot Side | TK3115-102° Crossfire Slot Side Wall | TK3116-102° Crossfire Slot Trailing Edge, Main Side | TK3117-186° Trailing Edge Main Stage Side | TK3118-192° Trailing Edge Pilot Stage Side | TK3119-192° Trailing Edge Main Stage Side | TK3121-282° Crossfire Slot Base | TK3122-282° Crossfire Slot Trailing Edge, Pilot Side | TK3123-282° Crossfire Slot Trailing Edge, Main Side |
| 59 | 57.464 | 73.650 | 241.88 | 239.21 | 187.69 | 236.41 | 7.3044 | 24.211 | 0.64779 | 29.822 | 187.03 | 142.70 |
| 60 | 42.901 | 65.340 | 218.34 | 210.75 | 178.50 | 209.83 | 6.3700 | 29.503 | 0.75941 | 23.432 | 147.57 | 110.51 |
| 61 | 33.372 | 61.983 | 225.58 | 215.29 | 194.86 | 215.43 | 4.0993 | 24.209 | -0.17497 | 22.417 | 169.38 | 123.04 |
| 62 | 13.932 | 63.575 | 277.76 | 268.07 | 224.51 | 248.74 | 1.3700 | 15.044 | -1.2187 | 22.291 | 163.49 | 108.93 |
| 63 | 10.328 | 77.877 | 308.21 | 299.84 | 234.87 | 273.33 | 1.9998 | 15.803 | -1.4236 | 26.945 | 205.91 | 130.70 |
| 64 | 6.1951 | 141.39 | 155.38 | 156.54 | 88.265 | 161.12 | 1.3733 | 8.6175 | -2.7386 | 14.498 | 205.33 | 193.72 |
| 66 | 8.4992 | 146.28 | 165.42 | 161.18 | 88.794 | 175.54 | 2.4121 | 8.8660 | -2.6010 | 12.065 | 177.29 | 186.28 |
| 67 | 3.0543 | 189.08 | 199.06 | 196.25 | 113.28 | 217.10 | -2.0283 | 2.4912 | -5.2429 | 13.539 | 200.45 | 228.33 |
| 68 | -2.4647 | 221.52 | 225.53 | 215.63 | 134.70 | 243.63 | -5.2901 | -3.8538 | -7.3503 | 16.533 | 216.81 | 255.93 |
| 69 | -2.7688 | 218.16 | 208.79 | 192.55 | 116.05 | 235.00 | -5.6364 | -4.6038 | -6.9363 | 15.022 | 179.24 | 259.71 |
| 70 | -3.7196 | 223.77 | 210.97 | 193.40 | 118.95 | 237.45 | -6.0851 | -5.5688 | -7.2350 | 15.400 | 194.96 | 265.25 |
| 71 | -5.5493 | 236.73 | 215.69 | 195.48 | 122.89 | 242.45 | -6.6759 | -6.7225 | -8.0697 | 15.729 | 64.540 | 276.19 |
| 72 | -5.7278 | 240.67 | 235.75 | 216.01 | 143.45 | 254.43 | -7.1829 | -7.1593 | -8.2764 | 16.851 | -128.45 | 267.12 |
| 73 | 44.294 | 58.939 | 186.90 | 183.66 | 131.31 | 182.16 | 11.637 | 21.867 | 2.7181 | 24.194 | 251.94 | 124.31 |

Table B-II. Combustor Metal Temperatures, Diesel No. 2 Fuel Test (Continued).

### d. Inner Liner Forward Panels

| Reading Number | ($T_{metal} - T_3$), Metal Temperature Rise, K | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TK3643-90° Panel 1 | TK3644-93° Panel 1 | TK3645-96° Panel 1 | TK3646-99° Panel 1 | TK3649-90° Panel 2 | TK3650-96° Panel 2 | TK3647-90° Panel 3 | TK3648-96° Panel 3 | TK3651-90° Panel 4 | TK3652-96° Panel 4 | TK3653-90° Panel 5 | TK3654-96° Panel 5 |
| 59 | 19.882 | 20.678 | 18.936 | 19.537 | 39.221 | 35.627 | 49.721 | 45.717 | 63.205 | 60.367 | 61.993 | 64.130 |
| 60 | 16.640 | 16.850 | 15.429 | 15.614 | 32.941 | 29.112 | 41.224 | 37.746 | 52.786 | 49.127 | 51.745 | 52.346 |
| 61 | 15.736 | 15.916 | 14.425 | 14.750 | 31.588 | 27.600 | 39.330 | 35.980 | 49.941 | 46.472 | 48.403 | 49.191 |
| 62 | 17.483 | 17.875 | 15.913 | 16.600 | 39.037 | 32.440 | 47.973 | 43.239 | 61.619 | 55.076 | 58.984 | 58.381 |
| 63 | 25.556 | 26.968 | 23.912 | 26.024 | 56.569 | 49.250 | 70.553 | 65.835 | 92.323 | 82.609 | 88.687 | 26.382 |
| 64 | 157.71 | 61.379 | 115.29 | 78.762 | 138.81 | 107.77 | 105.07 | 143.89 | 123.04 | 150.10 | 110.05 | 133.62 |
| 66 | 163.62 | 65.259 | 120.02 | 81.853 | 146.92 | 116.19 | 112.48 | 152.00 | 129.65 | 159.84 | 115.23 | 142.62 |
| 67 | 203.75 | 116.91 | 185.18 | 118.67 | 201.80 | 189.64 | 171.02 | 236.59 | 192.07 | 241.43 | 172.15 | 218.45 |
| 68 | 221.49 | 155.93 | 233.55 | 145.38 | 242.01 | 236.35 | 216.17 | 303.72 | 250.68 | 315.71 | 231.74 | 291.46 |
| 69 | 219.92 | 160.91 | 239.60 | 144.85 | 246.42 | 242.27 | 222.93 | 314.25 | 259.80 | 329.63 | 242.20 | 308.03 |
| 70 | 220.39 | 165.97 | 245.04 | 147.31 | 250.71 | 247.29 | 228.14 | 322.83 | 268.65 | 342.26 | 252.88 | 321.33 |
| 71 | 226.46 | 169.15 | 250.16 | 153.15 | 261.10 | 252.11 | 238.33 | 334.89 | 281.68 | 363.38 | 269.17 | 348.48 |
| 72 | 223.32 | 161.00 | 239.45 | 157.11 | 253.24 | 244.39 | 230.02 | 321.48 | 268.56 | 346.25 | 254.38 | 331.67 |
| 73 | 19.760 | 20.731 | 19.495 | 19.410 | 35.470 | 35.220 | 42.953 | 41.351 | 53.483 | 39.034 | 52.042 | 48.563 |

Table B-II. Combustor Metal Temperatures, Diesel No. 2 Fuel Test (Concluded).

e. Inner Liner Aft Panels

| Reading Number | ($T_{metal}$ - $T_3$), Metal Temperature Rise, K | | | | |
|---|---|---|---|---|---|
| | TK3655-90° Panel 6 | TK3656-96° Panel 6 | TK3658-93° Panel 7 | TK3659-96° Panel 7 | TK3660-99° Panel 7 |
| 59 | 55.958 | 51.103 | 63.565 | 68.915 | 65.072 |
| 60 | 46.335 | 41.229 | 53.136 | 56.750 | 53.356 |
| 61 | 42.694 | 37.779 | 48.577 | 52.485 | 48.553 |
| 62 | 50.299 | 42.370 | 55.451 | 58.903 | 55.057 |
| 63 | 74.429 | 59.885 | 78.042 | 81.283 | 78.301 |
| 64 | 121.53 | 115.42 | 81.399 | 101.27 | 130.68 |
| 66 | 126.24 | 123.82 | 86.617 | 110.60 | 140.47 |
| 67 | 172.55 | 176.48 | 121.40 | 161.26 | 195.87 |
| 68 | 232.50 | 224.03 | 160.64 | 206.08 | 250.86 |
| 69 | 242.44 | 236.73 | 168.23 | 218.10 | 264.22 |
| 70 | 255.69 | 244.90 | 174.95 | 224.82 | 274.43 |
| 71 | 275.90 | 262.39 | 189.99 | 242.09 | 293.98 |
| 72 | 257.83 | 251.17 | 181.76 | 231.88 | 279.70 |
| 73 | 44.800 | 37.518 | 48.328 | 51.006 | 48.003 |

Table B-III. Combustor Pressures, Diesel No. 2 Fuel Test.

a. Inlet Pressures

| Reading Number | Combustor Inlet Total Pressure, MPa | | | | Pilot Stage Dome Upstream Static Pressure, MPa | | | | Main Stage Dome Upstream Static Pressure, MPa | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PT 3101 -0° | PT 3102 -90° | PT 3103 -180° | Average | PS 3101 -0° | PS 3102 -90° | PS 3103 -180° | Average | PS 3104 -0° | PS 3105 -90° | PS 3106 -180° | Average |
| 59 | 0.28779 | 0.28953 | 0.28953 | 0.28895 | 0.13365 | 0.28805 | 0.28837 | 0.28821 | 0.28905 | 0.28973 | 0.28928 | 0.28935 |
| 60 | 0.34257 | 0.34515 | 0.34548 | 0.34440 | 0.14846 | 0.34434 | 0.34447 | 0.34440 | 0.34428 | 0.34580 | 0.34502 | 0.34503 |
| 61 | 0.41970 | 0.42286 | 0.42290 | 0.42182 | 0.17065 | 0.42154 | 0.42180 | 0.42167 | 0.42135 | 0.42325 | 0.42206 | 0.42222 |
| 62 | 0.85116 | 0.85726 | 0.85723 | 0.85522 | 0.31147 | 0.85361 | 0.85452 | 0.85406 | 0.85101 | 0.85488 | 0.85368 | 0.85319 |
| 63 | 1.1220 | 1.1318 | 1.1297 | 1.1278 | 0.40806 | 1.1287 | 1.1290 | 1.1289 | 1.1232 | 1.1289 | 1.1265 | 1.1262 |
| 64 | 1.5542 | 1.5742 | 1.5646 | 1.5644 | 0.56083 | 1.5644 | 1.5660 | 1.5652 | 1.5572 | 1.5667 | 1.5605 | 1.5615 |
| 66 | 1.5658 | 1.5817 | 1.5760 | 1.5745 | 0.54382 | 1.5598 | 1.5611 | 1.5605 | 1.5565 | 1.5617 | 1.5604 | 1.5595 |
| 67 | 2.0019 | 2.0270 | 2.0150 | 2.0146 | 0.70249 | 2.0211 | 2.0274 | 2.0242 | 2.0077 | 2.0155 | 2.0111 | 2.0114 |
| 68 | 2.5087 | 2.5469 | 2.5167 | 2.5241 | 0.099018 | 2.5368 | 2.5383 | 2.5375 | 2.5126 | 2.5218 | 2.5202 | 2.5122 |
| 69 | 2.5104 | 2.5454 | 2.5230 | 2.5263 | 0.098602 | 2.5387 | 2.5476 | 2.5431 | 2.5161 | 2.5255 | 2.5229 | 2.5215 |
| 70 | 2.6227 | 2.6543 | 2.6282 | 2.6351 | 0.099259 | 2.6456 | 2.6557 | 2.6507 | 2.6216 | 2.6309 | 2.6261 | 2.6262 |
| 71 | 2.8027 | 2.8431 | 2.8117 | 2.8192 | 0.099018 | 2.8337 | 2.8424 | 2.8380 | 2.8069 | 2.8145 | 2.8065 | 2.8093 |
| 72 | 2.7891 | 2.8358 | 2.8022 | 2.8090 | 0.099287 | 2.8338 | 2.8427 | 2.8383 | 2.8070 | 2.8193 | 2.8131 | 2.8131 |
| 73 | 0.29216 | 0.29329 | 0.29407 | 0.29317 | 0.10086 | 0.29559 | 0.29578 | 0.29569 | 0.29443 | 0.29507 | 0.29497 | 0.29482 |

Table B-III. Combustor Pressures, Diesel No. 2 Fuel Test (Continued).

**b. Outer/Aft Pressures**

| Reading Number | Pilot Stage Dome Downstream Static Pressure, MPa | | | | Outer Passage Panel 1 Static Pressure, MPa | | | | Outer Passage Panel 7 Static Pressure, MPa | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PS 3607 -0° | PS 3608 -90° | PS 3609 -180° | Average | PS 3610 -0° | PS 3611 -90° | PS 3612 -180° | Average | PS 3622 -0° | PS 3623 -90° | PS 3624 -180° | Average |
| 59 | 0.27953 | 0.27990 | 0.27924 | 0.27977 | 0.28546 | 0.28434 | 0.28492 | 0.28490 | 0.22443 | 0.28449 | 0.28404 | 0.28432 |
| 60 | 0.33977 | 0.33290 | 0.33281 | 0.33182 | 0.34043 | 0.33891 | 0.33975 | 0.33980 | 0.33882 | 0.33859 | 0.33825 | 0.33855 |
| 61 | 0.40260 | 0.40699 | 0.40676 | 0.40545 | 0.41633 | 0.41469 | 0.41562 | 0.41555 | 0.41484 | 0.41449 | 0.41430 | 0.41455 |
| 62 | 0.82034 | 0.82063 | 0.82089 | 0.82062 | 0.84202 | 0.83825 | 0.84055 | 0.84027 | 0.84042 | 0.83961 | 0.83855 | 0.83952 |
| 63 | 1.0855 | 1.0848 | 1.0843 | 1.0849 | 1.1112 | 1.1079 | 1.1101 | 1.1097 | 1.1086 | 1.1075 | 1.1067 | 1.1076 |
| 64 | 1.4925 | 1.4937 | 1.4966 | 1.4943 | 1.5407 | 1.5341 | 1.5371 | 1.5373 | 1.5385 | 1.5368 | 1.5340 | 1.5365 |
| 66 | 1.4894 | 1.4907 | 1.4948 | 1.4916 | 1.5373 | 1.5317 | 1.5375 | 1.5355 | 1.5485 | 1.5473 | 1.5447 | 1.5468 |
| 67 | 1.9319 | 1.9315 | 1.9323 | 1.9319 | 1.9871 | 1.9801 | 1.9842 | 1.9838 | 1.9839 | 1.9813 | 1.9833 | 1.9828 |
| 68 | 2.4251 | 2.4241 | 2.4230 | 2.4241 | 2.4943 | 2.4853 | 2.4902 | 4.4900 | 2.4880 | 2.4856 | 2.4845 | 2.4861 |
| 69 | 2.4284 | 2.4233 | 2.4265 | 2.4261 | 2.5010 | 2.4862 | 2.4939 | 2.4937 | 2.4925 | 2.4828 | 2.4878 | 2.4897 |
| 70 | 2.5275 | 2.5249 | 2.5284 | 2.5269 | 2.6034 | 2.5914 | 2.5961 | 2.5969 | 2.5996 | 2.5928 | 2.5998 | 2.5974 |
| 71 | 2.7136 | 2.7091 | 2.7102 | 2.7109 | 2.7880 | 2.7755 | 2.7831 | 2.7822 | 2.7870 | 2.7842 | 2.7838 | 2.7850 |
| 72 | 2.7119 | 2.7083 | 2.7120 | 2.7108 | 2.7909 | 2.7793 | 2.7846 | 2.7849 | 2.7723 | 2.7748 | 2.7726 | 2.7732 |
| 73 | 0.28385 | 0.38525 | 0.28501 | 0.28470 | 0.29108 | 0.28971 | 0.29042 | 0.29040 | 0.28876 | 0.28876 | 0.28854 | 0.28869 |

Table B-III. Combustor Pressures, Diesel No. 2 Fuel Test (Concluded).

## c. Inner/Aft Pressures

| Reading Number | Main Stage Dome Downstream Static Pressure, MPa | | | | Inner Passage Panel 1 Static Pressure, MPa | | | | Inner Passage Panel 7 Static Pressure, MPa | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PS 3613 -0° | PS 3614 -90° | PS 3615 -180° | Average | PS 3616 -0° | PS 3617 -90° | PS 3618 -180° | Average | PS 3619 -0° | PS 3620 -90° | PS 3621 -180° | Average |
| 59 | 0.28071 | 0.27981 | 0.28104 | 0.28052 | 0.28479 | 0.28546 | 0.28563 | 0.28529 | 0.28734 | 0.28708 | 0.28699 | 0.28713 |
| 60 | 0.33445 | 0.33303 | 0.33462 | 0.33403 | 0.33895 | 0.34007 | 0.34007 | 0.33970 | 0.34208 | 0.34163 | 0.34179 | 0.34183 |
| 61 | 0.40868 | 0.40680 | 0.40867 | 0.40811 | 0.41443 | 0.41581 | 0.41579 | 0.41534 | 0.41866 | 0.41840 | 0.41840 | 0.41849 |
| 62 | 0.82525 | 0.82134 | 0.82560 | 0.82406 | 0.83799 | 0.84113 | 0.84132 | 0.84015 | 0.84696 | 0.84825 | 0.84771 | 0.84764 |
| 63 | 1.0908 | 1.0850 | 1.0912 | 1.0890 | 1.1057 | 1.1105 | 1.1103 | 1.1088 | 1.1182 | 1.1180 | 1.1178 | 1.1180 |
| 64 | 1.5124 | 1.5019 | 1.5118 | 1.5087 | 1.5316 | 1.5360 | 1.5351 | 1.5342 | 1.5463 | 1.5478 | 1.5470 | 1.5470 |
| 66 | 1.5117 | 1.5037 | 1.5137 | 1.5097 | 1.5346 | 1.5424 | 1.5422 | 1.5397 | 1.5546 | 1.5576 | 1.5575 | 1.5566 |
| 67 | 1.9485 | 1.9407 | 1.9515 | 1 9469 | 1 9706 | 1.9766 | 1.9765 | 1.9746 | 1.9918 | 1.9931 | 1.9924 | 1.9924 |
| 68 | 2.4464 | 2.4374 | 2.4486 | 2.4442 | 2.4731 | 2.4807 | 2.4806 | 2.4781 | 2.4979 | 2.4973 | 3.4967 | 2.4973 |
| 69 | 2.4503 | 2.4360 | 2.4521 | 2.4461 | 2.4781 | 2.4821 | 2.8425 | 2.4809 | 2.4968 | 2.4979 | 2.4979 | 2.4975 |
| 70 | 2.5507 | 2.5440 | 2.5594 | 2.5514 | 2.5846 | 2.5892 | 2.5914 | 2.5884 | 2.6089 | 2.6082 | 2.6098 | 2.6090 |
| 71 | 2.7355 | 2.7259 | 2.7373 | 2.7329 | 2.7670 | 2.7754 | 2.7732 | 2.7719 | 2.7932 | 2.7969 | 2.7891 | 2.7931 |
| 72 | 2.7351 | 2.7181 | 2.7312 | 2.7281 | 2.7623 | 2.7662 | 2.7643 | 2.7643 | 2.7816 | 2.7808 | 2.7822 | 2.7815 |
| 73 | 0.28573 | 0.28421 | 0.28573 | 0.28522 | 0.28925 | 0.29009 | 0.28971 | 0.28968 | 0.29161 | 0.29045 | 0.29122 | 0.29109 |

Table B-IV. Turbine Exit Temperature Profile Factor, Diesel No. 2 Fuel Tests.

| Reading Number | T25, High Pressure Rotor Inlet Temperature, K | T49, High Pressure Turbine Exit Temperature, K (Overall Average) | $\frac{T_{49,\ \text{Immersion Average}} - T_{49,\ \text{Overall Average}}}{T_{49,\ \text{Overall Average}} - T_{25}}$ High Pressure Turbine Exit Radial Temperature Profile Factor | | | | |
|---|---|---|---|---|---|---|---|
| | | | A(Tip) | B | C | D | E(Root) |
| 59 | 310.95 | 769.69 | -0.086888 | 0.093487 | 0.063408 | 0.013225 | -0.066908 |
| 60 | 311.31 | 746.23 | -0.11271 | 0.10044 | 0.072797 | 0.019825 | -0.58095 |
| 61 | 312.94 | 735.05 | -0.13490 | 0.10767 | 0.085825 | 0.023901 | -0.054472 |
| 62 | 329.06 | 781.00 | -0.13272 | 0.13615 | 0.10113 | -0.002322 | -0.073121 |
| 63 | 341.87 | 856.27 | -0.12612 | 0.13423 | 0.094118 | -0.006293 | -0.068617 |
| 64 | 359.15 | 917.59 | -0.14422 | 0.039851 | 0.058215 | 0.047116 | 0.031517 |
| 66 | 358.84 | 909.47 | -0.15138 | 0.019859 | 0.044606 | 0.058373 | 0.056631 |
| 67 | 374.08 | 1010.7 | -0.15711 | 0.005761 | 0.039882 | 0.066200 | 0.075569 |
| 68 | 388.33 | 1118.5 | -0.15231 | -0.003234 | 0.037538 | 0.067898 | 0.080112 |
| 69 | 388.32 | 1112.6 | -0.15680 | -0.010935 | 0.031252 | 0.074705 | 0.093018 |
| 70 | 390.64 | 1132.2 | -0.15306 | -0.013149 | 0.030070 | 0.074537 | 0.092210 |
| 71 | 396.39 | 1173.0 | -0.14277 | -0.017372 | 0.027178 | 0.072623 | 0.089144 |
| 72 | 394.57 | 1167.8 | -0.14151 | -0.009168 | 0.033383 | 0.067475 | 0.077934 |
| 73 | 308.42 | 720.25 | -0.019235 | 0.072056 | 0.035687 | -0.006718 | -0.085150 |

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