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EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

Alternate Fuels Addendum
Phase II Final Report

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

A study was conducted to investigate the characteristics of current and advanced low-emissions combustors when operated with special test fuels simulating broader ranges of combustion properties of petroleum or coal-derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures - "zylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. Three CF6-50 engine size combustor types were evaluated; the standard production combustor, a Radial/Axial Staged Combustor, and a Double Annular Combustor. Performance and pollutant emissions characteristics at idle and simulated takeoff conditions were evaluated in a full annular combustor rig. Altitude relight characteristics were evaluated in a 60° sector combustor rig. Carboning and flashback characteristics at simulated takeoff conditions were evaluated in a 12° sector combustor rig. For the five fuels tested, effects were generally quite moderate, but well defined. CO, HC, NO_x and smoke emissions levels and peak liner metal temperatures increased with decreasing hydrogen content of the fuel which ranged from 12.2 to 13.7 percent by weight. CO, HC and smoke emissions levels also increased with final boiling point of the fuel which ranged from 529 to 607° K. Effects on other characteristics were quite small.

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SECTION 1.0

SUMMARY

The Alternate Fuels Addendum to the Phase II Experimental Clean Combustor Program was conducted to investigate the performance, durability, and pollutant emissions characteristics of current and advanced low-emissions combustors when operated with special test fuels that simulate broader ranges of combustion properties of petroleum or coal derived fuels. Five fuels were evaluated; conventional JP-5, conventional No. 2 Diesel, two different blends of Jet A and commercial aromatic mixtures - "xylene bottoms" and "naphthalene charge stock", and a fuel derived from shale oil crude which was refined to Jet A specifications. The evaluations were conducted concurrent with the Phase II Program in CF6-50 engine size combustor test rigs. The standard production CF6-50 combustor, a Radial/Axial Stages Combustor, and two Double Annular Combustor Configurations were evaluated for pollutant emissions, performance, altitude relight, and carboning/flashback characteristics.

Fuel effects were generally quite moderate but well defined and in the directions anticipated. Decreased hydrogen content (increased aromatic content) caused increases in CO, HC, NO_x, smoke emissions levels and peak liner metal temperatures. Increased final boiling point (reduced volatility) caused further increases in CO, HC and smoke emissions levels. The shale Jet A fuel had properties very similar to that of the JP-5 fuel except that it had a high nitrogen content which increased the NO_x emissions levels.

SECTION 2.0

INTRODUCTION

In order to cope with diminishing domestic petroleum resources and to avoid excessive dependence on foreign supplies, it is essential and inevitable that substitute fuels be developed, based on petroleum, shale oil, coal, or other domestically available resources. Aviation turbine fuels represent a significant fraction of total petroleum consumption and it is likely that in the future such fuels will be produced increasingly from nonpetroleum sources. The future availability of aviation turbine fuels could be increased if fuel specifications, such as aromatic content and final boiling point, were relaxed. However, this might result in penalties to engine performance, exhaust emissions characteristics and durability, thus, requiring changes in component designs or materials.

While large-scale production of aviation turbine fuels from shale or coal may be as much as 10 years away, the magnitude of the modifications required to aircraft turbine engine components and materials might be such that a similar time is required to implement the technology into commercial aircraft. Therefore, in 1974, NASA initiated a series of programs to define problems and evolve solutions to permit the use of synthetic fuels as they become available and to guide the industry in establishing practical fuels specifications. One of these programs was an addendum to the NASA/General Electric-Phase II Experimental Clean Combustor Program, which is the subject of this report.

The overall purpose of the multiphase Experimental Clean Combustor Program is to develop and demonstrate technology for the design of advanced combustors with significantly lower pollutant exhaust emissions levels than those of current technology combustors, for use in advanced CTOL commercial aircraft engines. The NASA/General Electric program is specifically directed towards providing advanced combustors for use in the General Electric CF6-50 engine. The Phase I Program was specifically directed towards screening and evaluating a large number and variety of combustor design approaches for obtaining low CO, HC, NO_x and smoke emissions levels. Descriptions and results of these investigations are presented in Reference 1. The Phase II Program was specifically directed towards further developing the two most promising combustor design approaches from the Phase I Program to define and provide a combustor design for engine demonstration testing in the Phase III Program. Descriptions and results of these investigations are presented in Reference 2.

The Alternate Fuels Addendum to the Phase II Program was specifically designed to investigate the performance, durability, and exhaust emissions characteristics of advanced low-emissions combustors when operated with special test fuels that simulate the broadened range of combustion properties of synthetic or petroleum fuels with relaxed specifications. The special test fuels were selected to investigate the possible effect of relaxing the current Jet A fuel specification to permit:

a) an increase in the final boiling point, and/or;

b) an increase in the aromatic concentration (reduction in hydrogen concentration).

The effort was conducted concurrent with the basic Phase II Program and included both performance and exhaust emissions tests of the current production CF6-50 combustor and two low-emissions combustor design approaches (Double Annular Combustor and Radial/Axial Staged Combustor).

SECTION 3.0

TEST FUELS

Five test fuels were utilized in these evaluations:

1. MIL-T-5624 Grade JP-5 Fuel (which meets the ASTM Jet A fuel specification) was used in these and all other Phase II Program evaluations.

2. ASTM Grade No. 2-D Diesel Fuel was used in these evaluations to investigate the effects of increased final boiling point and increased aromatic content.

3. Special Blend A Fuel (a blend of conventional Jet A fuel and mixed xylene compounds) was used to investigate the effect of increased aromatic content. "Xylene bottoms" is a commercial, polycyclic aromatic obtained from the Ashland Oil Company.

4. Special Blend B Fuel (a blend of conventional Jet A fuel and "naphthalene charge stock") was used to investigate the effect of increased aromatic content. Naphthalene charge stock is a commercial high boiling point aromatic mixture obtained from the Ashland Oil Company.

5. Shale Jet A Fuel. A fuel actually derived from shale oil crude and refined to Jet A fuel specifications was obtained for limited evaluations from the pilot project described in Reference 3.

The physical and chemical properties of these fuels are sumarized in Table 1. The properties most influential on combustion characteristics are:

1. Hydrogen content which ranges from 12.2 to 13.7 percent by weight and varies inversely with aromatic content.

2. Final boiling point which ranges from 529 to 607° K.

3. Nitrogen content, which ranges from nearly zero for conventional aviation fuels to 813 ppm by weight for the shale Jet A fuel. Generally, a large fraction of fuel bound nitrogen is converted to NO_x in a combustion process. If fully converted, 813 ppm of fuel bound nitrogen would produce a NO_x emission index of 2.67 g/kg fuel.

Table I. Test Fuel Properties.

Fuel Type	JP-5 (Jet A)	No. 2 Diesel	Blend A (Xylene Bottoms)	Blend B (Naphthalene Charge Stock)	Shale Jet A
Specific Gravity @ 289° K	0.8080	0.8520	0.8307	0.8498	0.8057
Viscosity @ 311° K, centistokes	1.56	2.60	1.04	1.41	1.56
Flash Point, °K	330	345	315	314	329
Smoke Point, millimeters	25.5	14.7	14.5	13.0	22.5
Freeze Point, °K	226	-	218	257	-
Pour Point, °K	-	246	-	-	-
Distillation					
Initial Boiling Point, °K	453	463	430	417	444
10% °K	470	492	437	459	466
20% °K	476	505	441	472	474
30% °K	479	517	-	479	480
50% °K	488	534	478	489	492
70% °K	496	554	-	498	508
90% °K	514	580	505	511	521
End Point °K	533	607	529	536	562
% @ 478°K	24.0	3.5	70.0	28.5	25.5
% Residue	0.6	0.9	0.7	0.6	1.0
% Loss	0.6	0.4	0.6	0.4	1.0
Net Heating Value, cal/g	10,349	10,144	10,139	10,117	10,345
Aromatics, vol %	14.9	34.0	38.4	35.9	17.3
Olefins, vol %	1.5	1.9	2.0	1.6	0.6
Napthalenes, vol %	<3.0	17.8	0.7	21.9	<3.0
Hydrogen, wt %	13.71	12.68	12.28	12.24	13.56
Sulfur, wt %	0.07	0.46	0.06	0.05	0.03
Nitrogen, wt ppm	-	88	4	8	813

SECTION 4.0

PROGRAM PLAN

In the fuels evaluations, three types of combustion tests were conducted:

1. Detailed exhaust emissions and performance evaluations for full-annular combustor configurations.
2. Altitude relight evaluations of 60° sector combustor configurations.
3. Carboning and flashback evaluations of 12° sector configurations.

Four combustor configurations were evaluated:

1. Standard production CF6-50 combustor.
2. Radial/Axial Staged Combustor Configuration R7.
3. Double Annular Combustor Configuration D7.
4. Double Annular Combustor Configuration D12/13.

A listing of combustor tests, configurations, and fuels used is contained in Table II.

This series of tests was conducted with the same apparatus and procedures utilized in the basic Phase II Program and are briefly described in the following sections. Detailed descriptions are presented in Reference 1 and 2.

Table II. Fuel Test Matrix.

Combustor Configuration	Type of Test Conducted (Rig Used)		
	Exhaust Emissions and Performance (Full Annular Rig)	Altitude Relight (60° Sector Rig)	Carboning and Flashback (12° Sector Rig)
Standard Production CF6-50 Combustor	JP-5 (Jet A) No. 2 Diesel Blend A Blend B Shale Jet A	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	Not Tested
Radial/Axial Staged Combustor Configuration R7	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) Blend B
Double Annular Combustor Configuration D7	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) Blend B
Double Annular Combustor Configurations D12A/13	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) No. 2 Diesel Blend A Blend B	JP-5 (Jet A) Blend B

SECTION 5.0

APPARATUS AND PROCEDURES

5.1 TEST FACILITIES

The exhaust emissions and performance tests were conducted in a full annular combustor test rig which exactly duplicates the aerodynamic flowpath and envelope dimensions of the CF6-50 engine. The rig was installed in a test cell equipped with an indirect-fired air heater and exhaust ducting systems for high pressure operation. Engine idle operating conditions were exactly duplicated, but for CF6-50 engine takeoff simulation, combustor inlet pressures were limited to about 10 atm. Included as part of this rig was an exit plane rotating rake assembly for obtaining outlet temperatures and pressures and for extracting gas samples. A cross-sectional drawing of the rig with a standard CF6-50 combustor installed is shown in Figure 1. A photograph of the exit rake traverse assembly is shown in Figure 2. The gas sampling rake locations and manifolding are shown in Figure 3. Fifteen of the probe elements were manifolded together for gaseous analyses. Ten probes were manifolded together for smoke analyses. Gas samples were obtained with the on-line system shown in Figure 4 and smoke samples were obtained with a standard filter paper method. Further details of the pollutant emissions measurement systems are presented in Reference 1.

The altitude relight tests were conducted in a 60° sector combustor test rig which also exactly duplicates the aerodynamic flowpath and envelope dimensions of the CF6-50 engine. This rig was installed in a test cell equipped with exhaust ducting systems and capabilities for simulating high altitude engine windmilling conditions. All of these tests were conducted with ambient inlet air and fuel temperature. A cross-sectional diagram and photograph of this rig is shown in Figure 5.

The carboning and flashback tests were conducted in 12° sector rigs installed in a test cell equipped with an indirect-fired air heater and exhaust ducting systems for high pressure operation. Engine takeoff conditions were simulated with combustor inlet pressures up to 18 atmospheres. Carboning tests evaluating the sectors of either the pilot or main stages of the Double Annular Combustor on the pilot stage of the Radial/Axial Staged Combustor were conducted with the on-cup sector rig shown in Figure 6. Flashback tests for the Radial/Axial Staged Combustor were conducted with a 12° sector rig shown in Figure 7.

5.2 TEST COMBUSTORS

The first series of tests were conducted with a standard production CF6-50 combustor (Model G16, S/N 000395) for which extensive emissions and performance with JP-5 fuel had been determined in a previous program. A

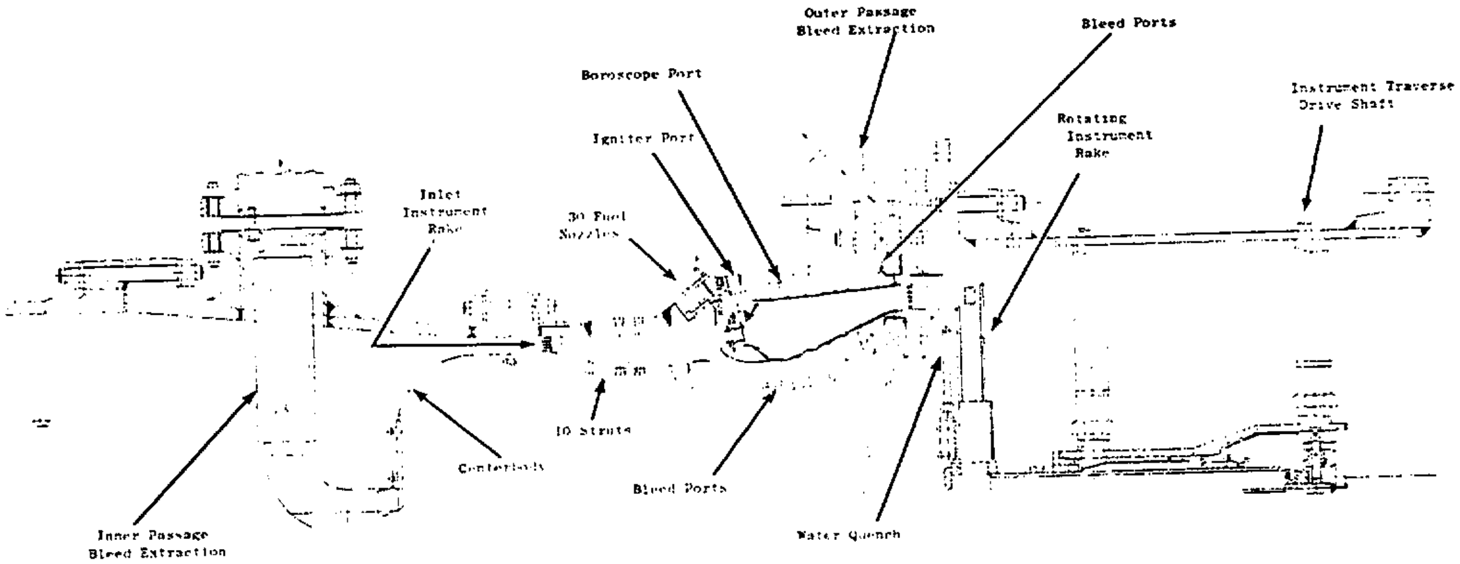


Figure 1. Full-Annular CF6-50 Combustor Test Rig, Axial Cross Section View.

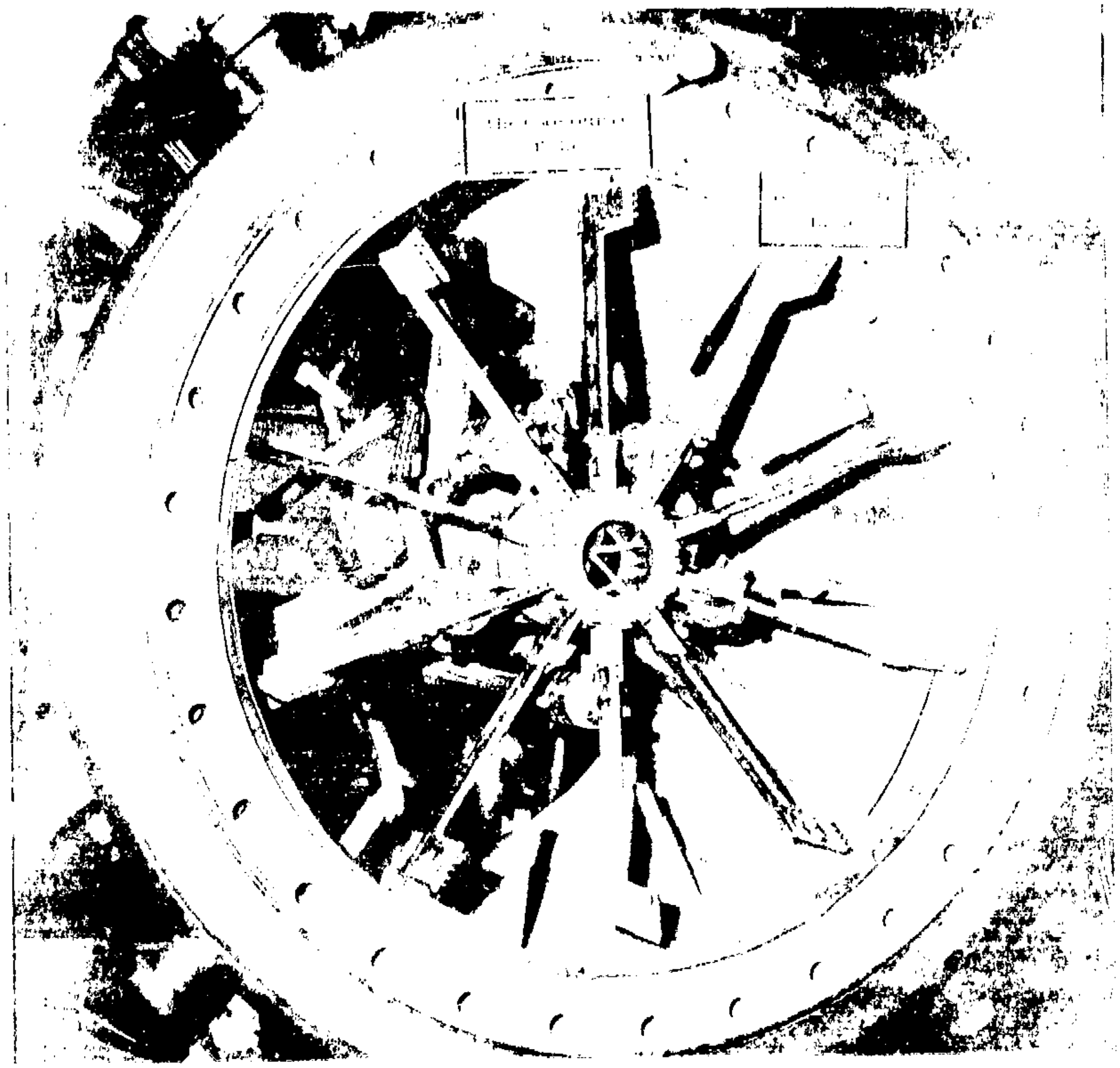
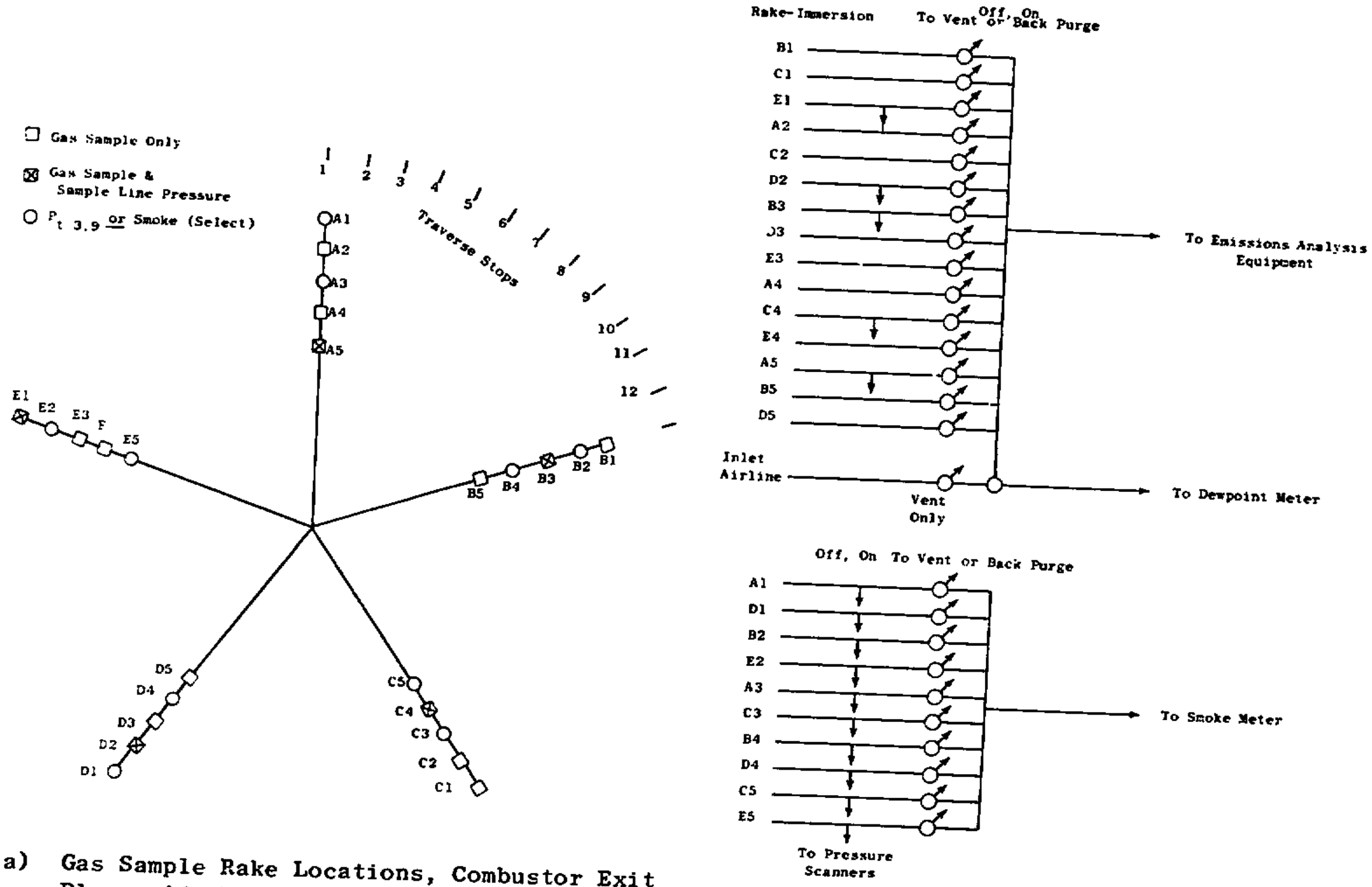


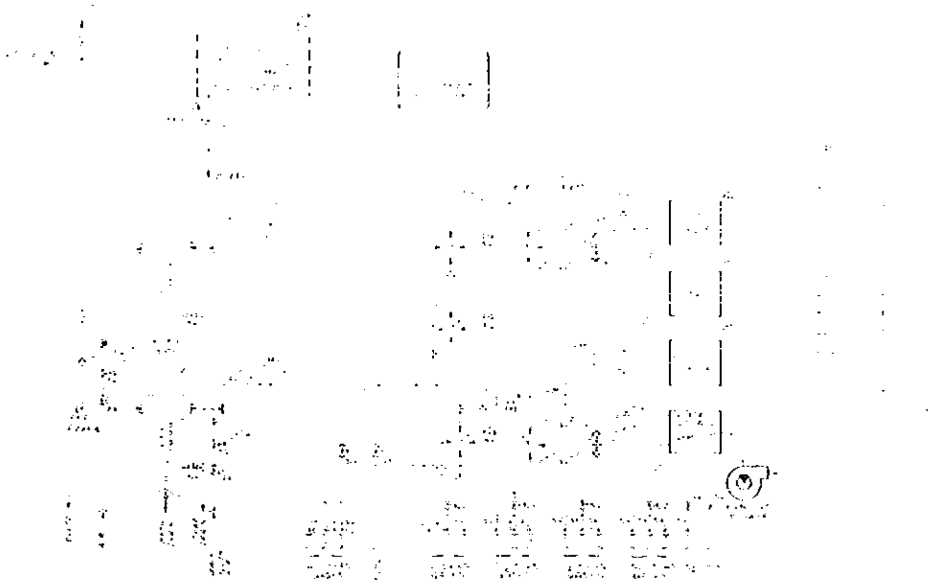
Figure 2. CF6-50 Combustor Exit Rake Traverse Assembly.



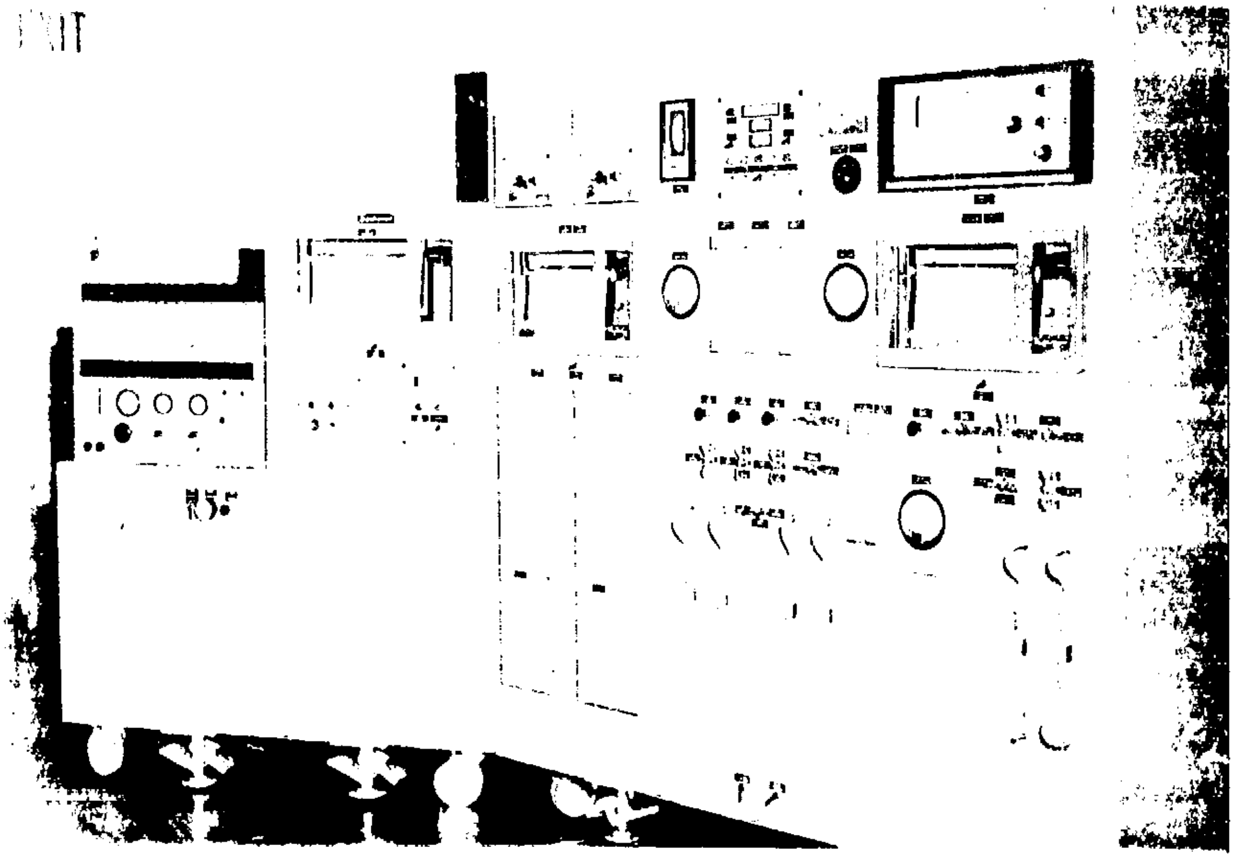
(a) Gas Sample Rake Locations, Combustor Exit Plane, Aft Looking Forward.

(b) Gas Sample Line Manifolding Diagram.

Figure 3. Gas Sample Location and Manifolding Diagrams.



(a) Flow Diagram



(b) Instrument Console

Figure 4. General Electric Emissions Measurement System.

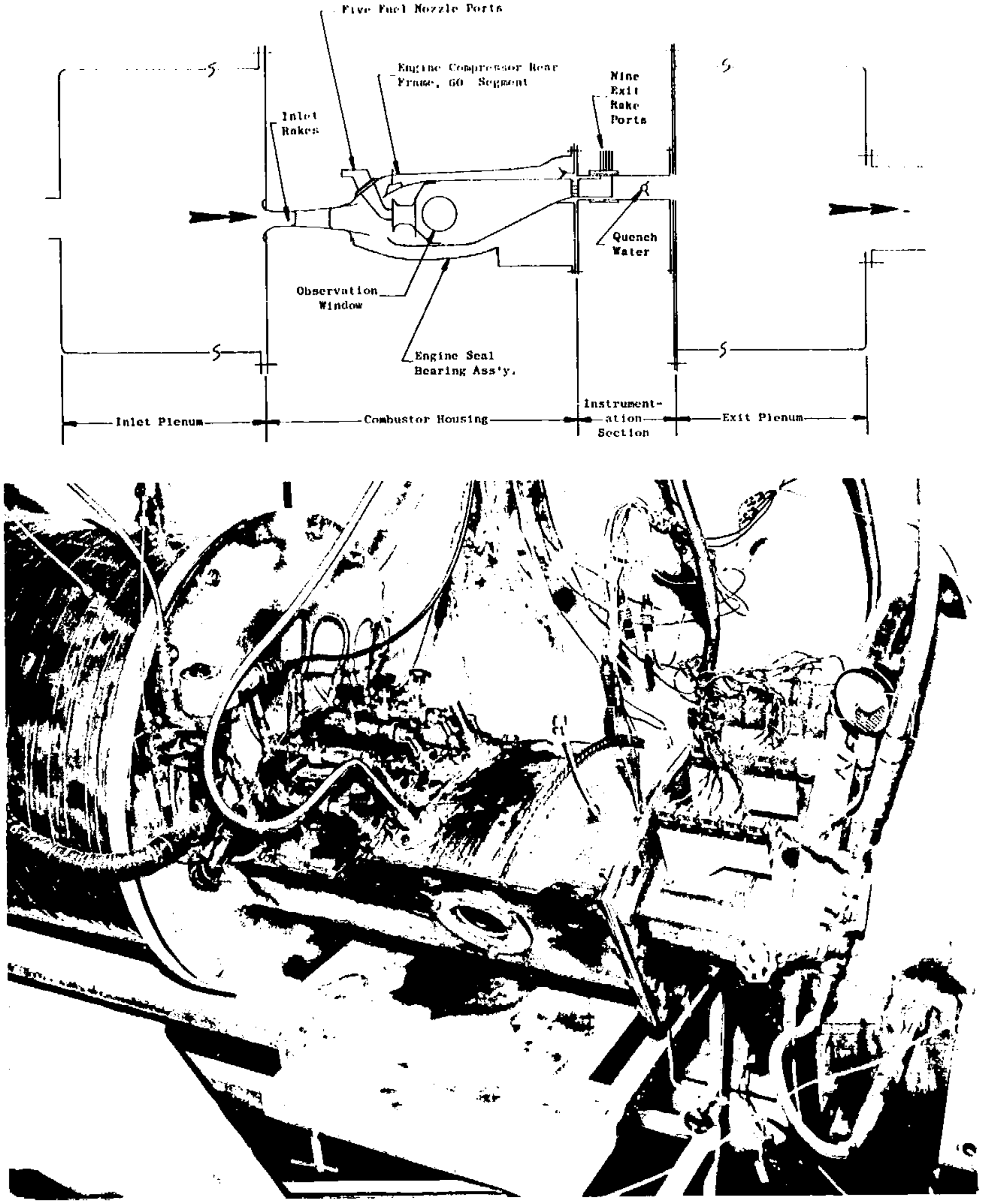
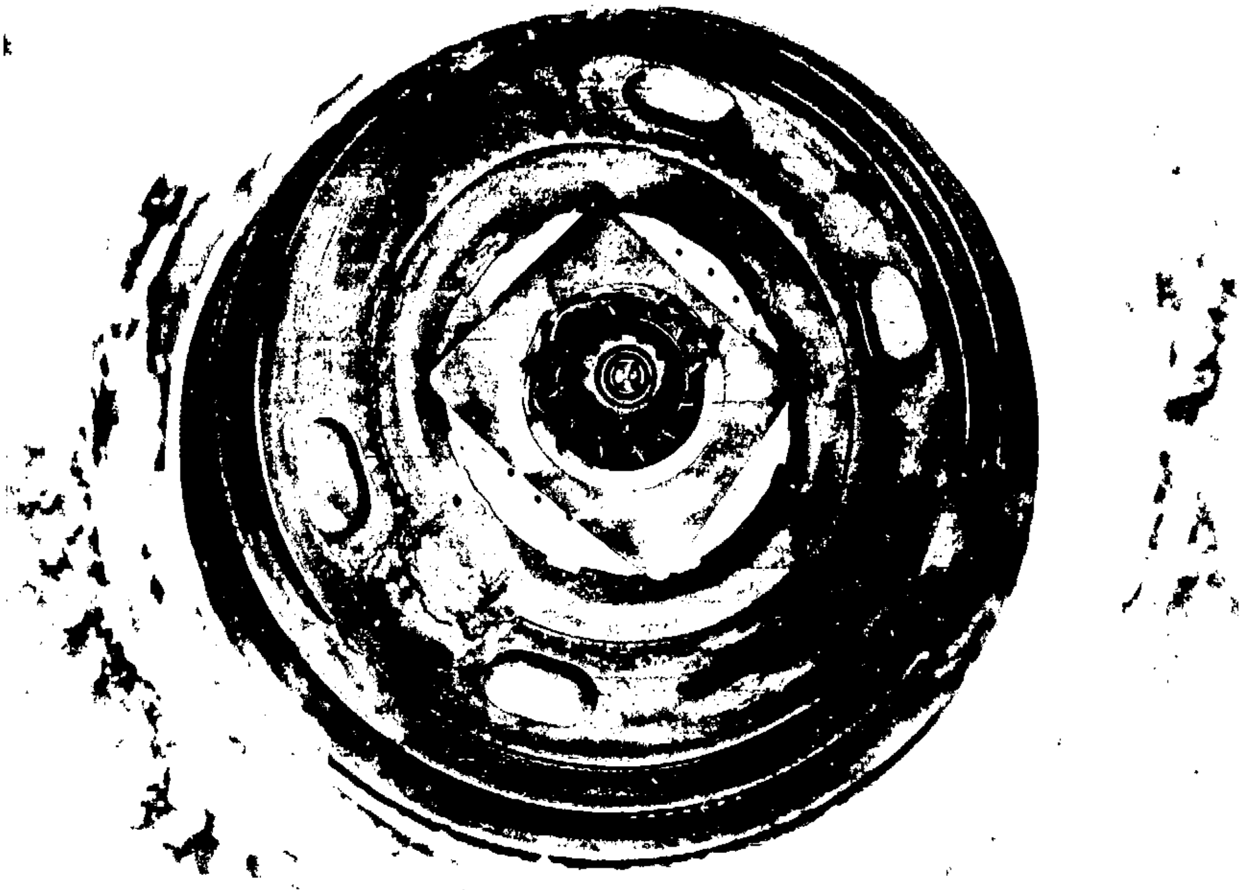


Figure 5. CF6-50 60° Sector Combustor Test Rig.

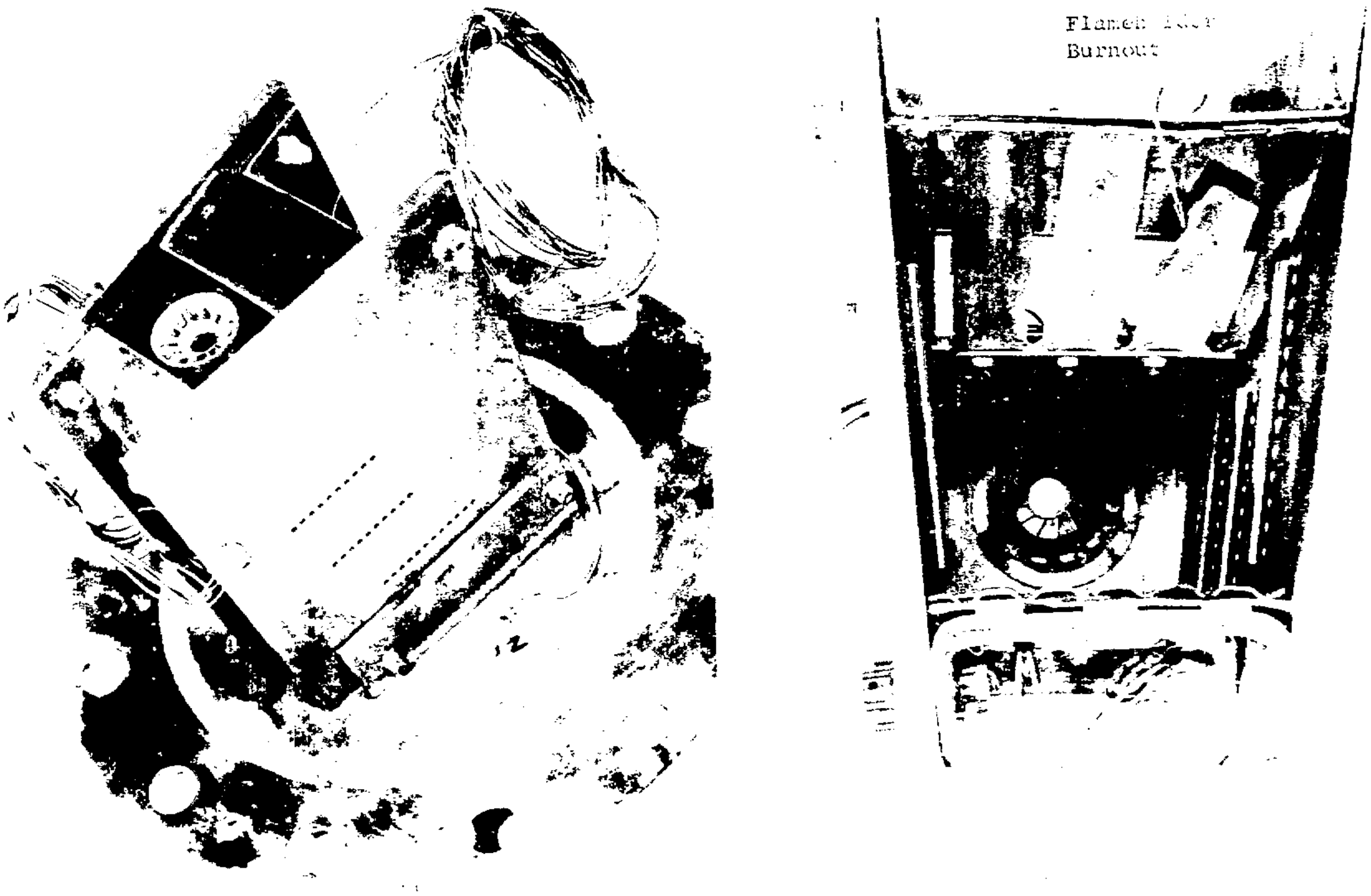
(a) Forward Looking Aft

Figure 6. 12" Sector Carboning Test Combustor.



(b) Aft Looking Forward

Figure 6. 12° Sector Carboning Test Combustor (Concluded).



(a) Forward Looking Aft

(b) Aft Looking Forward

Figure 7. 12° Sector Flashback Test Combustor.

photograph of the combustor assembly is shown in Figure 8. This combustor was designed for excellent performance and low smoke emissions characteristics, but not for low gaseous pollutant emissions characteristics. The combustor has 30 air swirlers and fuel nozzles. The odd numbered swirlers are equipped with dual-orifice fuel nozzles which are always fueled. The even numbered swirlers (except No. 14 which is midway between ignitors) are equipped with single-orifice fuel nozzles which are only fueled above idle power level and are matched so that all fuel nozzles flow the same at takeoff power level. Swirler No. 14 is always fueled with a special dual-orifice fuel nozzle. In the test rigs, the fuel nozzles were connected to two independently metered and controlled fuel supply systems, so that the engine characteristics could be duplicated. Further details of the standard production CF6-50 combustor are presented in Reference 1.

The second series of tests were conducted with the final Phase II Program modifications to the Radial/Axial Staged Combustor which was designated Configuration R7. A photograph of the combustor assembly is shown in Figure 9. Configuration details are shown in Figure 10. The low emissions Radial/Axial Staged Combustor design approach features a pilot stage sized specifically for idle power operation with all of the fuel supplied to it, thereby reducing CO and HC emissions levels. At the higher engine power operating conditions, the second or main stage is also fueled. This latter stage, which handles a high percentage of the airflow, is displaced both axially and radially from the pilot stage. The main stage fuel is premixed, to some degree, with its airflow. The fuel-air mixtures are lean and relatively uniform resulting in reduced NO_x emissions levels. The burning of these lean mixtures is stabilized by the pilot stage of the combustor.

The third and fourth series of tests were conducted with the Double Annular Combustor which were designated Configurations D7, D12A, and D13. A photograph of the combustor assembly is shown in Figure 11. Configuration details are shown in Figure 12. The low emissions Double Annular Combustor design concept also features the use of a pilot stage designed specifically for idle power operation with all of the fuel supplied to it. A high percentage of the combustion airflow is supplied to the main stage. However, in this design approach, the main stage is more conventional in that it is self piloting and utilizes direct fuel injection. Configuration D7 represents an interim modification to this combustor in the Phase II Program; afterwhich the Double Annular Combustor design approach was selected for Phase III Program engine demonstration. Configuration D12A closely simulates the engine combustor design including the use of prototype fuel injectors and air swirlers in the pilot stage. Configuration D13 combined D12A pilot stage features with a main stage dilution air scheme modified to provide a further reduction in high power NO_x emissions levels.

5.3 TEST CONDITIONS AND PROCEDURES

The test conditions employed in each type of test are shown in Table III.

Full annular rig tests were designed to measure the effects of fuel type on pollutant emissions, combustion efficiency, pressure loss, outlet

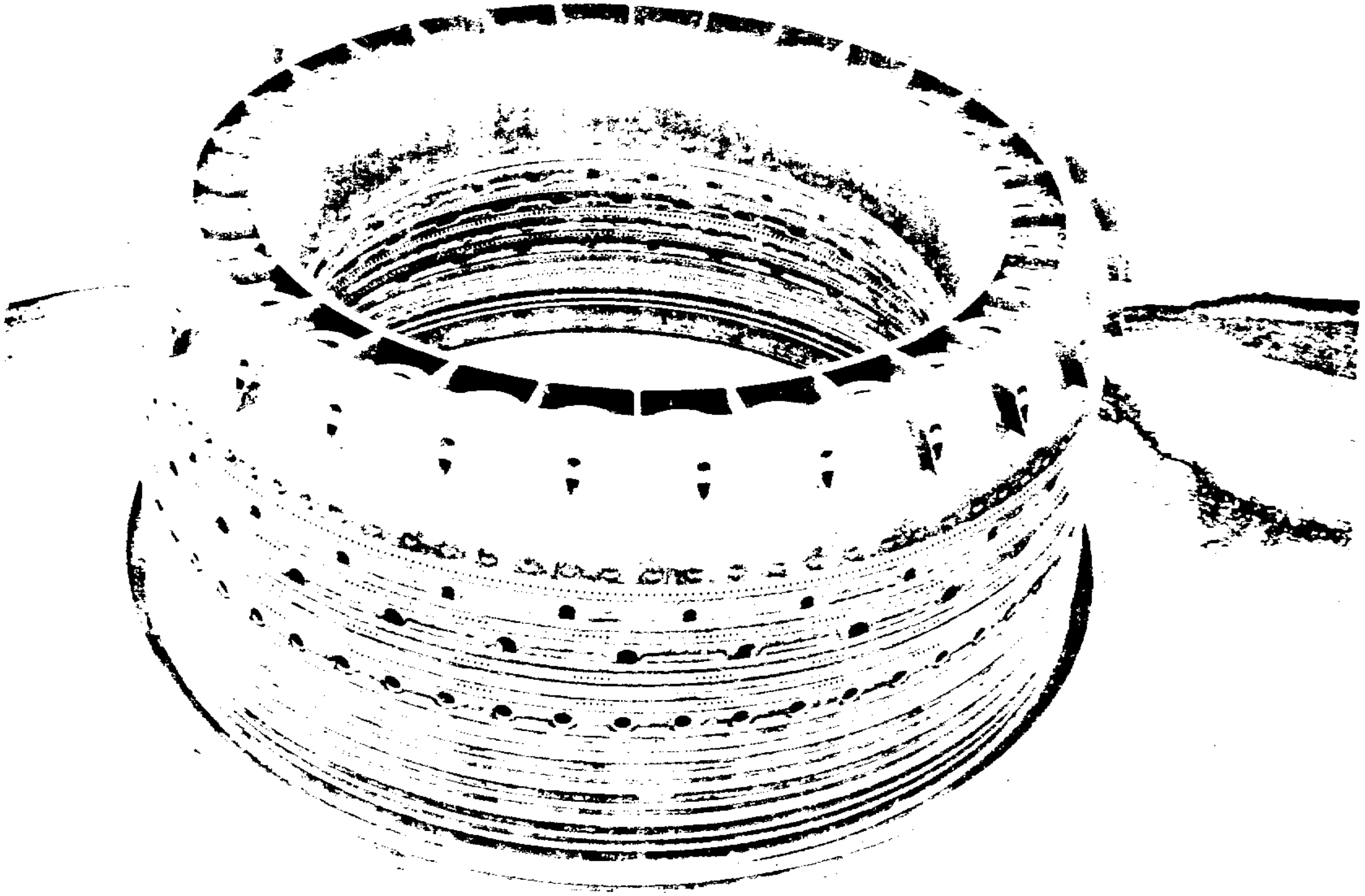


Figure 8. Standard Production CF6-50 Combustor Assembly.

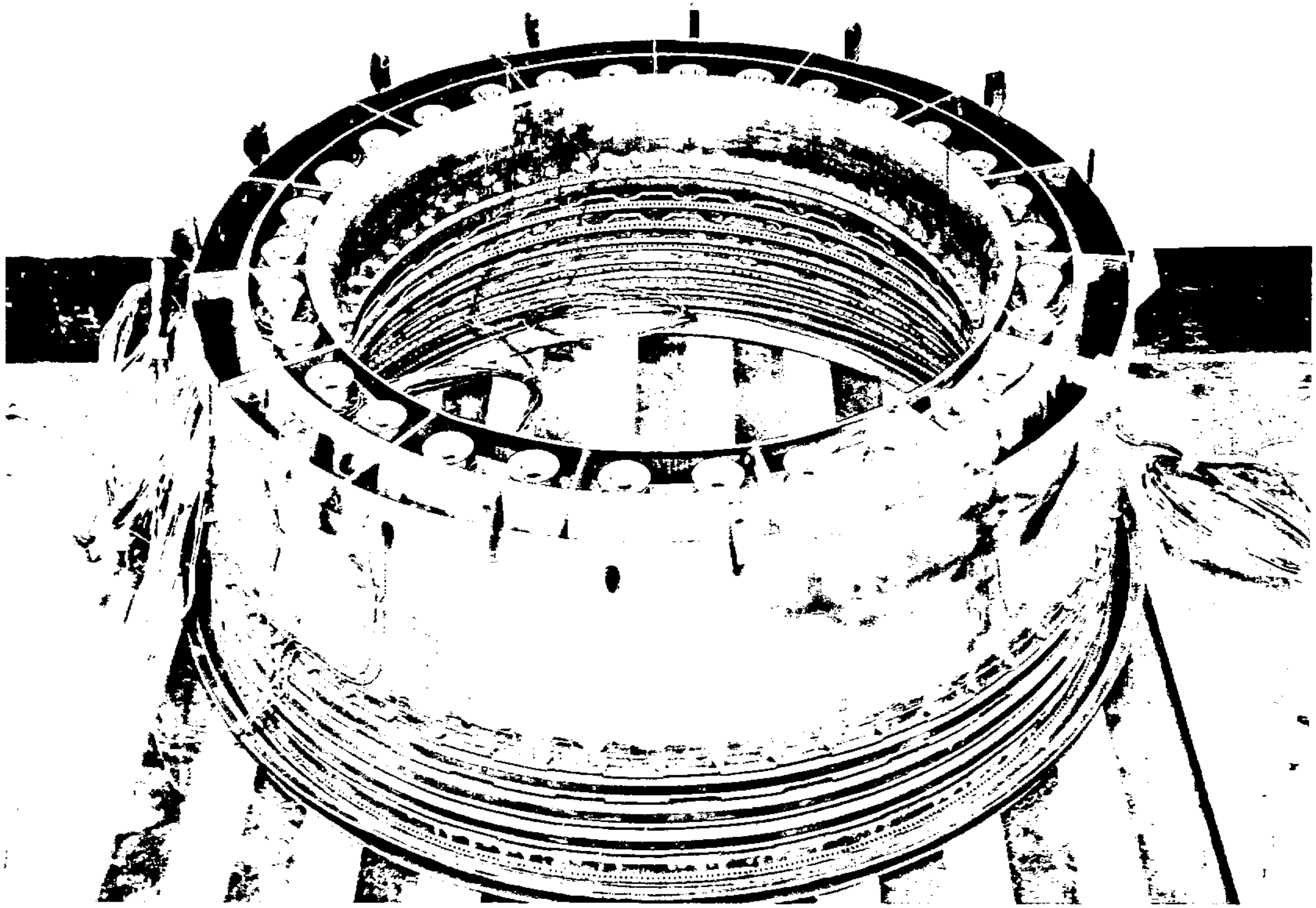
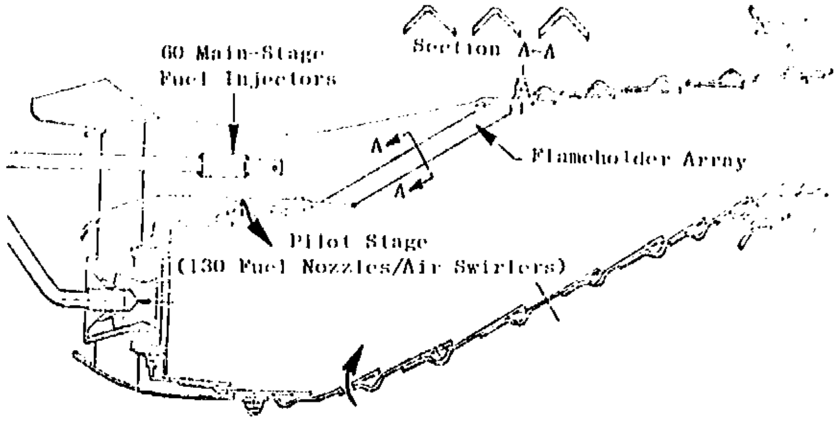


Figure 9. Radial/Axial Staged Combustor Assembly.



Rig	Full Annular	60° Sector	12° Sector*
Airflow Distribution, % W_c			
Pilot Stage Swirlers			
Fuel Nozzle Shroud	0.1	0.1	0.9
Primary Swirler	4.1	4.1	3.3
Secondary Swirler	11.5	11.5	8.2
TOTAL	15.7	15.7	12.4
Main Stage Flameholders			
TOTAL	47.2	47.2	48.5
Dilution			
Pilot Stage	5.5	0	4.3
Inner Liner	0	5.5	0
TOTAL	5.5	5.5	4.3
Cooling			
Pilot Stage	11.4	11.4	6.6
Flameholders	1.7	1.7	1.1
Outer Liner	7.2	7.2	-
Inner Liner	9.6	9.6	9.8
Seal Leakage	1.7	1.7	1.3
TOTAL	31.6	31.6	18.8
Premixing Length, cm	6.4	-	6.4
Number of Flameholders	120	20	4

* Not including Side Wall Cooling

Figure 10. Radial/Axial Staged Combustor Configuration Details.

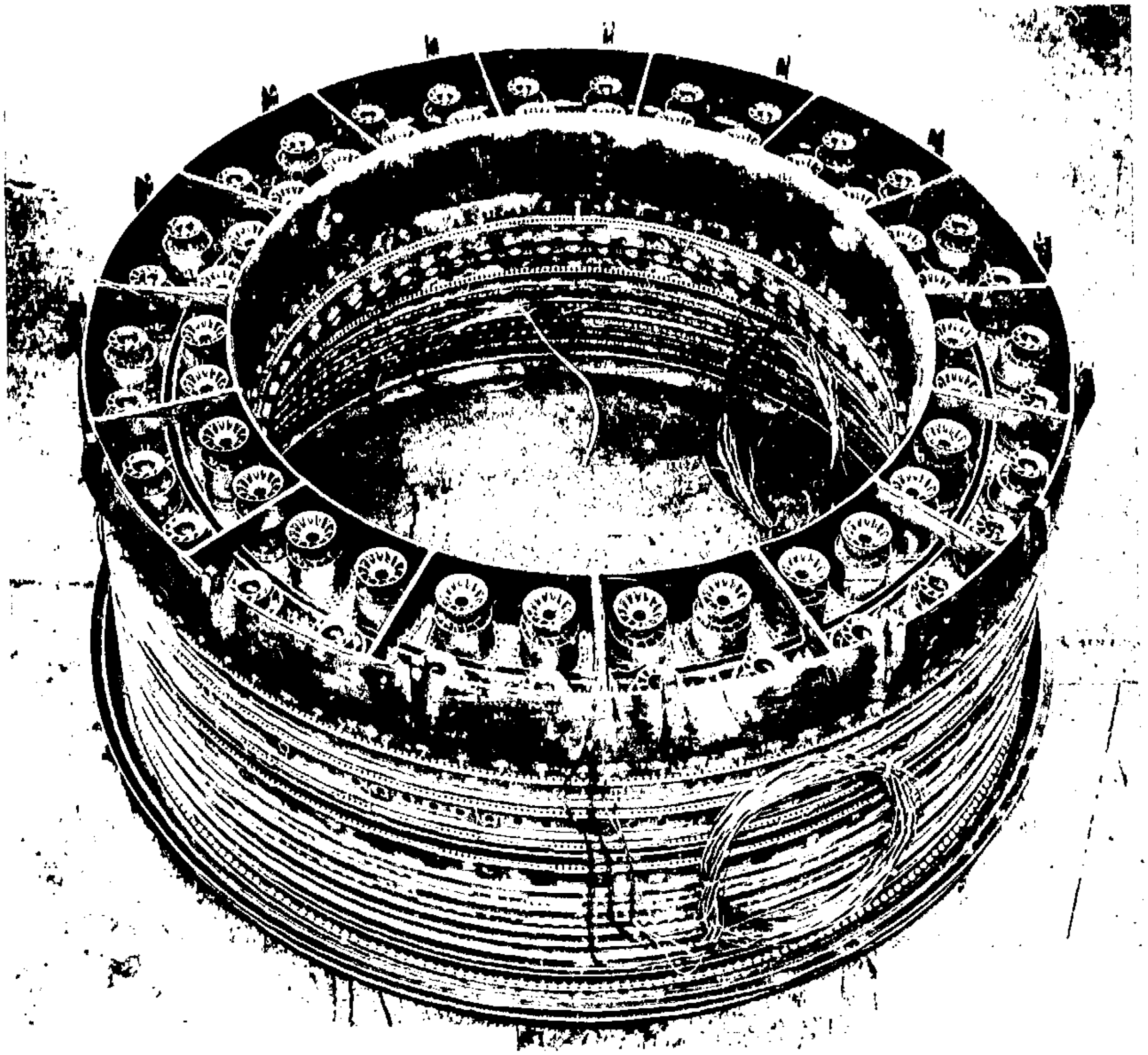
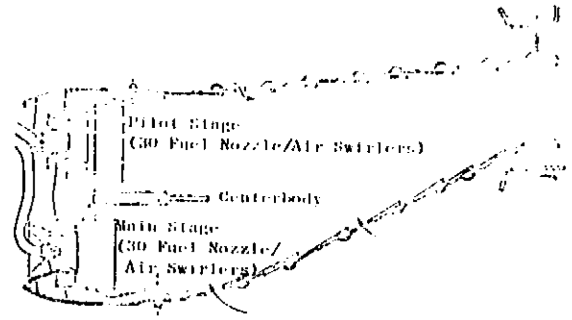


Figure 11. Double Annular Combustor Assembly.



	Rig	Full Annular			60° Sector		12° Sector	
	Configuration	D7	D12A	D13	D7	D12	D7	D12
Air Flow Distribution, % of W_c	Outer Swirl Cups							
	Fuel Nozzle Shroud	0.1	0.9	0.1	0.9	0.9	0.9	0.9
	Primary Swirler	3.6	5.2	5.1	3.6	5.2	4.4	5.2
	Secondary Swirler	8.8	7.4	7.3	8.9	7.4	8.2	7.4
	Total	12.5	13.4	12.5	13.3	13.4	13.5	13.4
	Inner Swirl Cups							
	Fuel Nozzle Shroud	0.1	0.1	0.1	0.1	0.1	--	--
	Primary Swirler	3.6	3.5	3.5	3.6	3.5	--	--
	Secondary Swirler	29.8	29.5	29.3	29.8	29.5	--	--
	Total	33.5	33.1	32.9	33.5	33.1	--	--
	Dilution							
	Outer Liner, Panel 1	4.7	0	0	0	0	--	--
	Outer Liner, Panel 2	0	4.7	4.6	0	4.7	--	--
	Inner Dome	4.9	0	0	4.9	0	--	--
	Inner Liner, Panel 1	10.9	10.8	17.0	10.9	10.8	--	--
	Inner Liner, Panel 2	0	0	0	0	0	--	--
	Inner Liner, Panel 4	0	4.9	0	4.0	4.9	--	--
	Total	20.5	20.4	21.6	21.8	20.4	--	--
	Cooling							
	Outer Liner	8.1	8.0	8.0	8.1	8.0	--	--
	Outer Dome	4.5	4.5	4.4	4.5	4.5	--	--
	Centerbody	4.0	3.9	3.9	4.0	3.9	--	--
	Inner Dome	4.1	4.1	4.1	4.1	4.1	--	--
	Inner Liner	11.3	11.2	11.1	11.3	11.2	--	--
	Seal Leakage	1.5	1.5	1.5	1.5	1.5	--	--
	Total	33.5	33.2	33.0	33.4	33.2	--	--
Pilot Stage Features	Fuel Nozzle Type							
	Development	X		X				
	Prototype		X		X	X	X	X
	Swirler Type							
	Development	X						
	Prototype		X	X	X	X	X	X
	Crossfire Slot							
	No	X			X	X		
	Yes		X	X			-	-

Figure 12. Double Annular Combustor Configuration Details.

Table III. Test Conditions.

Test Type	Simulated Engine Operating Condition	Combustor Operating Conditions				Comments
		Inlet Total Pressure P_3, atm	Inlet Total Temperature T_3, K	Reference Velocity V_r, m/s	Fuel-Air Ratio f	
Emissions/Performance (Full Annular Rig)	Idle (engine P_3 = 2.92 atm)	2.92	429	18.3	0.0117	True Engine f
					0.014	Variation in f
					0.010	Variation in f
					0.006	Variation in f
	Takeoff (engine P_3 = 29.5 atm)	9.52	821	25.6	0.0231	True Engine f
					0.020	Variation in f
					0.017	Variation in f
					0.014	Variation in f
Altitude Relight (40° Sector Rig)	Altitude Windmilling	~0.3 to 1.0	ambient	~6 to 39	Lean * Blowout to ~0.05	
Carboning/Flashback (12° Sector Rig)	Takeoff	to 18.4	821	25.6	0.0231	

Consistent with CF6-50 engine windmilling map.
Fuel Flow rate nominally 240 kg/hr (engine minimum flow schedule).

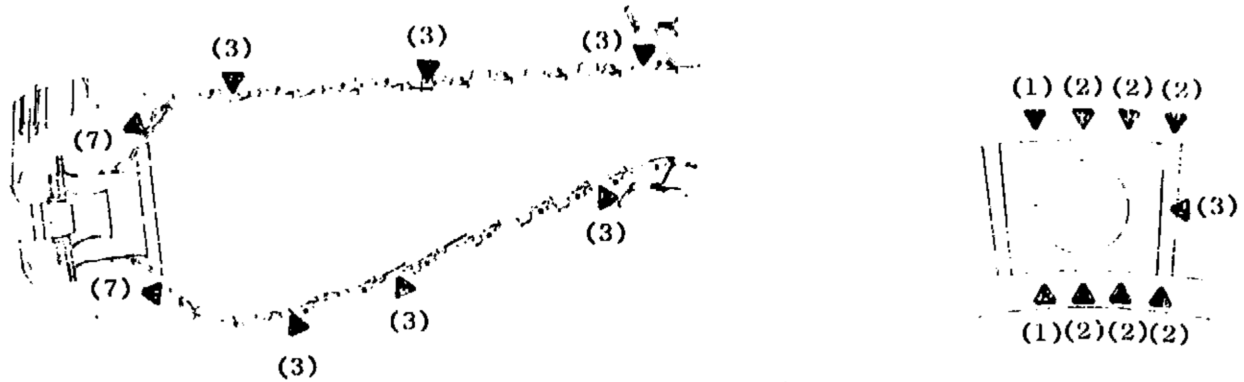
temperature distribution, and combustor metal temperatures. The combustors were instrumented with up to 35 metal thermocouples located as shown in Figure 13. These tests were conducted at simulated engine idle and takeoff conditions with variations in fuel-air ratio. A total of eight data points were obtained with each test fuel. The test fuels were stored in tanks adjacent to the test cell and connected so that fuel type could be changed during the tests without shutting down the combustor. The test sequence was as follows:

1. Lightoff the combustor with JP-5 fuel and set idle conditions.
2. Run the four JP-5 fuel idle test points.
3. Holding idle inlet conditions, change fuel type and run four fuel-air ratio test points.
4. Repeat step 3 for each of the special test fuels.
5. Change to JP-5 fuel and set takeoff conditions.
6. Run the four JP-5 fuel takeoff test points.
7. Holding takeoff inlet conditions, change fuel type and run four fuel-air ratio points.
8. Repeat step 7 for each of the special test fuels.
9. Change back to JP-5 fuel, run some check points at takeoff and idle, then shut down.

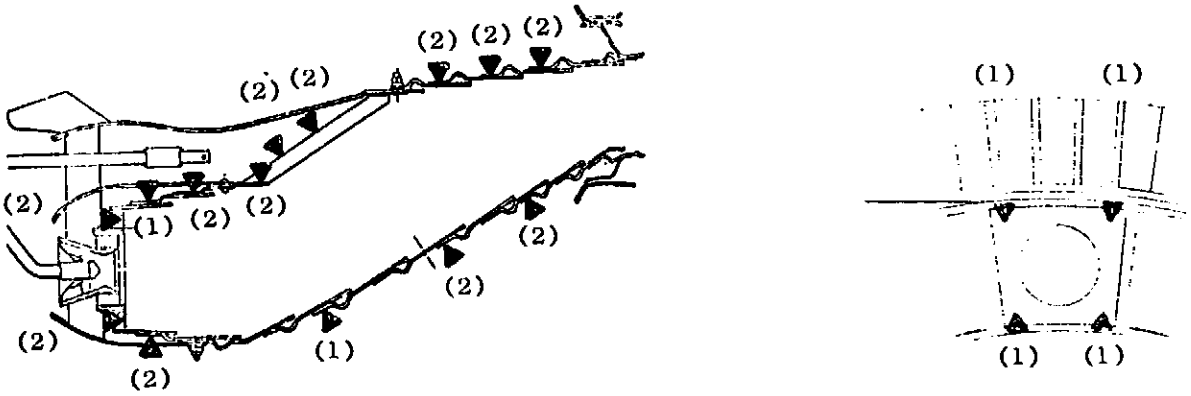
This sequence was selected to minimize the quantities of special test fuels required and also to provide back-to-back evaluations of fuel effects. In each fuel change, sufficient time was allowed to completely purge the previous fuel from the control and metering systems.

Altitude relight tests consisted of determining combustor ignition and blowout limits over a range of operating conditions selected from the CF6-50 engine altitude windmilling map with air and fuel flow rates scaled down for the 60° sector rig. Ignition attempts were usually made at a simulated engine minimum fuel flow rate of 249 kg/hr. When the ignition attempts were successful, pressure blowout and lean blowout limits were determined. The procedure was then repeated at progressively more severe conditions until the relight limits were mapped. Fuel type was then changed and the procedure repeated.

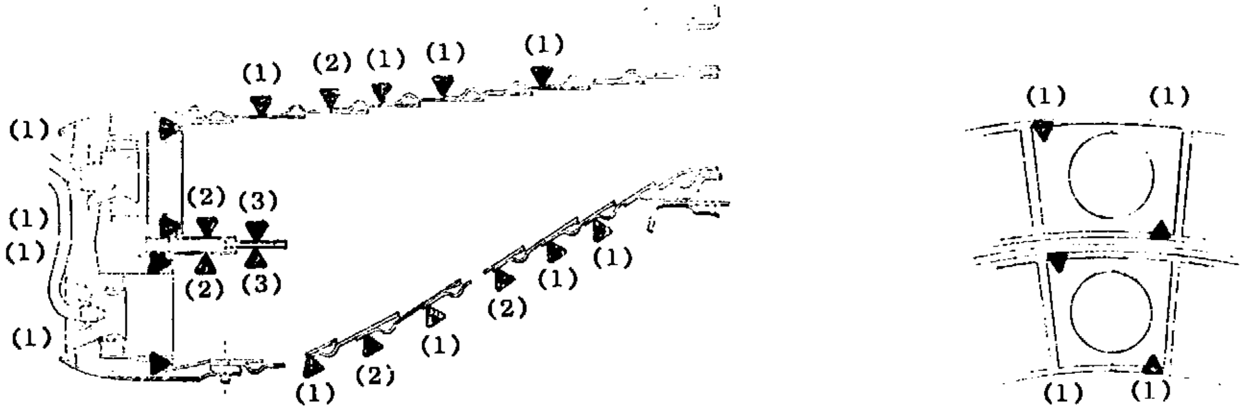
Carboning tests in the 12° sector rig were conducted after each configuration had undergone a standard test cycle and posttest inspection as part of the Phase II Program. The configurations were reinstalled, operated at simulated takeoff conditions for one hour with JP-5 fuel and an additional hour with the Blend B fuel, during which smoke emissions data were obtained.



Standard Production Combustor



Radial/Axial Staged Combustor



Double Annular Combustor

Figure 13. Combustor Metal Temperature Instrumentation Locations.

Flashback tests of the Radial/Axial Staged Combustor in the 12° sector rig were designed to determine where and if upstream burning in the main stage premixing passage occurs. The sector was instrumented to measure pressure loss, flameholder metal temperatures and gas temperatures in the premixing passage. Progressively more severe operating conditions were set until either the facility limits were reached or upstream burning occurred. Flashback testing was conducted with both JP-5 and Blend B fuel.

SECTION 6.0

RESULTS AND DISCUSSION

Detailed results for each test are tabulated in Appendix A. Key results are summarized in Table IV.

Effects of fuel type on exhaust emissions and combustor peak metal temperature levels for each combustor configuration are illustrated in Figures 14 through 21. The effects of fuel hydrogen content (W_H) and final boiling point (T_B) were assessed by curve-fitting these results with a fuel property correction factor of the form:

$$K_F = \left[\left(\frac{W_{H,i}}{W_{H,JP-5}}\right)^{a} \left(\frac{T_{B,i}}{T_{B,JP-5}}\right)^{b}\right]$$

Results of this analysis are summarized in Table V and illustrated in Figures 22 through 28.

6.1 CO AND HC EMISSIONS

CO and HC emissions levels at idle operating conditions were highly configuration and fuel-air ratio dependent as illustrated in Figures 14, 16, 18, and 20. The standard production combustor produced the highest emissions levels and the Double Annular Combustor produced the lowest emissions levels. The trends with fuel type were, however, the same for all four configurations. The emissions levels were highest with No. 2 Diesel fuel, intermediate with the blends, and lowest with normal JP-5 fuel. The shale Jet A fuel was hardly discernable from normal JP-5 fuel with respect to HC emissions levels, but the CO emissions levels were slightly higher. These results indicate that idle CO and HC emissions levels are influenced by both fuel hydrogen content (W_H) and fuel volitility as indicated by final boiling point (T_B). As indicated in Figure 22, the CO emissions levels correlate quite well when corrected by the factor:

$$K_{CO} = \left[\left(\frac{W_{H,i}}{W_{H,JP-5}}\right)^{0.7} \left(\frac{T_{B,i}}{T_{B,JP-5}}\right)^{-1.0}\right]$$

As indicated in Figure 23, the HC emissions levels correlate quite well when corrected by the factor:

$$K_{HC} = \left[\left(\frac{W_{H,i}}{W_{H,JP-5}}\right)^{1.8} \left(\frac{T_{B,i}}{T_{B,JP-5}}\right)^{-1.0}\right]$$

Table IV. Summary of Key Test Results.

[illegible]

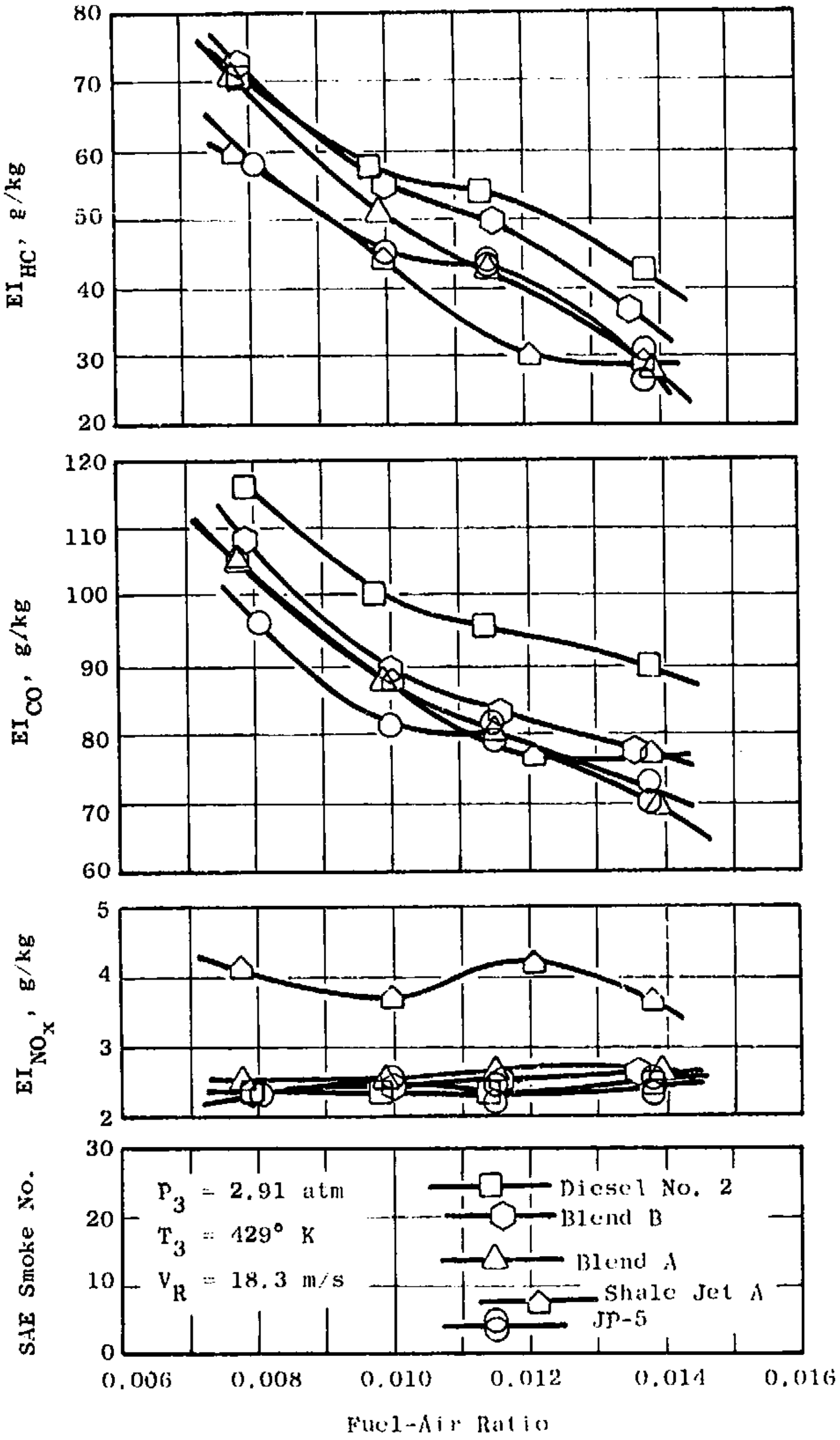


Figure 14. Effect of Fuel Type on Standard CF6-50 Combustor Emissions at Idle Conditions.

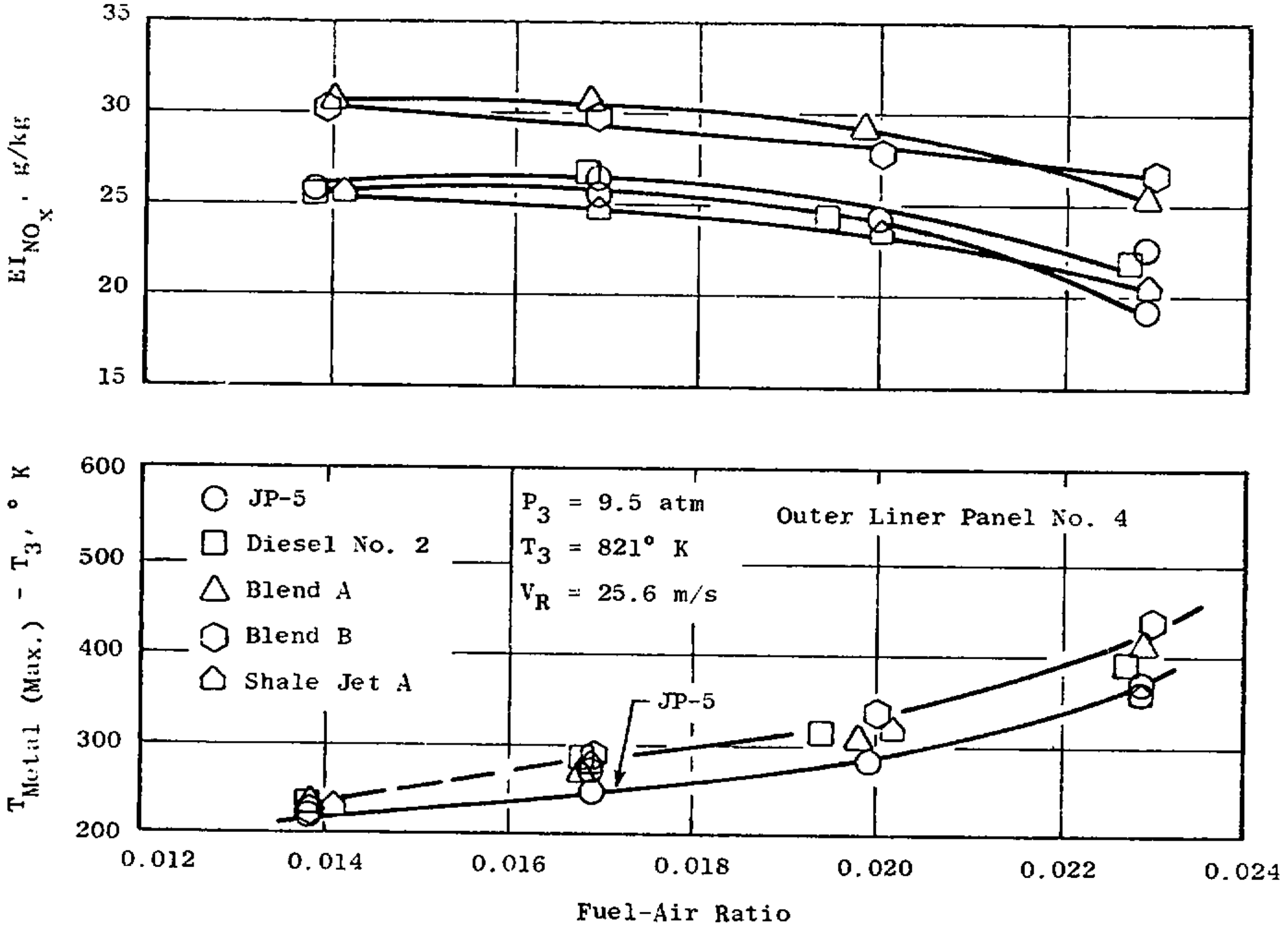


Figure 15. Effect of Fuel Type on Standard CF6-50 Combustor Performance at Simulated Takeoff Conditions.

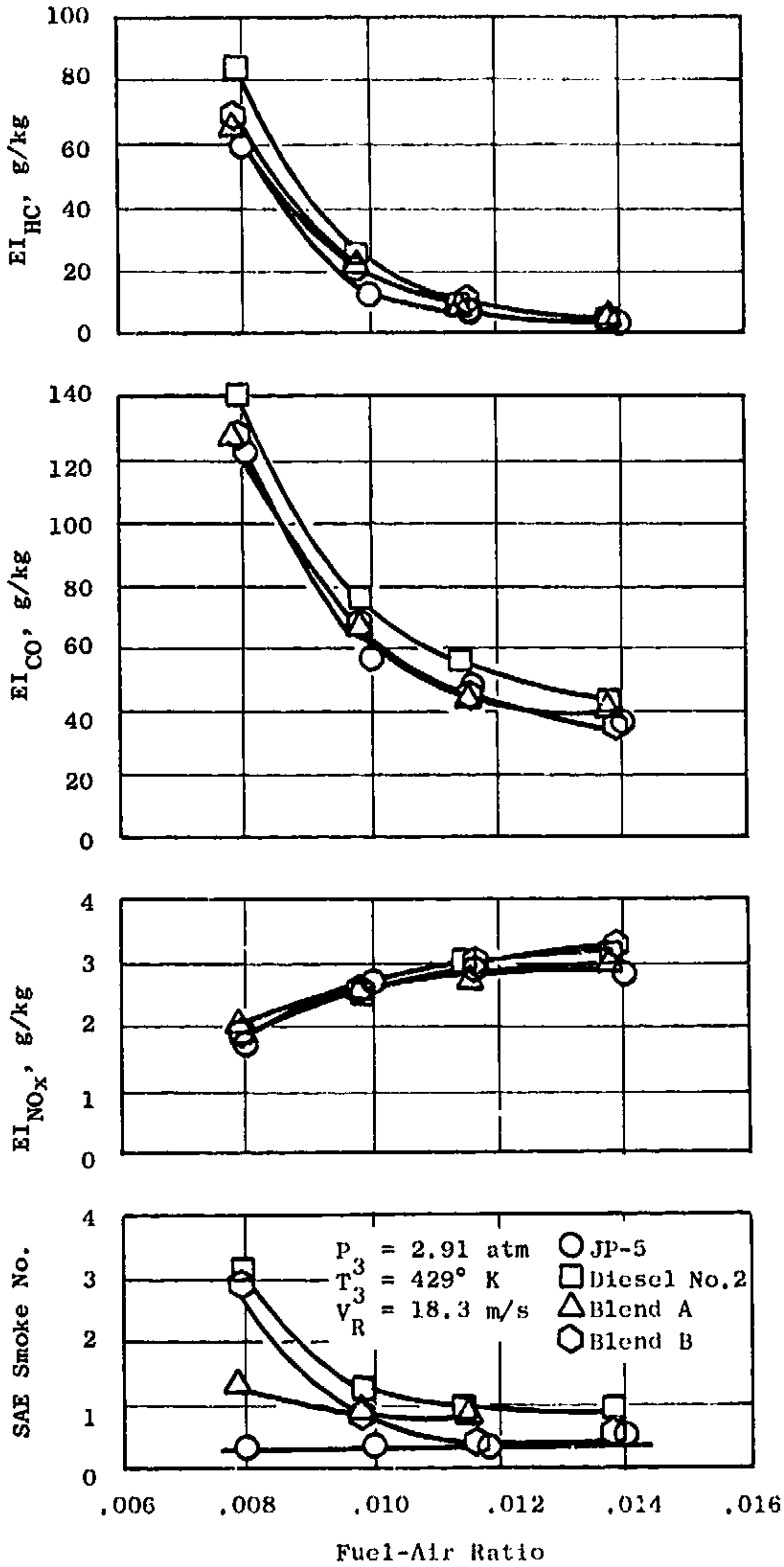


Figure 16. Effect of Fuel Type on Radial/Axial-Staged Combustor Emissions at Idle Conditions, Configuration R7.

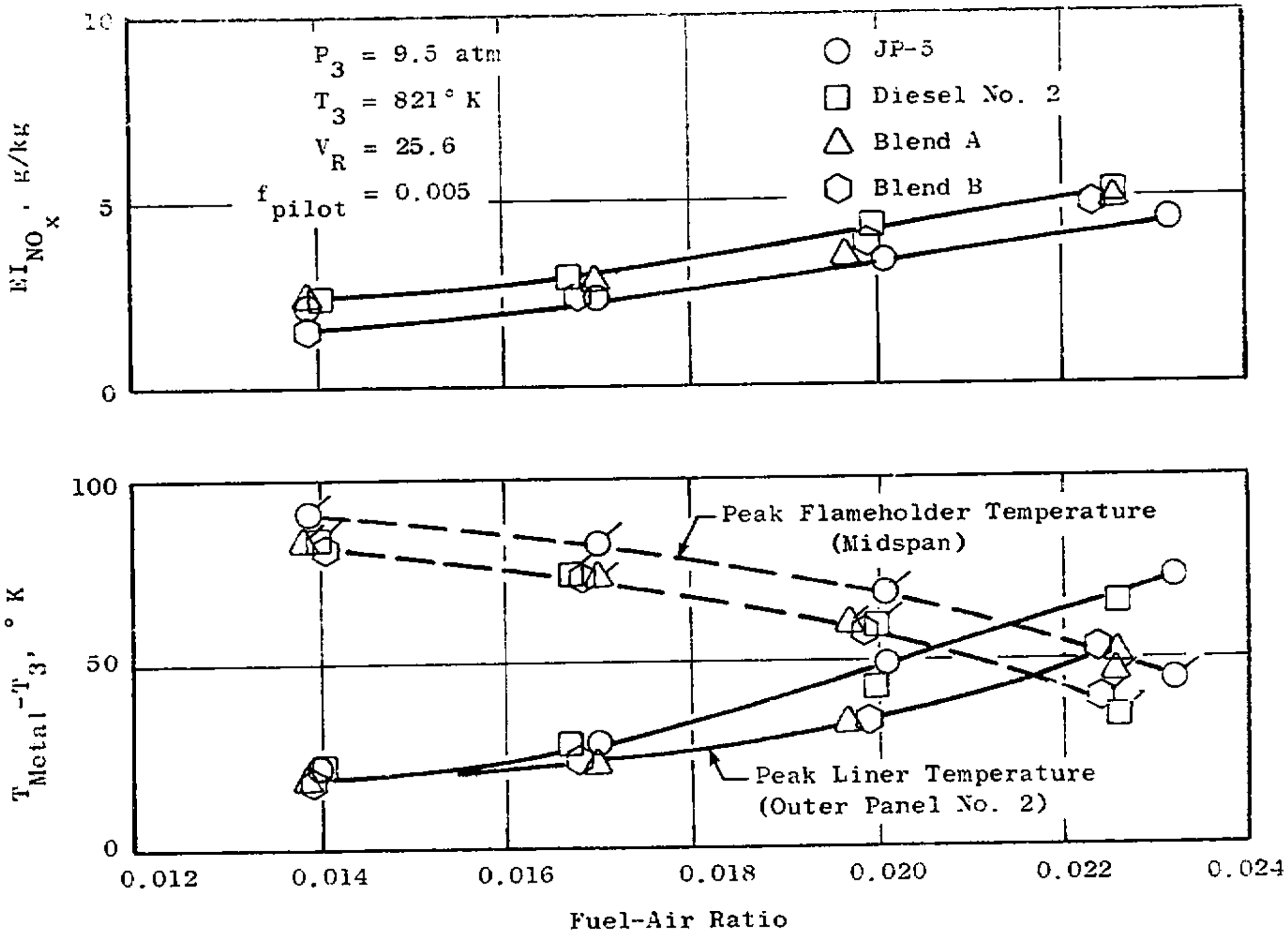


Figure 17. Effect of Fuel Type on Radial/Axial Staged Combustor Performance at Simulated Takeoff Conditions, Configuration R7.

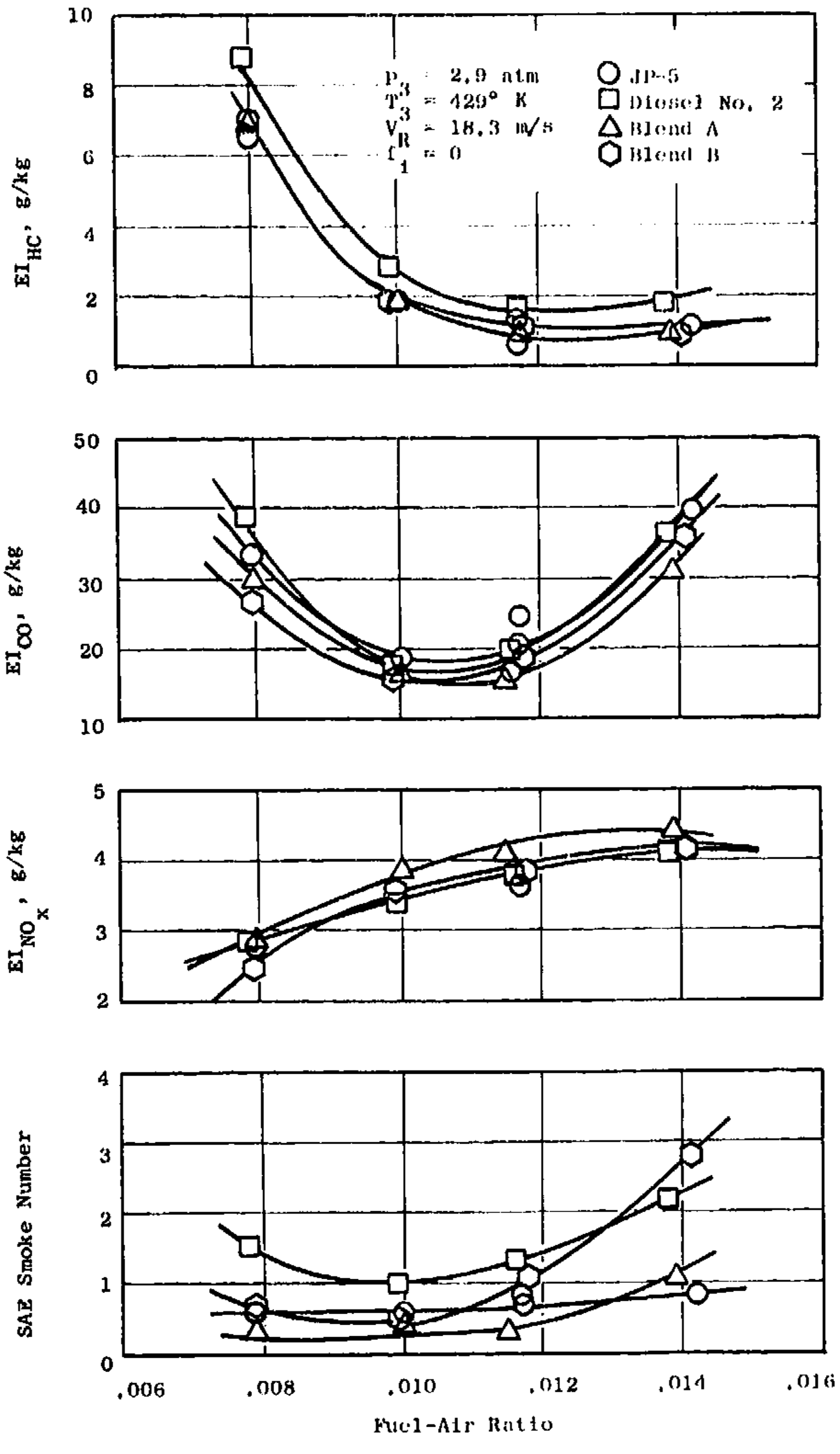


Figure 18. Effect of Fuel Type on Double Annular Combustor Emissions at Idle Conditions, Configuration D7.

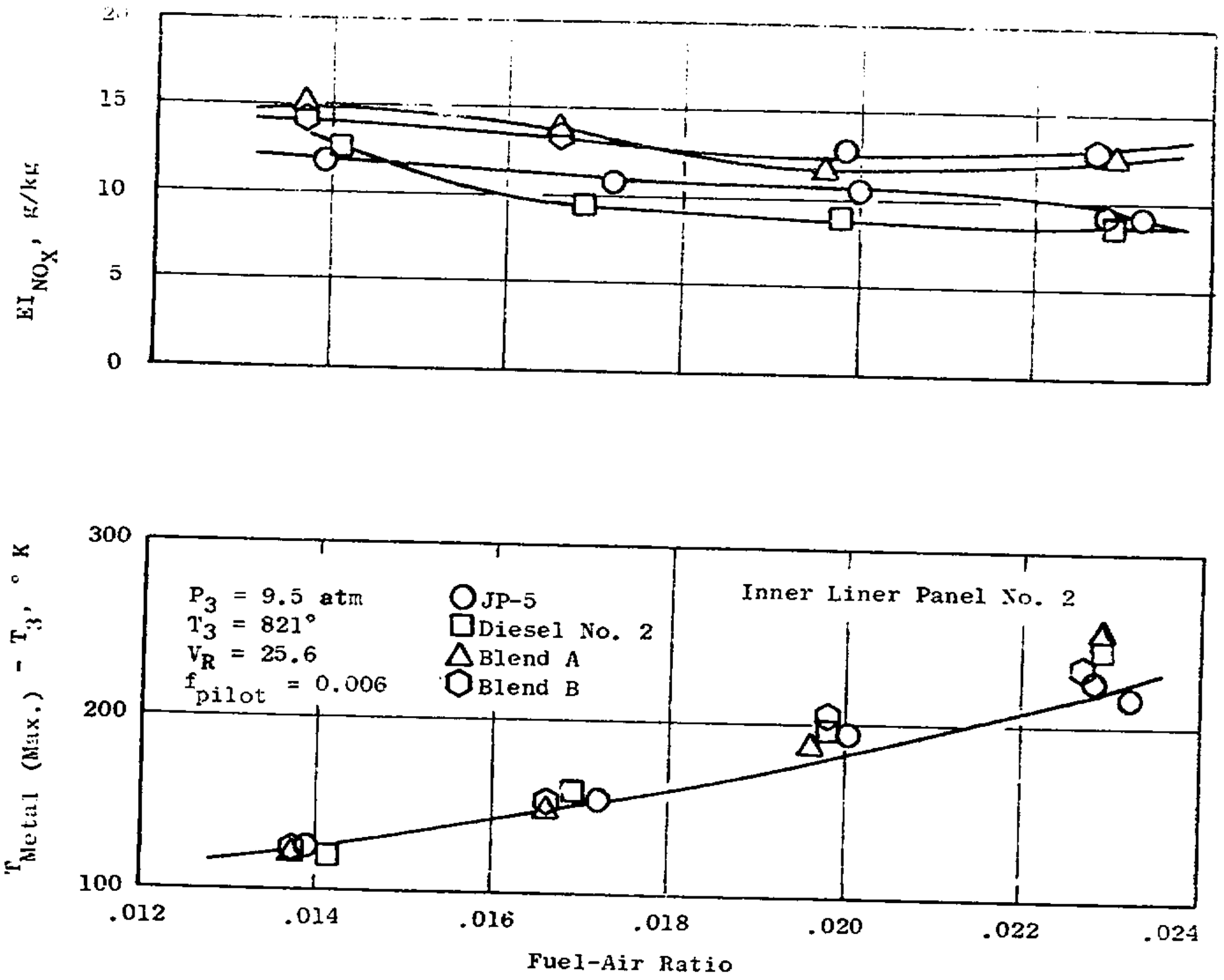


Figure 19. Effect of Fuel Type on Double Annular Combustor Performance at Simulated Takeoff Conditions, Configuration D7.

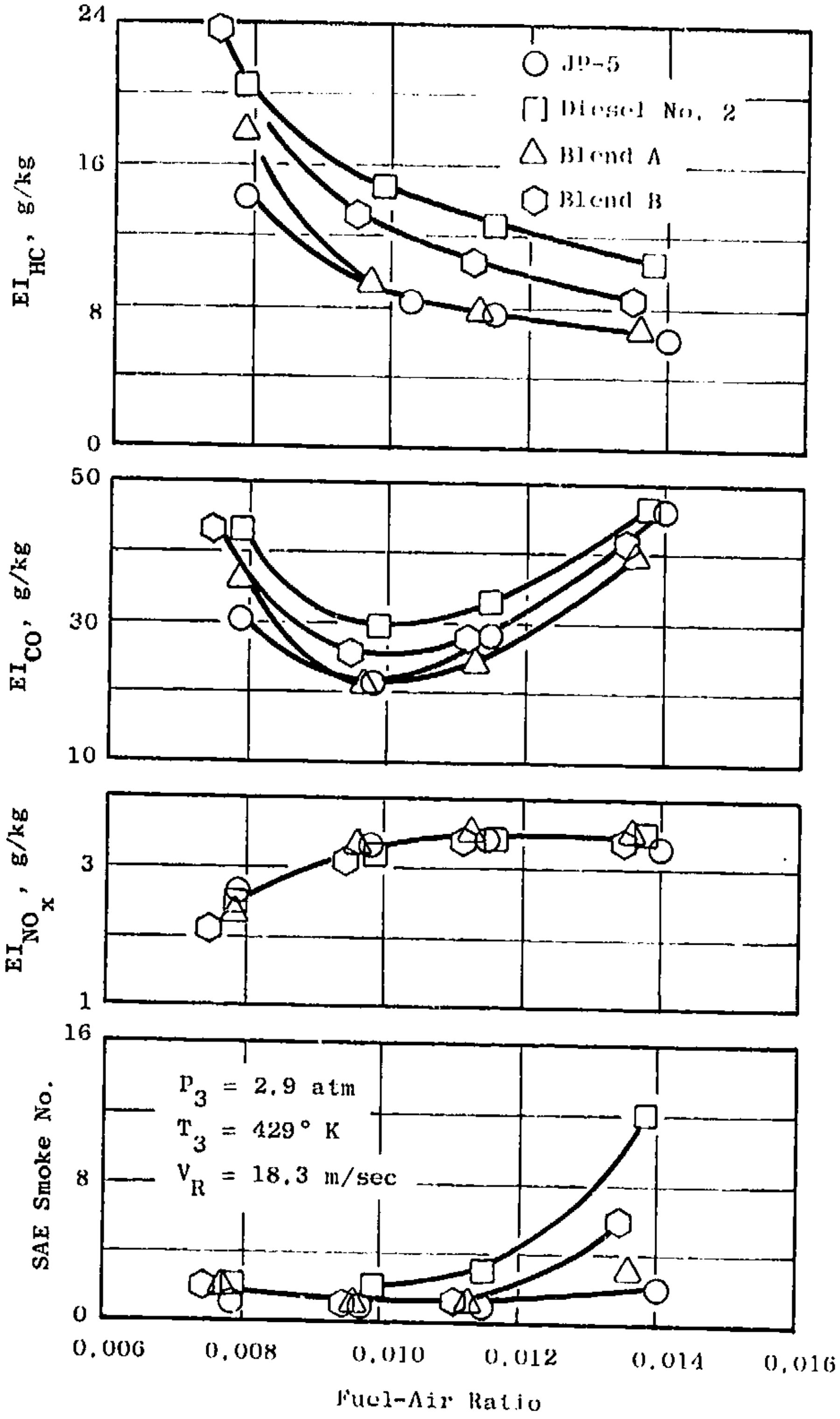


Figure 20. Effect of Fuel Type on Double Annular Combustor Emissions at Idle Conditions, Configuration D12A.

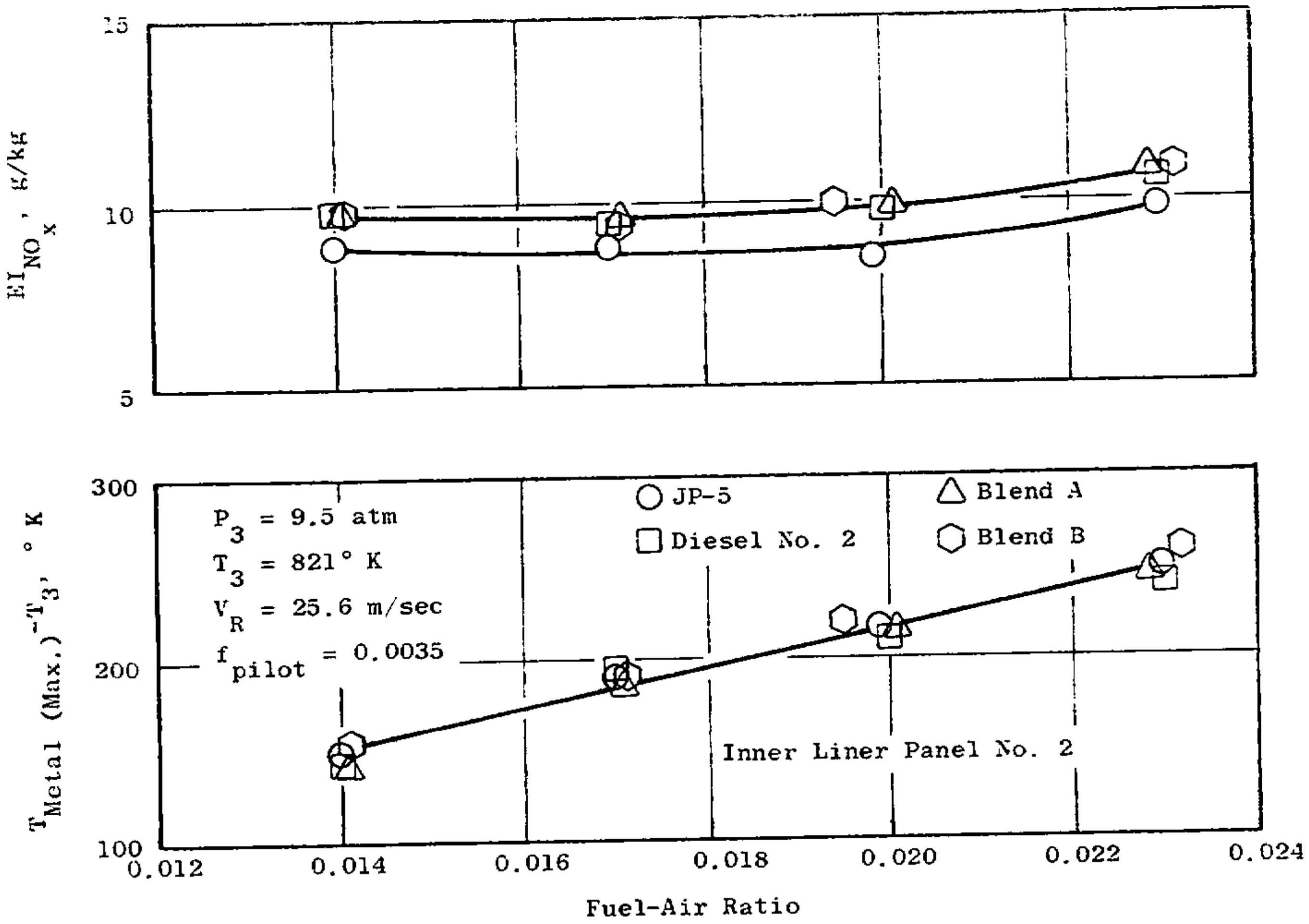


Figure 21. Effect of Fuel Type on Double Annular Combustor Performance at Simulated Takeoff Conditions, Configuration D13.

Table V. Emissions and Performance Correlation Parameters.

Fuel Type	Hydrogen Weight Fraction W_H	Final Boiling Point, °K T_B	Correlation Parameters				
			CO Emissions $\left(\frac{W_{Hi}}{W_{H\,JP\text{-}5}}\right)^{-0.7} \left(\frac{T_{Bi}}{T_{B\,JP\text{-}5}}\right)$	HC Emissions $\left(\frac{W_{Hi}}{W_{H\,JP\text{-}5}}\right)^{-1.8} \left(\frac{T_{Bi}}{T_{B\,JP\text{-}5}}\right)$	NO_x Emissions (1) $\left(\frac{W_{Hi}}{W_{H\,JP\text{-}5}}\right)^{-1.1}$	Smoke Emissions $\left(\frac{W_{Hi}}{W_{H\,JP\text{-}5}}\right)^{-1.0} \left(\frac{T_{Bi}}{T_{B\,JP\text{-}5}}\right)^{-0.5}$	Peak Metal Temperature $\left(\frac{W_{Hi}}{W_{H\,JP\text{-}5}}\right)^{-0.5}$
JP-4	0.1371	533.3	1.000	1.000	1.000	1.000	[illegible]
No. 2 Diesel	0.1268	607.2	1.203	1.310	1.090	1.154	[illegible]
Blend A	0.1228	529.4	1.072	1.209	1.129	1.112	1.057
Blend B	0.1224	536.1	1.087	1.231	1.133	1.123	[illegible]
Shale Jet A	0.1356	562.2	1.061	1.074	1.012	1.038	[illegible]

(1) Thermal NO_x Only

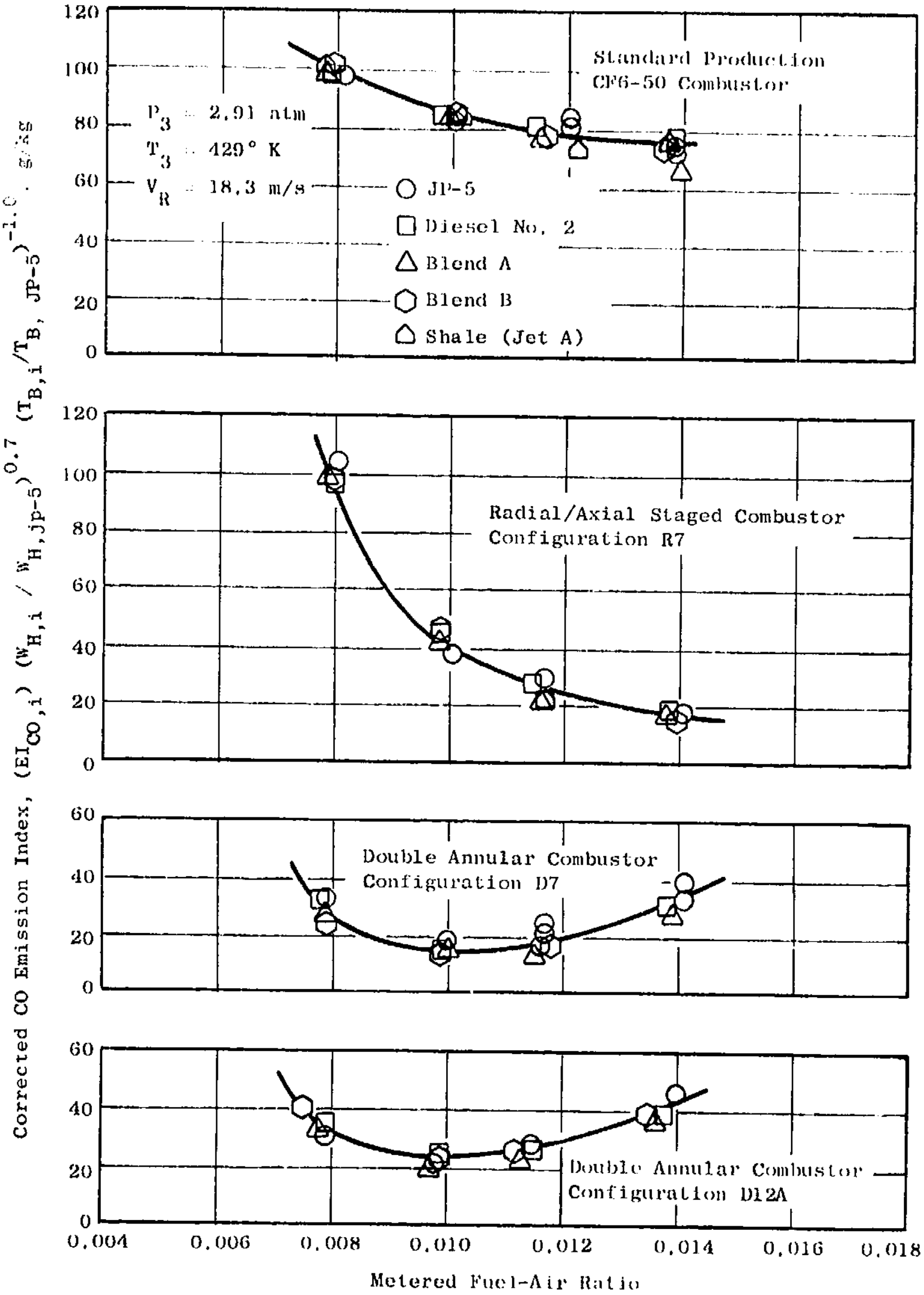


Figure 22. Correlation of Effects of Fuel Properties on CO Emmissions Levels at Idle Conditions.

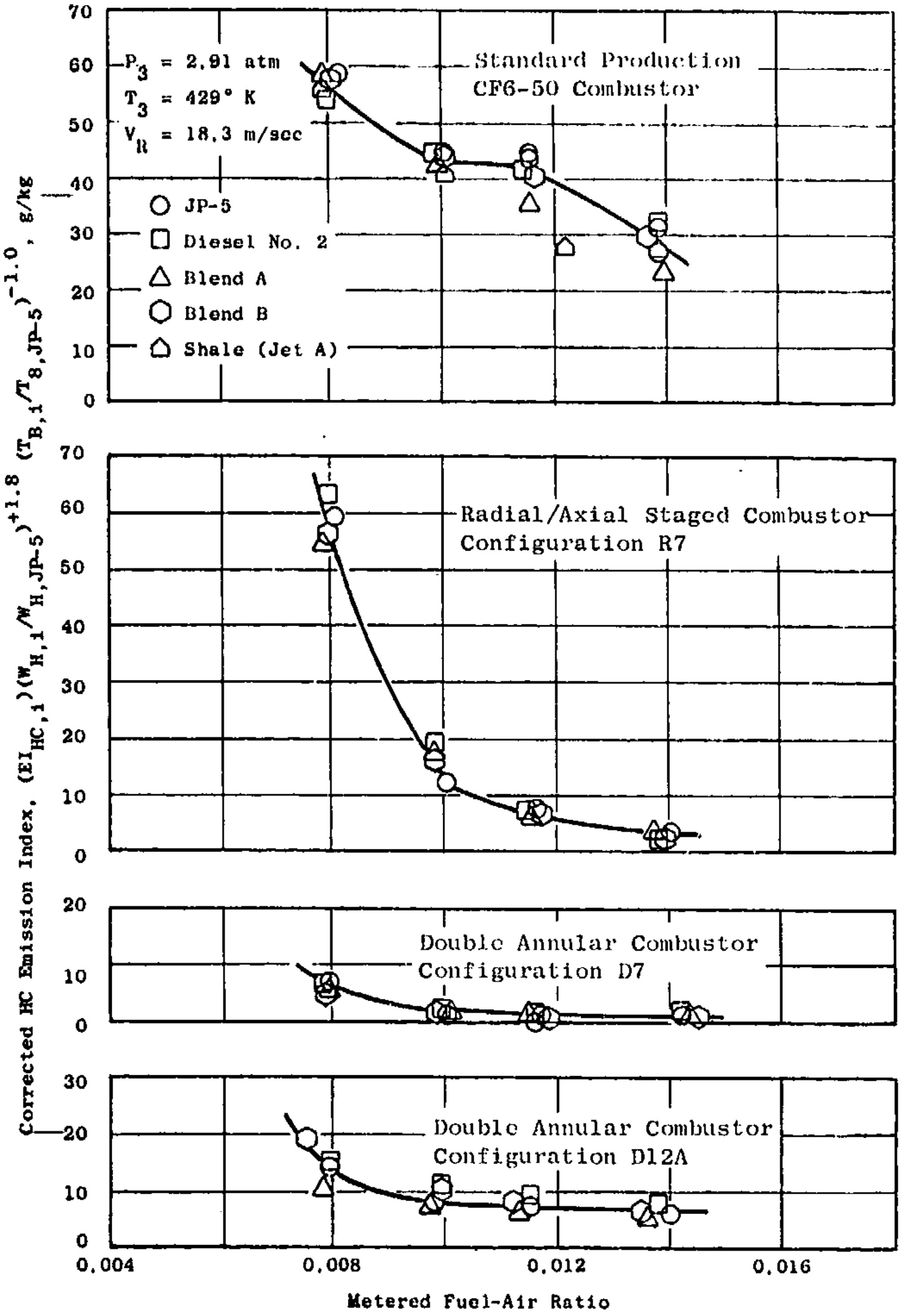


Figure 23. Correlation of Effects of Fuel Properties on HC Emissions Levels at Idle Conditions.

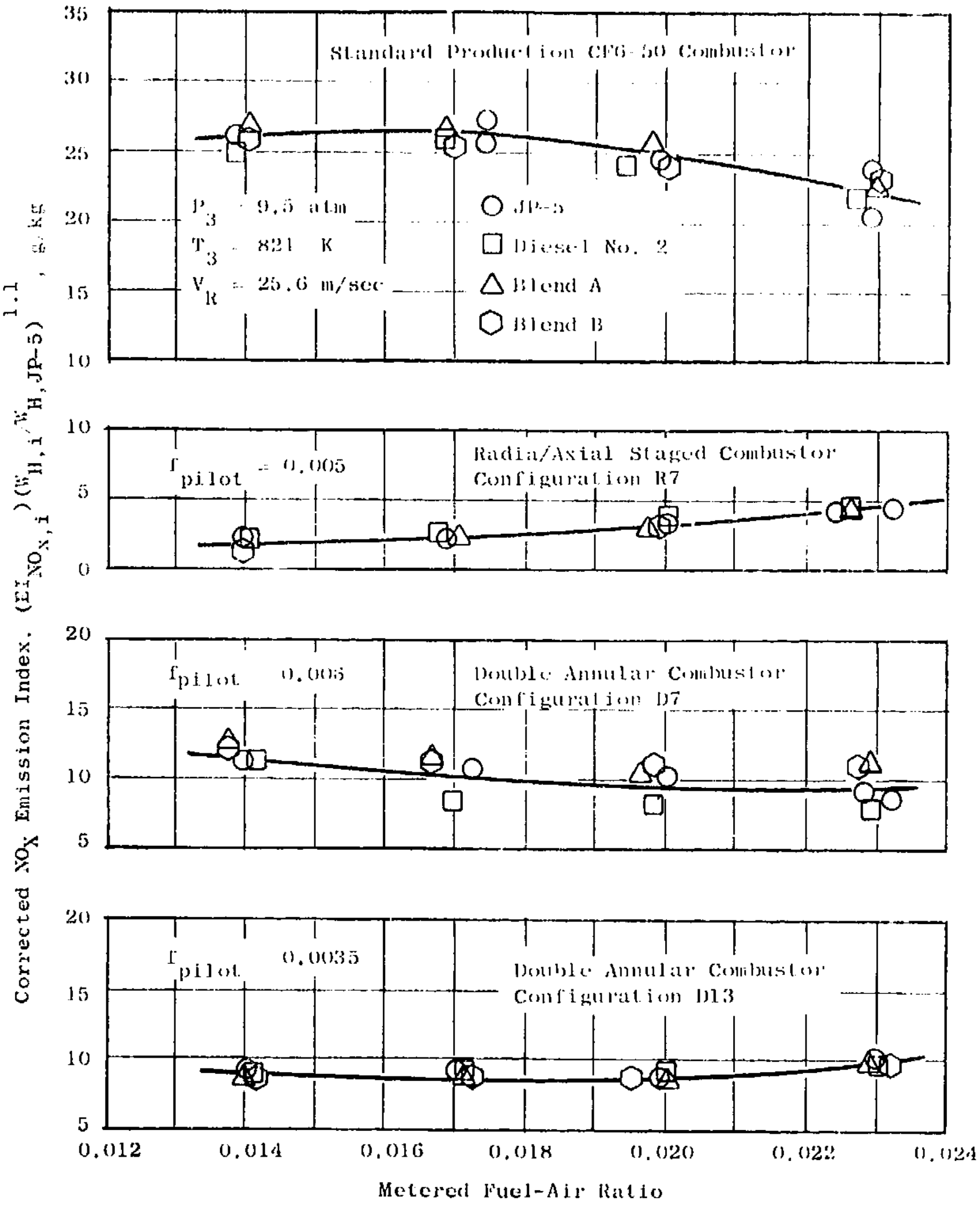


Figure 24. Correlation of Effects of Fuel Properties on NO$_x$ Emissions Levels at Simulated Takeoff Conditions.

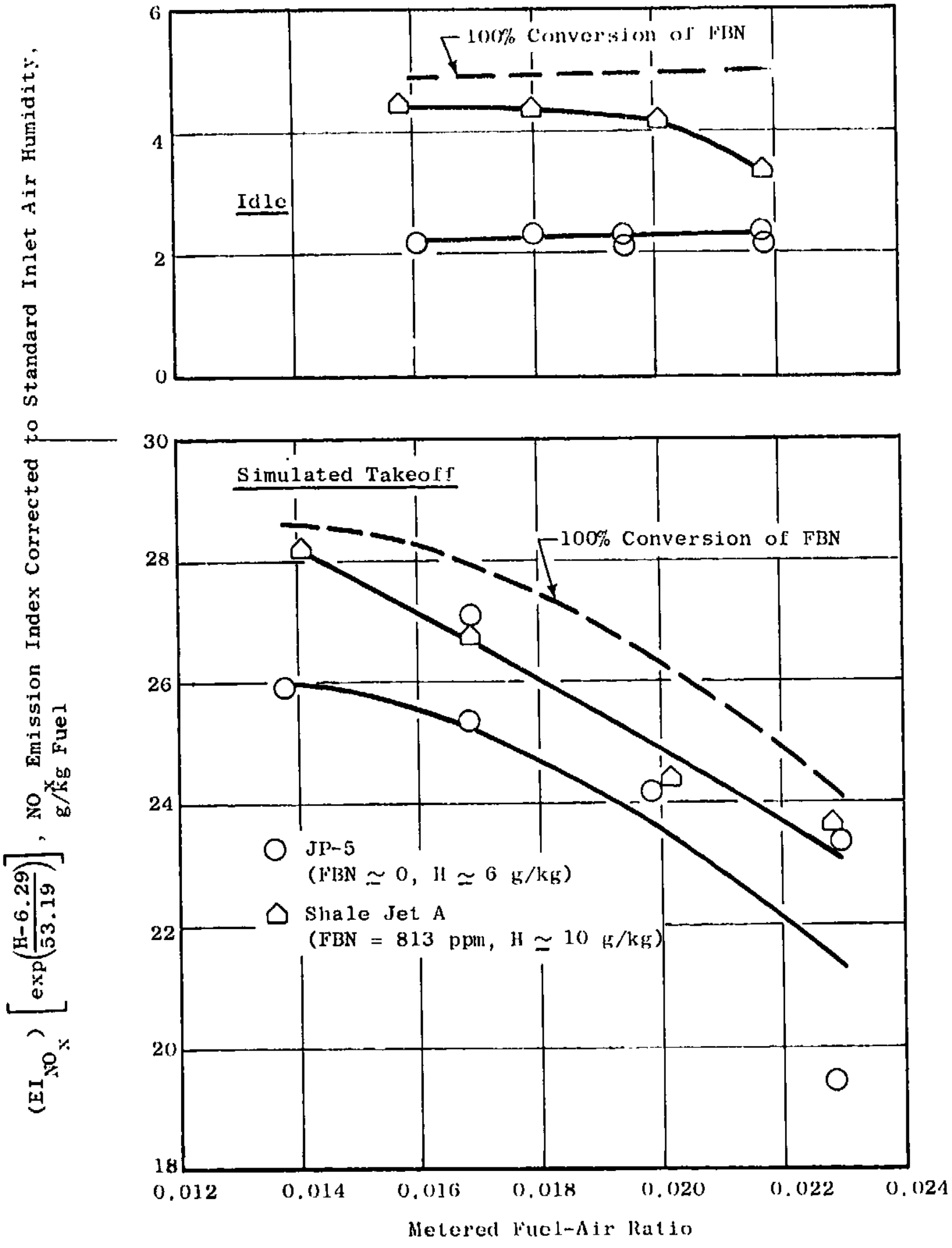


Figure 25. Effect of Fuel Bound Nitrogen (FBN) on NO_x Emissions Levels, Standard Production CF6-50 Combustor.

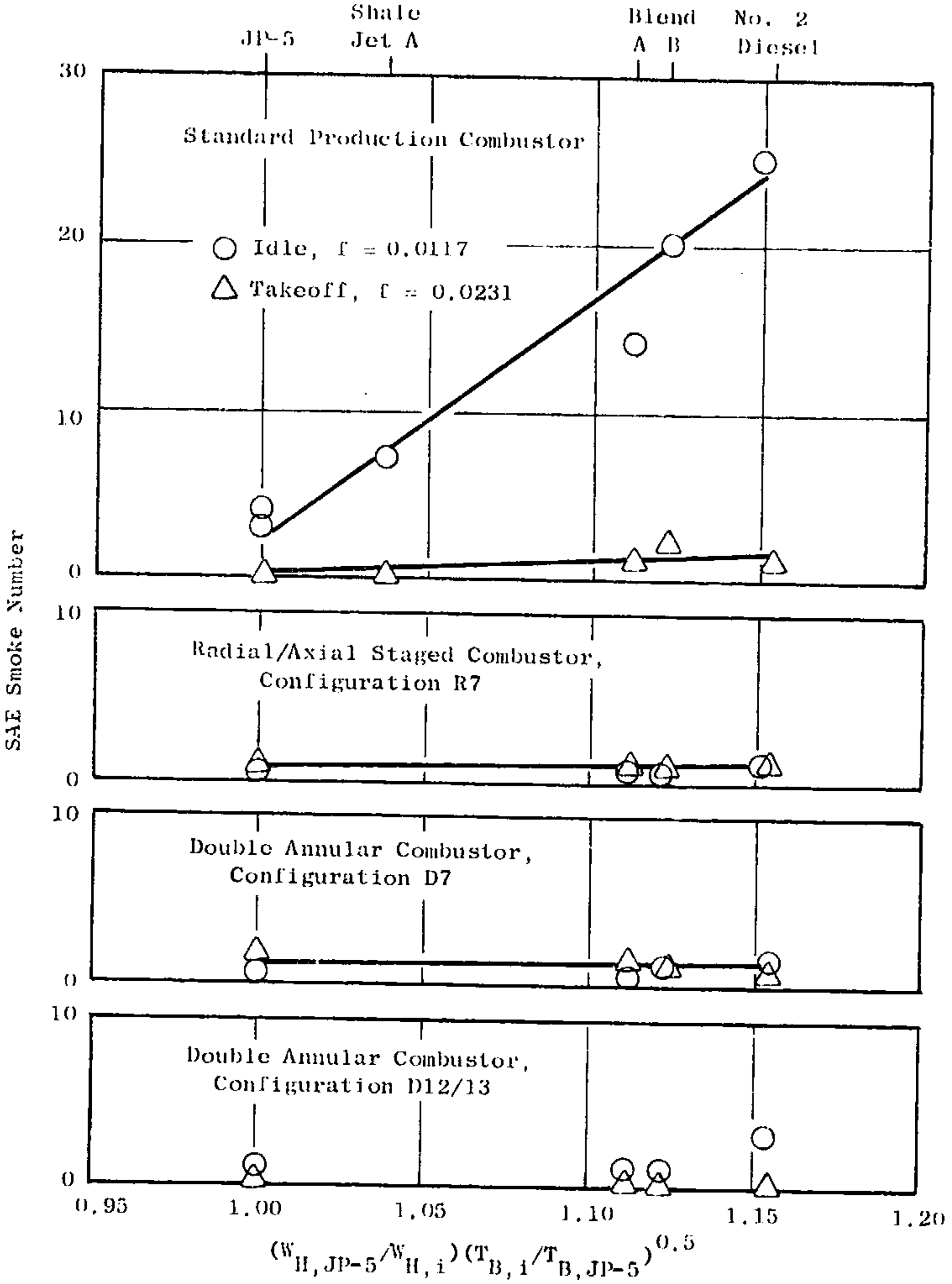


Figure 26. Effect of Fuel Properties on Smoke Emissions Levels.

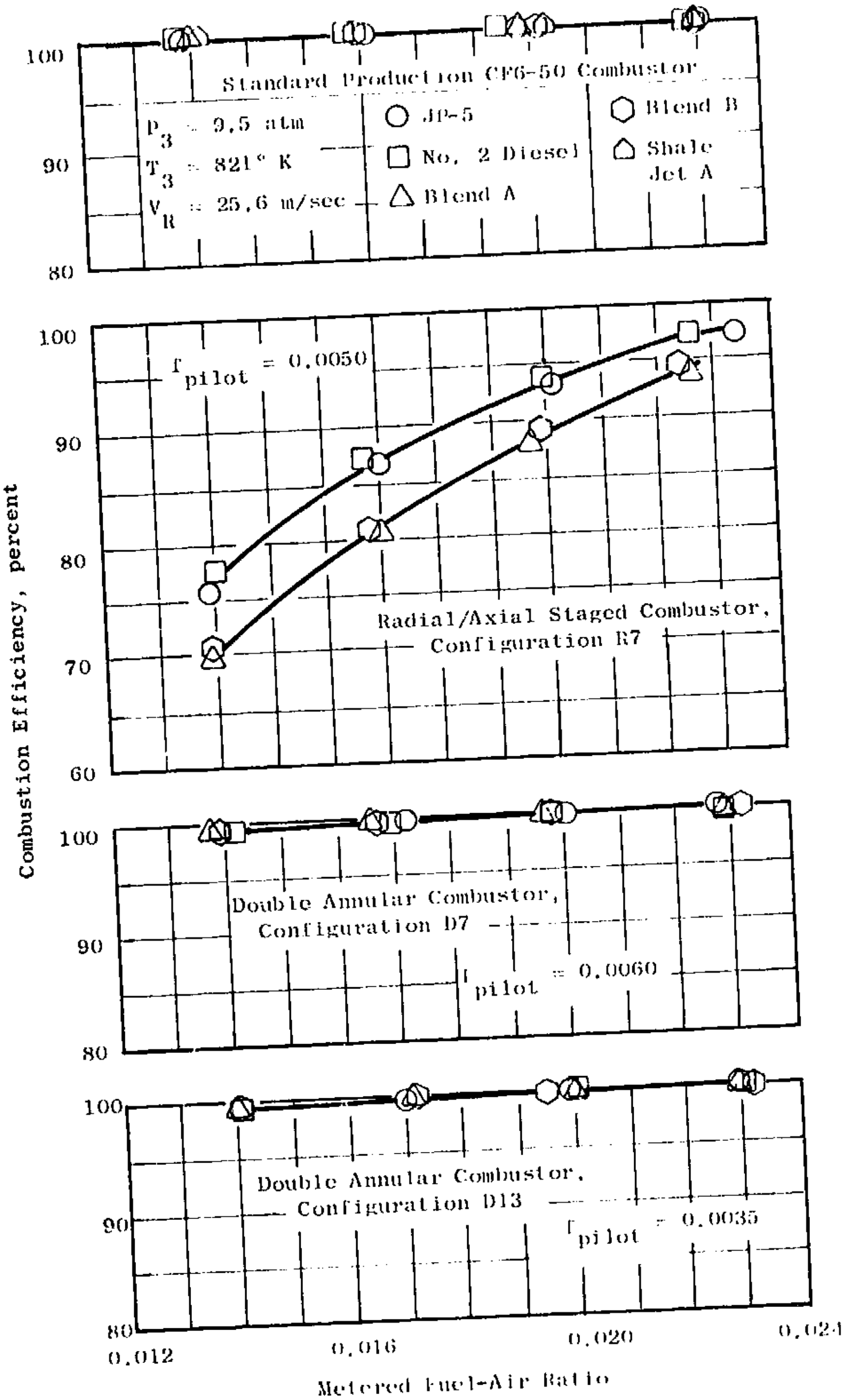


Figure 27. Effect of Fuel Type on Combustion Efficiency at Simulated Takeoff Conditions.

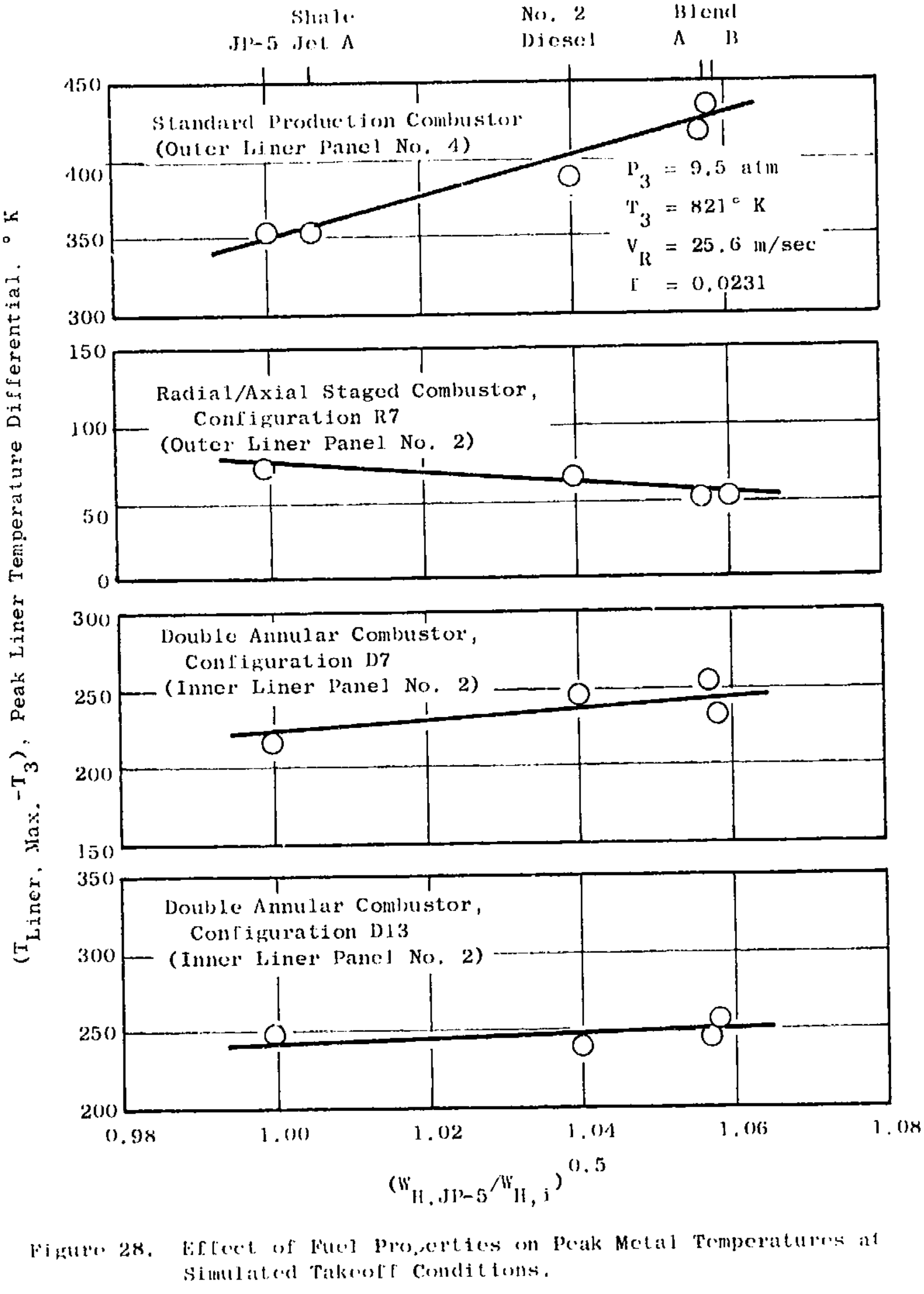


Figure 28. Effect of Fuel Properties on Peak Metal Temperatures at Simulated Takeoff Conditions.

HC emissions levels were thus more dependent upon fuel hydrogen content than were CO emissions levels, but the effect of final boiling point was about the same for both HC and CO emissions levels.

6.2 NO_x EMISSIONS

NO_x emissions levels were also highly configuration dependent. As illustrated in Figures 15, 17, and 19, the NO_x emissions levels at simulated takeoff conditions were highest with the standard production combustor and lowest with the Radial/Axial Staged Combustor, but with reduced combustion efficiency levels. The trends with fuel type were, however, the same for all four configurations. The NO_x emissions levels were highest with the aromatic blends and lowest with normal JP-5 fuel. As indicated in Figure 24, the NO_x emissions levels correlate quite well when corrected by the factor:

$$K_{NO_x} = \left(\frac{W_{H,i}}{W_{H,JP-5}}\right)^{1.1}$$

Final boiling point had no discernable effect on NO_x emissions levels, but fuel-bound nitrogen content did produce a measurable effect.

The NO_x emissions levels with normal JP-5 fuel and the shale Jet A fuel are compared in Figure 25. The inlet air humidity varied considerably during these tests (4 to 14 gH_2O/kg air), so the emissions levels have been corrected to standard humidity (6.29 g/kg). The shale Jet A fuel NO_x emissions levels are significantly higher than those with JP-5 fuel. This is attributed to partial conversion of the fuel-bound nitrogen to NO_x Conversion efficiencies from about 20 to 80 percent are indicated which are in general agreement with References 4 and 5.

6.3 SMOKE EMISSIONS

Smoke emission levels were generally very low with all four test configurations. As shown in Figure 26, the highest levels were produced by the standard production combustor at idle operating conditions with No. 2 Diesel fuel. Results indicate approximately the relationship:

$$SN \propto \left[\left(\frac{W_{H,JP-5}}{W_{H,i}}\right)\left(\frac{T_{B,i}}{T_{B,JP-5}}\right)^{0.5}\right]$$

In all of the other tests, smoke levels were virtually zero with any fuel. Older combustor designs utilized in References 4 and 5 had higher smoke levels and stronger effects of fuel hydrogen content were observed. Thus, advanced low smoke combustors appear to be relatively more tolerant to fuel properties.

6.4 COMBUSTOR PERFORMANCE

Generally, the effects of fuel type on combustor performance were very small. No discernable effect on pressure loss or exit temperature distributions were observed.

Combustion efficiency levels at simulated takeoff conditions are shown in Figure 27. All levels were virtually 100 percent except with the Radial/Axial Staged Combustor. Combustion efficiency levels for the Radial/Axial Staged Combustor were somewhat lower with the aromatic blends than with JP-5 or No. 2 Diesel fuels.

Combustor peak metal temperature levels and locations were dependent upon both configuration and test condition. As illustrated in Figure 28, the highest levels at simulated takeoff condition were found on the fourth panel of the outer liner of the standard production combustor. The results indicate approximately the relationship

$$\left(T_{Liner,max} - T_3\right) \alpha \left(\frac{W_{H,JP-5}}{W_{H,i}}\right)^{0.5}$$

which is a much weaker effect than reported in References 4 and 5. For the low emissions configurations, the temperature levels were lower and virtually independent of fuel type. Thus, low smoke and low gaseous emissions combustor designs appear to be relatively insensitive to fuel hydrogen content.

6.5 ALTITUDE RELIGHT

Altitude relight limits were approximately the same for all four test configurations and all four test fuels. However, these tests were conducted with ambient temperature air and fuel. Because of the higher flashpoint and viscosity of No. 2 Diesel fuel, greater differences could be expected with cold fuel and air.

6.6 CARBONING AND FLASHBACK

No discernable carbon buildup on either the fuel nozzle or primary air swirler venturi was observed in either of the tests conducted with JP-5 and Blend B fuels. This result was expected, since the configurations had been previously developed in Phase II Program tests using a heavy distillate fuel. With less developed configurations, some differences between JP-5 and Blend B fuels might be expected.

In the flahsback test of the Radial/Axial Staged Combustor, a flameholder burnout, occurred while operating with the Blend B fuel at simulated takeoff conditions. The resulting burnout can be seen in Figure 7. The Blend B fuel had a low flashpoint compared to normal JP-5 fuel (314 vs 330° K) which may have caused flashback and subsequent burnout. Thus, a potential problem with premix systems is indicated, particularly with a fuel having a low flashpoint.

SECTION 7.0

SUMMARY OF RESULTS

This series of tests provides a preliminary assessment of the possible impacts of using hydrocarbon fuels with physical and chemical properties significantly different from those of normal aviation kerosene on aircraft turbine engine combustor performance and exhaust emissions characteristics. Tests were conducted with the standard production CF6-50 combustor and two CF6-50 size low-emissions design approach combustors which evolved in the NASA/GE Experimental Clean Combustor Program. For the five fuels tested, the important fuel properties were found to be hydrogen content, which ranged from 12.2 to 13.7 percent by weight; final boiling point, which ranged from 529 to 607° K, and fuel nitrogen content, which ranged from near zero to 813 ppm.

Fuel effects were generally quite moderate, but well defined and in the directions anticipated, with respect to pollutant emissions characteristics (CO, HC, NO_x, and smoke) and peak liner temperatures. Decreased hydrogen content caused an increase in CO, HC, NO_x, and smoke emissions levels and in peak liner temperature. Increased final boiling point caused an increase in CO, HC and smoke emissions levels, but had no discernible effect on NO_x emissions levels or peak metal temperatures. Limited testing indicated fuel bound nitrogen conversion efficiencies from about 20 to 80 percent depending upon operating conditions.

SECTION 8.0

CONCLUDING REMARKS

In advanced low smoke combustors, like the CF6-50 combustor, fuel hydrogen content effects on smoke and liner temperatures appear to be relatively small. Some increases in gaseous emissions levels were noted as hydrogen content and/or final boiling was increased. Overall, however, these results suggest that these advanced turbofan engines can probably accommodate a wider range of fuel properties and, thus, be satisfactorily operated with a broader range of petroleum fuels and fuels derived from shale or coal sources.

The low emissions type combustors tested in this program appear to be even less sensitive to fuel hydrogen content and/or final boiling point. Thus, these combustors appear to offer additional promise for permitting the use of a wide range of alternate fuels in future engines.

Additional testing is recommended to verify these trends as properties of future fuels become better defined and/or as actual fuels become available in sufficient quantities for more extensive testing. In particular, the following types of tests are recommended:

1. Actual advanced turbofan engine operation. At high pressure, effects of fuel properties could be greater than indicated in these rig tests.

2. Relight tests with cold fuel and air. Effects of fuel properties could be greater than indicated in these ambient temperature rig tests.

3. Fuel thermal stability related tests. In these short tests with ambient temperature fuels, no fuel nozzle gumming or plugging was indicated, but with hot, aromatic fuels, some problems might develop.

APPENDIX A

DETAILED TEST RESULTS

This appendix contains summaries of the operating conditions, performance and exhaust emissions data for each test conducted in the Fuels Addendum.

The full annular rig performance and emissions test results are summarized in Tables A-I through A-IV. In these data tables, only the measured combustor airflows are shown for the sake of brevity. In conducting the tests, however, the total airflow and turbine cooling bleed airflows were set and measured. Nominally, the combustor airflow was 84 percent of the total inlet airflow. Reference velocity in these tables is based on total inlet airflow, total inlet density, and combuster housing area at the dome exit which is 3729 cm^2. The NO_x emissions indices are presented two ways: as measured at rig conditions and corrected to true engine operating conditions and standard inlet air humidity (6.29 gH_2O/kg air). Average exit gas temperature was calculated from metered fuel-air ratio and gas sample combustion efficiency. Exit gas profile and pattern factors are based on uncorrected thermocouple readings.

The 60° sector rig altitude relight results are summarized in Tables A-V through A-VIII. Simulated flight conditions were interpolated from the engine windmilling map (Figure A-1) using the measured airflow rate and inlet pressure. Successful lightoff is defined as full propagation as indicated by temperature rise from primary zone thermocouples downstream of each fuel nozzle. Blowout was visually determined.

The 12° sector rig results are summarized in Table A-IX.

Table A-I. Emissions and Performance Test Results, Standard Production CF6-50 Combustor.

Table A-II. Emissions and Performance Test Results, Radial/Axial Staged Combustor, Configuration R7.

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 Air	Reference Velocity, m/sec	Fuel-Air Ratio g Fuel/g Air				Sample Combustion Efficiency, %	Emission Indices g/kg Fuel				SAE Smoke Number	Total Pressure Loss, %	Average Exit Temperature, K	Maximum Metal Temperature, K	Profile Factor	Pattern Factor	Fuel Type
								Metered Main Stage	Metered Pilot Stage	Metered Overall	Sample Overall		CO	HC	NO_x	Engine NO_x							
[illegible]	[illegible]	2.94	533	13.7	0	---	18.[illegible]	0	0	0	0	---	---	---	---	---	---	1.8[illegible]	[illegible]	---	---	---	JP-[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	13.7	69[illegible]	[illegible]	18.0	0	.01[illegible]	.01[illegible]	.01[illegible]	[illegible]	17.[illegible]	[illegible]	2.8	2.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	132	2.92	[illegible]	13.7	[illegible]	[illegible]	18.2	0	[illegible]	[illegible]	[illegible]	[illegible]	18.8	7.[illegible]	2.8	2.6	[illegible]	3.17	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	[illegible]	2.91	529	13.7	[illegible]	[illegible]	17.8	0	[illegible]	[illegible]	[illegible]	[illegible]	56.3	22.1	2.7	2.1	[illegible]	3.23	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	[illegible]	2.91	[illegible]	13.7	[illegible]	[illegible]	17.8	[illegible]	[illegible]	[illegible]	[illegible]	91.2	[illegible]	50.2	1.7	[illegible]	[illegible]	[illegible]	729	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	121	[illegible]	[illegible]	[illegible]	681	[illegible]	17.[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	72[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	122	2.97	[illegible]	[illegible]	[illegible]	[illegible]	18.1		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3.0	2.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	76.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	124	2.97	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0077	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	131	[illegible]	533	[illegible]	687	[illegible]	18.2	[illegible]	.0137	.0137	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.8	[illegible]	[illegible]	[illegible]	715	[illegible]	[illegible]	[illegible]
[illegible]	132	[illegible]	[illegible]	13.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	134	2.95	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	141	[illegible]	[illegible]	13.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	142	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	143	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	144	2.93	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	818	12.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.12	JP-[illegible]
[illegible]	[illegible]	[illegible]	817	12.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	[illegible]	[illegible]	817	12.7	[illegible]	[illegible]	23.2	.0122	[illegible]	[illegible]	[illegible]	[illegible]	125	105	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	514	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-[illegible]
[illegible]	521	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	522	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table A-III. Emissions and Performance Test Results, Double Annular Combustor, Configuration D7.

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 Air	Reference Velocity, m/sec	Fuel-Air Ratio g Fuel/g Air				Sample Combustion Efficiency, %	Emission Indices g/kg Fuel				SAE Smoke Number	Total Pressure Loss, %	Average Exit Temperature, K	Maximum Metal Temperature, K	Profile Factor	Pattern Factor	Fuel Type
								Metered			Sample Overall												
								Outer Annulus	Inner Annulus	Overall			CO	HC	NO_x	Engine NO_x							
450	101	2.90	433	13.6	697	10.4	18.1	.0142	0	.0142	.0207	99.0	39.9	1.1	---	---	0.8	4.69	971	780	1.31	1.07	JP-5
451	102	2.90	433	13.8	582	7.2	18.2	.0117	0	.0117	.0159	99.4	20.7	1.3	---	---	0.7	5.04	885	751	1.29	1.50	JP-5
[illegible]	102	[illegible]	429	13.7	576	6.0	17.9	.0117	0	.0117	.0153	99.3	21.9	1.3	---	---	0.6	4.55	876	775	1.23	1.31	JP-5
[illegible]	102	2.95	426	13.8	577	7.2	17.9	.0116	0	.0116	.0167	99.6	16.7	0.8	3.6	3.7	---	4.78	[illegible]	[illegible]	1.28	1.24	JP-5
[illegible]	103	2.91	433	13.8	[illegible]	6.5	18.2	.0100	0	.0100	.0127	99.4	18.6	[illegible]	---	---	[illegible]	4.81	821	721	1.28	[illegible]	JP-5
453	104	2.91	433	13.8	[illegible]	6.5	18.0	.0079	0	.0079	.0092	98.5	[illegible]	[illegible]	2.8	2.7	0.6	4.88	[illegible]	[illegible]	1.23	[illegible]	JP-5
175	121	[illegible]	428	13.8	688	5.1	18.0	.0138	0	.0138	.0184	[illegible]	38.5	1.7	1.1	1.0	2.2	4.68	922	[illegible]	[illegible]	[illegible]	Diesel #2
176	122	2.92	427	13.8	[illegible]	5.0	18.0	.0116	0	.0116	.0162	99.4	29.5	1.9	[illegible]	3.7	1.3	4.68	[illegible]	778	1.27	[illegible]	Diesel #2
177	123	2.92	427	13.8	492	5.0	18.0	[illegible]	0	[illegible]	[illegible]	99.3	17.1	2.6	3.1	3.4	1.0	4.77	[illegible]	742	[illegible]	1.24	Diesel #2
178	124	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.8	.0078	0	.0078	.0101	98.2	38.5	6.8	4.9	2.8	1.5	4.76	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
179	131	[illegible]	427	[illegible]	687	6.0	[illegible]	[illegible]	0	[illegible]	[illegible]	99.2	30.9	0.9	1.4	4.1	1.1	4.69	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
180	132	2.92	426	13.8	574	6.2	18.0	.0115	0	.0115	.0165	99.5	15.4	0.9	1.1	4.0	0.3	4.71	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
181	133	[illegible]	426	[illegible]	[illegible]	7.8	17.6	[illegible]	[illegible]	[illegible]	.0132	99.1	16.1	1.8	[illegible]	3.8	0.4	[illegible]	[illegible]	[illegible]	1.22	[illegible]	Blend A
182	134	2.93	424	13.7	392	7.0	17.9	[illegible]	0	.0079	.0102	98.6	29.2	6.8	[illegible]	2.9	[illegible]	4.66	[illegible]	[illegible]	[illegible]	.77	Blend A
183	141	[illegible]	426	13.8	703	7.8	[illegible]	.0141	0	[illegible]	[illegible]	99.1	35.9	[illegible]	1.2	[illegible]	2.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend B
184	142	2.91	424	13.7	585	7.5	18.0	.0118	0	.0118	.0166	99.4	16.7	1.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	785	1.26	[illegible]	Blend B
185	143	2.92	426	13.8	[illegible]	[illegible]	18.0	[illegible]	0	[illegible]	.0131	99.3	15.6	1.9	3.5	3.6	0.5	4.81	815	727	1.23	[illegible]	Blend B
186	144	[illegible]	426	13.7	391	7.2	17.9	[illegible]	[illegible]	.0079	.0109	98.7	26.7	0.5	2.1	2.4	0.7	4.70	736	[illegible]	[illegible]	[illegible]	Blend B
[illegible]	511	[illegible]	822	32.7	[illegible]	[illegible]	25.3	[illegible]	.0173	[illegible]	.0267	100.0	1.8	[illegible]	9.3	15.7	[illegible]	4.92	[illegible]	1036	1.12	[illegible]	JP-5
173	516	9.57	[illegible]	[illegible]	2727	[illegible]	25.6	[illegible]	.0167	.0228	.0253	100.0	2.0	0	9.1	16.0	[illegible]	.92	1565	1047	[illegible]	[illegible]	JP-5
[illegible]	512	[illegible]	818	32.9	[illegible]	5.2	25.3	.0062	.0138	.0200	.0211	99.9	1.8	0.1	10.5	18.3	1.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-5
[illegible]	[illegible]	[illegible]	817	32.6	[illegible]	[illegible]	25.1	.0062	[illegible]	.0172	.0197	99.6	11.8	0.2	10.9	[illegible]	1.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	JP-5
[illegible]	[illegible]	[illegible]	821	[illegible]	[illegible]	[illegible]	25.1	[illegible]	.0078	[illegible]	.0165	[illegible]	[illegible]	[illegible]	[illegible]	20.1	1.5	[illegible]	[illegible]	911	[illegible]	[illegible]	JP-5
[illegible]	521	[illegible]	819	[illegible]	2736	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0258	99.9	[illegible]	0.2	8.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.12	[illegible]	Diesel #2
[illegible]	522	[illegible]	818	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0225	[illegible]	5.2	[illegible]	[illegible]	16.2	[illegible]	4.81	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	[illegible]	[illegible]	818	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	10.2	0.1	[illegible]	[illegible]	[illegible]	4.78	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	[illegible]	[illegible]	820	[illegible]	[illegible]	[illegible]	25.1	[illegible]	[illegible]	[illegible]	.0161	[illegible]	30.1	[illegible]	[illegible]	[illegible]	2.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Diesel #2
[illegible]	[illegible]	[illegible]	817	[illegible]	[illegible]	[illegible]	25.1	[illegible]	[illegible]	.0229	[illegible]	[illegible]	[illegible]	[illegible]	12.6	22.5	[illegible]	4.82	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
[illegible]	532	[illegible]	817	[illegible]	[illegible]	[illegible]	25.2	[illegible]	[illegible]	[illegible]	.0223	[illegible]	5.5	[illegible]	11.8	20.8	[illegible]	4.76	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	18.2	0.1	[illegible]	[illegible]	[illegible]	4.81	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.8	25.1	[illegible]	.0078	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2712	[illegible]	[illegible]	[illegible]	[illegible]	.0227	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	22.7	[illegible]	---	[illegible]	[illegible]	[illegible]	[illegible]	Blend B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0198	.0221	[illegible]	[illegible]	[illegible]	12.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.0077	[illegible]	[illegible]	98.8	11.7	1.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend B

Table A-IV. Emissions and Performance Test Results, Double Annular Combustor, Configuration D12/13.

Reading No.	Point No.	Inlet Total Press Atm	Inlet Total Temp K	Combustor Airflow kg/sec	Total Fuel Flow kg/hr	Inlet Air Humidity g/kg Air	Reference Velocity m/sec	Fuel-Air Ratio g fuel / g air Metered Outer Annulus	 Metered Inner Annulus	 Metered Overall	 Sample Overall	Sample Combustion Efficiency %	Emission Indices g/kg fuel CO	 HC	 NOx	 Engine NOx	SAE Smoke No.	Total Press Loss %	Average Exit Temp K	Maximum Metal Temp K	Profile Factor	Pattern Factor	Fuel Type
[illegible]	101	2.06	431	13.7	690	6.5	18.0	0.0140	0	0.0140	0.0162	98.5	46.0	6.1	3.3	3.2	2	4.79	[illegible]	[illegible]	1.41	1.36	JP5
140	102	[illegible]	432	13.8	571	7.4	18.0	0.0115	0	0.0115	0.0135	98.6	28.2	7.6	3.4	3.3	1	4.77	874	[illegible]	1.51	1.44	
[illegible]	104	[illegible]	432	13.9	490	7.3	18.2	0.0098	0	0.0098	0.0116	98.7	21.2	8.1	3.2	2.2	1	4.71	811	[illegible]	1.51	[illegible]	
[illegible]	[illegible]	2.04	429	14.0	395	6.6	18.1	0.0079	0	0.0079	0.0092	97.9	30.3	14.1	2.6	2.7	1	4.62	734	[illegible]	1.49	1.22	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	688	9.1	17.9	0.0138	0	0.0138	0.0159	97.8	[illegible]	10.7	3.5	3.6	12	4.67	846	[illegible]	1.41	1.17	Diesel #2
[illegible]	[illegible]	[illegible]	428	[illegible]	574	7.8	18.0	0.0115	0	0.0115	[illegible]	[illegible]	[illegible]	12.6	3.4	3.5	3	4.80	817	[illegible]	[illegible]	1.17	
[illegible]	[illegible]	2.04	[illegible]	[illegible]	494	9.1	18.0	0.0099	0	0.0099	0.0112	97.8	29.6	14.9	3.2	3.3	2	4.76	810	[illegible]	[illegible]	1.21	
[illegible]	124	[illegible]	428	[illegible]	397	7.4	18.0	0.0079	0	0.0079	0.0090	96.9	43.1	20.5	2.5	2.5	2	4.77	731	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	2.06	[illegible]	14.0	681	[illegible]	[illegible]	[illegible]	0	0.0136	0.0158	98.4	39.3	6.7	3.5	3.6	3	4.64	843	[illegible]	1.51	[illegible]	Blend A
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7.7	[illegible]	0.0113	0	0.0113	0.0132	98.6	24.4	7.7	3.5	3.5	1	4.81	[illegible]	[illegible]	[illegible]	1.22	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	487	[illegible]	[illegible]	0.0097	0	0.0097	0.0112	[illegible]	[illegible]	9.3	[illegible]	[illegible]	1	4.80	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	386	6.6	18.1	0.0078	0	0.0079	0.0089	97.3	30.1	15.0	2.4	2.4	2	4.74	730	[illegible]	1.47	1.32	
[illegible]	[illegible]	[illegible]	[illegible]	14.1	684	7.3	18.3	0.0135	0	0.0138	0.0156	98.2	41.6	8.4	3.4	3.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.17	Blend B
[illegible]	142	2.06	[illegible]	14.0	568	7.0	18.2	0.0112	0	0.0112	0.0128	98.3	27.4	10.6	3.4	3.4	1	4.79	860	[illegible]	1.41	1.25	
[illegible]	143	[illegible]	430	14.0	479	7.1	18.2	0.0094	0	0.0095	0.0109	98.1	25.7	13.1	3.1	3.1	1	4.86	[illegible]	725	1.47	1.22	
[illegible]	144	[illegible]	430	14.1	381	7.4	18.4	0.0077	0	0.0075	0.0086	[illegible]	43.6	[illegible]	2.1	2.2	2	4.75	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9.2	25.6	0.0035	0.0195	0.0230	0.0274	100.0	2.2	0.0	9.6	18.3	≈0	5.38	[illegible]	[illegible]	[illegible]	[illegible]	JP5
[illegible]	[illegible]	[illegible]	828	[illegible]	2373	9.0	[illegible]	0.0035	0.0164	0.0199	0.0238	100.0	3.4	0.0	8.4	15.5	↓	[illegible]	1494	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	830	[illegible]	2021	8.7	25.5	0.0035	0.0135	0.0170	0.0201	99.8	7.5	0.0	8.7	16.0	↓	5.24	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.4	[illegible]	0.0035	[illegible]	0.0140	0.0164	99.3	27.6	0.5	8.7	[illegible]	↓	5.31	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2741	8.2	[illegible]	0.0035	0.0195	0.0230	0.0268	99.9	2.9	0.0	10.5	19.2	↓	[illegible]	1541	[illegible]	1.26	[illegible]	Diesel #2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25.7	0.0035	0.0165	0.0200	0.0234	[illegible]	5.4	0.0	9.7	17.8	↓	[illegible]	[illegible]	[illegible]	[illegible]	1.44	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2028	[illegible]	[illegible]	[illegible]	0.0136	0.0171	0.0201	99.8	7.9	[illegible]	9.4	17.1	↓	5.29	1410	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25.4	[illegible]	0.0104	0.0140	[illegible]	[illegible]	28.5	0.4	9.7	17.5	↓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.2	25.7	[illegible]	0.0194	0.0229	[illegible]	[illegible]	2.7	0.0	10.7	19.8	↓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Blend A
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.3	[illegible]	[illegible]	[illegible]	0.0201	[illegible]	[illegible]	5.7	0.0	9.8	18.0	↓	[illegible]	1504	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2023	8.3	[illegible]	0.0035	[illegible]	0.0171	0.0199	99.8	9.5	0.1	9.5	17.3	↓	[illegible]	[illegible]	1324	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.4	[illegible]	0.0035	[illegible]	0.0140	0.0164	99.2	30.7	[illegible]	9.7	[illegible]	↓	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.4	[illegible]	[illegible]	[illegible]	0.0232	0.0268	99.9	[illegible]	0.0	10.6	19.4	↓	[illegible]	[illegible]	1274	[illegible]	[illegible]	Blend B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2298	[illegible]	25.4	[illegible]	0.0161	[illegible]	0.0235	99.9	[illegible]	0.0	9.9	17.4	↓	5.22	1454	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2028	9.4	25.4	[illegible]	[illegible]	[illegible]	0.0262	99.8	8.4	0.0	9.5	17.8	↓	[illegible]	1412	[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8.6	25.4	0.0035	[illegible]	[illegible]	[illegible]	[illegible]	28.3	0.4	9.8	18.1	↓	5.24	1310	[illegible]	[illegible]	[illegible]	

Idle Data were Obtained on D12A, Takeoff Data were Obtained on D13

Table A-V. Altitude Relight Test Results, Standard Production CF6-50 Combustor.

Table A-VI. Altitude Relight Test Results, Radial/Axial Staged Combustor, Configuration R7.

[illegible]

Table A-VII. Altitude Relight Test Results, Double Annular Combustor, Configuration D7.

Table A-VIII. Altitude Relight Test Results, Double Annular Combustor, Configuration D12.

[illegible]

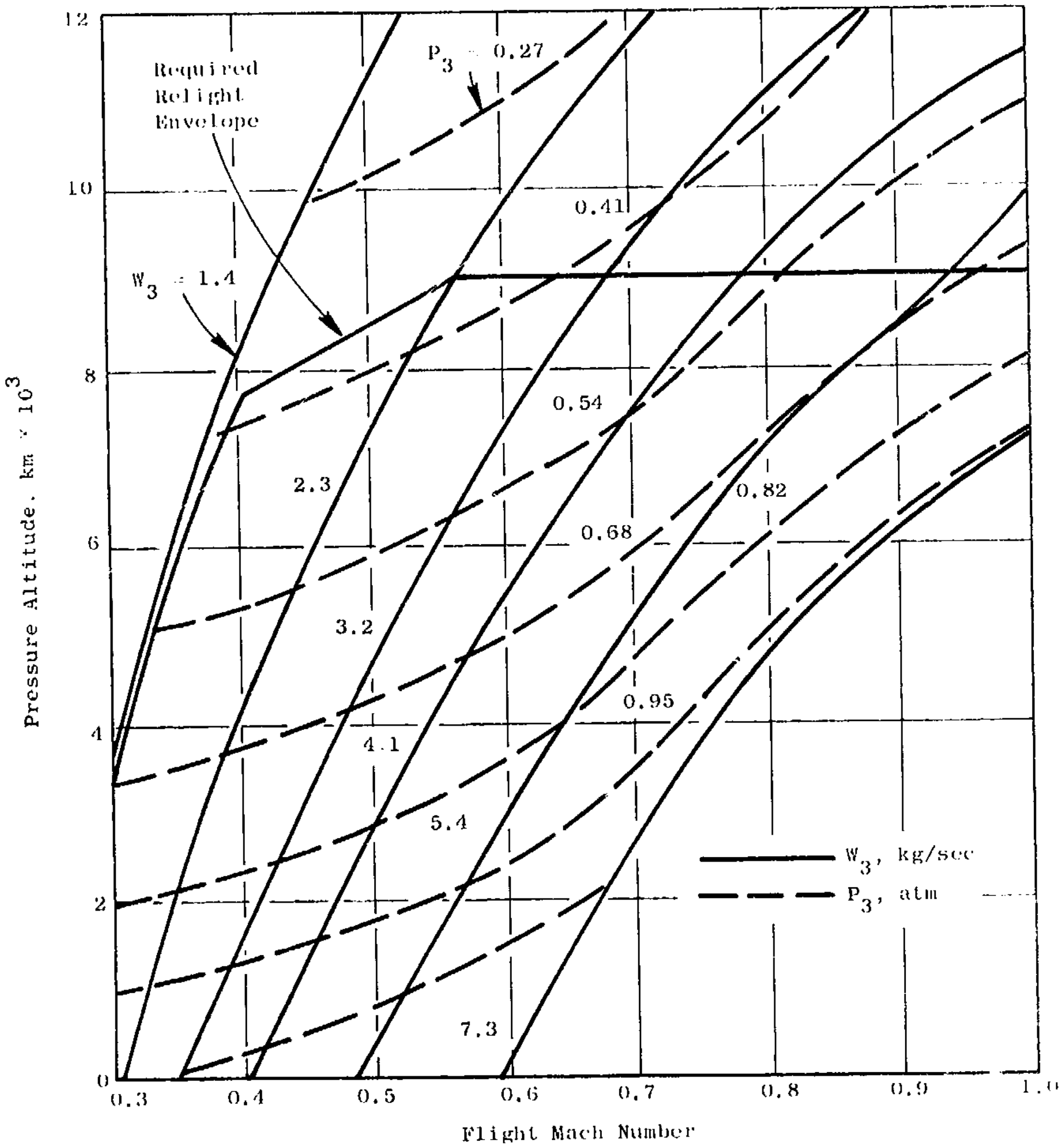

Figure A-1. CF6-50 Engine Windmilling Combustor Conditions.

Table A-IX. 12° Sector Test Results.

Combustor Configuration	Fuel Type	Combustor Operating Conditions				SAE Smoke Number	Flashback Indications	Post Test Inspection Carbon on	
		P_3 atm	T_3 K	V_r m/s	f -			Swirler Venturi	Fuel Nozzle
Radial/Axial Staged Combustor Configuration R7	JP-5	13.4	827	25.6	0.0231	1.7	NO	YES	YES
	Blend B	13.0	823	25.6	0.0231	4.9	NO		
	JP-5	16.1	829	25.6	0.0231	5.6	NO		
	Blend B	16.5	830	25.6	0.0231	6.3	YES		
Primary Swirler (1) Configuration 6 L_T/D_T = 0.58 A_{ES}/A_T = 0.32	JP-5	16.3	784		0.021	9.3	-	NO	NO
	Blend B	16.3	791		0.021	8.9	-		
	JP-5	18.4	822	25.6	0.0231	4.8	-		
	Blend B	18.4	820	25.6	0.0231	8.2	-		
Primary Swirler (1) Configuration 7 L_T/D_T = 0.58 A_{ES}/A_T = 0.38 Like Configuration D12/13	JP-5	11.7	634	23.2	0.014	1.7	-	NO	NO
	Blend B	11.8	630	23.2	0.014	0.7	-		
	JP-5	16.3	783	25.3	0.021	2.8	-		
	Blend B	16.3	783	25.3	0.021	0.9	-		
	JP-5	18.4	817	25.6	0.0231	2.7	-		
	Blend B	18.4	817	25.6	0.0231	2.1	-		

(1) Basis for Engine Design Selection of L_T/D_T = 0.58, A_{ES}/A_T = 0.36 where

A_{ES} = Primary Swirler Effective Flow Area

A_T = Venturi Throat Area ($\pi/4\ D_T^2$)

L_T = Distance from Primary Swirler to Venturi Throat

D_T = Venturi Throat Diameter

APPENDIX B

NOMENCLATURE

CO	Carbon Monoxide Emissions	
HC	Hydrocarbons Emissions (Assumed to have same composition as test fuel)	
NO_x	Oxides of Nitrogen Emissions (Calculated as NO_2)	
EI	Emissions Index	g pollutant/kg fuel
M_p	Flight Mach Number	---
P_3	Combustor Inlet Total Pressure	atm
T_3	Combustor Inlet Total Temperature	° K
T_f	Fuel Temperature	° K
T_B	Fuel Final Boiling Point	° K
V_r	Combustor Reference Velocity	m/s
W_3	Compressor Discharge Airflow Rate	kg/s
W_c	Combustor Airflow Rate (W_3) - (Turbine cooling airflow rate)	kg/s
W_f	Fuel Flow Rate	kg/hr
W_H	Fuel Hydrogen Content by Weight	g/g
f	Fuel-Air Ratio	---

APPENDIX C

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