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ERBS FUEL ADDENDUM
POLLUTION REDUCTION TECHNOLOGY PROGRAM
SMALL JET AIRCRAFT ENGINES

PHASE III - FINAL REPORT

by: T. W. Bruce, F. G. Davis
T. E. Kuhn, and H. C. Mongia

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

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16. Abstract

A Model TFE731-2 engine with a low-emission, variable-geometry combustion system was used to conduct a test to compare the effects of operating the engine on Commercial Jet A aviation turbine fuel and Experimental Referee Broad-Specification (ERBS) fuels. The engine was tested at the four Environmental Protection Agency (EPA), Landing and Takeoff (LTO) cycle-power points (taxi-idle, approach, climbout, and takeoff) on both fuels. Engine performance, gaseous emissions, smoke, and combustion liner wall temperature were measured.

The effect on engine performance was considered to be insignificant, with less than a 1-percent reduction in thrust measured with ERBS fuel at a corrected N_1 speed of 19,000 rpm (takeoff). Low-power emission levels were essentially identical; however, the high-power NO_x emission indexes were approximately 15-percent lower with the ERBS fuel. The exhaust smoke number was approximately 50-percent higher with ERBS at the takeoff thrust setting (31 for ERBS versus 22.5 for Jet A); however, both values were still below the EPA limit of 40 for the Model TFE731 engine. Primary-zone liner wall temperature ran an average of 25 K higher with ERBS fuel than with Jet A.

The test produced encouraging results for the possible adoption of broadened-properties fuels for gas turbine applications; however, extensive evaluation is still needed, especially in the areas of fuel-nozzle clogging, spray performance over long operating periods, low-temperature ignition, carbon formation, and liner durability.

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FOREWORD

This document is the final report for work performed as an addendum to the Phase III Pollution Reduction Technology Program for Small Jet Aircraft Engines - Class T1 (Contract NAS3-20819). This program addendum was conducted under the sponsorship and direction of the National Aeronautics and Space Administration (NASA) Lewis Research Center and the AiResearch Manufacturing Company of Arizona. The addendum program effort entailed evaluation of emissions and performance results obtained when using an Experimental Referee Broad-Specification (ERBS) fuel in the Garrett TFE731-2 engine with a low-emission combustion system, and comparison of these results with those obtained using Jet A fuel in the same engine.

The authors wish to acknowledge the assistance and guidance rendered by Mr. James S. Fear of the NASA Lewis Research Center, who was the Project Manager for the program.

NOTE: Effective January 1, 1981, the company name of AiResearch was changed to The Garrett Turbine Engine Company.

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A Model TFE731-2 engine with a low-emission, variable-geometry combustion system was used to conduct a test to compare the effects of operating the engine on Commercial Jet A aviation turbine fuel and Experimental Referee Broad-Specification (ERBS) fuels. The engine was tested at the four Environmental Protection Agency (EPA) Landing and Takeoff (LTO) cycle-power points (taxi-idle, approach, climbout, and takeoff) on both fuels. Engine performance, gaseous emissions, smoke, and combustion liner wall temperature were measured.

The effect on engine performance was considered to be insignificant, with less than a 1-percent reduction in thrust measured with ERBS fuel at a corrected N_1 speed of 19,000 rpm (takeoff). Low-power emission levels were essentially identical; however, the high-power NO_x emission indexes were approximately 15-percent lower with the ERBS fuel. The exhaust smoke number was approximately 50-percent higher with ERBS at the takeoff thrust setting (31 for ERBS versus 22.5 for Jet A); however, both values were still below the EPA limit of 40 for the Model TFE731 engine. Primary-zone liner wall temperature ran an average of 25 K higher with ERBS fuel than with Jet A.

The test produced encouraging results for the possible adoption of broadened-properties fuels for gas turbine applications; however, extensive evaluation is still needed, especially in the areas of fuel-nozzle clogging, spray performance over long operating periods, low-temperature ignition, carbon formation, and liner durability.

INTRODUCTION

Increasing fuel costs and the desire to reduce our national dependency on imported petroleum have prompted major research efforts regarding the utilization of alternative fuels and fuels manufactured from resources other than crude oil. With respect to aviation gas turbine engines, this emphasis has been on using fuels with broadened properties. Broadening the properties of fuels may allow them to become less expensive to produce and/or to be produced from alternative sources. To establish practical limits on broadened properties fuels, it is necessary to evaluate engine performance when using proposed fuels and to determine the degree of degradation, if any, in engine performance and durability as a result of the fuel change. That was the intent of this program.

The program was conducted as an addendum to Phase III of the NASA/AiResearch Pollution Reduction Technology Program (PRTP) for Small Jet Aircraft Engines. The overall goal of the program was to develop and demonstrate in engine tests an advanced technology combustion system that was capable of meeting the originally proposed EPA emission standards for T1 class engines, as established on July 17, 1973 (Reference 1). This was conducted in three phases. Phase I involved the rig test screening of three combustion concepts with several build iterations for their emission-reduction potential (Reference 2). Phase II took the two most promising concepts and further refined and optimized the systems for low emissions and engine-compatible performance (Reference 3). In Phase III, one of the combustor concepts, a variable-geometry system, was selected to undergo engine testing to verify emissions reductions and to evaluate engine performance (Reference 4).

The alternative fuel addendum to Phase III involved the engine testing of the final Phase III engine variable-geometry combustion system on ERBS fuel and comparing the test results with those obtained with Jet A aviation turbine fuel.

CHAPTER I

PROGRAM PLAN AND TEST FUELS

The ERBS Fuel Addendum to the Phase III NASA/AiResearch PRTP consisted of the following:

- Steady-state emissions and performance testing using ERBS fuel supplied by NASA on a Model TFE731-2 Turbofan engine with the Concept 2 variable-geometry combustion system installed.

- Analysis and comparison of the ERBS test data with the data previously taken using the same combustion system using Jet A aviation turbine fuel.

The engine test using the ERBS fuel was conducted immediately following the test on Jet A aviation turbine fuel. Tests were made at a total of four different engine power settings corresponding to the points required for the LTO Environmental Protection Agency Parameter (EPAP) calculations (taxi-idle, approach, climbout, and takeoff). Smoke and engine-performance parameters were also recorded at these power settings. These test conditions are shown in Table I.

NASA-supplied ERBS fuel was used for the test. This fuel has a final boiling point of 621 K and an aromatic content of 29.7 percent by volume, as compared to 538 K and 17 percent, respectively, for Jet A. Analyses of this fuel and Jet A are shown in Table II for comparison.

TABLE I. MODEL TFE731-2 ENGINE DESIGN DATA, SEA-LEVEL STATIC, STANDARD-DAY CONDITIONS.

Engine Mode	Net Thrust, kN	Fuel Flow kg/hr	Combustor Inlet Total Temp., K	Combustor Inlet Total Pressure, kPa	Combustor Fuel/Air Ratio
Taxi-idle	0.9	87.3	369.9	202.1	0.0105
Approach	4.7	241.4	504.5	531.8	0.0115
Climbout	14.0	667.6	665.9	1301	0.0147
Takeoff	15.6	754.3	684.6	1425	0.0154

TABLE II. CHEMICAL ANALYSIS OF ERBS AND JET A FUELS

	ERBS	Jet A
Hydrogen Content, (% wt)	13.09	13.57
Hydrogen/Carbon Weight Ratio	0.149	0.157
Aromatic Content (% vol)	29.7	17.0
Naphthalene Content (% vol)	--	1.6
Distillation Temperature (K)		
Initial Boiling Point	447	436
5 Percent	458	448
10 Percent	461	457
20 Percent	467	467
30 Percent	472	473
40 Percent	478	479
50 Percent	486	486
60 Percent	494	493
70 Percent	506	501
80 Percent	532	508
90 Percent	562	521
95 Percent	591	531
End Point	621	538
Percent Distilled	97	98.5
Viscosity Centistokes at 100°F	1.7	1.6
Freezing Point, °K	253	--
Flash Point, °K	339	334
Lower Heating Valve, btu/lb	18,310	18,520
Gravity, °API (Sp Gr) at 60°F	37.8 (0.836)	41.3 (0.819)

CHAPTER II

EQUIPMENT AND EXPERIMENTAL PROCEDURES

Except for the use of the ERBS fuel, the equipment and experimental procedures used in this addendum were identical to those used in the NASA/AiResearch PRTP Phase III. A brief description is included in the following paragraphs. A more detailed description can be found in Reference 4.

Model TFE731-2 Engine Description

The Model TFE731-2 is a two-spool turbofan engine utilizing a reverse-flow, annular combustion chamber. The engine is rated at 15.6 kN thrust and has a bypass ratio of 2.67. The front fan is coupled to the low-pressure (LP) compressor through a planetary gearbox that reduces the fan speed. The LP compressor is a four-stage axial configuration that is followed by a single-stage, centrifugal, high-pressure (HP) compressor. The turbine consists of a single-stage HP and three-stage LP sections. The engine is shown in Figure 1.

The Model TFE731-2, S/N 7353, engine was used exclusively for the Phase III and the ERBS Fuel Addendum testing. The development engine was slightly modified to accept the new combustion system hardware, with the major change being the replacement of the fuel pump with an AiResearch Model ATF3-6 engine pump. This pump was required to provide an additional fuel pressure source for actuation components of the variable-geometry combustion system.

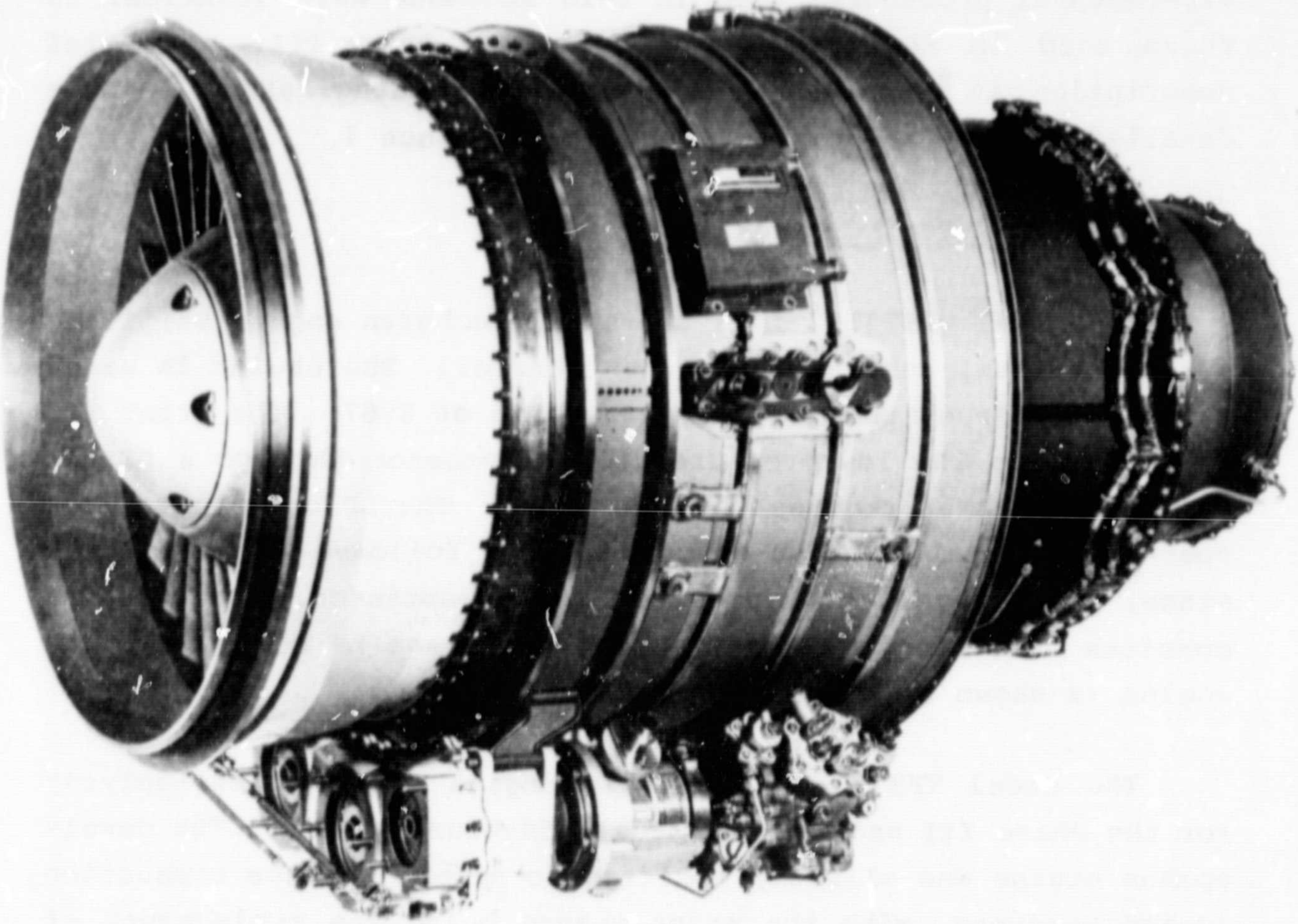

Figure 1. Left-Front View of AiResearch Model TFE731 Turbofan Engine.

MP-42778

Concept 2 Variable-Geometry Combustor

The combustion system utilized for this test was referred to as Concept 2 and employed variable geometry as a means for controlling the reaction-zone equivalence ratio and, hence, the emissions levels. The Concept 2 system was developed over the course of the three phases of the NASA/AiResearch PRTP and used butterfly valves mounted on the 20 combustor dome swirlers to control the airflow through this hardware. A typical valve-swirler assembly is shown in Figure 2. The valves were connected through linkages to a unison ring that was operated by a hydraulic actuator. The actuator was operated by fuel pressure and was controlled by an electronic control that allowed the valves to be set at any position between full closed and full open. Figure 3 shows a combustor assembly with the 20 valve-swirlers attached. Figure 4 is a photograph of the combustion system subassembly showing the unison ring and actuator.

The fuel injectors for the test were piloted airblast nozzles with 0.7 flow number* pressure-atomizing nozzles being used as pilots. A conventional engine flow-divider valve was modified to phase in fuel flow to the airblast nozzles at power settings above taxi-idle. Figure 5 shows the piloted airblast injector used in this test.

The combustor operation parameters at the sea-level, standard-day, static conditions at takeoff are presented in Figure 6.

$$\text{*Flow number} = \frac{\text{fuel flow rate}}{(\text{differential fuel pressure})^{1/2}}$$

Figure 2. Valve Housing Assembly.

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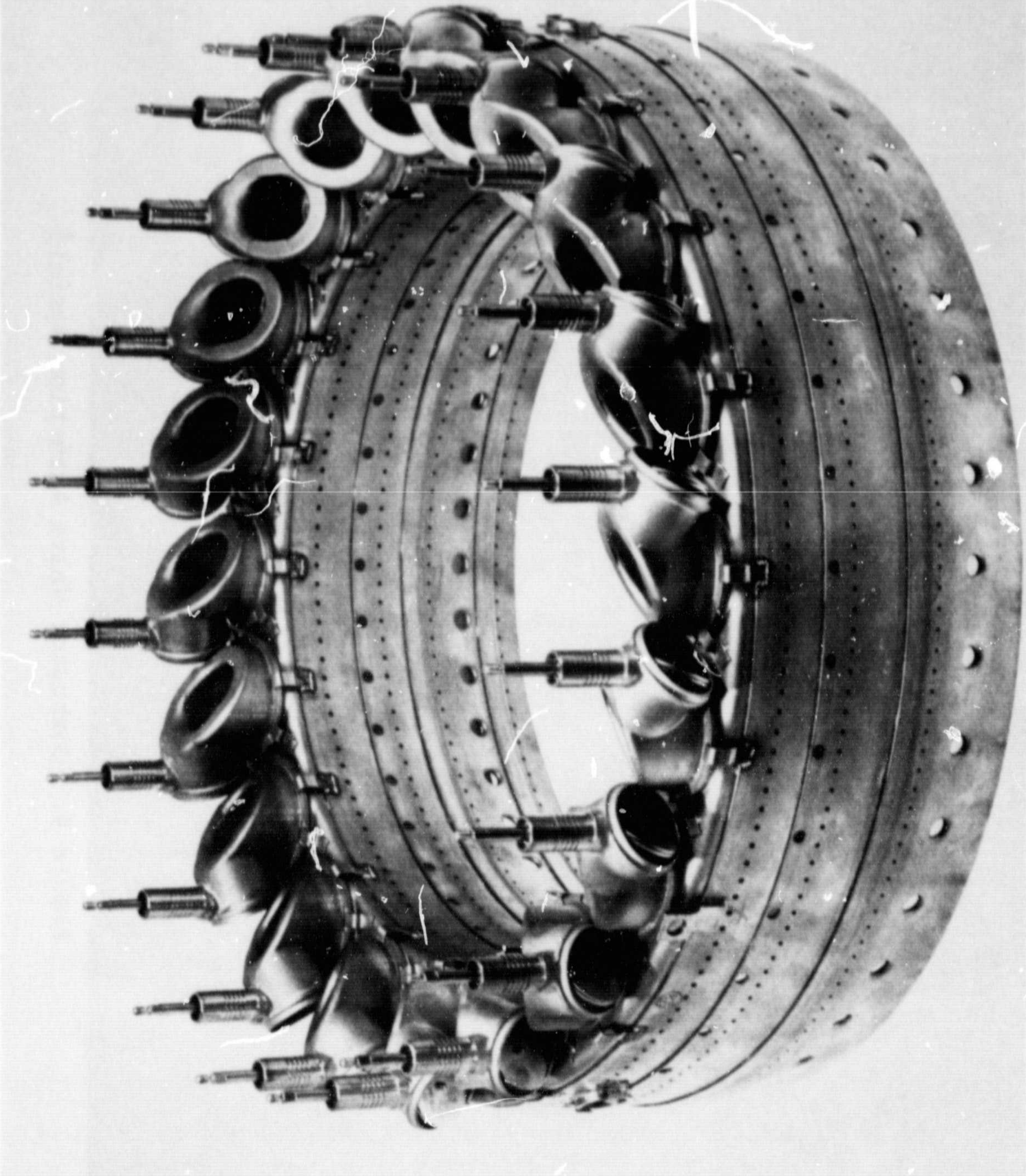

Figure 3. Combustor and Valve Assembly.

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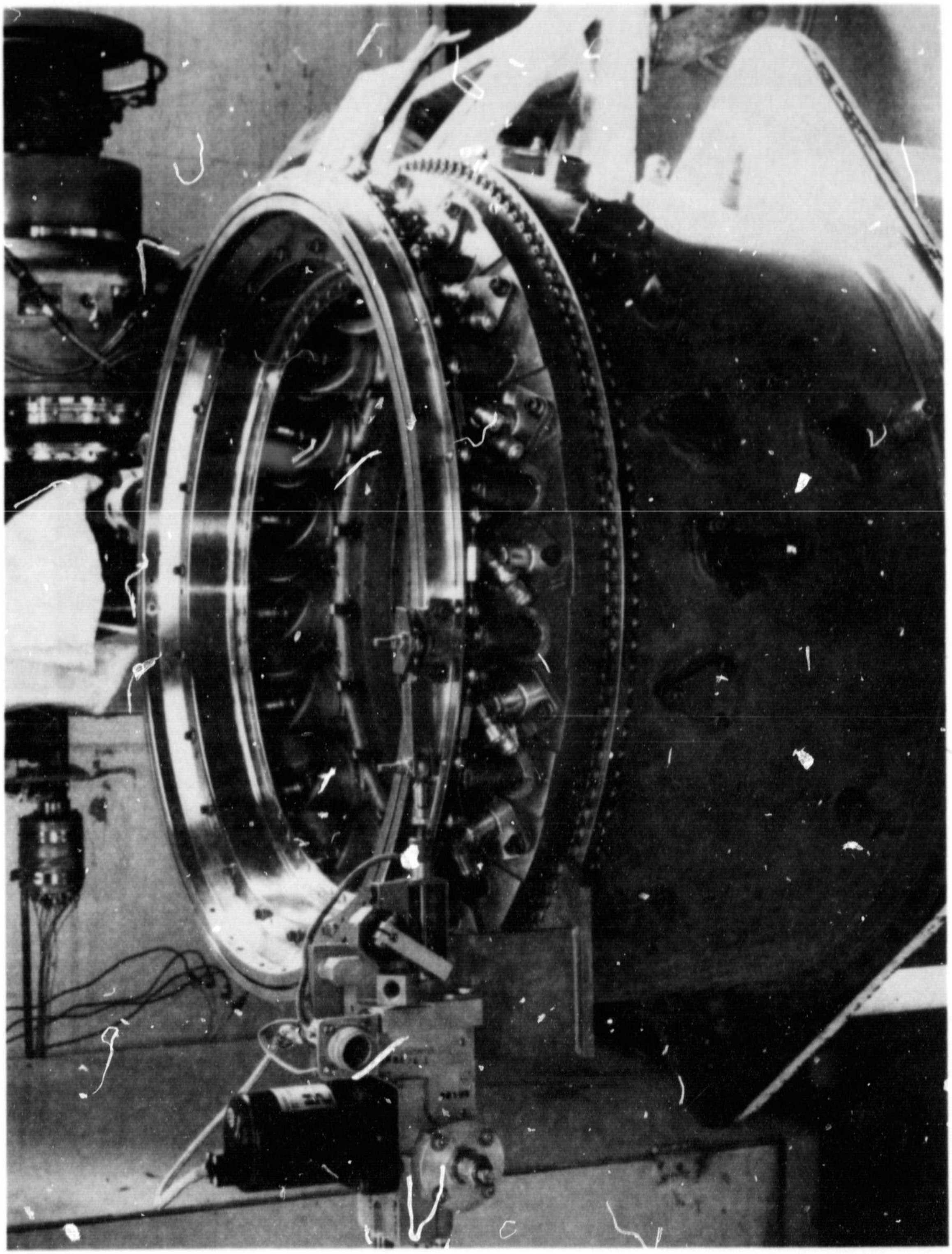

Figure 4. Combustor Valve Actuation System.

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Figure 5. Fuel Nozzle, Part 3551831

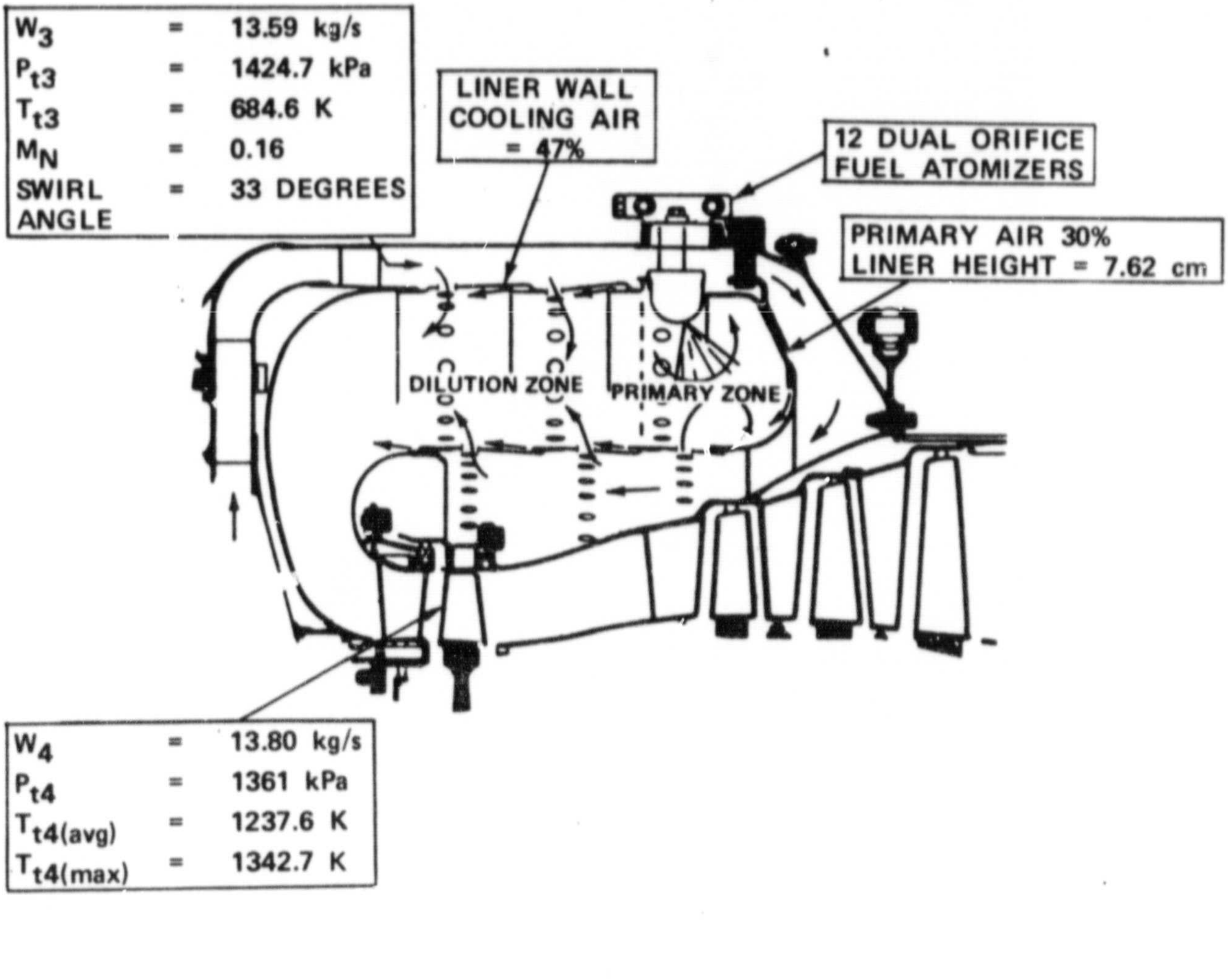


Figure 6. Production TFE731-2 Reverse-Flow Annular Combustor System, Sea-Level, Standard-Day, Static Conditions at Takeoff.

Test Facilities

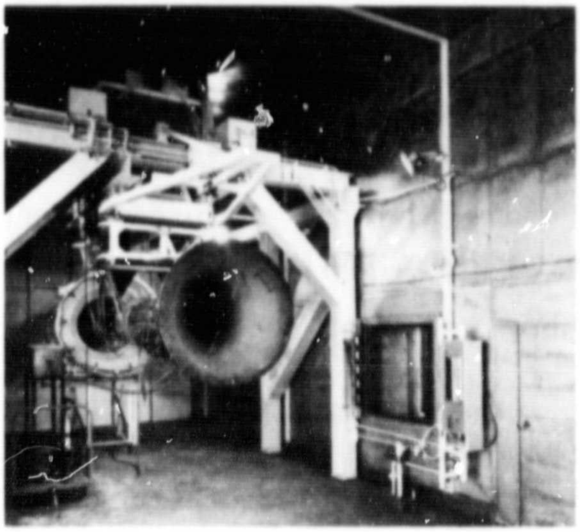
The Model TFE731-2 engine was tested in the AiResearch (Phoenix) engine test facility. This facility, shown in Figure 7, is utilized for development, qualification, and production testing of Garrett prime propulsion turbofan engines.

Engine/Combustor Instrumentation

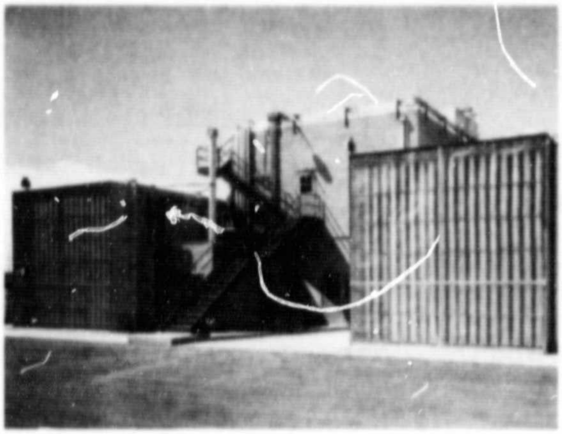
The instrumentation required to evaluate engine and combustor performance was incorporated during Phase III of the PRTP. This instrumentation was also used during the ERBS Fuel Addendum. A listing of the instrumentation is presented in Table III. In addition to this instrumentation, an emission-sampling probe was used to measure the gaseous and particulate emissions. The location of the probe installation is shown in Figure 8. The probe had 24 sampling points and could be operated on one of two 12-point circuits or one 24-point sampling mode. A photograph of the probe is shown in Figure 9.

In the Phase III engine testing, wall temperatures were determined by the application of temperature-sensitive paint to the liner walls. For the ERBS Fuel Addendum, to more precisely determine combustor-wall temperatures, 16 thermocouples were attached to the liner wall in areas that had previously been determined as hot zones and in intermediate positions. Figure 10 shows a typical installation of a portion of the thermocouples.

The AiResearch exhaust-gas emissions sampling and analysis equipment that was used in the program consisted of two basic types: that used for sampling gaseous emissions of NO_x, HC, CO, and CO_2; and that used to obtain the smoke number of insoluble particulates in the exhaust gas. The analyzers, together with



TYPICAL TEST CELL



DUAL TEST FACILITY FOR TURBOFAN/TURBOJET ENGINES

ENGINE TEST CONSOLE

DATA-ACQUISITION SYSTEM

Figure 7. Propulsion Engine Test Facility.

MP-62294.

TABLE IX. ENGINE INSTRUMENTATION.

Parameter	Symbol and Station	Unit	Engine Range	Total Req'd Recording Accuracy (Full Scale)	Sensor Type
Low rotor speed	N_1	rpm	4K-25K	±0.25%	1 monopole
High rotor speed	N_2	rpm	15K-30K	±0.3%	1 monopole
Burner plenum pressure	P_{CD}	kPa	200-1793	±0.5%	1 static tap
HPT discharge temperature	$T_{t5.0}$	K	422-1200	±5K	4 one-element probes
LPT discharge pressure	$P_{T7.0}$	kPa	103-207	±0.5%	5 five-element probes
Bellmouth total pressure	$P_{T1.2}$	kPa	90-103	±0.5%	6 one-element probes
Bellmouth static pressure	$P_{S1.2}$	kPa	90-103	±0.5%	6 static taps
Inlet screen temperature	$T_{t1.0}$	K	266-322	±2K	5 sets of 2 thermocouples
LPT discharge temperature	$T_{t7.0}$	K	394-922	±5K	5 two-element probes
LPT discharge pressure	$P_{T7.0}$	kPa	103-207	±0.5%	5 five-element probes
Primary nozzle discharge static pressure	$P_{S8.0}$	kPa	90-103	±0.5%	4 static taps
Fuel flow	W_F	kg/sec	0.024-0.376	±0.5%	2 turbine meters, 1 rotometer
Fuel pressure, primary	P_{WFP}	kPa	0-6895	±0.5%	1 transducer
Fuel pressure, secondary	P_{WFS}	kPa	0-6895	±0.5%	1 transducer
Specific gravity, fuel	FSG	-	0.7-0.9	±0.5%	
Fuel temperature	T_{FUEL}	K	283-311	±2K	1 thermocouple
Measured thrust	F_{MEAS}	kN	0-22.2	±0.5%	2 load cells
Barometric pressure	P_{BAR}	kPa	90-103	±0.5%	
Power lever angle	PLA	deg	0-120	±1°	
HPC discharge temperature	$T_{t3.0}$	K	355-755	±3K	6 one-element probes
HPC discharge pressure	$P_{T3.0}$	kPa	200-1793	±0.5%	6 one-element probes

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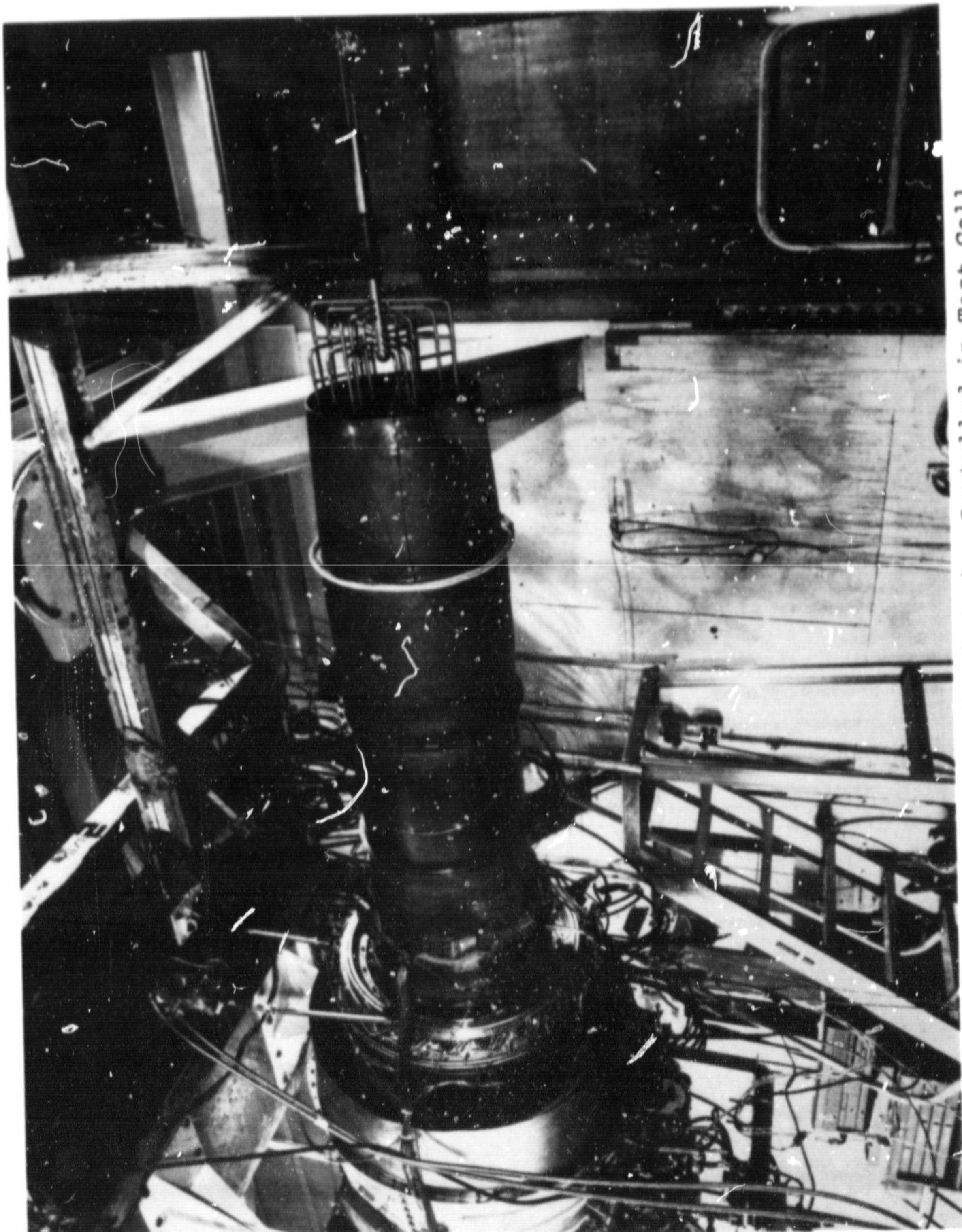


Figure 8. Model TFE731-2 Engine Installed in Test Cell.

MP-68502

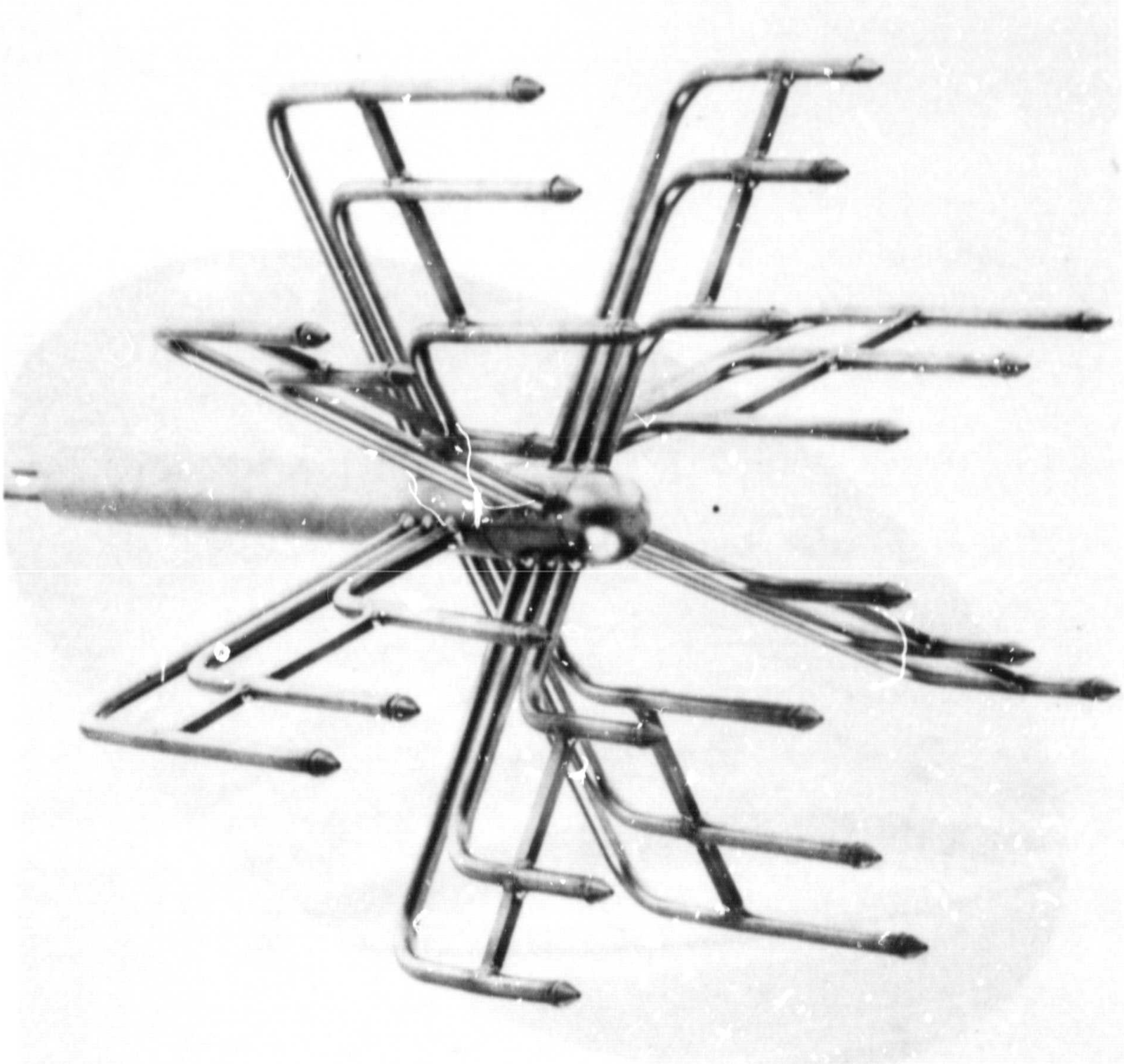


Figure 9. Emission Sampling Probe.

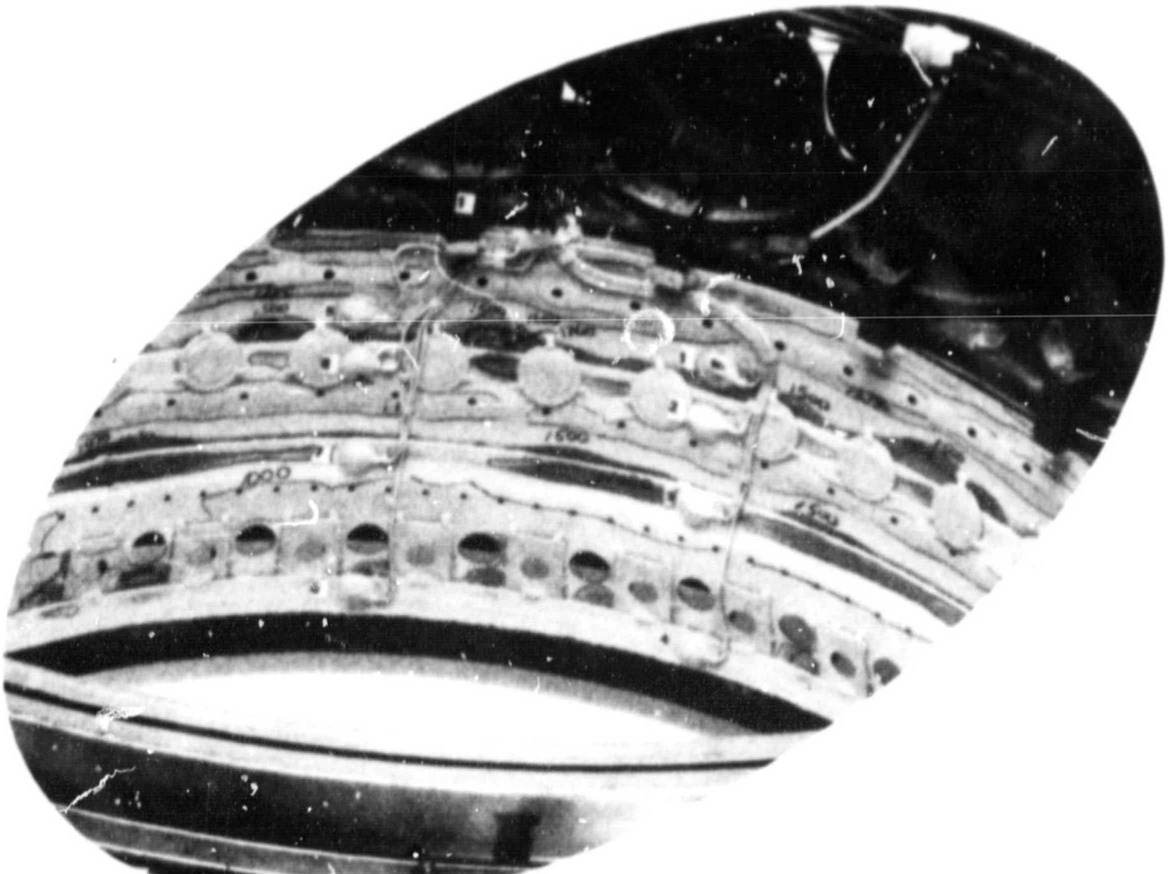


Figure 10. Typical Wall Thermocouple Installation

all required calibration gases and other support equipment, were installed in the mobile units shown in Figures 11 and 12. All equipment, including plumbing and materials, conforms to EPA recommendations on exhaust emission analysis, as specified in Section 87.82 of Reference 1. A schematic of the gas analyzer flow system is shown in Figure 13, and the exhaust smoke measurement system schematic is shown in Figure 14.

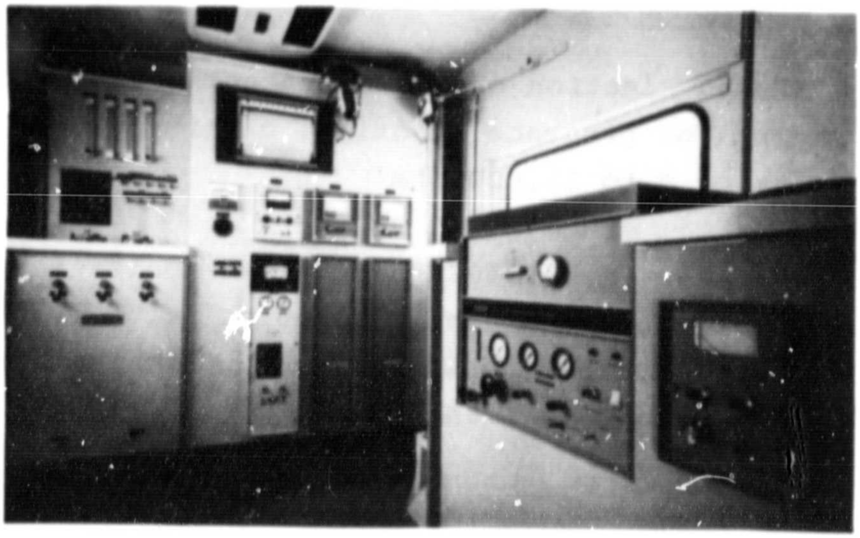
The gaseous emission analysis equipment consisted of the following analyzers, along with the refrigeration, gasifier, filtration, and pumping devices required for obtaining and processing the samples:

- A Thermo Electron chemiluminescent analyzer for determining the presence of oxides of nitrogen (NO_x) over a range of 0 to 10,000 ppm

- A Beckman Model 402 hot flame-ionization-detection hydrocarbon analyzer capable of discriminating unburned hydrocarbons (HC) in the sample over a range of 5 ppm to 10 percent

- A Beckman Model 315B carbon-monoxide (CO) analyzer. This analyzer has three discrete sensitivity ranges corresponding to 0 to 100, 0 to 500 and 0 to 2500 ppm

- A Beckman Model 315B carbon-dioxide (CO_2) analyzer. The sensitivity ranges of this analyzer correspond to 0 to 2, 0 to 5, and 0 to 15 percent. (The measurement of CO_2 is not specifically required for the determination of pollutant emission rates. However, AiResearch conducts analyses of CO_2 in engine exhaust gases to provide a carbon balance with the fuel consumed as a means of checking the validity of test data.)



GAS MEASURED	INSTRUMENT
OXIDES OF NITROGEN	CHEMILUMINESCENT ANALYZER
HYDROCARBONS	FLAME IONIZATION DETECTOR
CARBON MONOXIDE CARBON DIOXIDE	NON-DISPERSIVE INFRARED ANALYZER

Figure 11. Gaseous Exhaust Emissions Measurement Instrumentation.

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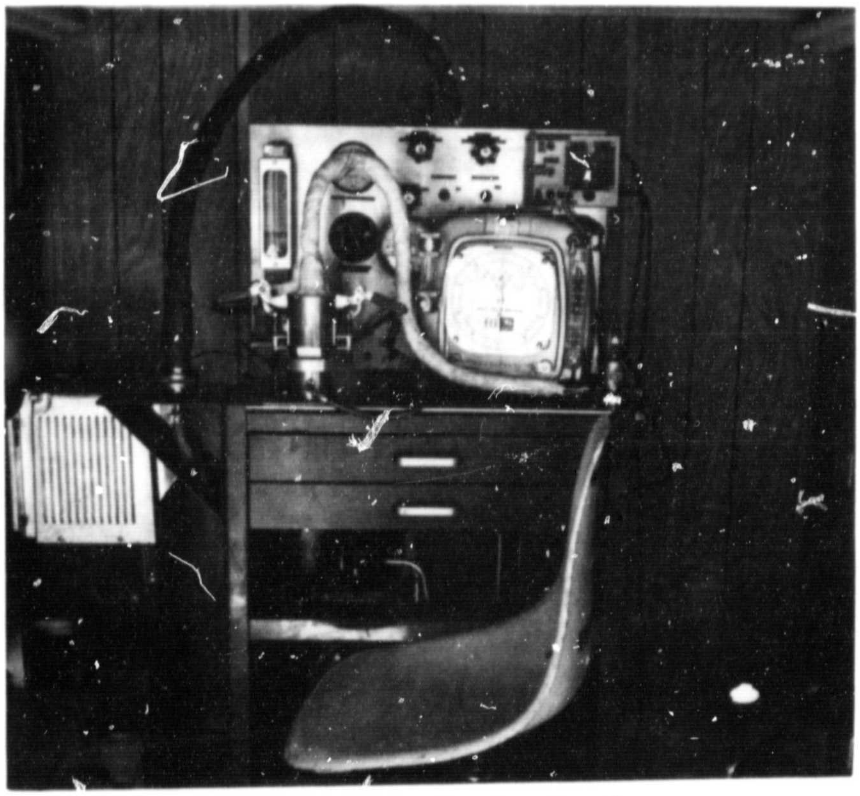

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Figure 12. Mobile Smoke Analyzer.

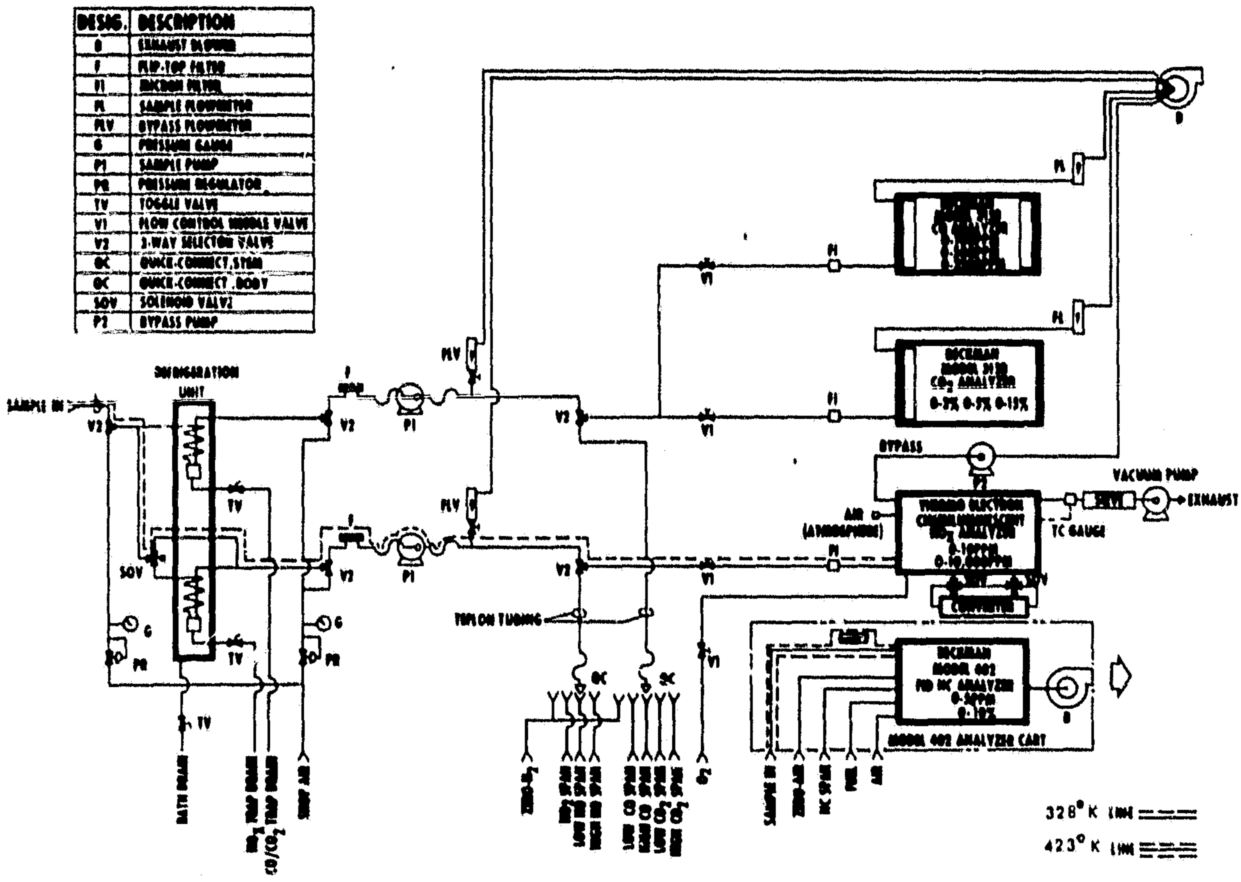

Figure 13. Exhaust Gas Analyzer Flow System.

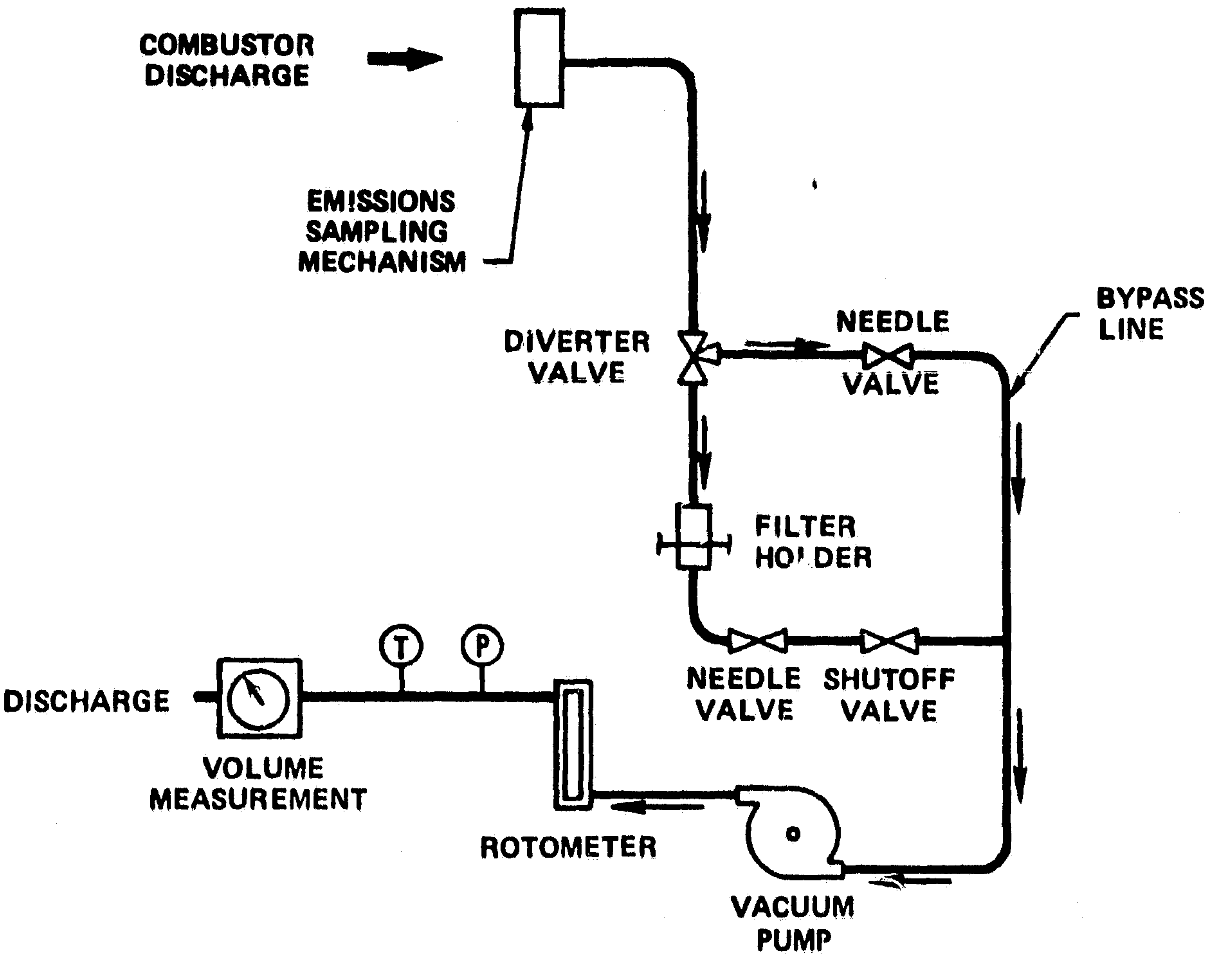

Figure 14. Particulate Analyzer Flow System.

All instruments, zero gases, and span gases were kept at a constant temperature to avoid drift. The equipment is capable of continuously monitoring NO_x, HC, CO, and CO_2 in exhaust gases. The zero and span gases used to calibrate the instruments are given in Table IV.

For exhaust smoke emissions, sample size measurements were made with a Precision Scientific Wet Test Meter accurate to within ±0.005 standard cubic meter. Wet test pressure and temperature were measured within ±68 Pa and 0.50 K, respectively. Sample flow measurements were conducted with a Brooks Rotormeter Model 110, accurate to within ±1.7 cm^3/min. A Duo-Seal Model 1405 vacuum pump, with a free-flow capacity of 0.57 cm^3/min and no-flow vacuum capability of 1 micron, was used. Reflectance measurements were conducted with a Welch Densichron Model 3837 photometer.

Data Acquisition and Reduction Procedure

All engine performance and emission data were recorded by a high-speed digital acquisition system (DAS). This system processed the data in real time and provided CRT displays of key engine and emission parameters for the purpose of setting accurate power points. In addition, the DAS provided "hard" copies of the CRT displays and stored test data on magnetic tape for more detailed data reduction that was performed at the conclusion of each test. This final data reduction program took the magnetic tape data and calculated engine-performance parameters and emission indexes for each specific power setting, and provided a printout, as typified in Figure 15. The emission indexes calculated from this program were manually selected and input into an EPAP calculation program. This program corrected NO_x emission-index values for variations in humidity and combustor inlet pressure and temperature by the expression:

TABLE IV. ZERO AND SPAN GASES

Gas	Concentration	Manufacturer
Zero Air and N_2	HC $<$ 1.0 ppm	Air Products
C_3H_8 in Air	6.3 ppm 52.0 ppm 105.0 ppm	Air Products
NO in N_2	16.9 ppm 46.5 ppm 109.0 ppm	Scott Research Labs
CO in N_2	65.0 ppm 250.0 ppm 440.0 ppm	Air Products Matheson Air Products
CO_2 in N_2	1.05% 9.97% 3.05%	Scott Research Labs

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ENGINE MFG.: AIRESEARCH        TEST FACILITY: PHX C-92        INSTR. DESCRIP.: REPORT 61-8747-H           CALC. DATE: 24 APR 74
MODEL NO.: TFE731-2            S/N: 7310-12005   ENGINE TYPE (CLASS): T1,TURBOFAN          CALC. I.D. 11484   UNITS: ENGLISH ENGR.
RATED POWER:   3500.0 LB. THRUST AT SEA LEVEL STANDARD DAY CONDITIONS
FUEL: ASTM D1655-73T,JET A-1   ATOMIC H/C RATIO:   1.928     LHV: 18479. BTU/LB     ADDITIVES:    NONE

******** EXHAUST EMISSIONS PER EPA CYCLE OF WORK OUTPUT ** CODE OF FEDERAL REGULATIONS TITLE 40 PART 87  17 JULY 1973 ********
                  HYDROCARBONS (HC AS CH4)          5.386 LB. POLLUTANT PER 1000 LB.-THRUST-HR. PER CYCLE
                  CARBON MONOXIDE (CO)             16.199 LB. POLLUTANT PER 1000 LB.-THRUST-HR. PER CYCLE
                  OXIDES OF NITROGEN (NOX AS NO2)   6.017 LB. POLLUTANT PER 1000 LB.-THRUST-HR. PER CYCLE
                  SMOKE                               46. SMOKE NUMBER, MAXIMUM AT  APPROACH  MODE.  75 PERCENT RATED POWER
TAXI-IDLE SETTING:   200.0 LB. THRUST ( 5.71 PERCENT RATED TAKE-OFF POWER )

************************************************* ENGINE DESCRIPTION ***************************************************
COMBUSTOR TYPE: REVERSE FLOW ANNULAR    P/N: 3072246-2  SURFACE/VOLUME:  .025 SQ IN/CU IN    FUEL INJ. TYPE:  PRESS.ATOMIZER
ENGINE TOTAL SERVICE:   NA     HR.   TIME SINCE ENGINE OVERHAUL:  NA      HR.
ENGINE ASSEMBLY AND MAINTENANCE INFORMATION:  LABORATORY DEVELOPEMENT ENGINE

AIRCRAFT INSTALLATION *** MFR.:      NA                          MODEL NO.:   NA
                          USER:      NA              ENGINE INSTALLATION POSITION:       NA

************************************************OPERATIONAL TEST DATA SUMMARY ********************************************
GASEOUS EMISSION TEST NO.: 145         DATE: 10 APR 74           TIME: 2100                BARO PRESS.:  28.510 IN. HGA.
AMBIENT AIR TEMP.:  77.00 DEG. F       RELATIVE HUMIDITY:  16.00 PERCENT       SPECIFIC HUMIDITY:  .003271 LB. H2O/LB. DRY AIR
AMBIENT AIR QUALITY    HYDROCARBONS (HC):   NT  PPMC     CARBON MONOXIDE (CO):  NT    PPMV    OXIDES OF NITROGEN (NOX):  NT    PPMV
SAMPLE LINE *** TEMP.:  300.00 DEG. F.     FLOWRATE:   14.16 LITERS/MIN.     TRANSPORT TIME:     .70 SEC.     LENGTH:   24.00 FT.

****************************************************** COMPUTED EMISSIONS *******************************************************
```

TEST CONDITION	1	2	3	4	5	6	7
ACTUAL POWER SETTING, LB. THRUST	3235.7	2934.2	2402.4	1631.9	903.5	445.3	207.5
CORR. POWER SETTING (STD DAY), PERCENT RATED	97.02	87.98	72.03	48.93	29.40	13.35	6.22
N1 SPEED, RPM	19846.28	19299.50	18039.00	15579.00	12549.50	8746.60	6072.70
N2 SPEED, RPM	29380.90	29014.00	28264.30	26924.50	25074.20	21533.20	17386.30
FUEL FLOW (MEAS.) LB./HR.	1688.1	1523.7	1235.5	849.0	539.0	284.7	169.0
CORR. ENGINE CORE AIRFLOW (CALC), LB/SEC	30.64	28.77	25.28	19.27	13.77	8.07	6.04
ENGINE PRESSURE RATIO	1.58	1.51	1.38	1.21	1.11	1.04	1.02
COMPRESSOR INLET AIR TOTAL TEMP., DEG F	78.8	79.7	79.4	79.1	79.2	79.0	80.0
COMPRESSOR INLET AIR TOTAL PRESS., PSIA	14.01	14.01	14.01	14.01	14.01	14.02	14.02
COMPRESSOR DISCHARGE AIR TOTAL PRESS., PSIA	179.87	167.18	141.63	102.37	60.05	40.77	27.09
COMPRESSOR DISCHARGE AIR TOTAL TEMP., DEG F	790.5	769.2	704.8	596.7	473.4	322.8	224.5
COMPRESSOR BLEED AIRFLOW (MEAS), LB/SEC							
TURBINE INLET GAS TOTAL TEMP., DEG F	1867.5	1748.6	1641.8	1505.1	1314.4	1059.5	894.8
TURBINE INTERSTAGE GAS TOTAL TEMP., DEG F	1596.9	1470.2	1382.9	1260.9	1095.6	897.0	794.7
EXHAUST GAS STATIC PRESSURE, PSIA							
EXHAUST GAS TOTAL PRESSURE, PSIA							
ENGINE EXHAUST GAS TEMP., DEG. F	1026.1	1009.2	955.5	897.6	853.0	783.6	760.8
EMISSION CONCENTRATION, WET ANALYSIS							
HYDROCARBON (HC AS CH4), PPMC	3.650	3.346	3.042	4.867	67.522	252.435	395.370
CARBON MONOXIDE (CO), PPMV	21.487	25.044	37.913	92.206	272.352	620.999	816.464
TOTAL OXIDES OF NITROGEN (NOX), PPMV	287.866	178.712	132.317	83.899	55.741	20.082	17.234
CARBON DIOXIDE (CO2), PERCENT BY VOL.	3.471	3.302	3.005	2.025	2.407	2.119	1.917
NITRIC OXIDE (NO), PPMV	183.024	156.658	115.401	70.212	45.623	18.949	5.576
EMISSION INDEX, LB. POLLUTANT/1000 LB. FUEL							
HYDROCARBONS (HC AS CH4)	.121	.113	.113	.197	3.073	13.180	22.482
CARBON MONOXIDE (CO)	1.242	1.485	2.405	6.534	21.689	48.321	61.130
TOTAL OXIDES OF NITROGEN (NOX AS NO2)	19.732	17.407	14.123	9.760	7.204	4.214	2.016
EMISSION RATE, LB. POLLUTANT/HR.							
HYDROCARBONS (HC AS CH4)	.204	.173	.140	.167	1.659	3.752	3.700
CARBON MONOXIDE (CO)	2.097	2.263	2.971	5.549	11.711	13.757	10.329
TOTAL OXIDES OF NITROGEN (NOX AS NO2)	33.318	26.523	17.448	8.286	3.910	1.206	.476
COMBUSTION EFFICIENCY, PERCENT (EMISSIONS)	99.96	99.94	99.93	99.83	99.22	97.71	96.59
F/A (EMISSIONS,CALC)	.0170	.0166	.0151	.0130	.0123	.0107	.0098

Figure 15. Example Exhaust Emissions per EPA Cycle of Work Output.

$$EI_{CORR} = EI_{MEAS} \left(\frac{P_{T_3\ MODEL}}{P_{T_3\ MEAS}} \right)^{0.5} e^{(T_{T_3\ MODEL} - T_{T_3\ MEAS})/288}$$

$$\times\ e^{19(H_{MEAS} - H_{STD})}$$

HC and CO emission indexes were corrected for variations in combustor inlet pressure by the expression:

$$EI_{CORR} = EI_{MEAS} \left(\frac{P_{T_3\ MEAS}}{P_{T_3\ MODEL}} \right)$$

where:

EI	=	Emission index, g/kg fuel
CORR	=	Corrected values used in EPAP calculation
MEAS	=	Measured values as recorded during the test
MODEL	=	Model values as predicted for a nominal engine at standard-day, sea-level, static conditions
P_{T_3}	=	Combustor inlet pressure, kPa
T_{T_3}	=	Combustor inlet temperature, K
H	=	Inlet specific humidity, g H_2O/g air
H_{STD}	=	0.00634 g H_2O/g air

The corrected emission indexes were then used to calculate the EPAPs. A sample printout is shown in Figure 16.

EPA CYCLE EMISSIONS COMPUTATION SUMMARY

MINIMUM EPA LTO-CYCLE PARAMETER FOR CARBON MONOXIDE EMISSIONS

CONCEPT NO. 2 TEST TFE731-2 7353-42/01 COMBUSTOR P/N 3551834-7 AIR HUMIDITY,GM H2O/GM AIR .0056082 TEST DATE 14,20MAY80
SWIRLERS 3551852-2 45DEG VANE FUEL MANIFOLD 3551831-1 .7FN PRI FUEL ERBS
NOX CORRECTION PRESSURE EXPONENT AT CLIMBOUT = .500 NOX CORRECTION PRESSURE EXPONENT AT TAKEOFF = .500
HUMIDITY CORRECTION FACTOR = EXP(19*(.00634-LB H2O/LB AIR))
HC AND CO EMISSION INDEX CORRECTED BY PCD MEAS./ PCD MODEL PRESSURE RATIO

MODE CONDITION NUMBER	TAXI-IDLE 2012	APPROACH 4003	CLIMBOUT 8293	TAKEOFF 9293	TOTAL PER CYCLE
TIME IN MODE,MINUTES	26.00	4.50	2.50	.50	33.50
RATED POWER,MEAS.,PERCENT	5.719	10.565	66.958	79.706	
CORRECTED NET THRUST,MEAS.,LBF.	200.151	369.779	2343.516	2789.693	
CORRECTED NET THRUST,MODEL,LBF.	200.000	1049.800	3148.600	3501.600	
1000 LB.THRUST-HR,MODEL	.08667	.07873	.13119	.02917	.32577
COMPRESSOR DISCHARGE PRESSURE,MODEL,PSIA.	29.319	77.137	188.658	206.633	
COMPRESSOR DISCHARGE PRESSURE,MEAS.,PSIA.	30.230	41.990	154.309	176.085	
COMPRESSOR DISCHARGE TEMP.,MODEL,DEG.F	206.200	448.400	738.200	772.500	
COMPRESSOR DISCHARGE TEMP.,MEAS.,DEG.F	232.907	335.875	703.635	751.618	
FUEL FLOW,MODEL,LB/HR(USED IN CYCLE CALC)	194.490	537.240	1485.570	1676.550	
FUEL FLOW,MEAS.,LB/HR	185.743	287.330	1235.410	1459.573	
FUEL/AIR RATIO (CALC. FROM EMISSIONS) AT MODE	.01653	.01151	.01484	.01554	
** HYDROCARBON EMISSIONS (HC) **					
INDEX,LB HC/1000 LB FUEL	.421	.743	.186	.278	
INDEX,LB HC/1000 LB FUEL,CORRECTED FOR PRESSURE	.434	.404	.152	.241	
RATE,LB HC/HR	.084	.217	.226	.404	
MASS,LB HC	.037	.016	.009	.003	.066
MASS,PERCENT OF TOTAL CYCLE	55.72	24.82	14.33	5.13	100.0
CYCLE,LB HC/1000 LB THRUST-HR PER CYCLE					.201
** CARBON MONOXIDE EMISSIONS (CO) **					
INDEX,LB CO/1000 LB FUEL	26.918	23.379	7.336	2.217	
INDEX,LB CO/1000 LB FUEL,CORRECTED FOR PRESSURE	27.754	12.726	6.000	1.919	
RATE,LB CO/HR	5.398	6.837	8.913	3.222	
MASS,LB CO	2.339	.513	.371	.027	3.250
MASS,PERCENT OF TOTAL CYCLE	71.97	15.78	11.43	.83	100.0
CYCLE,LB CO/1000 LB THRUST-HR PER CYCLE					9.977
** TOTAL OXIDES OF NITROGEN EMISSIONS (NOX) **					
INDEX,LB NOX/1000 LB FUEL	3.970	5.055	10.032	12.588	
INDEX,LB NOX/1000 LB FUEL,CORRECTED FOR PRESS.,TEMP.,HUMIDITY	3.662	8.396	11.693	13.691	
RATE,LB NOX/HR	.712	4.559	17.371	23.316	
MASS,LB NOX	.309	.338	.724	.194	1.565
MASS,PERCENT OF TOTAL CYCLE	19.72	21.61	46.25	12.42	100.0
CYCLE,LB NOX/1000 LB THRUST-HR PER CYCLE					4.804

** EMISSION INDEX LEVELS REQUIRED TO MEET EPA 1979 STANDARDS FOR CLASS T1 ENGINES **

EPA LTO-CYCLE

POLLUTANT	LBP/1000 LB THRUST-HR-CYCLE
CO	9.4
HC	1.6
NOX	3.7

REQUIRED EMISSION INDEX, LBP/1000 LB FUEL

POLLUTANT (MODE)	A	B
CO (IDLE)	26.1	25.5
HC (IDLE)	3.4	5.8
NOX (TAKEOFF)	10.7	8.4

A ASSUMES PROPORTIONAL REDUCTION OF POLLUTANT EMISSION INDEX AT EACH LTO CYCLE MODE
B ASSUMES (1) REQUIRED REDUCTION IN CO AND HC OBTAINED BY LOWERING EMISSION INDEX VALUES AT TAXI-IDLE MODE ONLY, CO AND HC EMISSIONS AT OTHER MODES REMAIN UNCHANGED, (2) REQUIRED REDUCTION IN NOX OBTAINED BY LOWERING EMISSION INDEX VALUES AT CLIMBOUT AND TAKEOFF MODES IN SAME PROPORTION AS MEASURED VALUES, NOX EMISSIONS AT TAXI-IDLE AND APPROACH MODES REMAIN UNCHANGED

Figure 16. EPA Cycle Emissions Computation Summary.

CHAPTER III

TEST RESULTS AND DISCUSSION

The engine test using ERBS fuel was run on May 19 and 20, 1980. The test was run in conjunction with a test using Jet A aviation turbine fuel to obtain a direct comparison of the engine performance and emission values of the two fuels. On May 19, low-power points were run. The variable-geometry actuator was not attached to ensure that the valves remained closed and sealed, since sealing was determined to be critical in earlier testing. Also, the secondary-fuel circuit was sealed to prevent the possibility of any fuel leakage through that circuit. Two taxi-idle points and an approach point were run on ERBS fuel, and then the engine was shut down and the fuel switched to Jet A. The same three points were then repeated.

Following the low-power points, the engine was shut down and the variable-geometry actuator connected. The secondary-fuel circuit was also connected at this time. Smoke data were then taken on Jet A fuel at six power settings. This procedure was repeated with the ERBS fuel. After the smoke test, thrust conditions above taxi-idle were run on ERBS fuel; however, high ambient temperature resulted in unacceptable test data, and further testing was postponed until the following day.

On May 20, four power settings were evaluated on ERBS fuel (taxi-idle, approach, climbout, and takeoff). The engine was then run on Jet A at similar points for comparative purposes. The complete results of the test are included in Appendix A.

The emission indexes for the test are plotted in Figures 17 through 19 as a function of fuel/air ratio. The data shows good repeatability between the May 19 and May 20 runs. Emissions of CO are slightly higher at low power but, for the most part, there

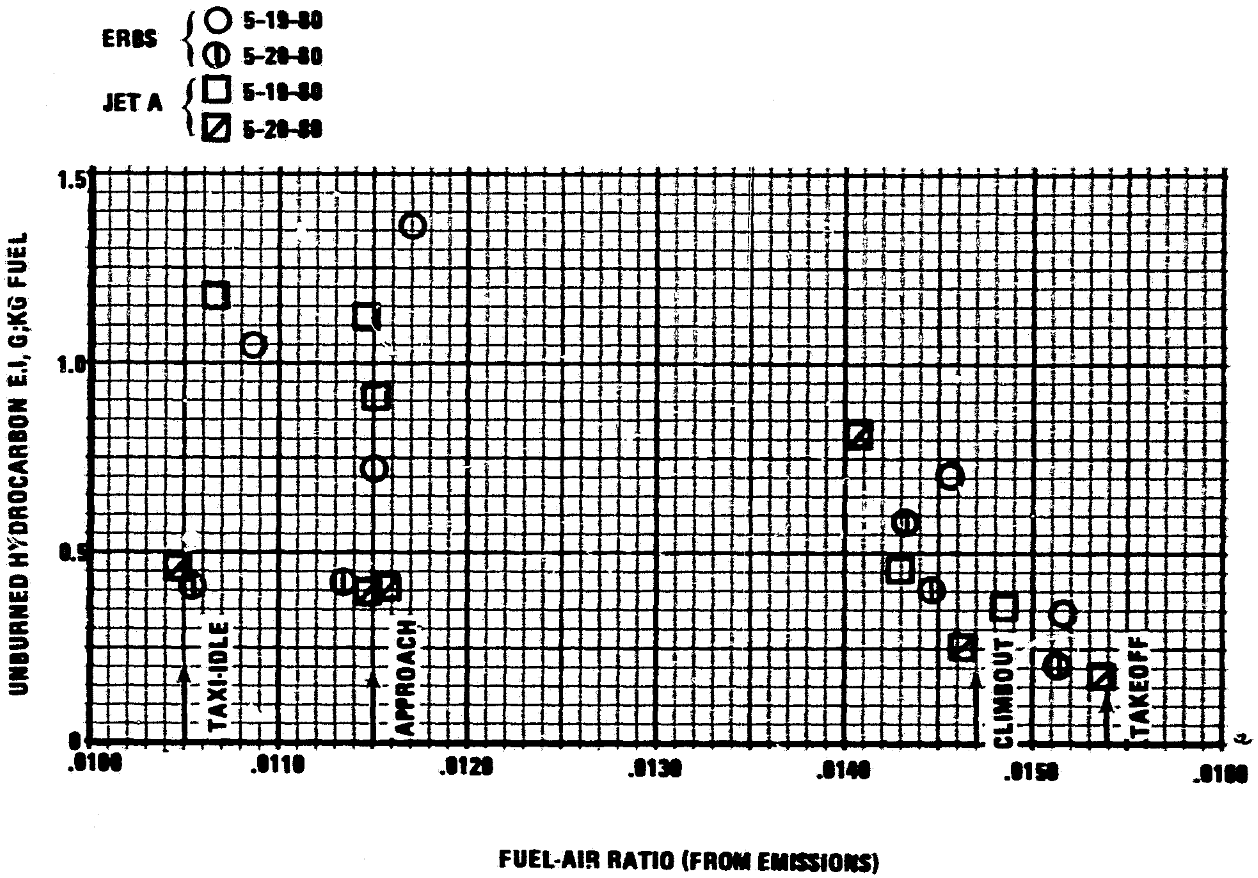

Figure 17. Comparison of Hydrocarbon Emissions Produced by ERBS and Jet A Fuels.

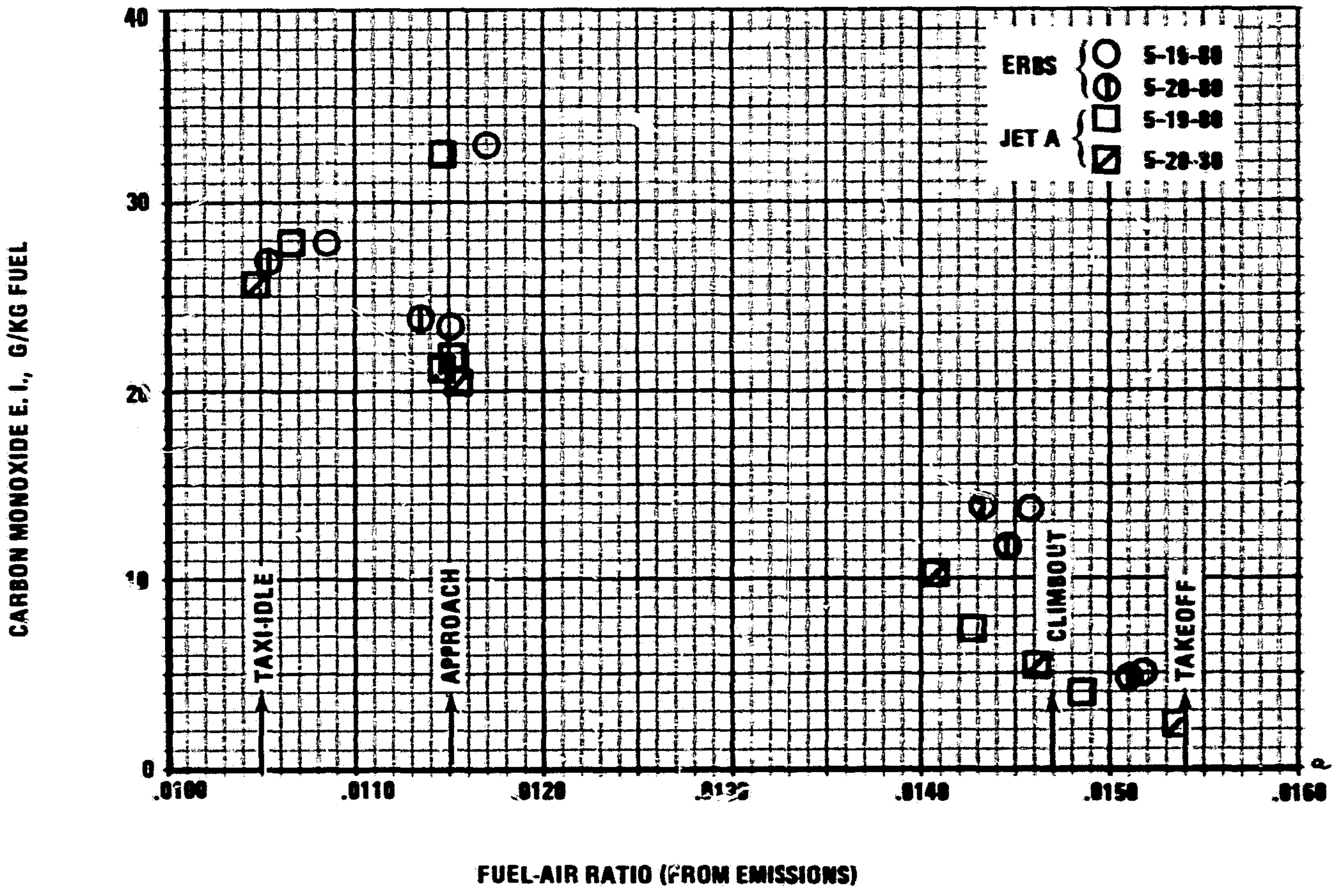

Figure 18. Comparison of Carbon Monoxide Emissions Produced by ERBS and Jet A Fuels.

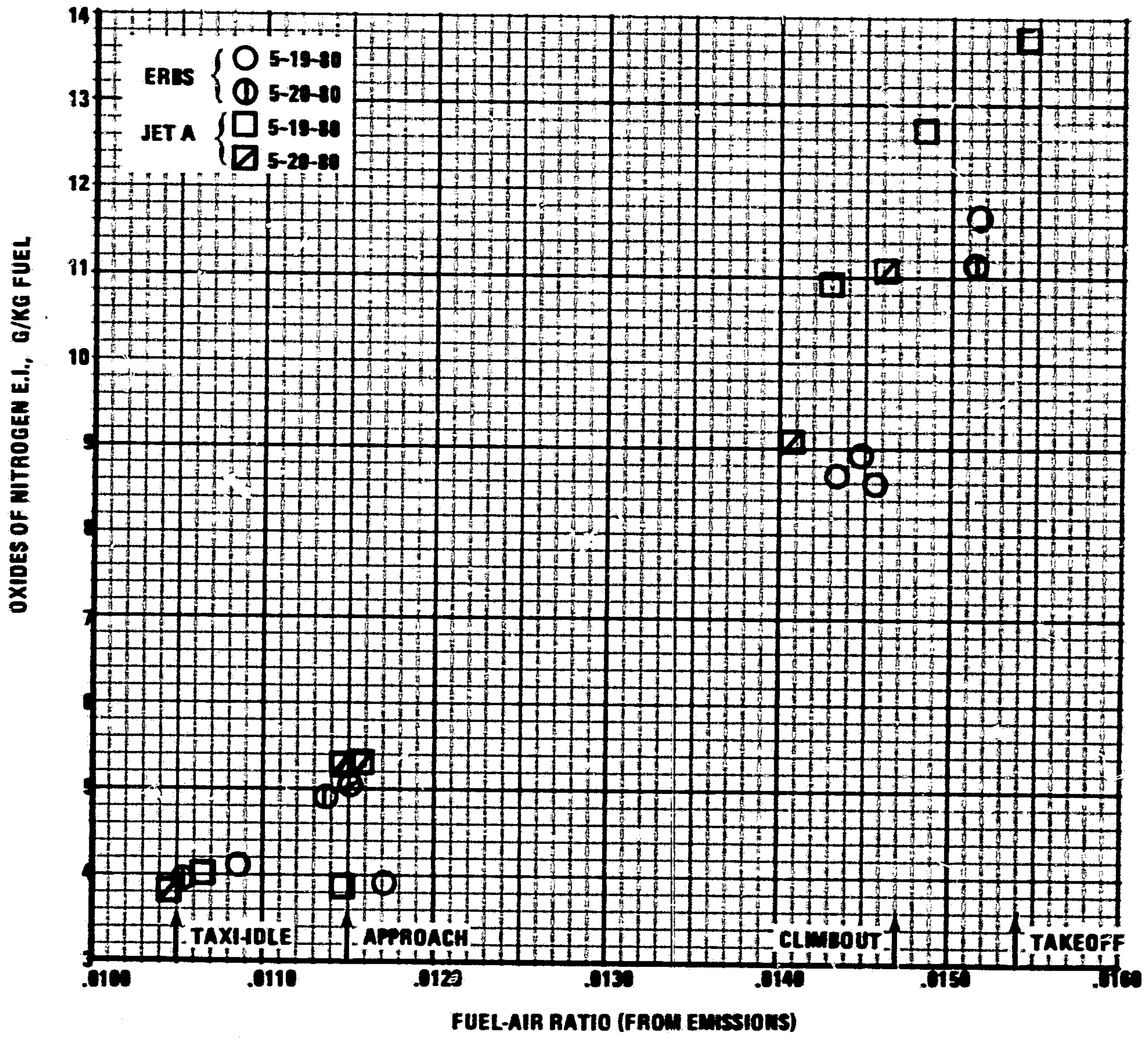

Figure 19. Comparison of Oxides of Nitrogen Emissions Produced by ERBS and Jet A Fuels.

is little significant difference in the emissions indexes produced by the two fuels with two exceptions: (1) the engine CO levels using ERBS fuel are higher at climbout than with Jet A; and (2) the NO_x levels at the climbout and takeoff power points are higher with Jet A. These emission values lead to the following EPAPs:

	LTO EPAPs		
	HC	CO	NO_x
Jet A	0.2	9.2	5.1
ERBS	0.2	10.0	4.8
Goals	1.6	9.4	3.7

There was a significant difference in smoke performance, as shown in Figure 20. On ERBS fuel, the smoke number was approximately 30 over the entire range from taxi-idle to takeoff, with an overall smoke number of 31. On Jet A, the smoke number started below 10 at taxi-idle and increased with increasing thrust to a maximum of 22.5 at takeoff. However, both values are below the PRTP goal of 40.

In terms of engine performance, there was no significant difference. At a corrected N_1 speed of 19,000 rpm, the engine produced a corrected thrust level of 12.1 kN on Jet A versus 12.0 kN on ERBS; a reduction of 0.7 percent.

The wall temperature of the combustion liner was increased as a result of using ERBS fuel. Figure 21 shows a direct comparison of the liner wall thermocouple readings taken at comparable power settings on both fuels. On ERBS fuel, the primary-zone liner temperatures were increased an average of 25K. A peak temperature difference of 40K was noted (1140K for ERBS versus 1100K for Jet A).

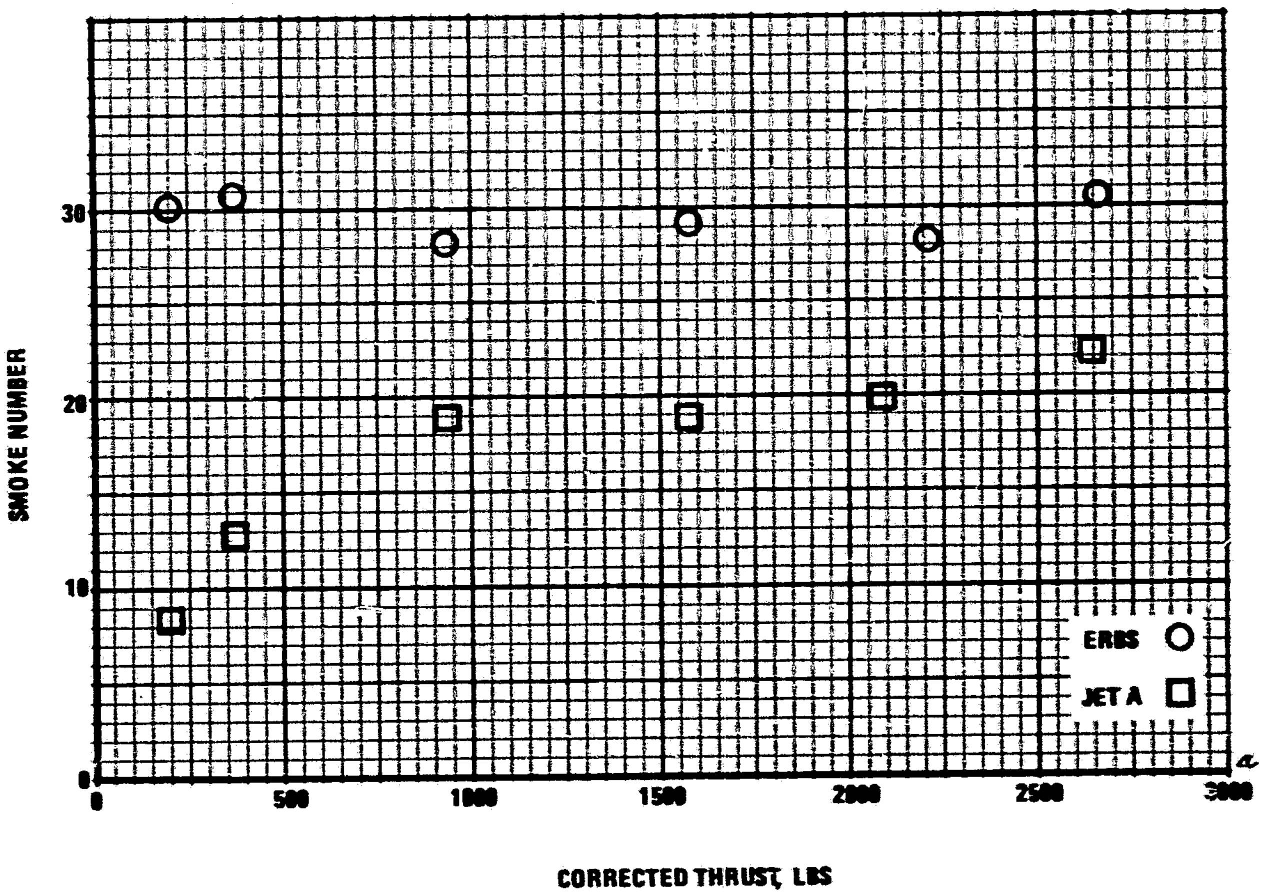

Figure 20. Comparison of Exhaust Smoke Produced by ERBS and Jet A Fuels.

MEASURED ENGINE PARAMETERS

	CORR. THRUST KN	F/A (EMISSIONS)	COMBUSTOR INLET PRESSURE (KPa)	COMBUSTOR INLET TEMPERATURE (K)
JET A	11.2	0.150	1132.1	658
ERBS	11.3	0.155	1132.3	658

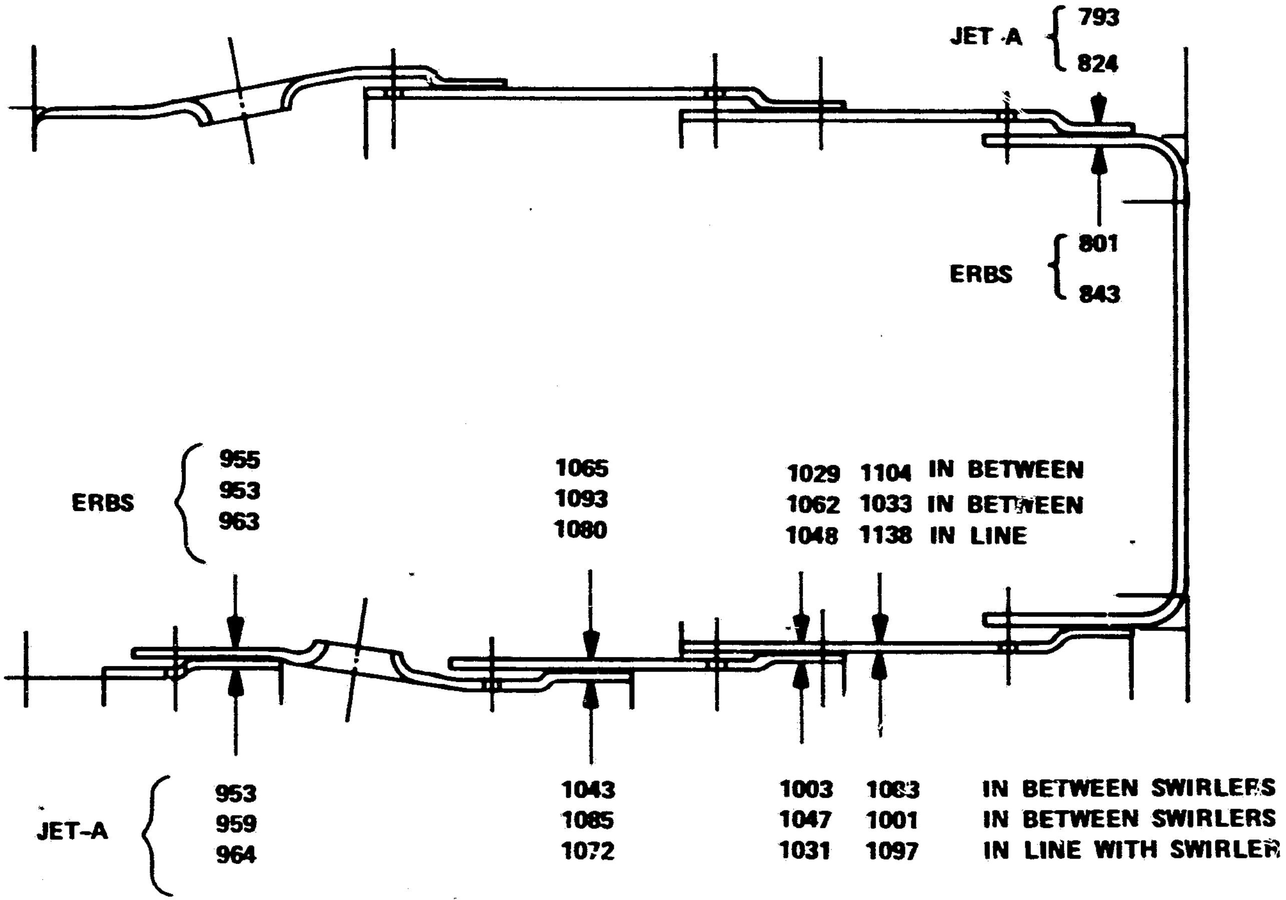

Figure 21. Comparison of ERBS Liner Temperature to Jet A at Takeoff Condition, K.

CHAPTER IV

CONCLUDING REMARKS

A Model TFE731-2 engine equipped with a variable-geometry combustion system designed to produce low emission levels was tested on ERBS and Commercial Jet A fuels. The purpose of the test was to determine the effect of a broadened-properties fuel on the performance and emission levels of the engine. The engine was tested at sea-level, standard-day, static conditions from taxi-idle to full power. The test results indicate little change in either the gaseous emissions levels or the engine performance when ERBS fuel was used, with the notable exception that the NO_x emissions were slightly less at the high-power points, and the smoke level with ERBS was higher at all thrust settings.

At the takeoff power setting, the NO_x emission indexes were approximately 12-percent less on ERBS fuel than with Jet A. At climbout, the ERBS fuel demonstrated NO_x emission indexes on the order of 18-percent less than those measured with Jet A. These decreases in NO_x were accompanied by the usual increase in CO with NO_x reduction; however, the reduction was unexpected and no experimental explanation could be found.

A smoke number of approximately 30 was measured at all power settings when operating on ERBS fuel. This was approximately 50-percent higher than the maximum smoke number measured on Jet A. However, both levels were below the EPA limit of 40, and visible smoke was not observed during the test.

Increased wall temperatures in the primary zone with ERBS fuel indicate potential liner-durability problems. The measured maximum liner temperature gradient was 338 K/cm with Jet A fuel and 344 K/cm with ERBS fuel. Using low-cycle fatigue empirical correlations for metal temperature gradients versus liner life, the decrease in combustor life was estimated to be 31 percent.

Although the test results are encouraging, an extensive amount of additional testing would be required before broadened-properties fuels such as ERBS fuel could be considered acceptable for commercial usage. Potential problem areas for the combustion system that need evaluation are as follows:

- Ignition, stability, and relight characteristics especially with cold fuel

- Liner durability/cooling

- Fuel-injector atomization performance over extended periods of operation as affected by fuel thermal stability

- Effect of increased particulate emissions on hot-end durability.

APPENDIX A

NASA T_1 ERBS FUEL ADDENDUM

Test Date	Eng. Test No.	Condition Number	Total Combustor Airflow, kg/sec	Total Fuel Flow kg/sec	Primary Fuel Flow kg/sec	Secondary Fuel Flow kg/sec	Thrust (Corrected) kN	Combustor Inlet Temperature, Deg. K	Combustor Inlet Total Pressure, kPa	Engine Inlet Temperature Deg. K	Engine Inlet Pressure kPa	Inlet Air Humidity g/g	Fuel-Air Ratio (metered)	Fuel-Air Ratio (carbon balance)	CO_2, % by Vol. (Wet)	COEI, g/kg fuel	HCEI, g/kg fuel	NO_xEI g/kg fuel (corr. for Humidity)	Combustion Efficiency (Gas Sample)	Comments.
									ERBS FUEL											
5-19/80	1	2007	2.20	0.0255	0.0255	--	0.91	397.8	208.2	305.3	97.2	0.005608	0.0116	0.0117	2.39	33.26	1.38	3.94	99.09	(1)
		2008	2.20	0.0246	0.0246	--	0.93	399.5	213.0	305.6	97.2		0.0111	0.0108	2.22	28.04	1.05	4.12	99.24	(2)
		4003	3.27	0.0362	--	--	1.64	442.2	289.6	305.4	97.2		0.0111	0.0115	2.36	23.38	0.74	5.06	99.38	(3)
		8092	8.47	0.1205	0.0428	0.0777	7.68	62[illegible].5	828.1	310.6	96.5		0.0142	0.0146	2.99	13.91	0.71	8.61	99.61	(5)
		9092	10.04	0.1497	0.0433	0.1064	9.76	665.8	1008.7	309.7	96.5		0.0149	0.0152	3.13	5.05	0.35	11.73	99.85	(6)
5/20/80	1	7093	9.74	0.1385	0.0432	0.0928	9.01	623.1	950.1	293.2	96.5	0.005608	0.0140	0.0143	2.94	13.96	0.59	8.75	99.62	(5)
		8093	10.00	0.1409	0.0432	0.0977	9.37	629.7	977.7	293.2	96.5		0.0141	0.0145	2.97	11.77	0.41	8.98	99.69	(5)
		9093	11.30	0.1681	0.0435	0.1246	11.30	658.3	1138.3	293.7	96.5		0.0149	0.0151	3.12	4.98	0.21	11.14	99.86	(6)
		2012	--	0.0234	0.0234	--	0.89	384.9	208.2	296.6	96.5		--	0.0105	2.16	26.92	0.42	3.97	99.33	(2)
		4005	3.35	0.0368	--	--	1.75	434.9	301.3	296.6	96.5		0.0120	0.0113	2.32	23.91	0.42	4.91	99.40	(3)
									COMMERCIAL JET A											
5-19/80	2	2009	2.27	0.0247	0.0247	--	0.90	398.4	210.3	305.8	97.2	0.006253	0.0109	0.0107	2.15	28.09	1.18	4.03	99.24	(2)
		2010	2.17	0.0259	0.0259	--	0.91	398.6	207.5	305.8	97.2		0.0119	0.0115	2.31	32.68	1.14	3.87	99.13	(1)
		4004	3.24	0.0372	--	--	1.69	445.6	292.3	306.7	97.2		0.0115	0.0115	2.33	22.05	0.94	5.20	99.40	(3)
		7091	9.45	0.1393	0.0440	0.0953	8.90	645.0	936.3	306.8	97.2		0.0147	0.0143	2.91	7.52	0.46	10.92	99.78	(5)
		8091	10.37	0.1583	0.0443	0.1139	10.17	668.2	1048.7	307.1	97.2		0.0153	0.0149	3.03	4.02	0.36	12.77	99.87	(6)
5-20-80	2	4006	3.93	0.0451	--	--	2.28	456.9	350.3	296.0	96.5	0.006253	0.0115	0.0116	2.35	20.87	0.42	5.34	99.47	(3)
		4007	3.91	0.0438	--	--	2.18	453.0	343.4	296.0	96.5		0.0112	0.0115	2.33	21.22	0.40	5.30	99.47	(3)
		2013	2.31	0.0240	0.0240	--	0.90	384.5	208.9	296.1	96.5		0.0103	0.0105	2.12	25.70	0.47	3.80	99.35	(2)
		7094	9.71	0.1389	0.0440	0.0949	9.07	625.7	949.4	296.1	96.5		0.0143	0.0143	2.86	10.46	0.83	9.13	99.68	(5)
		8094	10.65	0.1584	0.0718	0.1141	10.42	649.3	1063.2	297.1	96.5		0.0149	0.0146	2.98	5.42	0.27	11.12	99.85	(5)
		9094	11.83	0.1866	0.0447	0.1419	12.22	676.9	1214.2	296.7	96.5		0.0158	0.0154	3.14	2.49	0.18	13.70	99.93	(6)

(1) Taxi-idle, Surge Valve Open
(2) Taxi-idle, Surge Valve Closed
(3) Approach, Swirler Valves Closed
(4) Approach, Swirler Valves Open
(5) Climbout, Swirler Valves Open
(6) Takeoff, Swirler Valves Open

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