2-P(mix)

NASA CR-121094
FR-5295

FINAL REPORT

EFFECT OF FUEL ZONING AND FUEL NOZZLE DESIGN ON POLLUTION EMISSIONS AT GROUND IDLE CONDITIONS FOR A DOUBLE-ANNULAR RAM-INDUCTION COMBUSTOR

By
T. R. Clements

PRATT & WHITNEY AIRCRAFT
FLORIDA RESEARCH AND DEVELOPMENT CENTER

Prepared For
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-11159

63

49

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR- 121094		

4. Title and Subtitle	5. Report Date
Effect of Fuel Zoning and Fuel Nozzle Design on Pollution Emissions at Ground Idle Conditions for a Double-Annular Ram-Induction Combustor	February 1973
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
T. R. Clements Approved: J. H. Shadowen	FR-5295
	10. Work Unit No.
9. Performing Organization Name and Address Pratt & Whitney Aircraft Division of United Aircraft Corporation Florida Research and Development Center West Palm Beach, Florida 33402	11. Contract or Grant No. NAS3-11159
	13. Type of Report and Period Covered Contractor
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, P. J. Perkins, Air Breathing Engine Procurement Section, NASA Lewis Research Center, Cleveland, Ohio

16. Abstract

An exhaust emission survey was conducted on a double-annular ram-induction combustor at simulated ground idle conditions. The combustor was designed for a large augmented turbofan engine capable of sustained flight speeds up to Mach 3.0. The emission levels of total hydrocarbon (THC), carbon monoxide (CO), carbon dioxide (CO_2) and nitric oxide (NO) were measured. The effects of fuel zoning, fuel nozzle design, and operating conditions (inlet temperature and reference Mach number) on the level of these emissions were determined. At an overall combustor fuel/air ratio of 0.007, fuel zoning reduced THC emissions by a factor of 5 to 1. The reduction in THC emissions is attributed to the increase in local fuel/air ratio provided by the fuel zoning. An alternative method of increasing fuel/air ratio would be to operate with larger-than-normal compressor overboard bleed; however, analysis on this method indicated an increase in idle fuel consumption of 20%. The use of air-atomizing nozzles reduced the THC emissions by 2 to 1.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Combustor, Ram-Induction, Short-Length, Double-Annular, Exhaust Emissions, Ground Idle, Reduction	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	56	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

This report was prepared by the Pratt & Whitney Aircraft Division of United Aircraft Corporation under Contract NAS3-11159.

The contract was administered by the Air-Breathing Engine Procurement Section of the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

The period of performance for the contract was June 1968 through August 1972. This report summarizes the technical effort performed during the period September 1971 through August 1972. The earlier phases of the contract are discussed in references 1 and 2.

Preceding page blank

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS (Continued)

SUMMARY

An exhaust emission survey has been conducted on a double-annular ram-induction combustor operating at simulated ground idle conditions. The combustor was designed for a large augmented turbofan engine capable of sustained flight speeds up to Mach 3.0. The emission levels of total hydrocarbon (THC), carbon monoxide (CO), carbon dioxide (CO_2) and nitric oxide (NO) were determined.

Testing was conducted in a full-scale, 90-deg (1.57 radian) sector rig. The test conditions were set at a combustor inlet pressure of two atmospheres and at inlet temperatures and reference Mach numbers from 200°F (366°K) to 350°F (450°K) and 0.06 to 0.08, respectively. Emission data were obtained both with a stationary, 5-point sample rake located in the test rig exhaust duct well downstream of the combustor outlet, and with a circumferentially traversing, 5-point sample rake located in the combustor outlet. The traversing data taken in the combustor outlet, when averaged, compared closely with the stationary rake data taken in the exhaust duct where the combustion products were well mixed. However, large circumferential variations in emission levels were observed with the traversing rake in the combustor outlet. Thus, a small number of stationary probes at this location could give highly erroneous results.

Previously reported development efforts on this combustor have resulted in a configuration with good performance at the sea level takeoff and cruise design points (references 1, 2 and 3). The effort reported herein investigated various methods of reducing the emissions of the objectionable pollutants, THC and CO, at the ground idle condition by: (1) fuel zoning, whereby a portion of the combustor fuel nozzles are shut down, and all of the fuel passed through the remaining nozzles, and (2) fuel nozzle design. Three nozzle designs were tested: (1) a conventional pressure atomizing nozzle, (2) an air blast nozzle in which the fuel was atomized by a stream of high velocity air; the airflow driving potential being normal combustor pressure drop and (3) an air assist nozzle which also atomized the fuel with high velocity air, but with the air supplied by an external source. The effect of combustor inlet temperature and reference Mach number on the exhaust emissions was also investigated.

Fuel zoning proved to be very effective in reducing the emission levels of the objectionable pollutants. At an overall combustor fuel/air ratio of 0.007, fuel zoning reduced THC emissions by a factor of 5 to 1. The reduction in THC emissions is attributed to the increase in local fuel/air ratio provided by the fuel zoning. An alternative method of increasing fuel/air ratio would be to operate with larger-than-normal compressor overboard bleed; however, analysis on this method indicated an increase in idle fuel consumption of 20%.

The use of air-atomizing nozzles reduced the THC emissions by 2 to 1. The effect of combustor reference Mach number was dependent on the test conditions and the type of fuel zoning employed. In general, decreasing reference Mach number reduced THC and CO emissions. Increasing combustor inlet temperature reduced THC and CO emissions.

The NO emission index was small, being less than 2.0 $lb_m/1000\ lb_m$ fuel (g/kg) at all test conditions and fuel injection modes.

INTRODUCTION

With the growing public concern over the quality of the air it breathes, Government agencies and private industry have begun to take action to reduce the emission of dangerous or objectionable materials into the atmosphere. Although the contribution of aircraft to the total pollution problem is small in relation to other sources (reference 4), the atmospheric pollution in and around air terminals is largely the result of aircraft operations (reference 5). During ground idle and taxi operations the primary objectionable exhaust emissions from gas turbine engines are carbon monoxide and unburned hydrocarbons (reference 6). These products are the result of poor combustion efficiency at the idle condition. The poor idle efficiency of current engines is due to low combustor inlet temperatures, low fuel/air ratios, inadequate fuel atomization and inadequate mixing of the fuel and air.

One method of increasing combustion efficiency during idle is to increase the local fuel/air ratio in those regions where combustion is taking place. This can be accomplished by: (1) controlling the combustor airflow by some suitable means so as to alter the primary zone airflow to maintain a high primary zone fuel/air ratio, or (2) bleeding overboard large quantities of compressor discharge air at idle to raise the combustor fuel/air ratio, or (3) by zoning the fuel flow to obtain a locally high fuel/air ratio. The first course of action requires a variable area combustor, which is a major and complicated addition to any engine. The second method, while easy to design into a new engine, requires a major modification (new diffuser cases, etc.) if it is to be retrofitted on an existing engine. This method also requires an increase in idle fuel flow to maintain a constant idle thrust. The third method requires only a relatively minor addition to the fuel control system. For this reason, fuel zoning was selected for study since it offers a quick, practical method of reducing the THC and CO emission levels during idle and taxi operation on both new and existing engines.

In addition to fuel zoning, the method by which fuel is injected into the combustor can influence the emissions of THC and CO. Data reported in the literature (references 7 and 8) show that these emissions can be reduced by using air atomizing nozzles. Since a change in fuel nozzles represents a relatively minor engine modification, two types of air atomizing nozzles were investigated.

The test program was conducted at the Pratt & Whitney Aircraft Florida Research and Development Center in a full-scale rig that was a quarter section of a full annulus.

SCOPE OF THE INVESTIGATION

The emission levels of unburned hydrocarbons, carbon monoxide, carbon dioxide and nitric oxide were determined in a double-annular combustor operating at simulated idle conditions. The effects of fuel zoning, fuel nozzle design, and operating conditions on these emissions were determined.

Fuel Zoning

Two methods of fuel zoning were investigated in addition to the normal mode (all nozzles flowing). They were:

1. Radial zoning, all of the fuel was injected into the inner combustion zone of the double-annular combustor.

2. Circumferential zoning, all of the fuel was injected through every other nozzle in both the inner and outer combustion zones. The outer zone nozzles were staggered relative to the inner zone nozzles. See figure 1.

Fuel Nozzles

Three types of fuel nozzles were studied. They were:

1. A conventional pressure atomizing nozzle as shown in figure 2. This nozzle was used with the axial flow swirler shown in the figure. The flow curve for this nozzle is shown in figure 3.
2. An air blast type air atomizing nozzle as shown in figure 4. This type nozzle atomizes the fuel with a stream of high velocity air. The airflow driving potential is simply combustor pressure drop. The fuel flow curve is shown in figure 3.
3. An air assist type air atomizing nozzle as shown in figure 5. This type nozzle also atomizes the fuel with a stream of high velocity air, however, the nozzle airflow is provided by an external source. The fuel flow curve is shown in figure 3.

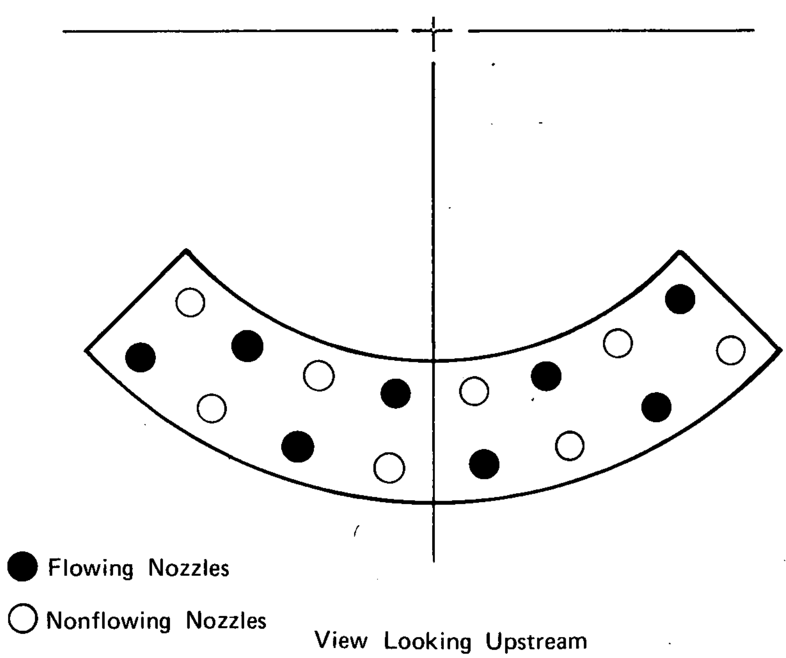
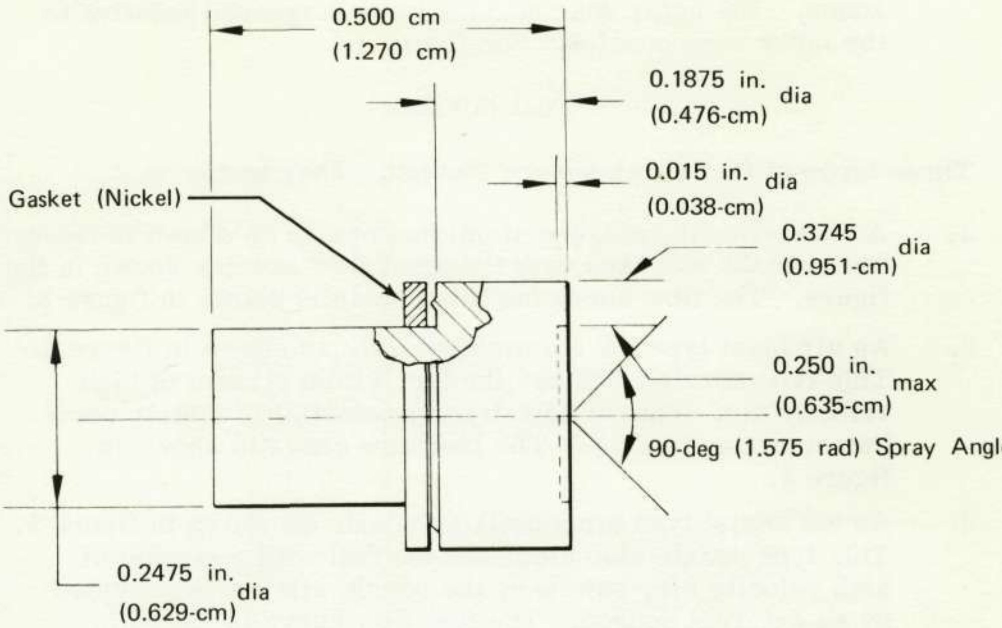


Figure 1. Staggered Circumferential Fuel Zoning FD 63821



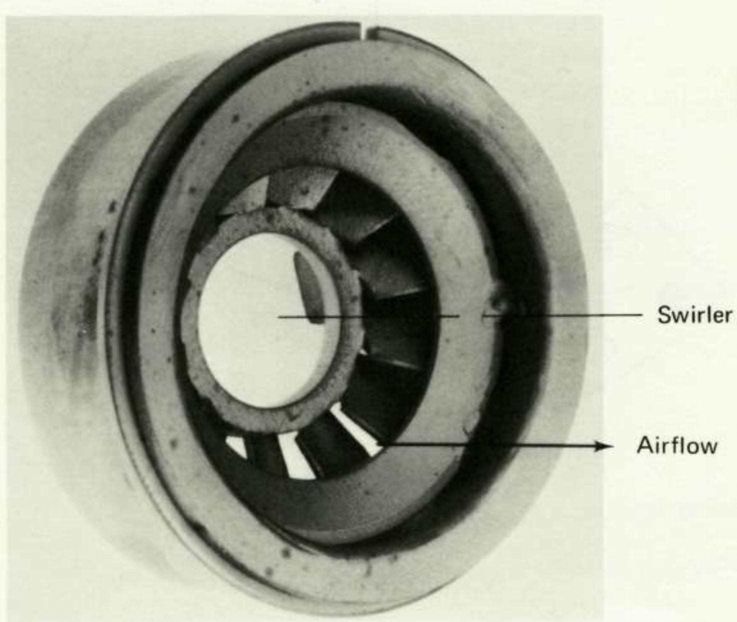


Figure 2. Simplex Fuel Nozzle and Axial Flow Swirler FD 63822

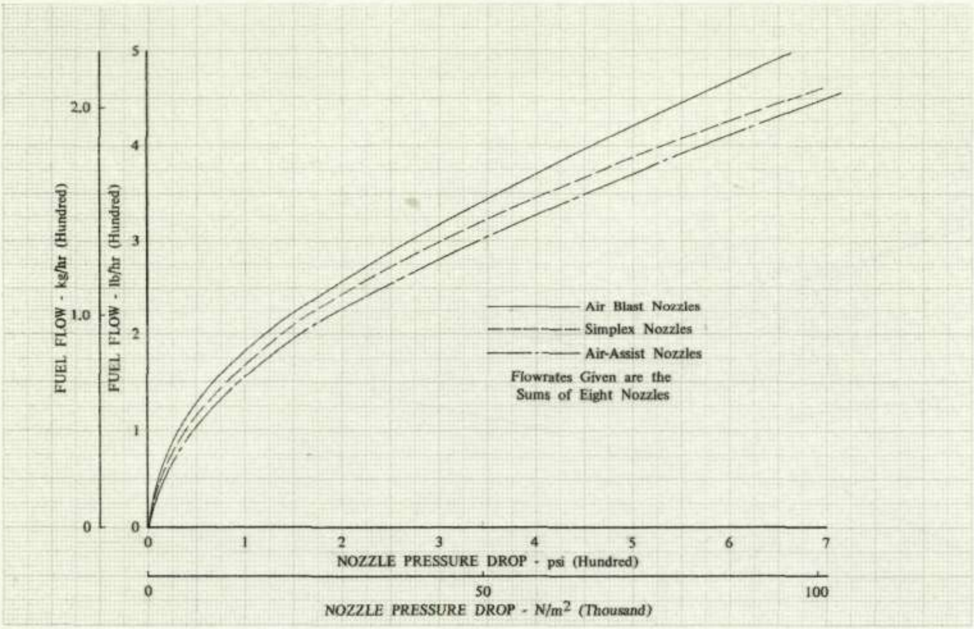


Figure 3. Nozzle Fuel Flow Curves DF 92624

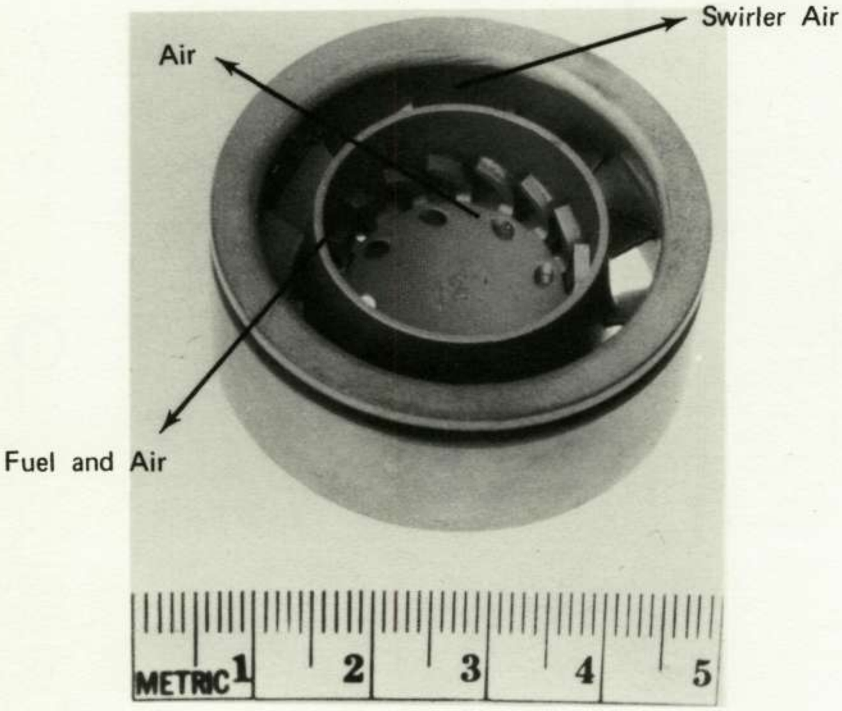


Figure 4. Air Blast Nozzle FD 63824

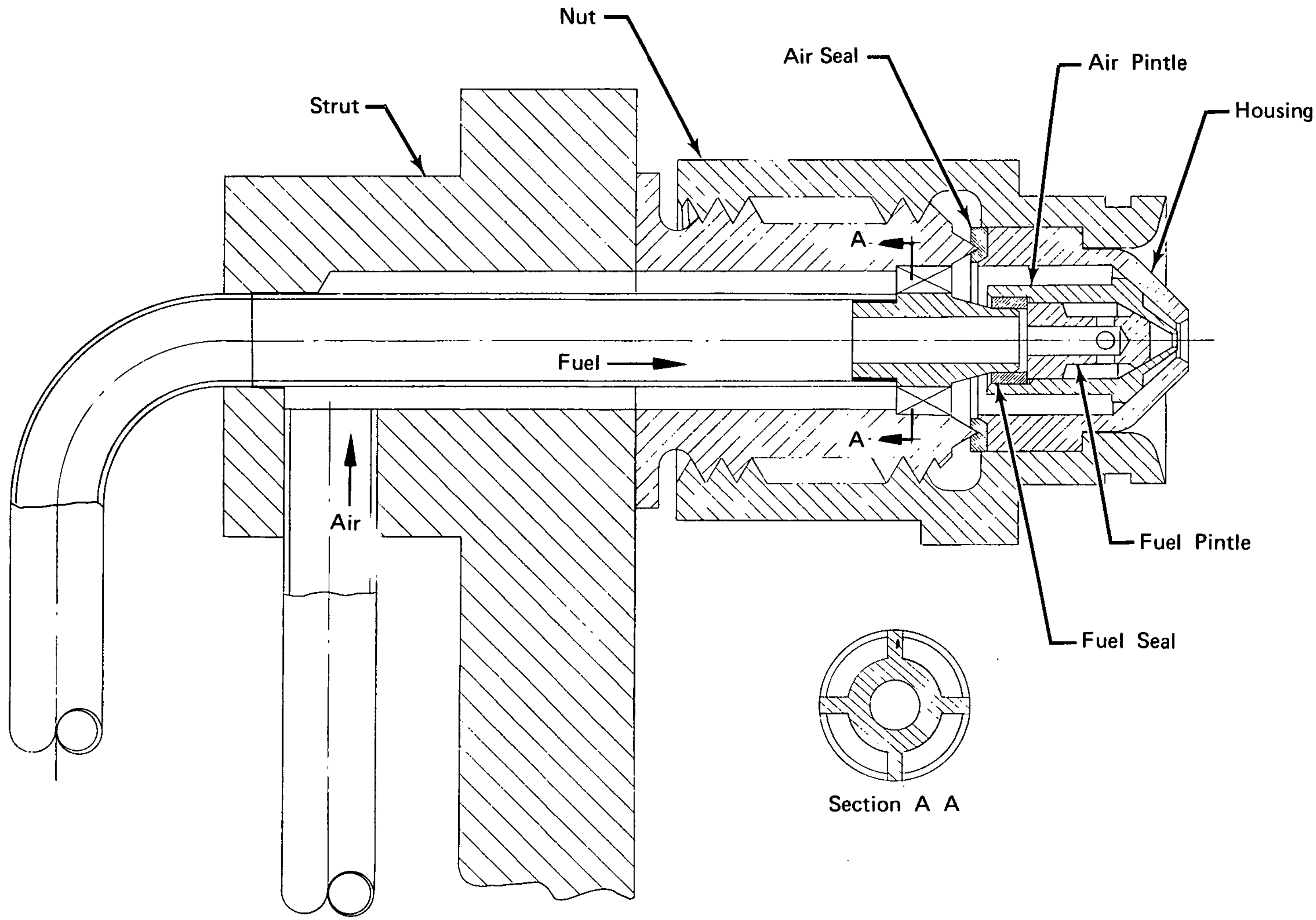


Figure 5. Air-Assist Nozzle Assembly, Shown Without Air Swirler

FD 63825

Measured Parameters

The test rig was instrumented to measure the following:

1. Combustor airflow
2. Combustor fuel flow
3. Inlet total and static pressure
4. Inlet total temperature
5. Outlet total temperature
6. Outlet total pressure (outlet static pressure was calculated)
7. Exhaust emission species CO_2, CO, THC and NO at two locations in the test rig. One location was in the exhaust duct at a distance of 13 L/D's downstream of the combustor outlet and the other was at the combustor outlet.

Test Conditions

The test conditions used in the program were designed to cover the range of ground idle conditions observed on many turbojet/turbofan engines in use or under development. All of the testing was conducted at an inlet total pressure of 2 atmospheres. The remaining test parameters were:

1. Inlet total temperature - 200° to 350°F (367° to 450°K)
2. Reference Mach number - 0.06 to 0.08
3. Fuel/Air Ratio - 0.007 to 0.014

COMBUSTOR DESIGN

Combustor

The combustor used in this program was a double-annular ram-induction combustor. This term was coined from the general design details of the combustor as well as the fundamental process by which air is admitted into the combustion zone. The combustor was constructed with two annular combustion zones arranged concentrically around each other. This arrangement increases the effective length to height ratio of the combustor thus allowing considerable reductions in combustion length to be realized. Each combustion annulus had its own separate fuel supply. In contrast with more conventional systems in which air is made to flow into the combustion zone by a static pressure difference across the combustor walls, the air in this combustor is forced into the combustor by the ram pressure of the inlet flow. The air entry ports are constructed as vaned turning elbows or scoops to aid in efficiently turning the air into the combustor. Figure 6 is a cross section of a typical double-annular ram-induction combustor. A more complete description of the ram-induction concept is presented in reference 9.

The test combustor (figure 7) had an effective flow area of approximately 256 in^2, (0.165m^2). The area distribution is shown in figure 8. The combustor had 256 scoops in a full annular design with 32 scoops in the primary and 32 in the secondary for each liner air entry. The scoop pattern was fully staggered as shown in figure 9 with the pattern repeating for each nozzle spacing. The primary scoops on the inner liner of the ID annulus and on the outer liner of the OD annulus were fitted with shroud capture hoods (figure 10) to aid in turning the air into the primary zone.

Diffuser

The diffuser used with this combustor (figure 11) is defined as a 7 deg (0.122 rad) equivalent conical angle (ECA, Appendix A for definition) snout-type diffuser. As shown in figure 11, the combustor inner and outer liners were extended into the diffuser thus providing three flow paths. The bulk of the diffusion occurred in the region from the diffuser inlet to the snout inlet. Diffusion was at a rate of 7 deg (0.122 rad) giving an area ratio of 1.245. Some additional diffusion was provided in the snout center passage to reduce dump losses. The snout inner and outer walls were contoured so that there was no diffusion in the inner and outer passages.

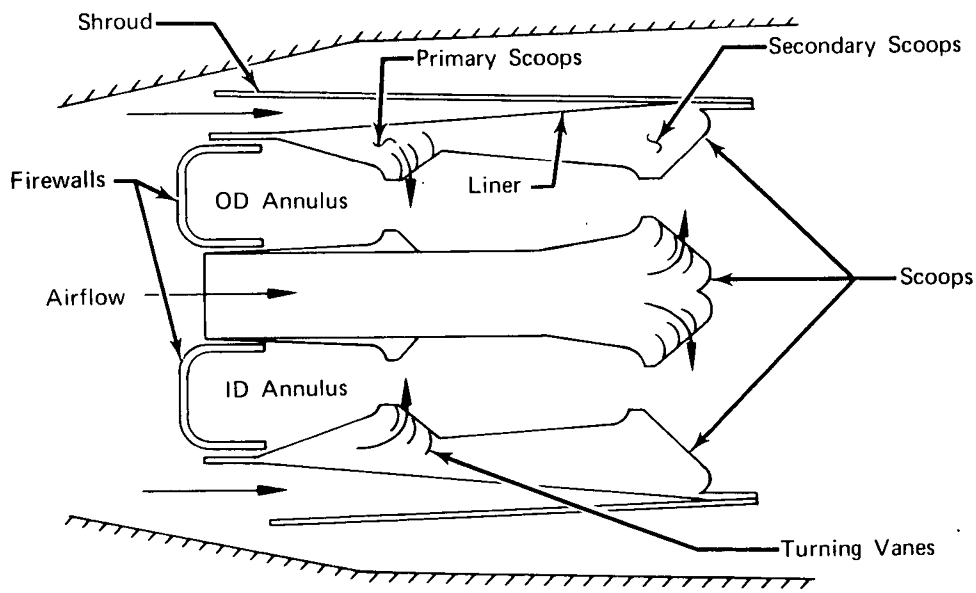


Figure 6. Ram Induction Concept in a Double-Annular Combustor FD 36572B

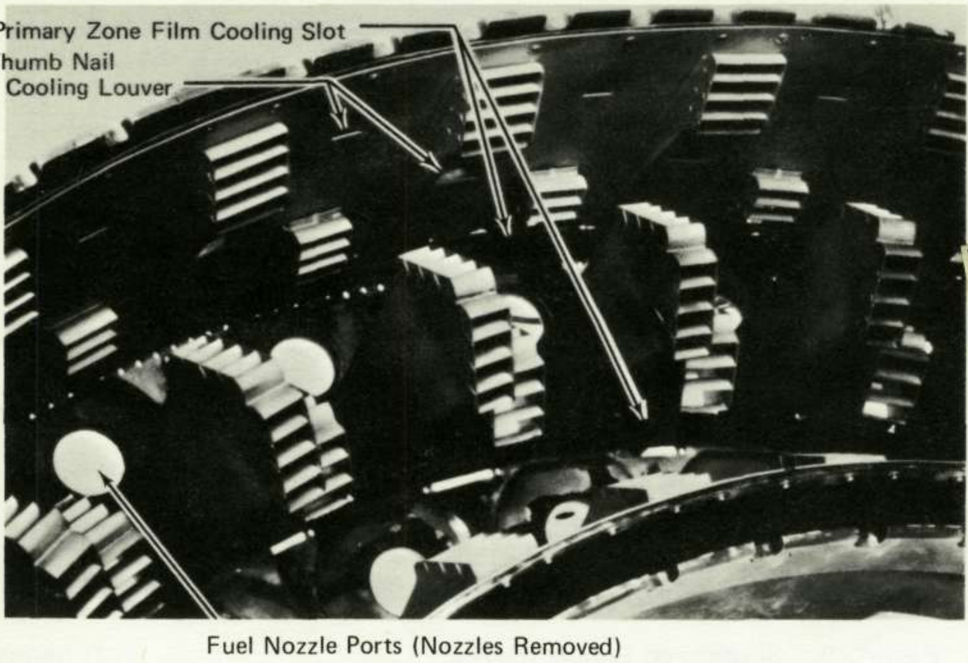


Figure 7. Test Combustor (View of Annular Segment, Looking Upstream) FE 100226C

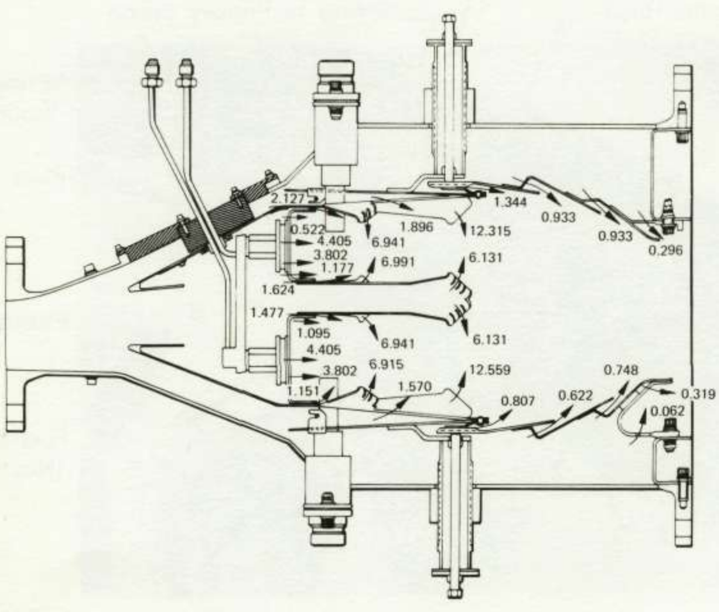


Figure 8. Flow Area Distribution of Test Combustor (Percent) FD 31997A

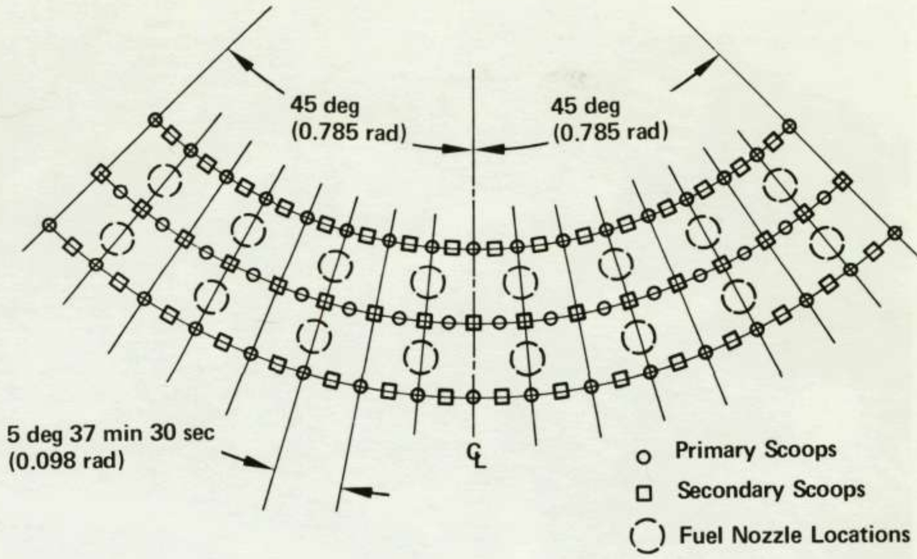


Figure 9. Staggered Scoop Pattern FD 36587

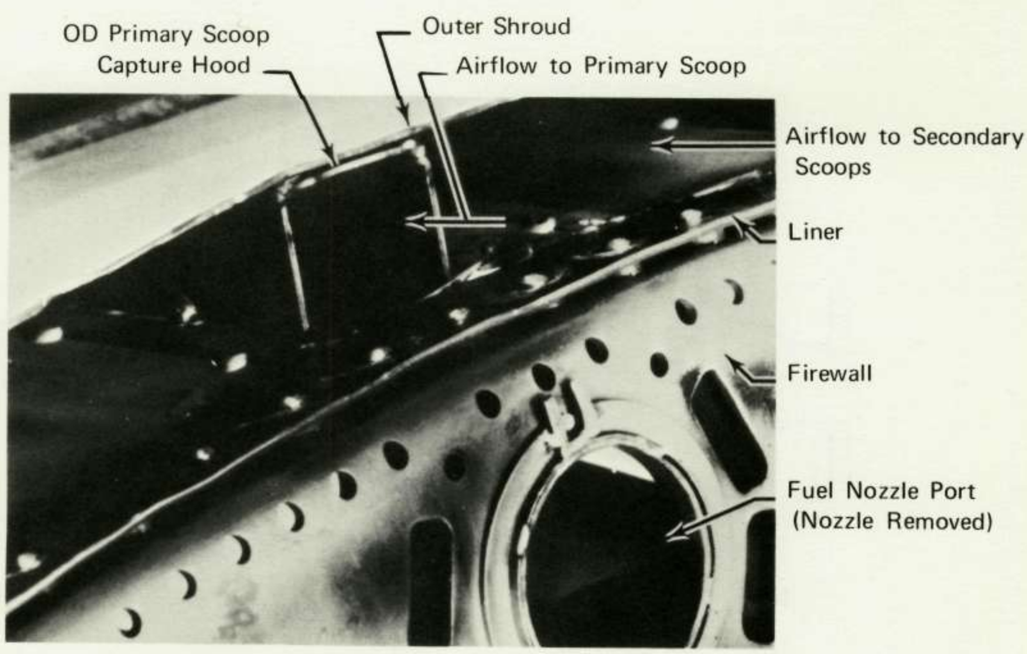


Figure 10. Capture Hoods (View of Annular Segment, Looking Downstream) FE 100223C

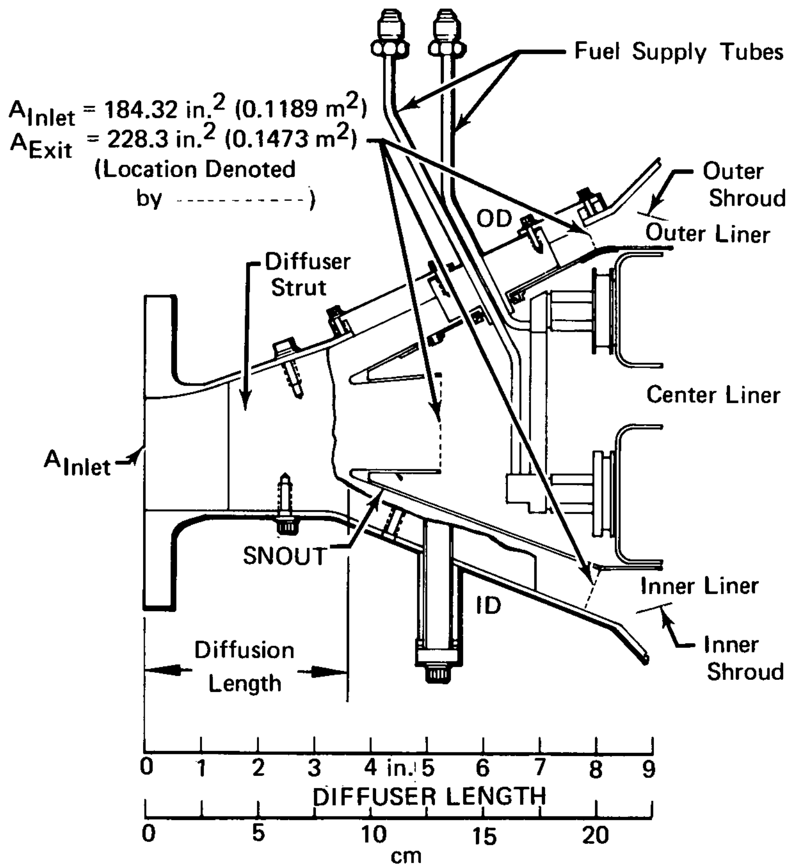


Figure 11. 7-deg (0.122-rad) ECA Snout-Type Diffuser FD 56939B

CALCULATIONS

Performance calculations included the determination of Reference Mach number, combustion efficiency, total pressure loss, the outlet temperature uniformity parameter, TPF, exhaust specie emission indices, and fuel/air ratio from the measured concentrations of CO_2, CO, and THC.

Reference Mach Number

Reference Mach number is calculated from continuity using the average inlet static pressure and assuming one-dimensional isentropic flow. Therefore, the Reference Mach number is determined by

$$M_{REF} = \frac{W_a \sqrt{T_{t3}}}{P_{s3} \; A_{REF}} \sqrt{\frac{R}{\gamma \left[1 + \left(\frac{\gamma - 1}{2}\right) M_{REF}^2\right]}} \qquad (1)$$

where:

M = Mach number

W_a = Airflow

T_{t3} = Average diffuser inlet total temperature

P_{s3} = Average diffuser inlet static pressure

A = Area

γ = Ratio of specific heats

R = Gas constant

The numerical subscripts refer to engine station. The subscript "REF" refers to reference area. The reference area is defined as the annular area between the inner and outer combustor shrouds. The reference area is equal to 711 in^2 (0.459 m^2) in a full-annular combustor.

Combustion Efficiency

Combustion efficiency is defined as the ratio of the measured temperature rise to the theoretical temperature rise. The theoretical rise is calculated from the fuel/air ratio (based on measured quantities of fuel and air flow), fuel properties, and inlet temperature. The efficiency is expressed as:

$$Eff_{mb} = \frac{T_{t4m} - T_{t3}}{T_{t4w} - T_{t3}} \qquad (3)$$

where:

Eff_{mb} = Combustion efficiency

T_{t4m} = Mass weighted average of 105 outlet total temperatures

T_{t4w} = Theoretical outlet total temperature

Total Pressure Loss

The combined diffuser-combustor total pressure loss is given by:

$$\frac{\Delta P}{P} = \frac{P_{t4} - P_{t3}}{P_{t3}} \tag{4}$$

where:

$\frac{\Delta P}{P}$ = Total pressure loss expressed as a percentage of inlet total pressure

P_{t3} = Mass weighted average of 25 diffuser inlet total pressures

P_{t4} = Mass weighted average of 105 combustor outlet total pressures

Outlet Temperature Pattern Factor (TPF)

Outlet Temperature Pattern Factor (TPF) is defined as the ratio of the maximum positive deviation from the average outlet temperature to the average temperature rise, or:

$$TPF = \frac{T_{t4\,max} - T_{t4}}{T_{t4} - T_{t3}} \tag{5}$$

where:

TPF = Temperature pattern factor

$T_{t4\,max}$ = Maximum temperature at any location in the combustor outlet

T_{t4} = Average combustor outlet temperature

Outlet Radial Temperature Profile

Outlet Radial Temperature Profile is determined from the average of 21 outlet total temperatures measured circumferentially at each of 5 radial positions.

Exhaust Specie Emission Index

Exhaust Specie Emission Index is defined as the lb_m (grams) of any exhaust specie per 1000 lb_m (kilograms) of fuel burned.

When the specie is measured as ppm by volume the EI is given by:

$$EI = \frac{X_s}{10^3}\left[\left(\frac{M_s}{M_e}\right)\left(\frac{1 + f/a}{f/a}\right)\right]$$

where:

EI = Emission index, lb_m (g) of specie per 1000 lb_m (kg) of fuel

X_s = Volume concentration of specie, ppm

M_s = Molecular weight of specie

M_e = Molecular weight of exhaust gases ≈ molecular weight of air

f/a = Fuel/air ratio (from measured values of fuel and air flow)

If the exhaust specie is measured in percent volume then the EI is given by:

$$EI = 10X_s\left[\left(\frac{M_s}{M_e}\right)\left(\frac{1 + f/a}{f/a}\right)\right]$$

Where the volume concentration, X_s, is expressed as a volume percent.

Fuel/Air Ratio Calculated From Exhaust Emission Measurements

The combustor fuel/air ratio was calculated from the concentrations of CO_2, CO and THC by the following equation:

$$f/a = \left[\frac{M_c + M_h\left(\frac{H}{C}\right)}{M_a}\right]\left[\frac{\left[\frac{CO}{10^4} + CO_2\right]\left[1 + \frac{THC}{2(10^6)}\right] + \frac{THC}{10^4}}{100 + \left[\frac{CO}{10^4}\left(\frac{H/C}{4} - \frac{1}{2}\right)\right] + CO_2\left(\frac{H/C}{4}\right)}\right]$$

where:

THC = Concentration of hydrocarbons in ppmv (wet basis)

CO = Concentration of CO in ppmv (dry basis)

CO_2 = Concentration of CO_2 in % (dry basis)

f/a = Fuel/air ratio

H/C = Hydrogen/carbon ratio of fuel

M_c = Molecular weight of carbon

M_h = Molecular weight of hydrogen

M_a = Molecular weight of air

This equation was derived assuming:

1. Dry intake air

2. No free H_2 in exhaust

3. Hydrogen/carbon ratio of unburned hydrocarbons equals the hydrogen/carbon ratio of fuel. Also, the molecular weight of the unburned hydrocarbons equals the molecular weight of the fuel.

4. The combustion of the fuel in air yields only the products CO, CO_2, C_aH_b, H_2O, O_2, NO and N_2

5. The perfect gas law applies.

RESULTS AND DISCUSSIONS

An exhaust emission survey has been conducted on a double-annular ram-induction combustor operating at simulated ground idle conditions. Measurements of CO, CO_2, THC, and NO were made. Various methods of reducing the emissions of CO and THC were investigated. These included: (1) fuel zoning, (2) fuel nozzle design, and (3) operating conditions. The results, that are discussed below, are summarized in table I. Two methods of extracting gas samples from the flow were investigated and the results compared.

Fuel Zoning

THC Emissions

Figure 12 shows that radial fuel zoning reduced the emission levels of THC by over 5 to 1. This result was obtained with the simplex nozzles operating in the radial (ID annulus only) injection mode. For a given overall combustor fuel/air ratio each ID annulus fuel nozzle was flowing twice the amount of fuel that it would normally flow if both OD and ID annuli were operating. The test condition was set at T_{t3} = 200° to 226°F (366° to 381°K), M_{REF} = 0.057 - 0.060 and fuel/air ratio = 0.007 - 0.008. As the fuel/air ratio was increased the effects of fuel zoning became less, as expected, until at the 0.014 f/a point there was no benefit in zoning the fuel flow.

Table I. Exhaust Emission Summary

Test No.	Inlet Total Temperature, °F	°K	Inlet Total Pressure, psia	N/m² x 10⁻⁴ abs	Ref Mach No.	Airflow, lb_m/sec	kg/sec	Fuel Flow Outer lb/hr	Outer kg/hr	Inner lb/hr	Inner kg/hr	Fuel Nozzle Type Simplex	Air Blast	Air Assist	Air Assist Pressure,ʹ psi	N/m²	Fuel/Air Ratio Air & Fuel Flows	Traverse Sample Data	Fixed Sample Data	Outlet Temperature, °F	°K	Combustor Efficiency, %	TPF	Traverse Emission Data* CO_2	CO	NO	NO_2	THC**	Exhaust Duct Emission Data* CO_2	CO	NO	NO_2	THC**	Remarks
201	304	424	29.4	20.3	0.083	14.0	6.35	340	154	330	150	X					0.0132	0.0132	0.0120	1005	814	69	0.474	2635	203	0.34	---	95	2399	190	0.20	---	88	Test data for tests
202	330	439	29.7	20.5	0.083	13.9	6.30	300	136	280	127	X					0.0116	0.0118	0.0112	989	805	73	0.475	2643	219	0.44	---	109	2505	209	0.20	---	107	No. 201 through
203	303	424	29.4	20.3	0.083	14.0	6.35	420	191	420	191	X					0.0167	0.0157	0.0149	1278	965	78	0.364	2768	138	0.19	---	32	2617	132	0.17	---	29	205 in error due to
204	302	424	29.7	20.5	0.082	14.0	6.35	0	0	420	191	X					0.0083	0.0076	0.0077	784	691	72	1.110	2555	159	0.21	---	57	2598	158	0.13	---	50	faulty fuel flow readout.
205	295	419	29.4	20.3	0.056	9.8	4.45	310	141	270	122	X					0.0164	0.0167	0.0154	1305	980	83	0.474	3091	104	0.07	---	28	2834	105	0.15	---	25	
206	347	448	29.5	20.3	0.082	13.5	6.12	174	79	174	79	X					0.0071	0.0073	0.0066	609	594	45	0.541	1937	201	2.08	---	372	1729	192	2.23	---	345	
207	343	446	29.6	20.4	0.082	13.5	6.12	240	109	240	109	X					0.0098	0.0143	0.0131	887	748	71	0.531	3917	255	1.04	---	127	3607	237	0.60	---	115	CO_2 Analyzer Malfunction
208	357	454	29.6	20.4	0.082	13.3	6.03	338	153	338	153	X					0.0140	0.0208	0.0192	1305	980	90	1.120	4565	140	0.91	---	22	4204	135	0.59	---	19	CO_2 Analyzer Malfunction
209	363	457	30.0	20.7	0.081	13.4	6.08	0	0	336	152	X					0.0069	0.0116	0.0119	850	728	86	1.240	4688	175	1.24	---	148	4809	176	1.29	---	149	CO_2 Analyzer Malfunction
210	328	438	29.7	20.5	0.056	9.8	4.45	182	83	182	83	X					0.0103	0.0094	0.0090	862	734	67	0.527	2251	198	0.82	---	144	2147	187	0.97	---	133	
211	325	436	29.6	20.4	0.057	9.9	4.49	261	118	261	118	X					0.0147	0.0130	0.0120	1303	979	89	0.462	2664	100	0.85	---	21	2574	98	0.62	---	18	
212	319	433	29.7	20.5	0.057	10.0	4.54	135	61	131	59	X					0.0074	0.0055	0.005	498	532	31	0.809	912	84	1.56	---	528	764	77	1.37	---	505	
213	225	380	29.8	20.5	0.058	11.0	4.99	205	93	205	93	X					0.0104	0.0105	0.009	764	690	68	0.521	2366	211	0.88	---	195	2175	196	1.28	---	180	
214	227	381	29.8	20.5	0.058	10.9	4.94	157	71	158	72	X					0.0079	0.0069	0.0061	446	503	35	0.808	965	79	1.21	---	614	901	97	1.29	---	516	
215	228	382	29.5	20.3	0.059	11.0	4.99	289	131	289	131	X					0.0146	0.0153	0.0145	1209	926	89	0.480	3115	126	0.68	---	34	2963	123	0.63	---	30	
216	221	378	29.7	20.5	0.081	14.7	6.67	268	122	268	122	X					0.0101	0.0095	0.0094	747	670	67	0.546	2130	238	0.66	---	192	2153	226	0.67	---	180	
217	226	381	29.6	20.4	0.082	14.7	6.67	375	170	375	170	X					0.0141	0.0133	0.0125	1108	871	82	0.526	2573	190	0.59	---	74	2411	172	0.51	---	68	
218	231	384	29.7	20.5	0.082	14.6	6.62	187	85	187	85	X					0.0071	0.0059	0.0058	443	501	38	0.655	846	82	0.90	---	621	1037	71	0.90	---	538	
219	240	389	29.5	20.3	0.082	14.4	6.53	375	170	375	170		X				0.0144	---	0.0135	1074	852	78	0.474	---	---	---	---	---	2451	185	0.39	1.33	107	
220	238	388	29.6	20.4	0.082	14.5	6.58	268	122	268	122		X				0.0102	---	0.0085	773	685	69	0.373	---	---	---	---	---	1920	203	0.32	2.32	158	
221	227	381	29.6	20.4	0.082	14.6	6.62	188	85	188	85		X				0.0071	---	0.0060	592	584	67	0.215	---	---	---	---	---	1770	224	0.64	3.06	217	
222	218	376	29.8	20.5	0.056	10.5	4.76	289	131	289	131		X				0.0152	---	0.0147	1318	988	99	0.300	---	---	---	---	---	2626	139	0.12	2.24	107	
223	215	375	29.7	20.5	0.058	10.8	4.90	206	93	206	93		X				0.0106	---	0.0107	898	754	86	0.315	---	---	---	---	---	2570	157	0.43	4.87	166	
224	215	375	29.5	20.3	0.058	10.8	4.90	145	66	145	66		X				0.0074	---	0.0066	546	559	59	0.231	---	---	---	---	---	1697	171	0.50	13.11	321	
225	217	376	29.4	20.3	0.062	11.3	5.13	289	131	286	131		X				0.0141	---	0.0130	1165	903	91	0.371	---	---	---	---	---	2392	135	0.37	---	141	
226	220	378	29.4	20.3	0.061	11.2	5.08	206	93	207	94		X				0.0102	---	0.0098	821	711	79	0.317	---	---	---	---	---	2412	143	0.00	---	169	
227	216	375	29.3	20.2	0.061	11.3	5.13	146	66	145	66		X				0.0071	---	0.0060	539	555	59	0.248	---	---	---	---	---	1658	157	0.28	---	288	
228	210	372	29.5	20.3	0.060	11.3	5.13	0	0	280	127	X					0.0068	---	0.0073	652	618	82	0.915	---	---	---	---	---	3007	135	1.22	---	73	
229	215	375	29.6	20.4	0.060	11.2	5.08	0	0	413	187	X					0.0102	---	0.0109	861	734	84	1.111	---	---	---	---	---	3109	126	0.71	3.10	57	
230	215	375	29.5	20.3	0.061	11.5	5.22	0	0	541	245	X					0.0131	0.0135	0.0147	1043	835	83	1.070	3027	109	0.87	2.51	56	3342	119	0.93	3.26	45	
231	223	379	29.7	20.5	0.082	14.8	6.71	0	0	540	245	X					0.0101	---	0.0105	745	669	67	0.978	---	---	---	---	---	2529	197	1.53	2.45	189	
232	223	379	29.7	20.5	0.082	14.8	6.71	0	0	376	171	X					0.0070	---	0.0078	651	617	77	0.740	---	---	---	---	---	3017	184	1.60	3.92	98	
233	222	379	29.4	20.3	0.061	11.3	5.13	***	***	289	131	X					0.0070	---	0.0063	512	540	55	0.532	---	---	---	---	---	1827	143	1.53	0.15	293	
234	201	367	29.4	20.3	0.063	11.8	5.35	***	***	412	187	X					0.0097	---	0.0090	614	596	59	0.878	---	---	---	---	---	2008	174	1.31	---	260	
235	201	367	29.6	20.4	0.062	11.7	5.31	***	***	528	239	X					0.0125	0.0128	0.0126	921	767	75	0.634	2638	159	1.09	---	155	2653	166	1.20	---	129	
236	298	421	29.7	20.5	0.083	14.0	6.35	0	0	338	153	X					0.0066	---	0.0072	728	660	83	0.728	---	---	---	---	---	3067	168	0.15	---	48	
237	291	417	29.2	20.1	0.084	14.2	6.44	0	0	482	219	X					0.0094	---	0.0102	869	738	81	0.918	---	---	---	---	---	3024	186	0.11	---	67	
238	313	429	29.3	20.2	0.062	10.7	4.85	0	0	261	118	X					0.0067	---	0.0073	749	671	83	0.829	---	---	---	---	---	3177	140	0.94	---	30	
239	312	429	29.7	20.5	0.061	10.6	4.81	0	0	374	170	X					0.0098	---	0.0108	978	799	89	0.831	---	---	---	---	---	3399	93	0.20	---	14	
240	305	425	29.5	20.3	0.060	10.5	4.76	0	0	522	237	X					0.0138	---	0.0154	1229	938	91	0.868	---	---	---	---	---	3474	81	0.24	---	10	
241	232	384	29.4	20.3	0.081	14.4	6.53	188	85	188	85			X	20	13.8	0.0072	---	0.0064	564	569	60	0.141	---	---	---	---	---	1675	194	0.82	12.40	313	
242	217	376	29.6	20.4	0.081	14.7	6.67	266	121	267	121			X	20	13.8	0.0100	---	0.0096	841	723	78	0.232	---	---	---	---	---	2412	182	0.32	3.00	143	
243	217	376	29.5	20.3	0.081	14.6	6.62	375	170	375	170			X	20	13.8	0.0142	---	0.0142	1173	907	88	0.364	---	---	---	---	---	2889	133	0.43	2.32	54	
244	220	378	29.5	20.3	0.081	14.6	6.62	188	85	188	85			X	10	6.89	0.0071	---	0.0046	462	512	42	0.365	---	---	---	---	---	717	92	0.54	43.11	447	CO_2 Analyzer Malfunction
245	220	378	29.7	20.5	0.080	14.5	6.58	210	95	210	95			X	0	0	0.0081	---	0.0045	441	500	33	0.335	---	---	---	---	---	482	60	0.36	89.0	424	CO_2 Analyzer Malfunction
246	242	390	29.8	20.5	0.081	14.5	6.58	268	122	268	122			X	0	0	0.0102	---	0.0092	---	---	---	---	---	---	---	---	---	1882	170	1.28	14.0	262	Outlet temperature rake
247	242	390	29.7	20.5	0.081	14.4	6.53	375	170	375	170			X	0	0	0.0144	---	0.0135	---	---	---	---	---	---	---	---	---	2642	127	1.15	3.51	74	malfunction tests 246
248	240	389	29.8	20.5	0.081	14.4	6.53	375	170	375	170			X	10	6.89	0.0144	---	0.0136	---	---	---	---	---	---	---	---	---	2729	122	1.23	3.14	53	through 249 and 251.
249	239	388	29.5	20.3	0.082	14.5	6.58	268	122	257	117			X	10	6.89	0.0100	---	0.0094	---	---	---	---	---	---	---	---	---	2237	211	1.82	4.37	161	
250	224	380	29.6	20.4	0.081	14.7	6.67	0	0	378	171			X	20	13.8	0.0071	---	0.0074	710	650	87	0.464	---	---	---	---	---	2851	175	1.13	3.05	77	
251	226	381	29.9	20.6	0.082	14.8	6.71	0	0	521	236			X	20	13.8	0.0097	---	0.0094	---	---	---	---	---	---	---	---	---	2259	180	0.47	3.18	200	

*Exhaust emission data given as lb_m (g) specie per 1000 lb_m (kg) fuel burned

**THC (total hydrocarbon) presented as equivalent methane

***Circumferentially zoned fuel injection mode

---Data not taken

ʹAir assist pressure listed is the air pressure drop.

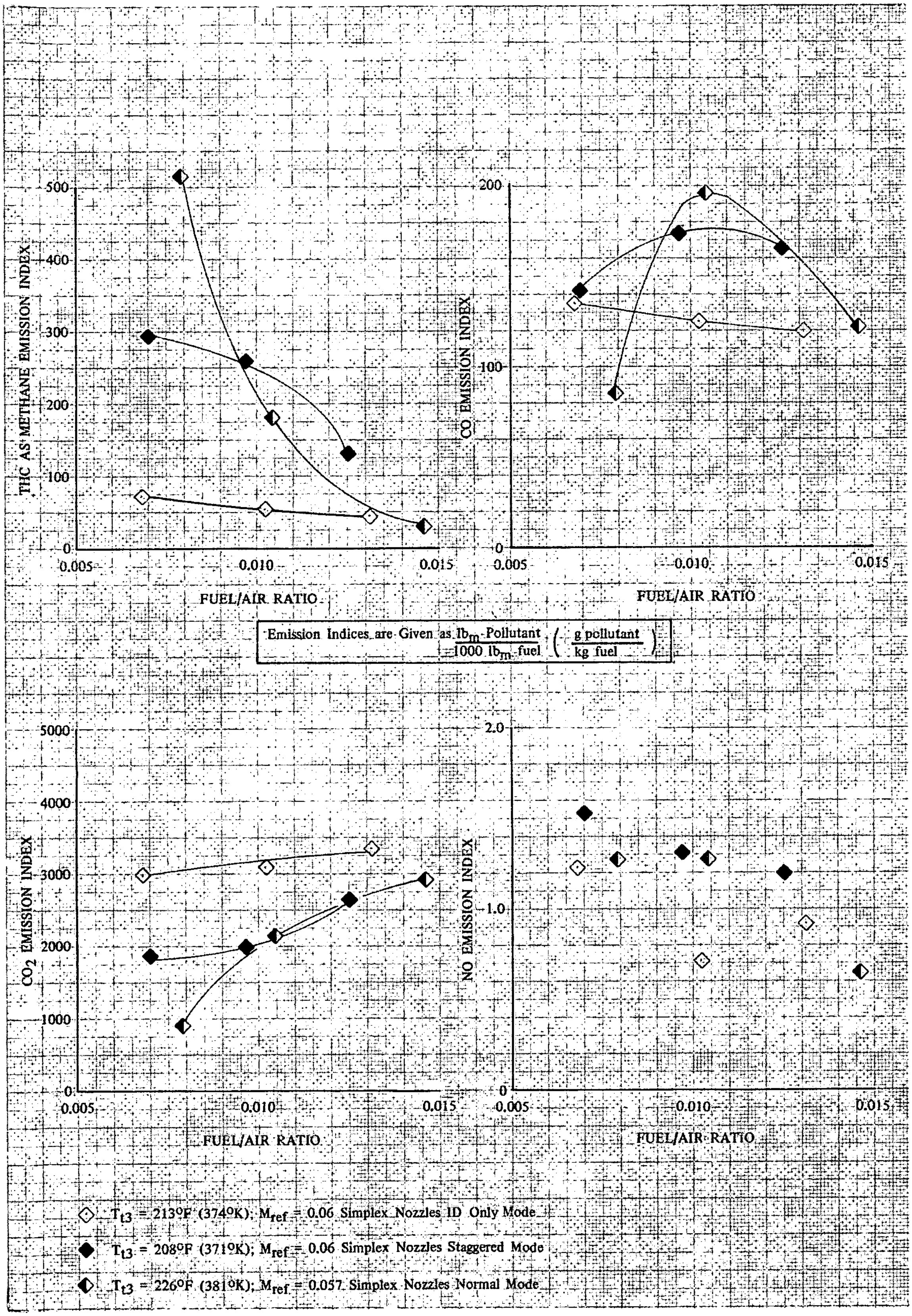


Figure 12. Comparison of Exhaust Emission Indices for Simplex Nozzles Operating in Normal, ID Annulus Only, and Staggered Modes: Data Obtained With Fixed Rake Only

DF 92672

The staggered circumferential zoning (figure 1) did not reduce the THC emissions as well. This is probably due to excessive quenching of the combustion process brought about by the very large nozzle spacing of this arrangement. Each pocket of burning gases is completely surrounded by a region of cold, nonreacting gases. Consequently, heat rejection to the surroundings is increased, resulting in premature quenching of the flame. By radially zoning the fuel to the inner annulus the exposure of the hot combustion gases to cold surroundings is greatly reduced. This suggests that circumferential zoning of the type shown in figure 13 would result in a reduction of THC emissions comparable to that of radial zoning.

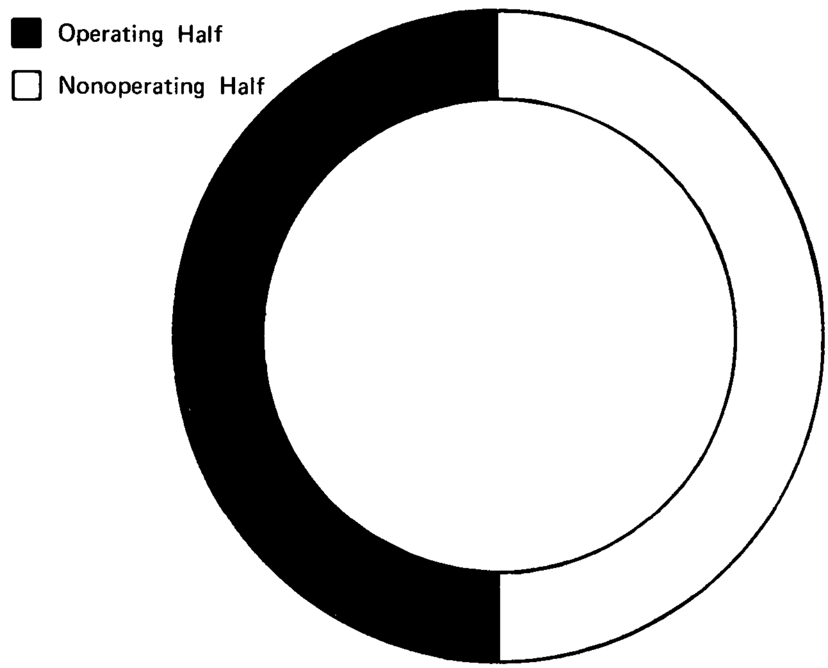


Figure 13. One Method of Circumferential Fuel Zoning FD 63823

CO Emissions

The effect of fuel zoning on the emission levels of CO was quite different. At the 0.007 f/a test points, normal mode fuel injection (all nozzles flowing) produced the lowest CO emissions. As the fuel flow was increased the normal mode emission level increased to a peak at a f/a around 0.010, after which it began to fall, whereas in the radially zoned mode the emission level was highest at the 0.007 f/a and decreased with increasing f/a. The reason for this difference in CO emissions between the zoned and unzoned injection modes can be explained by examining the behavior of the combustion efficiency with f/a. Figure 14 is a plot of combustion efficiency for the test points of figure 12. The normal mode efficiency at the 0.007 f/a point is so low (35%) that the bulk of the fuel passed out of the combustor unburned, consequently, very little CO was produced. As the f/a (and efficiency) increased, the production of CO increased. At a f/a of approximately 0.010, the oxidation rate of CO to CO_2 became large enough to result in a decrease in CO. When the fuel is zoned, the combustion efficiency at the low f/a point is improved to the point where a larger production of CO results.

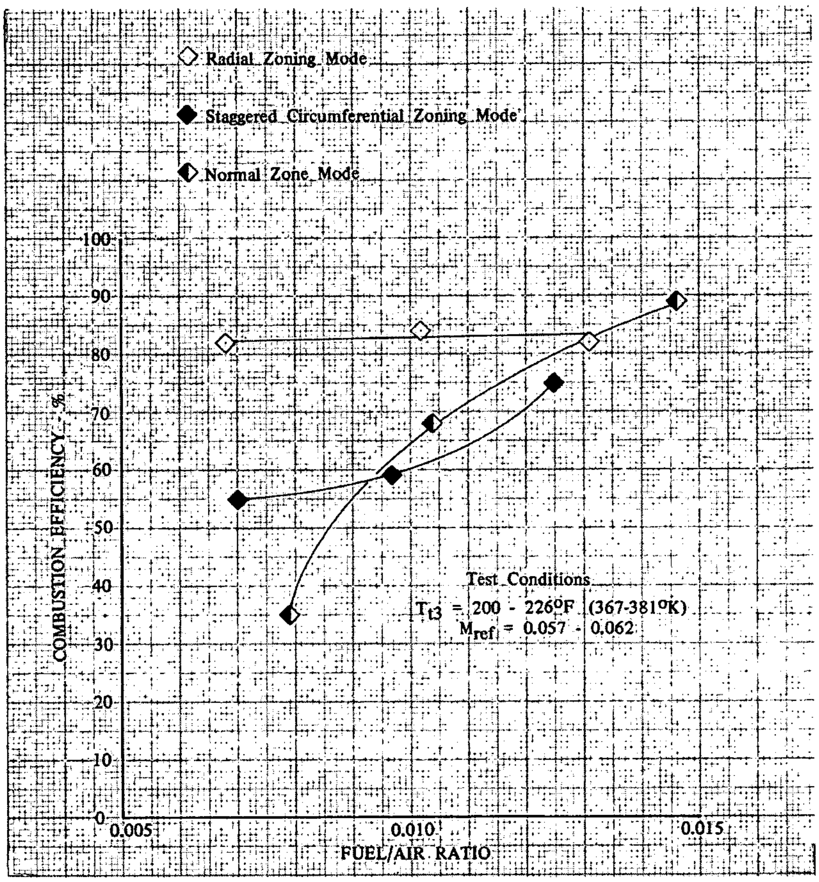


Figure 14. Effect of Fuel Zoning on Combustion Efficiency DF 92629

A possible problem associated with fuel zoning is the effect of the distorted outlet radial or circumferential temperature profiles on the structural integrity of an engine's hot sections. Figure 15 is a plot of the radial temperature profile obtained with the radially zoned injection mode at a f/a of 0.014. The profile distortion is not severe and the maximum profile temperature is well within the capabilities of current turbine materials.

Fuel Nozzles

Three types of fuel nozzles were investigated. They were: (1) a simplex-type pressure atomizing nozzle, (2) an air blast air atomizing nozzle, and (3) an air assist air atomizing nozzle. For the sake of clarity, the differentiation between air blast and air assist nozzles is presented again. Air blast refers to those air atomizing nozzles that operate on combustor pressure drop. Air assist refers to those air atomizing nozzles that receive their atomizing air from an external source.

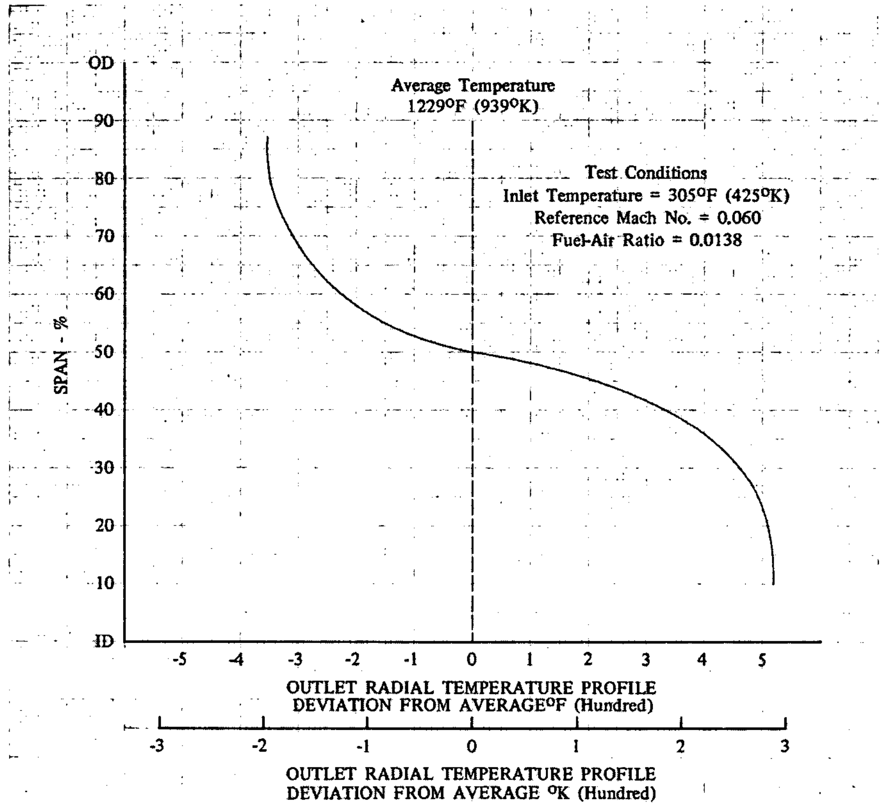


Figure 15. Outlet Radial Temperature Profile, Radially Zoned Fuel Injection DF 92675

A comparison of the results obtained from each of the three nozzles is shown in figure 16. The nozzles were operating in the normal fuel injection mode at an inlet temperature between 217°F and 242°F (376°K and 390°K). The reference Mach number was between 0.080 and 0.082. The air assist nozzle was operated with a nozzle air pressure drop of 20 psi (13.8×10^4 N/m^2).

At the lower f/a test point, both of the air atomizing nozzles gave lower THC emissions. The data of figure 16 show that reductions in THC emissions of 2 to 1 were obtained with the air-atomizing nozzles. The CO emissions followed the same trend described in the discussion of fuel zoning. As the f/a was increased the performance of the air blast nozzle became worse in relation to the other nozzles. This is apparently due to the test procedure. The tests were conducted at a constant airflow and pressure at all fuel/air ratios, consequently, the air energy available for atomization was constant. As the fuel flow was increased the air atomization energy per unit of fuel flow decreased. This resulted in a decrease in atomization quality with increasing fuel flow. This indicates that fuel zoning would not be as effective with this nozzle as with the Simplex nozzle. Zoned fuel injection tests with the air blast nozzle were not conducted. The air assist nozzle did not suffer from this because a portion of the fuel atomization was accomplished conventionally by fuel pressure drop; as fuel flow was increased the pressure atomizing energy also increased.

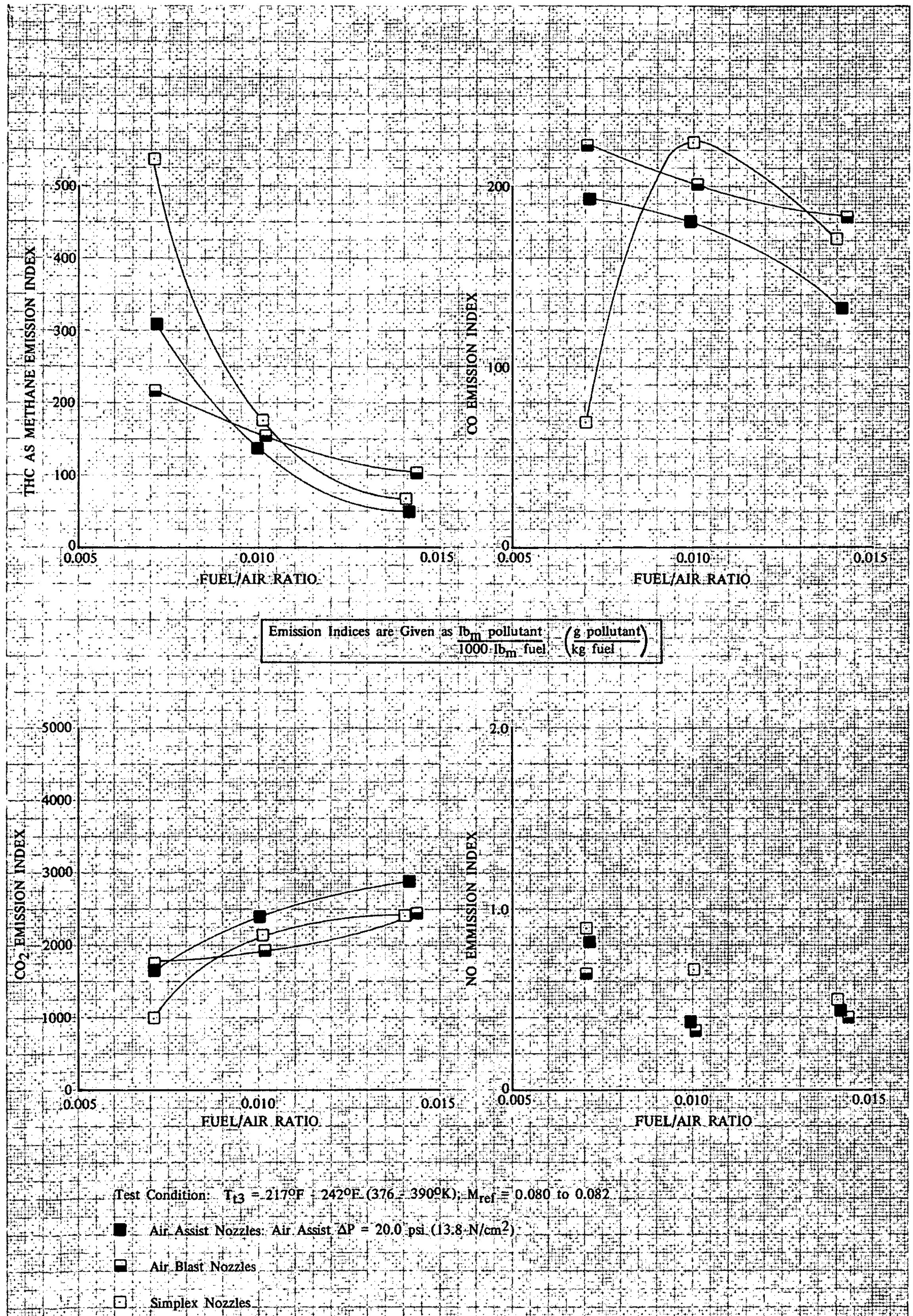


Figure 16. Comparison of Emission Characteristics of Three Fuel Nozzle Types Using Normal Fuel Injection Mode: Data Obtained With Fixed Rake Only DF 92673

The effect of air assist nozzle air pressure drop is shown in figure 17. The THC emission index is plotted against fuel/air ratio for various air assist pressure drops. Figure 17 shows that increasing the nozzle airflow reduced the THC emissions.

A comparison of the air assist and Simplex nozzles operating in the radially zoned fuel injection mode is shown in figure 18. The data were obtained at the low inlet temperature (200°F, 367°K) and high reference Mach number (0.08) test condition. Two important points are evident in the data: (1) by fuel zoning, the Simplex nozzles achieved emission levels as low as those achieved with the air assist nozzles without their attendant complexities, and (2) the fuel loading in the inner combustion zone has exceeded the maximum allowable for peak efficiency. That this should occur at such a relatively low f/a ratio is evidently due to the high reference Mach number and the low inlet temperature. At the high reference Mach number the residence time is reduced; there is less time for fuel vaporization, ignition and reaction. The low inlet temperature inhibits fuel vaporization and reduces the chemical reaction rate. Together these two effects act to reduce the allowable fuel loading for peak efficiency.

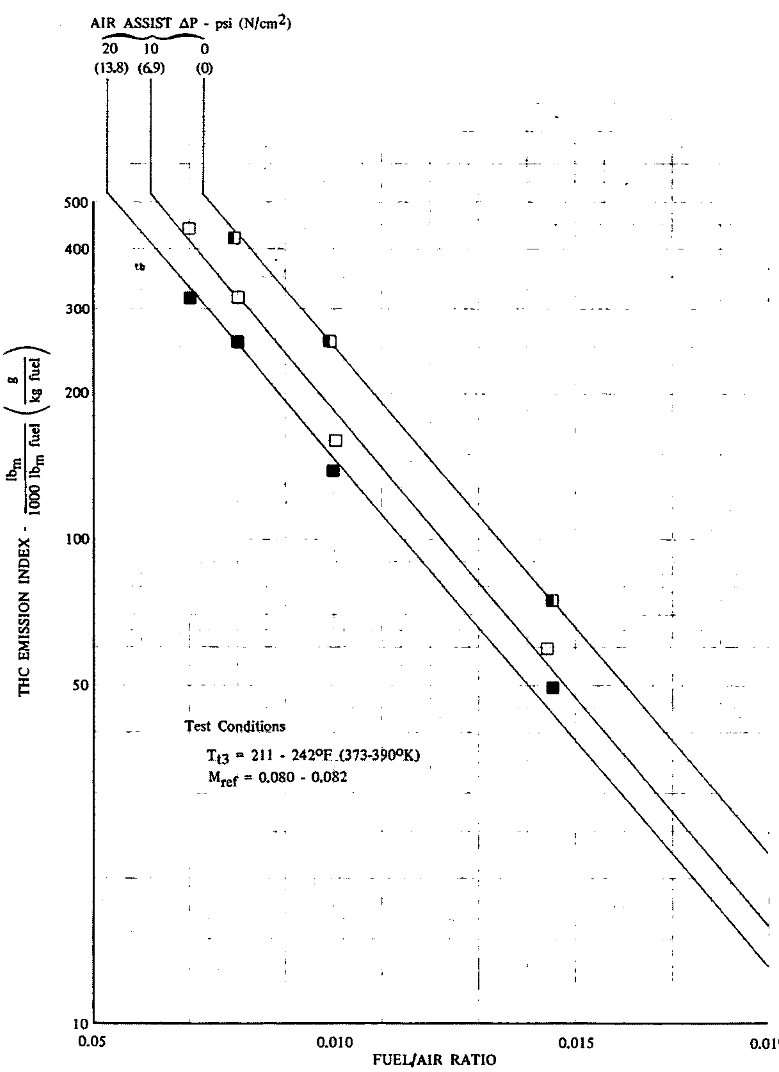


Figure 17. Effect of Air Assist ΔP on THC Emission Levels

DF 92628

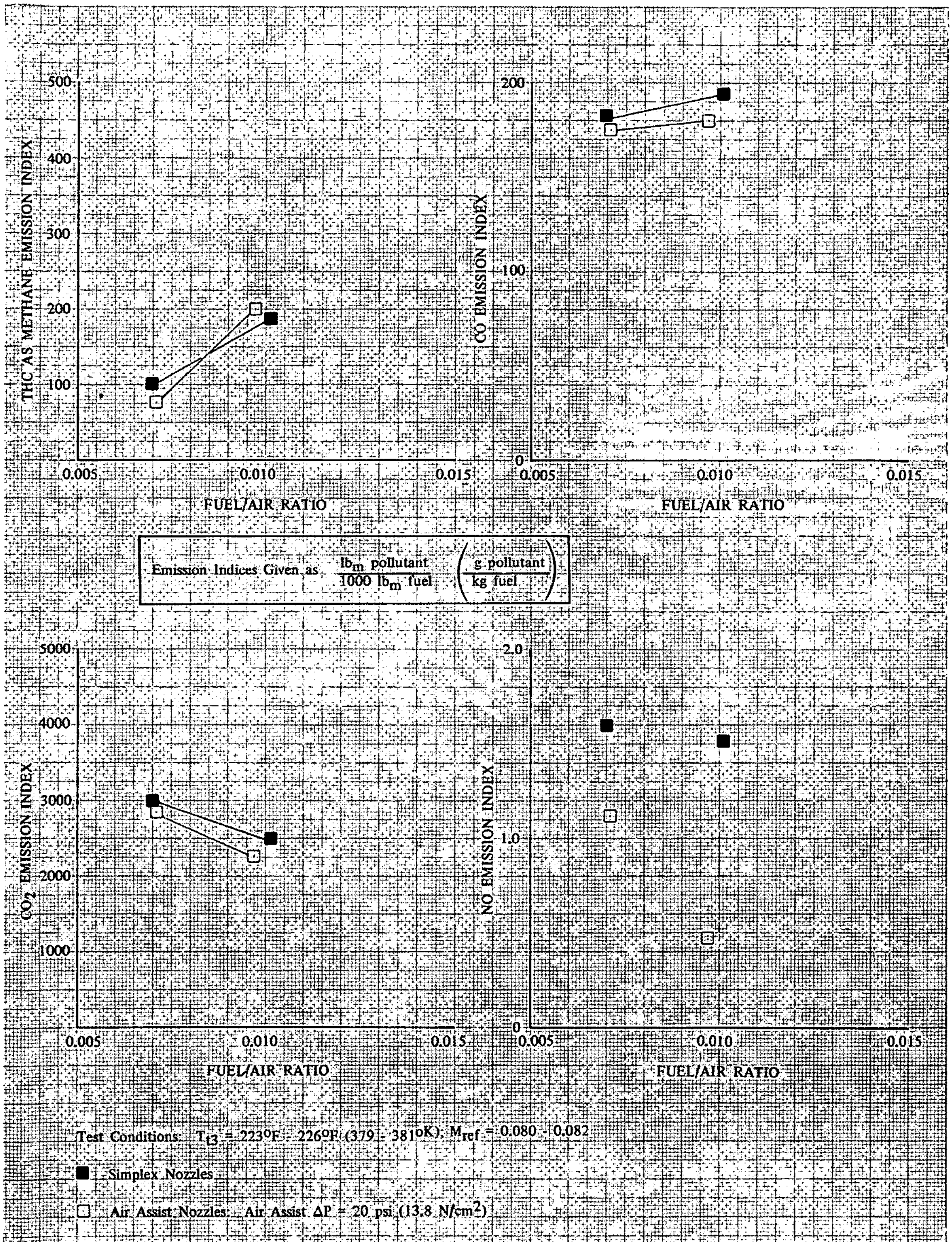


Figure 18. Comparison of Simplex and Air-Assist Nozzles, Radially Zoned Fuel Injection: Data Obtained With Fixed Rake Only DF 92674

Inlet Temperature and Reference Mach Number

The effect of inlet temperature and reference Mach number (M_{REF}) on THC emissions is presented in figures 19 and 20. Figure 19 is plotted for the Simplex nozzles in the radially zoned mode. Figure 20 is plotted for the Simplex nozzles in the normal mode. The data of both figures show that an increase in inlet temperature reduces THC emissions. This is the result of an improvement in fuel vaporization and an increase in chemical reaction rate brought about by the higher temperature. The effect of M_{REF} is not so clear cut. In the radially zoned injection mode an increase in M_{REF} resulted in an increase in THC emissions. However, in the normal injection mode the THC emissions decreased with increasing M_{REF}. This shift in the influence of M_{REF} on the THC emissions is apparently due to the decrease in fuel atomization brought about by the lower fuel flows at the lower M_{REF}.

Nitric Oxide Emissions

The data for nitric oxide are very scattered as table I shows. Little can be discerned in the data except that the emissions are very low, less than 2 lb_m/1000 lb_m fuel (g/kg fuel).

Compressor Bleed

As stated in the introduction, idle emissions of THC and CO can be reduced by bleeding overboard large quantities of compressor discharge air. This raises the combustor fuel/air ratio, thus raising the combustion efficiency and lowering the levels of the emissions. However, idle fuel consumption is increased if idle thrust is maintained. Figure 21 shows the increase in fuel flow required for a P&WA™ JT8D-9 turbofan engine to maintain a constant thrust of 840 lb (3737N) for overboard bleeds up to 30%. At the above thrust level an overboard bleed of 30% gives a combustor fuel/air ratio of 0.014, which is high enough to effect considerable reductions in THC and CO emissions. This combustor study showed a reduction in THC emission index from 500 to 30 when the f/a was increased from 0.007 to 0.014. Depending on customer service bleed requirements, an overboard bleed of 30% requires almost a 20% increase in idle fuel flow. However, idle fuel consumption is such a small portion of aircraft operating expense that this is not a large increase in overall cost. A more significant expense, as far as current engines are concerned, is the retrofitting of new or modified diffuser cases to provide the higher bleed flows. For future engines, no significant cost increase should result if this feature is included in the original design.

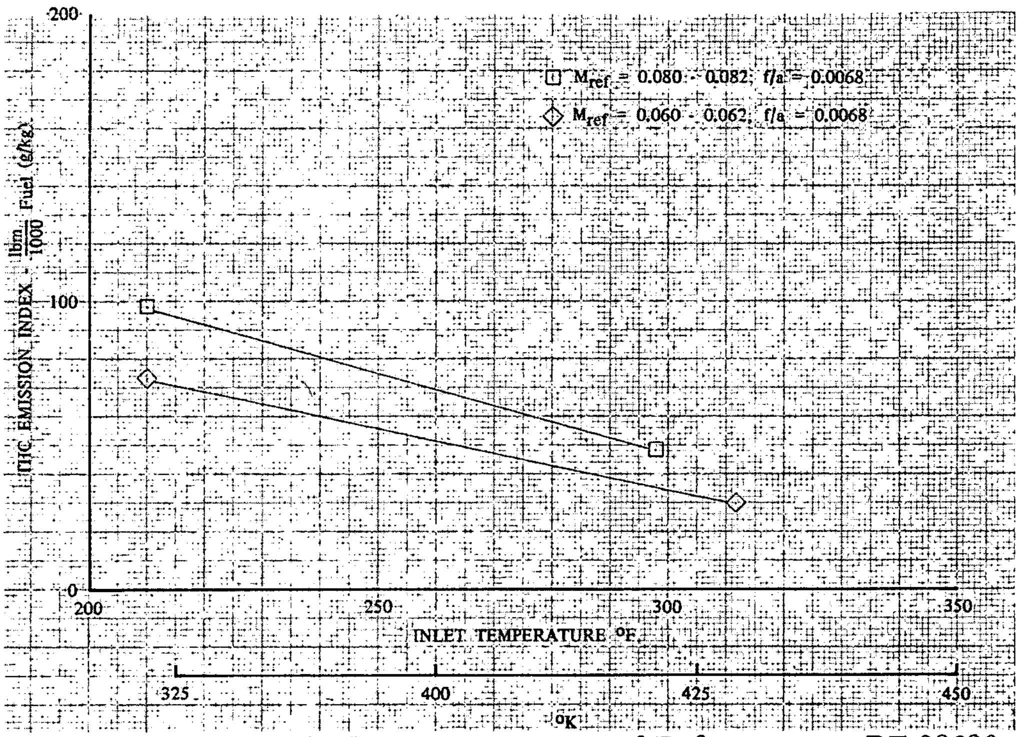


Figure 19. Effect of Inlet Temperature and Reference Mach Number on THC Emission Index, Simplex Nozzles Radially Zoned DF 92630

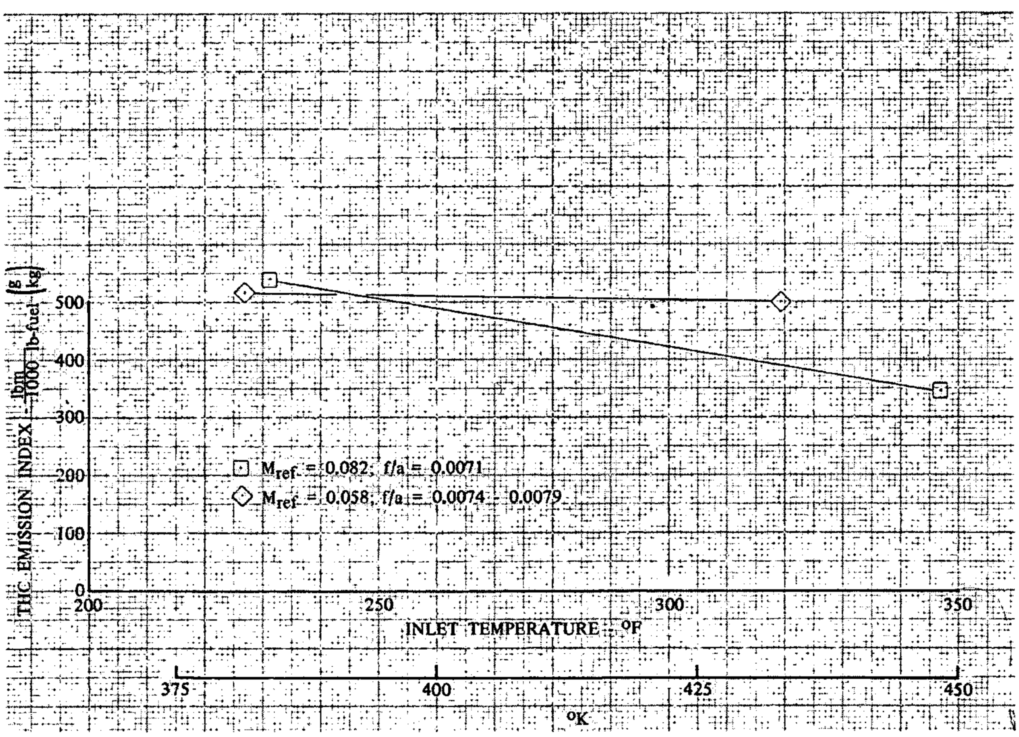


Figure 20. Effect of Inlet Temperature and Reference Mach Number on THC Emission Index, Simplex Nozzles Normal Mode DF 92631

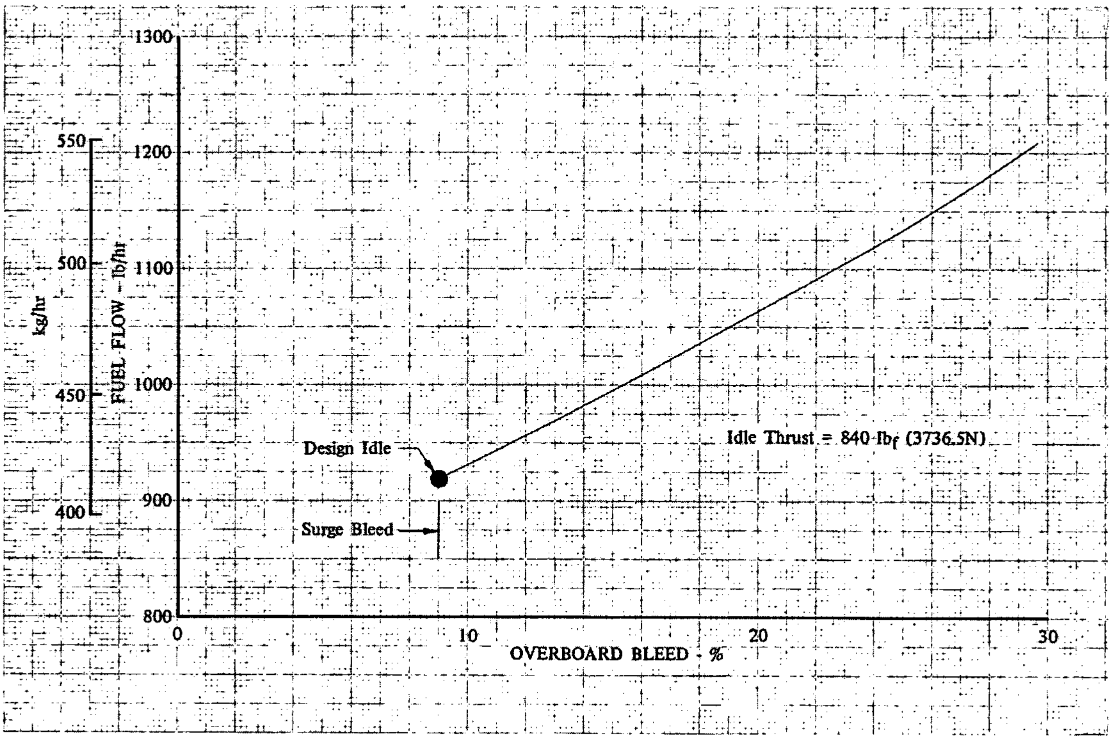


Figure 21. Fuel Flow vs Percent Bleed - P&WA JT8D-9 Turbofan Engine DF 92676

Sampling Technique

Gas samples were extracted from the exhaust stream at two locations: (1) at the combustor outlet and (2) in the test rig exhaust duct approximately 13 duct L/D's downstream from the combustor outlet. At the combustor outlet the sample was obtained by traversing with a 5-point, air-cooled rake. A more complete description of the sampling equipment is presented in Appendix C. The five sampling tips were connected to a common manifold so that an average radial sample was obtained at each circumferential location. The sample was then volume weighted to account for temperature variations, and an average emission index for each exhaust-specie of interest calculated. In the exhaust duct the sample gas was extracted at a fixed location with a 5-point, air-cooled rake. The sample points were uniformly spaced across the duct.

Although traversing the combustor outlet is the most accurate method of obtaining emission data, it is a time consuming process. Test time was almost doubled when a sample traverse was taken. Consequently, the primary reason for using the fixed rake was to reduce test time. Use of this rake may incur slight errors due to the increased reaction time provided by the additional duct length, and condensation of unburned hydrocarbons on the duct walls. To reduce the latter, the exhaust duct was uncooled for most of the tests except in the immediate vicinity of the combustor outlet. A comparison of the THC and CO_2 data obtained with each rake is shown in figures 22 and 23. The data from the fixed rake are within 10% of being in exact correspondence with the traversing rake. Consequently, most of the data taken during the test program were obtained with the fixed exhaust duct rake.

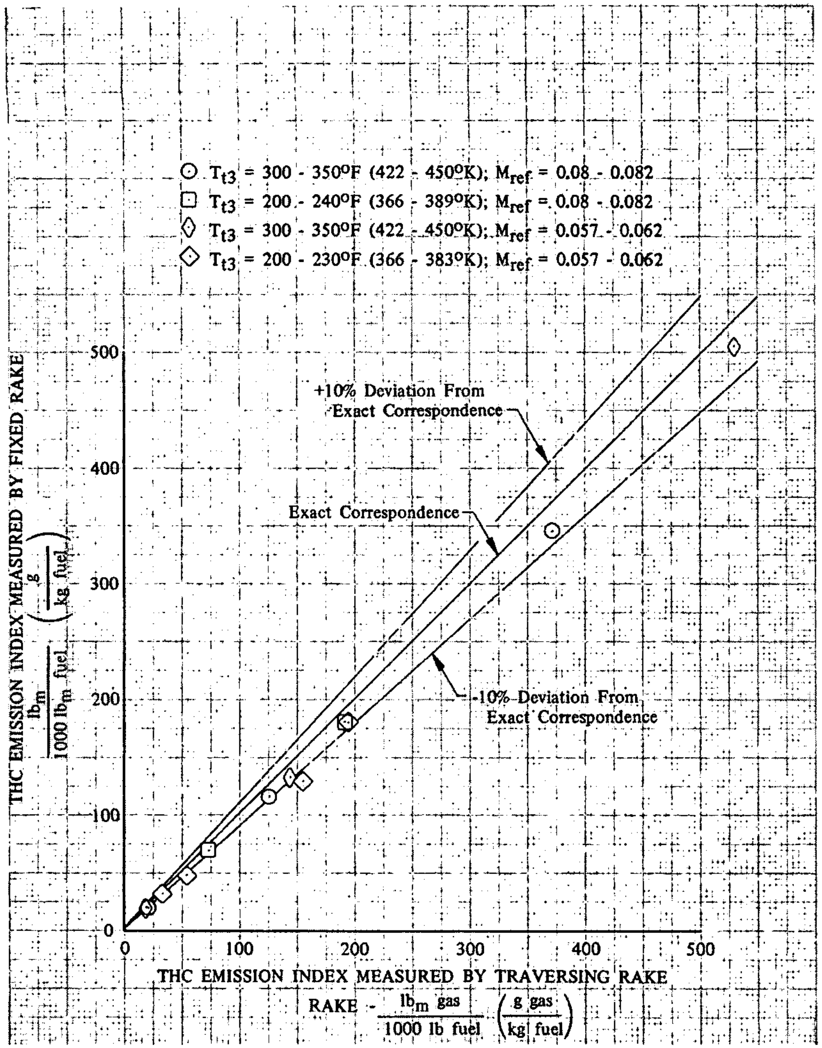


Figure 22. Comparison of THC Emission Indices for Fixed and Traversing Rakes DF 92625

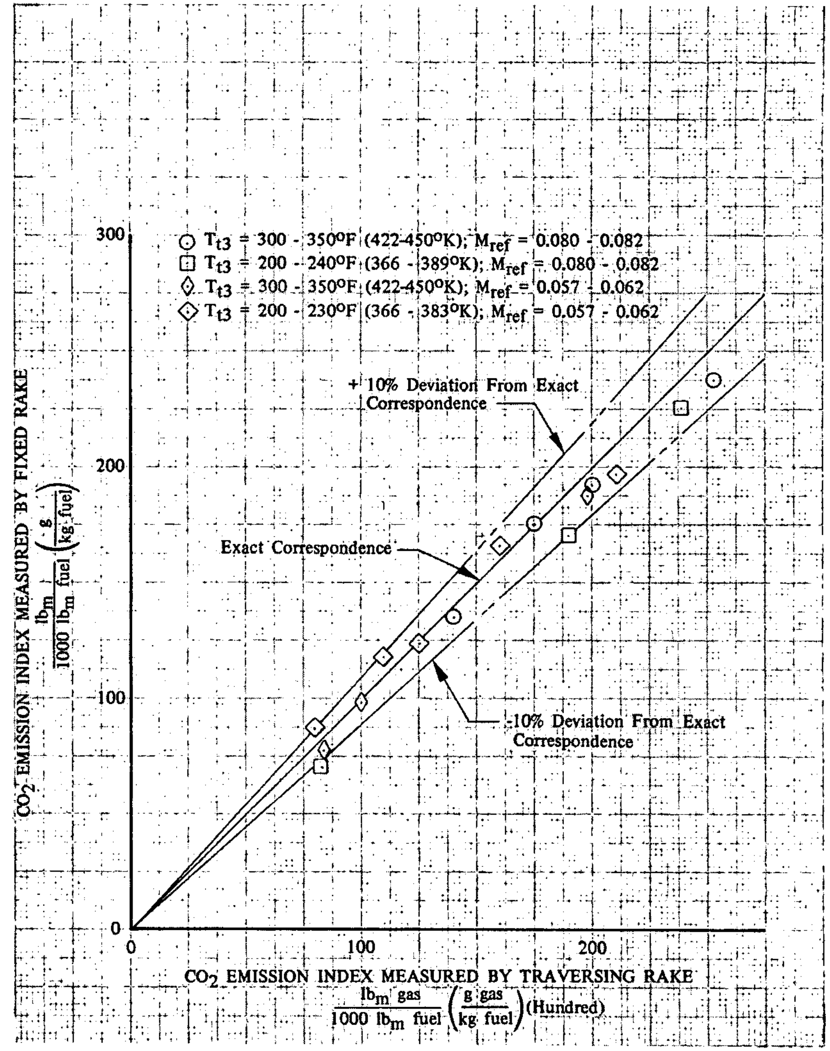


Figure 23. Comparison of CO_2 Emission Indices for Fixed and Traversing Rakes DF 92626

Figure 24 shows typical circumferential profiles of emission index for the various exhaust species measured during the program. The data were taken with the traversing rake during test No. 235 (table I). Note the extreme variation in the emission indices across the combustor outlet. If fixed sampling rakes were randomly installed across the combustor outlet the errors in the data could have been as large as 167% for the example given.

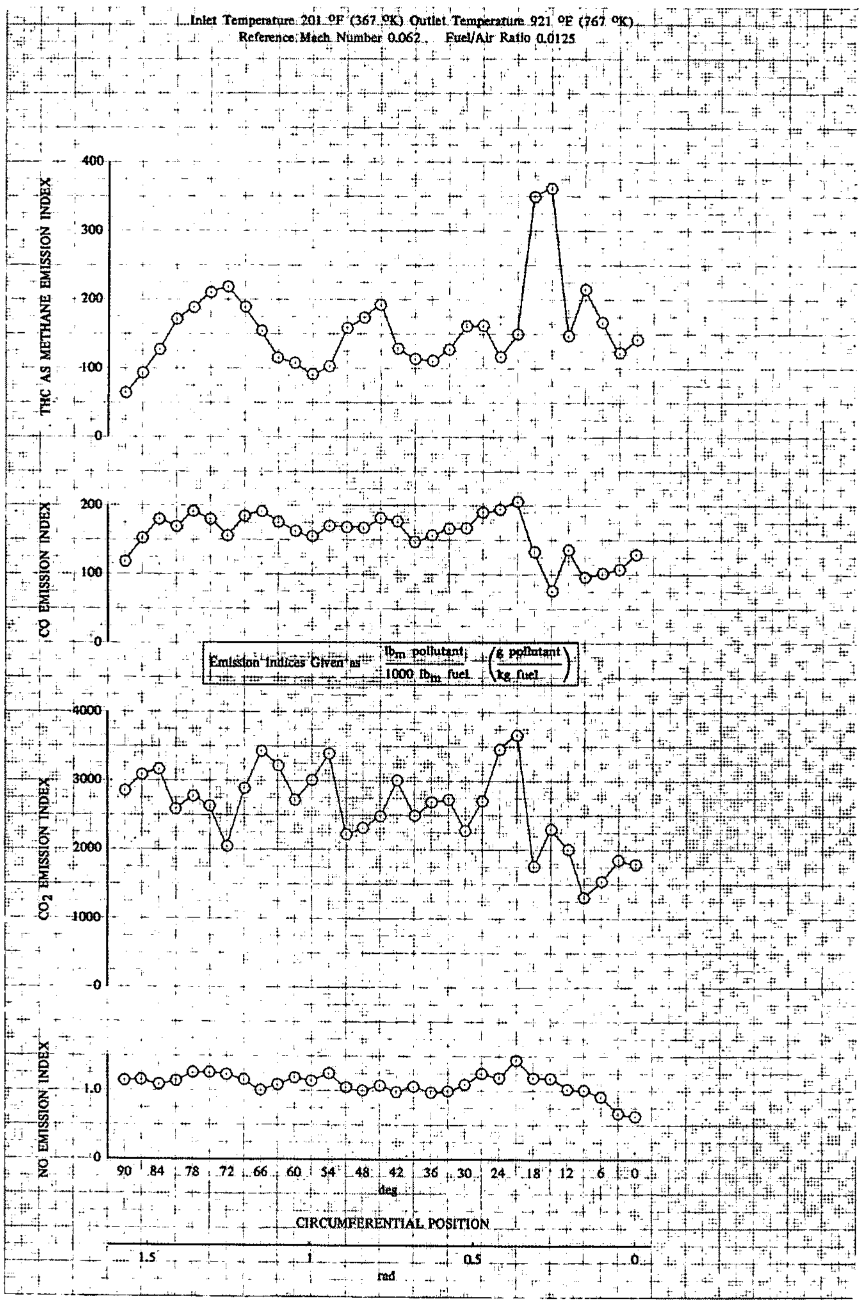


Figure 24. Circumferential Profiles of Exhaust Indices, Test No. 235 DF 94460

A measure of the accuracy of the emission data is presented in figure 25. The bulk of the sample calculated fuel/air ratios fall within 10% of the fuel/air ratios determined from measured fuel and airflows.

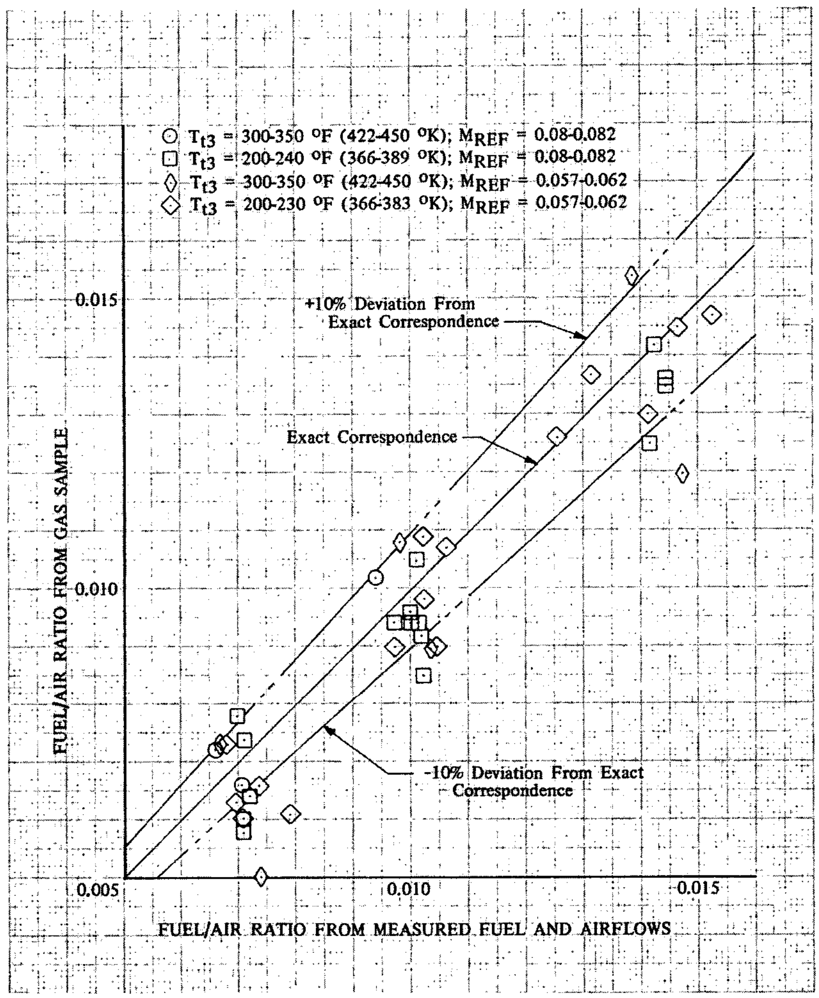


Figure 25. Comparison of f/a Calculated From Emission Data With f/a Calculated From Measured Fuel and Airflows

DF 92627

SUMMARY OF RESULTS

An exhaust emission survey has been conducted on a double-annular ram-induction combustor operating at simulated ground idle conditions. The emission levels of CO, CO_2, unburned hydrocarbons and NO were measured. Various means of reducing these emissions were investigated including (1) fuel zoning, (2) fuel nozzle design and (3) operating conditions. Following is a summary of the important results:

1. Fuel zoning is an excellent method of reducing the emissions of CO and unburned hydrocarbons. By radially zoning the fuel flow (passing all of the fuel through the inner combustion annulus) a reduction in unburned hydrocarbon emissions of 5 to 1 was demonstrated.
2. To achieve the best results with fuel zoning, widely separated pockets of burning gases should be avoided since this causes premature quenching of the flame.
3. Use of air atomizing nozzles can reduce idle emissions of unburned hydrocarbons and CO. Reductions in hydrocarbon emissions of 2 to 1 were demonstrated.
4. The air blast nozzle suffered from a decrease in fuel atomization with increasing fuel flow due to the constant airflow and pressure test condition. This result indicates that fuel zoning would be less effective with this type of nozzle.
5. The THC emission levels obtained with the Simplex nozzles used herein in the radially zoned fuel injection mode were as low as those obtained with the air assist nozzles in the same fuel zoning mode.
6. Increasing the combustor inlet air temperature decreases the THC and CO emission levels.
7. The effect of combustor reference Mach number on the emission levels of CO and THC is dependent upon the change in fuel atomization quality with changing Mach number. If the atomization quality remains high a decrease in reference Mach number results in a decrease in the above emissions. If, however, the fuel atomization quality deteriorates significantly with a decrease in reference Mach number, because of lower required fuel flow, the emissions will increase.
8. The outlet radial temperature profile obtained with the radially zoned fuel injection mode poses no problem to the structural integrity of an engine's hot sections.
9. The nitric oxide emissions were low (less than 2.0 lb_m/1000 lb_m fuel (g/kg) for all test conditions and fuel injection modes.

10. A reduction in hydrocarbon emissions similar to that obtained with fuel zoning should also be obtainable by operating with higher-than-normal compressor bleed flow. However, analysis indicates a 20% increase in idle fuel consumption is incurred with this approach.

11. Large circumferential variations in emission levels were observed at the combustor outlet. Accurate emission measurements can be obtained at the combustor outlet only by traversing the entire outlet or using a very large number of stationary probes.

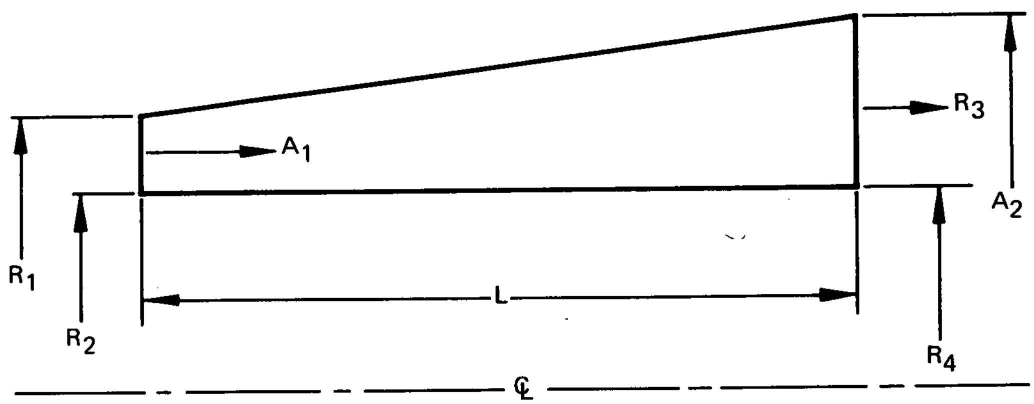
APPENDIX A
EQUIVALENT CONICAL ANGLE

Definition

The equivalent conical angle (ECA) is defined as the included angle of a conical diffuser that has the same area ratio, inlet area, and wetted surface area as the diffuser under investigation. For annular diffusers, ECA may be approximated by the following equation:

$$ECA = 2 \tan^{-1} \left[\frac{\left(\frac{A_2}{A_1} - 1 \right) A_1}{\pi L \; (R_1 + R_2 + R_3 + R_4)} \right]$$

where the symbols are defined by:



Application

The above equation for ECA does not consider the presence of struts in the diffusing passage. The equation was used only to arrive at an area ratio for a given ECA and diffusing length assuming that no struts were in the passage. In adding struts, the diffuser wall exit radii were adjusted to maintain the same area ratio.

APPENDIX B
TEST FACILITY AND TEST RIG DESCRIPTION

Test Facility

All combustion tests were conducted on test stand D-33B at the P&WA Florida Research and Development Center. Combustion air was supplied by bleeding the compressor discharge of a JT4 turbojet engine. Airflow rate was controlled by a pneumatically operated 10 in. (25.4 cm) inlet butterfly valve with vernier control by a 4 in. (10.16 cm) pneumatically operated supply line bleed valve.

The test stand fuel system was capable of supplying each of three combustion zones with 300 pph (136.08 kg/hr) of ASTM-A1 type fuel at 750 psig (517 N/cm^2) fuel pressure. Control room monitoring of fuel pressure and temperature was provided for each zone.

The test facility had high pressure air service available for cooling the gas sample rakes.

Test Rig Description

A brief description of the major components of the combustor test rig is presented below. For reference, a cross section of the rig is presented in figure 26. The rig was constructed entirely of AISI type 300 Series stainless steel.

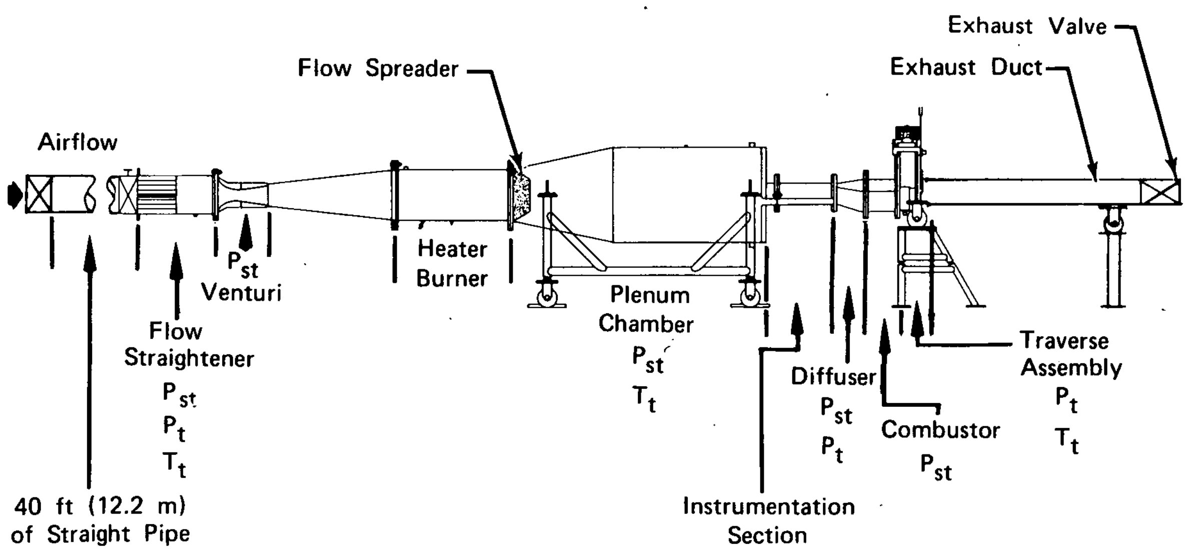


Figure 26. Double-Annular Combustor Test Rig FD 13874D

Flow Straightener

This section was designed to smooth out any irregularities in rig inlet airflow and to provide a near stagnation region for accurate measurement of inlet total pressure and temperature. The flow straightener was fabricated from a 12 in. (30.480 cm) diameter cylinder 24 in. (60.960 cm) long. A bank of 1.5 in. (3.81 cm) diameter tubes 12 in. (30.480 cm) long was used to straighten the inlet airflow.

Venturi

This section provided accurate airflow measurement with minimum pressure loss. The rig airflow entered through a constant radius inlet to a 4.7483 in. (12.0607 cm) diameter throat. Transition from the venturi throat to the preheater inlet was provided by a conical diffusing section 40.840 in. (103.7 cm) long with a 12 deg, 31 min (0.218-rad) included angle.

Preheater

The preheater was not used in this portion of the test program. The inlet temperature to the combustor was simply that obtained from the JT4 slave engine compressor bleed air.

Plenum Chamber

The plenum chamber functioned to provide airflow to the rig test section at uniform temperature and pressure. This was accomplished by discharging the airflow from the preheater through a multihole flow spreader into a large volume container. The plenum was fabricated from a cylinder 29.250 in. (74.295 cm) in diameter and 48 in. (121.920 cm) long. To ensure a uniform profile into the rig test section, a bellmouth flange was incorporated to transition from the plenum exit area to the test section inlet area. Bosses were installed near the exit of the plenum for the installation of temperature sensors to measure the combustor inlet temperature.

Instrumentation Section

This section housed the instrumentation used to determine the diffuser inlet total pressure, static pressure, and pressure profiles. It was designed to simulate a quarter section of the compressor discharge of a full-scale engine.

Diffuser-Combustor Case

This section housed the combustor hardware and functioned to direct the inlet airflow into the combustor liners.

Traverse Case

This section housed the outlet temperature and pressure traversing rake and the traversing gas sample rake.

Exhaust Duct

This section housed the fixed gas sample rake. It was sufficiently long to thoroughly mix the exhaust gases and to develop a uniform flow profile.

Exhaust Valve

This was an electrically driven valve used to back pressure the test rig.

APPENDIX C
INSTRUMENTATION

Basic Performance Instrumentation

Instrumentation was provided to measure the following parameters.

1. Combustor airflow
2. Fuel flow for each combustion zone (combustor outer and inner annuli)
3. Fuel temperature and pressure for each zone
4. Combustor inlet total temperature, total pressure and static pressure
5. Combustor outlet total temperature and pressure. The outlet static pressure was assumed to be ambient.
6. Miscellaneous diffuser and combustor total and static pressures.

A cross section of the test rig, showing the location of the various instrumentation planes, is shown in figure 27. A brief description of the instrumentation and monitoring equipment used is described below.

Airflow

As mentioned in the section on test rig hardware (Appendix B), the combustor airflow was measured with a venturi meter. The inlet total temperature and pressure sensors were located in the flow straightener approximately 12 in. (30.480 cm) upstream of the venturi throat. Two chromel-alumel, shielded thermocouples spaced 180 deg (3.141 rad) apart measured total temperature, and two kiel-type pressure probes spaced 180 deg (3.141 rad) apart measured total pressure. The static pressure at the venturi throat was measured with two wall taps spaced 180 deg (3.141 rad) apart.

The venturi inlet temperature was monitored on a 0°F to 1600° F (255.4° K to 1144.3° K) indicating potentiometer, and the total and static pressures on 0 to 80 in. (0 to 2.03 m) mercury-filled, U-type manometers.

Fuel Flow

Fuel flow to each of the two combustion zones was measured by turbine-type flowmeters. The data from these meters were monitored on a 5-channel, preset digital counter. Fuel temperature was measured by a chromel-alumel immersion thermocouple and monitored on an indicating potentiometer. Fuel pressures were measured by wall static pressure taps located in the inlet supply lines and were monitored on 0 to 1000 psig (0 to 699.6 N/cm^2) pressure gages.

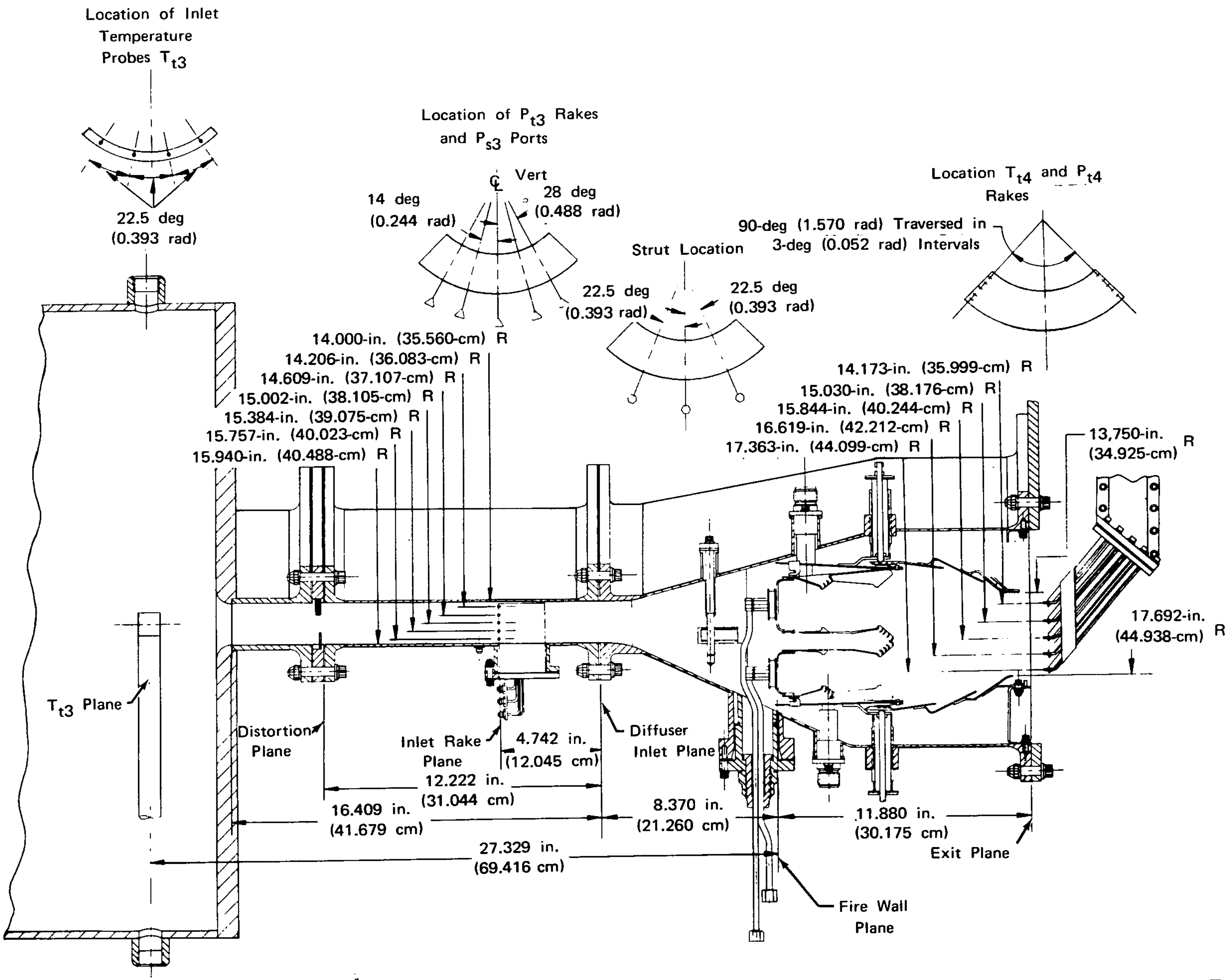


Figure 27. Test Rig Cross Section Showing Basic Performance Instrumentation Planes, Shown Without Exhaust Ducting or Gas Sample Rakes

FD 36590A

Test Section Inlet

Instrumentation to measure airflow properties at the test section inlet included:

1. Four, shielded, chromel-alumel thermocouples located as shown in figure 27. These thermocouples were monitored on a 0 to 1600°F (225.4°K to 1144.3°K) indicating potentiometer.
2. Five, 5-point, total pressure rakes (figure 28) located as shown in figure 27. The data from these rakes were monitored on 0 to 80 in. (0 to 2.03 m), mercury-filled U-type manometers.
3. Five wall static pressure taps located as shown in figure 27. The data from these sensors were monitored on 0 to 80 in. (0 to 2.03 m), mercury-filled, U-type manometers.

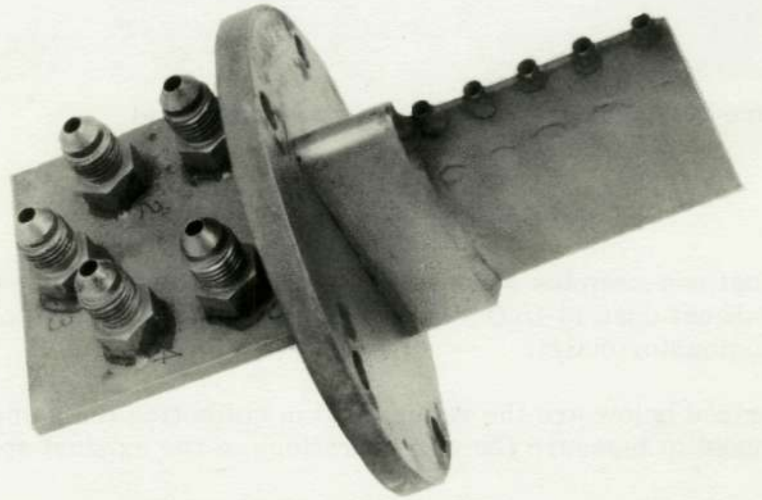


Figure 28. 5-Point Inlet Total Pressure Rake FE 92891

Combustor Outlet

Airflow properties at the combustor outlet were measured with a 5-point total temperature and pressure rake (figure 29). The temperature measurements were obtained with aspirated platinum - 20% rhodium/platinum - 5% rhodium thermocouples. The pressure difference between test pressure and ambient served to aspirate the thermocouples. The temperature data were taken in 3 deg (0.052 rad) increments across the combustor outlet and were measured on 0-10 millivolt digital voltmeter.

The outlet total pressure was measured by the five 1/8 in. OD tubes shown in figure 28. These tubes were cupped on the end to increase the acceptance angle at which accurate data could be obtained. These pressure data were measured on 0 to 80 in. (0 to 2.03 m), mercury-filled, U-type manometers. The outlet static pressure was calculated using measured airflow, total pressure and temperature.

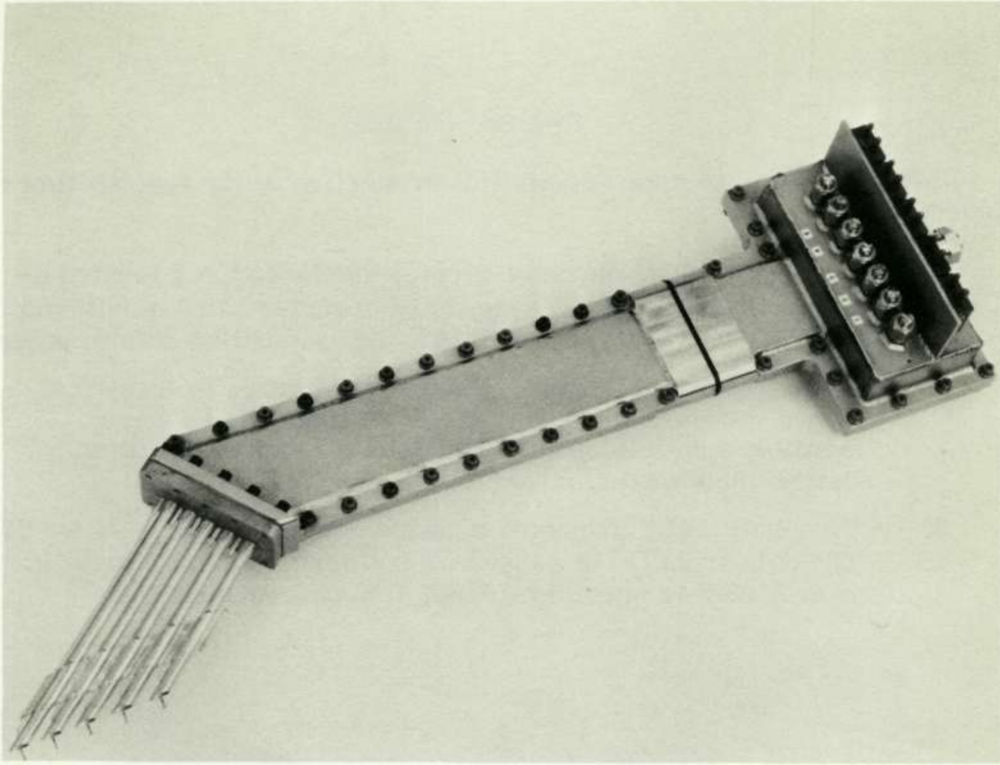


Figure 29. Outlet Total Temperature and Total Pressure Rake FE 55370

Gas Sample Instrumentation

Exhaust gas samples were extracted from the test rig at two locations: (1) in the exhaust duct 13 L/D's downstream from the combustor outlet and (2) at the combustor outlet.

Described below are the rakes used in collecting the samples and the equipment used to measure the concentrations of the exhaust species of interest.

Fixed Exhaust Duct Gas Sampling Rake

This rake, figure 30, was a 5-point rake with all the sample ports connected to a common manifold. The probe was constructed as a double-walled tube, the center tube being the gas sample manifold. High pressure air at approximately 100° F (311°K) is passed through the annular passage between the sample manifold and the outer tube to cool both the probe and the sample gas. The cooling airflow was regulated to maintain the sample temperature within 300 to 400°F (422 to 478°K).

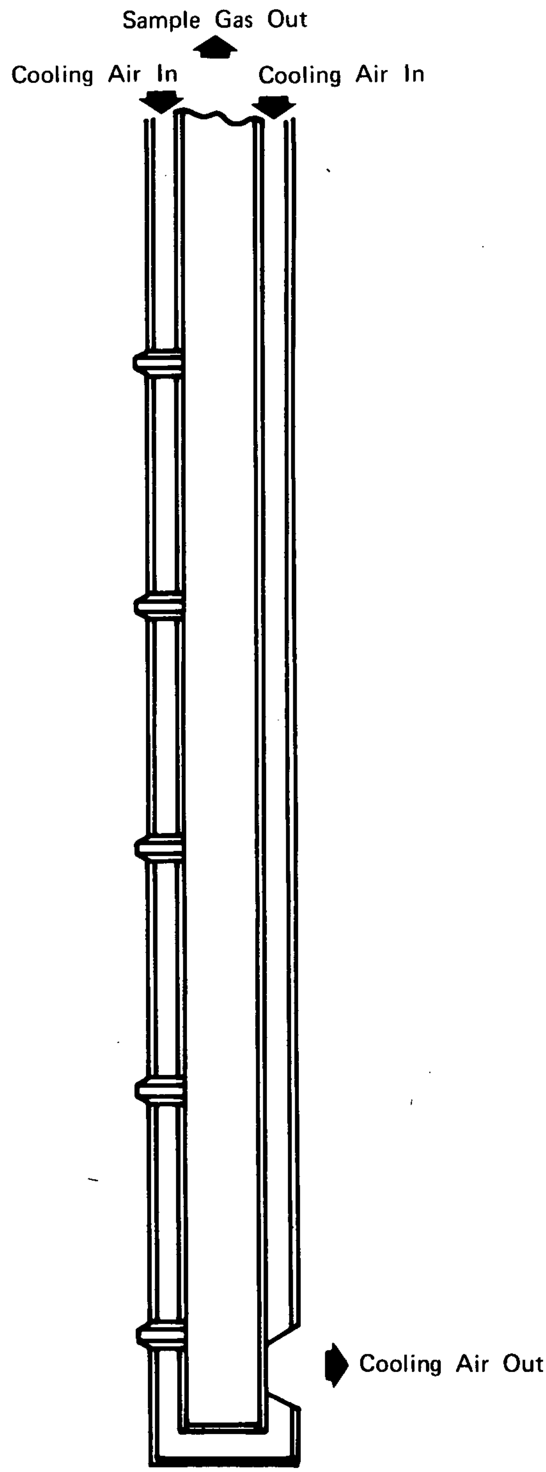


Figure 30. Exhaust Enclosure Stationary Gas Sampling Probe

FD 47396A

Traversing Gas Sampling Rake

This rake, figure 31, was a 5-point rake with all of the sample ports connected to a common manifold. As shown, the rake attached directly to the total temperature rake so the same actuating mechanism could drive both rakes. The sample ports were spaced at the same radial locations as the temperature and pressure sensors. The sample rake was mounted 6 deg from the temperature and pressure rake. Since data were taken in 3 deg increments, temperature and pressure data were available at each sample point. From this the sample data could be volume weighted to account for temperature and pressure variations across the combustor outlet. The sample gas was cooled in the same manner as the fixed exhaust duct rake. The sample manifold tube was placed inside another tube and high pressure cooling air was passed through the annular gap between the two. The cooling airflow could be regulated to maintain the sample temperature within 300 to 400 °F (422 to 478 °K). This assembly was placed in a water-cooled housing to protect it from locally high temperatures which result from zoned fuel injection.

Sample Transfer Line

The sample transfer line (figure 32) was an electrically heated teflon line approximately 10 ft (3.048 m) long. The line was insulated with foam rubber and asbestos insulation. A plastic tube outer covering served as a weather protection.

Sample Analyzing Instrumentation

The sample measuring instruments used in the program were all of the on-line continuous monitoring types. The concentration of unburned hydrocarbons was determined with a flame ionization detector (FID). The concentrations of CO, CO_2 and NO were measured with NDIR (Nondispersive Infrared) instruments. The concentrations of NO_2, when taken, were obtained with a NDUV (Nondispersive Ultraviolet) instrument. These instruments were mounted on a mobile cart (figure 33) to place them as close to the test rig as possible. A plumbing schematic of the equipment cart is shown in figure 34.

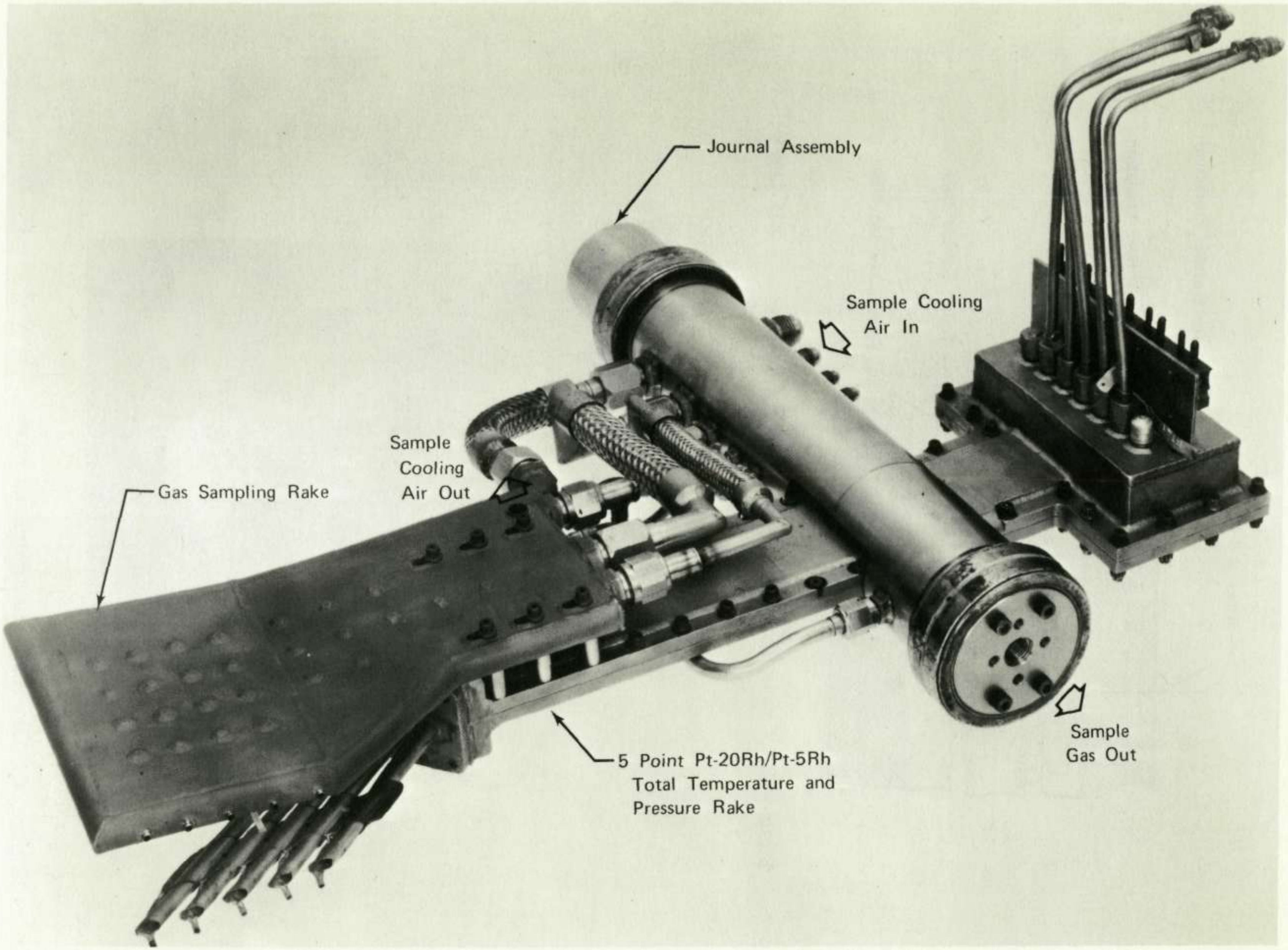


Figure 31. Traverse Rake Assembly

FD 63827

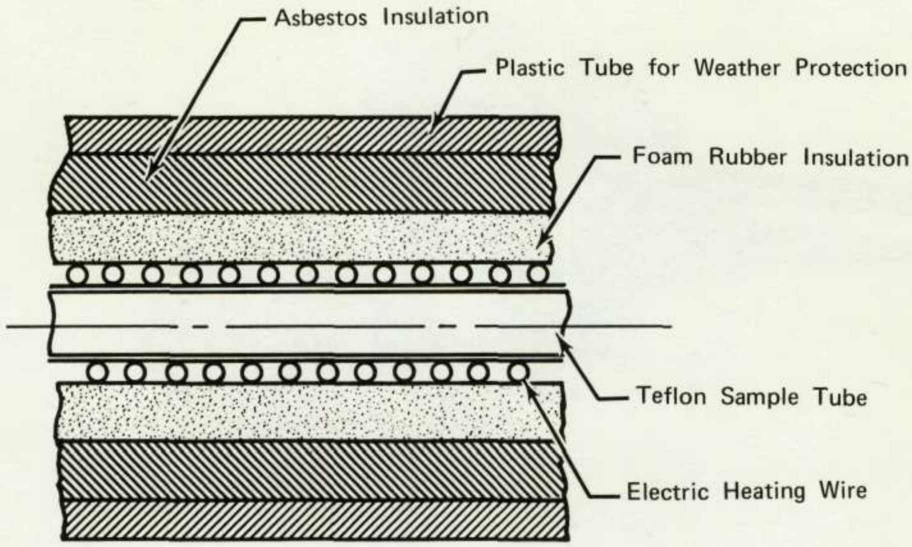


Figure 32. Cross Section of Sample Transfer Line FD 63828

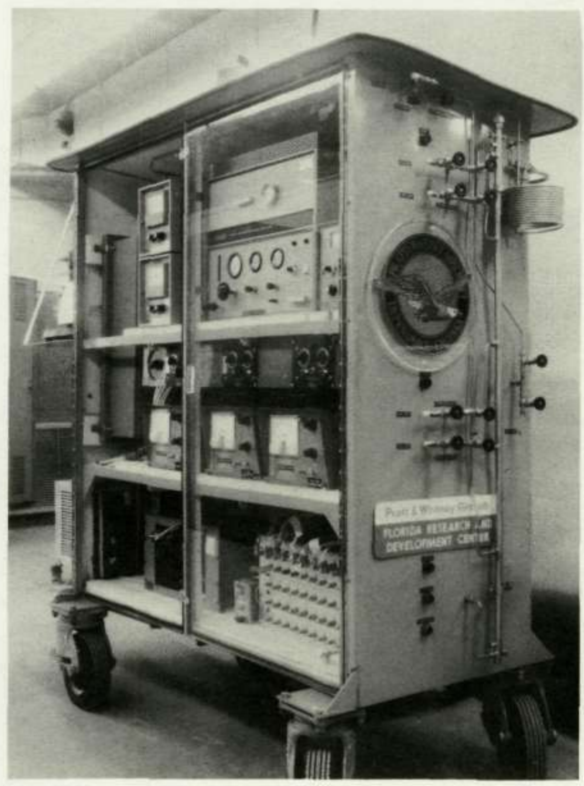


Figure 33. Gas Analysis Equipment Cart FC 25301

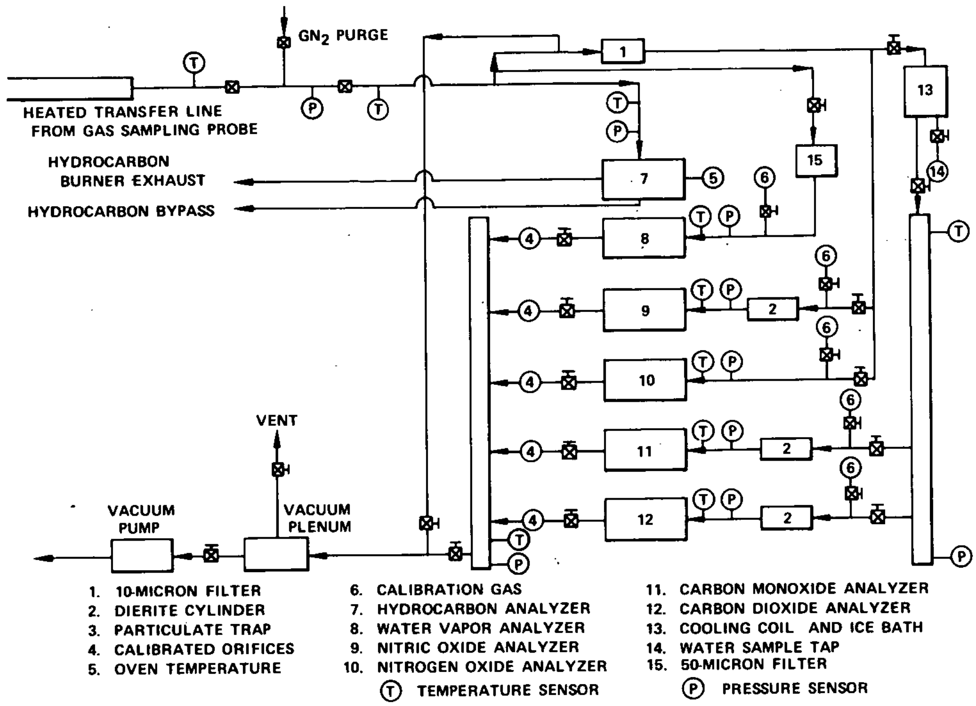


Figure 34. Flow Schematic - Gas Analysis Equipment Cart

FD 58417

REFERENCES

1. Clements, T. R., "Interim Report - 90-Degree Sector Development of a Short Length Combustor for a Supersonic Cruise Turbofan Engine," NASA CR-72734, 1970.

2. Clements, T. R., "Second Interim Report - Development of a Short Length Combustor for a Supersonic Cruise Turbofan Engine Using a 90-Degree Sector of a Full Annulus," NASA CR-120908, 1972.

3. Perkins, Porter J., Donald F. Schulz, and Jerrold D. Wear, Full-Scale Test of a Short-Length Double-Annular Ram-Induction Turbojet Combustor for Supersonic Flight," NASA TN-D6254, 1971.

4. Sawyer, Robert F., "Reducing Jet Pollution Before it Becomes Serious," Astronautics and Aeronautics, April, 1970.

5. Anon., "Nature and Control of Aircraft Engine Exhaust Emissions," Report No. 1134-1, Northern Research and Engineering Corp., 1968.

6. Heywood, John B., James A. Fay, and Lawrence H. Linden, "Jet Aircraft Air Pollutant Production and Dispersion," Paper presented to AIAA 8th Aerospace Sciences Meeting, New York, New York, 1970.

7. Norster, E. R., and A. H. Lefebvre, "Effects of Operating Condition and Fuel Injection Method on Gas Turbine Combustor Emissions," Cranfield Institute of Technology, Date Unknown.

8. Grobman, Jack, "Effect of Operating Variables on Pollutant Emissions From Aircraft Turbine Engine Combustors," NASA TMX-67887, 1971.

9. Chamberlain, John, "The Ram-Induction Combustor Concept," presented to AIAA third Propulsion Joint Specialist Conference, Washington, D. C., 1967.