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AIRESEARCH QCGAT ENGINE PERFORMANCE AND EMISSIONS TESTS

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SUMMARY

A Quiet, Clean, General Aviation Turbofan (QCGAT) engine and nacelle system was designed and tested by the AiResearch Manufacturing Company of Arizona under Contract to the NASA Lewis Research Center. The engine utilized the core of AiResearch Model TFE731-3 engine and incorporated numerous noise and emissions reduction features. Endurance, performance, and emissions tests were conducted on the engine prior to the acoustic test sequence. Test results proved that the engine met most of the design goals, and a teardown inspection of the engine following the tests showed the unit to be in excellent condition.

INTRODUCTION

Performance and emission tests were conducted on a specially designed AiResearch QCGAT engine in the 17,793-N (4,000-lb) thrust class. Testing included aerodynamic performance, emission testing, and acoustic tests. This paper discusses the performance and emissions tests and inspection results of those tests.

Due to the requirement to perform a complex series of acoustic tests, as well as performance and emissions tests, two separate test areas were used. Most of the fully instrumented performance testing was conducted in the Phoenix development and qualification test cells shown in figure 1. Another series of performance comparisons were run at the AiResearch San Tan remote test site (fig. 2) to establish a baseline for the subsequent acoustic tests.

The test sequence was set up to ensure the structural integrity of the engine and to obtain baseline performance in both acoustic and hardwall installation configurations. By working around the clock, the testing phase was compressed into six weeks. The engine was subsequently refurbished, acceptance tested, and delivered on schedule. Figure 3 outlines the AiResearch test schedule. Scheduled dates were met with the cooperation of the weather, but more significantly, with the excellent support and response AiResearch received from the NASA engineering staff.

The first run of any new airplane engine is referred to as a "green run". A green run is a preliminary test to determine how well the unit runs, and to determine potential problem areas. It also establishes normal values for vibration, oil pressure, temperatures, etc. On completion of the QCGAT green run, the engine was completely disassembled, inspected, reassembled, and cycled into a 40-hour endurance test prior to beginning performance and acoustic testing.

The endurance cycle (table 1) was intended to duplicate the conditions of a jet cycle while wearing in the engine. Approximately 40 hours were run to wear in the seals, bearings, etc. This provided performance and engine conditions representative of a typical engine.

TEST OBJECTIVES

The primary objectives of the QCGAT test program were to demonstrate the engine capabilities required to meet the program goals, to prove the structural integrity, and to measure engine performance, emission, and acoustic characteristics. The series of tests included operation with various combinations of inlets, thrust nozzles, and acoustic treatments. Table 2 lists the performance goals for the QCGAT engine.

The 1979 emission goals set by the EPA in 1973 for the class T1 engines are listed in table 3. These standards have since been dropped by the EPA, but were maintained as QCGAT program goals. The EPA parameter (EPAP) is determined from emissions measurements made at four power settings and then added together. The time weighing factor (table 4) used in this calculation is derived from the time established by EPA as being the typical time spent in each operating mode for an airplane with T1 Class engines.

The smoke standard is established as a function of rated engine power and approximately represents the threshold for visible smoke from an engine exhaust. The standard is expressed as Smoke Number (SN), and is a function of the amount of light reflected from a sample of particulate collected on a piece of filter paper exposed to the engine exhaust. The higher the SN, the greater the amount of particulates; hence, the greater the smoke visibility. Smoke measurements were made at the same four power settings as the gaseous emission test. The highest SN of the four power settings was considered the smoke number for the engine.

AERODYNAMIC PERFORMANCE

A fully instrumented engine was installed in the Phoenix development and qualification test cell. Figure 4 shows the engine without the inlet attached. Figure 5 shows the engine with a calibrated bellmouth. The first tests were run with a coannular nozzle (fig. 6) to establish baseline performance against which the mixer compound nozzle (fig. 7) could be compared. In total, seven performance calibrations were made (table 5). As the test sequence progressed, the coannular nozzle was replaced with the mixer compound nozzle. The subsequent combinations calibrated the flight simulator lip and nacelle lip to the coannular nozzle and mixer compound nozzles, respectively. Before final calibration, the engine was removed from the test cell, and the hardwall fan duct was replaced with the acoustic fan duct. Since the fan duct contains most of the accessories and plumbing, this became a relatively major change. The engine was reinstalled and final performance calibration was run.

Acoustic testing and final acceptance tests were then begun on the engine. As measured, engine performance was found to be close to what had been expected. With the exception of the fan, the new components met or exceeded their estimated performance. As anticipated, the mixer compound nozzle provided a significant improvement to the engine. Table 6 shows the results of four of the configurations compared at a constant low-pressure rotor speed (N_1) of 1938 rad/s (18,510 rpm).

Performance Calibration 2 - Using the mixer compound nozzle, this calibration resulted in a significant increase in airflow and thrust at a constant N_1. The mixer compound nozzle has a bypass stream area that is effectively much larger than the coannular nozzle. This provided a rematch of the fan to a higher efficiency and flow. The core stream area is effectively smaller than the coannular nozzle and caused a greater low-pressure (LP) turbine discharge pressure. The engine had a greater high-pressure (HP) turbine discharge temperature because of the increased total airflow, thus requiring more power from the LP turbine. This increased power was supplied by increasing the turbine-inlet temperature, resulting in a higher HP rotor speed (N_2) and compressor discharge pressure (P_{t3}). The increased thrust resulted principally from the increased airflow.

Performance Calibration 5 - Using the nacelle-lip inlet with the mixer compound nozzle, the engine performance (i.e., thrust, TSFC, etc.) was similar to performance calibration 2, which also used the mixer compound nozzle.

Performance Calibration 7 - Using the nacelle-lip inlet, the mixer compound nozzle, and full acoustic treatment in the bypass duct, the acoustic treatment had little effect on the performance of the engine as compared to calibration 5. Similar tests confirmed this conclusion.

Table 7 shows two engine configurations compared with the pretest analytical model. Thrust, airflow, and a high-rotor speed approximated the model parameters; however, fuel flow, TSFC, and turbine discharge temperature ($T_{t4.2}$) were discrepant. Analysis of this and other data showed that at maximum sea level static thrust, the fan was lower than predicted in efficiency and in airflow. This characteristic is typical of most fans in this size class wherein compromises in aerodynamic configurations imposed by design for bird strike cause unfavorable airfoil loadings with consequent decrease in efficiency and airflow capacity.

COMPARISON TO AERODYNAMIC GOALS

Table 8 is a comparison of the tested engine performance to the QCGAT program goals. The largest difference occurred on the uninstalled engine where the fan performance, as well as a one percent lower than estimated thrust coefficient for the coannular nozzle, resulted in a specific fuel consumption slightly over the estimate.

When the nacelle was installed, including the mixer nozzle, the sea level static TSFC is seen to be 1.4 percent over the goal. In this case, a comparison of the engine tested performance versus the analytical model showed that the mixer nozzle exceeded the estimate, while the fan performance was below the estimate.

Extrapolation of the tested data to the altitude cruise condition shows that the cruise TSFC would be below the estimated level. Since the majority of the mission fuel is consumed at cruise, it is concluded that the program fuel consumption goals were achieved and that QCGAT has demonstrated a significant advancement in engine efficiency.

EMISSIONS TEST

Work on the combustion system design of the AiResearch QCGAT engine was conducted under separate contract for the T-1 combustor, initially selected for the program. However, schedule incompatibilities prevented direct incorporation of the T-1 combustor in the program and an interim design was used.

The combustor liner used in the QCGAT tests (fig. 8) was a modification of the production TFE731 burner. These modifications consisted of several variations, and included punched versus pierced holes. Different hole locations and sizes were incorporated for smoke number reduction. The actual burner used in the test was an experimental interim design. As a result, the temperature pattern factor was higher than desired during early testing. This condition was corrected on later burners.

Control of the gaseous emissions at idle was accomplished by supplying air to the secondary atomizers of the fuel nozzles. This air improved emissions two ways: It caused all of the fuel to pass through the primary nozzle instead of allowing a small portion of fuel to flow out of the secondaries. The air also improved the vaporization of the fuel coming out of the primary atomizer.

Figure 9 depicts the combustor air assist system. Air for the assist system was provided from a laboratory system that approximated the characteristics of engine supply air. The air was provided at a pressure and temperature that simulated compressor bleed air, and was cooled with a simple air-to-air heat exchanger in the fan duct.

The air was supplied from a laboratory compressed-air source with a supply pressure of 14.4 kPA (300 psig). After passing through a 20-micron filter, the air was heated by an electric heater to between 366K (200°F) and 422K (300°F). This simulated an air assist system where the discharge temperature from the heat of compression for the assist air would be similar to air extracted from the boost compressor. The air then passed through a flow measuring section and was introduced to the secondary fuel line. For this test, the line was disconnected from the flow divider and the flow divider path capped. A schematic of this system is shown in figure 10.

Emissions were collected for measurement with a 24-element probe similar to the one shown in figure 11. Measurements were taken only with the coannular nozzle since there was no standard technique of measuring established for the mixer compound nozzle.

The HC and CO goals were met by using an air assist inlet pressure of 5.027 kPa (105 psid) and a temperature of 389K (240°F) at taxi idle. The results are presented in table 9. This pressure and temperature is relatively easy to obtain with a boost compressor on an aircraft engine. Lower air-assist pressure would have resulted in higher emission index values (i.e., g/kg fuel) for both HC and CO. Since more than 90 percent of the HC and CO EPAP values are contributed by the taxi-idle terms, small changes in HC and CO emission index values at that power setting resulted in significant changes in the overall EPAP values for the two pollutants.

The CO and HC emissions met the goals and NO_x was significantly reduced, but slightly above goal. The smoke number was also above goal. However, the engine showed no sign of visible smoke while operating at the test point in several tests.

TEARDOWN INSPECTION

After completion of all tests, the engine was completely disassembled, inspected, and refurbished prior to shipment to NASA. With almost 70 accumulated hours of testing including 70 starts, the majority of parts were in excellent condition and only three components showed any unusual signs of wear. A single sun-gear tooth had developed a small pit as shown by the arrow under magnification in figure 12. This was later found to be the result of a flaw in the basic material from which the part was constructed. The wear pattern was judged to be good and commensurate with the time and load on the gear system.

The second discrepancy was microscopic surface cracks radiating from a couple of the special instrumentation bosses (see arrow) of the turbine plenum shown in figure 13. These were the results of torch brazing the HP compressor discharge total-pressure probes into the plenum after the part had completed the normal stress-relieving process. This is a problem that is unique to the highly instrumented test engine and would not appear on production-type plenums.

The third problem noted was a crack in the surface of one HP turbine cooled stator vane (figure 14). This crack resulted from a single hot streak in the engine. This was the result of using the experimental low-smoke combustion liner that had not been sufficiently developed at the time this test was run. This characteristic was subsequently corrected, and later production low-smoke combustor liners did not exhibit a hot streak.

All three of the problems found during teardown inspection were determined to be the result of outside factors and not the result of design deficiency. The basic engine design fulfilled design requirements. All AiResearch QCGAT engine discrepancies were removed prior to shipment to NASA.

TECHNICAL ACCOMPLISHMENTS

The technical accomplishments demonstrated by the AiResearch QCGAT test program are numerous. Most important is the fact that the engine met the design goals in almost every case (i.e., thrust, TSFC, emissions, etc.). Performance was slightly better than predicted for the installed configuration with the mixer compound nozzle at the design point of 12,192 m (40,000 ft), 0.8 Mach number.

Performance of the AiResearch QCGAT engine was excellent throughout all testing. No serious mechanical malfunctions were encountered, and no significant test time was lost due to engine-related problems. Emissions were drastically reduced over similar engines, and the engine exhibited good smoke performance.

The testing of the AiResearch QCGAT engine provided evidence of the engine reliability and performance. After 82 hours and 77 starts the unit remained trouble-free. The few problems encountered were mostly associated with laboratory or cell equipment. Engine performance remained satisfactory with very little degradation as the unit accumulated time.

Though the LP turbine did not have the benefit of rig testing, it proved to meet design goals for the engine. Similarly, the full-scale mixer compound nozzle was found to perform better than anticipated.

CONCLUSION

As shown by the test program, the AiResearch QCGAT engine met almost all of the program goals. This is graphic evidence that the application of large engine acoustic technology to small engines as well as the application of specialized small engine technologies can result in low-noise, low-emissions, and reduced fuel consumption general aviation turbofan engines.

TABLE 1. QCGAT ENDURANCE TEST CYCLE.

Condition	Cycle Time (min.)
Start	-
Idle	5
Takeoff	5
Max. Continuous	10
Max. Cruise	45
Idle	5
75% Max. Cruise	5
Idle	5
Approach	5
Idle	5
Shutdown	15
Total	1 hr 45 min.
23 Cycles = total run time of 34.5 hr	

TABLE 2. ENGINE PERFORMANCE GOALS.

Condition	Goals	
	Thrust N (lbf)	TSFC kg/N·h (lbm/hr/lbf)
Takeoff, Sea Level Static, Standard Day:		
o Uninstalled	17,513 (3,937)	0.0426 (0.418)
o With ground test nacelle and acoustic treatment and mixer compound nozzle	17,312 (3,892)	0.0431 (0.423)
Design Cruise, 12,192-m (40,000-ft) Altitude, 0.8 Mach Number:		
o Uninstalled	3,954 (889)	0.0775 (0.760)
o With ground test nacelle and acoustic treatment and mixer compound nozzle	4,017 (903)	0.0759 (0.744)

TABLE 3. EMISSIONS PROGRAM GOALS.

Pollutant	EPAPS Program Goal, kg/4448 N-h/cycle (lbm/1000 lbf-hr/cycle)
Unburned Hydrocarbon (HC)	0.73 (1.6)
Carbon Monoxide (CO)	4.26 (9.4)
Oxides of Nitrogen (NO_X)	1.68 (3.7)
Smoke	38*

*EPA smoke number.

TABLE 4. EMISSIONS CYCLE.

Mode	Percent Rated Power	Time Minutes
Taxi-out	Taxi-idle	19.0
Takeoff	100	.5
Climbout	90	2.5
Approach	30	4.5
Taxi-in	Taxi-idle	7.0
	Total	33.5

TABLE 5. PERFORMANCE CALIBRATIONS AND ENGINE CONFIGURATIONS.

Calibration No.	Description
1	Bell mouth and Coannular Nozzle
2	Bell mouth and Mixer Compound Nozzle
3	Flight-Simulator Lip and Coannular Nozzle
4	Nacelle Lip and Coannular Nozzle
5	Nacelle Lip and Mixer Compound Nozzle
6	Filght-Simulator Lip and Mixer Compound Nozzle
7	Flight-Simulator Lip, Mixer Compound Nozzle and Acoustically Treated Ducts

TABLE 6. QCGAT TEST RESULTS.

Parameter	Configuration/Result by Test Number			
	1	2	5	7
Acoustic Treatment	Hardwall	Hardwall	Hardwall	Acoustic Panel
Inlet Configuration	Bellmouth	Bellmouth	Nacelle	Simulator
Exhaust Configuration	Coannular	Mixer	Mixer	Mixer
Test Parameter				
o Thrust, N(lbf)	15,413 (3,465)	16,525 (3,715)	16,903 (3,800)	16,792 (3,775)
o TSFC, kg/N.h (lbm/hr/lbf)	0.0457 (0.448)	0.0443 (0.434)	0.0437 (0.429)	0.0438 (0.430)
o High rotor speed N_2, rad/s (rpm)	3,011 (28,760)	3,024 (28,880)	3,033 (28,970)	3,035 (28,990)
o HP turbine discharge temperature $T_{t4.2}$, K(°F)	1,105 (1,530)	1,119 (1,555)	1,125 (1,566)	1,119 (1,554)
o Total airflow, kg/s (lbm/sec)	60.87 (134.2)	63.55 (140.1)	-	-

TABLE 7. TEST RESULTS COMPARED TO ANALYTICAL MODEL.

Parameter	Coannular Nozzles		Mixer Compound Nozzle	
	Model	Test	Model	Test
Thrust, N(lbf)	18,055 (4,059)	18,038 (4,055)	15,813 (3,555)	16,503 (3,710)
TSFC, kg/N•h (lbm/hr/lbf)	0.0443 (0.434)	0.0457 (0.448)	0.0432 (0.424)	0.0443 (0.434)
High Rotor Speed N_2, rad/s (rpm)	3,024 (28,887)	3,061 (29,240)	2,970 (28,364)	3,024 (28,880)
Low Rotor Speed N_1, rad/s (rpm)	2,042 (19,500)	2,042 (19,500)	1,937 (18,500)	1,937 (18,500)
HP Disc Temperature $T_{t4.2}$, K(°F)	1,123 (1,562)	1,141 (1,594)	1,083 (1,490)	1,119 (1,554)
Fan Nozzle Inlet Temperature T_{t17}, K(°F)	327 (129.6)	330 (135.0)	322 (119.6)	324 (124.0)
Fan Nozzle Total Pressure P_{t17}, N/cm^2 (psi)	14.58 (21.15)	14.60 (21.18)	14.38 (20.85)	14.08 (20.42)
Engine Total Airflow W_{AT}, kg/s (lb/sec)	65.6 (144.6)	65.3 (143.9)	62.3 (137.4)	63.5 (140.1)

TABLE 8. QCGAT TEST RESULTS VERSUS PERFORMANCE GOALS.

Flight Condition	THRUST, N (lbf) Goal	THRUST, N (lbf) Test	% Δ	TSFC, kg/N-h (lbm/hr/lbf) Goal	TSFC, kg/N-h (lbm/hr/lbf) Test	% Δ
Sea level, static, standard day, uninstalled (Bellmouth and Coannular Nozzle)	17,513 (3,937)	17,513 (3,937)	0	0.0426 (0.418)	0.0459 (0.450)	+7.7
Sea level, static, standard day, installed (nacelle lip and mixer compound nozzle)	17,312 (3,892)	17,312 (3,892)	0	0.0431 (0.423)	0.0437 (0.429)	+1.4
Design cruise (extrapolated from static data), Mach 0.8, 12,192m, (40,000 ft), installed (nacelle lip and mixer compound nozzle)	5,016 (903)	4,016 (903)	0	0.0759 (0.744)	0.0756 (0.741)	-0.4

TABLE 9. EMISSIONS TEST RESULTS VERSUS PROGRAM GOALS.

Pollutant	EPAPS, kg/4448 N-h/cycle (lbm/1000 lbf-hr/cycle) Program Goal	EPAPS, kg/4448 N-h/cycle (lbm/1000 lbf-hr/cycle) Test Result
Unburned Hydrocarbon (HC)	0.73 (1.6)	0.73 (1.6)
Carbon Monoxide (C))	4.26 (9.4)	3.63 (8.0)
Oxides of Nitrogen (NO_x)	1.68 (3.7)	2.09 (4.6)
Smoke	38*	42*

*EPA Smoke number.

Figure 1. Development and Qualification Test Area.

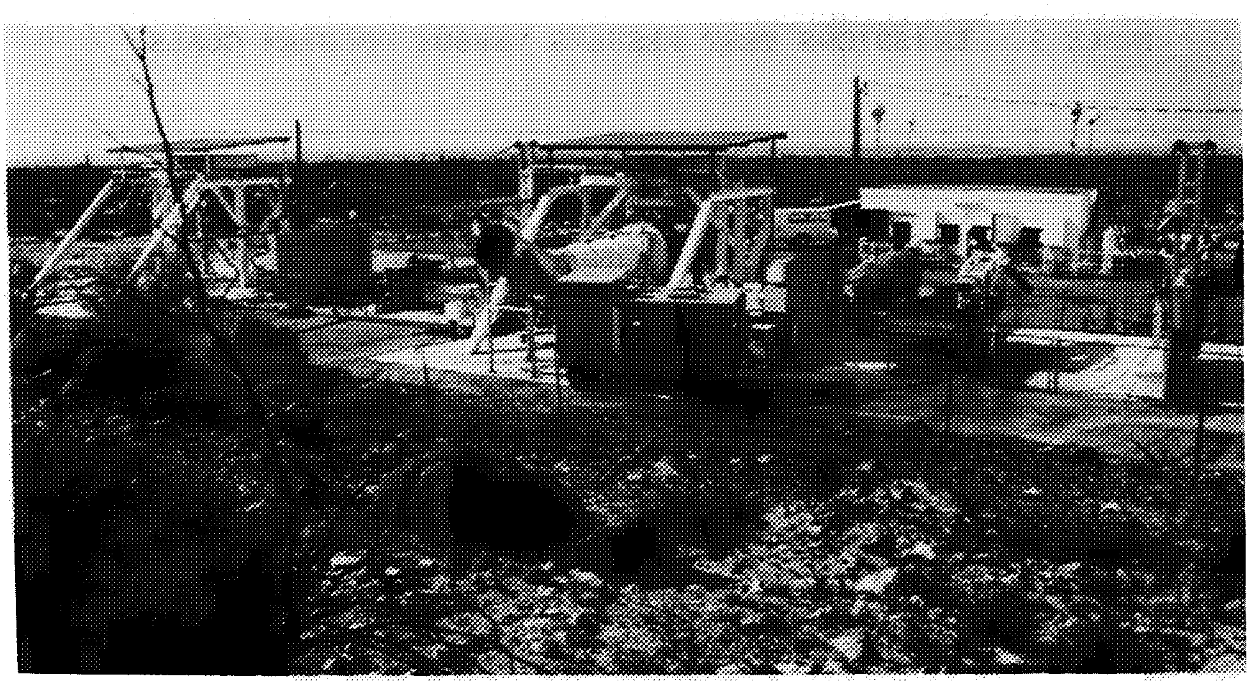

Figure 2. San Tan Test Center.

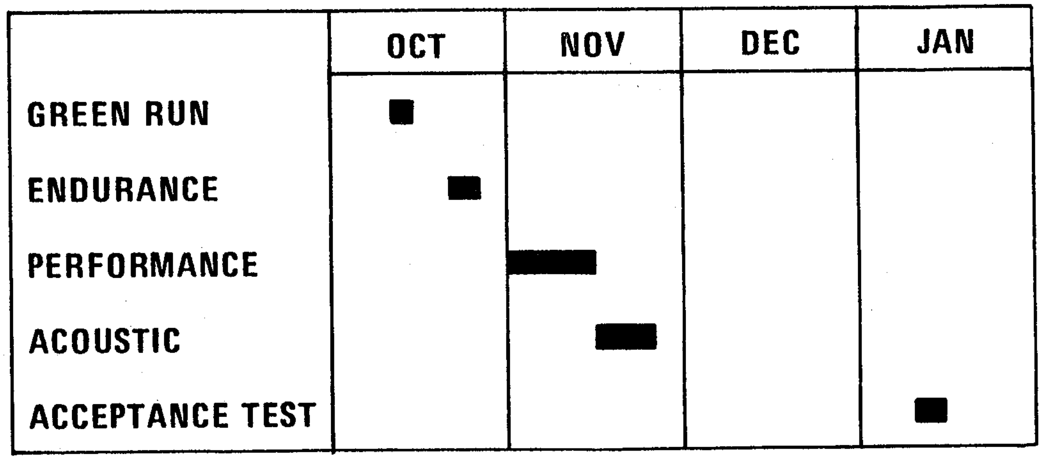

Figure 3. QCGAT Engine Test Schedule.

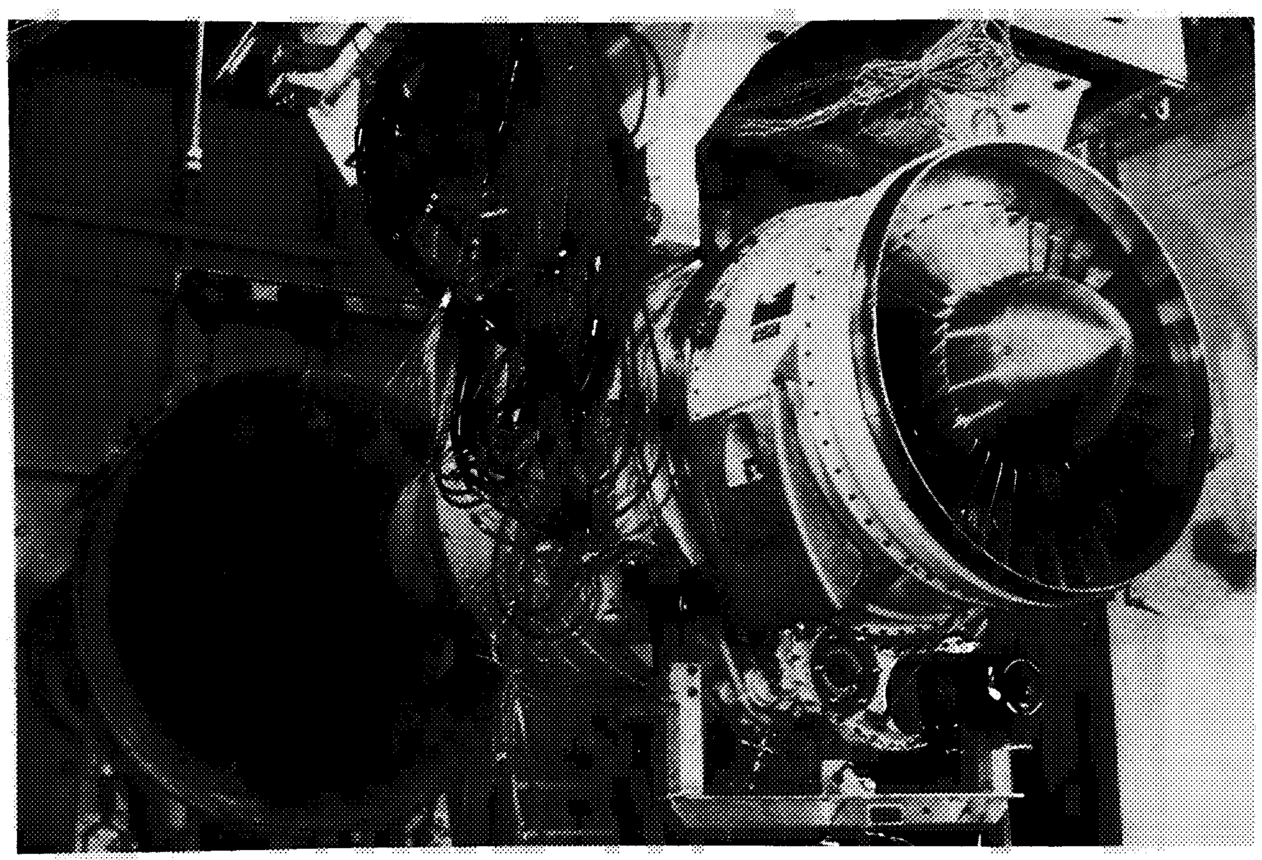

Figure 4. Instrumented QCGAT Engine.

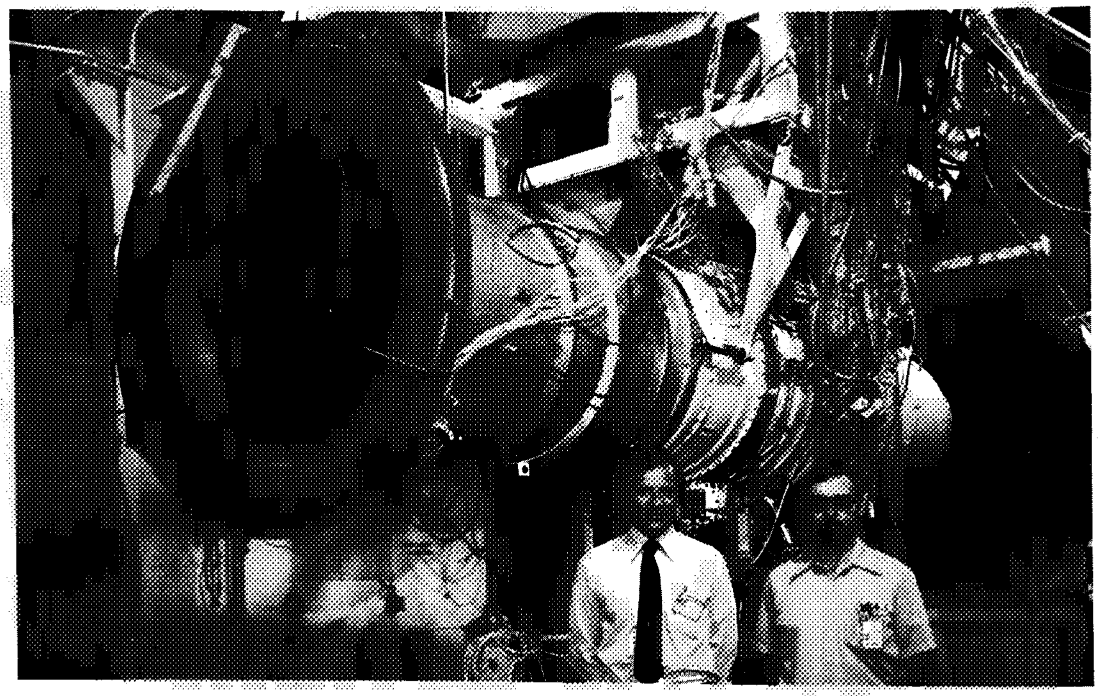

Figure 5. Engine with Calibrated Bellmouth.

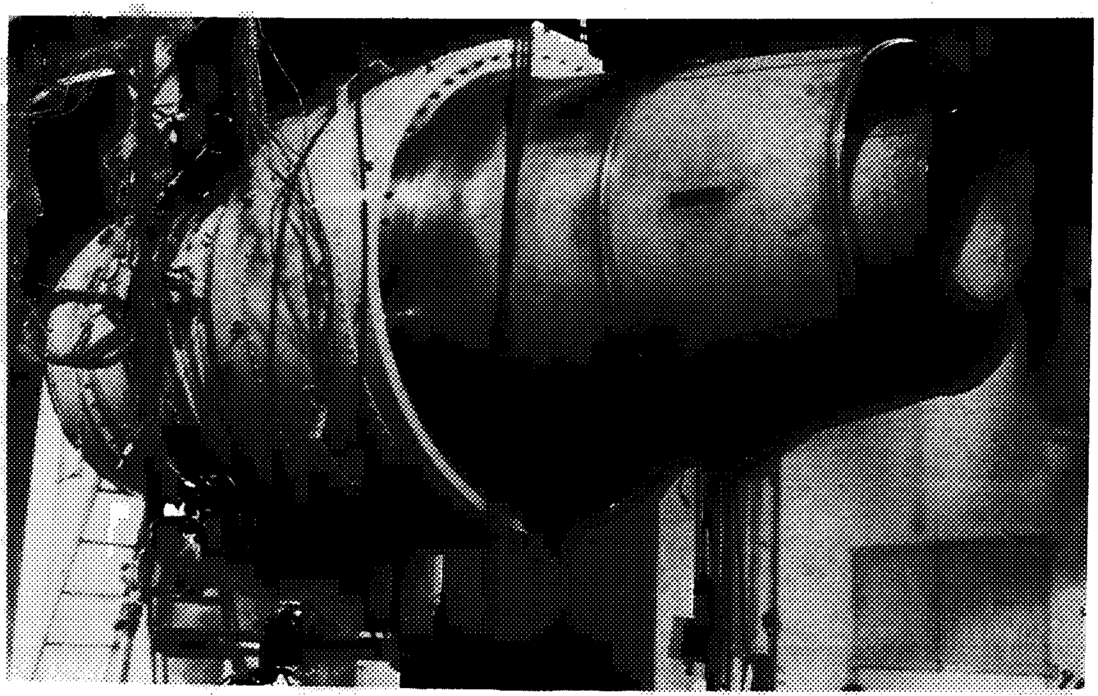

Figure 6. Engine with Coannular Nozzle.

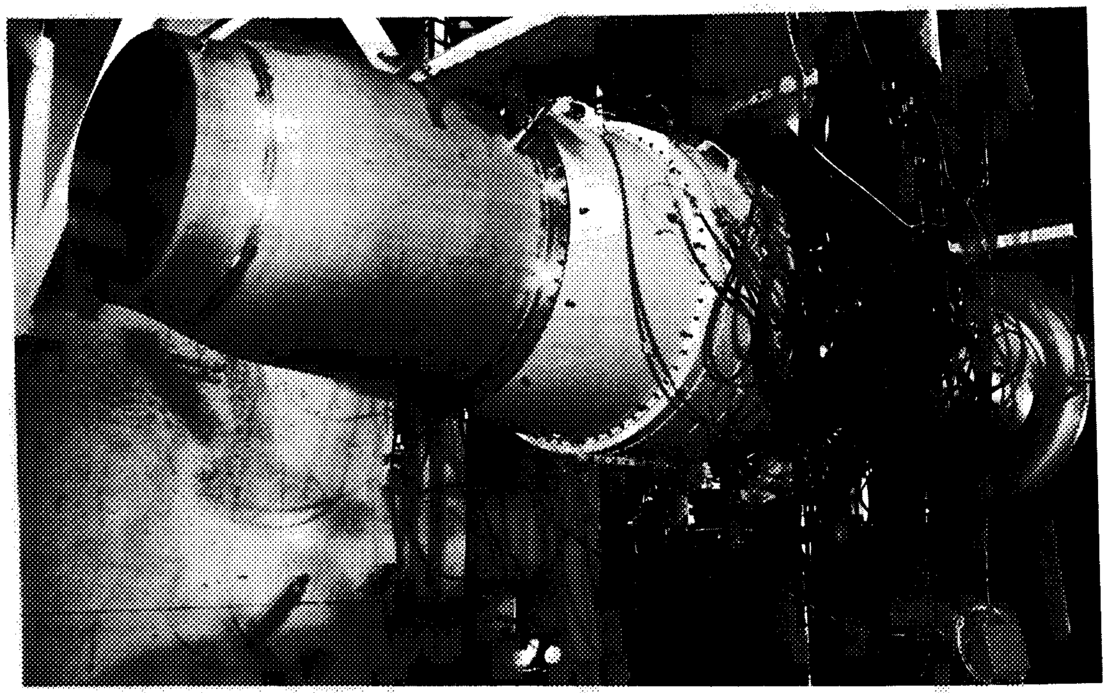

Figure 7. Engine with Mixer Compound Nozzle.

Figure 8. QCGAT Combustor.

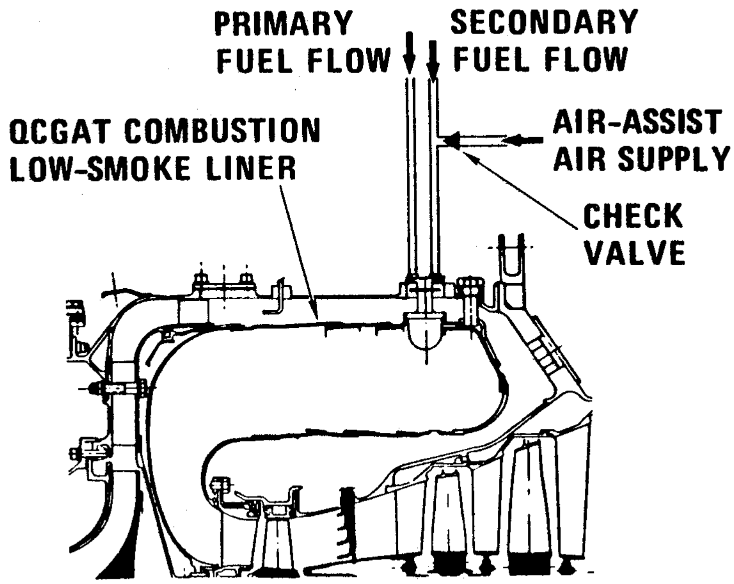

Figure 9. QCGAT Combustor Air Assist System.

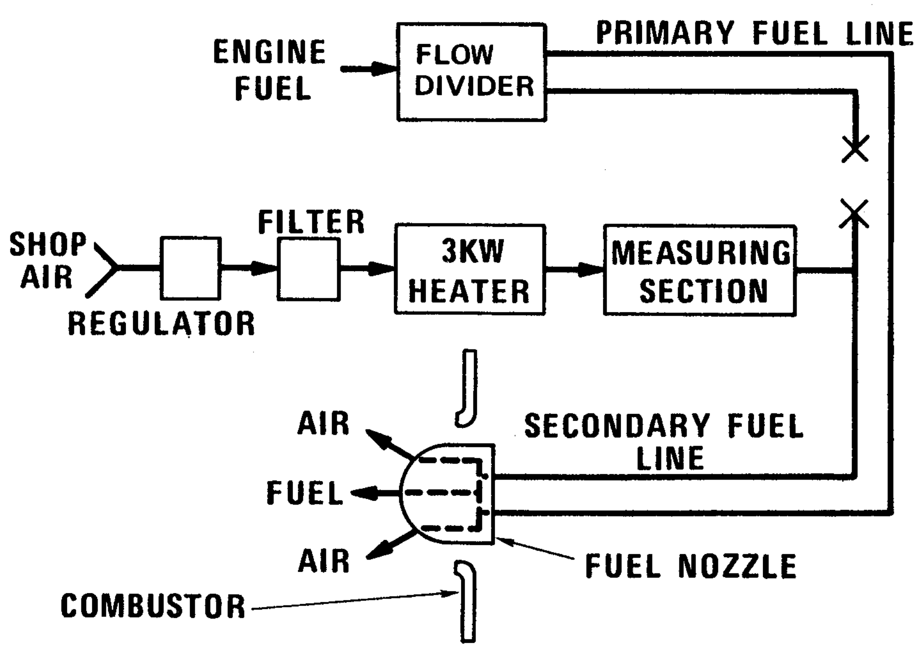

Figure 10. Air Assist System Schematic.

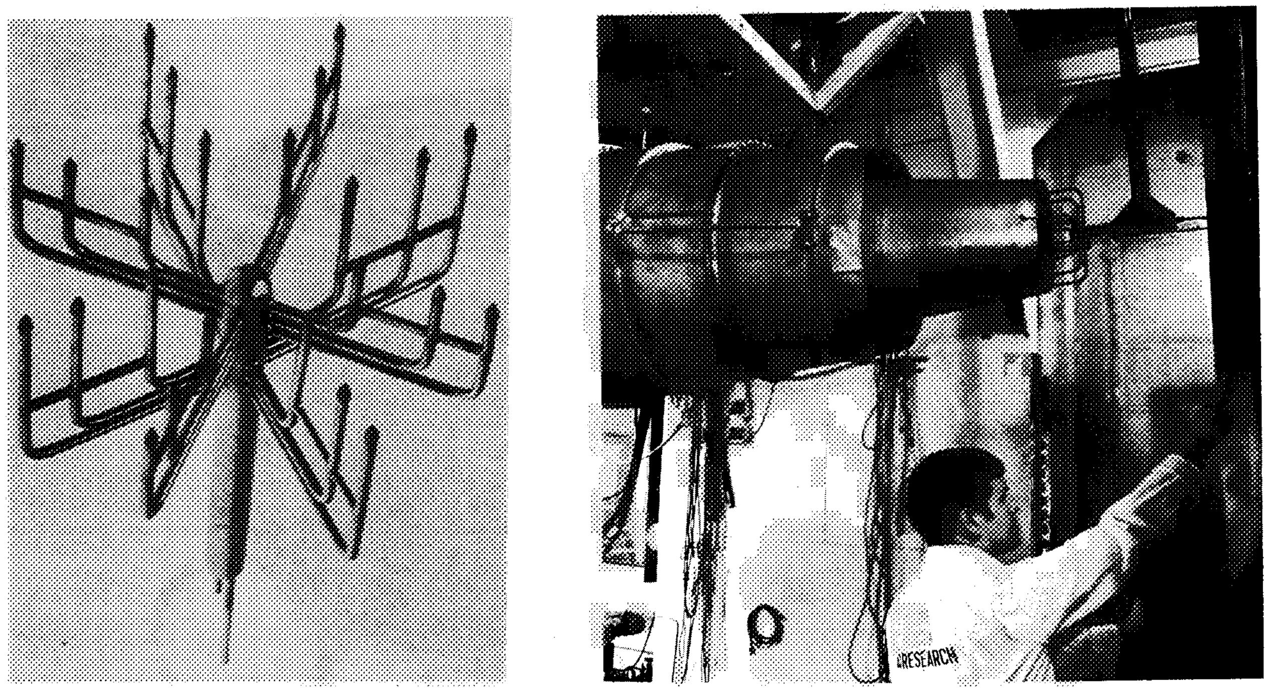

Figure 11. Emissions Probe

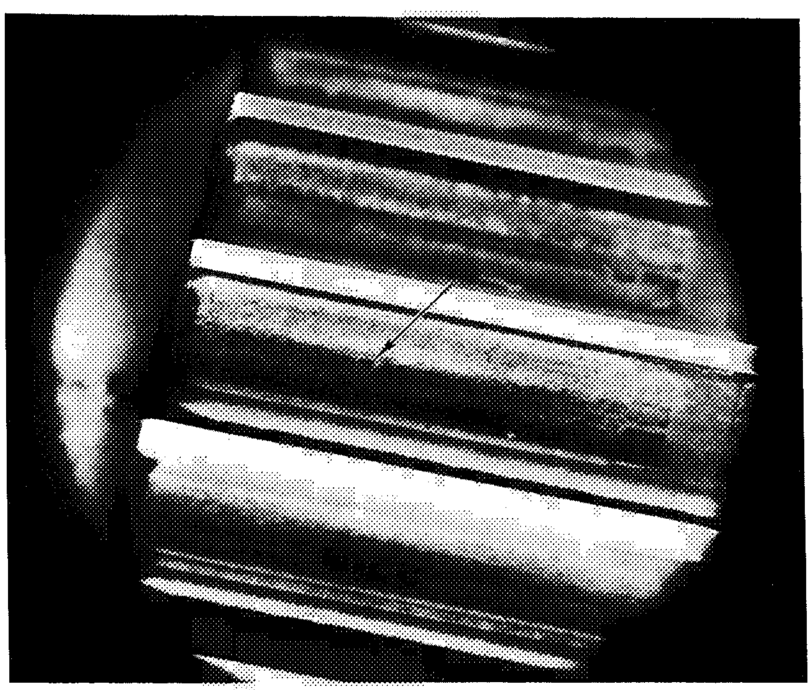

Figure 12. Sun Gear Tooth Wear.

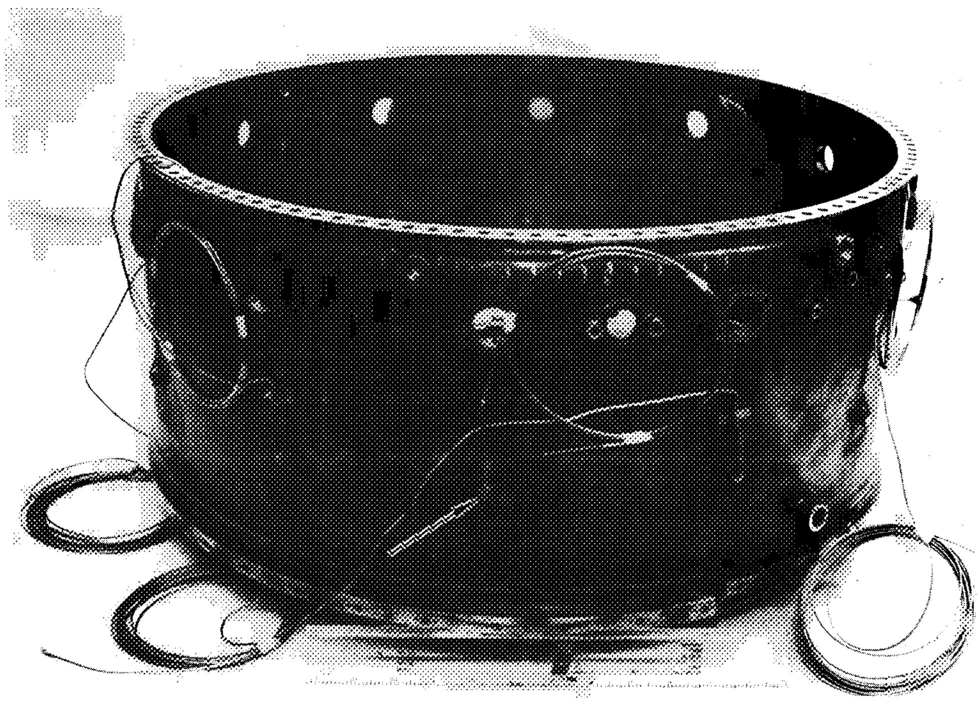

Figure 13. Turbine Plenum and Special Instrumentation.

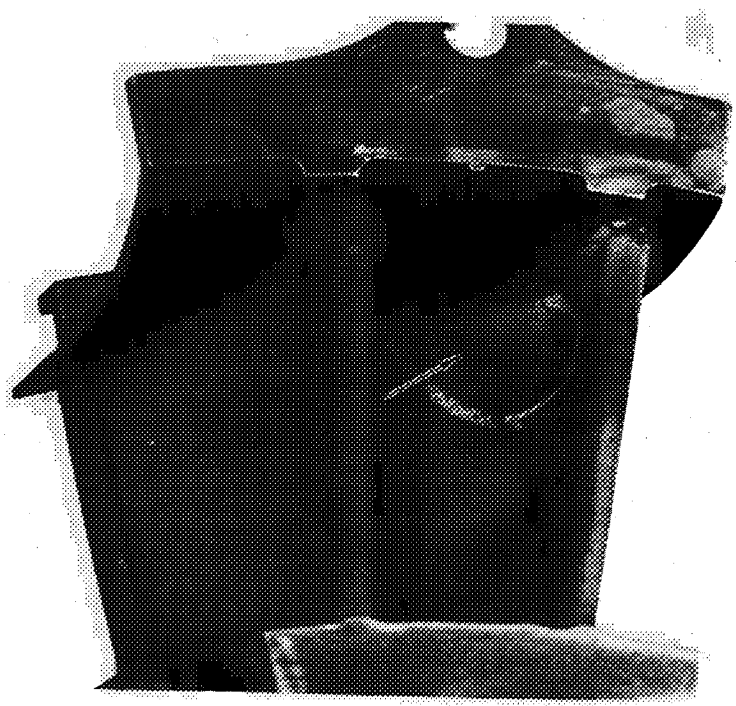

Figure 14. HP Turbine Stator Segment.