80N 2233

AVCO LYCOMING QCGAT PROGRAM DESIGN CYCLE, DEMONSTRATED PERFORMANCE AND EMISSIONS

Phil Fogel and Angelo Koschier
Avco Lycoming Division

SUMMARY

Lycoming was awarded a NASA contract to design and build a quiet, clean, general aviation turbofan (QCGAT) using existing technology for noise and emissions reduction. In addition, to the noise and emissions considerations, the Lycoming QCGAT engine was designed to provide both minimum fuel consumption in cruise and maximum take-off capability. The engine, which was built and tested at Lycoming, has met and, in some cases, surpassed the design goals for emissions. The engine program has also demonstrated that emissions and noise reduction technology can be effectively applied to small turbofan engines without significant performance penalties.

INTRODUCTION

This paper describes the basis for the cycle and component selection, for the Avco Lycoming - NASA QCGAT engine, and the resulting demonstrated performance and emissions of the complete engine. An artist's conception of a cut-away view of the propulsion system is shown in figure 1.

The Avco Lycoming QCGAT engine is a high bypass ratio, twin spool turbofan engine of modular design. It incorporates a front fan module driven by the LTS101 core engine modified, as required, to achieve the QCGAT goals. The engine is housed in a nacelle incorporating full length fan ducting with sound treatment in both the inlet and fan discharge flow paths.

Design goals of components developed under this contract and results of component tests are presented, herein, together with full engine test results.

In the emissions portion of this paper, the rational behind the combustor design selected for the Avco Lycoming QCGAT engine is presented as well as the test results. Total system (engine and nacelle) test results are also presented.

Lycoming's goal under this contract was not only to demonstrate the transfer of state-of-the-art acoustics and emissions technology currently used on large engines to small engines, but to build this around a high performance engine and airframe system attractive for the 1980's and beyond. It is clear that a high performance fan engine integrated with an advanced airframe design concept is advantageous primarily for high performance twin engine aircraft currently propelled by piston or small turboprop engines in the 373 (500) to 746 (1000) kilowatt (shaft horsepower) class. This segment of the market which has recently shown a strong growth, is expected to continue, especially with the introduction of a quiet, clean high performance aircraft which offers the highest benefit, in terms of noise and pollution reduction, for those communities living at airport boundaries.

The engine installed in the aircraft must offer modern high performance, economical cruise speeds beyond the reach of present turboprop applications and a range over 2224 kilometers (1200) (nautical miles). Prime cruise altitude was targeted for 7620 m (25,000 ft.) at Mach 0.6, with a potential to climb and cruise at 12,192 m (40,000 ft.). These targets were based on data received from aircraft operators.

PERFORMANCE CYCLE ANALYSIS

Design and trade-off studies were performed to define the optimum cycle in terms of noise, emissions and performance. The rational used to select the overall engine characteristics and the fan configuration is exemplified in figures 2 and 3. The optimization study assumed component efficiencies expected at the critical operating conditions:

sea level, static take-off
7620 m (25,000 ft.) Mach 0.6 cruise
1524 m (5,000 ft.), hot day single engine climbout

Figure 2 shows engine specific fuel consumption (SFC) versus fan pressure ratio for selected values of bypass ratio. As shown, there is a point of minimum specific fuel consumption for each fan bypass ratio. Higher bypass ratios coupled with lower fan pressure ratios results in lower specific fuel consumption. This, however, has to be moderated because of two factors: installation losses and mechanical complexity. An increase in engine bypass ratio results in increased engine-nacelle drag and weight, which in turn causes an increase in airframe weight or reduction in payload. Also, further increase of the bypass ratio would require a variable geometry exhaust nozzle to prevent excessive fan unloading with resulting loss in fan cruise efficiencies.

The effect of an increase in cycle pressure ratio on SFC is shown in figure 3. Although, increasing cycle pressure ratio decreases SFC, any increases in high compressor pressure ratio beyond approximately 10.2 would require the added complexity of an additional low pressure turbine stage.

As a result of the design study, an initial design bypass ratio of 9.6 and high compressor pressure ratio of 10.2 were selected. Installation weight and nacelle drag effects were considered.

The impact of the selected cruise design point on the maximum thrust, at the critical single engine climbout condition 308°K (555°R) ambient day at 1524 m (5,000 ft.), 69.5 m/sec (135 knots) was examined. This flight requirement was used to size the engine.

It was found that the 7620 m (25,000 ft.) Mach 0.6 design point, when lapsed to 1524 m (5,000 ft.), produces a maximum thrust for the selected bypass ratio.

The selected design cycle is presented in table 1. The changes in the engine parameters, shown in the table 1, from initial performance analysis were caused by detail component design and final cycle optimization for maximum thrust at the single engine climbout condition.

The QCGAT engine installed performance goals for the two prime flight conditions are shown in table 2. This installed performance is with the nacelle system including the flight lip, mixer nozzle and acoustic treatment. The sea level static take-off thrust is 7166 N (1611 lb_f) and specific fuel consumption is 0.037 kg/hr/N (0.363 lbm/hr/lb_f). For the 7620 m (25,000 ft.) Mach 0.6 cruise, the thrust is 2157 N (485 lb_f) and specific fuel consumption is 0.064 kg/hr/N (0.628 lbm/hr/lb_f).

A mixer nozzle, reference 1, was chosen for the engine configuration because of acoustic and performance reasons. Figure 4 presents the estimated variations of specific fuel consumption, along an engine operating line, with total net thrust at the selected cruise condition, for the split and forced mixer exhaust systems. As shown, a potential performance gain, at the cruise thrust, of approximately 3.0 percent could be realized with a mixer.

COMPONENT DEVELOPMENT AND TEST

Core Engine Definition

The Avco Lycoming LTS101 turboshaft engine was selected as the basic core for QCGAT engine. Core component modifications required, to meet QCGAT design goals, were Lycoming funded.

Component Development

The major components developed, under the NASA contract, were the fan module, reduction gearing and the nacelle system which includes the forced mixer nozzle. The fan and nacelle were designed with low noise as a primary criteria.

In addition, combustor system modifications were made, as required, to meet the emissions goals.

Core Compressor

The core compressor was tested to establish mechanical and aerodynamic performance with the turbofan inlet duct. The compressor performance and surge characteristics with pressure distortion as measured during the fan component testing were also established.

The rig test results showed that the compressor efficiency was within 1.0 percent of the design goal.

The compressor showed high tolerance to pressure distortion produced by the fan.

Also, the turbofan inlet duct caused a reduction in airflow to the compressor of 1.0 percent at the QCGAT operating conditions.

Gas Producer Turbine

Rig tests on the initial gas producer turbine hardware confirmed that the design efficiency of this stage was met within 1.0 percent. However, the nozzles were substantially larger in flow area than design.

An attempt was made to correct for flow size, by reducing the annulus area formed by the inner and outer wall contour. This corrected the flow area problem but caused cascade losses which reduced stage performance by approximately 3 points.

In addition, the interturbine duct pressure losses increased because of a resulting change in the turbine exit swirl angle.

A redesign of the nozzle and rotor, to recover gas producer efficiency, was completed in July 1979 and the revised hardware is being procured.

Fan Component

An experimental evaluation of the QCGAT fan module has shown that the bypass performance has exceeded design goals. At the design pressure ratio (1.38) and speed (11,200 RPM), stage polytropic efficiency of 0.875 was demonstrated. This exceeded the design goal efficiency of 0.870. Bypass airflow at this point was 33.7 kg/sec (74.3 lbm/sec) compared with a goal of 33.6 kg/sec (74.0 lbm/sec).

Limited distortion testing was done to insure satisfactory engine operation. The response of a turbofan to inlet distortion is of prime importance from the viewpoint of aerodynamic performance and mechanical integrity of the blades. Significant distortions occur in aircraft installations as a result of intake flow separation induced either by crosswinds or high angles of attack.

The Lycoming QCGAT fan rotor demonstrated very good aerodynamic and mechanical performance under inlet distortion conditions which are representative, or in excess, of those found in typical turbofan installations.

Low Pressure Turbine

The low pressure turbine, which was not rig tested, appeared to perform as anticipated based on measured engine data.

COMPONENT STATUS SUMMARY

Engine performance estimates obtained from math model simulations, based upon component test results, showed that further component development of the core, which was initiated in the spring of 1979, was required to achieve performance goals.

However, as a result of the analysis, it was concluded that the Lycoming QCGAT engine was a viable vehicle for demonstrating noise, emissions and specific fuel consumption improvements which were the program's objectives.

FULL ENGINE TESTS

Referee Configuration

Following the component rig tests, the full engine and nacelle system tests were conducted. Two engine configurations have been tested. The referee configuration consists of a calibrated bellmouth followed by a straight inlet duct to the fan shroud as shown in figure 5.

In the exhaust system, the bypass and core flows are physically separated (see figure 6). Separate exhaust nozzles permit individual change of fan pressure ratio and variation of the power split between the fan and core.

Test Nacelle Configuration

The QCGAT test nacelle configuration is shown, in figure 7, with the flight inlet lip and diffusing duct which is mounted to the fan shroud. The flight lip can be readily interchanged with the bellmouth or the approach simulator inlets.

Details of the test nacelle are shown in figure 8. The diffusing duct following the inlet contains interchangeable hardwall or acoustically treated softwall liners. The nacelle rear section consists of a core cowl covering the core engine while providing a smooth aerodynamic inner wall contour for the fan flow surrounding the core. The common mixed exhaust nozzle clamps to the rear face of the fan frame and contains the removable duct portion of either hardwall or softwall panels.

Engine Test Plan

Various combinations of the two basic engine configurations, the referee and test nacelle, were tested during the performance calibration sequence.

Table 3 shows an overview of the 7 prime engine configurations which were tested in order to determine the performance characteristics of the engine and nacelle system components. Prior to these tests, a baseline engine configuration was tested with a calibrated bellmouth coupled to a constant area duct and split exhaust.

The first three configurations, listed in table 3, with the split, or referee exhaust system, were tested with the diffusing flight inlet duct and the various interchangeable inlet lips.

All tests with the split exhaust were performed without the acoustic panels. The referee configuration with a bellmouth inlet was also used for the emissions sampling.

The test nacelle configuration with the mixed exhaust was initially tested, for performance purposes, only with the bellmouth inlet. First, tests were conducted with hardwall panels in the inlet and fan bypass exhaust. Then acoustic panels were placed in the inlet only. Finally, the engine was tested with acoustic panels in both the inlet and fan bypass exhaust. The installed performance demonstration was with the flight nacelle inlet, mixer nozzle and full acoustic treatment.

Referee Engine Tests

The purpose of the initial tests with the referee configuration was to evaluate mechanical engine operation and stress levels on fan and gear components.

Subsequent tests using the referee system, were conducted to evaluate overall engine and component performance prior to evaluating losses associated with acoustically treated nacelle system. Variations in performance attributed to the mixer system was also to be determined.

The purpose of these tests were twofold: first, to establish a base calibration for determining component performance. Secondly, to evaluate inlet pressure losses associated with the diffusing duct coupled to the various inlet lips. As previously stated, emissions sampling was also conducted using the split exhaust configuration.

Detailed analysis of test data has indicated that the diffusing duct and various inlets had a negligible impact on the overall engine performance. The engine test results with the referee configuration confirmed the predicted engine performance.

Nacelle Engine Tests

Following the referee system performance and emissions tests, the installed nacelle test sequence was conducted. The purpose of these tests was twofold: first, to establish engine performance with a mixer nozzle; second, to evaluate the impact of the inlet and fan bypass exhaust acoustical panels on engine performance. After the performance evaluation tests, the engine was transferred to the acoustic test site for noise evaluation.

Table 4 shows a comparison between the demonstrated installed engine thrust and specific fuel consumption with the design goals. The measured static thrust and specific fuel consumption are 6485 N (1458 lb_f) and 0.0400 kg/hr/N (0.392 lbm/hr/lb_f). The cruise performance was estimated based upon engine static test data and component rig test results.

PERFORMANCE SUMMARY

Engine test results indicated that the acoustic panels, used for noise reduction, had a negligible influence on the overall engine performance. The estimated cruise performance of the Avco Lycoming QCGAT engine, in terms of specific fuel consumption, is approximately a 10.0 percent improvement over currently available small turbofan engines in the 13,344 N (3000 lb_f) or less thrust class.

Also, although the program performance goals were not achieved, the loss in engine performance has been identified as deficiencies in the turbine section of the core engine. The performance of the fan, which was developed under the NASA contract, exceeded the design goals. A redesign of the affected hardware has been completed under a separate Lycoming funded program. Rig tests are scheduled to be conducted to evaluate the redesign as soon as the hardware is available.

EMISSIONS

Emission Standards

In 1970, Congress passed the Clean Air Act. This Act, which was to be effective in 1979, directed the Environmental Protection Agency to establish emissions standards applicable to aircraft. These standards, reference 2, for small turbofan aircraft, which have now been abandoned by the EPA, were kept as NASA goals for the QCGAT engine program. To achieve these emissions limits, the basic combustor design used in the LTS101 engine, references 3 and 4, was selected.

Combustor Design

This design, which is a circumferentially stirred combustor, is shown in figure 9. In principle, the primary air is admitted through slots in the liner header producing flow circulation about a circumferential mean line. Air jets, called "folding jets" entering through the inner wall reinforce the primary zone recirculation, and the vortex fills the full annular height of the liner.

The vortex spreads circumferentially in both directions and is forced to turn in the axial direction on either side of the folding jets and the mean path of the combustion zone flow vortex takes the shape of a horseshoe. The number of fuel injectors is thereby reduced by one half, compared with normal practice, because of this unique combustor primary zone aerodynamic concept.

Emissions Projections

Emission measurements, for this type of combustor, attained from the LTS101 engine were available for use in predicting emissions for the QCGAT performance cycle. Table 5 shows the estimated emissions values, for the QCGAT cycle, with the production LTS101 combustor. These EPA parameters were generated for a take-off and landing cycle for class T1 aircraft (reference 2).

These emissions projections indicated that further development of the LTS101 combustor was required to reduce smoke. The hot end durability was in question because of the more severe operating conditions of the QCGAT engine.

Combustor Modifications

Airblast injectors, which replaced the dual orifice injectors, were selected to reduce smoke. The introduction of the airblast injectors also increased combustor efficiency and oxides of nitrogen (NOx) at idle.

Increasing the combustor pressure drop for temperature distribution control, also increased NOx and combustor efficiency while appreciably decreasing carbon monoxide and unburned hydrocarbons. This is typical of the improved primary zone mixing, which results from the higher pressure drop.

Air partition modifications were then made, as required, to meet the design goals for NOx.

Figure 10 presents the effect of air partition modifications on NOx. Unburned hydrocarbons and carbon monoxide were within the goals in all tests. Initially, the NOx slope for the LTS101 combustor was as predicted, and met the goal. However, as the combustor pressure drop was increased to reduce smoke, NOx increased.

Air partition modifications, as previously stated, were then made to meet the NOx emissions goal.

The final selected QCGAT liner, which met the goal, has a slightly steeper slope than the initial configuration.

The Lipfert correlation, reference 5, for conventional combustors is shown for comparison.

Emissions Sampling

Development and initial emissions testing of the combustor was conducted in the laboratory. After the laboratory tests, the QCGAT liner was transferred to the engine for demonstrated emissions sampling.

The emissions test probes were installed as shown in figure 11. The probes, which are cruciform-shaped, were set at two angular positions. One probe measured along the horizontal and vertical axes. The other probe was rotated 45 degrees.

Table 6 is a comparison of the emissions test results with the NASA goals. Measurements from the engine test showed that the unburned hydrocarbons were 60 percent lower than required. The carbon monoxide was 30 percent lower, oxides of nitrogen 1.0 percent higher and the smoke number 50 percent lower than the goal.

EMISSIONS SUMMARY

The emissions requirements of the QCGAT engine have been met and, in most cases, surpassed. The QCGAT combustor provides substantial margin for carbon monoxide and unburned hydrocarbons emissions while meeting the goal for NOx within the scope of the program.

The combustor system modifications required to meet the emissions goals had a negligible effect on engine performance.

CONCLUSION

The QCGAT development program was designed to demonstrate, as well as advance, state-of-the-art technology with regard to noise, emissions and fuel economy of small turbofan engines used in general aviation-type aircraft. The program objectives, in terms of emissions and fuel consumption, were met.

With the knowledge and experience gained through the NASA-Avco Lycoming engine program, the thrust and SFC goals, although not demonstrated within the time period of the program, are achievable with additional component development.

REFERENCES

1. J. F. Hurley, L. I'Anson, and C. Wilson, "Design of an Exhaust Mixer Nozzle for the Avco-Lycoming Quiet, Clean General Aviation Turbofan (QCGAT)." Avco-Lycoming Div., Avco Corp., Proj. FEDD, NASA CR-159426, 1978.

2. Emissions Standards and Test Procedures, Title 40, CFR Part 87, published in the Federal Register, July 17, 1973.

3. U.S. Patent 3,671,171, "Annular Combustors", Brian W. Doyle.

4. U.S. Patent 3,645,095, "Annular Combustor", Jerry O. Melconian

5. Lipert, F.W., "Correlation of Gas Turbine Emissions Data", ASME Paper 72-GT-60.

RESULTS OF DESIGN STUDY

ALTITUDE = 7620m(25,000 FT), MACH = 0.6

	SELECTED DESIGN
Fan Pressure Ratio	1.36
Cycle Pressure Ratio	13.7
Core Compressor Pressure Ratio	10.3
Thrust/Total Airflow, N/kg/sec(lbf/lbm/sec)	113.7(11.6)
Bypass Ratio	9.4

Table 1.

AVCO QCGAT PERFORMANCE GOALS

(STANDARD DAY, INSTALLED)

	SEA LEVEL STATIC	7620m(25,000 ft) MACH = 0.6
Rating	Takeoff	Cruise
Thrust, N(lbf)	7166(1611)	2157(485)
SFC, kg/hr/N(lbm/hr/lbf)	0.0370(0.363)	0.0640(0.628)

Table 2.

ENGINE CONFIGURATIONS TESTED

(PERFORMANCE TESTS)

ENGINE CONFIGURATION		ACOUSTIC TREATMENT	
INLET	EXHAUST	INLET	BYPASS
REFEREE CONFIGURATION			
*Bellmouth	Split	Hardwall	Hardwall
Flight	Split	Hardwall	Hardwall
Approach Simulator	Split	Hardwall	Hardwall
TEST NACELLE			
Bellmouth	Mixer	Hardwall	Hardwall
Bellmouth	Mixer	Softwall	Hardwall
Bellmouth	Mixer	Softwall	Softwall
Flight	Mixer	Softwall	Softwall

*Emission Test Configuration

Table 3.

AVCO QCGAT PERFORMANCE

(STANDARD DAY, INSTALLED)

	GOAL	DEMONSTRATED
SEA LEVEL, TAKEOFF		
Thrust, N(lbf)	7166(1611)	6485(1458)
SFC, kg/hr/N(lbm/hr/lbf)	0.0370(0.363)	0.0400(0.392)
DESIGN CRUISE, 7620m(25,000 ft) MACH = 0.6		
Thrust, N(lbf)	2157(485)	1850(416)*
SFC, kg/hr/N(lbm/hr/lbf)	0.064(0.628)	0.074(0.723)*

*Estimated from Static Data

Table 4.

INITIAL ESTIMATED QCGAT EMISSIONS

LTS 101 COMBUSTOR

	UHC	CO	NOx	SMOKE NUMBER
Estimated Values*	0.034 (1.2)	0.238 (8.4)	0.096 (3.4)	70.0
NASA Goals*	0.045 (1.6)	0.266 (9.4)	0.105 (3.7)	45.0

*g/kNs (lbm/1000 lbf thrust hr-cycle)

Table 5.

QCGAT EMISSIONS RESULTS

	UHC	CO	NOx	SMOKE NUMBER
Goal*	0.045 (1.6)	0.266 (9.4)	0.105 (3.7)	45
Engine Test*	0.017 (0.6)	0.193 (6.8)	0.106 (3.75)	24
Engine Test/Goal	0.4	0.7	1.01	0.5

*g/kNs (lbm/1000 lbf thrust hr-cycle)

Table 6.

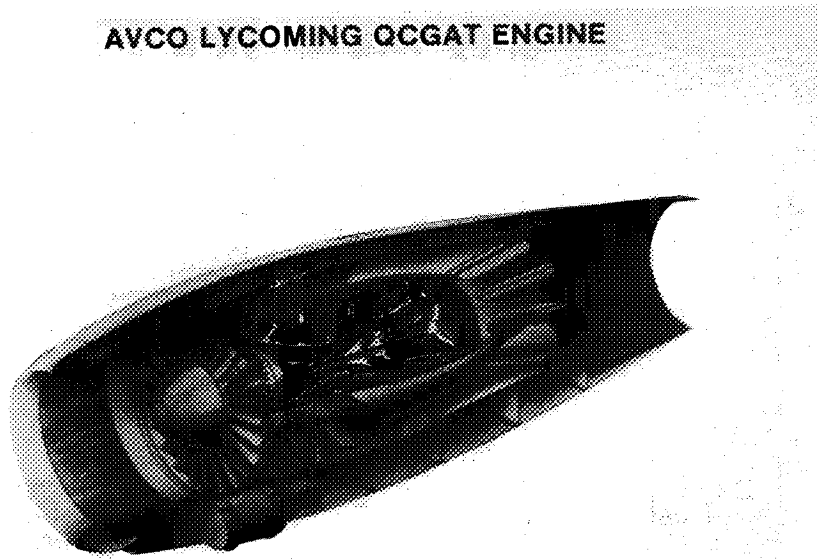

Figure 1

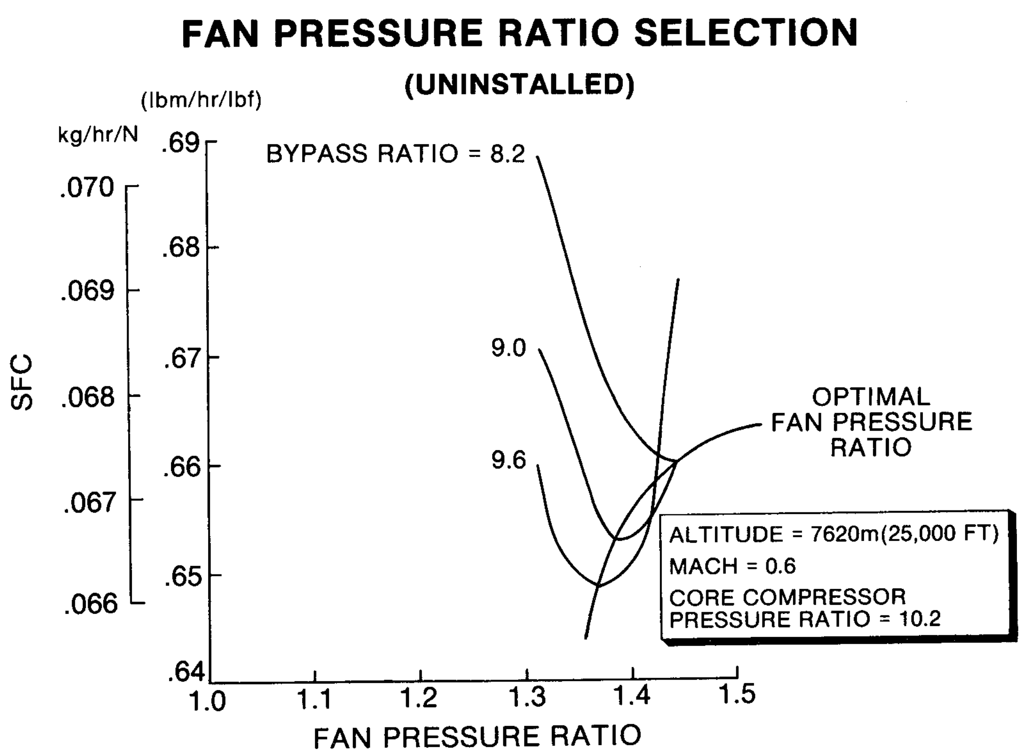

Figure 2

SELECTED DESIGN

(UNINSTALLED)

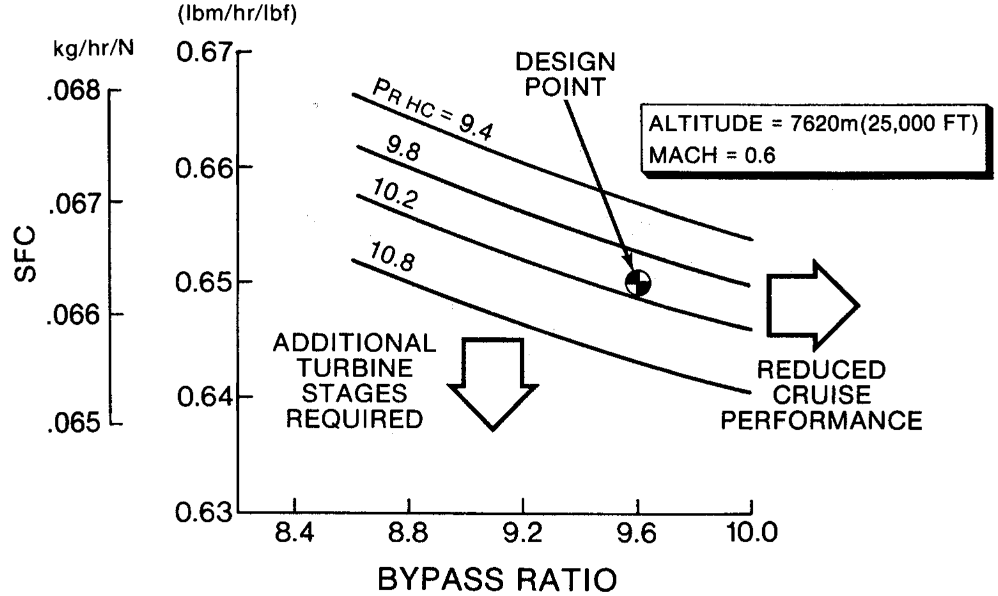

Figure 3

PREDICTED INFLUENCE OF MIXER

Fn vs SFC

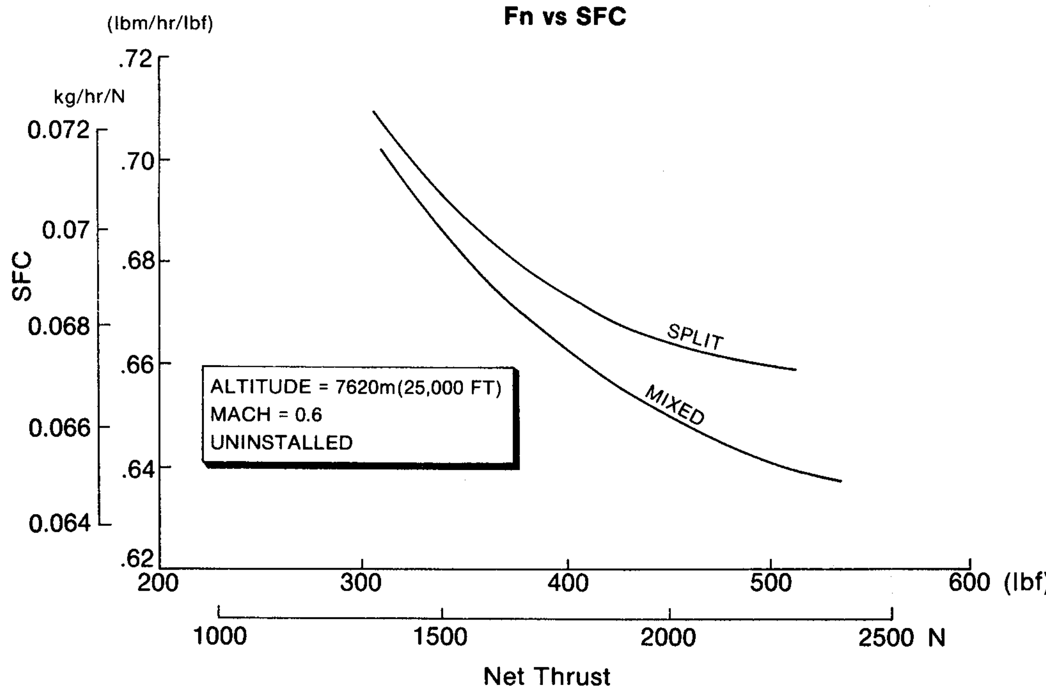

Figure 4

QCGAT REFEREE CONFIGURATION

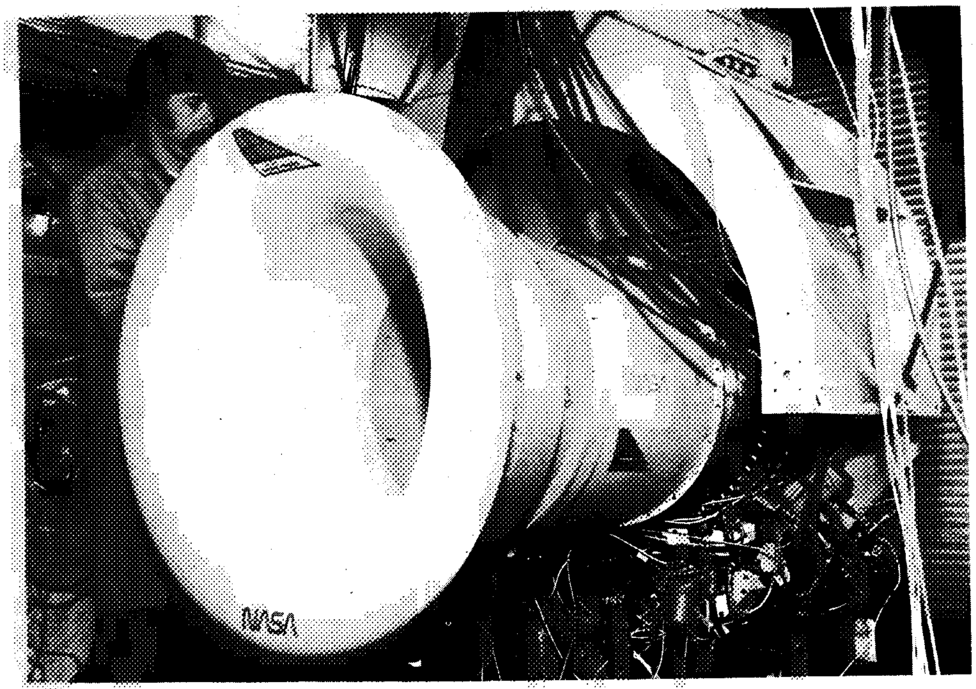

Figure 5

QCGAT REFEREE CONFIGURATION

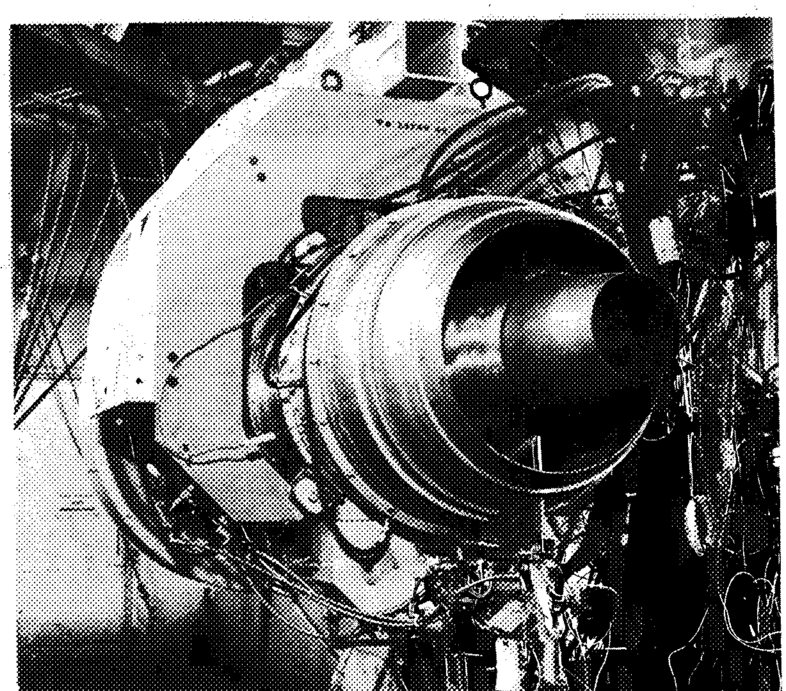

Figure 6

QCGAT TEST NACELLE

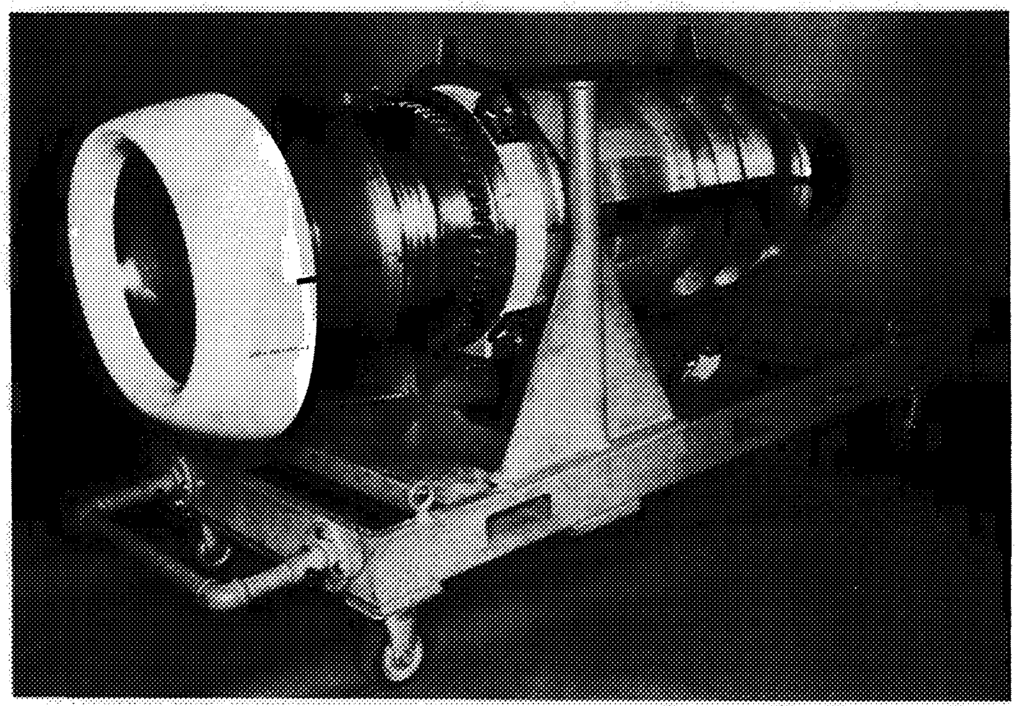

Figure 7

QCGAT TEST NACELLE

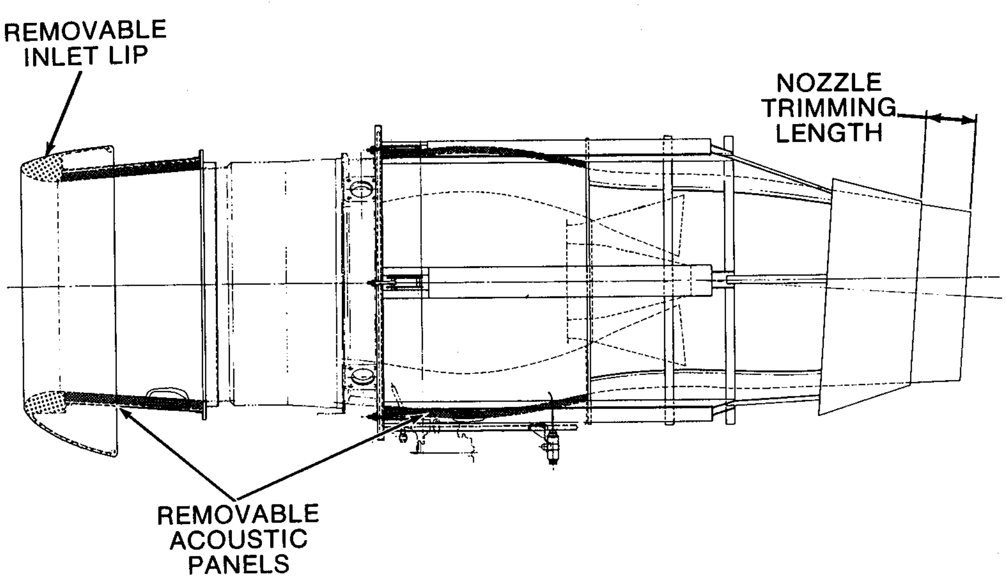

Figure 8

QCGAT COMBUSTOR

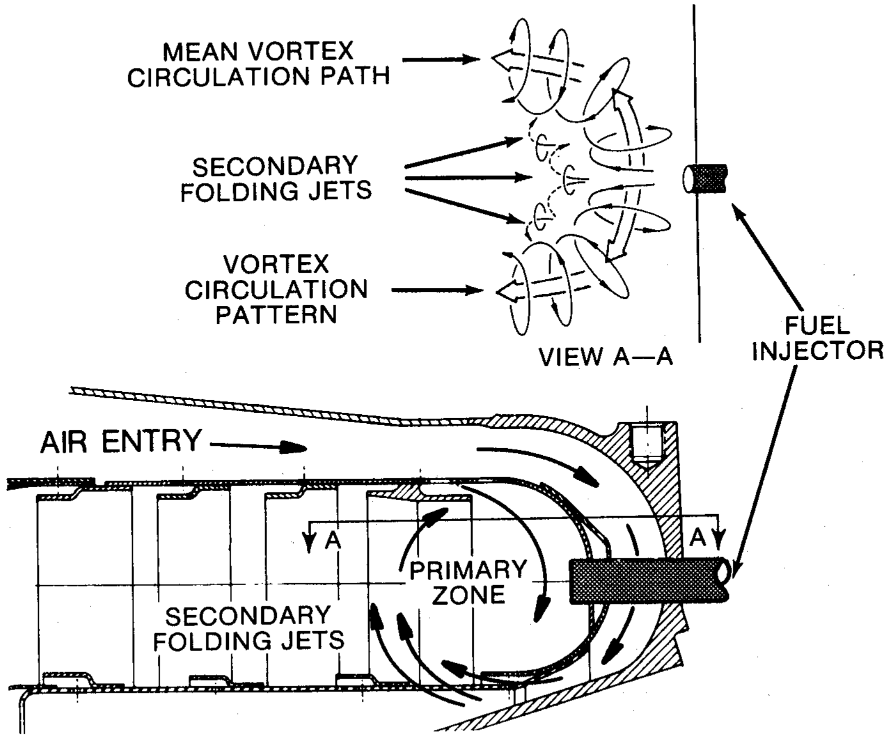

Figure 9

NOx vs COMBUSTOR INLET TEMPERATURE

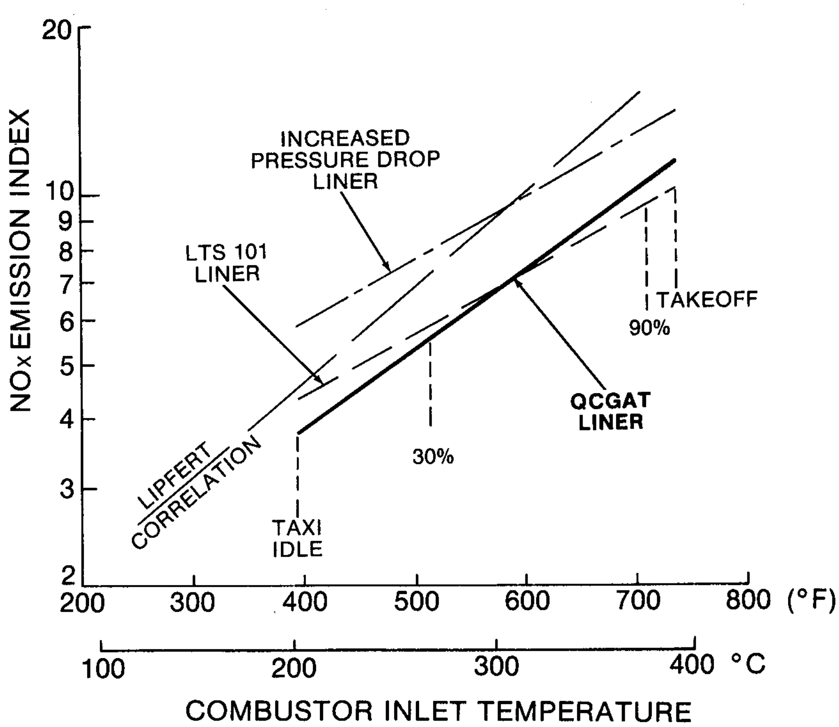

Figure 10

ENGINE EMISSIONS SAMPLING TEST

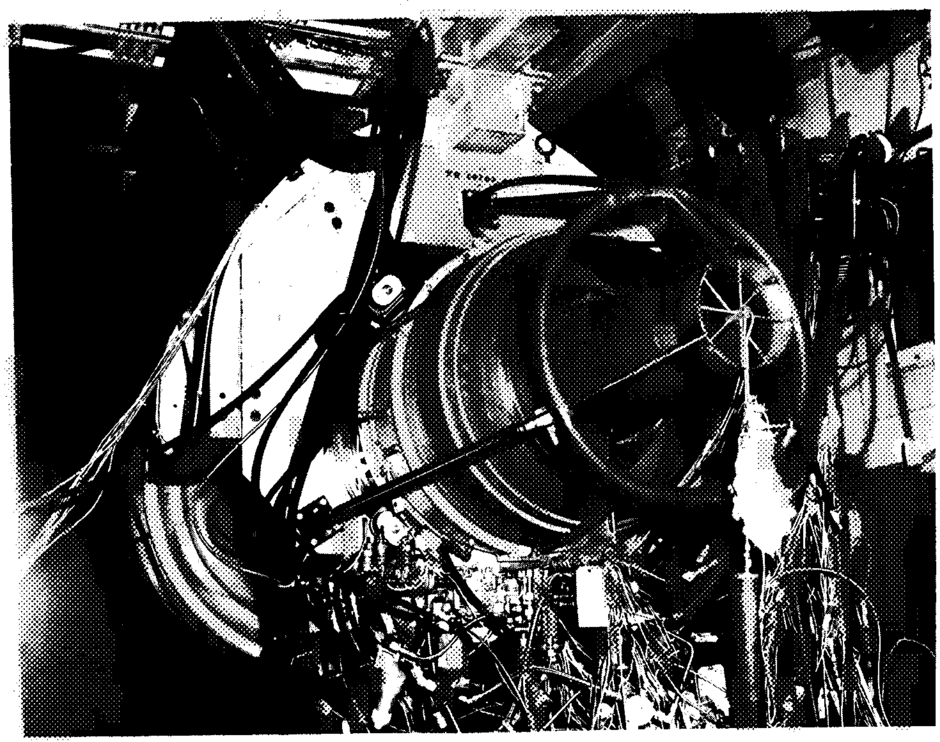

Figure 11