80N22328

AIRESEARCH QCGAT ENGINE, AIRPLANE, AND NACELLE DESIGN FEATURES

Roger W. Heldenbrand
AiResearch Manufacturing Company of Arizona
A Division of The Garrett Corporation

SUMMARY

The Quiet, Clean, General Aviation Turbofan (QCGAT) engine and nacelle system was designed and tested by the AiResearch Manufacturing Company of Arizona under Contract to NASA Lewis Research Center. The engine utilized the core of the AiResearch Model TFE731-3 engine and incorporated several unique noise- and emissions-reduction features. Major performance, emissions, and noise goals were demonstrated, and the engine and nacelle were delivered to NASA Lewis Research Center for additional testing.

INTRODUCTION

The design features of the QCGAT engine, airplane and nacelle are described in this paper. Test programs and results of the engine performance, emissions, and noise tests are discussed in subsequent papers.

An isometric cutaway of the QCGAT engine in a flight-type nacelle is shown in figure 1. The engine was designed around the core of the AiResearch Model TFE731-3 turbofan engine. This engine is a production unit used in several domestic and foreign business jets. The engine consists of the TFE731-3 high-pressure (HP) spool and low-pressure (LP) compressor, plus several unique and new components including a low-speed fan, a fan gearbox, associated ducts and structure, a reduced-emissions combustion system, and an LP turbine.

An airplane design, synthesized by Garrett in order to evaluate the QCGAT Engine, was selected to be similar to business jets using Model TFE731 Engines, but somewhat larger, thus taking advantage of the higher thrust level.

Two nacelles were designed for the program:

- A production flight-weight nacelle featuring integral acoustic treatment

- A 'workhorse' nacelle, fabricated especially for this test program and featuring replaceable inlets, acoustic panels, and a special mixer compound nozzle.

An overall task schedule is shown in figure 2. The QCGAT Phase II experimental program was divided into ten major tasks. These culminated with delivery of an engine, associated test support equipment, and spares at the end of 25 months. As experienced with most hardware-oriented programs, difficulties and delays were experienced with design iterations and fabrication schedules. However, the test program was accelerated, and the engine was shipped on schedule.

The technical goals for the program are listed in table 1. Performance goals represented a TSFC improvement of approximately 9 percent over other turbofan engines. The noise goals were 10- to 15-EPNdB below the Federal Aviation Administration's FAR Part 36 requirements. The emissions goals were identical to the EPA 1979 standards for T-1 class engines. (The EPA subsequently determined that general aviation was not a significant source of air polution and therefore did not impose these standards).

ENGINE DESIGN

The principal program objective was to demonstrate the application of large turbofan noise- and emissions-reduction technology to small general aviation turbofans. To do this, a number of unique features were incorporated in the basic design of the QCGAT engine in order to reduce the emissions and noise levels below those of the already quiet TFE731 engine. This work was initiated in 1975 during the QCGAT Phase I study. Twelve candidate engine configurations were screened. Many parameters were considered, including:

- Fan pressure ratios at takeoff and cruise
- Thrust
- TSFC
- Lapse rate
- Fan diameter
- Installed weight
- Noise
- Nacelle drag
- Acoustic shielding
- Cost.

The engine cycle selected for the program represented a practical engine from the standpoints of cost, weight, airplane/nacelle interference drag, and cruise propulsion efficiency. The engine also exhibited high potential for reduction of turbomachinery and jet noise, and reduction of chemical and visible exhaust emissions. The design point for the engine (typical for most modern business jets) and principal engine cycle parameters are listed in table 2.

Figure 3 is a cross-section of the overall QCGAT engine design. The QCGAT engine is based on the core of TFE731-3, but incorporates a fan used in the AiResearch Model ATF3 engine. The fan is driven by a new low-pressure turbine via a newly designed five star-gear gearbox. The low-pressure compressor is driven directly by the low-pressure turbine. The HP spool consists of a centrifugal compressor driven by a cooled axial turbine. The combustor is an adaptation of a production TFE731 combustor that was designed for low smoke. Accessories and the fuel control are driven by the HP spool through a tower shaft. A finned heat exchanger in the fan bypass duct cools the oil for the fan gearbox and engine lubrication system. The flange-to-flange length of the engine is 143.15 cm (56.36 in.) and the fan diameter is 77.47 cm (30.5 in.). When fully instrumented and wet, the test engine weighs approximately 426.38 kg, (940 lb). Figure 4 shows the engine in the test cell prior to initial calibration.

The major acoustic design features of the QCGAT engine and nacelle system are shown in figure 5 and outlined below:

- No inlet guide vanes
- High inlet throat Mach number
- Low tip speed, single-stage fan (36 blades)
- Phased inlet acoustic treatment
- Optimized fan blade-to-stator vane count
- 2.12 rotor-chord, fan-to-stator spacing
- Phased fan bypass duct acoustic treatment
- Low fan jet velocity

- Reverse-flow annular combustor
- High-work, low-pressure turbine with low core-exhaust velocity
- 12-lobe mixer compound nozzle.

With the possible exception of the reverse-flow combustor and the mixer compound nozzle, each of these features above is based on work done with large engines and is a direct application of that technology.

COMPONENT DESIGNS

The QCGAT fan (fig. 6) is a 36-blade design derived from the fan used on the AiResearch Model ATF3 Turbofan engine. The principal design features are given on table 3 with the design point at 12,192 m (40,000 ft), standard day at a flight Mach number of 0.8. This fan is approximately 10-percent larger in diameter than the TFE731 fan, and rotates at 17-percent slower speed. Thus, fan turbomachinery component noise levels are lower. The fan-stage flow path (fig. 7) was designed to minimize the core-flow Mach number and to prevent large accelerations in the strut regions. Absolute local Mach numbers, and blade and vane counts are also shown. The bypass stator location is slightly more than two rotor-chord lengths downstream. The vane counts of both stators were selected to minimize rotor and stator noise interaction. The bypass performance map (fig. 8) shows the engine operating lines for co-annular nozzle and mixer compound exhaust nozzle from idle through takeoff. Slightly greater surge margin was achieved with the mixer compound nozzle. A fan component rig test was not conducted. However, adequate data was available from the Model ATF3 fan rig tests, and actual QCGAT engine operation to define the QCGAT fan for the engine performance model.

The fan gearbox (fig. 9) is similar to that of the TFE731. However, the overall gear ratio was changed from 0.5559 to 0.4634 to match lower fan speed. Resilient mounts were incorporated on the star gears to maintain gear alignment during high-torque loads. The star-gear shafts were precision ground to form the bearing inner race, and the star gears were counterphased and nonfactored. The gear reduction system transmits in excess of the 2.74 MW (3675 hp) required for the QCGAT engine, and has been designed for life greater than 5000 hours at higher power.

The fan support structure (fig. 10) includes the fan support housing, intermediate case, and the engine support housing (main engine mount), as well as the fan gearbox and fan itself. These components were designed to survive a 1.8-kg (4-lb) bird strike at a velocity of 250 knots and the loss of two adjacent fan blades (but not simultaneously). Finite-element stress analyses were performed on the major structural pieces for the loads listed in table 4. Stress isopleths and displacements are shown in figure 11.

The low-pressure compressor, high-pressure compressor, and high-pressure turbine are standard components of the TFE731-3 engine and were used without design changes. The design-point characteristics of these components are listed given on table 5.

The LP turbine, which drives the fan, and the low-pressure compressor, is a 3-stage shrouded axial design. The QCGAT engine design-point operating conditions are given in table 6. Several critical constraints were imposed on the design of the turbine. Since the QCGAT engine was based on the TFE731 core, the overriding ground rule was to minimize changes to existing TFE731 hardware.

Because the QCGAT low-pressure turbine is larger in diameter and axially longer than that of the TFE731, it was necessary to design a gas flow path that would not cause disruption of airflow distribution in the combustor plenum. Location of the TFE731 aft turbine bearing was retained. The unusual shape of the third-stage disk (fig. 12) was the result of this latter constraint. Since LP spool speed is fixed by the TFE731 LP compressor, the larger turbine represented a major design challenge from the standpoints of stress, vibration, blade flutter, life, and materials. In addition, use of the 12-lobe compound mixer nozzle required low exit swirl angles. Total-to-total efficiency goal was set at 90 percent. As a result of these constraints, numerous compromises were necessary during design. Although it is not feasible to include the detailed results of all aerodynamic, thermodynamic, and mechanical design analyses in this report, all constraints were satisfied, including that of efficiency.

It was originally intended to use only a hydromechanical control system for the QCGAT engine. However, because the hydromechanical unit is considered a backup system on the TFE731, it was decided to use a production TFE731 electronic control system as the primary control. The control (fig. 13) is a full-authority system providing speed control, overtemperature, and overspeed protection under all operating conditions. These include start, transient, and steady state. A comparison of QCGAT engine characteristics and the TFE731-3 was made to determine if modifications were necessary to the existing computer. This comparison showed that the basic logic was satisfactory, and the adjustment ranges were adequate.

The QCGAT combustor (fig. 14) is a version of the TFE731 burner in production at the initiation of the program. In-house modifications for the TFE731 engine, which consisted of hole-pattern variations for smoke reduction, were incorporated in the

QCGAT engine. During engine testing, emissions were controlled with a system adapted from the NASA/AiResearch T1 Pollution Reduction Technology Program. Air was supplied to the secondary fuel nozzles at the taxi-idle power setting only. This aided the fuel atomization process (see fig. 15). At all power settings except taxi-idle condition, the fuel was reconnected to the secondary fuel circuit. An air-assist system was not used. (This system is discussed in a subsequent paper.)

Accessories for engines like QCGAT and the TFE731 normally consist of customer-furnished equipment. The accessory drive gearbox, shown at the bottom of the engine in figure 16, provides mounting pads and drives on the forward side of the gearbox for a hydraulic pump or similar equipment. These items not normally required for airplane service were not supplied with the QCGAT engine. A starter-generator was furnished, and although not shown in figure 16, mounts on the pad occupied by the laboratory air-turbine starter.

QCGAT AIRPLANE DESIGN

The airplane synthesized for the engine was based primarily on the Learjet 35/36, although it also had minor features found on other business airplane using TFE731 engines. The major differences between the AiResearch QCGAT airplane (fig. 17) and the Learjet 35/36 are the elongated fuselage to increase payload (passenger) capacity, a slightly higher wing loading, and the relocation of the horizontal tail. The increased payload was possible because of the higher-thrust engines. The increased wing loading was the consequence of the combined wing and flap configuration. The horizontal tail was moved to avoid engine exhaust. The airplane definition had two principal objectives: First, to provide an airplane that utilized the installed thrust of the QCGAT engine to produce takeoff and approach flight profiles for which noise estimates could be computed for sideline, takeoff, and approach FAR Part 36 measurement locations shown in figure 18. Without a well-defined airplane configuration, it would not have been possible to make realistic and consistent comparisons of in-flight noise levels. The second objective was to represent a viable airplane with respect to its ability to transport passengers and cargo with a fuel efficiency comparable to current business-jet airplane. At maximum takeoff gross weight of 8,674 kg (19,122 lb), the 12-passenger AiResearch QCGAT airplane takes full advantage of the higher thrust of the QCGAT engine, yet meets the noise goals at all three FAR Part 36 measurement locations.

Table 7 gives the principal airplane design parameters. As listed in this table, the wing incorporates double-slotted flaps for good low-speed performance. The relatively high wing loading of 354.5 kg/m^2 (72.6 lb/ft^2) assures a smooth ride comparable to commercial jets.

The takeoff profile presented in figure 19 shows lift-off after a takeoff roll of 914 m (3000 ft) and, at 6.48 km (3.5 nmi) from brake release, an altitude of more than 1,067 m (3500 ft) with thrust cutback and approximately 1158 m (3800 ft) with full thrust. As indicated on the payload-range chart, (fig. 20), the QCGAT airplane with a maximum payload of 1231 kg (2714 lb) has a maximum range of 3445 km (1860 nmi). This would allow the airplane to fly non-stop from Phoenix to New York City at an altitude of 1524 m (5000 ft) with more than 30 minutes reserve fuel.

NACELLES

During preliminary design tasks, two nacelle designs were selected; a flight nacelle and a workhorse nacelle. Only the workhorse nacelle was carried through to detail design and fabrication. The flight nacelle was used primarily to look at airplane installation characteristics and weight estimates.

The flight nacelle (fig. 21) incorporated integrally phased acoustic treatment in the inlet barrel, the inner and outer bypass duct, and the aft fan duct. It also incorporated the extra nozzle mixing length for the core exhaust mixer. The workhorse nacelle essentially duplicated the internal aerodynamic design and acoustical treatment of the flight nacelle except for a section in the area immediately aft of the fan that had no acoustic treatment in the flight nacelle. The weight of the flight nacelle was estimated at 134 kg (295 lb). The total installed propulsion system weight was estimated at 513 kg (1130 lb).

A cross section of the workhorse nacelle is shown with the engine in figure 22. This nacelle was designed to provide maximum test configuration versatility for the QCGAT engine. Figure 22 also shows the basic component arrangements. The principal components include the inlet barrel, that accommodates a flight-simulator lip, a conventionally shaped nacelle lip, the inner and outer bypass ducts located opposite the engine hot section, the aft barrel, the core mixer, and the nozzle.

The inlet barrel (fig. 23) incorporates two sets of interchangeable duct liners--one set of acoustic-treatment panels and one set of hardwall panels, as well as the two different inlet lips. The flight-simulator lip (fig. 23) is designed to control and direct the inlet airflow, thus simulating actual flight conditions. The conventional nacelle lip is installed on the engine as shown in figure 24. The inlet barrel was designed for high-inlet recovery at a relatively high-throat Mach number of 0.79 at cruise (fig. 25). When the inlet barrel is removed, a reference bellmouth assembly can be installed directly on the engine inlet flange. Detailed performance tests were conducted with the bellmouth and will be discussed later.

The inner and outer bypass duct section (fig. 26) also incorporated two sets of duct liners--acoustical-treatment and hardwall panels. As in the inlet barrel, these replaceable panels were in 180-degree sections and were radially adjustable so that the flow-path continuity could be controlled. The outer bypass duct contained a faired service strut that provided for extensive pressure and temperature instrumentation, as well as support of the aft section of the engine. The aft flange of the outer bypass duct was common to two nozzle schemes--the mixer compound nozzle and the coannular nozzle. Figure 27 shows half the outer bypass duct section removed. The service strut is visible, and the core section of the coannular nozzle is installed.

A 12-lobe core mixer (fig. 28) was designed for the AiResearch QCGAT engine to improve both performance and takeoff noise. With the mixer compound nozzle, a 1-percent TSFC improvement in sea-level performance was demonstrated. A 3.2-percent TSFC improvement at cruise was estimated based on mixer model and engine tests. A 3- to 5-EPNdB reduction in takeoff noise from the coannular configuration was achieved with the mixer compound nozzle. As shown in figure 29, smoke traces on the mixer centerbody indicated that the mixer compound nozzle was performing as predicted. Similar smoke traces were observed in the nozzle section downstream of the mixer.

The final sections of the workhorse nacelle assembly (fig. 30) are the aft barrel, which has hardwall and acoustic panels, and the nozzle. These sections are used only when the mixer is installed. They are removed when the coannular nozzle system is used.

The complete workhorse nacelle assembly is shown in figures 31 and 32. These figures show the engine mounted on the test stand at AiResearch's remote desert test facility in the San Tan mountains, southeast of Phoenix.

CONCLUSION

The following points summarize the design of the AiResearch QCGAT engine and nacelle system:

- An existing turbofan engine core was utilized for an experimental demonstrator engine. This was a requirement of the original problem statement and was particularly important with respect to minimizing costs and maximizing reliability.

- Several unique components were successfully adapted to this core: fan, gearbox, combustor, low-pressure turbine, and associated structure. These components formed the basis for meeting the main program objective demonstrating the application of large turbofan engine design, emissions, and noise technology in small general aviation turbofans.

- A highly versatile workhorse nacelle incorporating interchangeable acoustic and hardwall duct liners, showed that large-engine attenuation technology could be applied to small propulsion engines. The application of the mixer compound nozzle demonstrated both performance and noise advantages on the engine.

The QCGAT program made several significant contributions to general aviation propulsion:

- o Application of exhaust-emissions reduction techniques.

  1. Hydrocarbon and carbon monoxide goals were met.

  2. Nitrogen oxides were greatly reduced.

- o With the aid of NASA, improved small engine noise-analysis techniques, including core noise and static-to-flight correlations, were developed.

- o Major noise reduction, beyond that of an already quiet engine, was obtained. The AiResearch QCGAT engine is significantly quieter than any other business jet engine.

TABLE 1. AIRESEARCH QCGAT ENGINE, TECHNICAL GOALS.

A. Performance	Thrust N (lbf)	TSFC kg/N.h (lbm/hr/lbf)
Takeoff (SLS,ISA)		
o Uninstalled	17,512 (3,937)	0.0426 (0.418)
o Installed	17,312 (3,892)	0.0431 (0.423)
Cruise [12,192 m (40,000 ft), M = 0.8]		
o Uninstalled	3,954 (889)	0.0775 (0.760)
o Installed (with mixer nozzle)	4,017 (903)	0.0759 (0.744)

B. Noise (FAR Part 36)	EPNdB
Takeoff	73.3
Sideline	82.3
Approach	87.3

C. Emissions (EPA 1979 Standards T-1)	EPAP
Hydrocarbon (HC)	1.6
Carbon Monoxide (CO)	9.4
Oxides of Nitrogen (NO_x)	3.7
Smoke Number	38.0

D. Weight kg (lbm)	E. Life hr
377 (832)	10,000

TABLE 2. QCGAT CYCLE PARAMETERS.

Design point	12,192 m (40,000 ft), M = 0.8, ISA
Thrust	4,017 N (903 lbf)-installed
TSFC	0.0759 kg/N.h (0.744 lbm/hr/lbf)
Bypass ratio	3.71
Fan pressure ratio	1.62
Cycle pressure ratio	17.7
Turbine inlet temperature	1,266K (1,820°F)
Corrected fan airflow	77.8 kg/s (171.6 lb/sec)
Corrected core airflow	11.5 kg/s (25.4 lb/sec)

TABLE 3. QCGAT FAN DESIGN FEATURES.

At Design Point--12,192 m (40,000 ft, 0.8M, ISA).	
Diameter	77.5 cm (30.5 in.)
Radius ratio	0.46
Inlet corrected airflow	77.8 kg/s (171.6 lbm/sec)
Bypass ratio	3.7
Bypass pressure ratio	1.62
Core pressure ratio	1.55
Inlet tip relative Mach No.	1.39
Inlet corrected tip speed	6.985 m/s (1375 ft/sec)

TABLE 4. QCGAT DESIGN LOADS.

Item Description	Radial Load N (lbf)	Moment Load J (lbf-in.)	Fan Thrust N (lbf)	Bird Strike Torque J (lbf-in.)
Fan support	289,134 (65,000)	-- --	14,679 (3,300)	-- --
Intermediate case	289,134 (65,000)	832,473 (614,000)	14,679 (3,300)	454,199 (335,000)
Engine support housing (main engine mount)	289,134 (65,000)	1,128,041 (832,000)	14,679 (3,300)	454,199 (335,000)

TABLE 5. MODEL TFE731-3 ENGINE COMPONENTS, DESIGN POINT CHARACTERISTICS.

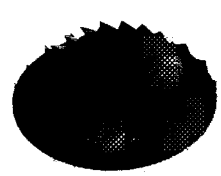
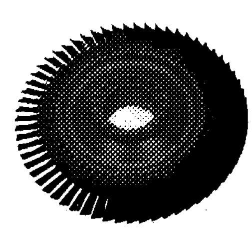
Design Point Parameters	Low-Pressure Compressor	High-Pressure Compressor	High-Pressure Turbine
Type	Four-stage axial	Single-stage centrifugal	Single-stage cooled axial
N/	2,094 rad/s (20,000 rpm)	2,295 rad/s (21,917 rpm)	1,406 rad/s (13,431 rpm)
P/P	4.27	2.57	1.832
W /	11.11 kg/s (24.5 lb/sec)	2.99 kg/s (6.60 lb/sec)	2.129 kg/s (4.693 lb/sec)
T_{inlet}	--	--	1,329K (1,933°F)
			

TABLE 6. QCGAT LOW-PRESSURE TURBINE.

Engine Operating Conditions at Design Point:
Cruise Mach No. 0.8 at 12,192 m (40,000 ft), ISA

Pressure ratio (total-to-total rating)	5.707
Efficiency (total-to-total rating)	90.2%
Max flow rate	5.055 Kg/s (11.145 lbm/sec)
Speed	2,118.0 rad/s (20,229 rpm)
Specific work	406.515 kJ/kg (174.77 Btu/lbm)

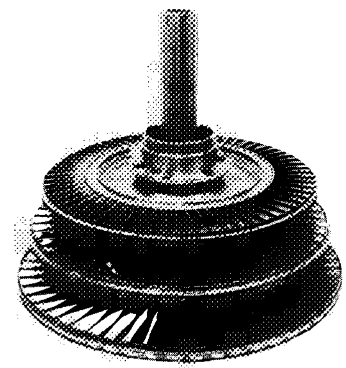


TABLE 7. AIRESEARCH QCGAT AIRPLANE PARAMETERS.

Wing area	24.49 m^2 (263.6 ft^2)
Sea level static thrust (Installed-ISA + 283.15K (273.15°C)	16,845 N (3,787 lbf)
Flaps	Double-slotted
Flap span/wing span	0.700
Sea level static thrust/takeoff gross weight [ISA + 283.15K (273.15°C)]	0.396
Takeoff gross weight with respect to wing area	107.97 Kg/m^2 (72.55 lbm/ft^2)
Capacity (crew + passengers)	2 + 12
Operating weight empty	4,808 Kg (10,599 lbm)
Takeoff gross weight	8,674 Kg (19,122 lbm)
Maximum ramp weight	8,787 Kg (19, 372 lbm)
Maximum fuel weight	3,152 Kg (6,948 lbm)
Maximum useable fuel	3,140 Kg (6,922 lbm)
Maximum payload	1,231 Kg (2,714 lbm)
Maximum landing wiehgt	6,775 Kg (14,936 lbm)
Zero fuel weight with maximum payload	6,021 Kg (13,273 lbm)
Fuel weight with maximum payload	2,766 Kg (6,099 lbm)
Payload with maximum fuel	846 Kg (1,865 lbm)

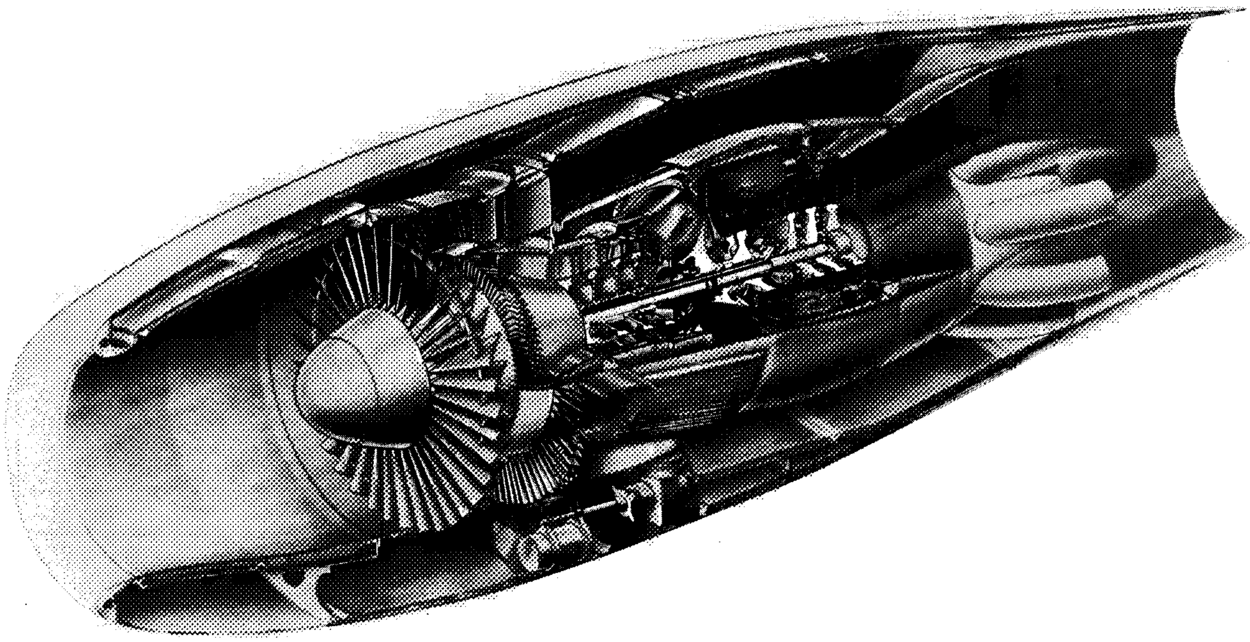


Figure 1. AiResearch QCGAT Engine.

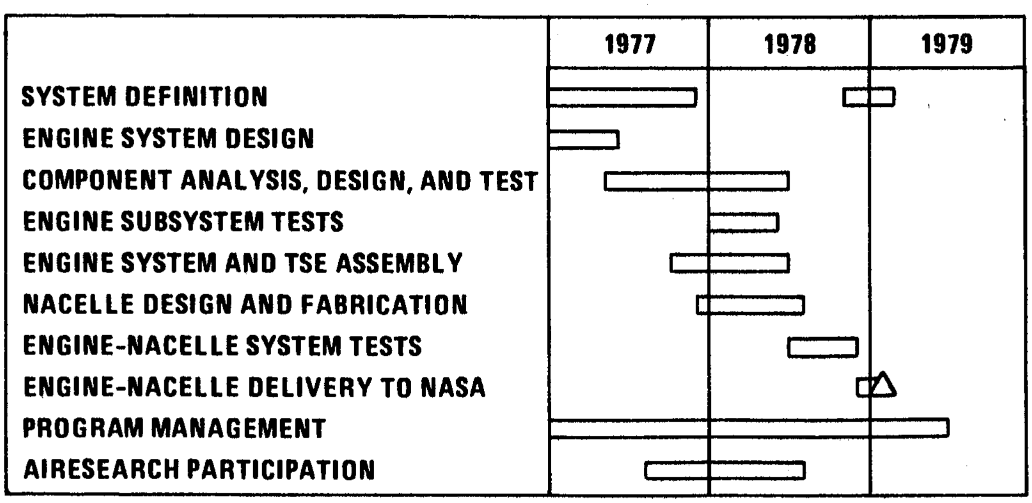
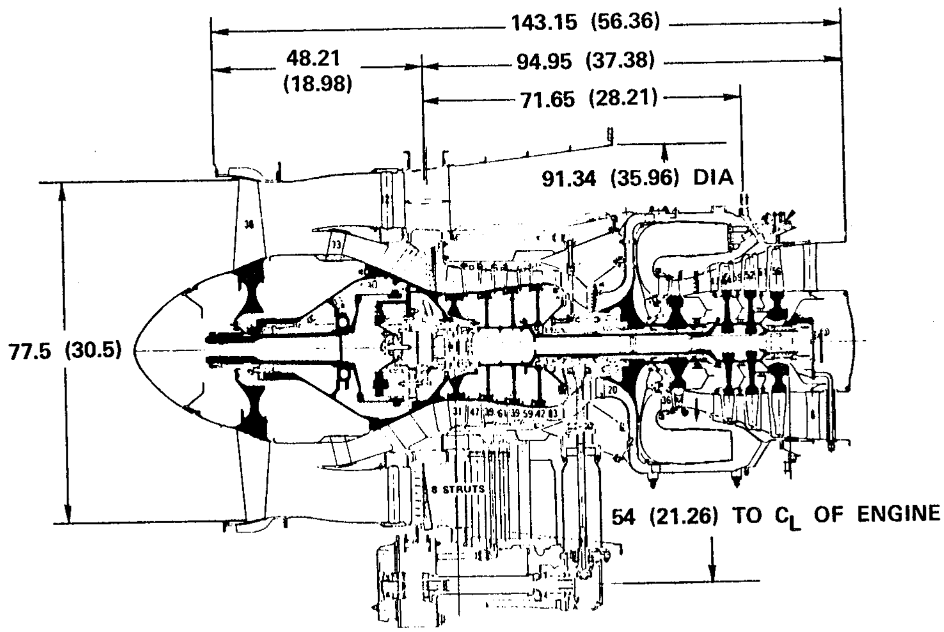


Figure 2. AiResearch QCGAT Schedule.



NOTE: DIMENSIONS ARE IN CENTIMETERS WITH INCHES GIVEN IN PARENTHESES.

Figure 3. Cross Section of AiResearch QCGAT Engine.

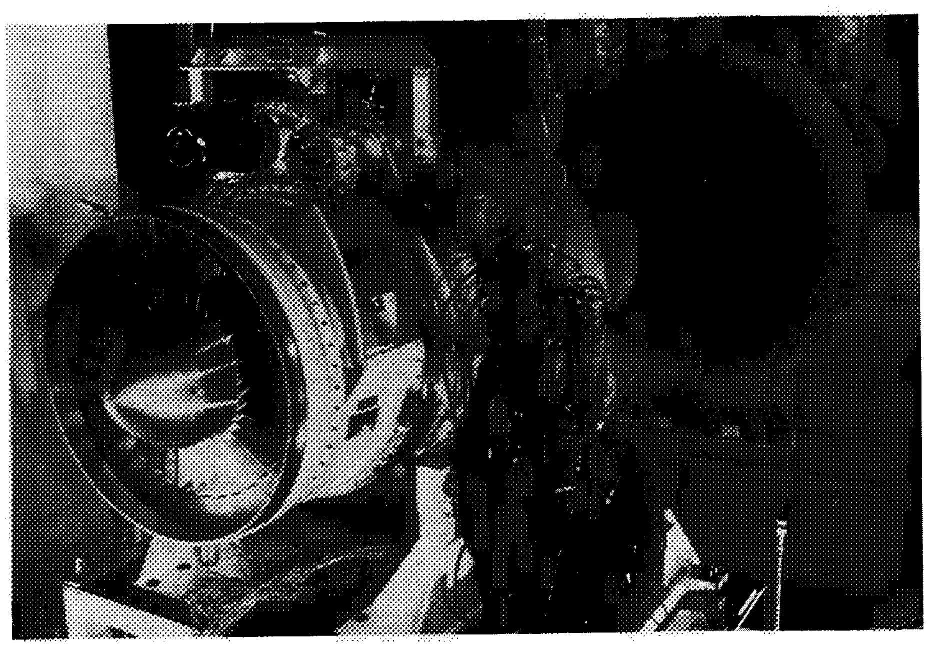


Figure 4. AiResearch QCGAT Engine.

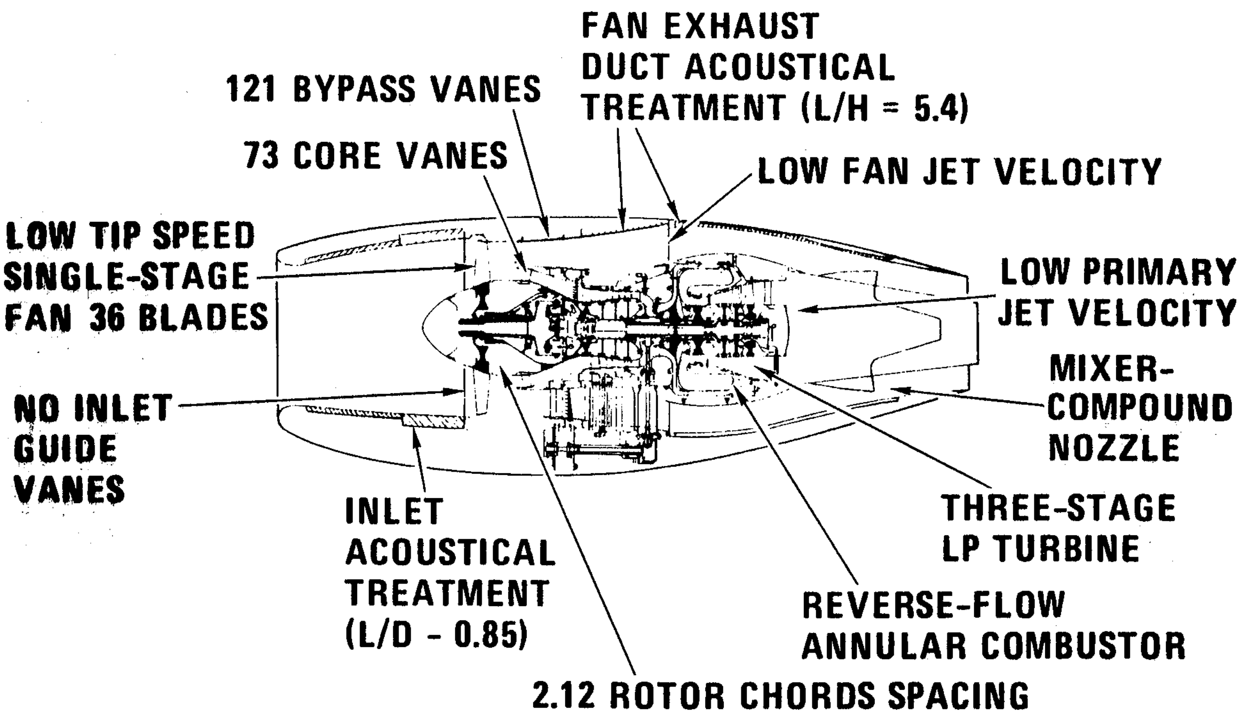


Figure 5. Major Acoustic Design Features of the QCGAT Engine Nacelle.

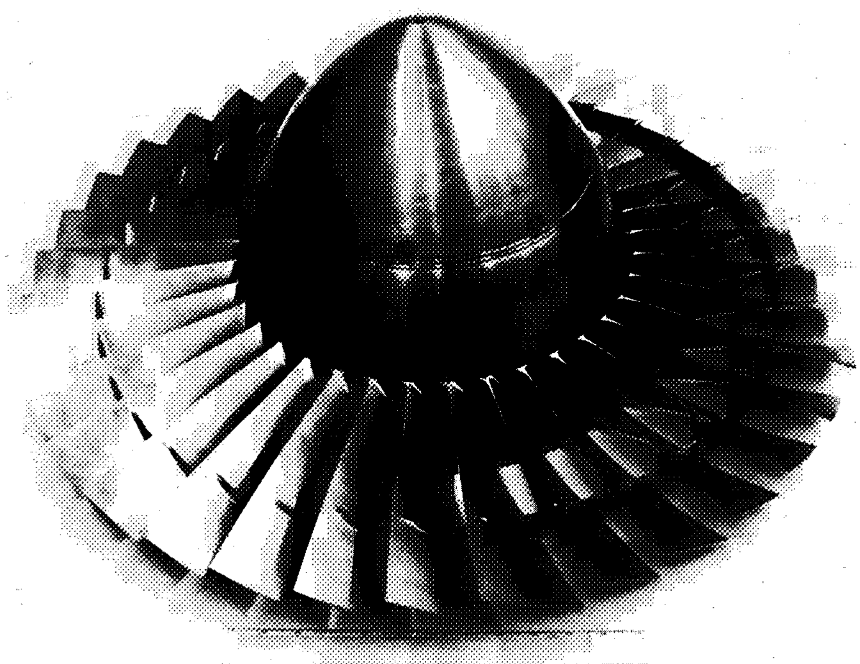


Figure 6. QCGAT Fan Rotor.

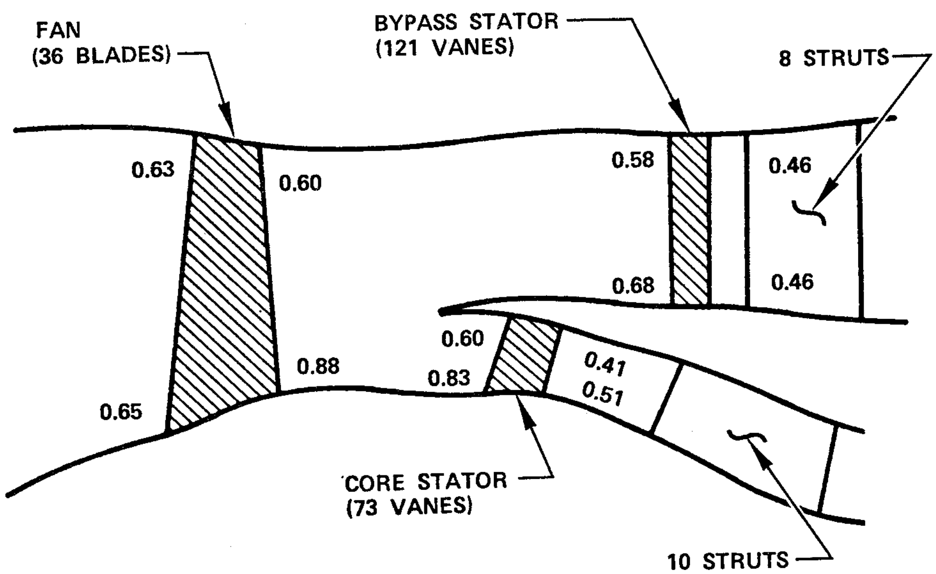


Figure 7. Mach Numbers (Absolute) for Fan Stage and Transition Ducts.

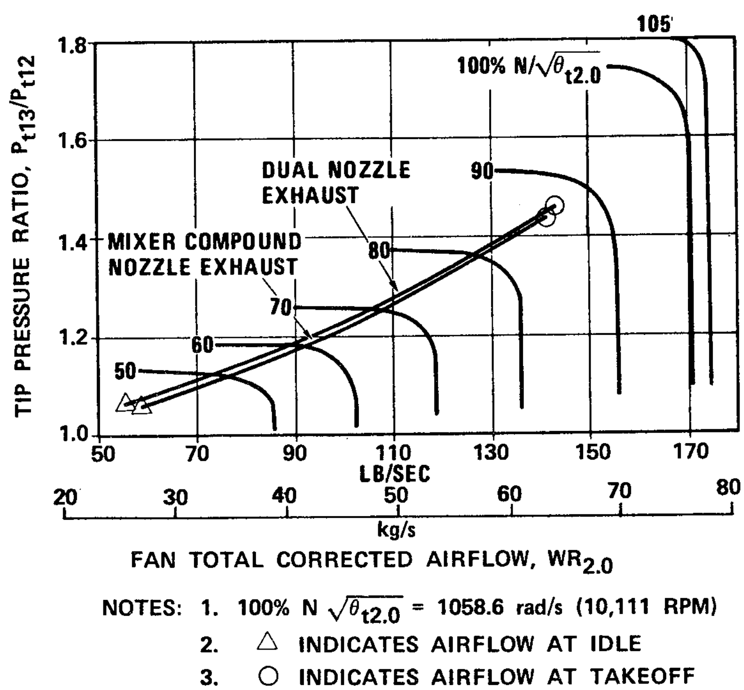


Figure 8. Estimated Performance of AiResearch QCGAT Engine.

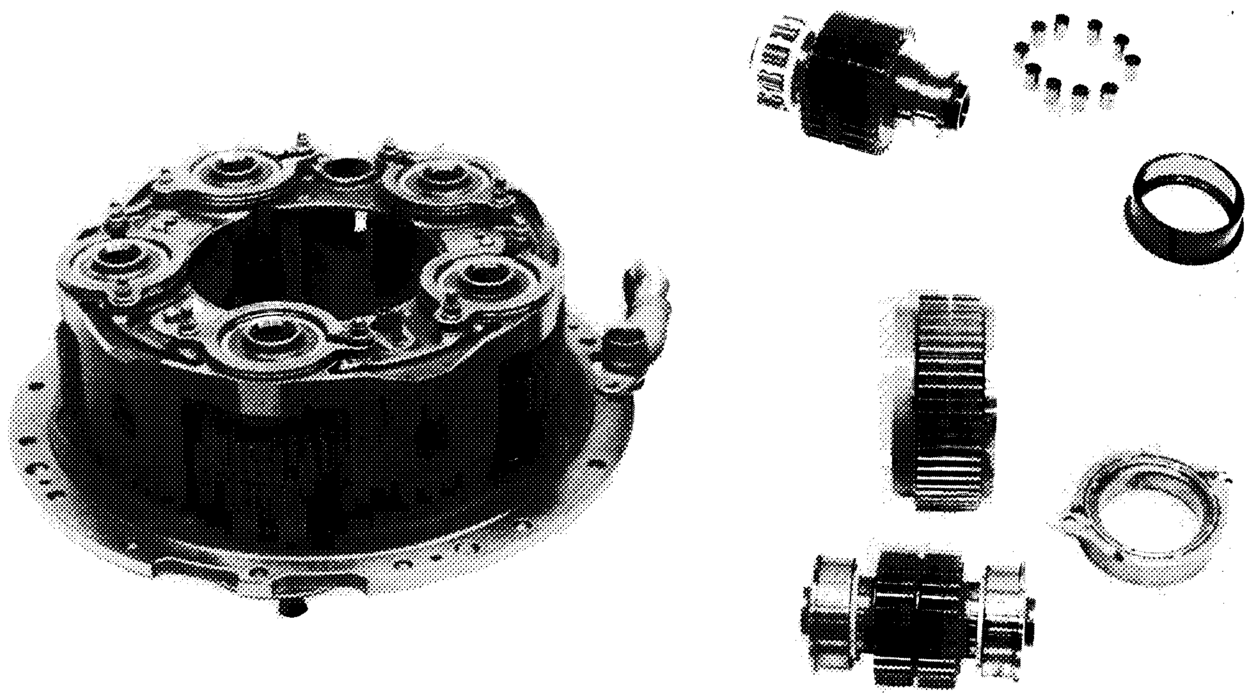


Figure 9. QCGAT Fan Gearbox.

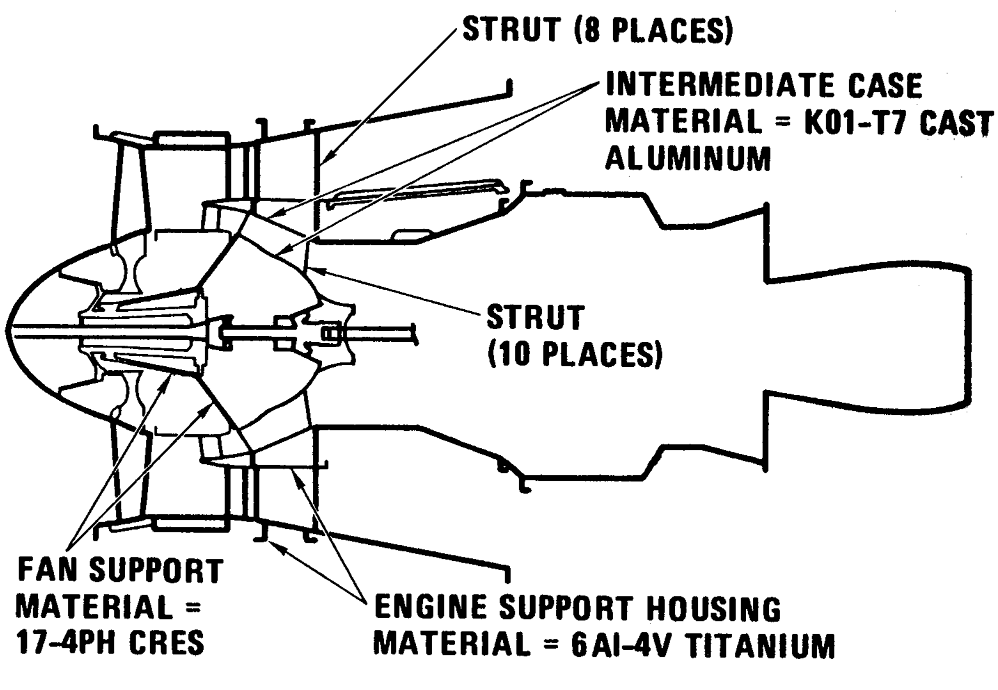


Figure 10. QCGAT Fan Support Structure.

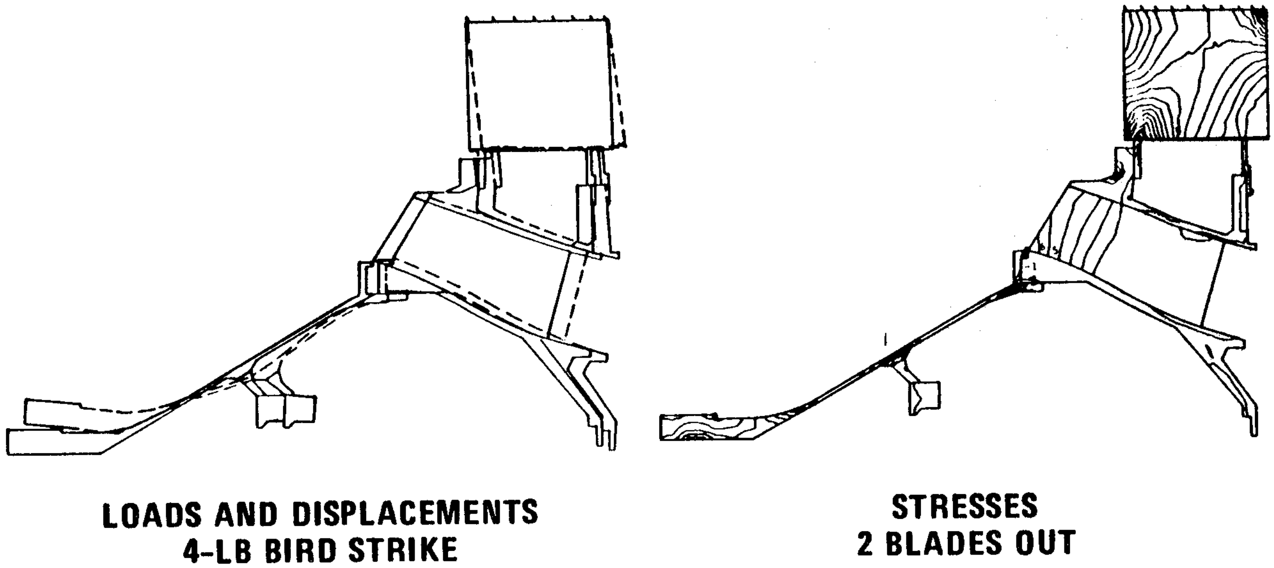
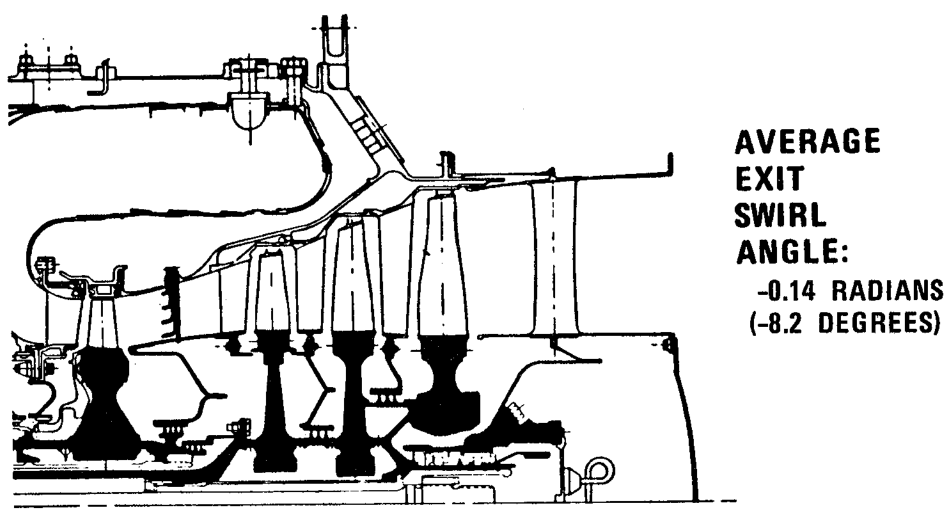


Figure 11. Fan Support Structure Stress and Loads.



STAGE	FIRST	SECOND	THIRD
BLADE MATERIAL DISC MATERIAL	MAR-M 247 WASPALOY B	INCO 713LC WASPALOY B	INCO 713LC WASPALOY B

Figure 12. QCGAT Low-Pressure Turbine.

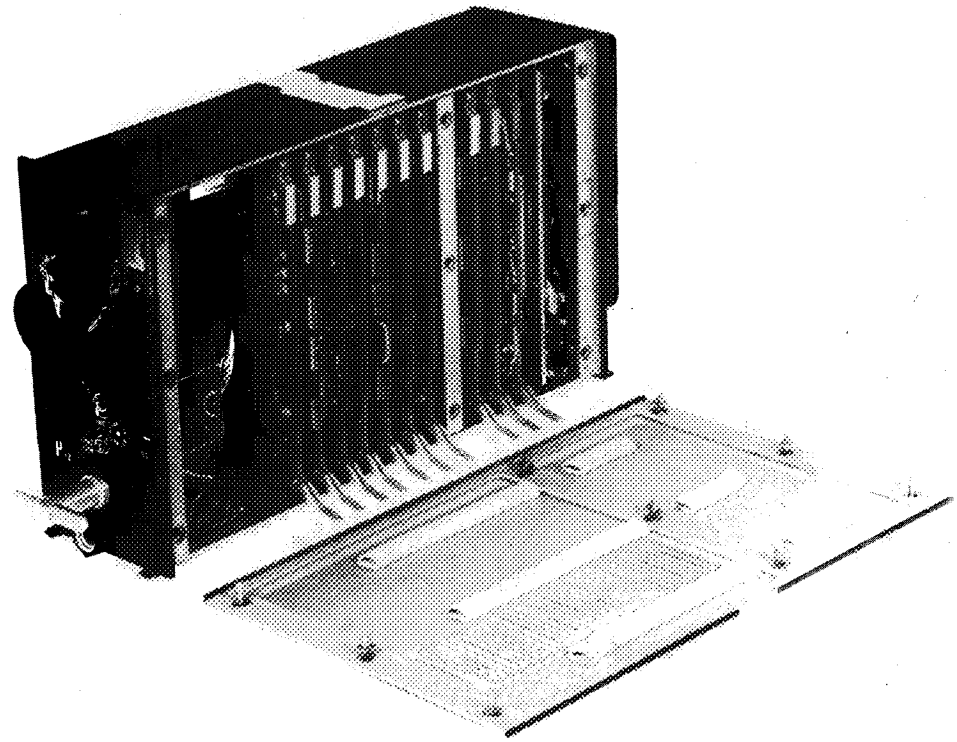


Figure 13. Electronic Fuel Control Computer.

Figure 14. QCGAT Combustor.

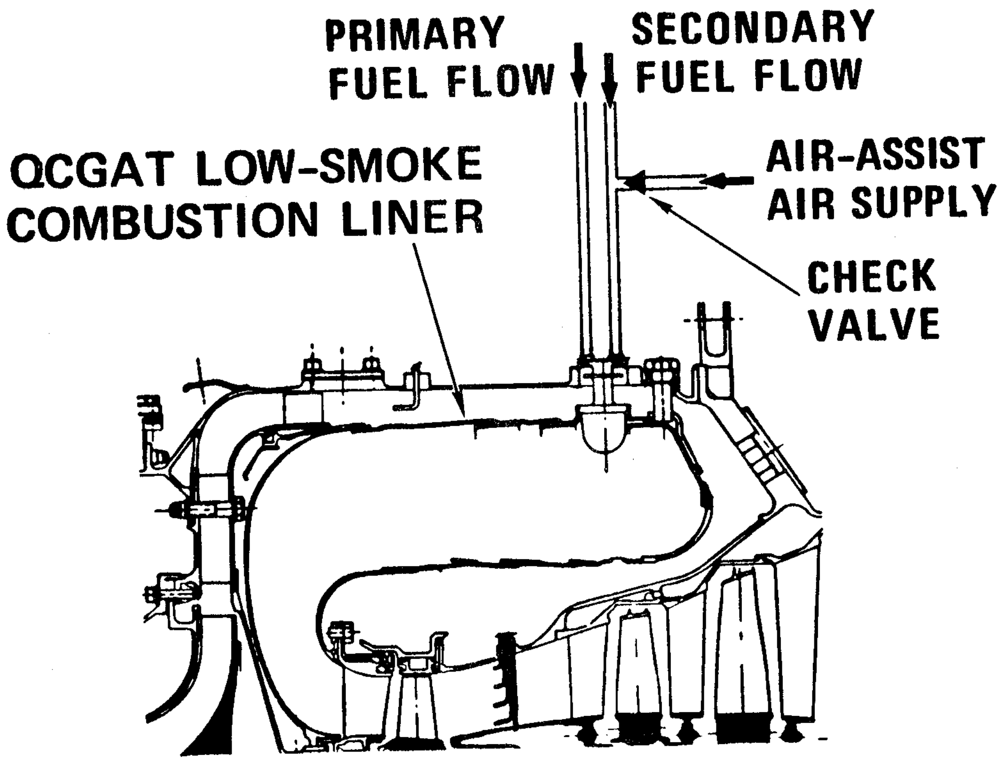


Figure 15. QCGAT Combustor Air Assist System.

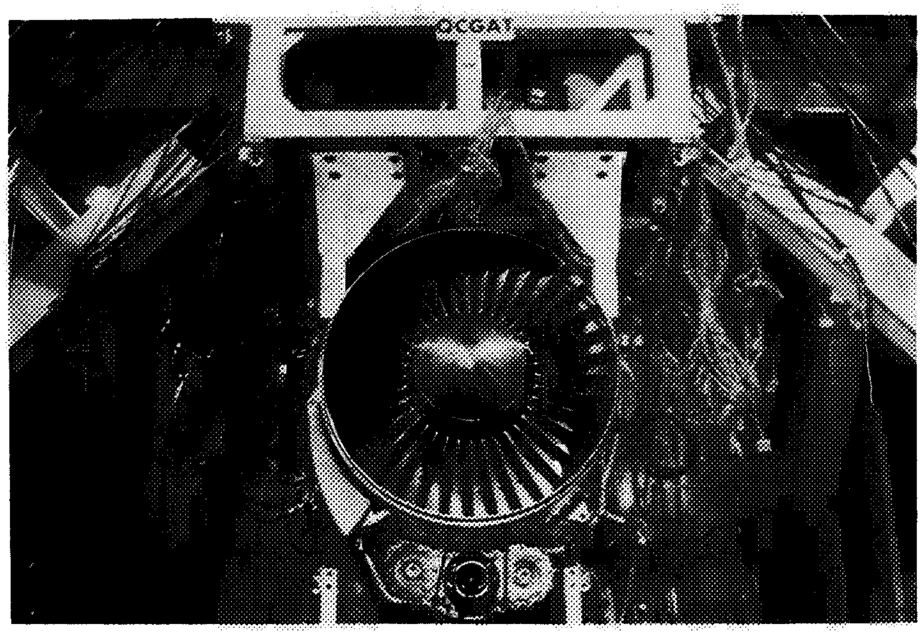


Figure 16. Front View of QCGAT Engine.

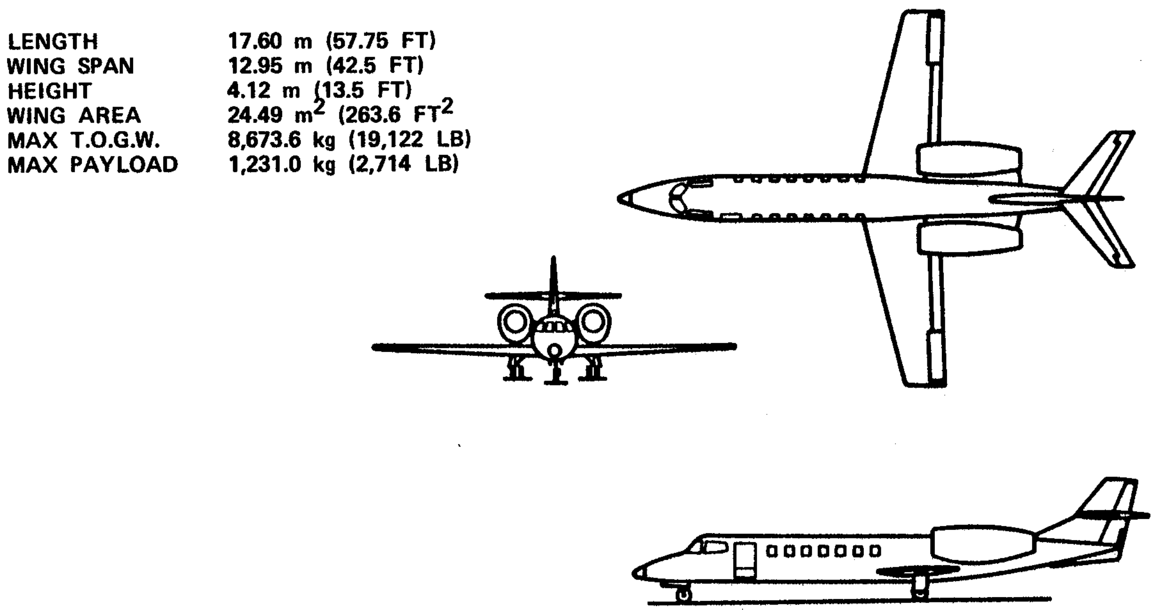


Figure 17. AiResearch QCGAT Airplane.

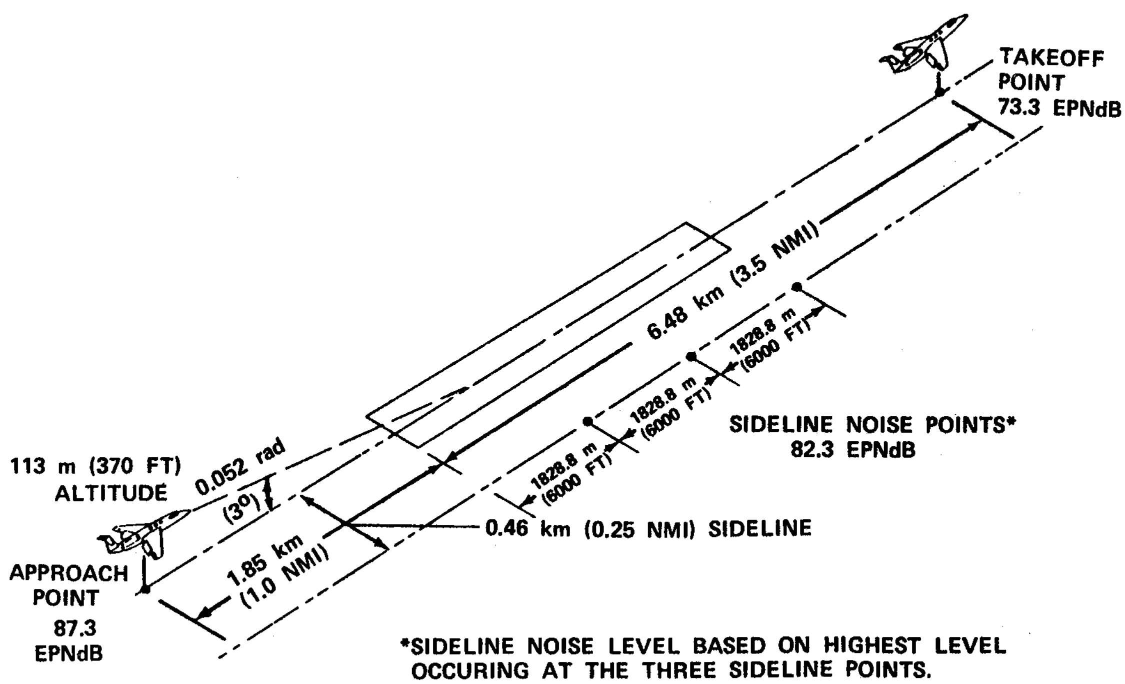


Figure 18. QCGAT Airplane Noise Goals.

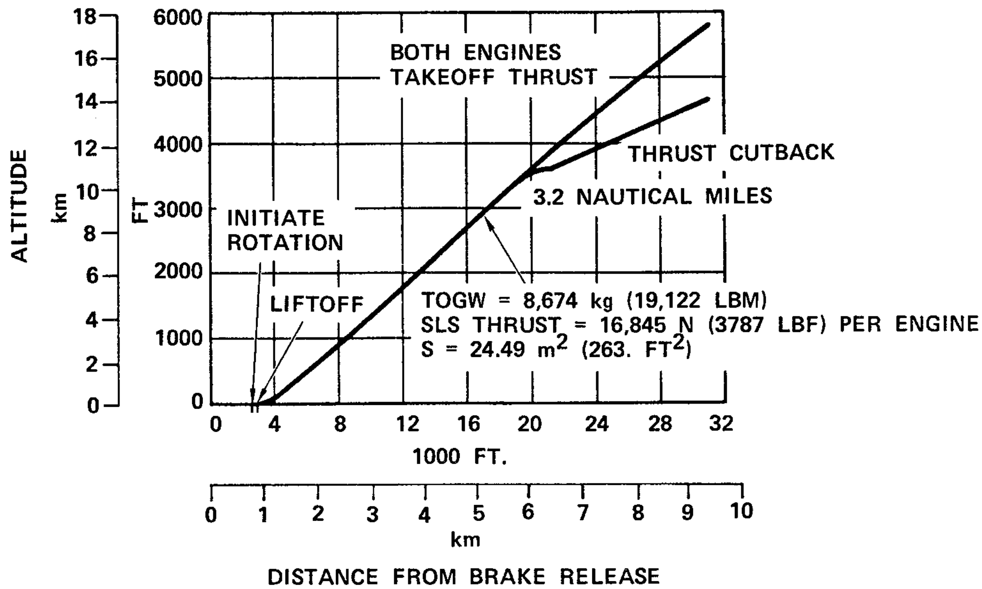


Figure 19. AiResearch QCGAT Airplane Takeoff Profile.

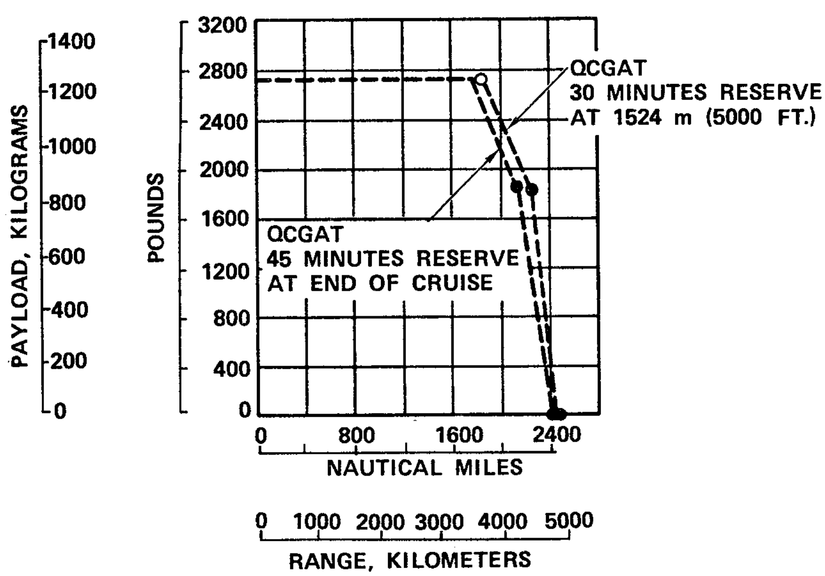


Figure 20. AiResearch QCGAT Airplane Payload versus Range.

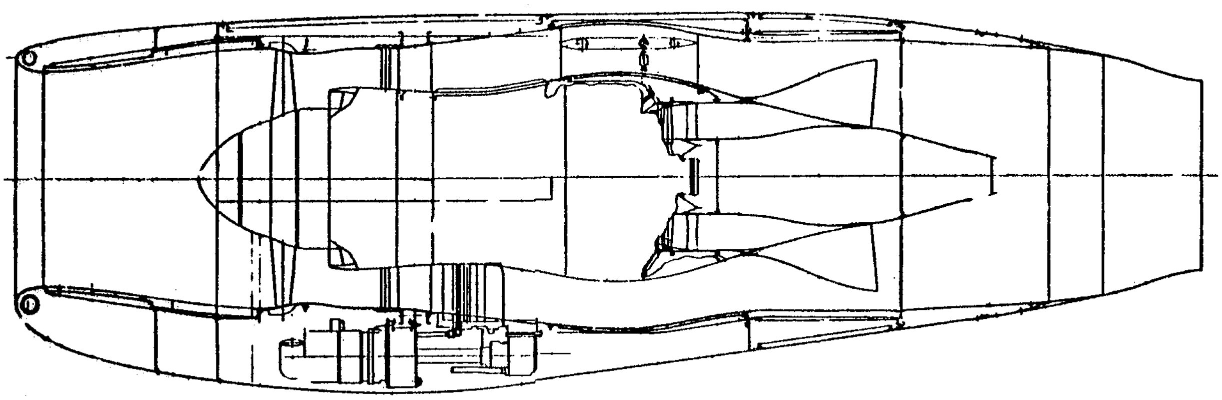


Figure 21. QCGAT Flight Nacelle.

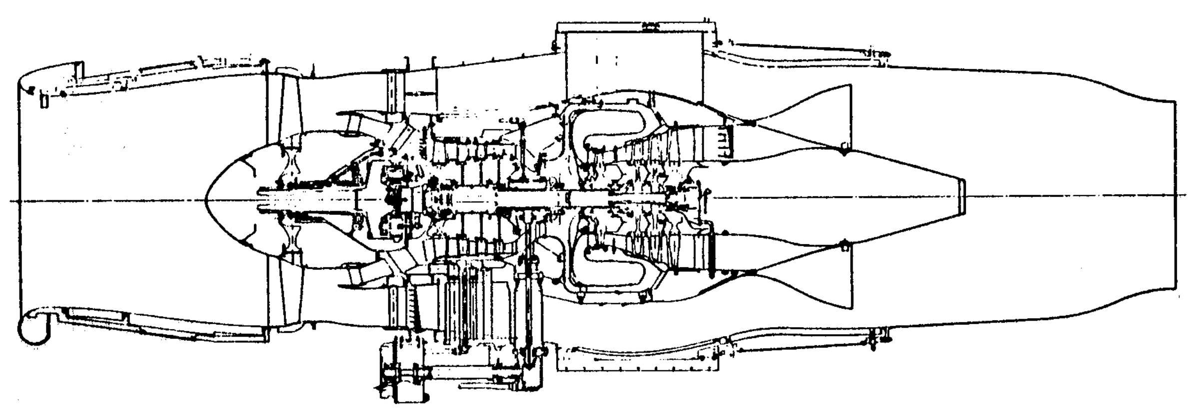


Figure 22. QCGAT Workhorse Nacelle.

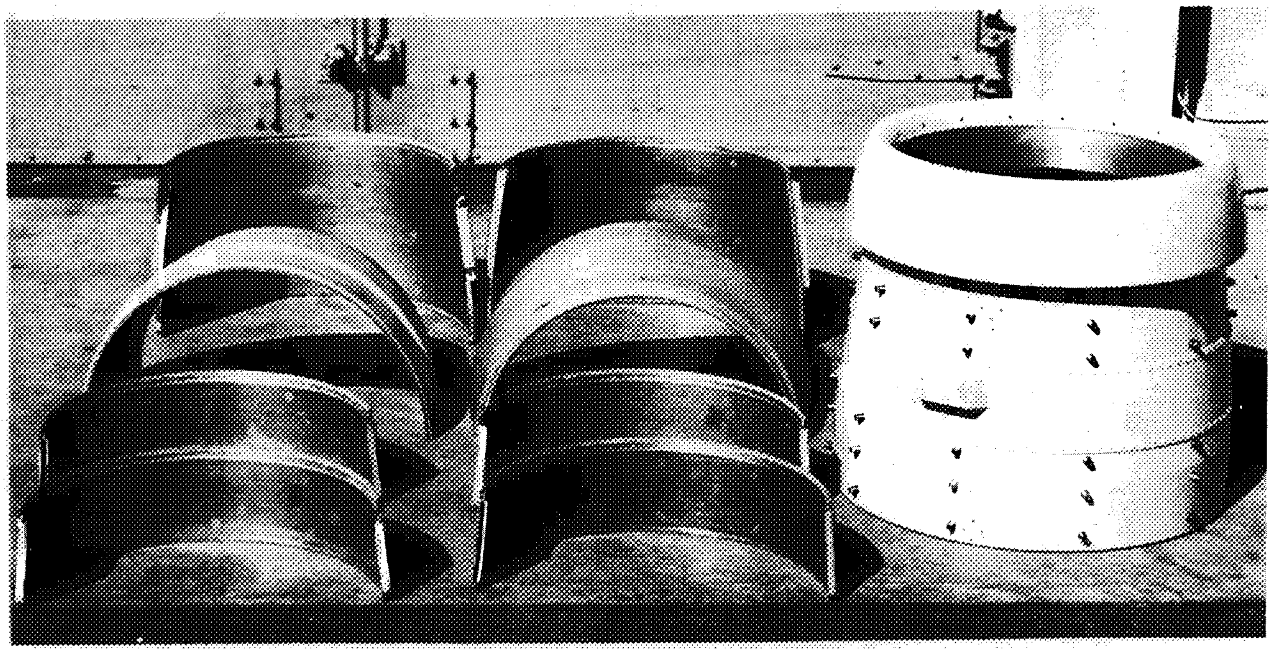


Figure 23. Inlet Barrel.

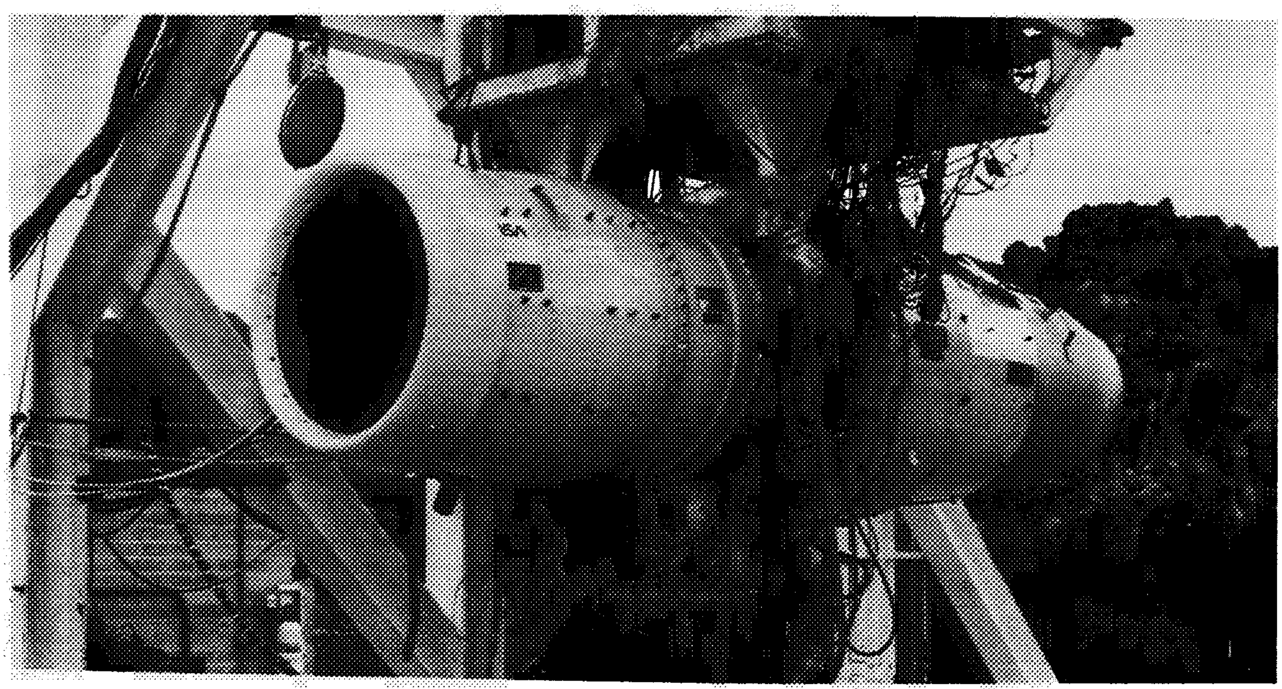


Figure 24. QCGAT Engine with Nacelle Inlet Lip.

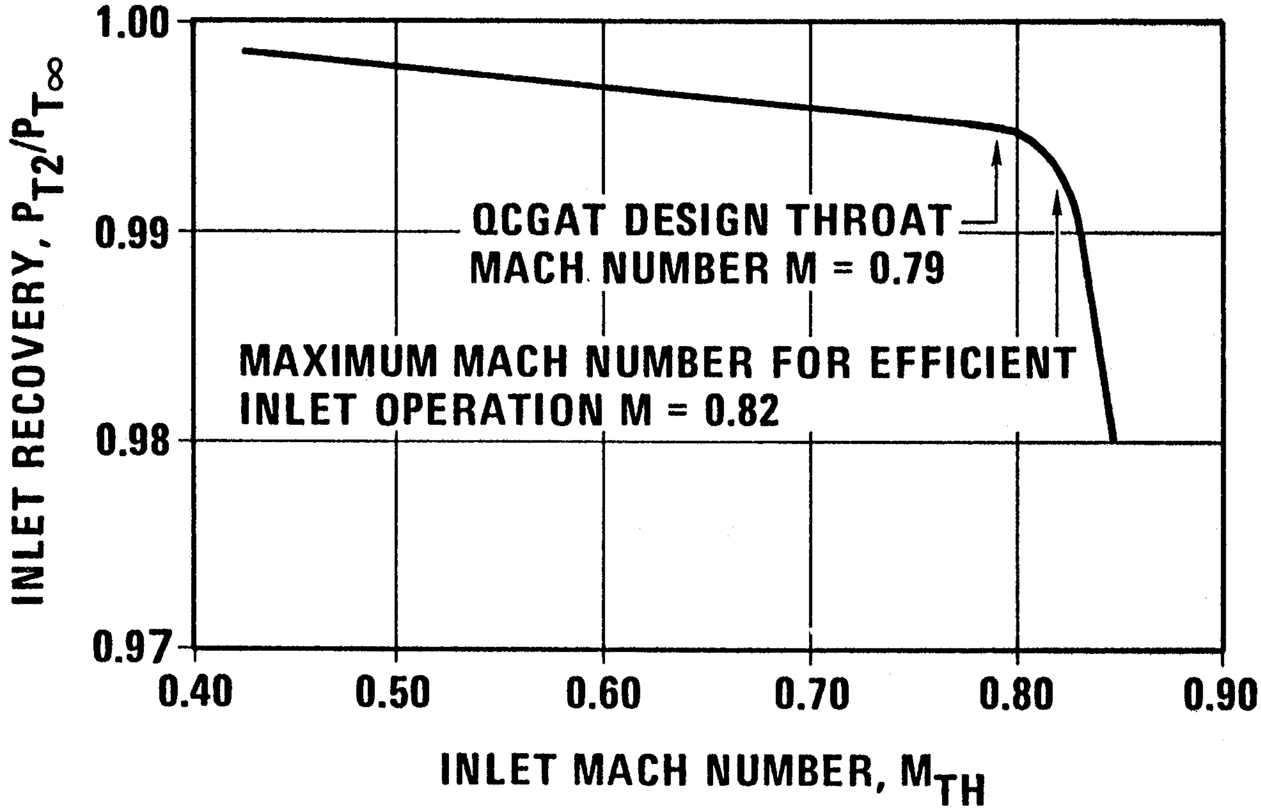


Figure 25. QCGAT Inlet Recovery Characteristics.

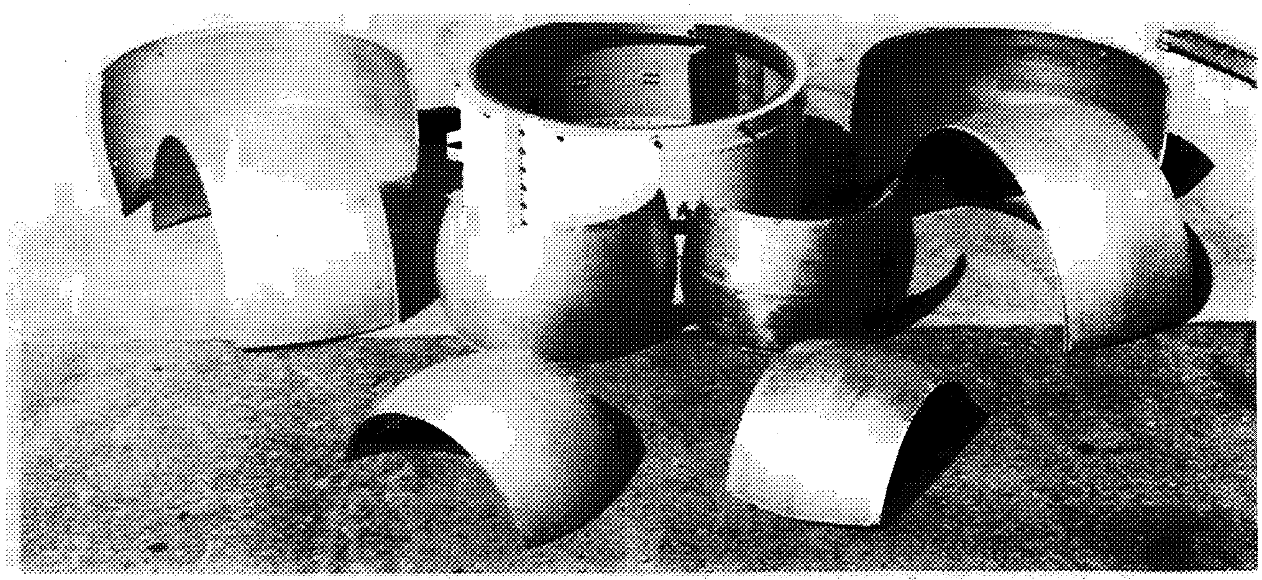


Figure 26. Workhorse Nacelle Inner and Outer Bypass Duct.

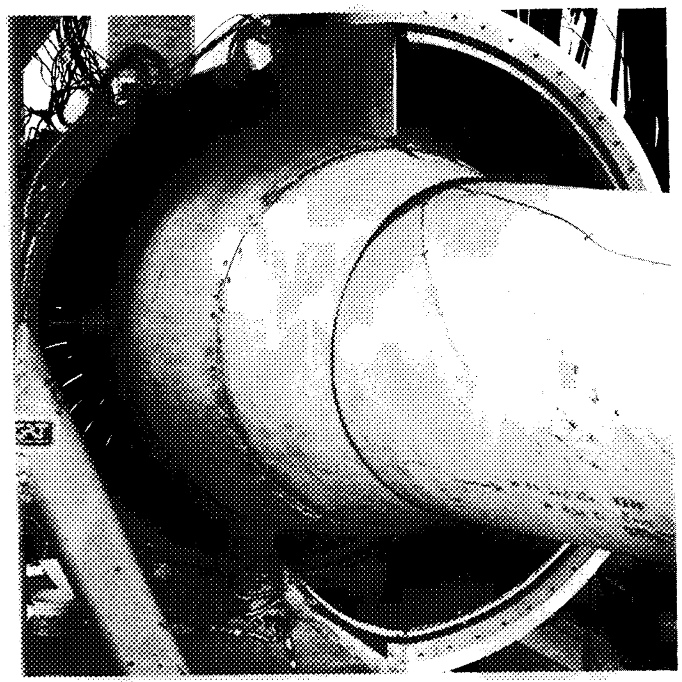


Figure 27. Workhorse Nacelle--Service Strut.

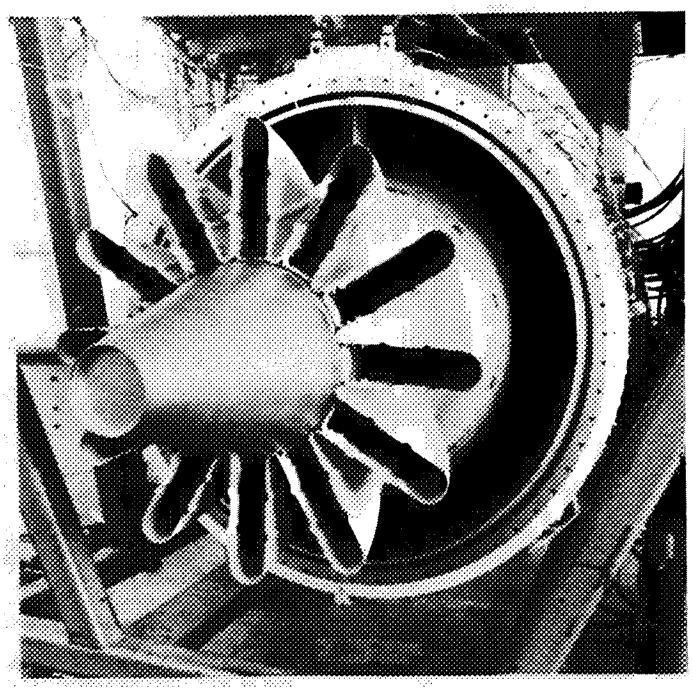


Figure 28. QCGAT Mixer Nozzle.

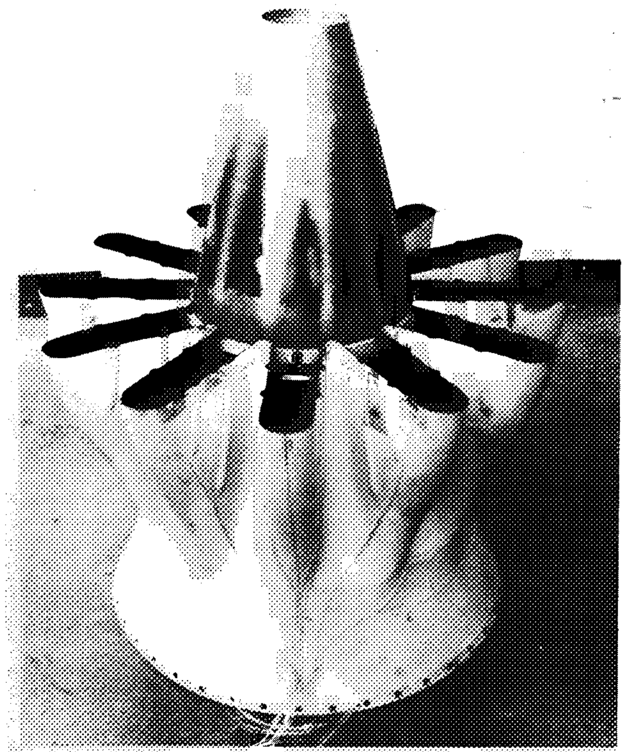


Figure 29. QCGAT Mixer Nozzle.

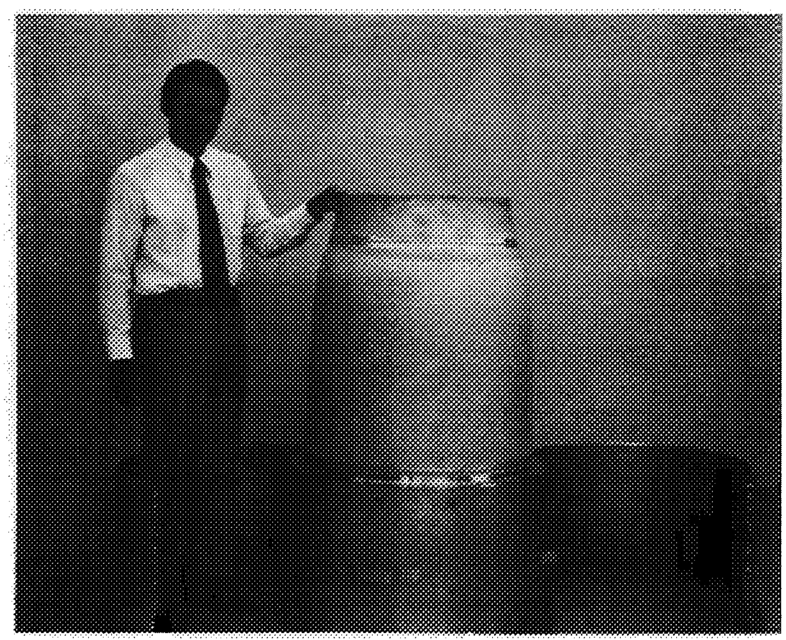


Figure 30. QCGAT Nacelle Aft Barrel and Nozzle.

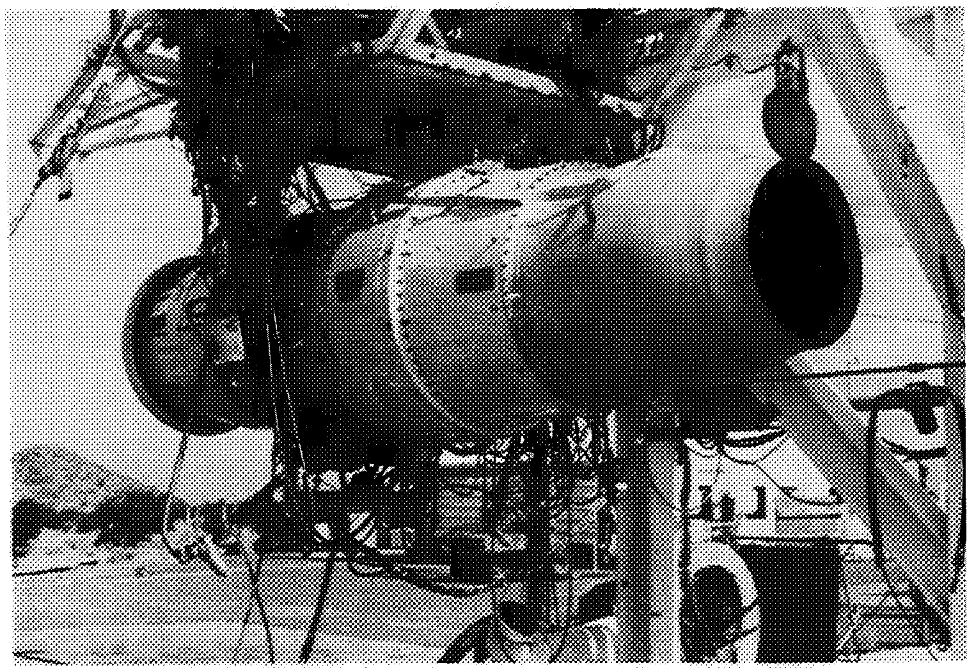


Figure 31. QCGAT Nacelle Assembly Fully Installed in Test Stand (Side View Looking Forward).

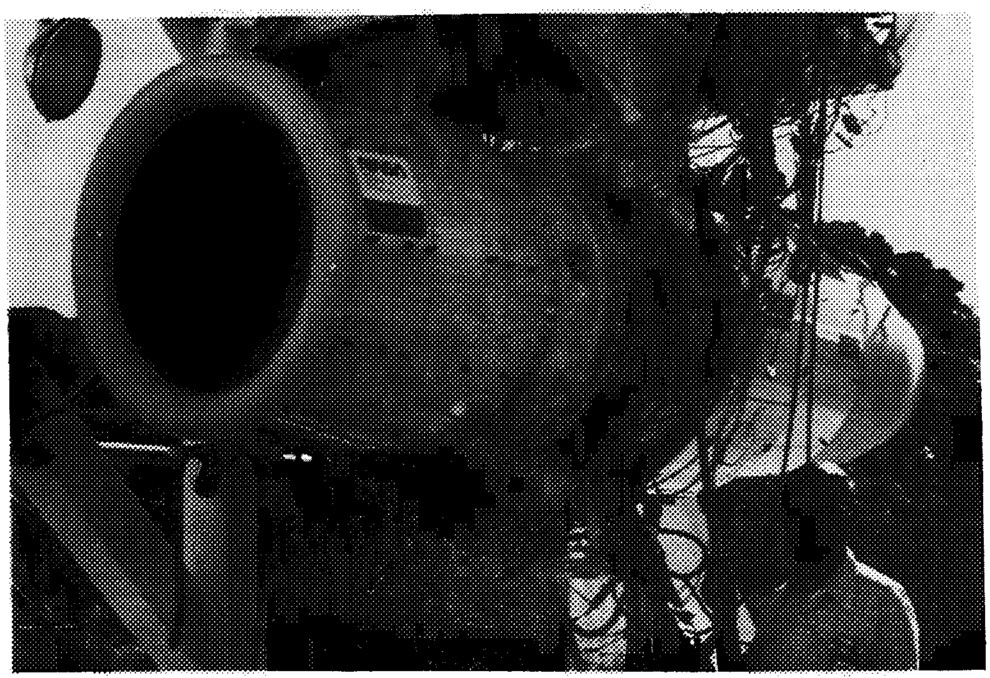


Figure 32. QCGAT Nacelle Assembly Fully Installed in Test Stand (Side View Looking Aft).