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Quiet Clean Short-Haul Experimental Engine (QCSEE) Final Report

by

William S. Willis

GENERAL ELECTRIC COMPANY

August 1979

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16. Abstract The QCSEE Program included the design, fabrication, and testing of two experimental propulsion systems for powered-lift transport aircraft. The Under-the-Wing (UTW) engine was intended for installation in an externally blown-flap configuration and the Over-the-wing (OTW) engine for use in an upper-surface-blowing aircraft. The UTW engine included variable-pitch composite fan blades, main reduction gear, composite fan frame and nacelle, and a digital control system. The OTW engine included a fixed-pitch fan, composite fan frame, boilerplate nacelle, and a full-authority digital control. Many acoustic, pollution, performance, and weight goals were demonstrated; all planned testing was satisfactorily completed prior to delivery of the engines to NASA for further testing.					
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1.0 SUMMARY

The Quiet Clean Short-haul Experimental Engine (QCSEE) program was conducted by General Electric Advanced Engineering and Technology Program Department under contract from NASA Lewis Research Center. The program included the design, fabrication, and testing of turbofan propulsion systems for two short-haul transport aircraft and delivery of these systems to NASA for further testing. One propulsion system was designed for an Under-the-Wing (UTW), externally blown flap application; the other was configured for Over-the-Wing (OTW) upper-surface blowing.

Major objectives of the program were to develop the technology needed to meet the stringent noise, exhaust emissions, performance, weight, and transient thrust-response requirements of future short-haul aircraft. Specific program goals are as listed in Table I.

Table I. QCSEE Program Goals.

Parameter	UTW	OTW
Noise at 152.4 m (500 ft) Sideline Takeoff and Approach, EPNdB Maximum Reverse Thrust, PNdB	95 100	95 100
Exhaust Emissions	1979 EPA Standards for Carbon Monoxide, Unburned Hydrocarbons, and Oxides of Nitrogen	
Performance Uninstalled Thrust, kN (lbf) Installed Thrust, kN (lbf) Uninstalled sfc, g/sec/N (lbm/hr/lbf) Max Reverse Thrust, % of Max Forward	81.4 (18,300) 77.4 (17,400) 0.0096 (0.34) 35	93.4 (21,000) 90.3 (20,300) 0.0102 (0.36) 35
Thrust to Weight Ratio, N/kg (lbf/lbm) Uninstalled Installed	60.8 (6.2) 42.2 (4.3)	72.6 (7.4) 46.1 (4.7)
Thrust Transient, seconds Approach to Takeoff Approach to Max Reverse	1 1.5	1 1.5

Major design features selected for the engines include: low tip-speed fans, composite fan frames, high throat Mach number inlets, main reduction gears, and digital electronic control systems. In addition the UTW propulsion system contains a variable-pitch fan with composite blades, a variable-area fan-exhaust nozzle, and a complete composite nacelle with integral acoustic treatment. The OTW propulsion system includes a fixed-pitch fan with titanium blades, a "D" shaped exhaust nozzle, a target-type thrust reverser, and a boilerplate nacelle with interchangeable acoustic treatment. Figure 1 shows the test configuration of the UTW propulsion system with the composite nacelle, and Figure 2 shows the OTW propulsion system with the boilerplate nacelle.

The UTW propulsion system completed a total of 153 hours of testing at General Electric's Peebles, Ohio outdoor acoustic test side 4D and was delivered to NASA in August 1978. The OTW propulsion system completed 58 hours of testing at the same site and was delivered in July 1977. Major results of the test program are as listed in Table II.

Table II. QCSEE Test Results.

Parameter	UTW	OTW
Demonstrated Sideline Noise Levels		
Approach, EPNdB	95.7	94.5
Takeoff, EPNdB	97.2	97.2
Max Reverse, PNdB	105*	107
Exhaust Emissions	Met 1979 EPA Standards in Combustor Rig Test	
Performance		
Uninstalled Thrust	Met Goal	Met Goal
Installed Thrust	Met Goal	Met Goal
Uninstalled sfc	Met Goal	3% Better Than Goal
Max Reverse Thrust	27%	Exceeded Goal
Thrust Transients		
Approach to Takeoff	Not Demonstrated	Met Goal
Approach to Max Reverse	Not Demonstrated	Not Demonstrated

*at 27% Reverse Thrust

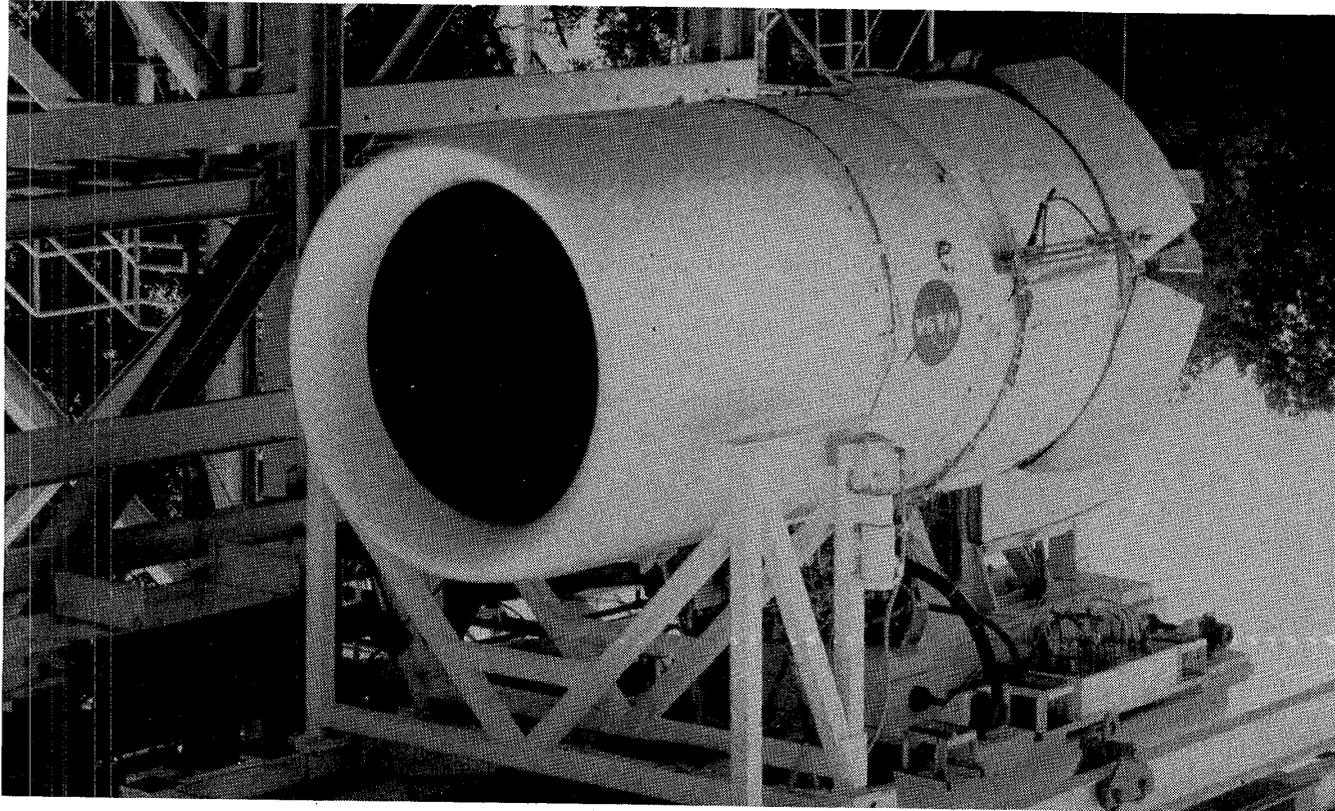


Figure 1. UTM GCSE.

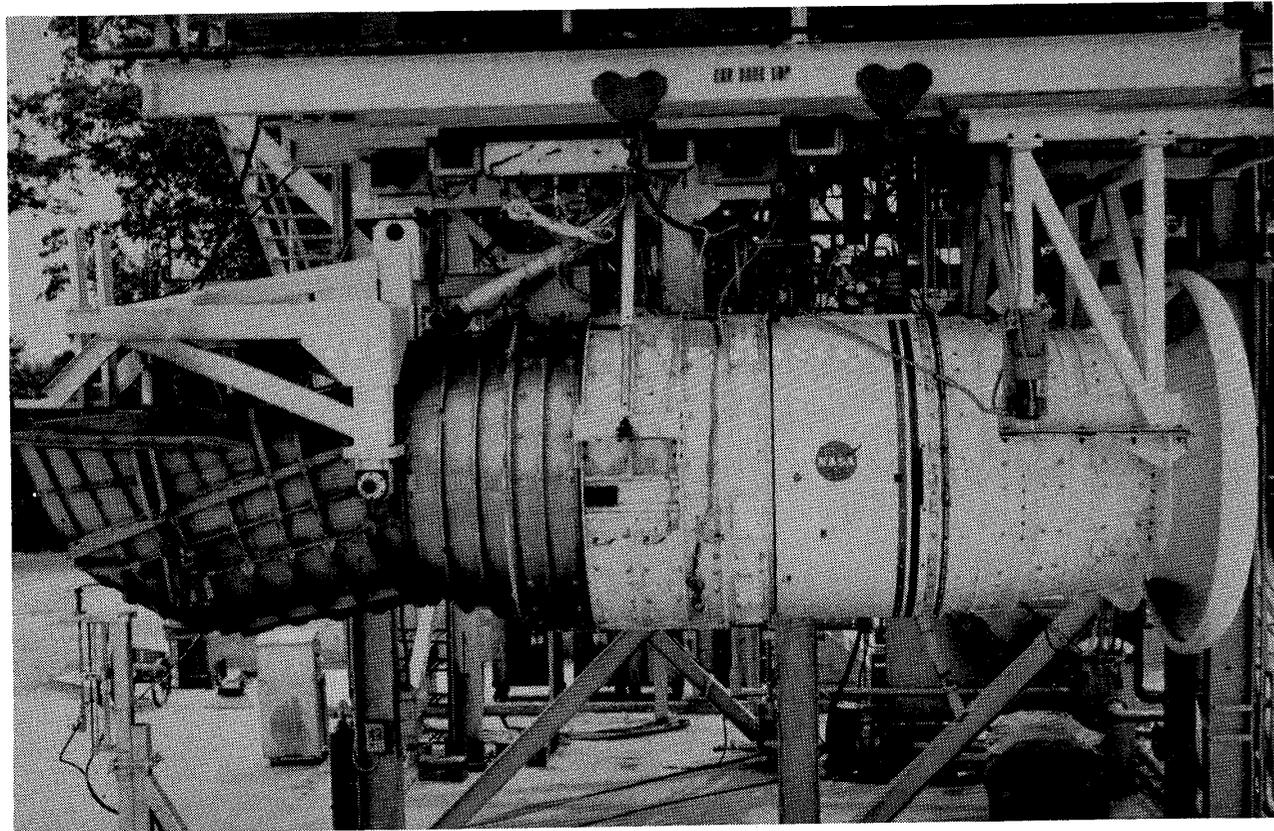


Figure 2. OTW QCSEE.

From an overall standpoint, both engines either met or closely approached all significant program objectives. The following advanced-technology components performed very successfully:

- Low Pressure-Ratio Fans
- Main Reduction Gearing
- Variable-Pitch Actuation Systems
- Composite Frame
- Composite Nacelle
- Digital Control
- Low-Emissions Combustor

As a general conclusion, the QCSEE program demonstrated that propulsion systems can be produced to meet the demanding short-haul requirements, including those for noise and pollution, without seriously compromising the economics of the transport system.

2.0 INTRODUCTION

The General Electric Company has recently completed the QCSEE program under Contract NAS3-18021. This program included the design, fabrication, and testing of two advanced turbofan propulsion systems intended to develop the technology that will be needed by powered-lift, short-haul-transport aircraft in the future.

2.1 BACKGROUND

The major problems facing the air transport industry in the early 1970's were noise and airport congestion. Noise had forced the closing of certain runways, the imposition of curfews at some airports, and the use of special flight restrictions such as reduced-throttle climb and low-altitude turns that were generally considered to be undesirable procedures. The congestion problem was manifested by traffic and parking problems, baggage-handling delays, and (especially in bad weather) long delays in departures and arrivals due to congested air space. Furthermore, air passenger traffic was increasing at a 7% annual rate, threatening to make these problems worse.

A solution to these problems was envisioned in the introduction of a separate, short-haul-transport system to cover the routes of 800 km (500 miles) or less. This system would utilize a fleet of new aircraft that would operate from smaller airports close to city centers and from auxiliary runways at the larger airports. A 610-m (2000-ft) runway capability was set as an objective, requiring that the aircraft incorporate some form of powered lift. Of the various suggested powered-lift concepts, two emerged as potentially attractive. These were the externally blown flap system used by Douglas in the YC-15 and the upper-surface-blowing concept used by Boeing in the YC-14.

Pre-QCSEE contracted studies were conducted to explore engine cycles and concepts. These studies resulted in the recommendation for very low fan pressure ratios and correspondingly high bypass ratios. They also indicated that a variable-pitch fan might be a practical means of providing reverse thrust, with less weight penalty than a conventional reverser, for a high-bypass engine. On the basis of these study results and other NASA test programs, the broad objectives and specific goals for the QCSEE program were established.

2.2 DESIGN APPROACH

Jet/flap interaction noise is a major contributor to the total noise signature of powered-lift aircraft. The under-the-wing installation results in direct impingement of the exhaust jet on the wing flap; the over-the-wing installation provides some noise shielding for the sideline observer. As shown in Figure 3, jet velocities were selected for each of the engines to keep this noise source about 3 dB below the total system noise for a balanced acoustic

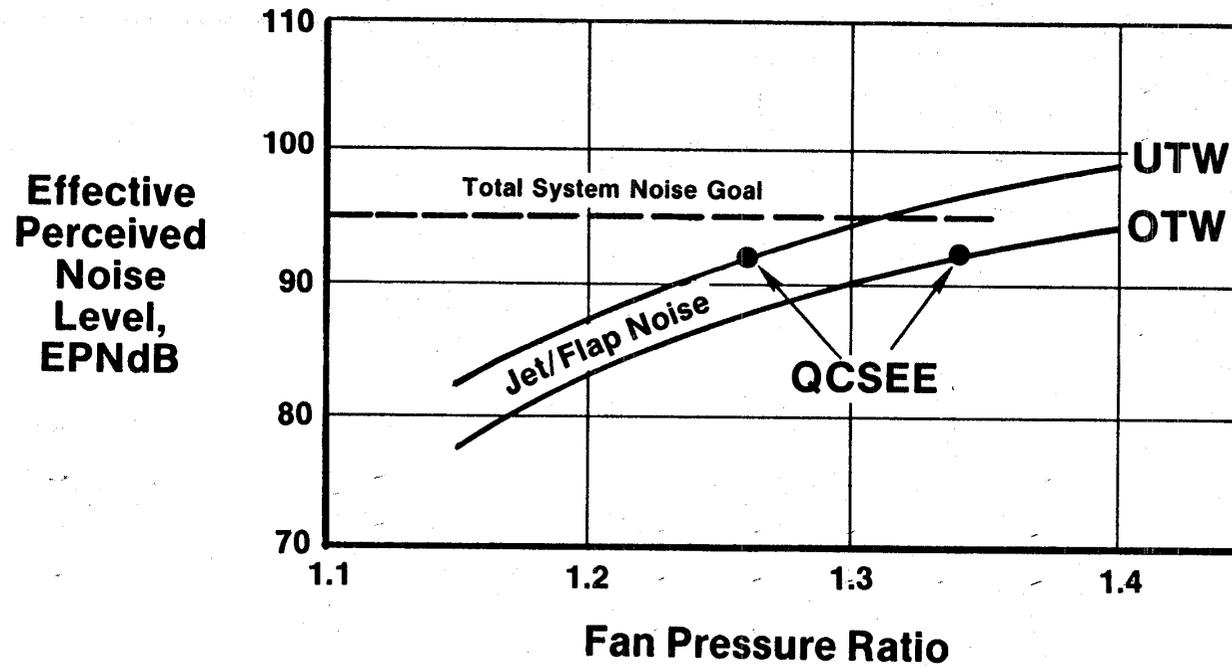


Figure 3. Effect of Jet Flap Noise on Fan Pressure Ratio Selection.

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design. A very low jet velocity (and very low fan pressure ratio) was required for the UTW engine. The low noise goal also dictated a low-tip-speed fan having reduced blade-passing frequency as well as careful selection of the numbers of fan blades and vanes and adequate spacing between them.

Forward-radiated noise was reduced by the use of a high throat Mach number inlet - shown in the drawing of the UTW propulsion system, Figure 4. Further suppression was added as needed by structural acoustic panels and by an acoustic splitter in the fan discharge duct.

Both QCSEE's incorporated the YF101 core to take advantage of its advanced state of development. The combustor used in this core was already smoke-free, but it did not meet the pollution objectives. A new double-annular combustor was conceived to fit into the same envelope and to reduce emissions. This design was a spin-off from the NASA Lewis Experimental Clean Combustor Program.

The need for a high thrust-to-weight ratio was addressed by the extensive use of graphite and Kevlar composites in the fan blades, frame, and nacelle. This permitted the nacelle wall to be made integral with the engine, combining two structures into one. For example, the outer casing of the fan frame functions as the engine outer flowpath as well as a portion of the external nacelle.

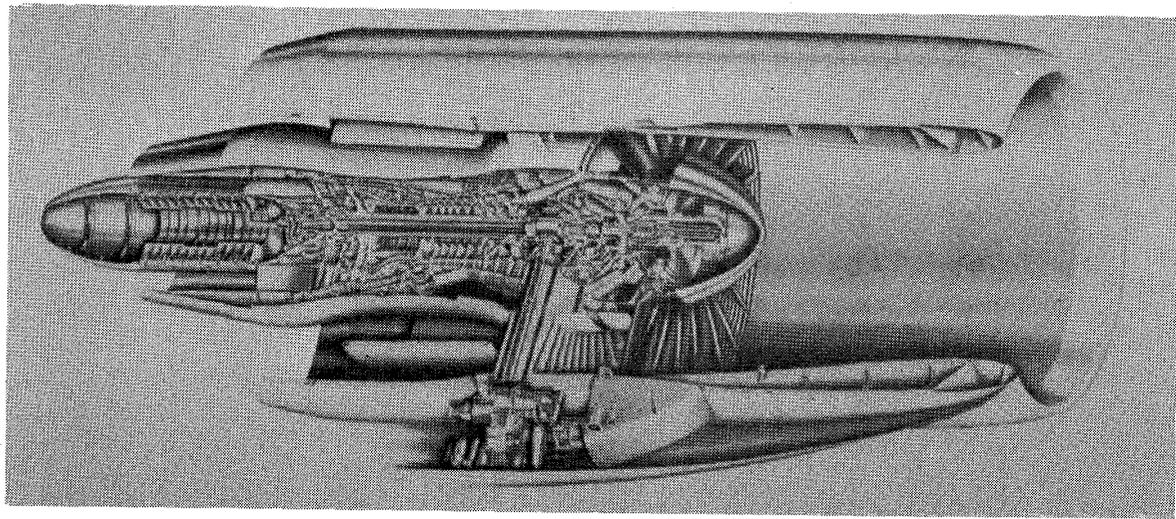
Short-haul aircraft tend to require fairly high thrust-lapse rates so that the engines can operate near the bottom of the sfc bucket at moderate cruise altitude. Low-pressure-ratio fans inherently have this characteristic. The best efficiency for low-pressure-ratio fans occurs at relatively low fan-tip speeds. A variable-area fan-exhaust nozzle was necessary to keep the fan pressure ratio from dropping too low at cruise, with detrimental effects on sfc, and to provide sufficient altitude thrust. Though high lapse rate is needed for STOL aircraft, the very low pressure ratio fans used for low noise have an even higher lapse rate than desired.

Another characteristic needed to achieve low sfc levels is a high cycle pressure ratio. Selection of the YF101 core was made for reasons of program cost and risk and the appropriately advanced technology level. The use of a low-pressure-ratio fan with this core resulted in an overall cycle pressure ratio lower than desired. A more optimum cycle could have been produced by adding booster stages to the fan or by increasing the pressure ratio of the core, but this technology is already well in hand and was not considered to be worth the added program cost.

The short-takeoff requirement implies a short landing and an effective thrust reverser. The low-pressure-ratio UTW cycle lends itself to a reverse-pitch fan that can provide reverse thrust without heavy, variable-geometry, nacelle components.

A digital control was required to permit optimum coordinated control of the variable-pitch fan, the variable nozzle, and the core engine with acceptable pilot work load. Numerous other functions were also provided such as

Figure 4. UTW Propulsion System.



maintenance of safety limits and condition-monitoring functions. Top-mounted accessories were used on the UTW engine to permit lower weight, better maintainability, and low drag.

The OTW engine is shown in Figure 5. It required a "D" shaped exhaust nozzle to turn the flow downward and spread it over the wing and flap. Area control was provided by variable side doors. Since this engine has a fixed-pitch fan, thrust reversal is provided by pivoting the roof of the nozzle to form a target-type reverser blocker.

System studies conducted by McDonnell-Douglas and Boeing helped direct the engine-design activity. Baseline UTW and OTW aircraft designs were established to identify propulsion and installation requirements. Economic studies were conducted to assess the payoff of the new engine technologies. American Airlines contributed requirements for the aircraft and an operational scenario for the short-route structure. They were also consulted on maintenance features, mechanical design, and reliability.

Figure 6 shows the baseline aircraft projected by Douglas using the UTW engine. It would employ four QCSEE's mounted under the wing and is based on the Douglas YC-15 technology. The major characteristics are listed on the figure.

Figure 7 shows the baseline aircraft projected by Boeing using the OTW engine. It is somewhat larger, taking advantage of the greater thrust of four OTW engines, and is based on technology developed for the YC-14. The two aircraft were shown to be very competitive for short-haul operation.

These studies reached the conclusion that the 610-m (2000-ft) runway requirement was too stringent; 915 m (3000 feet) is more realistic based on projected airport availability. Another significant result was recognition that, in both installations, the engines would be mounted so high that a work stand would be required for all maintenance operations regardless of accessory location. This fact permitted the engine and aircraft accessories to be mounted in the pylon area to reduce nacelle drag for both installations and allow shorter, more direct, service lines from the wing.

The above approach resulted in the specific engine designs described in the next section of this report.

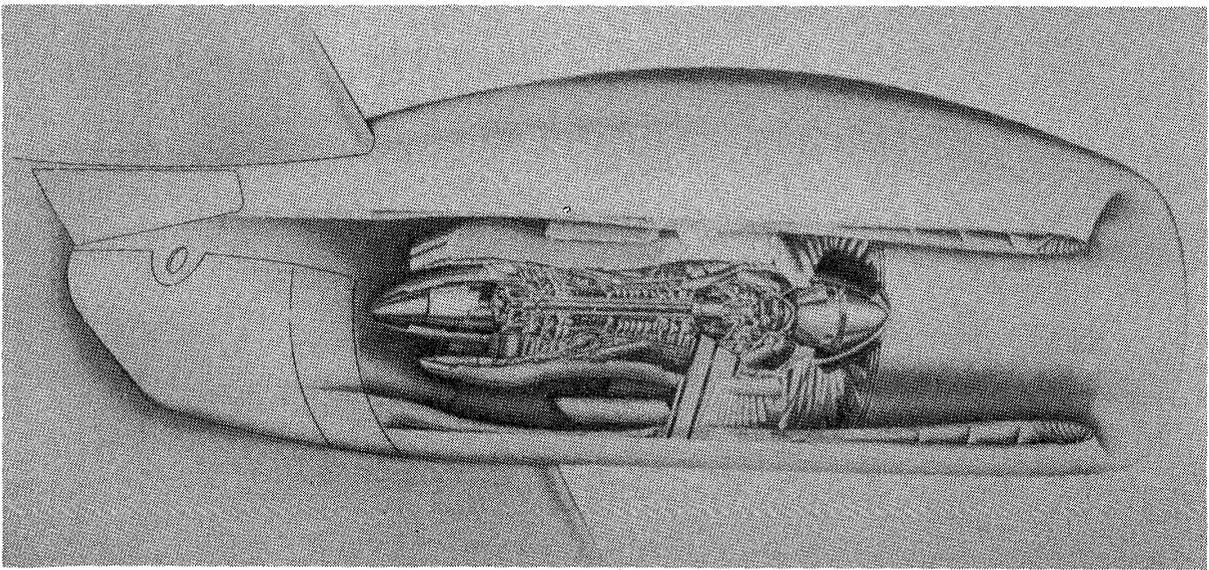


Figure 5. OTW Propulsion System.

70,620 kg (155,700 lb) TOGW
926 km (500 n.mi.) Range
162 Passengers
914.4 m (3000 ft) Runway
4 Engines @ 81,400N (18,300 lb) Thrust

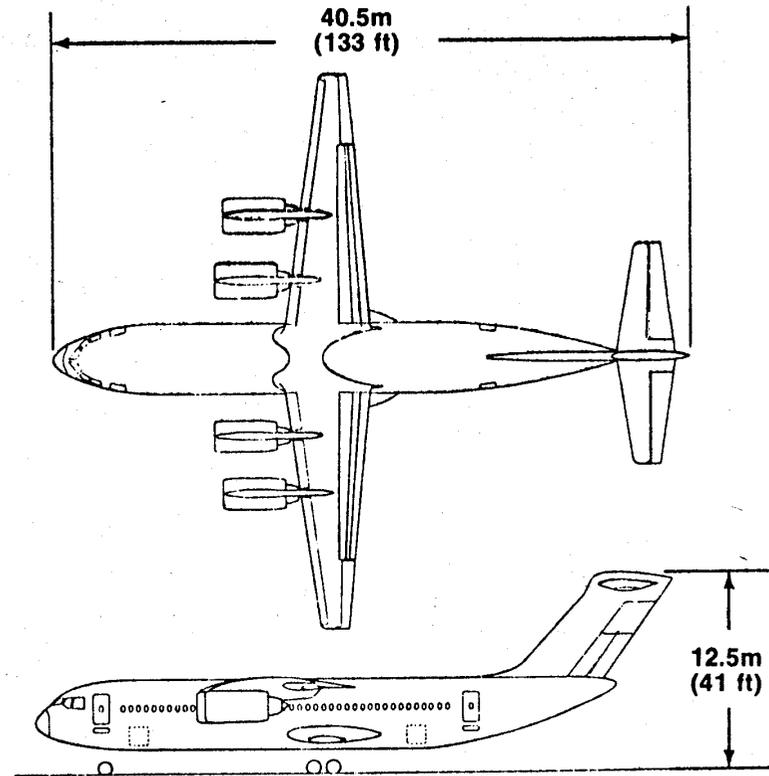
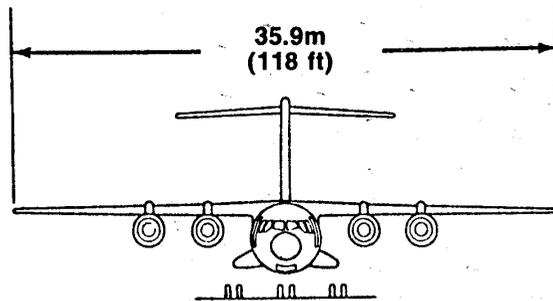


Figure 6. Baseline UTW Aircraft.

90,040 kg (198,500 lb) TOGW
926 km (500 n.mi.) Range
197 Passengers
914.4 m (3000 ft) Runway
4 Engines @ 93,408 N (21,000 lb) Thrust

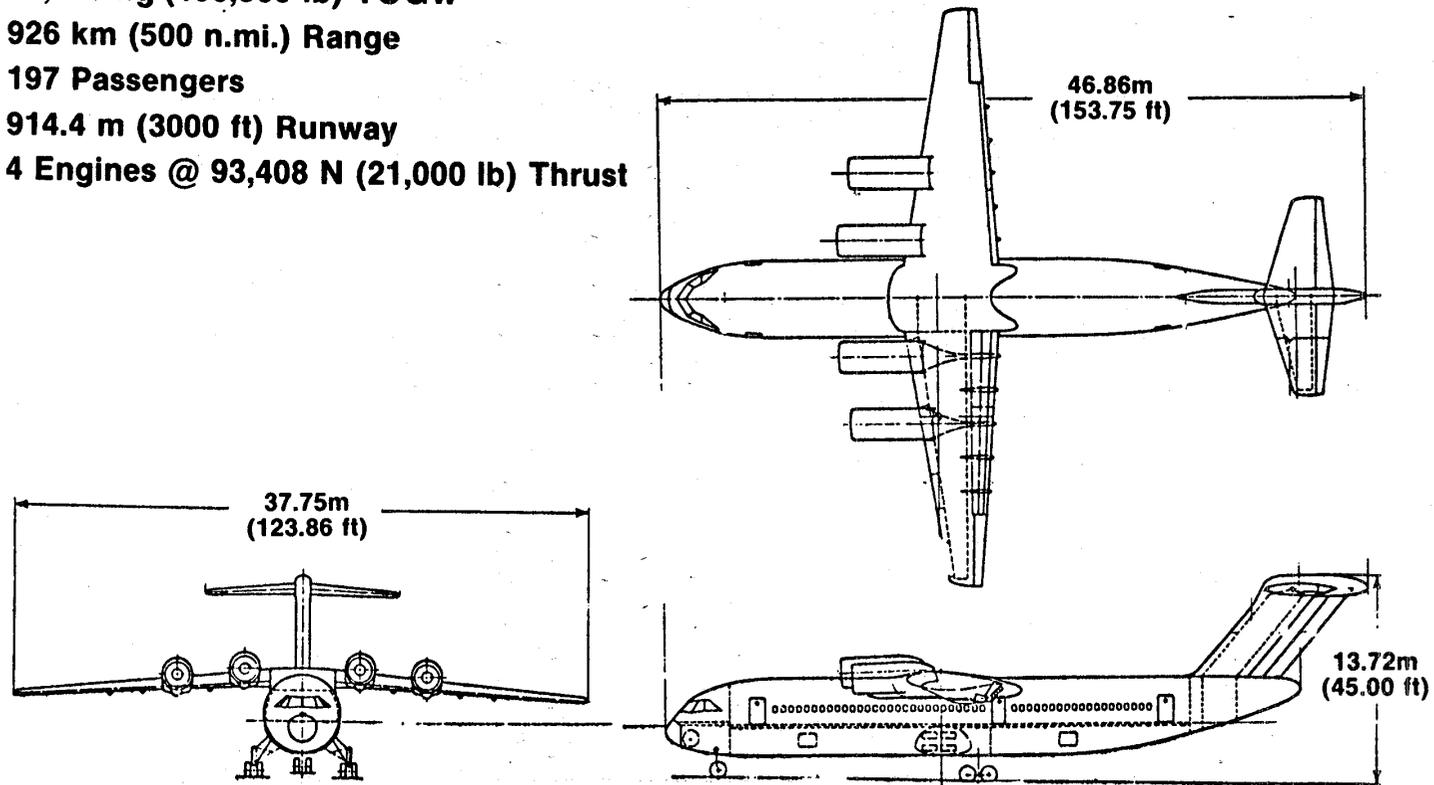


Figure 7. Baseline OTW Aircraft.

3.0 ENGINE DESIGN

This section will describe overall design of the UTW and OTW engines with particular emphasis on the advanced-technology components. Results of component testing are also included where they contributed to the final engine design.

3.1 OVERALL ENGINE DESCRIPTION

Details of the UTW engine can be seen in Figure 8. The inlet, fan blades, fan frame, fan outer duct, and fan variable nozzle are all made of graphite or Kevlar with an epoxy matrix. The fan inner duct is made of graphite with NASA-developed PMR polyimide resin for higher temperature operation. Acoustic treatment is used in the inlet, fan frame, core inlet duct, fan exhaust duct and splitter, and core exhaust nozzle. The latter includes a two-level acoustic absorber for high and low frequencies. A two-stage F101 power turbine drives a star-type, epicyclic, main reduction gear. The reduction gear was designed and developed by Curtiss-Wright Corporation. The fan nozzle is shown in the cruise position. It opens part way for takeoff and approach and further for reverse, where it functions as an inlet.

Recognizing the critical nature of the blade pitch-control system, many concepts were studied, and two variable-pitch systems were built and tested. A cam/harmonic-drive design was supplied by Hamilton Standard, and a ball spline system by General Electric. Both systems were whirl tested prior to use in a QCSEE to verify the ability to position the blades under centrifugal loading.

The major design parameters of the UTW engine are listed in Table III. The low fan-tip speed, used in conjunction with a 2.5-reduction gear ratio, permitted the use of a conventional high-speed, low-pressure turbine. The low fan pressure ratio resulted in a very low jet velocity and helped meet the acoustic requirement discussed earlier. Note the high bypass ratio made possible by the energetic core and the low-pressure-ratio fan.

A cross section of the OTW engine is shown in Figure 9. All nacelle components were of boilerplate construction for reasons of cost and to allow the evaluation of interchangeable acoustic panels. The fan uses fixed-pitch, titanium blades; the geometry would allow substitution of composite materials. The "D" shaped exhaust nozzle was tested in an inverted position so that the exhaust was directed downward in reverse-thrust mode, away from the test facility and instrumentation lines.

Major design parameters of the OTW engine are listed in Table IV. The tip diameter and airflow are identical to those of the UTW engine to permit the same inlets and fan frames to be used. A somewhat higher fan-tip speed is used to achieve the higher allowable exhaust velocity and fan pressure ratio with resultant higher overall pressure ratio and lower bypass ratio.

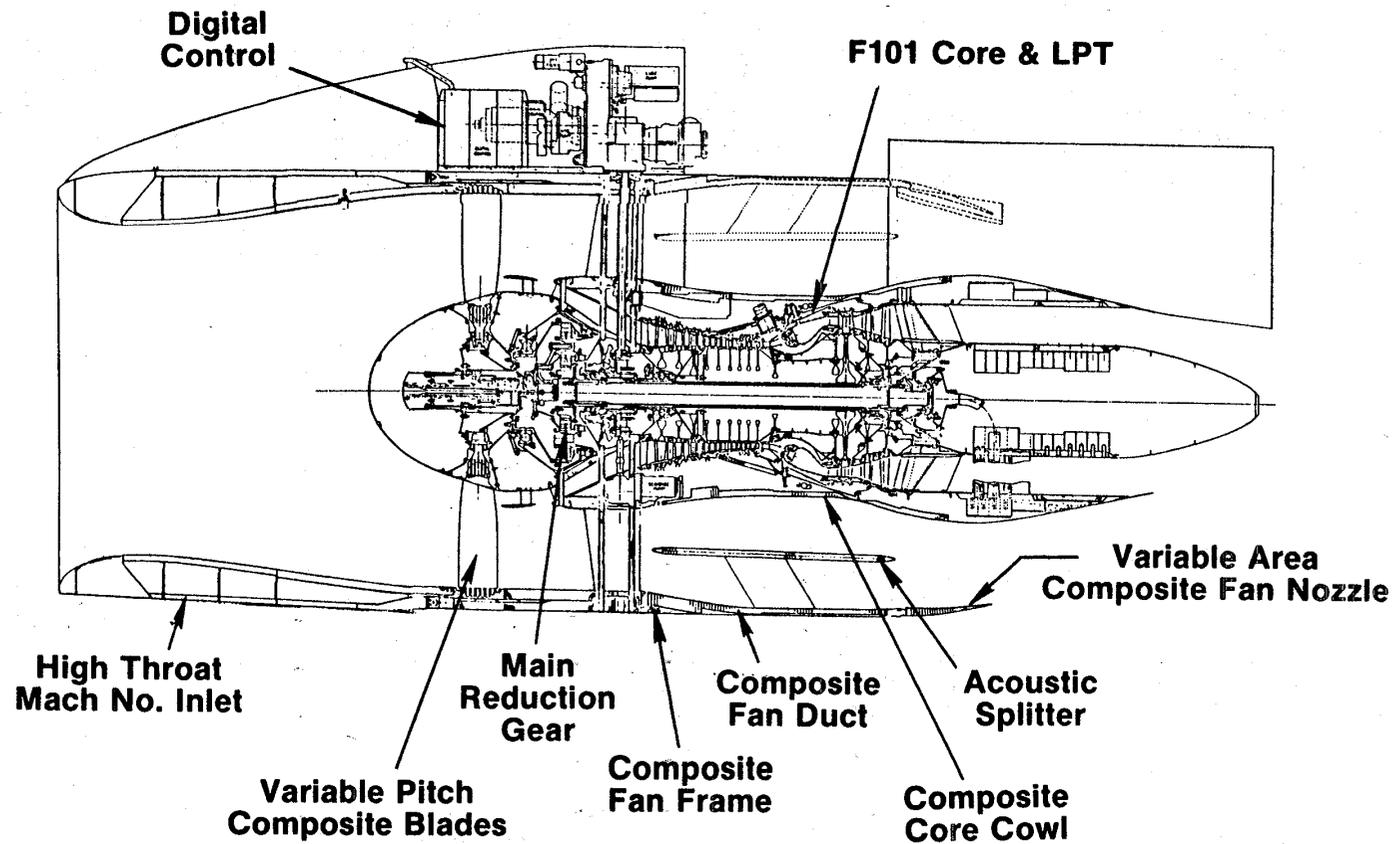


Figure 8. UTW Engine Cross Section.

Table III. UTW Design Parameters.

Total Airflow, kg/s (lb/sec)	_____	405.5 (894)
Fan Tip Diameter, cm (in.)	_____	180.3 (71)
Fan Tip Speed, m/s (ft/sec)	_____	289.6 (950)
Bypass Ratio	_____	11.8
Fan Pressure Ratio	_____	1.27
Overall Pressure Ratio	_____	13.7
Jet Velocity (Core), m/s (ft/sec)	_____	244.7 (803)
Jet Velocity (Bypass), m/s	_____	204.2 (670)
Gear Ratio	_____	2.5

Table IV. OTW Design Parameters.

Total Airflow, kg/s (lb/sec)	_____	405.5 (894)
Fan Tip Diameter, cm (in.)	_____	180.3 (71)
Fan Tip Speed, m/s (ft/sec)	_____	350.5 (1150)
Bypass Ratio	_____	10.2
Fan Pressure Ratio	_____	1.34
Overall Pressure Ratio	_____	17.0
Jet Velocity (Core), m/s (ft/sec)	_____	} Mixed 239.9 (787)
Jet Velocity (Bypass)	_____	
Gear Ratio	_____	2.1

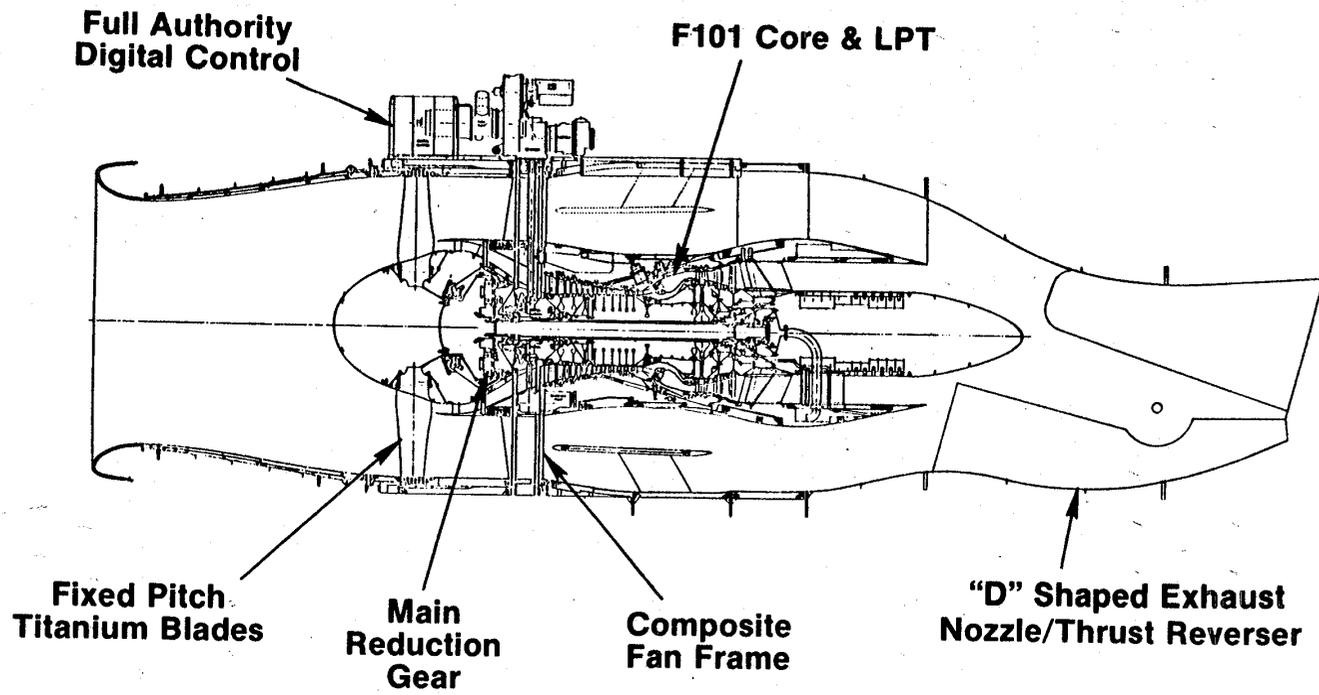


Figure 9. OTW Engine Cross Section.

Hub pressure rise is higher than outer panel pressure rise to permit better supercharging.

An electronic control system was designed, for both engines, to provide a digital interface with an aircraft on-board computer. The control accepts a percent-rated-thrust command. Several safety limits are automatically maintained including a calculated maximum temperature. Numerous provisions in the control are included to reduce the pilot work load. Inlet Mach number is automatically maintained at 0.8 consistent with acoustic requirements. Rapid thrust response is achieved via automatic blade and nozzle-area variations with minimum required fan- and core-speed variations. In the OTW engine, fuel flow and compressor stator vane angles are automatically adjusted to provide maximum rate of thrust change with minimum required core speed change. Automatic restructuring of the control computer is provided via Kalman-Bucy filtering techniques to permit operation with failed sensors.

Forty-eight items of condition-monitoring information are provided to the aircraft computer by a digital data bus. The control is engine mounted, cooled by fan-inlet-induced airflow, and designed to be compatible with the engine environment.

3.2 FAN AERODYNAMICS

Two different fans were designed for the QCSEE program; each was tailored to a particular engine cycle and operational requirements. The reversible-pitch fan for the under-the-wing engine is described first; aerodynamic design and scale-model test results are presented. The design of the fixed-pitch fan for the over-the-wing engine is described in the second subsection.

3.2.1 UTW Fan Aerodynamics

Aerodynamic Design - A cross section of the fan for the UTW engine is shown Figure 10. One of the notable features of this fan is the low-aspect-ratio, unshrouded, composite rotor. The low tip-speed rotor blades are attached to a variable-pitch mechanism and are fully reversible through either flat pitch or stall pitch. The flowpath over the rotor tip is a portion of a sphere to avoid changes in tip clearance as the rotor pitch varies. Circumferential-groove casing treatment is used over the rotor tip to increase stall margin at cruise with little or no efficiency penalty.

Another notable feature of the design is the unusual arrangement of the fan stators. The inner stator vane is placed under a ring-shaped island, closely coupled to the fan rotor, which serves as the primary splitter dividing the bypass flow from flow to the core engine. An annular slot is left open aft of this assembly, and a second flow splitter is provided at the rear of the slot for use during reverse operation. The split-stator arrangement was chosen over more conventional alternatives, such as a full-span stator, because it reduces the length required from fan rotor to core compressor inlet, and because it allows the full loading potential of the rotor hub to be

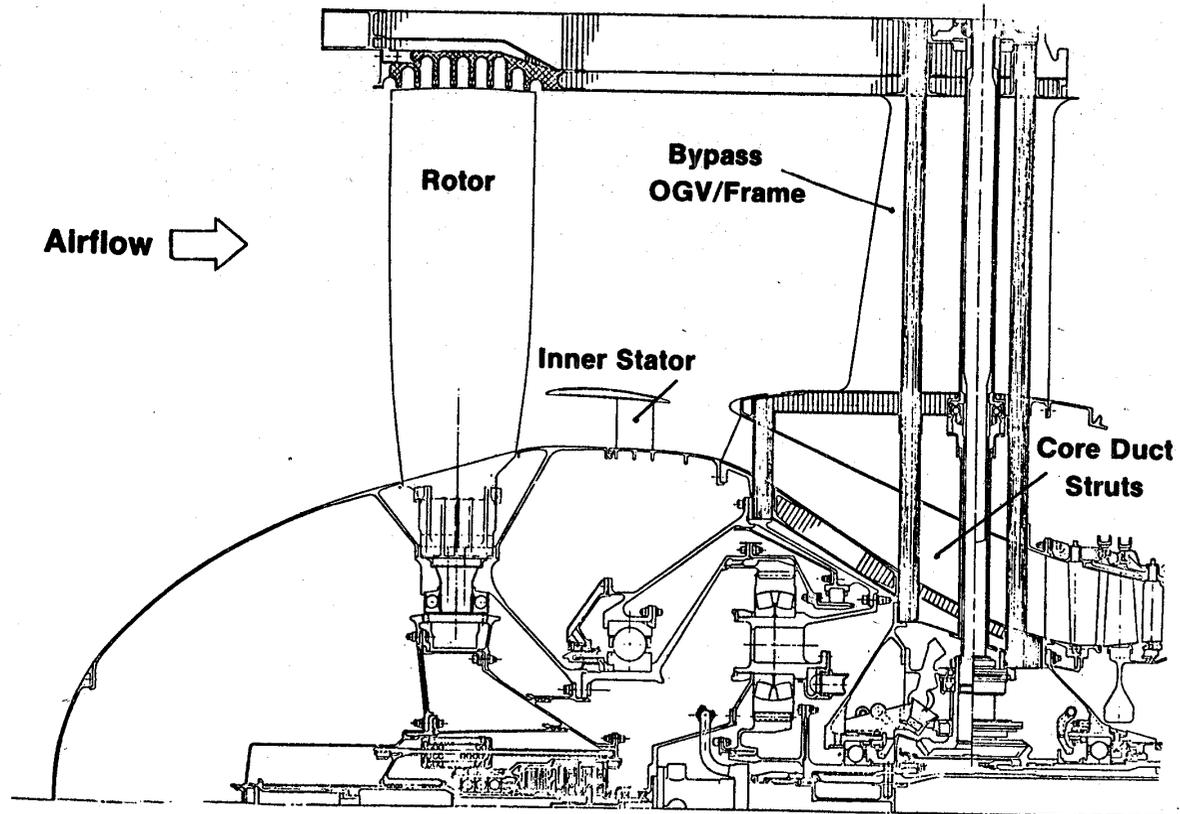


Figure 10. UTW Fan Cross Section.

used without incurring high stator hub Mach numbers or loadings. The close-coupled splitter and inner stator arrangement by itself is unsatisfactory for reverse operation because flow drawn backwards through the bypass outlet guide vanes and entering the core engine would impinge upon the highly cambered inner stators at incidence angles of perhaps minus 70° . The annular slot is provided to allow air to be drawn directly into the core engine in reverse operation - significantly improving the pressure recovery of the core flow.

The bypass outlet guide vanes serve as structural elements in the fan frame. The pylon nose is integrated into the vane/frame, and circumferentially varying airfoil geometry is used to guide the flow smoothly around the pylon. A wide spacing between the fan rotor and the bypass vane/frame is used to reduce noise.

Key operating points for the UTW fan are indicated on the portion of the predicted-performance map shown in Figure 11. The takeoff point was selected to be on a low operating line, at a bypass stream pressure ratio of 1.27, to keep jet velocity low for reduced noise. The engine inlet was sized at this point to have a high throat Mach number of 0.79 to reduce forward-radiated fan noise. The maximum cruise point pressure ratio of 1.38 is on a higher operating line, reached by closing the variable exhaust nozzle, to increase thrust at altitude. The corrected airflow at cruise was limited to the takeoff value because inlet losses would become unacceptable if the inlet-throat Mach number increased. The aerodynamic design point of the fan was chosen to be on an intermediate operating line.

Some advantages of the variable-pitch rotor for forward-mode operation are shown in Figure 12. The dashed speedlines indicate how fan flow at a given speed could be varied by changing rotor pitch. At the takeoff condition it was estimated that the fan speed required to achieve the objective flow and pressure ratio could be reduced approximately 3% by opening the rotor pitch 2° . This could result in a worthwhile reduction in noise. At cruise, the speed could be increased several percent by closing the rotor pitch 2° to increase fan stall margin and also to reduce the low pressure turbine loading - thereby increasing its efficiency. Variable pitch could thus allow the trends of fan efficiency versus speed and pitch angle, and of turbine efficiency versus speed and loading, to be exploited to seek a minimum level of fuel consumption at cruise.

A summary of fan aerodynamic design parameters is given in Table V. The low tip speed, 306 m/sec (1005 ft/sec), and the high bypass ratio, 11.3, are notable features. Also notable is the low solidity of the fan rotor; the solidity was less than 1.0 across the full span of the blade to permit the blades to be reversed.

A photograph of the full-scale UTW fan rotor is shown in Figure 13. The black color of the blades is a result of the graphite-epoxy material used; the metal strip on the leading edge is for erosion resistance. The low aspect ratio and low solidity of the blades are apparent in this photo. Part of the variable-pitch mechanism can be seen in the hub of the fan.

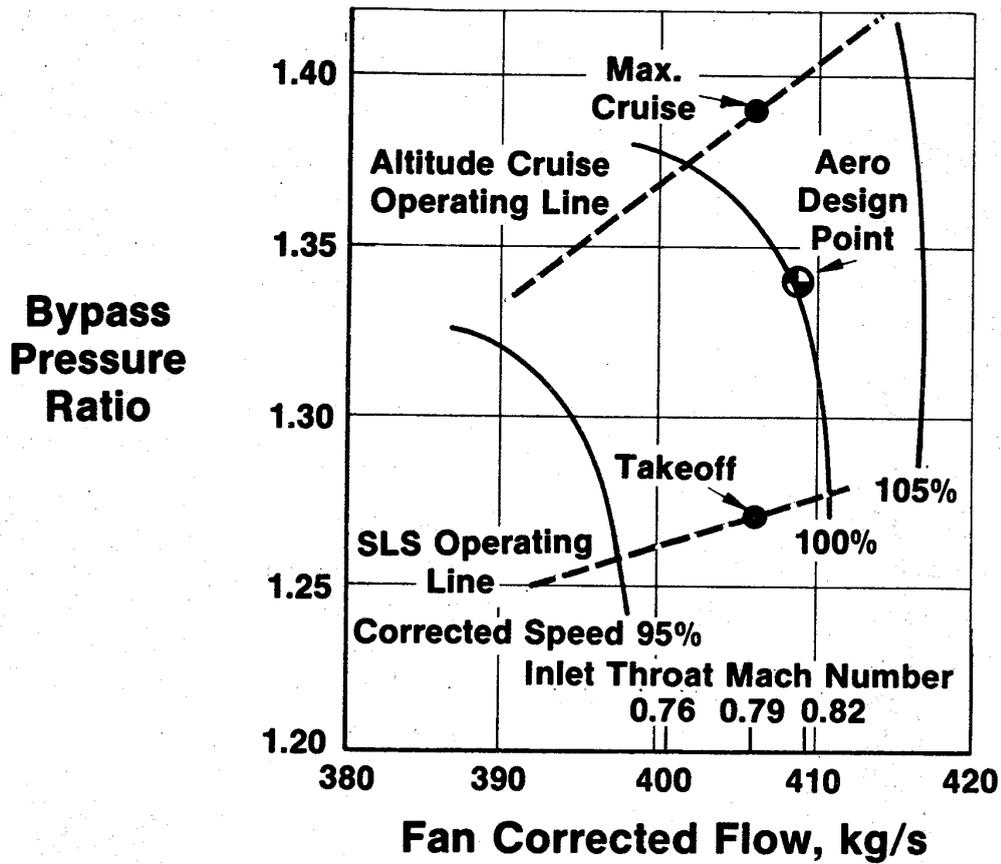


Figure 11. UTW Variable-Pitch Fan Design Map.

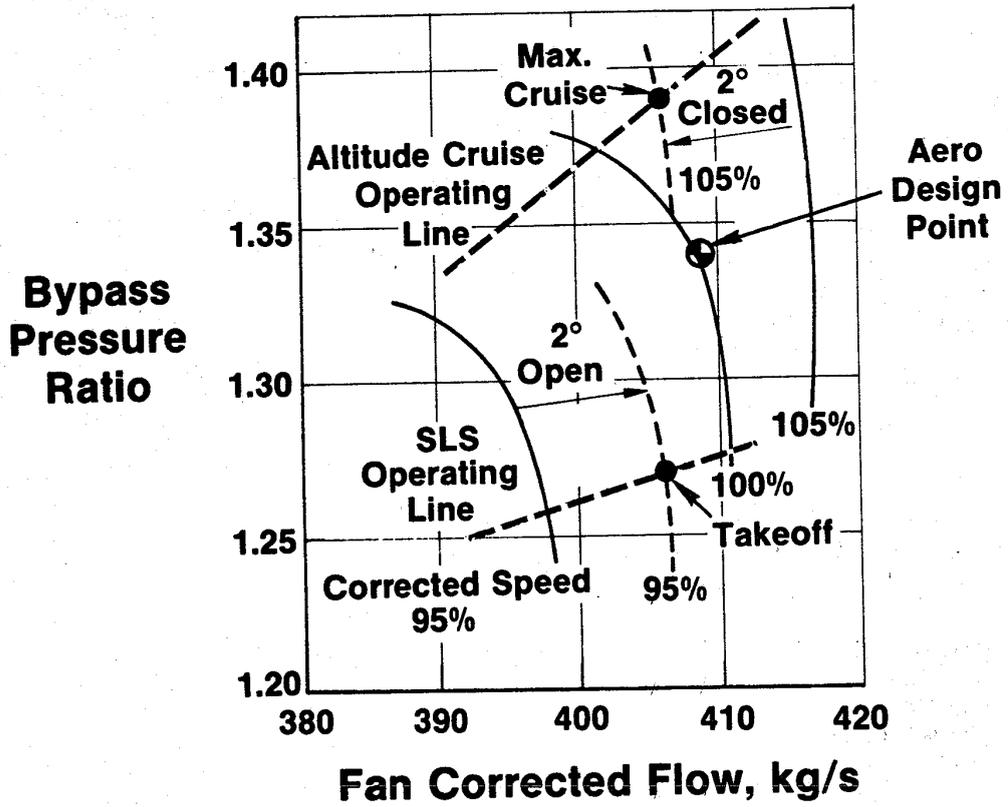


Figure 12. UTW Variable-Pitch Fan Design Map.

Table V. UTW Fan Aerodynamic Design Features.

Tip Speed	306 m/s (1005 ft/sec)
Radius Ratio	0.44
Specific Flow	199 kg/sec-m² (40.8 lbm/sec-ft²)
Bypass Pressure Ratio	1.34
Core Pressure Ratio	1.23
Bypass Ratio	11.3
Inlet Tip Relative Mach No.	1.13
Rotor Tip Solidity	0.95
Rotor Hub Solidity	0.98
Rotor Aspect Ratio	2.1
Number of Blades	18
Number of OGV's/Inner Stators	33/96

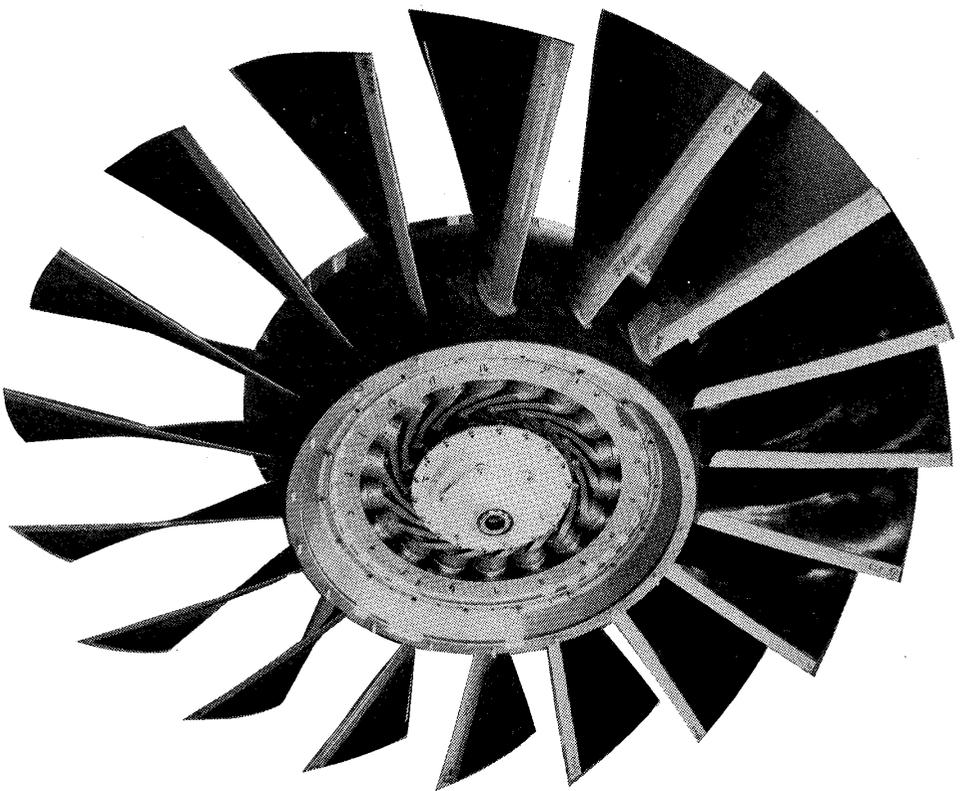


Figure 13. UTW Pan Rotor.

A section through the bypass vane/frame is shown in Figure 14. Each of the 33 low-aspect-ratio vanes is a structural member made of composite material. The pylon extends forward to the leading edge of the vane row and contains the accessory drive shaft. The leading edge of the pylon nose is a cambered airfoil shaped to properly align with the approaching flow. Five different types of airfoils, each with its own unique camber and stagger, are used to divert the flow smoothly around the pylon. Two of the five types of airfoils are shown. A nonstandard vane spacing is used on the left side, or suction surface, of the pylon nose to help reduce a local high-back-pressure region to avoid potential performance losses or noise sources.

The generation of reverse thrust by changing the rotor pitch is illustrated in the next series of figures. A top view of the rotor at nominal design pitch angle in forward-mode operation is shown in Figure 15 for reference. Airflow approaches the rotor axially because there are no inlet guide vanes to impart swirl. Hub, pitch-line, and tip blade sections are shown to illustrate the twist required to keep the blade aligned with the relative flow direction.

As shown in Figure 16, when the blade is reversed through flat pitch the blade is closed some 70° to 90° . During closure, the normal forward flow drops smoothly to zero, then reverse flow is gradually established. In reverse, flow is drawn backward through the bypass vane/frame, and the absolute flow vector is given swirl opposite to the direction of rotor rotation. The twist of the blade is in the wrong sense in reverse mode; flow through the hub is blocked off by the rotor, and only the tip section pumps air out the inlet duct. It can also be seen that blade camber is in the wrong sense when the blade is reversed through flat pitch since the flow is deflected away from the axial direction. In order to pump air despite the reverse camber, the blade must operate at a high incidence angle; therefore, it is expected that the pumping ability and the efficiency of the fan will be relatively low when reversed through flat pitch.

Blade orientation when reversed through stall is shown in Figure 17. In this case the blade is opened 95° to 105° . Initially a stall takes place; after further opening, normal airflow ceases and reverse flow becomes established. The trailing edge of the rotor becomes the effective leading edge during reverse-through-stall-pitch operation. Although rotor twist is still in the wrong sense, and the flow is still blocked at the hub, the camber is now in the proper direction for a compressor blade. It is thus expected that pumping and efficiency will be highest when the rotor is reversed through stall.

Scale Model Test Results - A 50.8-cm (20-in.) diameter model, 0.282 linear scale factor, of the UTW fan was built for aeroperformance and acoustic testing. A photograph of the scale-model fan is shown in Figure 18. Adjustable metal blades were used for the test rig. These could be fixed at any pitch angle but could not be varied while running. Tests were conducted both in forward and in reverse operating modes at several pitch angles in each mode.

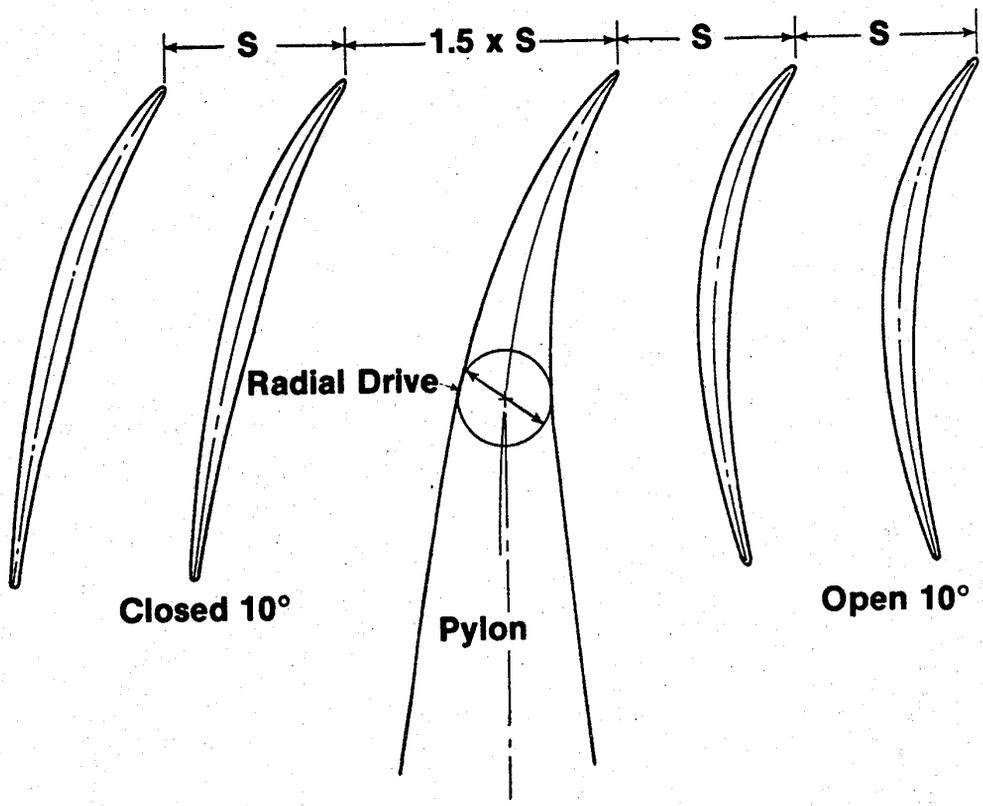


Figure 14. UTW Fan Bypass OGV Design.

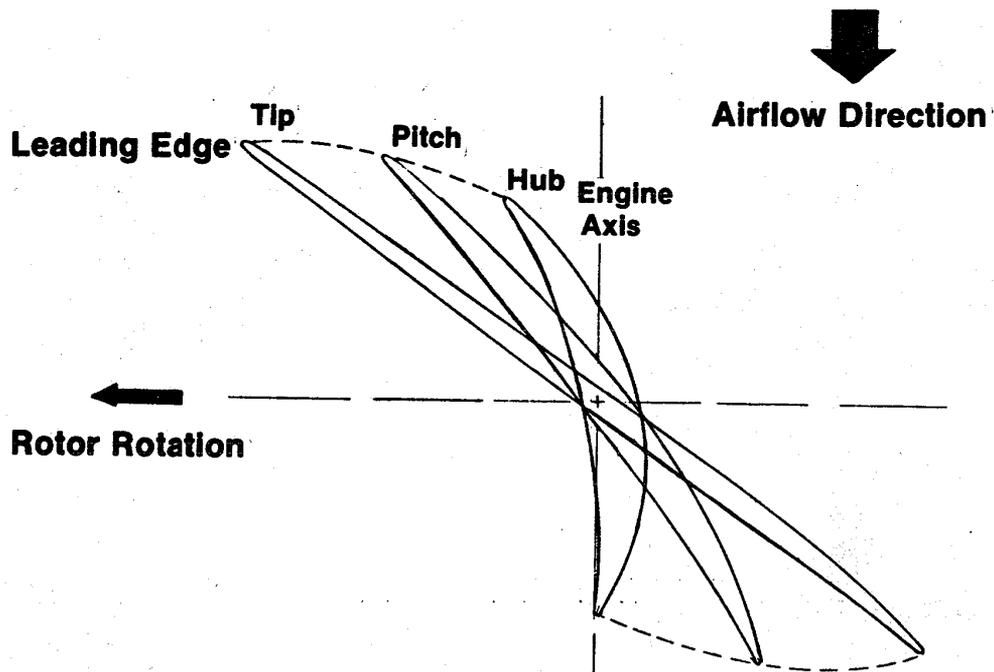


Figure 15. UTW Fan Rotor Blade; Forward-Mode Operation.

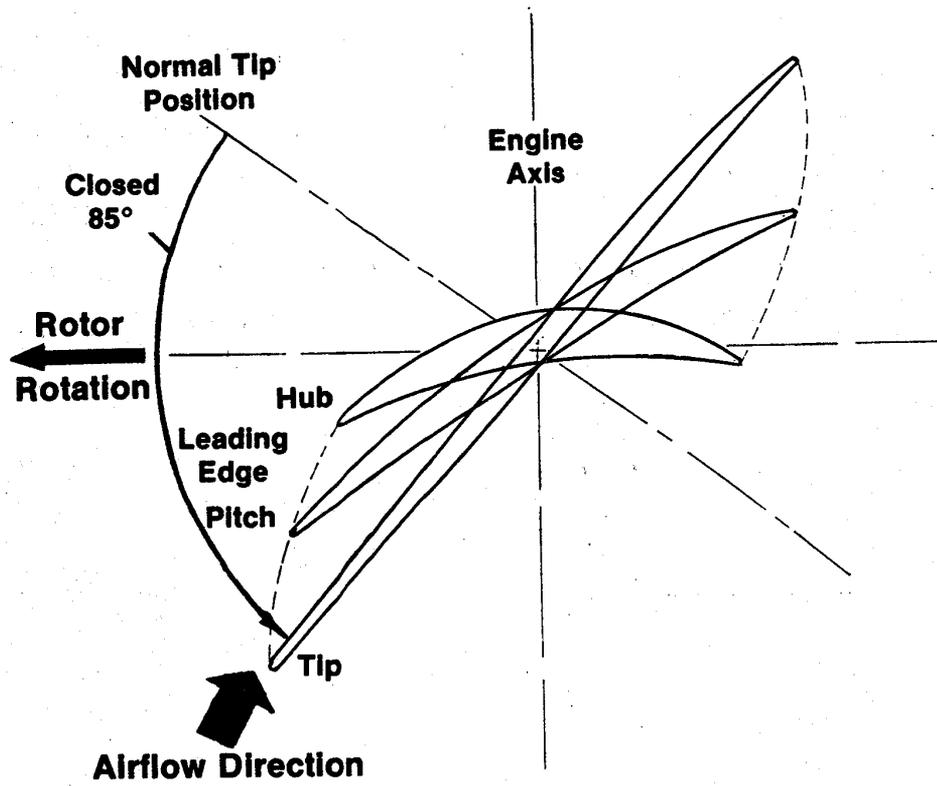


Figure 16. UTW Fan Rotor Blade; Reverse Through Flat Pitch Operation.

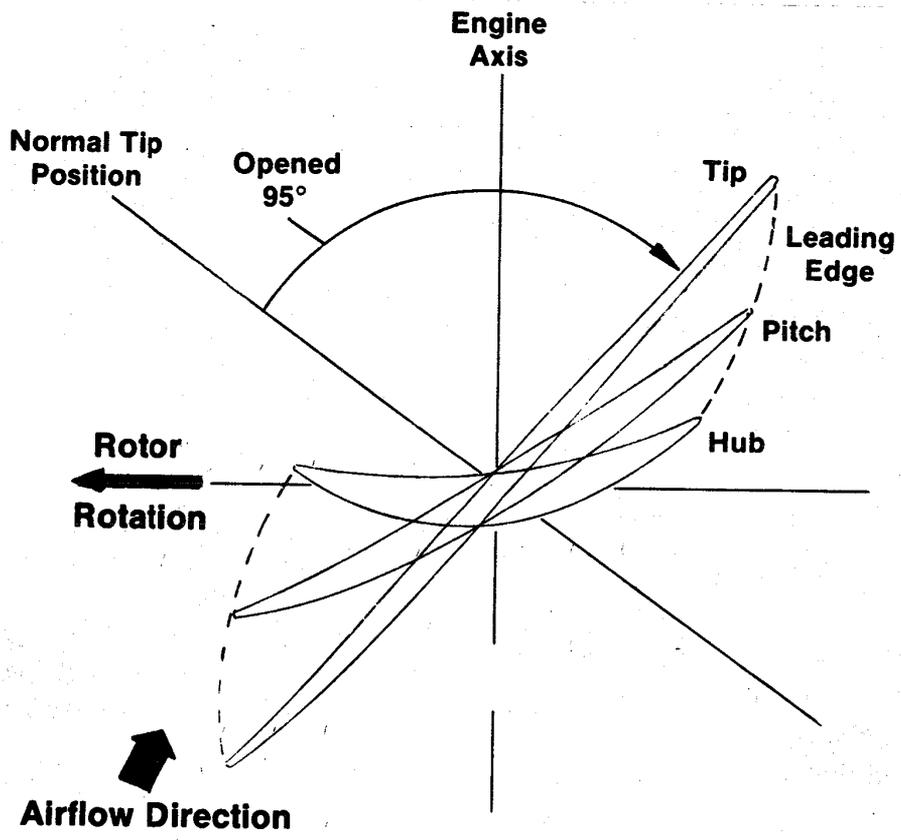


Figure 17. UTW Fan Rotor Blade; Reverse Through Stall Operation.

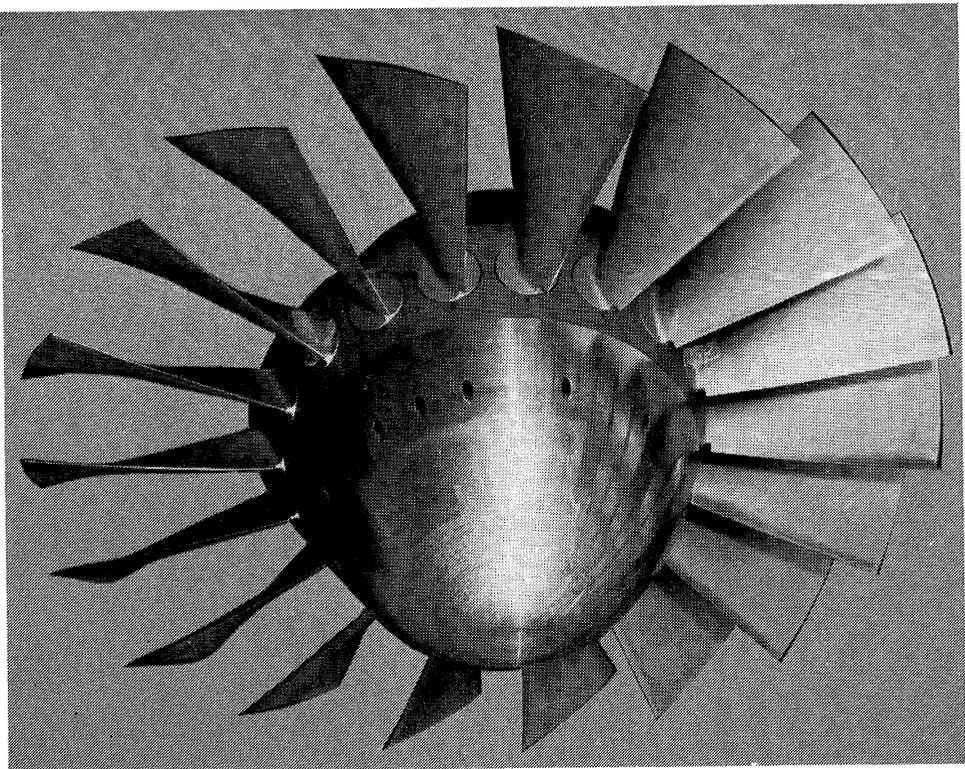


Figure 18. UTW Scale-Model Fan.

A performance map for the bypass portion of the fan flow in forward-mode operation at the nominal design rotor pitch angle is shown in Figure 19. The design pressure ratio, flow, and efficiency are indicated by the target symbols, and the objective stall line is shown dotted. Performance maps similar to the one shown were also obtained at 5° open and 5° closed rotor-pitch-angle settings. Test results indicated that stall margin goals and the design-point efficiency goal of 86.5% had been met. At 100% speed the design flow was achieved at low operating lines, but flow and pressure ratio were below objectives on an operating line through the design point. Analysis indicated that the rotor blade-tip sections lacked circulation capacity at higher loadings. A redesign to increase rotor camber would have increased the pumping of the fan on the design operating line, but (because of the low solidity) this might have reduced efficiency by opening the throat areas. For this reason, and because of a tight fabrication schedule, it was decided that the blades for the full-scale engine would not be redesigned.

The 95% speed lines obtained at the three pitch angles are shown in Figure 20. This is the fan speed at which takeoff thrust was to be obtained in the demonstrator engine; the objective takeoff flow, pressure ratio, and efficiency are indicated in the figure by solid symbols. Despite the lower-than-design pumping capacity, the flexibility of the variable-rotor-pitch feature enabled the fan to meet the very important flow and pressure-ratio goals of the engine system at takeoff simply by opening the rotor 3° from nominal instead of 2° as originally estimated.

Fan hub performance measured during scale-model tests at 100% design corrected speed, for the three rotor pitch angles, is shown in Figure 21. Design hub pressure ratio was nearly achieved at design flow with the nominal design pitch angle. The 78% hub efficiency goal was met at the design operating line and was exceeded by a substantial margin at higher operating lines.

Reverse-mode test results from the fan scale-model program are shown in Figure 22. Fan pressure ratio from the OGV exit to the engine inlet throat is plotted versus rotor corrected flow for five different reverse-pitch angle settings: closed through flat pitch to 73° and 79°; and opened through stall pitch to 95°, 100°, and 105°. The data points for a given pitch angle represent different speeds. Only a single operating line could be evaluated at each pitch angle since the engine inlet (which serves as the exhaust nozzle in reverse-mode operation) was a fixed-geometry device. The various combinations of flow and pressure ratio needed to achieve the reverse-thrust objective of 35% of takeoff thrust are indicated by the heavy, dark band. Although the reverse-thrust goal could not be met when reversing through flat pitch, because of speed limits or high rotor stresses, the reverse-thrust objective was met for all three of the reverse-through-stall-pitch angles tested.

3.2.2 OTW Fan Aerodynamics

A cross section of the fan for the OTW engine is shown in Figure 23. The OTW fan has a conventional, fixed-pitch rotor and has a higher tip speed, a

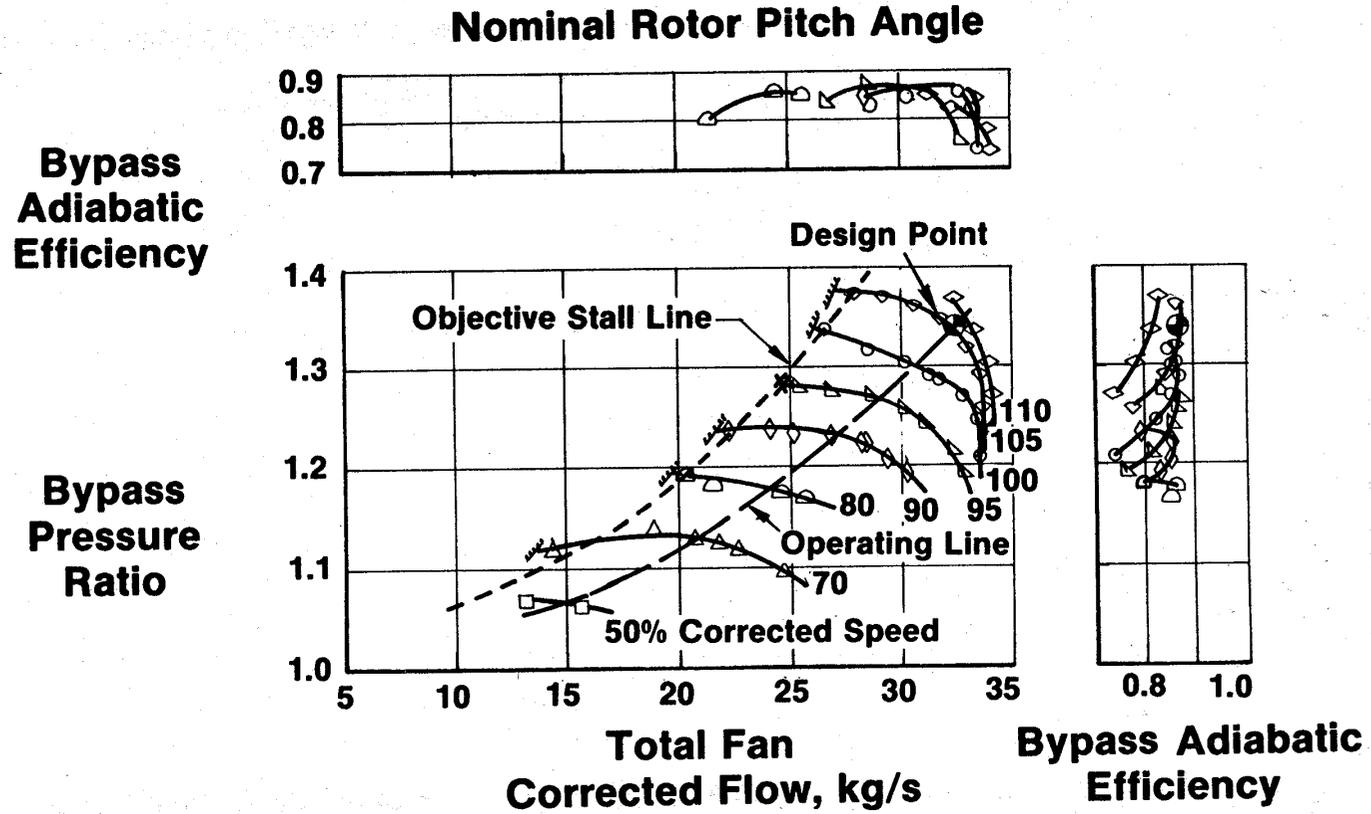


Figure 19. UTW Fan, Scale-Model, Bypass Performance.

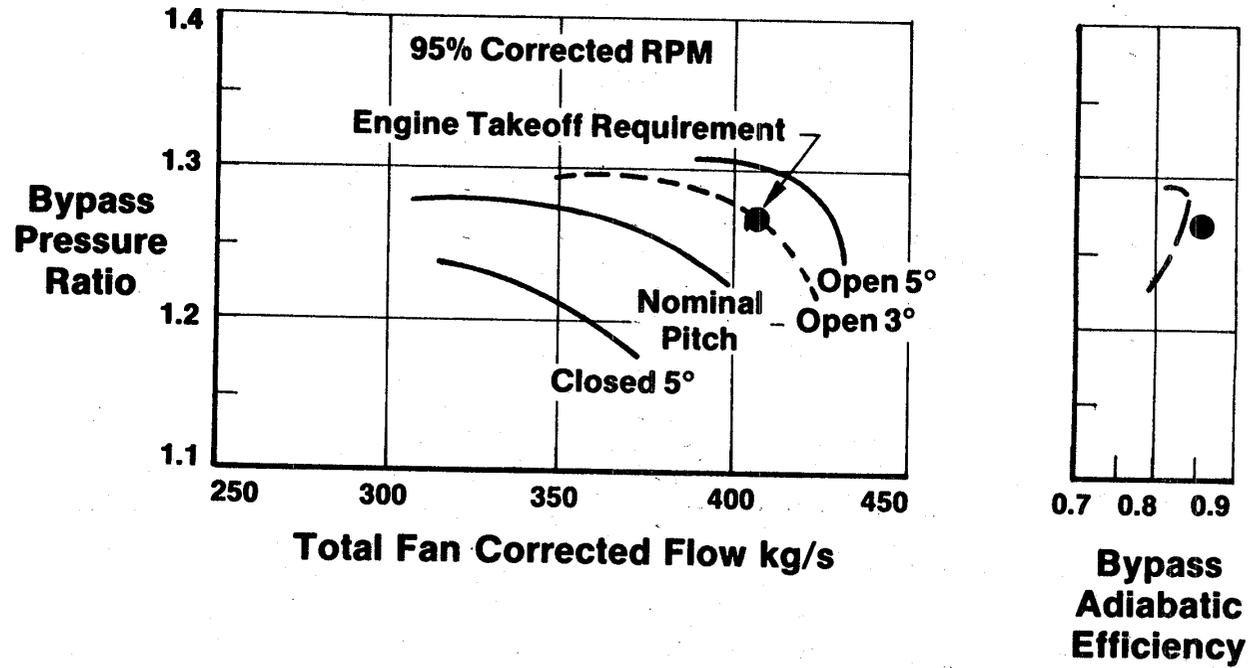


Figure 20. UTW Fan Takeoff Operation Scaled from Model Data.

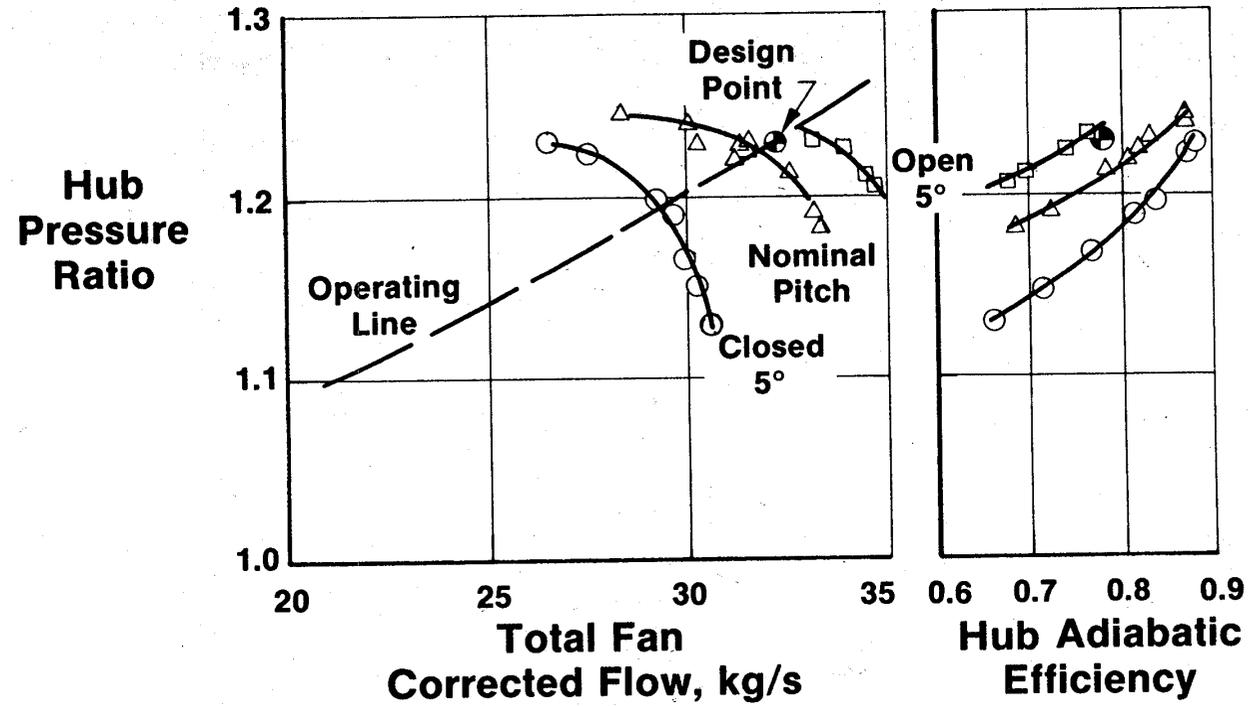


Figure 21. UTW Fan, Scale-Model, Hub Performance at 100% Corrected Speed.

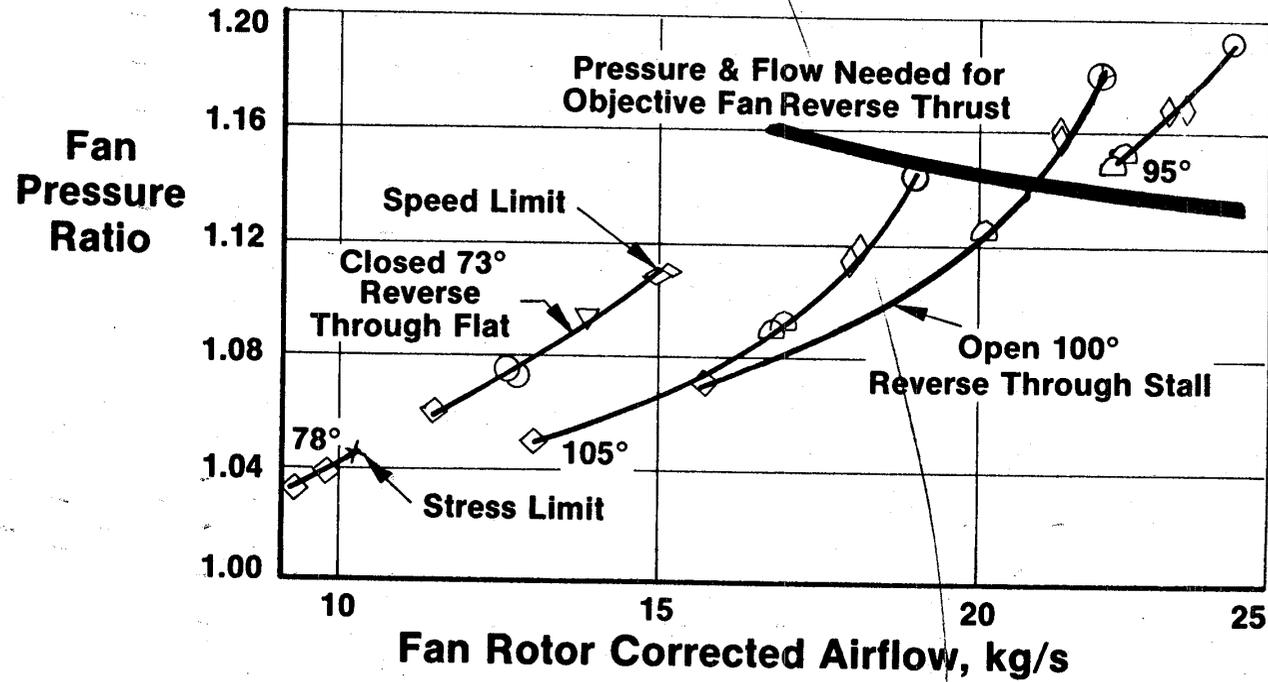


Figure 22. UTW Fan, Scale-Model, Reverse-Mode Performance.

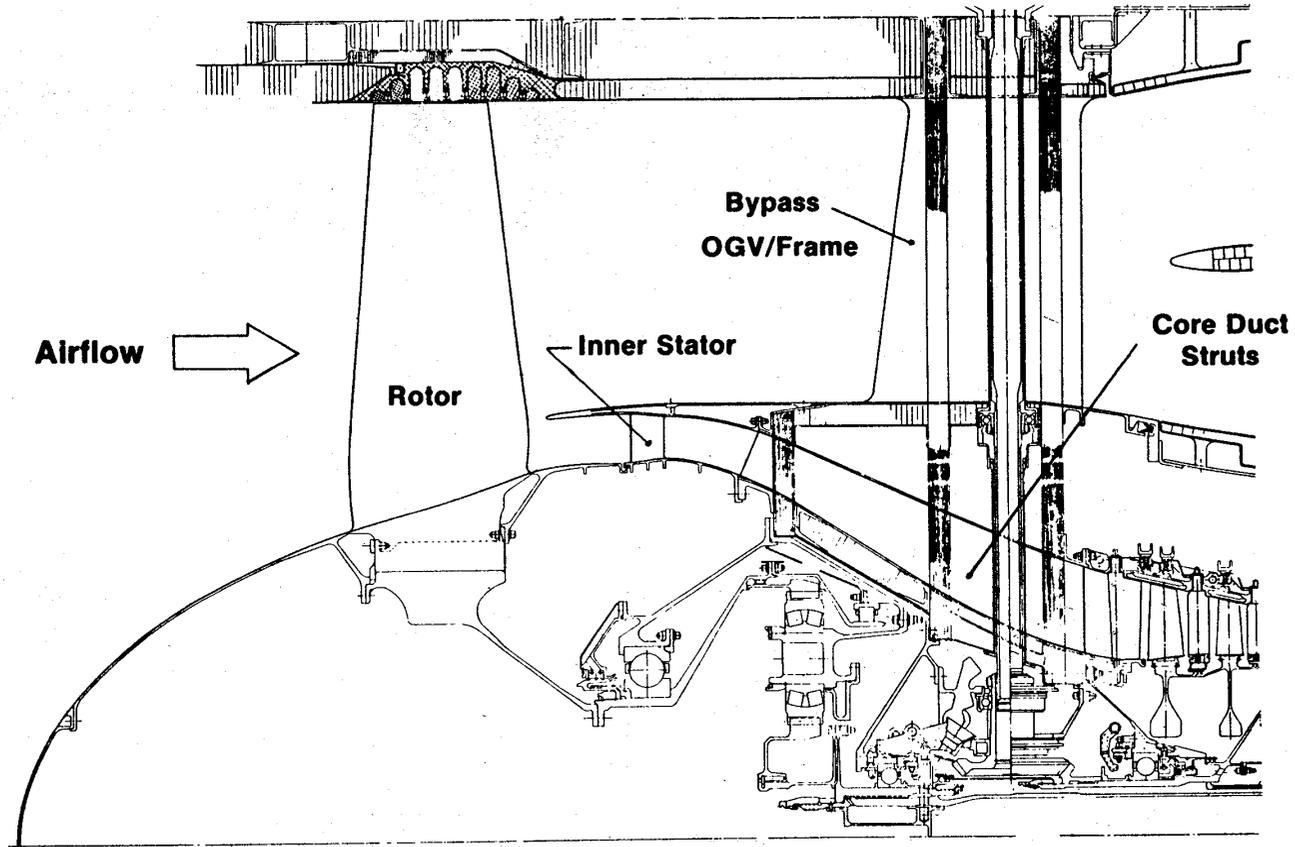


Figure 23. OTW Fan Cross Section.

higher pressure ratio, and a higher rotor solidity compared to the UTW fan. It also has low-aspect-ratio, unshrouded, rotor blades that are designed to be fabricated from composite materials - although titanium blades were used in the QCSEE OTW demonstrator. A flow splitter and inner stator are closely coupled behind the rotor, and the composite bypass vane/frame is identical in aerodynamic design to that used in the UTW engine.

A portion of the predicted OTW fan-performance map is shown in Figure 24. The aerodesign-point bypass pressure ratio was 1.36. This point was selected to be midway between the lower, takeoff, operating line and the higher, cruise, operating line. A variable exhaust nozzle enabled the fan operating line to be adjusted to meet flight conditions. Maximum cruise and takeoff again occurred at the same flow because of inlet throat Mach number limits.

A summary of OTW fan aerodynamic design parameters is listed in Table VI. The fan-tip speed of 358 m/sec (1175 ft/sec), while higher than in the UTW engine, is still a relatively low value. Of those features listed, probably the aerodynamic design feature of greatest significance in the OTW fan is the effort to achieve a high hub pressure ratio. The design radial profile of total pressure ratio at the fan rotor exit is shown in Figure 25. The average hub pressure ratio is 1.43 - higher than the 1.36 average value in the bypass stream. The tip speed is 17% higher than the UTW fan, and a higher rotor hub solidity (made possible by use of a fixed-pitch rotor) is used to aid in achieving the high core supercharging.

A photograph of the rotor for the OTW fan is shown in Figure 26. The low aspect ratio (2.1) of the 28 unshrouded titanium blades is evident in this view.

3.3 COMPOSITE FAN BLADES

3.3.1 Design Requirements

The mechanical design and the materials selected for the UTW fan blades were dictated by the requirements associated with variable-pitch (VP) capability. The blades had to be capable of a very large angle of rotation over the whole engine-speed range. To allow blade rotation, the number of blades in the stage had to be kept small, with short chord lengths, so they could pass each other with no interference. To allow actuation of these blades at high rotor speeds, with reasonable actuation forces, the blades had to be very light. To provide acceptable elastic stability with the blade geometry dictated by the variable-pitch-capability, the materials required very high specific stiffness and strength-to-density ratios. Composite materials made of graphite, S-glass, Kevlar, and boron fibers in an epoxy matrix have these properties.

Figure 27 indicates the effects of the VP requirement on fan-blade geometry. On the left is a picture of the VP UTW fan, on the right is a picture of the OTW fan which did not have a VP requirement. Note the wide spaces

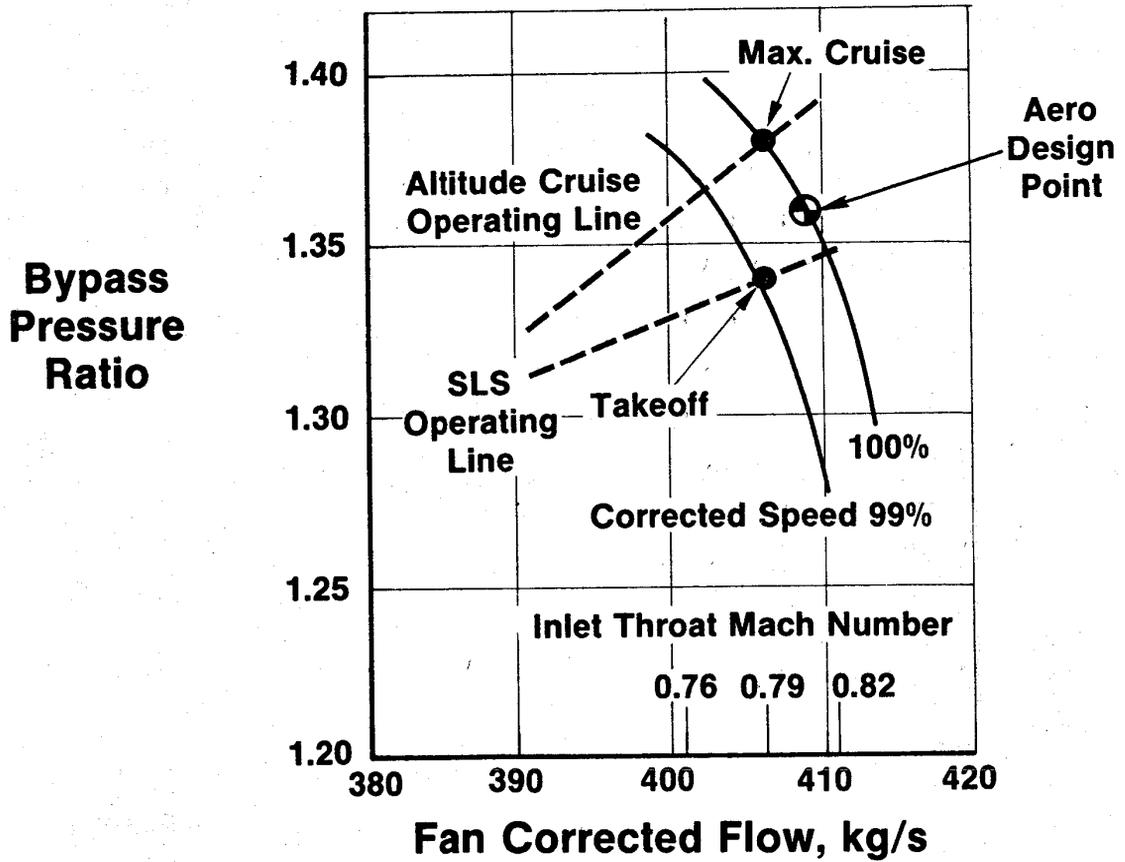


Figure 24. OTW Fan Design Map.

Table VI. OTW Fan Aerodynamic Design Features.

Tip Speed	358 m/s (1175 ft/sec)
Radius Ratio	0.42
Specific Flow	194 kg/sec-m² (39.8 lbm/sec-ft²)
Bypass Pressure Ratio	1.36
Core Pressure Ratio	1.43
Bypass Ratio	9.9
Inlet Tip Relative Mach No.	1.22
Rotor Tip Solidity	1.30
Rotor Hub Solidity	2.23
Rotor Aspect Ratio	2.1
Number of Rotor Blades	28
Number of OGV's/Inner Stators	33/156

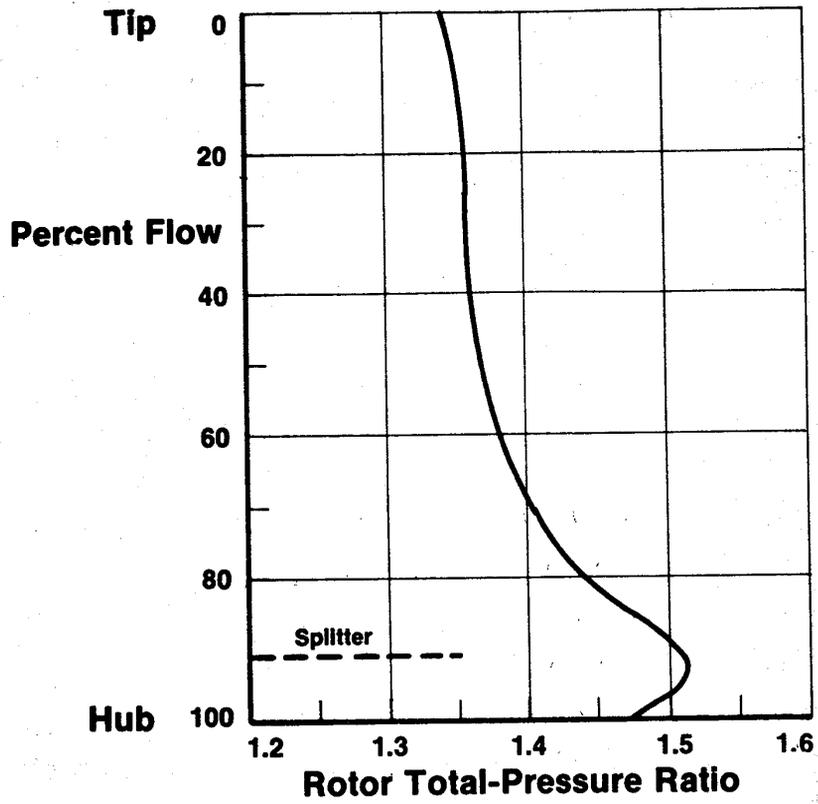


Figure 25. OTW Fan Rotor Design Total-Pressure Ratio Radial Profile.

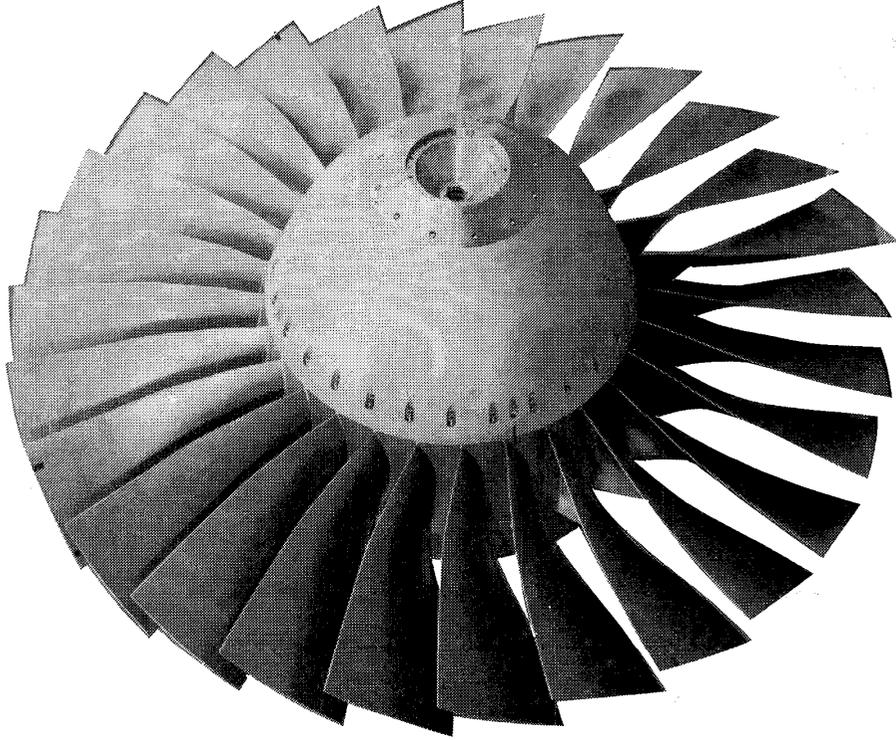
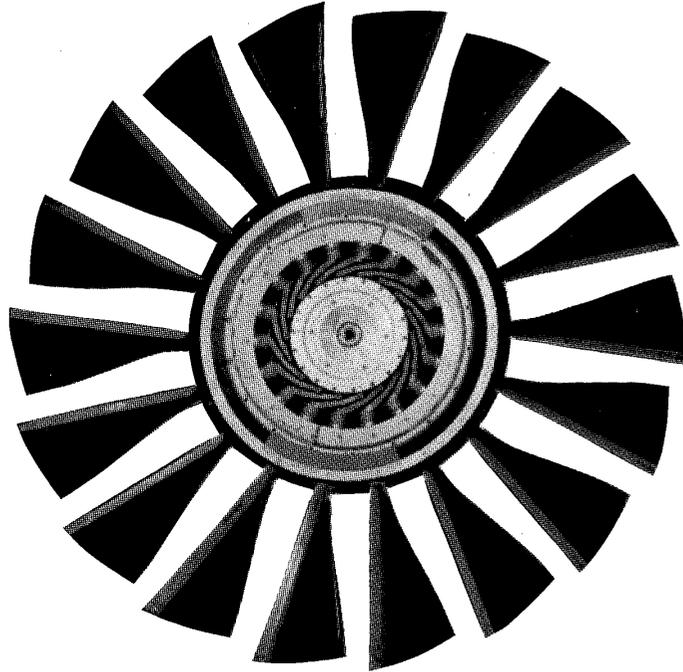


Figure 26. OTW Fan Rotor.

UTW



OTW

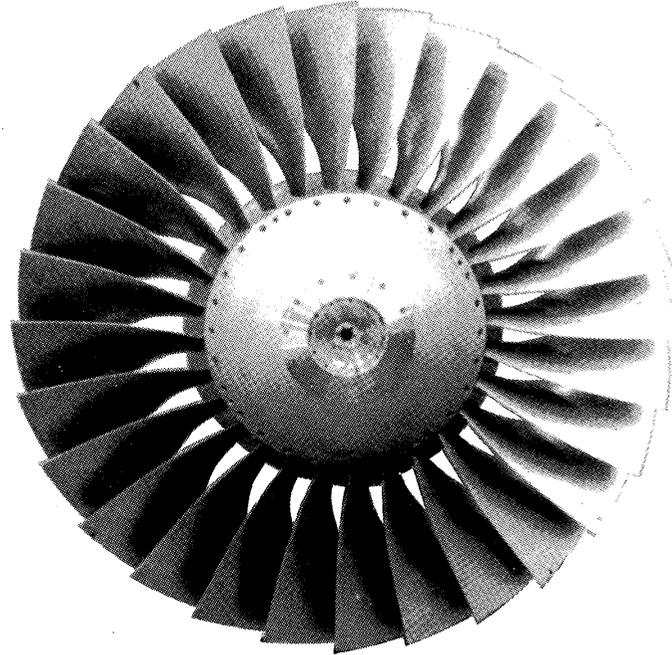


Figure 27. Fan Rotors.

between the UTW blades. This fan rotor has 18 blades with root-chord lengths of 14.7 cm (5.8 in.) compared to 28 blades with root chords of 20 cm (7.87 in.) used in the OTW rotor. Both blades were originally designed to use composite materials. The UTW blades weighed 43.3 kg (95.4 lb) while the composite OTW blades would have weighed 55.3 kg (122 lb). The OTW blades used in the experimental engine were fabricated from titanium.

The aerodynamic design requirements for the UTW fan blades are shown in Table VII. Note that the airfoil solidity is less than 1.0 at all radial sections.

The mechanical design requirements of the fan blade fall into two major categories: variable pitch and structural integrity. Those requirements associated with variable pitch are uniquely the result of the need to be able to rotate the blades. For the UTW application, the blades had to be capable of rotation from the flat pitch to the stall pitch position - which encompassed a blade rotation of over 170°. Obviously, to accomplish any rotation, shrouds could not be used. Finally, in order to be able to rotate the blades over the engine-rotor-speed range with reasonable actuation forces, the blade weight had to be limited to less than 2.5 kg (5.5 lb) each. The actual blade weight was 2.4 kg (5.3 lb).

The design requirements associated with structural integrity were defined based on GE blade-design practices and the engine-mission application. They encompass vibrational and steady-state stresses, fatigue, FOD resistance, and maintainability considerations. The design and materials selected for the blade were primarily dictated by the aeromechanical stability requirements, i.e., to avoid blade excitation at natural frequencies by forcing functions due to aerodynamic flow.

Short-term, steady-state, structural margin is defined as the capacity to operate the blade at 141% speed with no failure. (This represents a load factor of 2.) Thus, all blade stresses at this condition must be less than ultimate.

The blade must be capable of infinite high-cycle-fatigue life ($>10^6$ cycles) and have a low-cycle capability of 48,000 engine starts. For aircraft use, the blades must pass the FAA certification test which defines bird-strike tolerance. Finally, from an economic standpoint, the blade design must exhibit easy maintenance features such as on-the-wing replacement.

3.3.2 Design Description

Figure 28 shows the design features of the composite blade. The airfoil and dovetail were fabricated from a number of 0.25-cm (0.010-in.) thick plies of composite preimpregnated fibers cut to various shapes and carefully laid-up to satisfy the blade geometric requirements. These plies, of several different materials, were oriented in 0°, ±45°, and 90° directions to give the blade

Table VII. Aerodesign Requirements.

<u>Aero Definition</u>	<u>UTW</u>
Tip Speed _____	306 m/sec (1005 ft/sec)
Tip Diameter _____	180 cm (71 in.)
Radius Ratio _____	0.44
Number of Blades _____	18
Bypass Pressure Ratio _____	1.27 Takeoff
Aspect Ratio _____	2.11
Tip Chord _____	30.3 cm (11.91 in.)
Root Chord _____	14.8 cm (5.82 in.)
Solidity	
— Tip _____	0.95
— Root _____	0.98

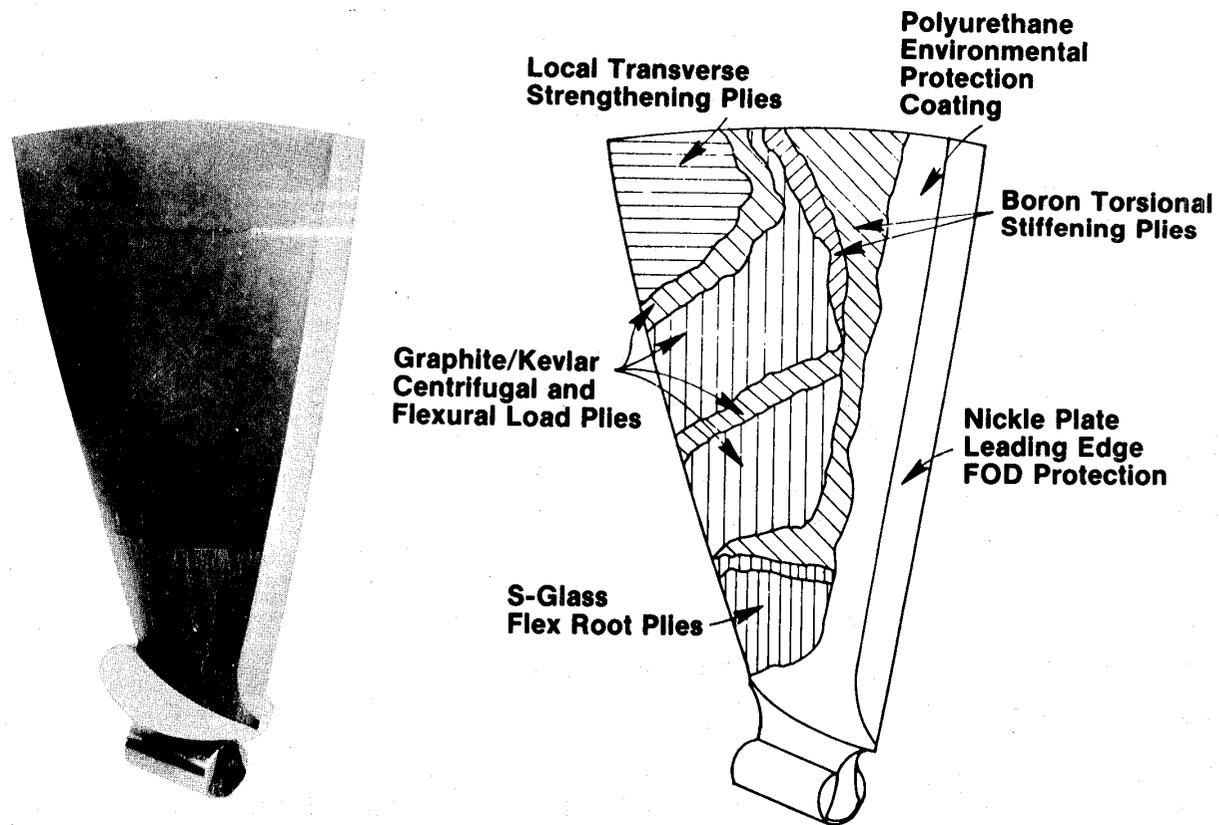


Figure 28. UTW Engine Composite Fan Blade Features.

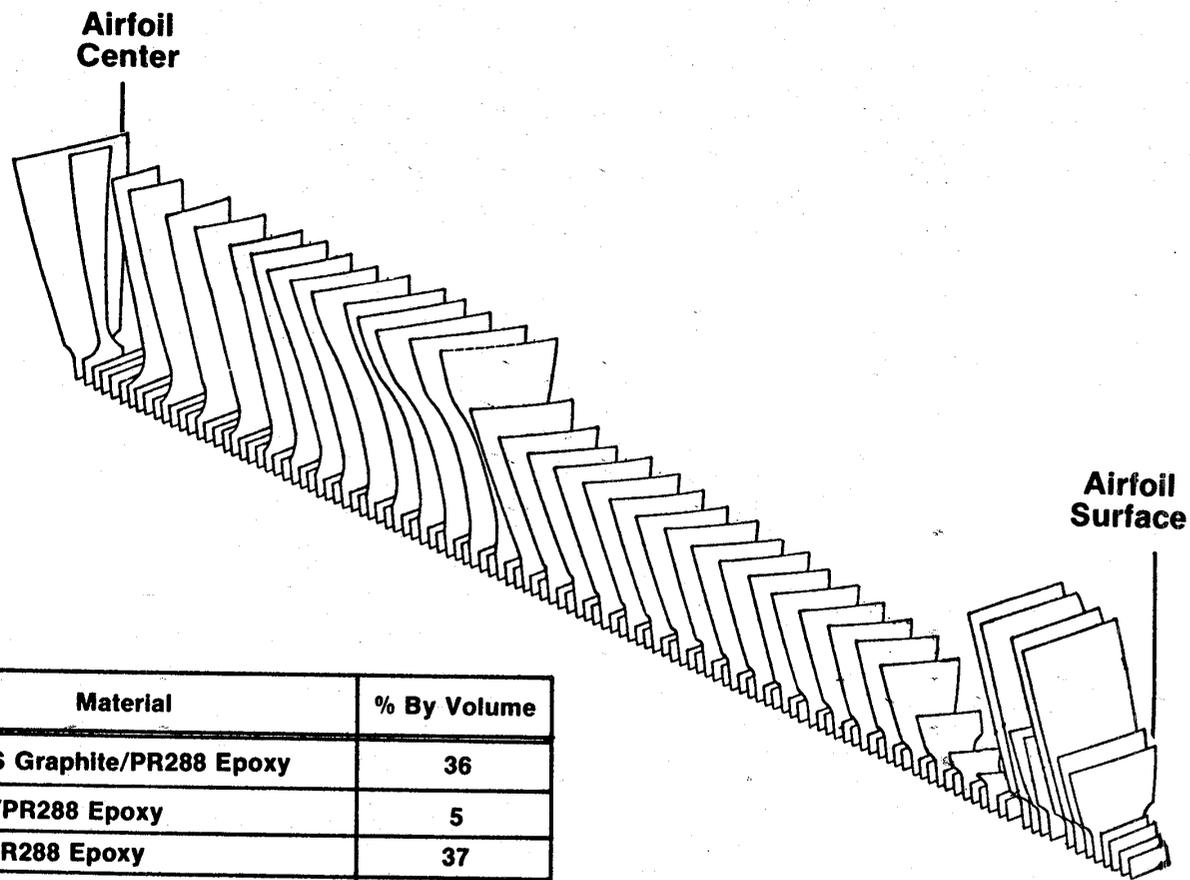
the directional strength and stiffness needed. The plies were laid-up in a die and pressed in a carefully controlled time/temperature/pressure cycle. The leading edge was nickel plated to improve the erosion and FOD characteristics of the blade. The nickel was plated onto a stainless steel wire mesh that was bonded to the airfoil in a secondary operation. The remaining area of the airfoil was coated with a thin layer of polyurethane to reduce erosion due to dust, sand, and water. The platform, which forms part of the inner-annulus flowpath, is round to allow blade rotation and still maintain a smooth inner flowpath for the air. The composite dovetail is bell-shaped and encased in a 7075-T6 aluminum outsert. The outsert is cylindrical and allows the blade to rotate during bird impacts. This feature is designed to help eliminate blade breakage at the root during foreign-object impact.

Figure 29 shows half of the composite material plies that make up the blade. Four different materials are used in the blade. Note that the shape of each ply is different. Also shown are the proportions of the various materials used. The overall fiber volume fraction is 60%.

The platform is an integral part of the blade, as shown in Figure 30. It is put on the blade in a secondary operation. The round, flowpath portion is made up of a number of graphite-epoxy plies bonded to the airfoil. The flowpath piece is supported by a lower face sheet also made of graphite-epoxy. An aluminum-honeycomb core is sandwiched between the flowpath and lower face-sheets for stiffness. Finally, a leading-edge strap of graphite-epoxy is put all around the lower face sheet. The purpose of this strap is to hold the platform onto the blade in the event the shear bond fails; it is really a safety bandage.

The natural-frequency characteristics of the blade/disk are shown on the Campbell diagram (Figure 31) as a function of fan speed. The blade was sized to satisfy aeroelastic stability criteria. This required the level of first-torsional frequency shown. The second requirement was to have a good separation between the blade natural frequencies and all excitation lines at the 100% speed condition. The third goal was to have the first-flexural natural frequency above the 2/rev excitation line. This could not be done within the other design requirements; thus, the first-flexural frequency was set to cross the 2/rev excitation line at about 67% speed - a transient condition. During engine testing, it was found that stresses exceeded scope limits at the first-flex, 2/rev, crossover condition. The OTW blade also had a crossover of the first flex with the 2/rev excitation line but, because the longer blade-hub chord and the higher fatigue strength of titanium, the stresses were well below scope limits.

The Goodman diagram (Figure 32) was constructed using blade and specimen test data. The allowable curve was defined as 85% of test data. The test data were based on no delamination of specimens and blades for 10^6 cycles. Thus, this diagram represents a very conservative estimate relative to Goodman diagrams, used for metals, which are based on material fracture. For engine testing, the scope limits were set at 5.86 kN/cm^2 (8.5 ksi) to account for



Material	% By Volume
Type AS Graphite/PR288 Epoxy	36
S-Glass/PR288 Epoxy	5
Kevlar/PR288 Epoxy	37
Boron/PR288 Epoxy	22

Figure 29. Composite Fan Blade Ply Assembly.

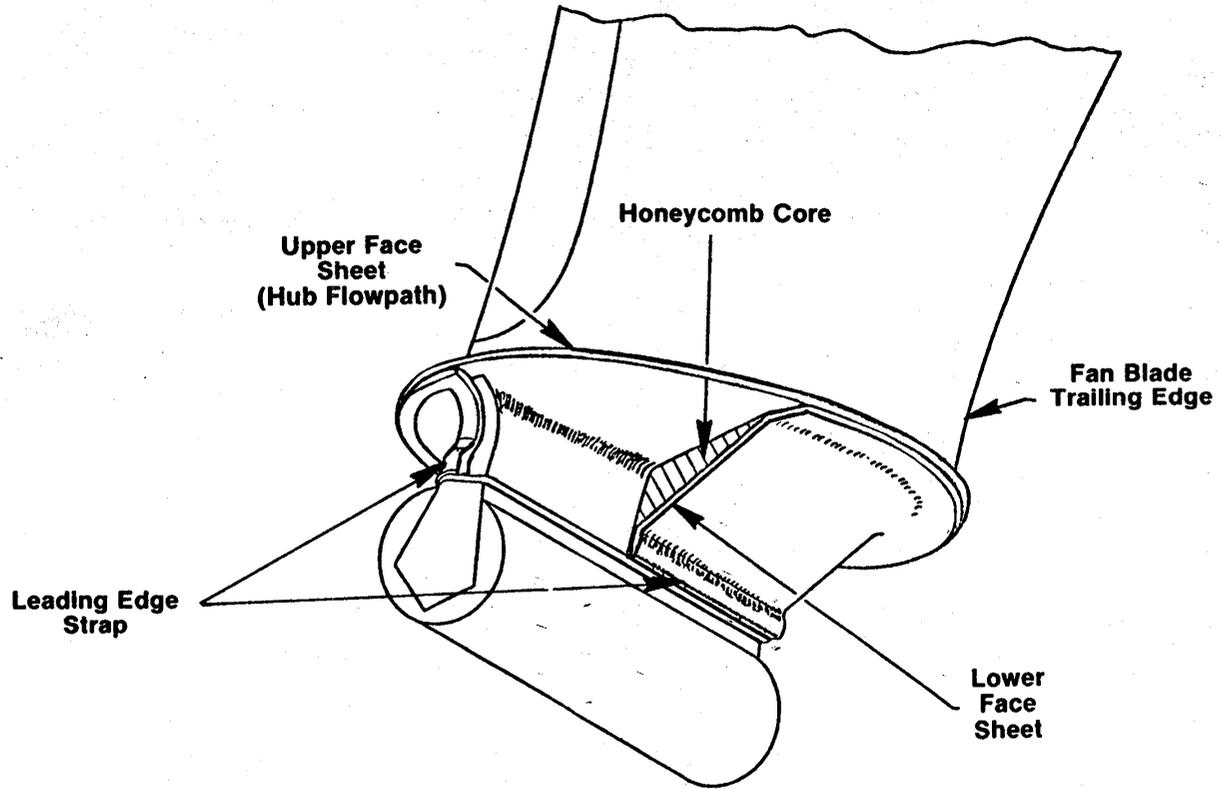


Figure 30. Composite Fan Blade Platform Construction.

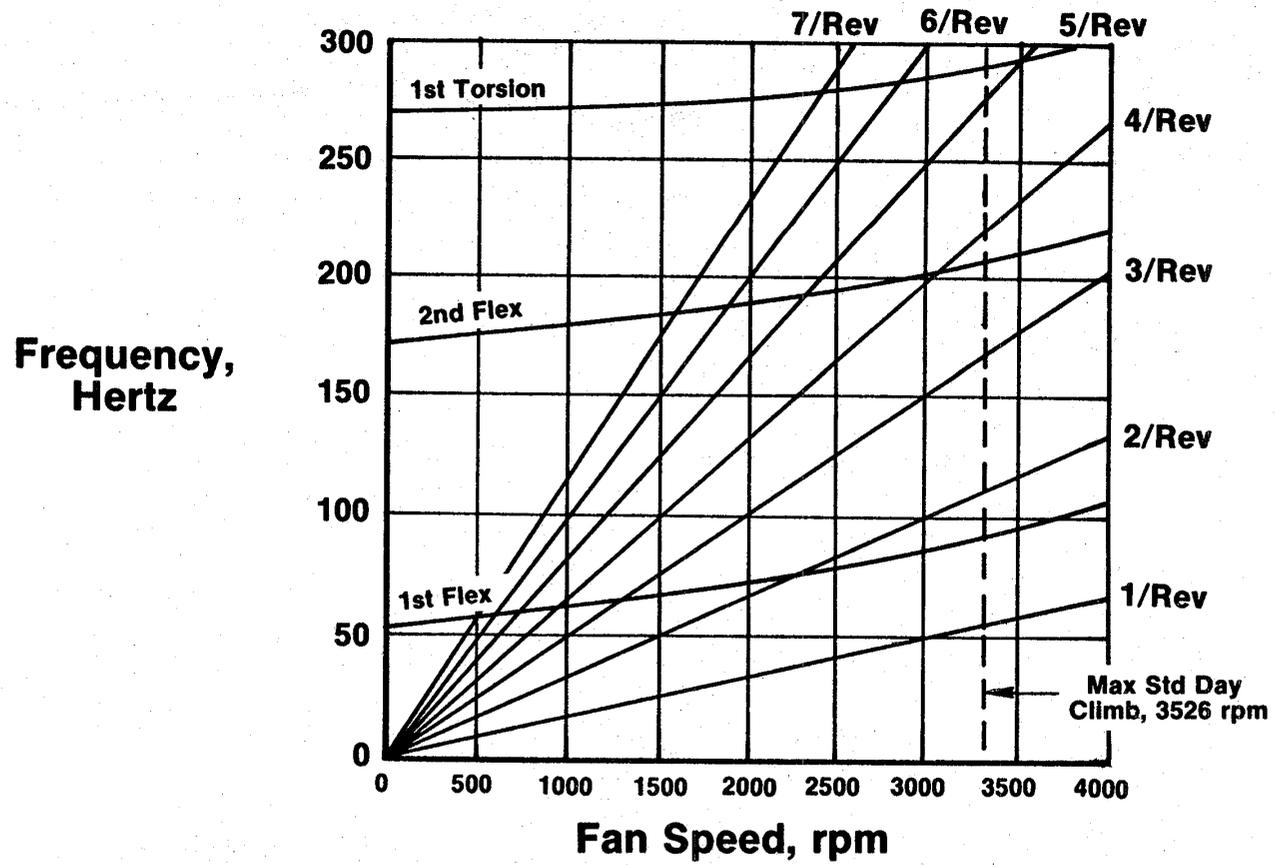


Figure 31. Composite Fan Blade Campbell Diagram.

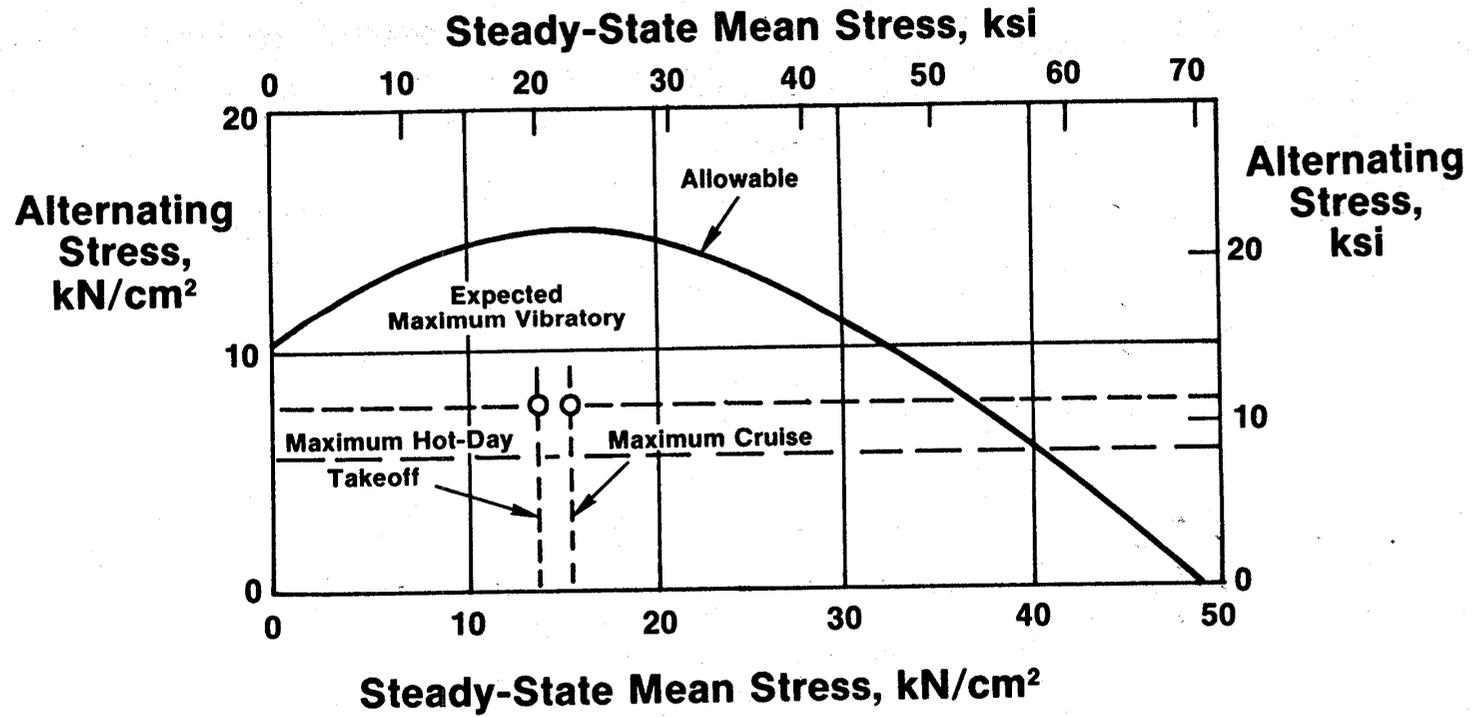


Figure 32. Composite Fan Blade Goodman Diagram.

blade-to-blade variations, electronic errors, etc. Thus scope limits were very conservative. During testing, scope limits were exceeded significantly a number of times; however, no delaminations have been found in the blades.

3.3.3 FOD Resistance

The initial blade-development effort was addressed to foreign object damage (FOD) requirements. The FAA requirements for bird impacts are shown in Table VIII. In addition, the more stringent GE goals are shown. GE's requirements are more demanding in the area of small birds. The rationale for the GE goals is based on experience with titanium blades and economics.

The FOD resistance of the preliminary blade design was evaluated in a whirligig impact facility (Figure 33). In these tests, the blades were rotated, and a simulated RTV rubber bird was injected into the path of the blade. The results of one of the two tests are shown in Figure 34. Blade serial number QP005 was impacted at simulated aircraft takeoff conditions with a 0.907-kg (2.0-lb) bird. The test conditions simulated an impact at the blade 80% span location for an aircraft forward velocity of 41.2 m/sec (80 knots). The bird-to-blade relative velocity was 275 m/sec (904 ft/sec), the incidence angle was 33°, and the weight of the bird slice was 0.227 kg (1/2 lb). The blade did not break at the root. Keyhole rotation was noted in the movies. Posttest inspection of the blade showed it had lost 7% of its weight, and approximately 90% of the airfoil was delaminated. Based on this result, it was concluded that the UTW composite fan blade design would not satisfy the FAA FOD requirements. Further, it was decided not to pursue the development of an FOD-resistant design under this program.

3.4 VARIABLE-PITCH-ACTUATION SYSTEMS

Because of the criticality of the actuation system to the operation of a variable-pitch fan, many concepts were evaluated. Two were selected for detail design and development. These were a cam/harmonic system, designed and produced by Hamilton Standard under subcontract, and a ball spline system designed and produced by General Electric. Both systems were engine-tested in the UTW propulsion system.

3.4.1 Cam/Harmonic Variable-Pitch System

Design Requirements - The design criteria for the actuation system were established consistent with the demands of commercial service. The mission cycles, major component life, and bearing life values used for the design, Table IX, reflect this philosophy. No compromises in design criteria or weight were made for the fact that the system was to be used in a short-test-life, experimental engine. The only deviation from this approach was in selection of readily available items such as hydraulic motors and servovalves.

Table VIII. UTW Composite Fan Blade Bird-Impact Design Requirements.

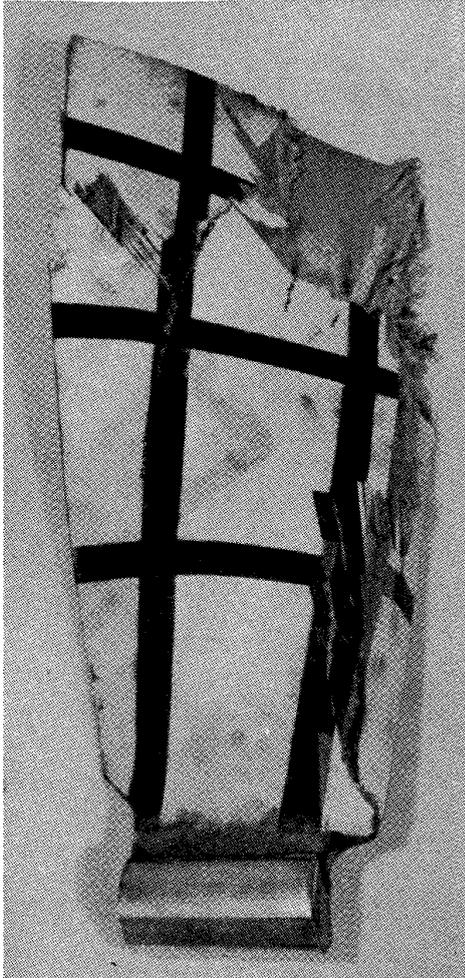
Bird Size kg (lbs)	Max No. Birds Ingested	FAA Requirement	GE Goals
.085 (.188)	16	Maintain 75% Engine Thrust	No Blade Damage
.68 (1.5)	8	Maintain 75% Engine Thrust	Maintain 75% Engine Thrust
1.8 (4)	1	Safe Shutdown	Safe Shutdown

Table IX. Design Requirements for Variable-Pitch-Actuation System.

- **48,000 Missions**
 36,000 Hours Major Components
 9,000 Hours Bearings and Expendables
- **Actuation Rate 135°/sec**
- **Feedback Accuracy $\pm 1/4^\circ$**
- **Net Blade Twisting Moment — Function of Blade Angle**



Figure 33. Composite Fan Blade Whirligig
Impact-Test Facility.



Test Conditions

- **Aircraft Takeoff**
- **1.5 Pound Bird**

Results

- **7% Weight Loss**
- **90% Delamination**
- **No Root Failure**

Figure 34. Bird-Impact-Test Results.

The high rate of pitch-change capability designed into the system (Table IX), reflects the need, dictated by STOL aircraft operation, to change very rapidly to reverse thrust; in addition, it facilitates rapid thrust response for go-around operation. The feedback accuracy stipulated in Table IX is important to obtain control-system accuracy. The actuation system is required to overcome the twisting (moment) loads inherently present in a variable-pitch system; these loads vary as a function of blade angle as shown in Figure 35. The centrifugal moment curve is sinusoidal, and it is a function of the mass distribution of the blade about the pitch-change axis and the centrifugal field. The aerodynamic-twisting moment is the torque generated by the center of pressure about the pitch-change axis. The sum of these two torques is the net value. The frictional moment of the blade-retention bearing due to centrifugal pull is assumed to be a constant, maximum value. The 0° setting is the static, takeoff setting.

The large range of blade-angle travel was initially established so that reversing of the fan could be accomplished through stall, that is the open-pitch direction, as well as in the closed-pitch direction. Scale-model fan testing conducted while the design was in process showed that much higher levels of reverse thrust could be achieved by the through-stall approach. As a result, the closed-pitch method was never implemented in the hardware phase.

Alternate Concepts Studied - Prior to initiation of the design effort, an in-depth study was conducted to select an optimum concept. Ten designs of various mechanical and hydraulic arrangements were studied, and a comparative assessment was made using weight plus six other criteria such as reliability and development risk. The matrix was reduced to six choices for more in-depth evaluation, and the matrix of criteria was increased to ten factors. The selected cam/harmonic system scored heavily in the areas of weight, reliability, simplicity, and accessibility of controls.

Description of Selected System - The key elements of the mechanism are depicted on the block diagram and schematic shown in Figures 36 and 37. The input from the digital control system is a blade-angle position command to the electrohydraulic servovalve; the servovalve meters flow from a remote hydraulic source to power a hydraulic motor, the output of which drives a high-speed, flexible shaft.

The output position of the hydraulic motor provides a feedback signal from a Linear-Variable Differential Transformer (LVDT) to the digital control. Although the remainder of the system is open loop, it does provide a high degree of positioning accuracy. A differential gear transfers the torque of the flex shaft from the stationary reference to the rotating fan. This torque is then increased, with a large corresponding speed decrease, by the harmonic drive. The output of the harmonic drive is transmitted to the blade through the cam, which rotates the trunnion arm. The combination of the trunnion arm and the contour of the cam track provides the desired output torque-versus-blade-angle characteristic. The no-back is a simple locking device that fixes blade angle in the absence of any input motion on the flex shaft. The key

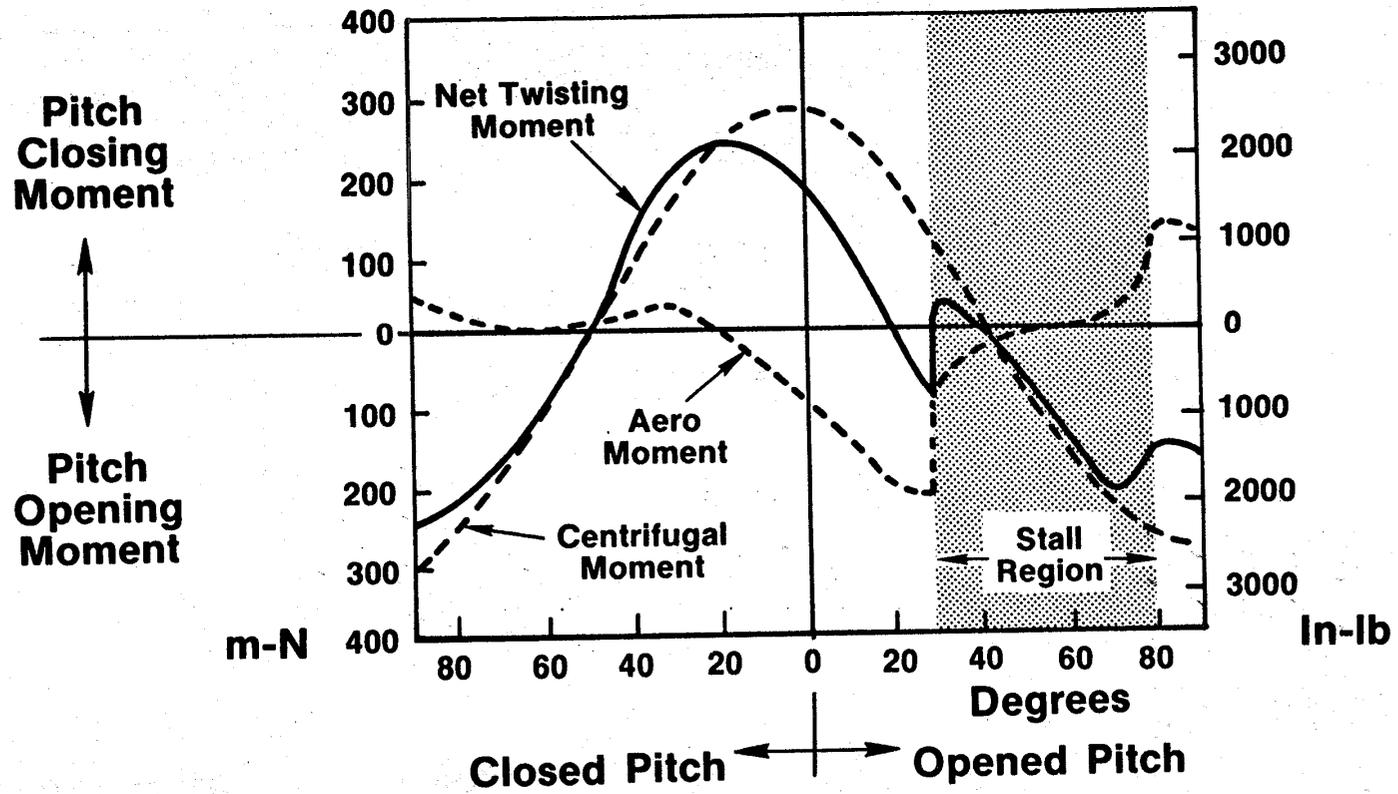


Figure 35. UTW Fan Blade Twisting (Moment) Loads.

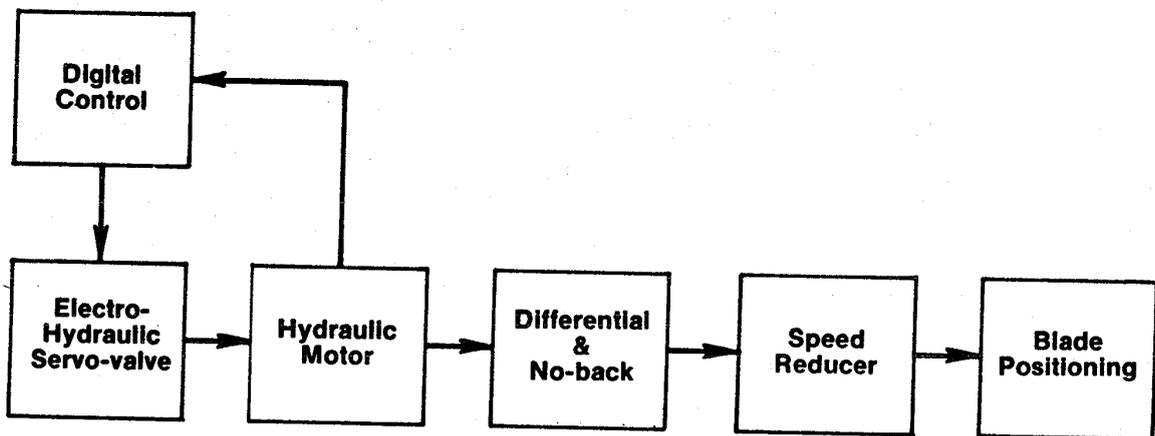


Figure 36. Block Diagram of Pitch-Change Mechanism.

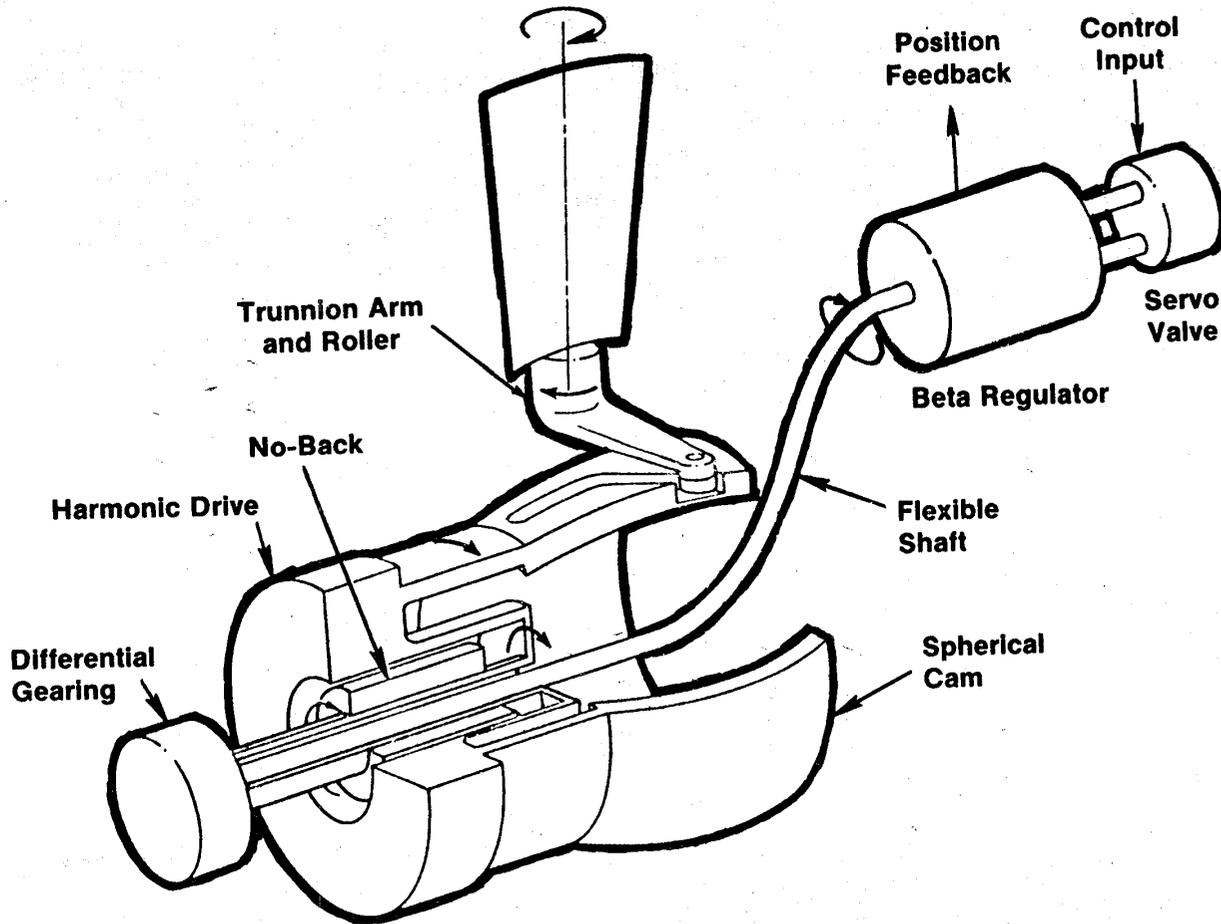


Figure 37. Schematic of Pitch-Change Mechanism.

design features of the system are more apparent in Figure 38. The beta regulator comprises a servovalve, hydraulic motor, and feedback signal. It is packaged as a unit and mounted remotely from the fan for ease of replacement since the control portion of actuation systems have historically been the major contributor to unscheduled removals. In addition, the remote mounting is a less hostile environment compared to a location inside the fan close to the gearbox.

The overall gear ratio between the hydraulic motor and the fan blade is 1000:1. Of this, 200:1 is provided by the harmonic drive. This high reduction is provided in a very small envelope and for a minimum weight. The no-back is a coil-spring device that, as noted earlier, locks the system when there is no input motion from the beta regulator. The system is self-energizing; a very low magnitude of back-drive torque will lock it. Similarly, it is released by extremely low levels of input drive torque.

The QCSEE fan has a large disk, and it operates at higher rpm than previous variable-pitch systems. This would result in a significant weight penalty of oil required to fill the disk; in addition, there is increased risk of leakage due to the high centrifugal-induced oil pressure. As a result of these considerations, dry lubrication was used for the cam track and roller. The blade retention used grease-packed bearings. As a consequence, the interior of the rotor is accessible for visual inspection.

Such features as the low-torque, high-speed drive between the beta regulator and the harmonic drive, elimination of oil in the disk, and the lightweight no-back made this concept the lightest of the 10 systems that were evaluated.

Lubrication for the flex shaft, no-back, differential gear, and harmonic drive is provided by a low oil flow from the beta regulator through the flexible-drive housing. This flow is centrifuged into these components and returns to the gearbox scavenge area. A benefit of this configuration is the elimination of high-pressure hydraulic transfer across the compressor inlet or through the gearbox, thereby improving safety and reliability.

Another maintenance feature is the ability to replace the flexible shaft from the beta regulator end without disturbing the fan assembly.

The harmonic drive is one of the key elements in achieving a lightweight design. The operating principle is illustrated by Figure 39. Rotation of the input-wave generator, which has three lobes, causes a distortion of the thin flex-spline member. The passage of two lobes past a given point on the output lobe causes the output circular spline to advance one tooth. Since there are three lobes, the output motion per revolution of the wave generator is three teeth, as indicated; combined with the number of teeth used, 600, this provides a 200:1 ratio. Because the teeth are quite small, a key design parameter is ratcheting capacity - that is, the ability to resist "skipping" or "slipping." The harmonic drive was tested as a component, under the combination of load-induced deflection and thermal effects, prior to initiation of

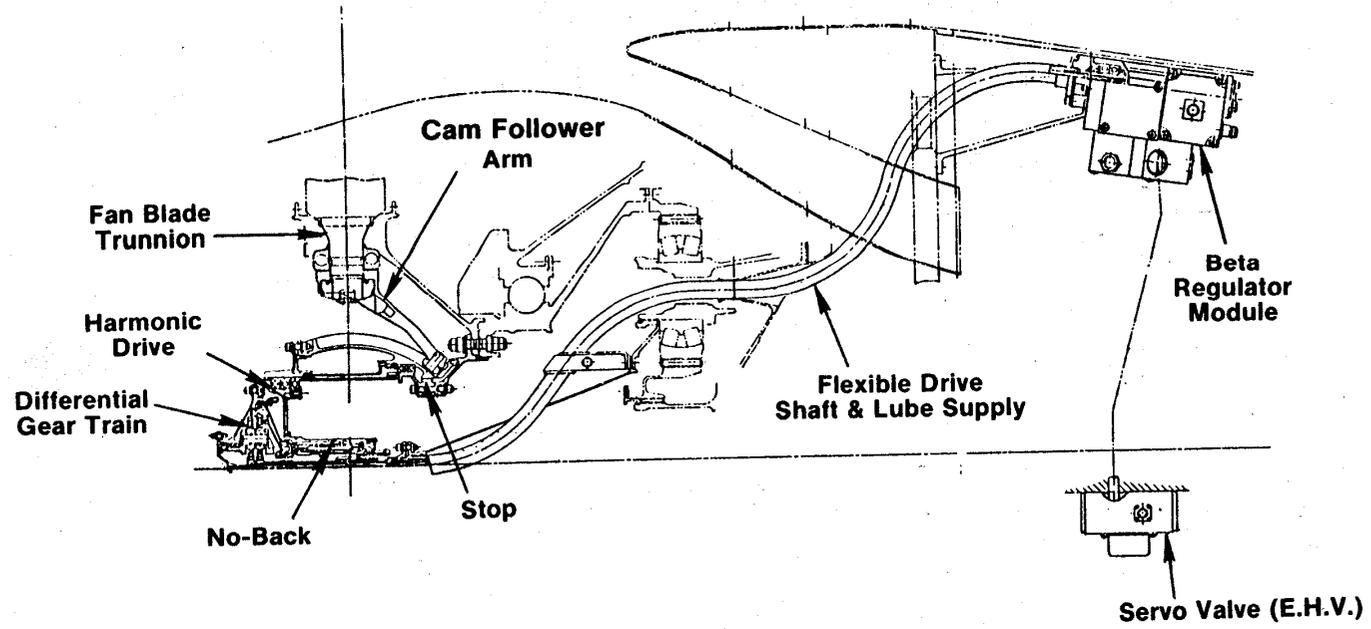


Figure 38. Cam/Harmonic Variable-Pitch Actuator System.

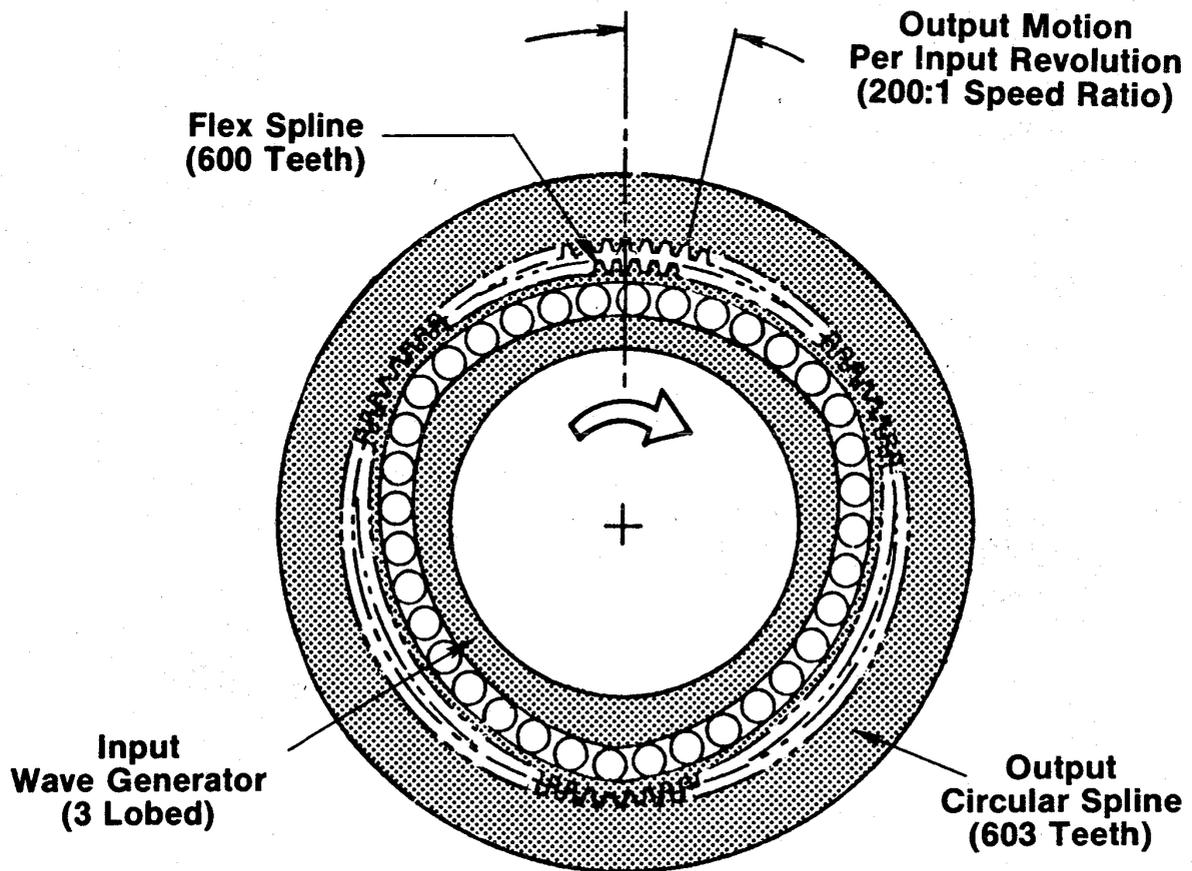


Figure 39. Harmonic Drive.

the whirl-rig test. This device has been used in such applications as the duct-tilting mechanisms on the Bell X-22 VTOL aircraft and on the wheel-drive system for the lunar rover.

The harmonic-drive components are shown in Figure 40; the wave generator and circular spline are designed for high radial stiffness to minimize radial deflection under load. The flex spline is, of course, designed to continually deform during its operating lifetime.

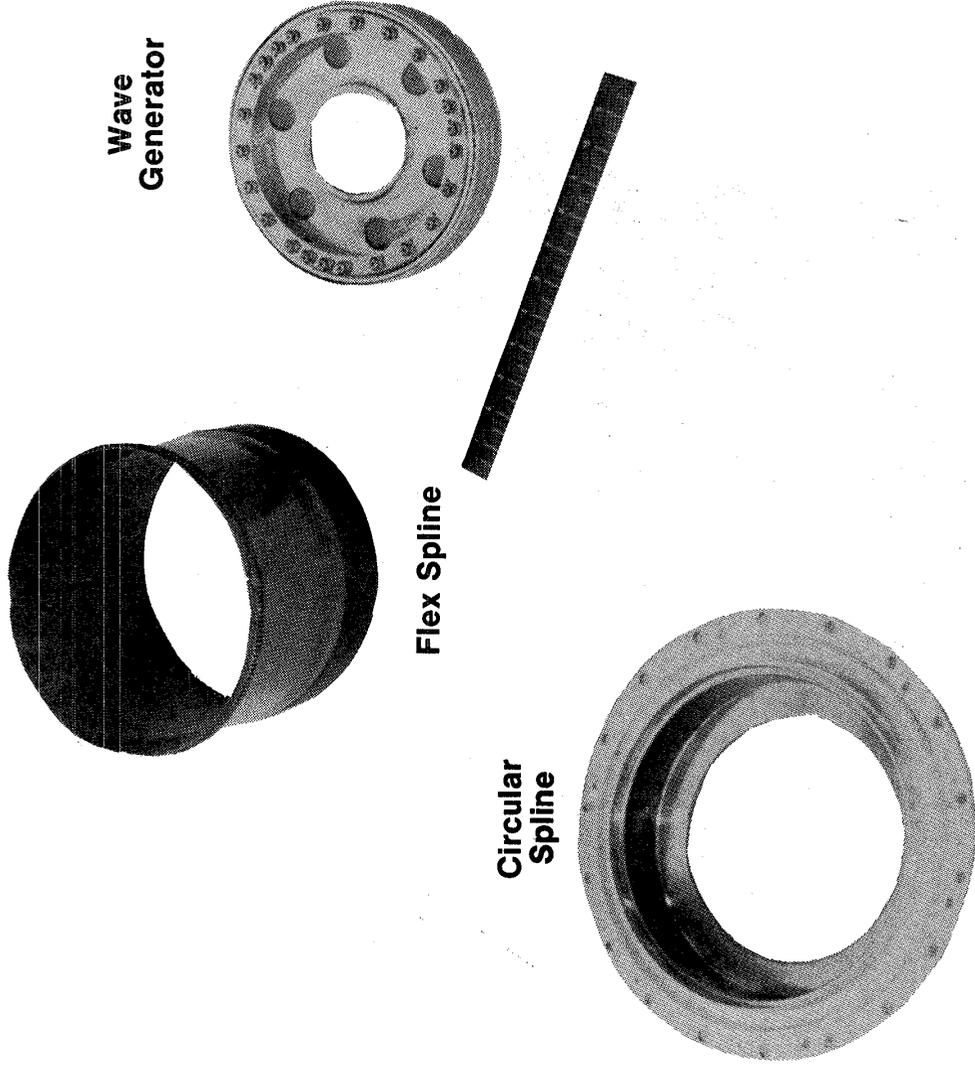
The cam, shown in Figure 41, provides contoured tracks for the 18 cam-follower arms and bearings. The cam contour, coupled with the variation in the effective moment arm, provides the variable torque ratio required to match the load-versus-blade-angle requirements shown earlier. This hollow structure is made of hardened steel; diameter is dictated by the envelope required to locate the grooves on a spherical surface as well as by the structural requirements of the groove walls.

Whirl-Rig Test - A 60-hour, whirl-rig test using an electric motor drive was performed on the system prior to engine test. A disk and 18 counterweights were used for this purpose. The counterweight provided twisting (moment) loads by virtue of mass distribution when operating in a centrifugal field. The whirl-rig test was conducted using the entire actuation system including the beta regulator assembly. The objectives of the program were designed to prove acceptable performance and durability characteristics prior to engine test by demonstrating actuation rates and position accuracy and by (limited) endurance operation.

Figure 42 is a photograph of the test rig. The rotor assembly is shown in the background; the 18 blade counterweights and cam arms are also visible. The housing in the foreground was used to mount the flexible drive shaft and the beta regulator. The drive shaft was configured exactly as it would be in the engine even though the fan in this test was being driven from the front; this method was used for ease of testing.

The test program consisted of functional, structural, and endurance testing. Test results produced an average pitch-change rate of $116^\circ/\text{sec}$ with a maximum rate of $135^\circ/\text{sec}$. Although this was less than the $135^\circ/\text{sec}$ average value specified, it was judged to be a satisfactory level of performance. Perhaps more important was the demonstration of blade travel from positive thrust to full reverse thrust through stall of approximately one second. The required blade-positioning accuracy of $\pm 1/4^\circ$ was attained, and (although not a requirement) a hysteresis of $1-1/2^\circ$ was demonstrated - as was the ability to provide a minimum step change of $1/2^\circ$ in blade angle.

The most important result of the test was demonstration of compliance with the load capability of the system as measured against the levels, specified by GE, which were presented earlier. The no-back was demonstrated to hold the fan blade in a locked position under the maximum load or overspeed condition. A total of 550 simulated mission cycles were accomplished; each cycle consisted of 16 blade-angle/rpm combinations including one reverse cycle.



**Wave
Generator**

Flex Spline

**Circular
Spline**

Figure 40. Harmonic-Drive Components.

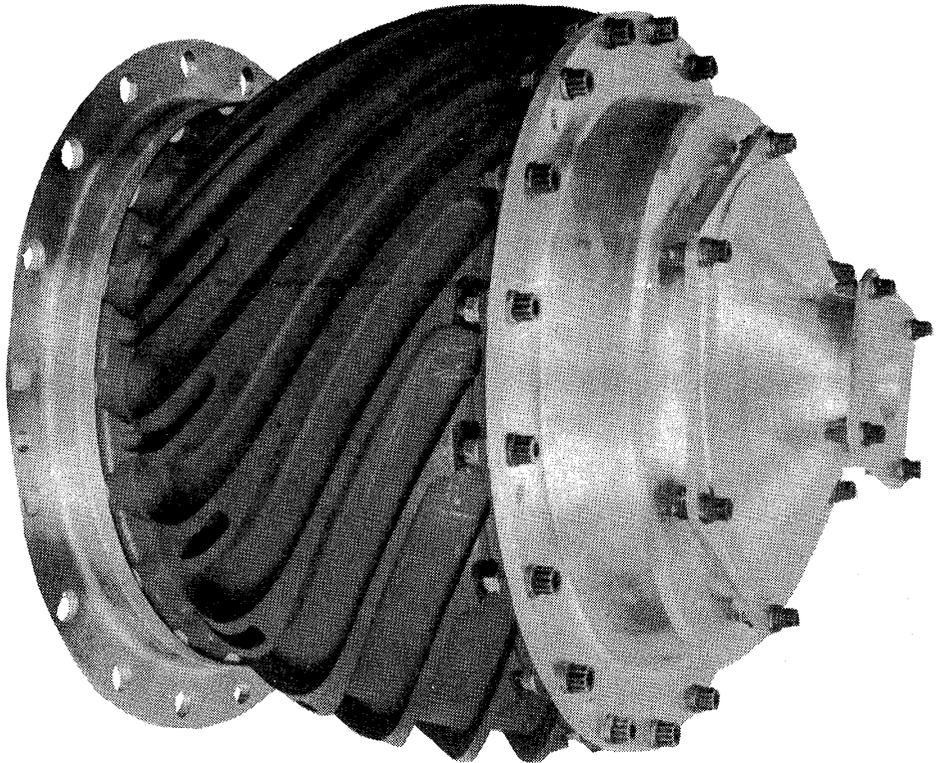


Figure 41. Harmonic-Drive Cam.

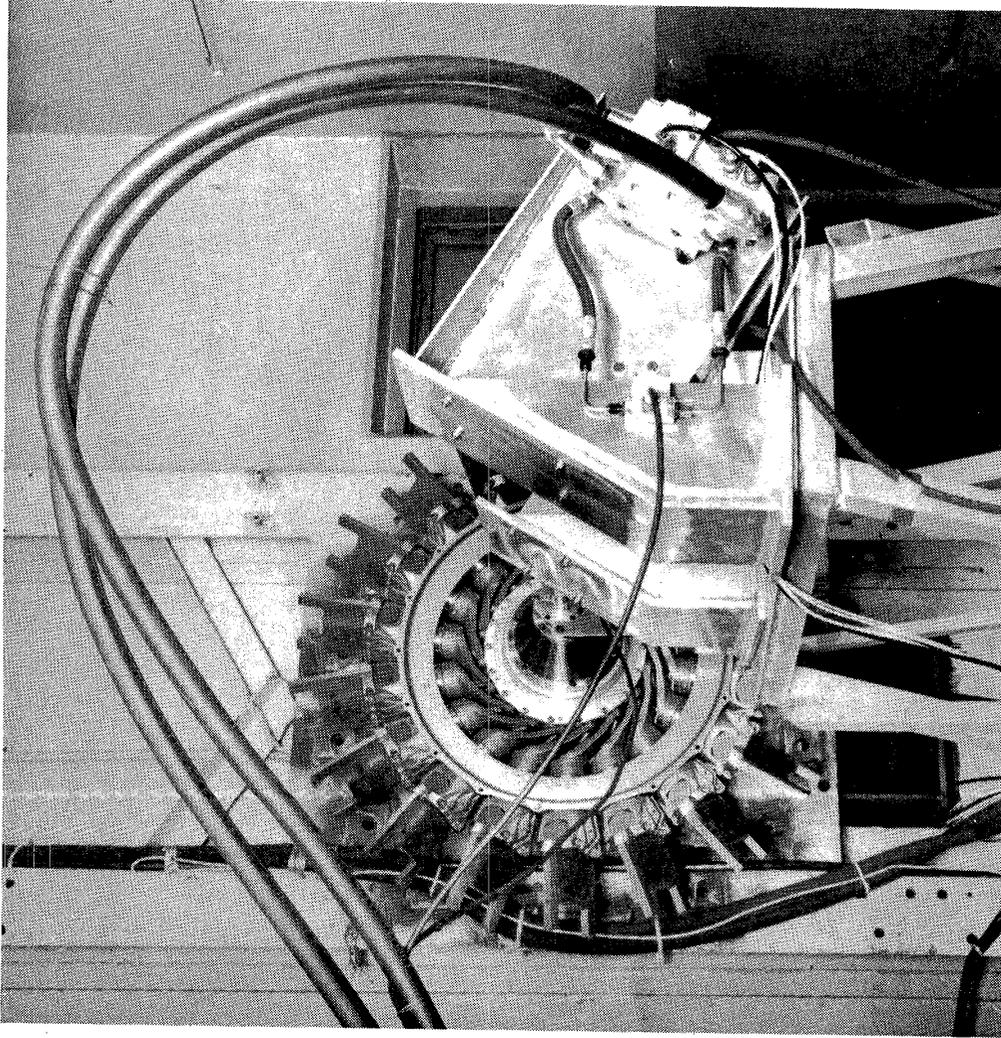


Figure 42. Actuator in Whirl Rig.

The results of the test were, in an overall sense, positive. Very little "fix" and retest was required. Moreover, the system was judged to have satisfied specification requirements; therefore, it was subsequently assembled into the under-the-wing QCSEE.

3.4.2 Ball Spline System

Design Requirements - The ball spline pitch-actuation system was designed to meet the same requirements specified for the cam/harmonic system (Table IX).

System Selection - Using technology demonstrated on previous variable- and reverse-pitch fan rigs, a second-generation ball spline actuator was studied. Several alternate concepts were also evaluated, including worm gearing, "mini" gearboxes, individual screwjacks, and a single planetary gearbox - all designed to the same conditions as the ball spline. The ball spline with two output ring gears was selected because it was the least complex and was extremely rugged. Its reduced parts count promised a lightweight, highly reliable design.

Description of System - The actuator system, as shown in Figure 43, is made up of a ball screw, ball spline, and two ring gears. The ring gears collect and synchronize the individual pinions that are attached to each of the 18 blade trunnions. As the input drive shaft is rotated, the two ring gears move in opposite directions. This imparts two equal reactions to each pinion, thus minimizing gear loads and providing a redundant load path.

The pitch-change mechanism is shown schematically in Figure 44 and as a block diagram in Figure 36. It is made up of blade positioning, speed reducer, differential, and no-back; it is driven by a piston-type hydraulic motor that is controlled by the servovalve. The servovalve is operated by the digital control while the control, in turn, receives position intelligence from the feedback. Motor output drives through the differential gearing and no-back. The no-back accommodates input movement in either direction of rotation but prevents fan blade torque from back-driving the system. A stage of reduction gearing is required to match the output of the motor with the blade-positioning mechanism. Figure 45 shows the details of the system including: hydraulic motor, feedback, gearing, no-back, thrust bearings, ball screw, ball spline, torsion stops, ring gears, and pinions.

In order to actuate the fan blades, large axial forces must be generated in the load path formed by the ball screw, thrust bearings, and inner member of the ball spline. The key to minimizing actuator weight is keeping this closed-loop load path short and on a small radius.

Key design features include the motor and feedback location near the actuator for crisp blade movement and accurate positioning. Redundant ring gears reduce steady-state loads and improve reliability. The ball spline and ball screw are rugged, proven designs. The differential gearing and no-back are packaged together in order to simplify actuator assembly.

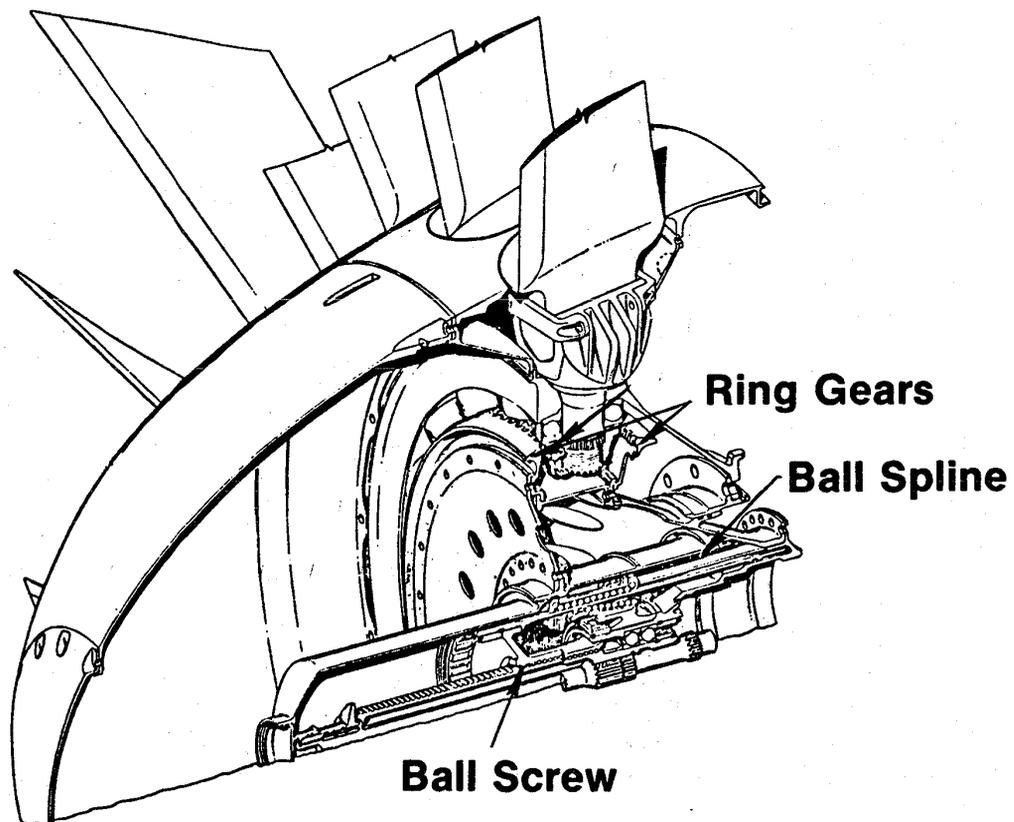


Figure 43. GE Ball Spline Actuator System.

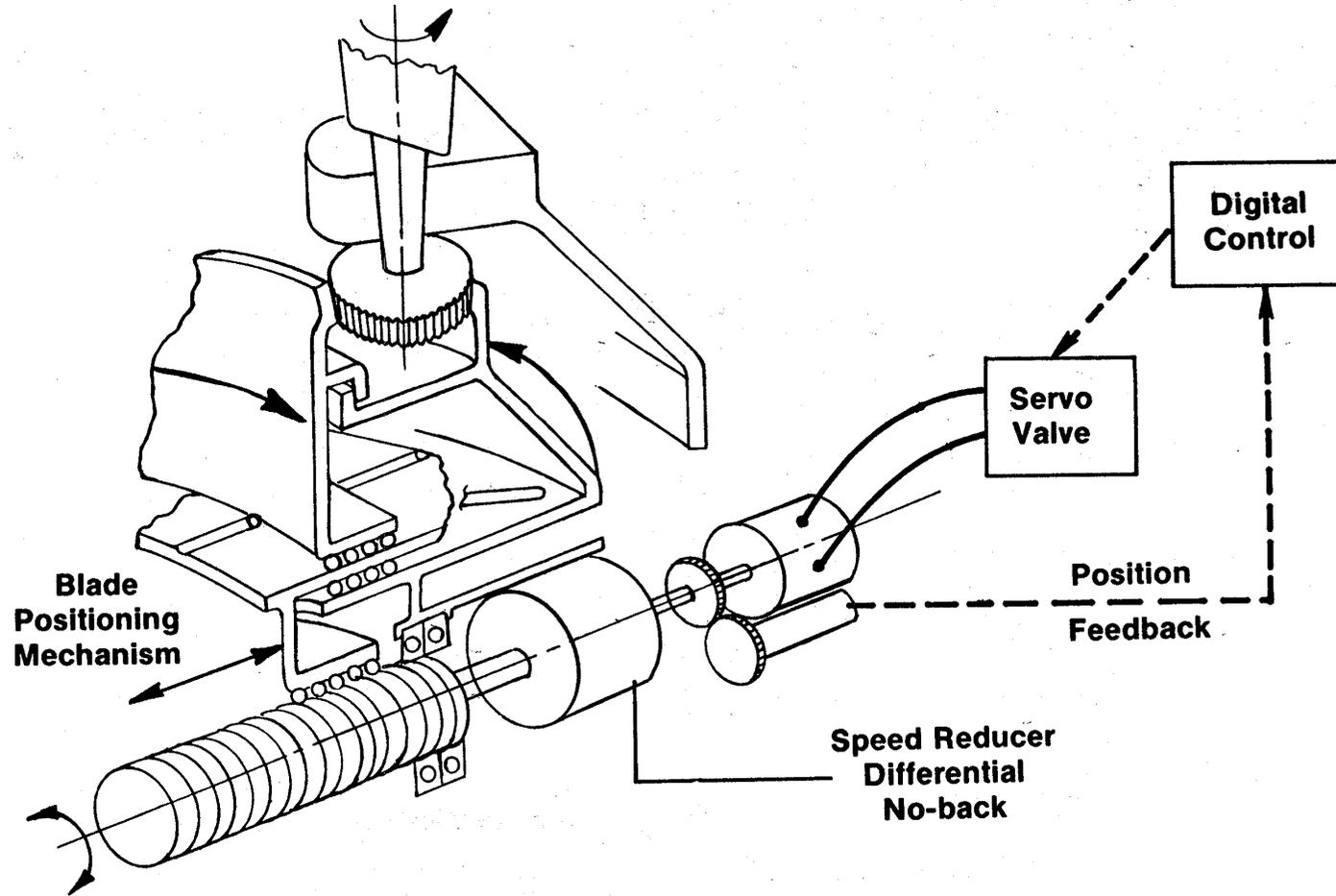


Figure 44. Pitch-Change Mechanism.

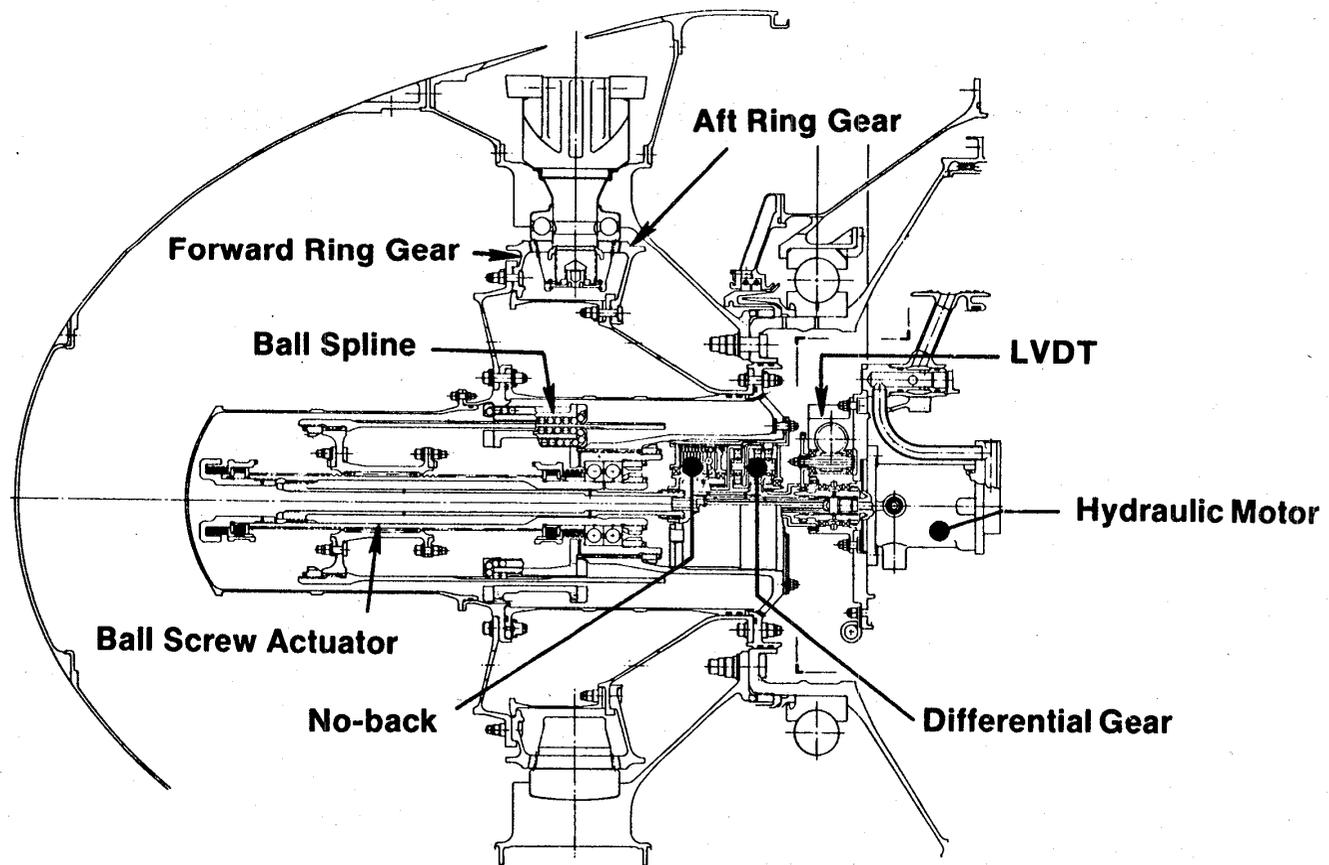


Figure 45. Ball Spline Actuation System.

The ball spline and ball screw shown in Figure 46 are the heart of the actuator assembly. Recirculating tracks of balls are lubricated by engine oil and transmit the required forces smoothly and efficiently. Ball tracks are hardened steel to assure long life. The drive package provides the input force and position intelligence for the actuation system. Two motion-feed-back transducers are mechanically coupled to the motor output shaft by gears and a spring-loaded thread arrangement.

Rig Testing - An actuator whirl-rig test was run at General Electric using the breadboard digital control. Test objectives were:

- Proof test prior to engine running
- Demonstrate actuation rates and propulsion accuracy
- Demonstrate endurance during limited testing
- Investigate compatibility with digital control

Figure 47 shows the GE system mounted in the whirl rig. This view is aft looking forward with respect to the engine. The drive package and the simulated fan blades are clearly visible.

Testing of the GE system was completed in less than two weeks. Demonstrated average actuation rate was $125^\circ/\text{sec}$. The system was compatible with the breadboard digital control, and blade positioning accuracy was demonstrated within $1/4^\circ$ in the forward-thrust mode. A system hysteresis of 3° was uncovered when actuated back and forth at zero speed, but it did not compromise testing, and no effort was made to reduce the value. Clearances that exceed design predictions in the actuator assembly appear to be responsible for this observed hysteresis.

No-back holding above maximum fan speed was demonstrated, and 50 mission cycles were run.

3.5 MAIN REDUCTION GEAR

The NASA/GE QCSEE concept is based on a lightweight, high-speed, power turbine driving a slower speed, quiet fan. This objective required a compatible, compact, lightweight, high-power-capability, main reduction gear. Two reduction gears designed, manufactured, and rig-tested by Curtiss-Wright under subcontract to General Electric have given trouble-free performance throughout the engine-demonstration program.

3.5.1 Design Requirements

The UTW QCSEE main reduction gear is shown in Figure 48. One point of interest is the maximum diameter of the gear, only 63.5 cm (25 in.). This is

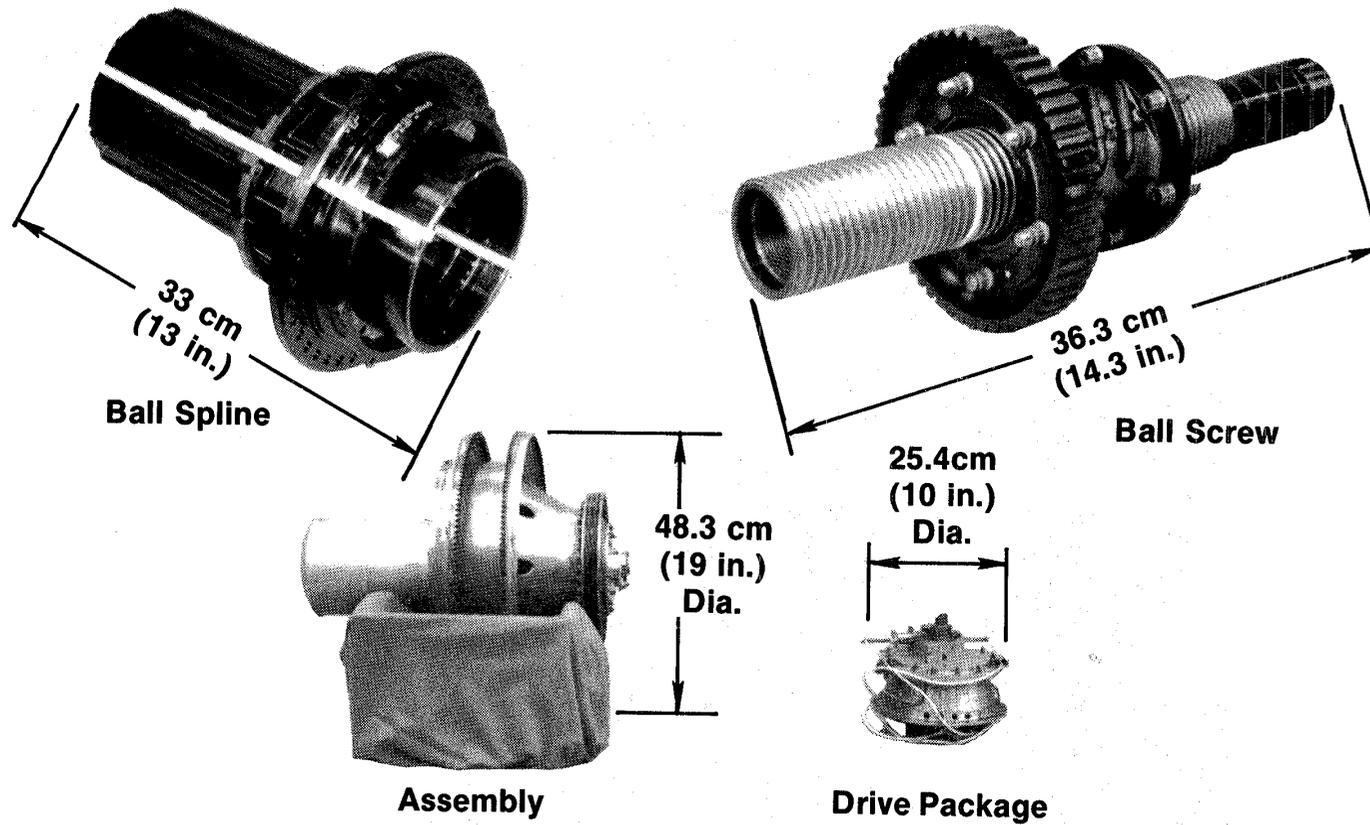


Figure 46. Pitch-Actuator Components.

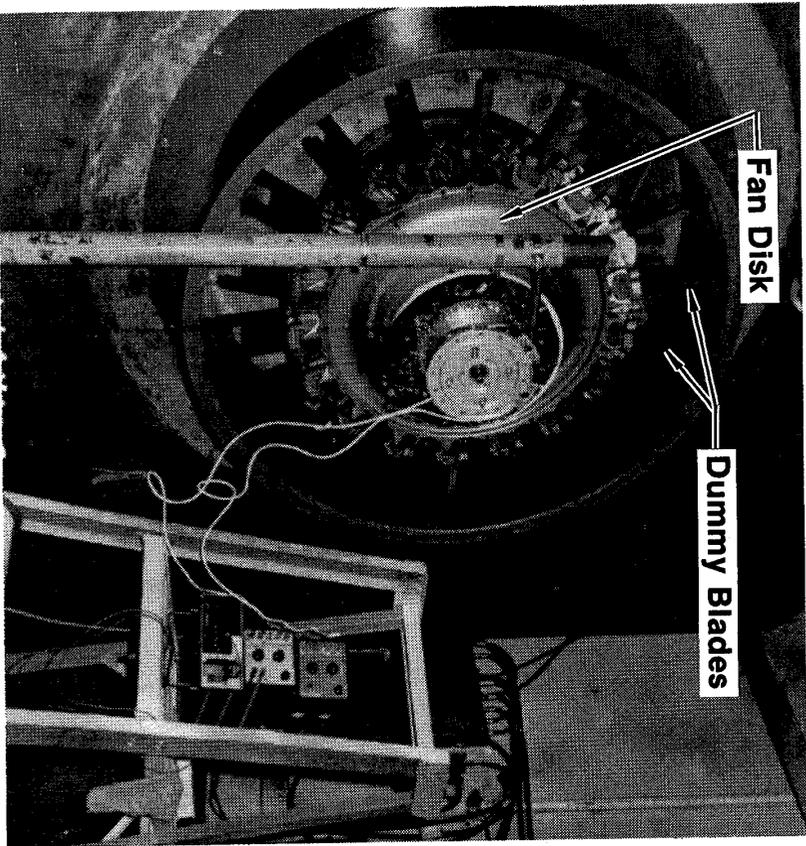


Figure 47. Whirl-Rig Test Setup.

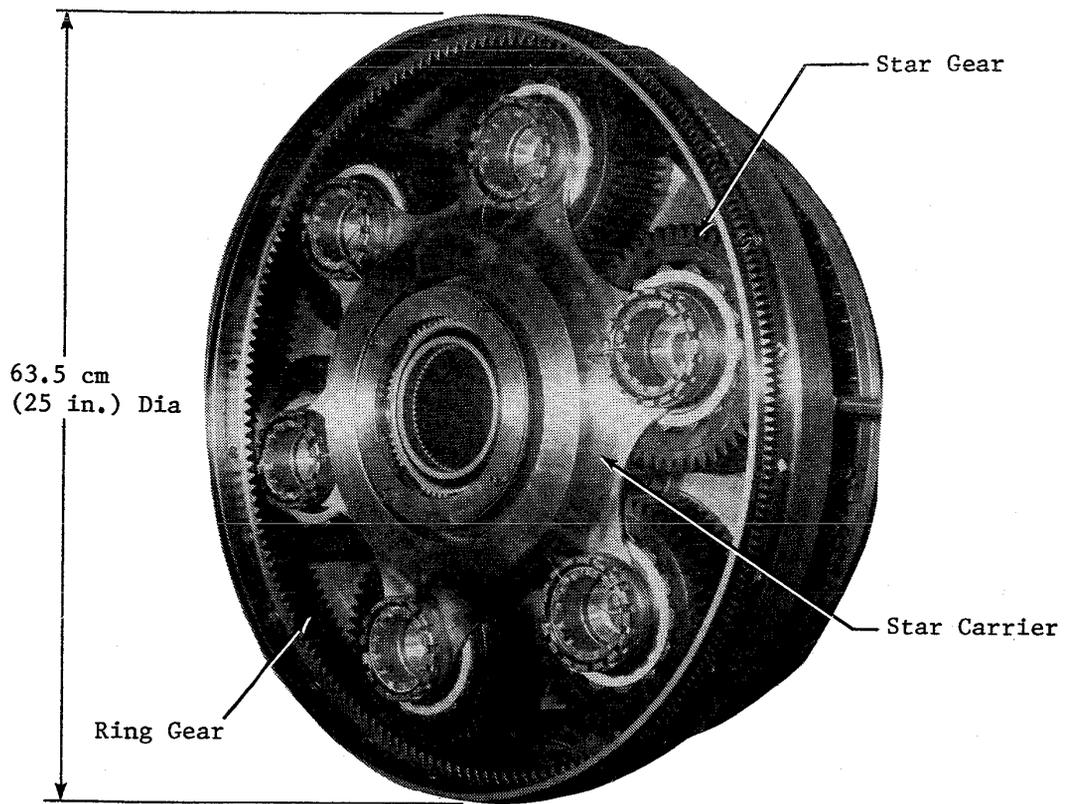


Figure 48. QCSEE UTW Main Reduction Gear.

the maximum permissible to be compatible with the required engine-housing air-flow paths.

The under-the-wing (UTW) and over-the-wing (OTW) engine concepts were based on using the same core engine but differing fan-performance characteristics. This dictated different reduction ratios and power ratings. The main reduction gear feasibility studies were directed toward approximately 2.5:1 ratio and 9321 kW (12,500 hp) at 3197 rpm fan speed for the UTW engine and approximately 2.1:1 ratio and 11,282 kW (15,130 hp) at 3782 rpm fan speed for the OTW engine. The specified operating life objectives included 36,000 hours with a minimum of 6000 hours time between overhauls (TBO).

Since light weight and minimum complexity were prime requirements for the engines, a single lubrication system for the turbine, accessory drive, and main reduction gear, using either MIL-L-7808 or MIL-L-23699 lubricant, was specified. This also meant that special attention to gear design factors (such as tooth-spacing accuracy, involute-profile modification, surface finish, gear misalignment, and contact stress) was required to ensure against scoring for these high performance gears.

Since the UTW and OTW reduction gears were both to be used on the same basic engine, identical interfaces between the reduction gears and the engine were specified. These interface points included;

- Power turbine coupling to input gear
- Gear support attachment to engine housing
- Power output gear to fan shaft
- Lubrication supply connection

Other important considerations were the capability of the reduction gear unit to be installed and removed as an assembled module and a low noise level for the reduction gear.

3.5.2 Design Approach

A number of years ago, Curtiss-Wright developed a 671-kW (9000-hp) turbo-prop military engine that included a two-stage, epicyclic, reduction gear. That reduction gear, Figure 49, had an overall reduction ratio of 7.0:1 which included a 2.67:1 reduction in the primary stage. During an early conceptual phase of the QCSEE program, use of the original YT-49 primary-stage gear was considered. As engine design studies progressed, the need for higher power capability and a different ratio were indicated, but the YT-49 reduction gear technology was still applicable. Features of the YT-49 gear utilized in the QCSEE main reduction gears include the fixed carrier star configuration, flexibility in the sun and ring gears and supports, straight spur gears, and double-row spherical roller bearings with the outer race integral with the star gear.

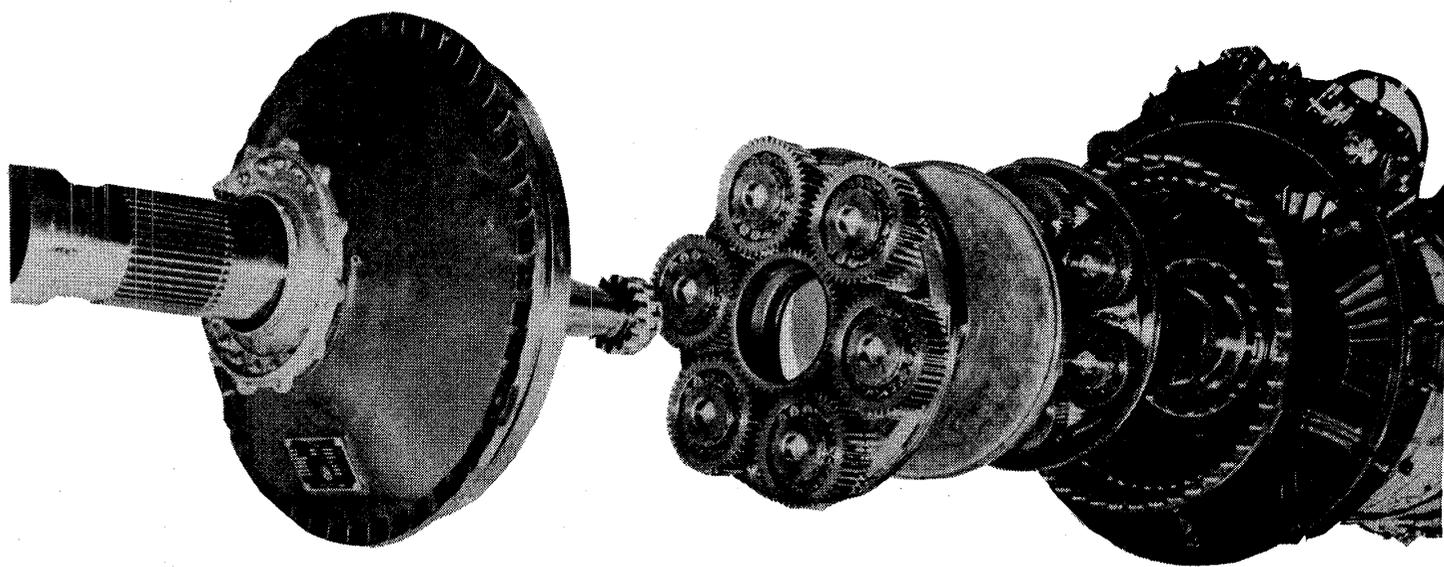


Figure 49. YL49-W-1 Reduction Gear.

A cross section of a QCSEE fixed-carrier, epicyclic, star-system reduction is shown in Figure 50.

The major components of this epicyclic star gear system are:

- Fixed star gear support
- Diaphragm-type sun gear coupling
- Sun gear
- Star gears
- Ring gear
- Lubrication system components

These gearsets were to be installed within the engine housing with the star carrier supported by the engine frame, the input gear supported by the power turbine shaft, and the output gear supported by the fan shaft.

The power input to the reduction gear is through the sun gear. With the fixed star gear carrier or support, the star gears serve as idler gears providing multiple power paths between the input sun gear and the output ring gear. In this configuration, the star gear bearings are subjected to only the tangential gear tooth loads and not to added centrifugal loads as they would be in the case of a conventional planetary with the carrier rotating.

Lubrication of the gearing is provided from the engine system through a single connecting tube to an oil manifold attached to the star gear trunnion support. An annular passage distributes oil to the individual trunnions where radial passages in the trunnions and bearing inner races provide lubrication to the star gear bearings. Spray tubes on the forward side of the manifold provide lubrication and cooling to the sun and star gear teeth. The spray tubes, which are not shown in this figure, have a number of jets spaced to distribute oil across the faces of the gear teeth.

Flexibly mounted gears are important for achieving load equalization between power paths and across the faces of the gear teeth. A double-diaphragm-type coupling is used between the turbine shaft and the sun gear. The sun gear also incorporates flexibility in the web. The objective here is to allow the sun gear to be positioned by the mesh contacts with the star gears and be subjected to minimum influence of any relative radial motion between the turbine shaft and the star gear support. With the accurate machining of the star gear bearing trunnion locations and the gears, a very high degree of load equalization with the individual star gears is achieved. A flexible section between the ring gear and the spline attachment to the fan shaft allows this gear also to be positioned by the mesh contacts with the star gears and be subjected to minimum influence of any relative radial motion between the fan shaft and the star support. A cylindrical roller bearing between the aft end

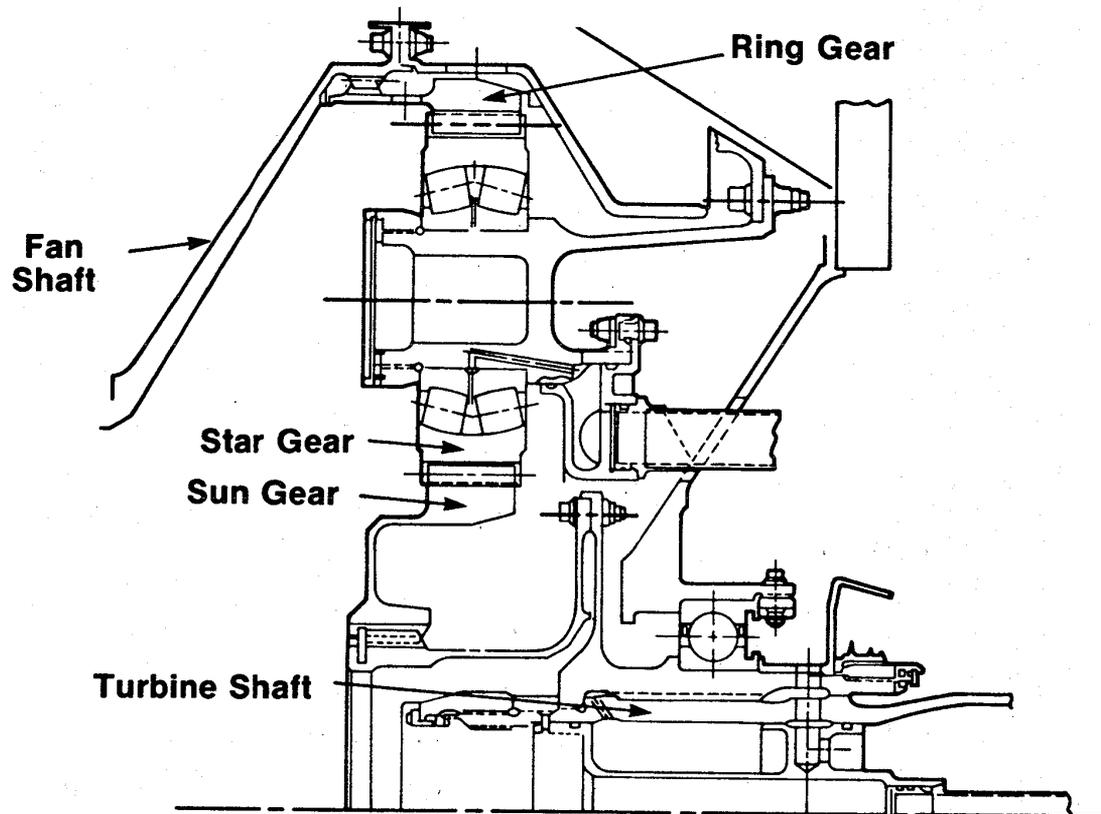


Figure 50. Reduction Gear.

of the fan shaft and the member to which the star gear support is attached also helps to maintain the relative position of the fan shaft to the star gears.

Mounting of the star gear on a double-row, spherical roller bearing allows the gear to operate in a plane defined by the loaded tooth contacts with the sun and ring gears, thus providing good load distribution across the face width. In the design of the gear rims and star gear trunnion supports, section moduli are selected to provide relatively close matching of gear and tooth deflections for the mating gear teeth at each mesh. Consequently, deviation of the plane of rotation for the star gear bearing outer race from the plane of the inner race is very small.

Design factors contributing to smooth operation and low gear noise are the use of a minimum gear-contact ratio (2) and numbers of gear teeth selected for hunting and nonfactorizing. A minimum contact ratio of 2 means that there are never less than two teeth in each gear in contact at each mesh.

In designing for hunting and nonfactorizing, the number of teeth in each gear is selected such that no two teeth in the gearset enter engagement simultaneously, and the same two teeth in mating gears repeat engagement only after engagement with all other teeth in the mating gear.

3.5.3 Design Summary

Engine and fan trade-off performance studies resulted in changes in power requirements and speed for the final UTW and OTW main reduction gear designs as shown in Table X. The UTW power increased approximately 4%, and the fan speed decreased slightly to 3157 rpm. The OTW power increased approximately 12%, and the fan speed increased to 3860 rpm. These requirements were accommodated within the originally specified envelope. The number of star gears shown, six for the UTW gear and eight for the OTW gear, are the maximum that can fit in the available space allowed by the reduction ratios.

The UTW pitch-line velocity of 97.5 m/sec (19,200 ft/min) is only slightly higher than in the YT-49 gear; that for the OTW unit is approximately 30% greater. Neither of these are considered excessive.

The star gear bearing 0.74×10^6 DN value [bearing bore (mm) x outer race rpm] for the UTW gear compares favorably with the 0.72×10^6 DN value for the YT-49 reduction gear. The 0.90×10^6 DN value for the OTW star gear bearing is higher than any known previous experience for a double-row, spherical roller bearing.

Design oil-flow rates shown are divided between the star gear bearings and the gears. Approximately 35% of the flow goes to the bearings and 65% goes to the gear through the spray-tube jets. The flow split for each spray tube is approximately 50% to the sun gear and 50% to the star gear on the out-of-mesh side.

Table X. Main Reduction Gear Design Summary.

	<u>UTW</u>	<u>OTW</u>
• Gear Ratio	2.465	2.062
• Power Transmitted, kW (HP)	9708 (13,019)	12,610 (16,910)
• Maximum Fan Speed, RPM	3157	3860
• Number of Star Gears	6	8
• Pitch Line Velocity, m/s (ft/min)	97.5 (19,200)	119.3 (23,450)
• Pressure Angle, Degrees	21	21
• Diametral Pitch	7.5321	7.1884
• Bearing dN	.74 x 10 ⁶	.9 x 10 ⁶
• Oil Flow, m ³ /s (GPM)	.0833 (22)	.0945 (25)
• Heat Rejection, kJ/s (BTU/min)	116 (6600)	190 (10,800)
• Maximum bearing Temp., K (°F)	417 (290°)	417 (290°)

Materials selected for the QCSEE main reduction gears were carburized AMS 6265 for the sun gear, star gears, and the coupling; nitrided AMS 6470 for the ring gear; and AMS 6415 for the star gear carrier. Heat-treat data for the gears are:

Sun and star gear teeth:

Finished case depth - 0.635-0.889 mm (0.025-0.035 in.)

Case hardness - R_c 60-63

Core hardness - R_c 32-40

Star gear spherical raceway:

Finished case depth - 1.524-1.778 mm (0.060-0.070 in.)

Case hardness - R_c 60-63

Ring gear -

Nitride depth - 0.51 mm (0.020 in.)

Case hardness - 15N91 minimum

Maximum limits selected for the gear design stresses were approximately 24.1 kN/cm² (35 ksi) bending and 93.1 kN/cm² (135 ksi) contact. These are well below AGMA allowables and Curtiss-Wright operating experience.

The spherical roller bearings have CEVM M-50 steel inner races and rollers and AMS 4616 silicon bronze, silver-plated cages.

3.5.4 Hardware Fabrication

Two UTW gearsets and three OTW sets were manufactured. Two sets of each were required for the back-to-back rig test, and one each of these test gearsets were subsequently installed in the engines.

3.5.5 Rig Testing

Primary objectives of the rig test program were to demonstrate satisfactory operation and to determine operating characteristics of each of the reduction gear designs prior to installation in the engine. Testing was conducted with two essentially identical reduction gears installed in a back-to-back test rig and torque-loaded to simulate engine operating conditions.

Figure 51 shows a schematic cross section of the upper half of the test rig in which some engine reduction gear cavity and oil scavenging characteristics are simulated. The reduction gears are mounted by the star gear support in each end of the rig. The sun gears are connected through engine-type

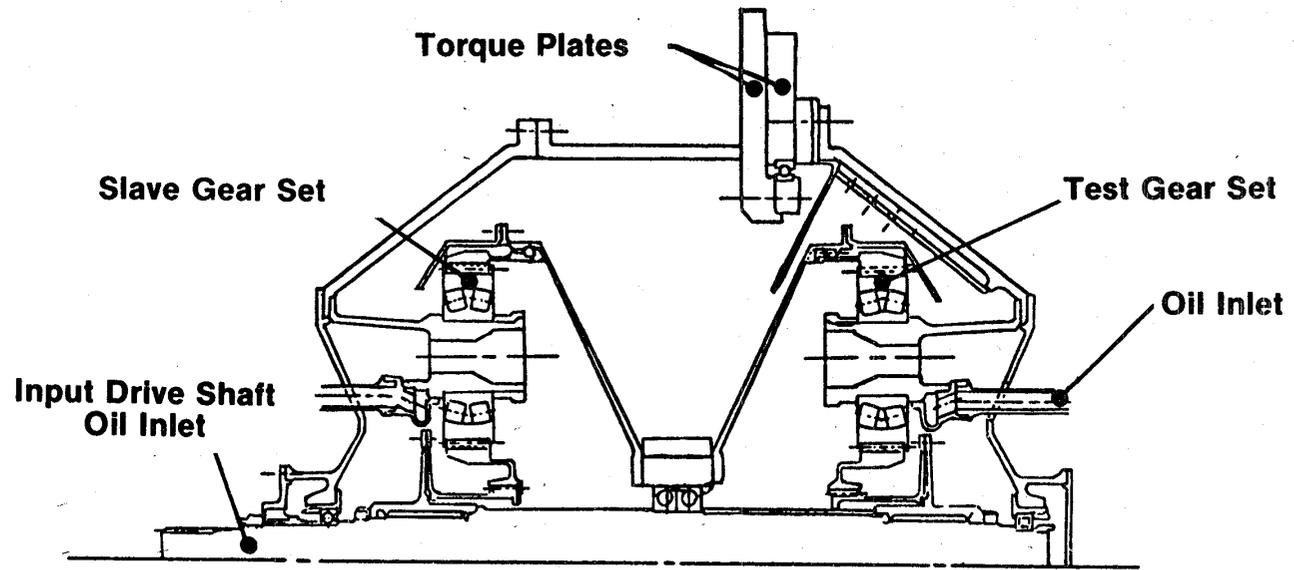


Figure 51. Main Reduction Gear Test Rig Schematic.

diaphragm couplings and the input drive shaft. The ring gears are supported and connected by simulated fan shafts. An engine-type antichurning and scavenging oil screen was installed in the test gear end of the rig. Oil is supplied to the gears through engine-type oil-inlet tubes. Rotation of one gear assembly relative to the other introduces the torques into the gear system.

Figure 52 shows the drive end of the test rig and also the torque-loading hydraulic cylinders that, by the application of hydraulic pressure, rotate one end of the rig relative to the other and apply the load to the gears.

Significant results of the rig test are shown on Table XI. The reason for the OTW unit not being operated to 100% speed at 100% torque was not the fault of the gear but rather an overestimate of the capability of an aged motoring dynamometer when planning the test program.

The reduction gear efficiencies were a little lower than had been expected, but it is believed improvement could have been accomplished through some lubrication and scavenging development in the vicinity of the sun and star gears.

The engine-hardware oil-baffle screen was installed in the test gear end of the rig at the start of the test program to verify or predict the scavenging characteristics of the engine. The rig operation appeared to indicate marginal scavenging accompanied by oil churning. Several scavenging and baffle-screen modifications were evaluated. The OTW gear, with the higher pitch-line velocity, appeared to be the more critical.

Upon conclusion of the rig test programs, the test gears were thoroughly inspected and prepared for installation in the engines.

3.6 COMPOSITE FAN FRAME

One of the major areas of new technology investigated under the QCSEE program was the application of advanced composite materials to major engine hardware. Two types of static structure were demonstrated during the program. The first of these was the fan frame, a structure requiring both high strength and stiffness. This is the main support point for the engine and will be discussed in some detail covering the frame requirements, structural description, design, analysis, fabrication, and testing. The second type of static structure that utilized advanced composite material was the nacelle; the nacelle is discussed in the next section.

The graphite/epoxy fan frame, shown in Figure 53, is the largest highly loaded advanced-composite structure yet built for a turbofan engine. It is the first time the major structural support for such an engine was constructed utilizing advanced composite materials for virtually all components. It has been estimated, based on two smaller composite-frame programs conducted in 1972 through 1974, that this type of application could save from 25% to 35% in weight over an equivalent metal frame. These previous programs generated sufficient technical confidence to undertake the design and fabrication of advanced composite frames without a backup metal frame.

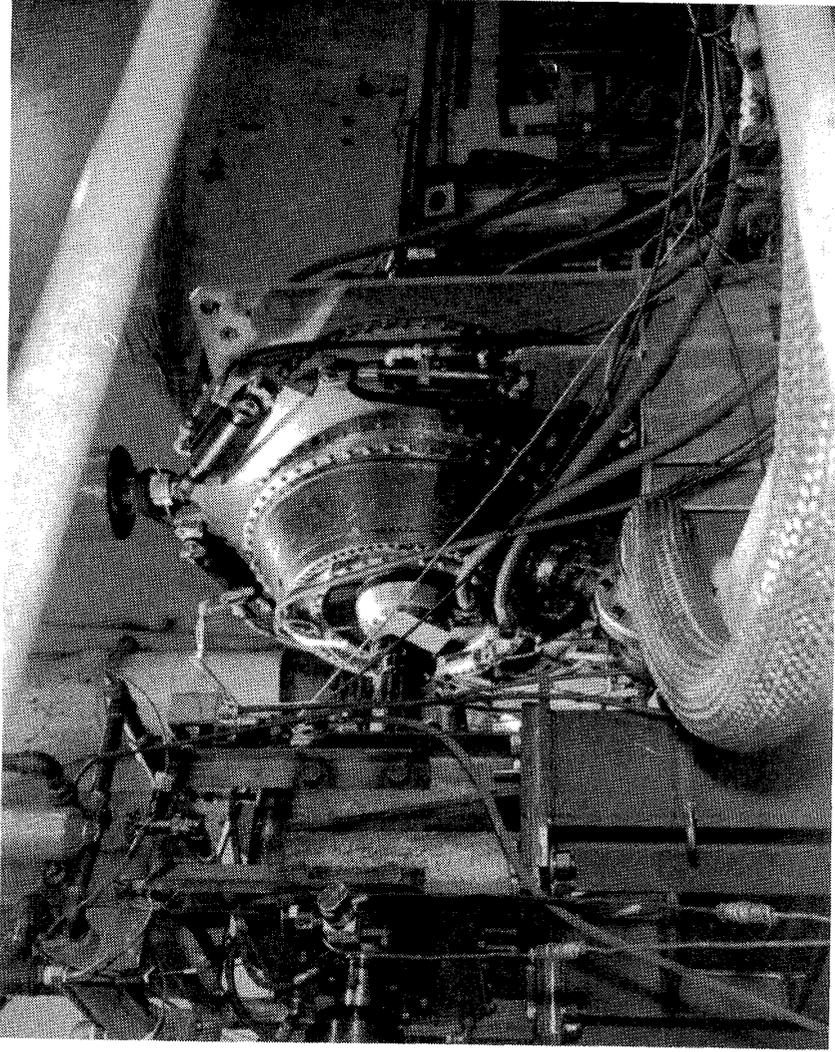


Figure 52. Main Reduction Gear Test Rig,
Slave Unit (Drive) End.

Table XI. Rig-Test Results.

	<u>UTW</u>	<u>OTW</u>
• Demonstrated		
Speed/Torque, %	100/125	80/109*
	105/50	95/50*
		*Limited by Drive Power
• Completed	48.8 hr	36 hr
• At Max Speed and Torque, 344K (160° F) Oil Inlet		
Oil ΔT =	294K (70° F)	321K (119° F)
Oil Flow =	80 kg/min (177 lb/min)	91 kg/min (200 lb/min)
η Mech =	98.9%	98.7%
• Developed Lube/Scavenging System Through Several Configurations		

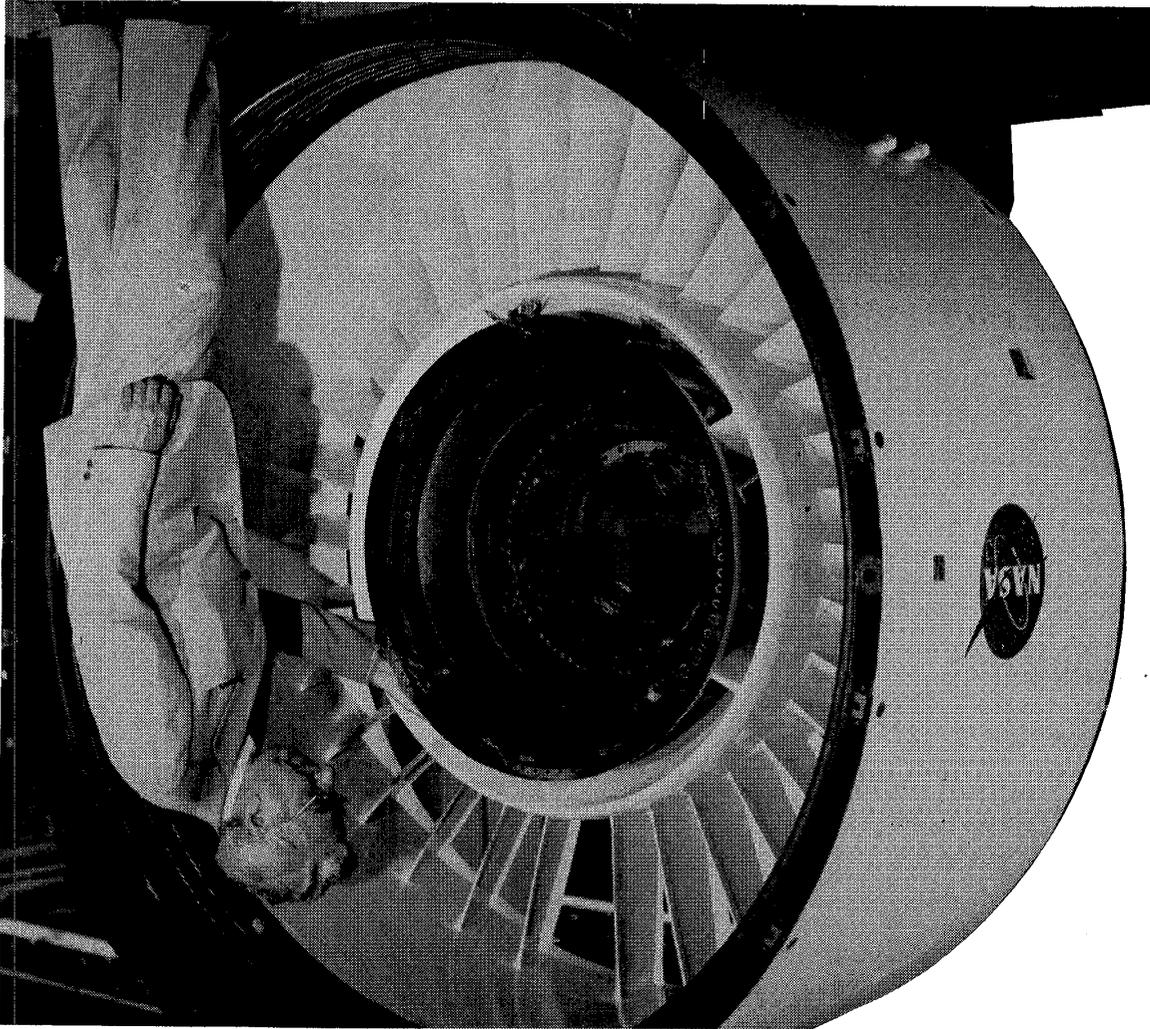


Figure 53. GCSEH Fan Frame.

This program thus provided the somewhat unique opportunity to design a major composite structure from an original-equipment point of view rather than a replacement component in an existing-engine design. This permitted a much more integrated structure than is possible when constrained by the necessity of mating with existing hardware.

The differences between the OTW and UTW frames were so minor as to have no effect on the basic frame structure. For simplicity, all further discussion will pertain to the frame used in the UTW propulsion system.

3.6.1 Design Requirements

The QCSEE frame design was governed by the necessity for performing the following major structural and aerodynamic functions:

- Provide the main engine forward-attachment points for thrust, vertical, and side loads.
- Support the fan thrust bearing, variable-pitch system, reduction gear, and compressor thrust bearing.
- Support the inlet, aft outer, and aft inner core cowls.
- Support the core compressor at the forward casing flange.
- Support the fan hub OGV's.
- Provide the mounting position for the accessory gearbox and digital control.

3.6.2 Structural Description

As can be seen in Figure 54, the QCSEE integrated fan frame is a graphite/epoxy structure that incorporates the fan casing, fan bypass stator vanes, and core frame into one all-bonded structure. It provides the primary support for the engine. Fan blade-tip treatment and containment are provided by the grooved and Kevlar-filled structure integrated in the forward portion of the outer casing. Positioning of the fan and core engine-bearing supports relative to the integral nacelle/outer casing is provided by 33 bypass vanes that also provide flow-turning of the fan discharge. Due to the blockage caused by a pylon at the 12 o'clock position, the camber of these vanes is tailored individually depending on circumferential position.

The hub of the frame is connected to the frame splitter through six equally spaced struts. The inner shell of the outer casing, the bypass duct and core duct surfaces of the frame splitter, and the pressure faces of the bypass vanes are perforated to provide acoustic suppression within the frame structure.

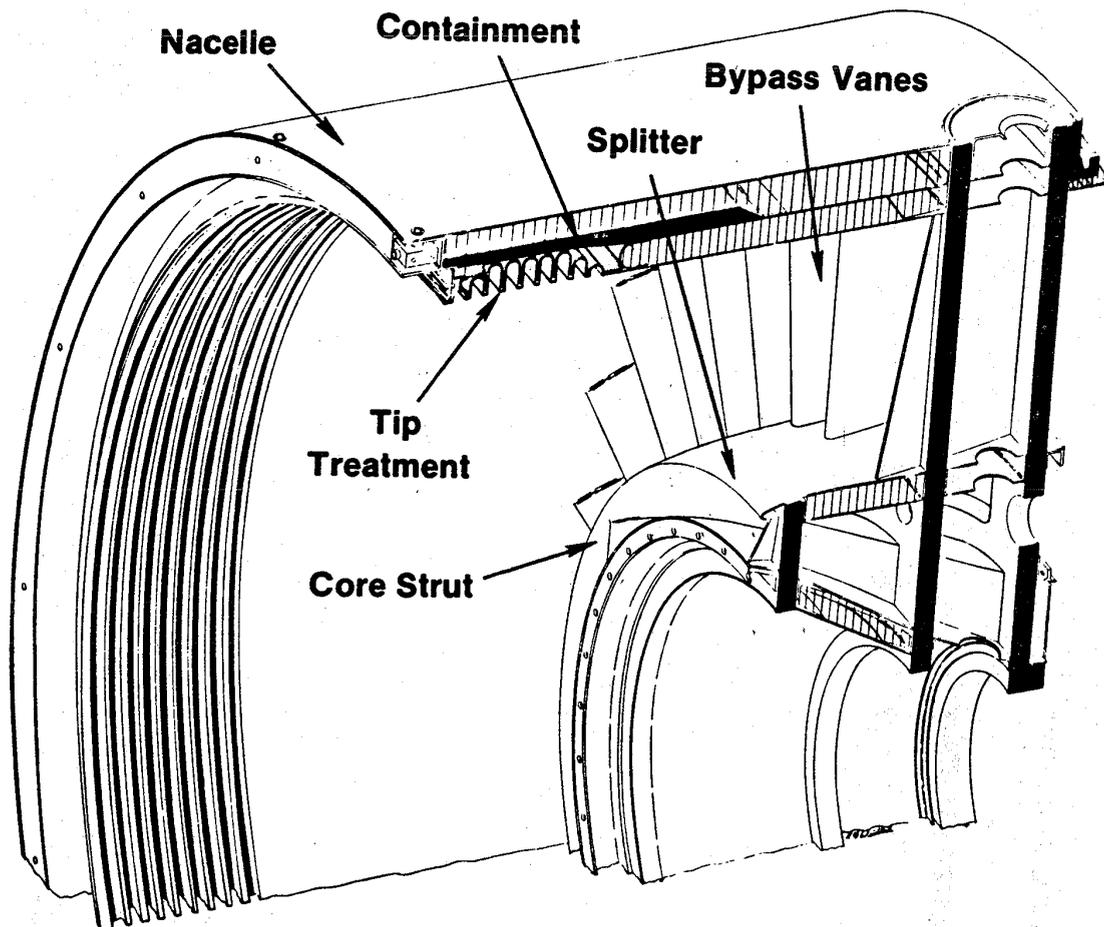


Figure 54. QCSEE Integrated Fan Frame.

The frame was designed based on the load conditions shown in Table XII. The magnitudes of some of the more critical of these loads are shown in Figure 55. The basic structural concept used in the frame design is also shown in this figure. The primary radial members of the frame consist of three wheel-like structures. The forward wheel is a flat-spoked wheel comprised of a splitter ring, hub ring, and six spokes. The middle and aft wheels are flat-spoked wheels consisting of an outer casing ring, splitter rings, and 33 spokes connecting the outer casing ring to the splitter ring. Shear panels of the proper aerodynamic shape are bonded to these wheels to form the fan bypass stator vanes and the struts in the core flowpath.

The aft splitter ring contains the engine-mount attachment points. These consist of a metal uniball at the 12 o'clock position, to react vertical and side load, and two metal thrust brackets located 45° down on either side of the uniball.

The internal load distribution for the frame was determined using a finite-element computer program which represented the frame structure as a combination of curved beams, straight beams, and plates, all capable of having orthotropic material properties. A graphic comparison of the analytical model to the actual hardware is shown in Figure 56. In the core region of the frame, the struts were modeled as three straight beams (representing the spokes of the wheels) connected to curved beams in the hub and splitter region (rims of the wheels), all tied together by plates representing the flowpath and splitter walls. The fan flowpath area was represented by radial beams representing the bypass vanes (wheel spokes and flowpath panels were lumped together and appropriate section properties used for these pseudobeams) tied to plates representing the outer casing forward to the inlet. Appropriate structure was also included to represent the mount structure and the compressor case back to the turbine frame.

Several iterations were made on thickness and orientations of the various elements of the model to arrive at an efficient structure which would meet the design requirements. By these iterations it was possible to take advantage of the ability to tailor composite materials to the specific load requirements of the individual components. As can be seen in Table XIII, a considerable amount of tailoring was possible.

Once the material configurations were selected, the computer model was used to determine the final internal stresses in the frame components. Several of the most critical of these are shown in Table XIV along with the allowable stress for the specific layup pattern for the component. The "design calculated stress" for the "critical flight" conditions shown is a conservative three times the actual calculated stress for that condition. As can be seen in Table XIV, the stress allowable, as verified by material-properties tests, always exceeded the design calculated - indicating a safe design. The effect of different thermal coefficients where the titanium bearing cones attached to the composite structure was also accounted for, as shown in Table XV.

Table XII. Frame Loading Conditions.

- **Operating**
 - **Flight and Landing**
 - **Gust Load Plus Crosswind and Max Thrust**
 - **Side Load — 4g Plus 1/3 of Gust Load**

- **Emergency**
 - **Seizure — Decelerating From Max. Speed to Zero in One Second**
 - **Crash — 9g Fwd, 2.25g Side, 4.5g Down,
Max Thrust — 12g Fwd at Zero Thrust**
 - **Blade Out — Loss of Five Adjacent Composite Fan Blades at Max. RPM**

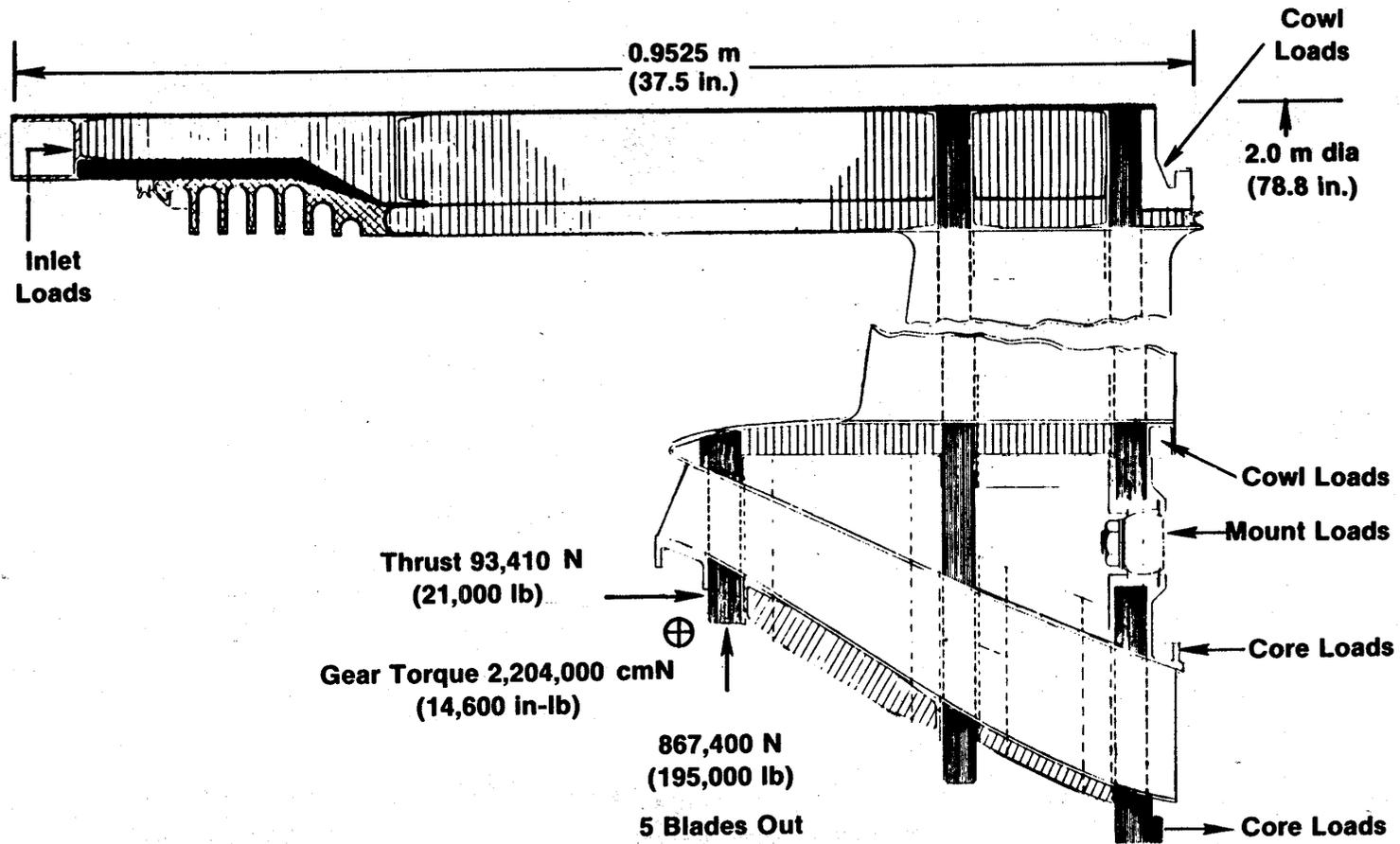


Figure 55. QCSEE Composite Frame.

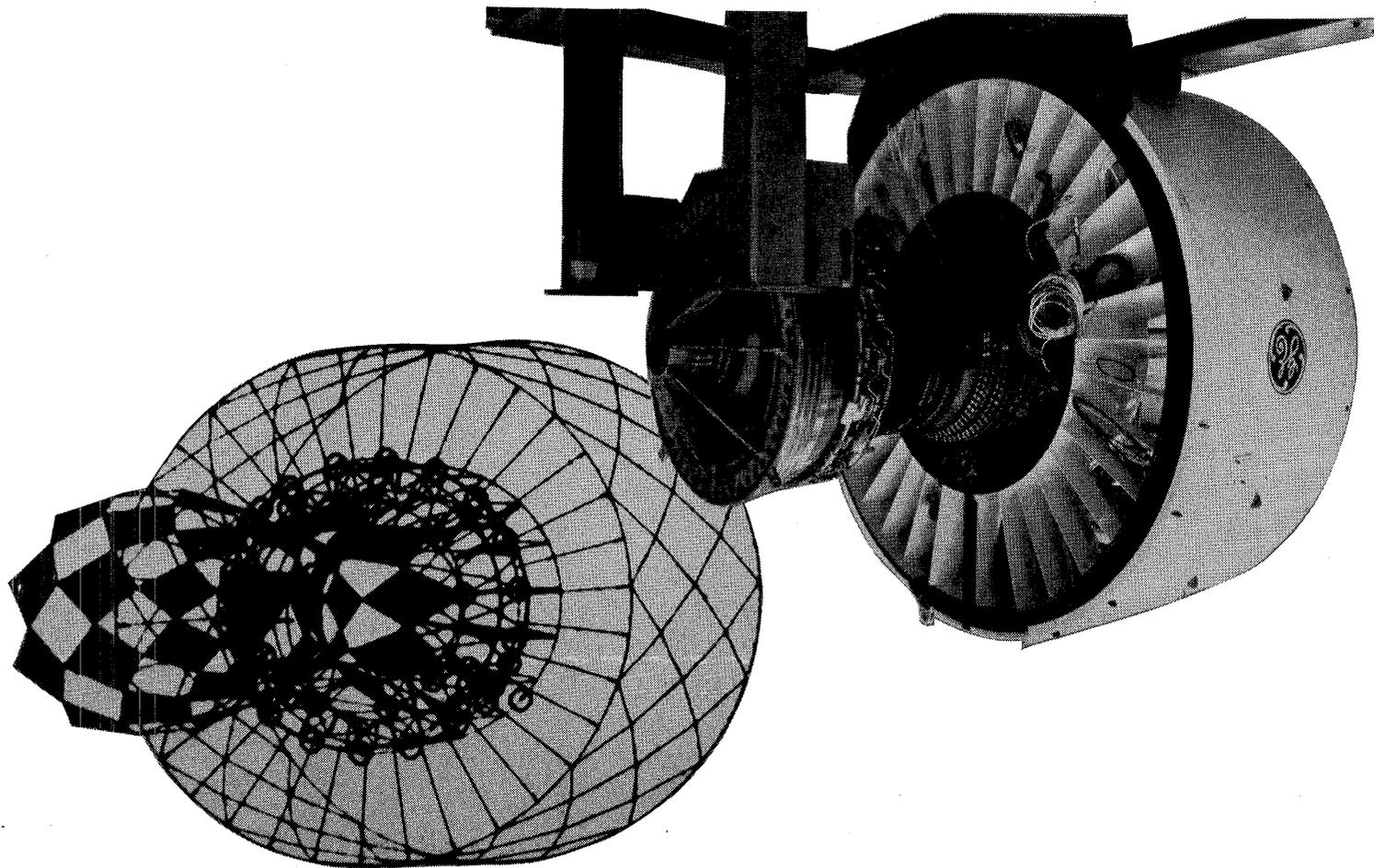


Figure 56. Analytical Model Comparison.

Table XIII. Geometry of Composite Frame Components.

Material Type-AS Graphite/3501 Epoxy

<u>Item</u>	<u>Layup Conf.</u>			<u>0° Datum</u>
	0°	± 45°	90°	
Forward "Wheel"	50%	20%	30%	Radial
Middle "Wheel" and Aft	30%	20%	50%	Radial
Nacelle Panel	28.5%	57%	14.5%	Axial
Bypass Vane Panel	40%	40%	20%	Radial
Bypass Vane Spoke	80%	20%	0%	Radial
Bypass Vane Outer Ring	30%	20%	50%	Radial
Core Vane Panel	25%	50%	25%	Axial
	40%	40%	20%	Axial

Table XIV. Frame Component Stress.

<u>Load Condition</u>	<u>Location</u>	<u>Design Calculated Stress N/cm² (psi)</u>	<u>Stress Allowable N/cm² (psi)</u>
5 Airfoils Out	Forward "Wheel" Hub Ring	37,230 (54,000)	42,750 (62,000)
5 Airfoils Out	Forward "Wheel" Spoke	53,570 (77,700)	65,500 (95,000)
Critical Flight	Bypass Vane Panel	40,920 (59,349)	57,230 (83,000)
5 Airfoils Out	Core Panel	8600 (12,471)	17,240 (25,000)
Critical Flight	Nacelle Panel	12,700 (18,417)	27,580 (40,000)

Table XV. Effect of Different Thermal Coefficients.

<u>Ring</u>	<u>$\alpha(\text{RING} - \text{G/E})$ cm/cm/°K x 10⁻⁶ (In/In/°F x 10⁻⁶)</u>	<u>$\alpha(\text{BRG} - \text{T 6-4})$ cm/cm/°K x 10⁻⁶ (In/In/°F x 10⁻⁶)</u>	<u>Thermal Stress N/cm² (psi)</u>	<u>Total Ring Stress Ncm² (psi)</u>	<u>Allowable Stress N/cm² (psi)</u>
FWD HUB	4.5 (2.5)	8.46 (4.7)	2070 (3000)	39,300 (57,000)	42,700 (62,000)
MID HUB	2.34 (1.3)	8.46 (4.7)	4830 (7000)	25,500 (37,000)	60,000 (87,000)
AFT HUB	2.34 (1.3)	8.46 (4.7)	4830 (7000)	18,600 (27,000)	60,000 (87,000)

Since one of the most critical areas of composite structures is the joining of the individually molded pieces, either by bonding or mechanical fastening, the critical joint areas of the frame were investigated by a series of individual subcomponent tests representing these areas. A total of 36 specimens representing 21 different areas of the frame were fabricated and tested to failure. In all cases, the failing load of the subcomponent was in excess of the maximum design requirements of the area represented. A summary of some of the more critical of these tests is shown in Table XVI, and a typical failed subcomponent is shown in Figure 57.

3.6.3 Fabrication

Designing the frame was only the first part of the problem. It then remained to devise means for fabricating this large composite structure that, by its very nature, required new frame-fabrication concepts.

The fabrication of the QCSEE composite frame was a cyclic manufacturing process of bonding numerous premolded-graphite/epoxy parts and then machining the required interfaces in preparation for the next bonding cycle.

Since only two frames were to be fabricated, the fabrication process was designed to require a minimum amount of tooling - substituting hand benching and machining in its place. Although this is counter to the approach that would be employed in a production situation, it was felt that this would result in a lower overall cost in this case.

The frame was fabricated as two major subassemblies: the basic frame structure and the fan casing.

The basic frame subassembly required the prefabrication of the three wheels that provide the frame backbone. The forward wheel was cured-out as one piece; however, the much larger middle and aft wheels were made by adhesively bonding a great many precured pieces in a steam-heated press. The assembly of the pieces of such a wheel is shown in Figure 58, and the completed wheel, just out of the press and prior to machining, can be seen in Figure 59.

After these wheels were complete, the frame assembly was initiated by bonding the middle wheel to the aft wheel using preassembled honeycomb-box structures to space the wheels axially at both the outer rings and the splitter rings. The forward wheel was then added in the same fashion. This assembled wheel structure is shown in Figure 60.

To complete this subassembly, the precured sump cone was bonded in place as well as the precured core-strut skins and bypass-vane skins. With the addition of appropriate reinforcing structure, this completed the frame subassembly.

Table XVI. Subcomponent Test Results.

<u>Type</u>	<u>Location</u>	<u>Required</u>	<u>Test</u>
Core Strut/Ring	FWD	177,900 N (40,000 lb)	245,530 N (55,200 lb)
Core Strut/Ring	MID	214,000 N (48,100 lb)	298,000 N (67,000 lb)
Core Strut/Ring	AFT	20,000 N (4,500 lb)	105,000 N (23,700 lb)
Core Strut/Ring (Bending)	FWD	128,800 cmN (11,400 in.-lb)	165,000 cmN (14,600 in.-lb)
Core Ring (I.D. in Comp.)	FWD	18,080 cmN 1,600 in.-lb	427,140 cmN 37,800 in.-lb)

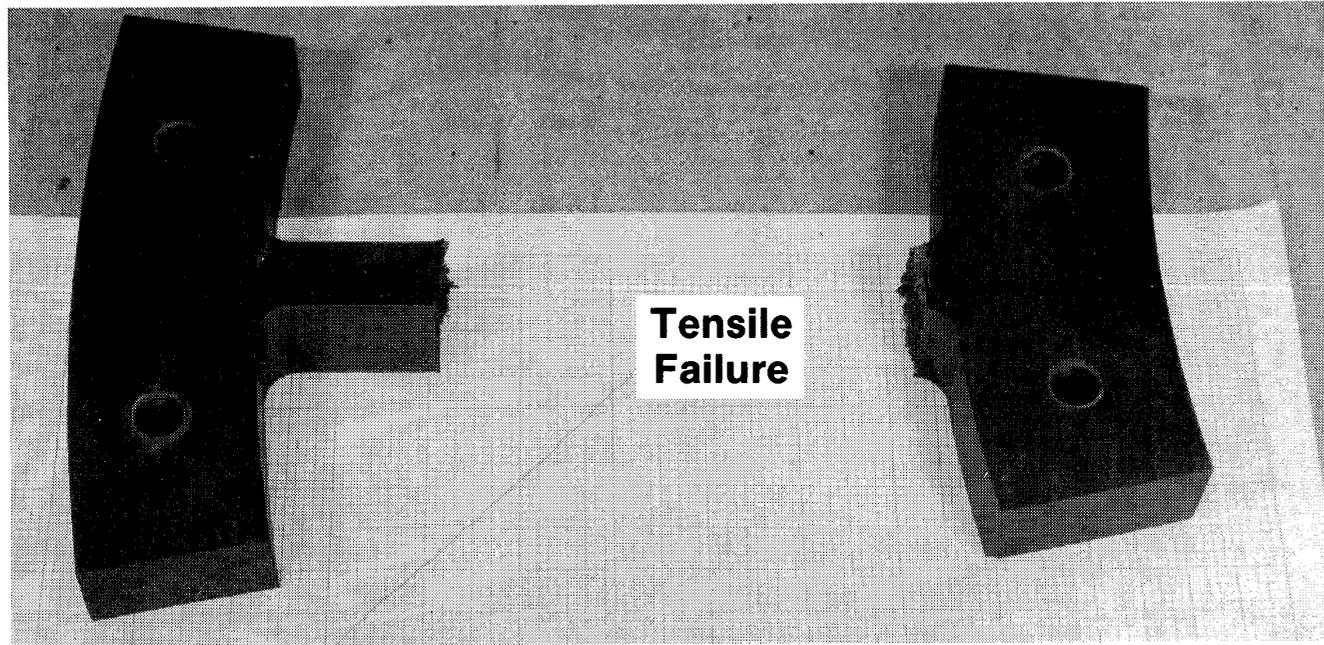


Figure 57. Spoke Subcomponent Test.



Figure 58. Assembly of Aft Wheel.

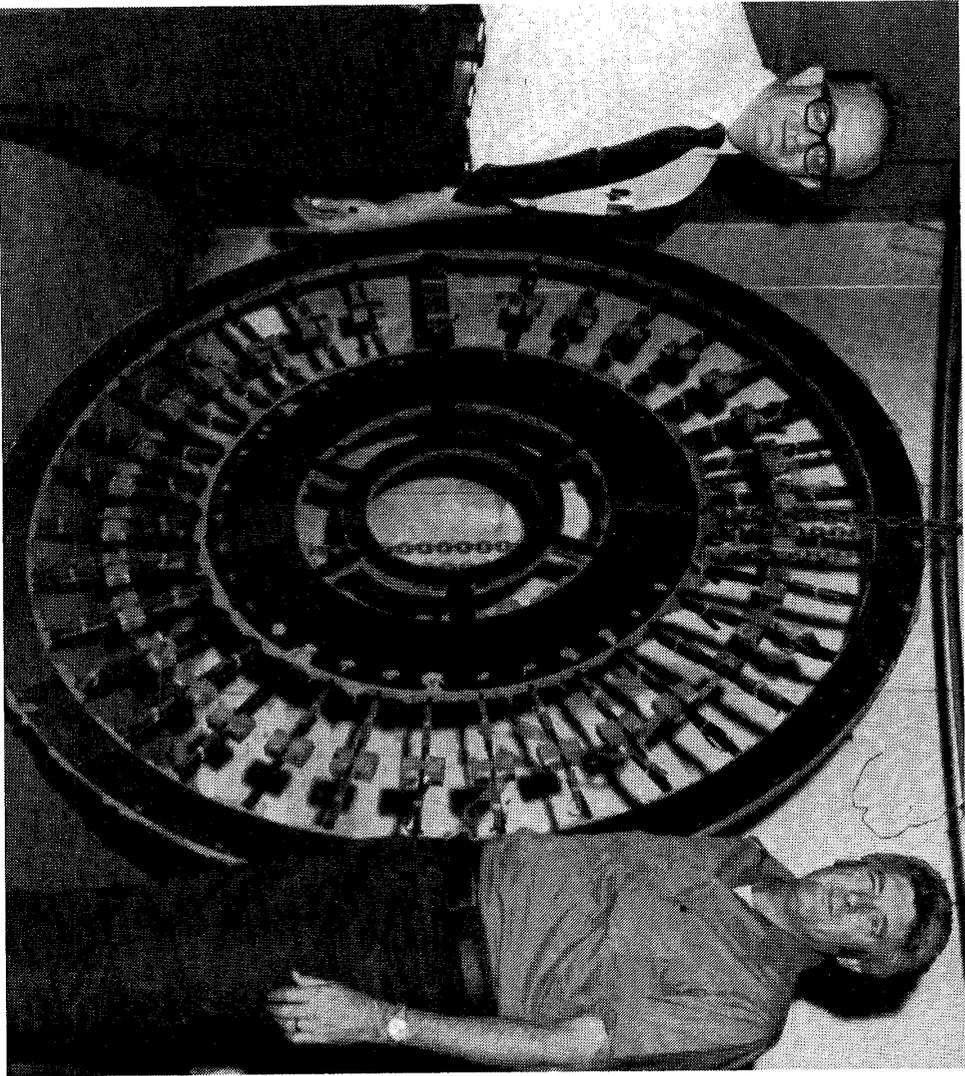


Figure 59. QCSEE Art Wheel.

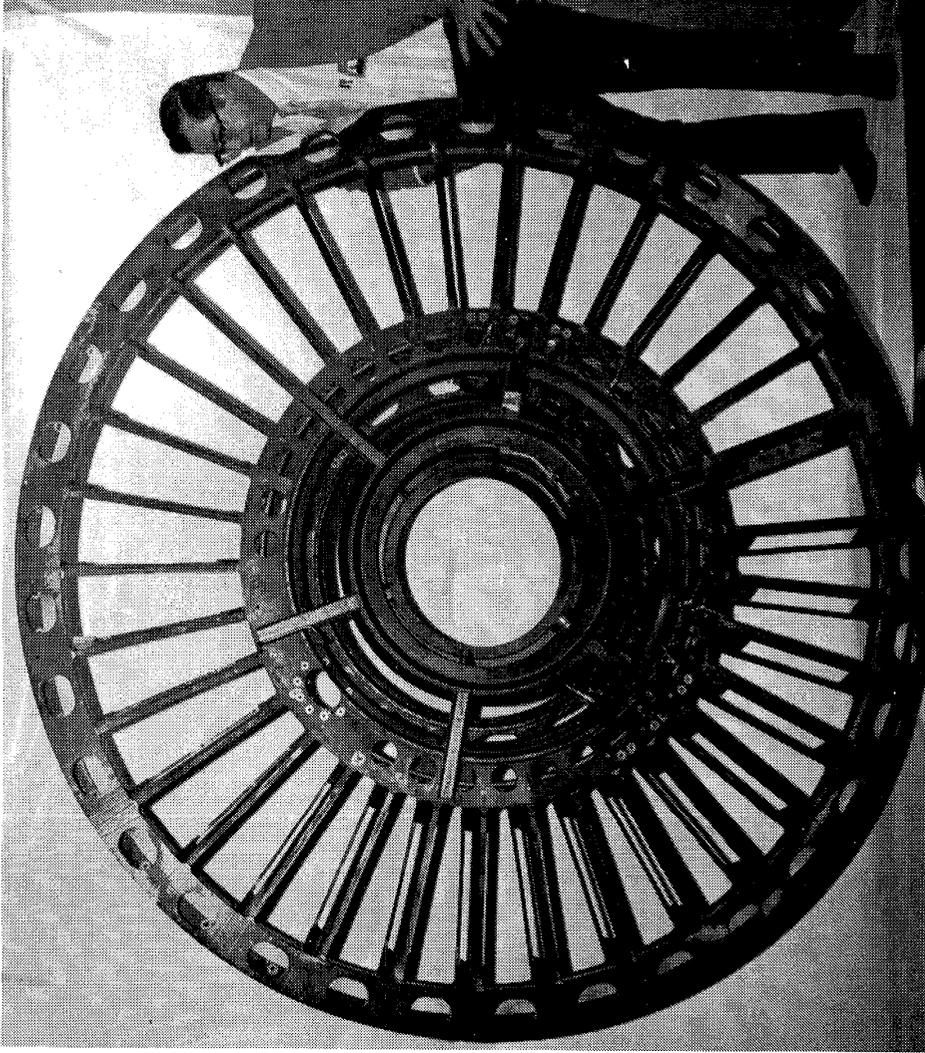


Figure 60. Assembled Wheel Structure.

The outer casing subassembly was sequentially assembled on a male tool, cylindrical in shape, while the skins that went into the assembly were precured in 120° segments in a female tool.

The first step was to precure the fan flowpath skins. This was the surface requiring acoustic holes. These holes were laser drilled as shown in Figure 61. This skin was put on the male tool and the tip-treatment components bonded in place as shown in Figure 62. A layer of aluminum honeycomb of the proper depth for the acoustic requirements was then bonded in place and a septum skin added to provide the back face of the acoustic panel. The containment system was installed at this time. Another layer of honeycomb was then added to obtain the proper casing depth. This completed the basic structure of the fan casing subassembly, seen in Figure 63, since the outer skin would not be attached until the casing was assembled to the basic frame.

At this point, the two major subassemblies were mated (Figure 64), the fan casing outer diameter ground to the proper dimensions, and the fan casing outer skin bonded in place. This completed the frame structure. All penetrations into the core were sealed, instrumentation and services installed, and the frame painted. The completed frame is shown in Figures 65 and 66.

3.6.4 Testing

The fan frame was subjected to a series of static-load tests to verify the overall structural adequacy. All loads were applied to the frame through a simulated forward-fan-bearing cone and a simulated inlet. To simulate the proper boundary conditions on the frame, it was bolted to a simulated core engine. This assembly was then supported from the facility through the actual engine-mount locations (Figure 67). In addition to determining the actual frame stiffnesses, the frame was tested to the loads imposed by the maximum operating thrust, thrust plus a 51.4-m/sec (100-knot) crosswind, and thrust plus the unbalance due to one blade out. The frame survived these tests with no damage, and recorded stress levels were in good agreement with predictions.

3.7 COMPOSITE NACELLE

The flight-type nacelle for the UTW engine was a major area of composite application to static structures in the QCSEE program. Virtually everything shown in Figure 68, except for the test facility and some tubing, is constructed from advanced composite materials. In addition to the fan frame discussed in the previous section, the inlet, outer cowl, and the fan nozzle can be seen. In addition, the inner cowl was also constructed of advanced composite material. These can be seen in the cut-away drawing shown in Figure 69.

3.7.1 Inlet

The inlet is of fairly conventional composite construction utilizing Kevlar/epoxy skins on aluminum-honeycomb core. The inner barrel comprises

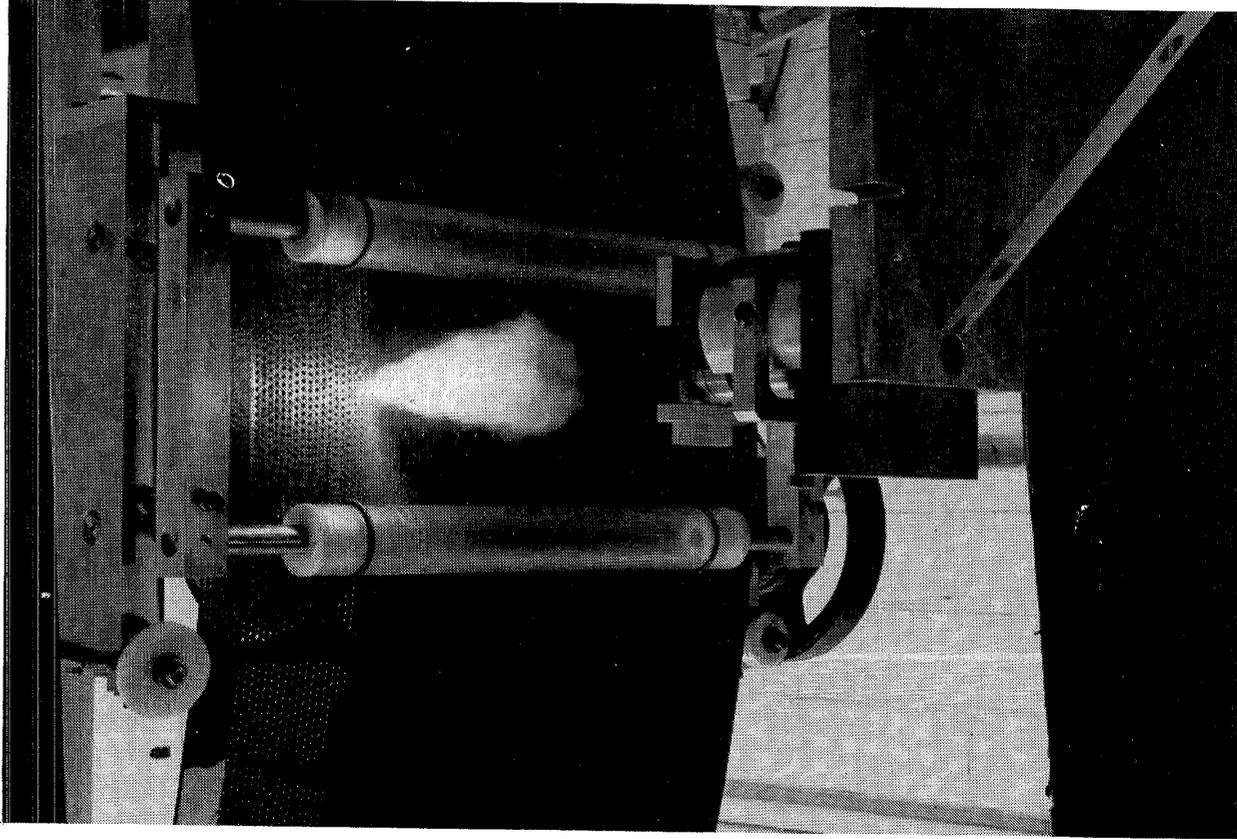


Figure 61. Laser Drilling of Acoustic Holes.

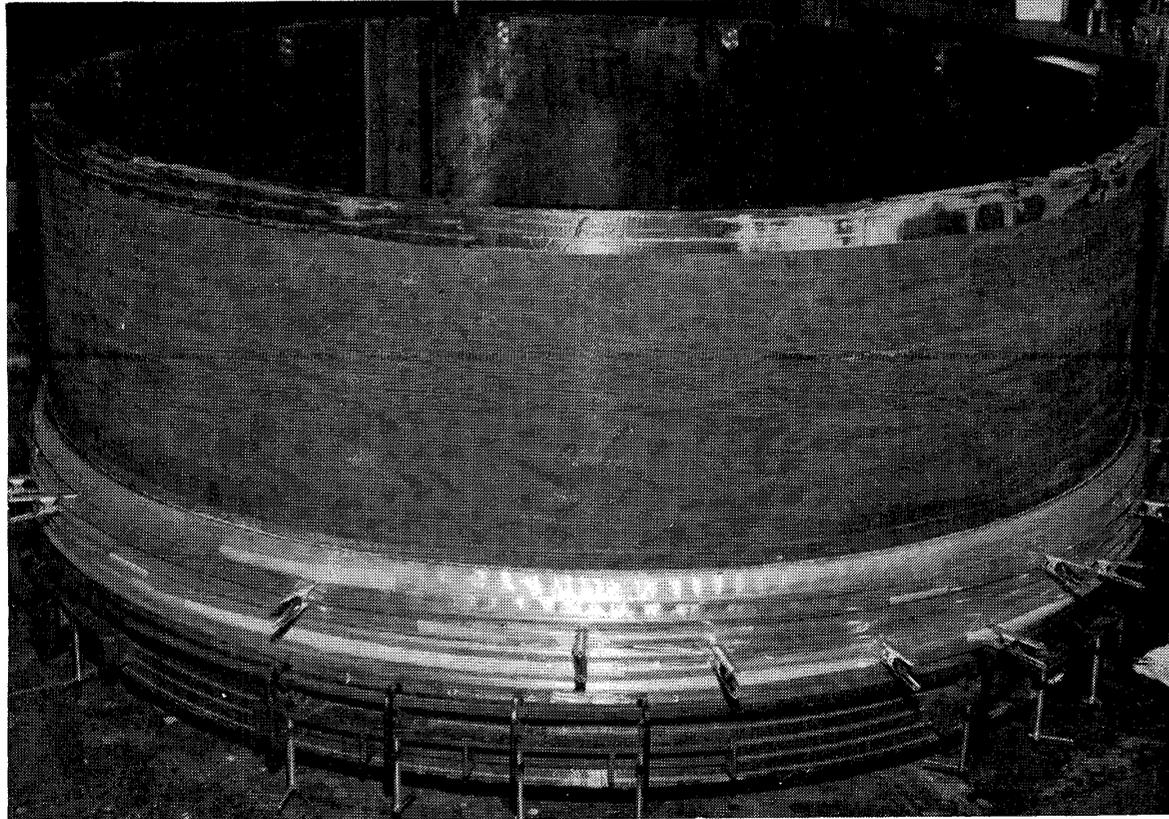


Figure 62. Fan Casing Fabrication.

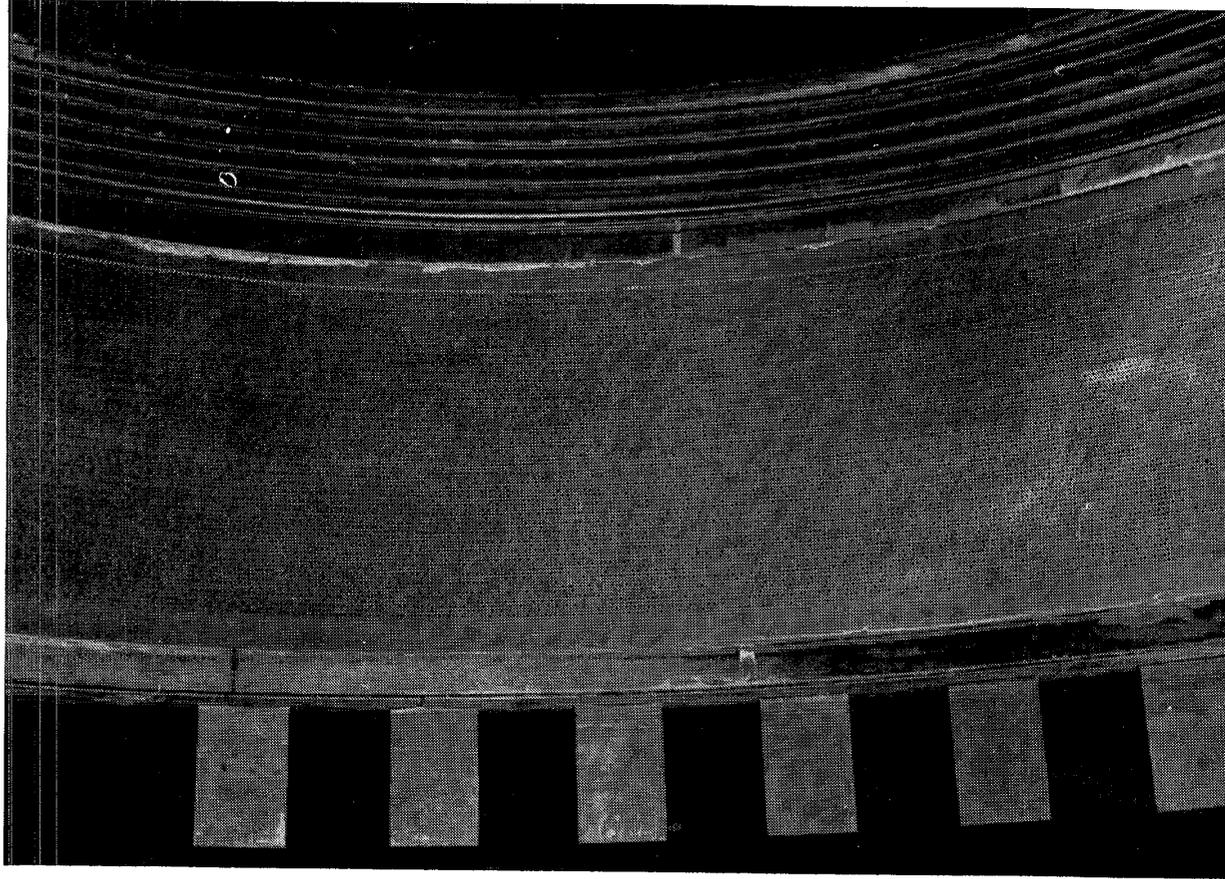


Figure 63. Fan Casing Subassembly.

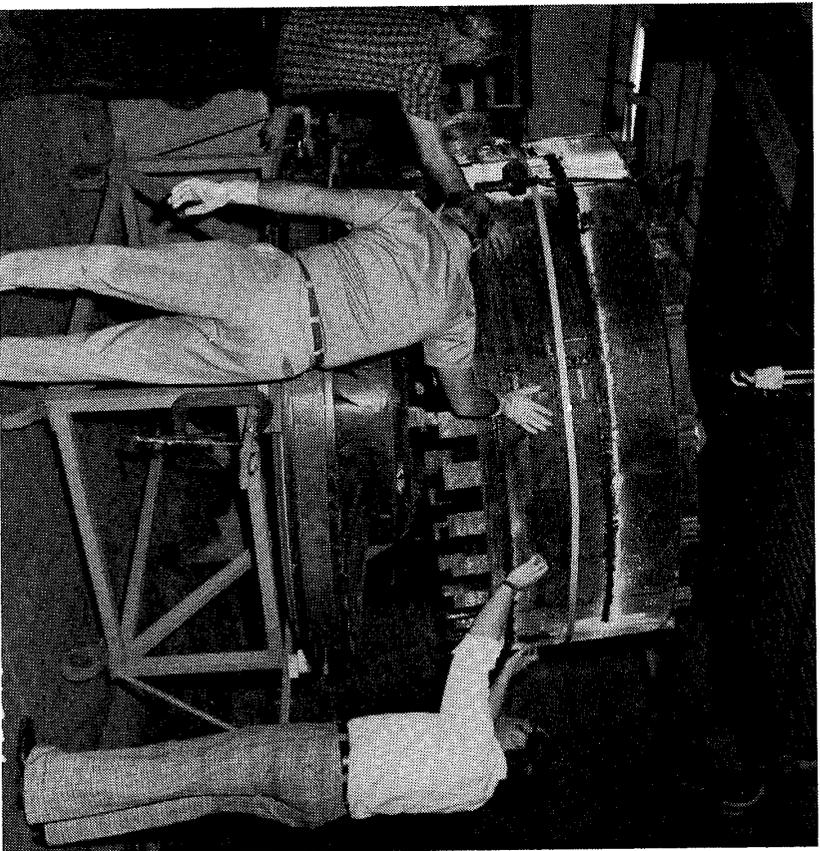


Figure 64. Assembling Fan Case to Frame.

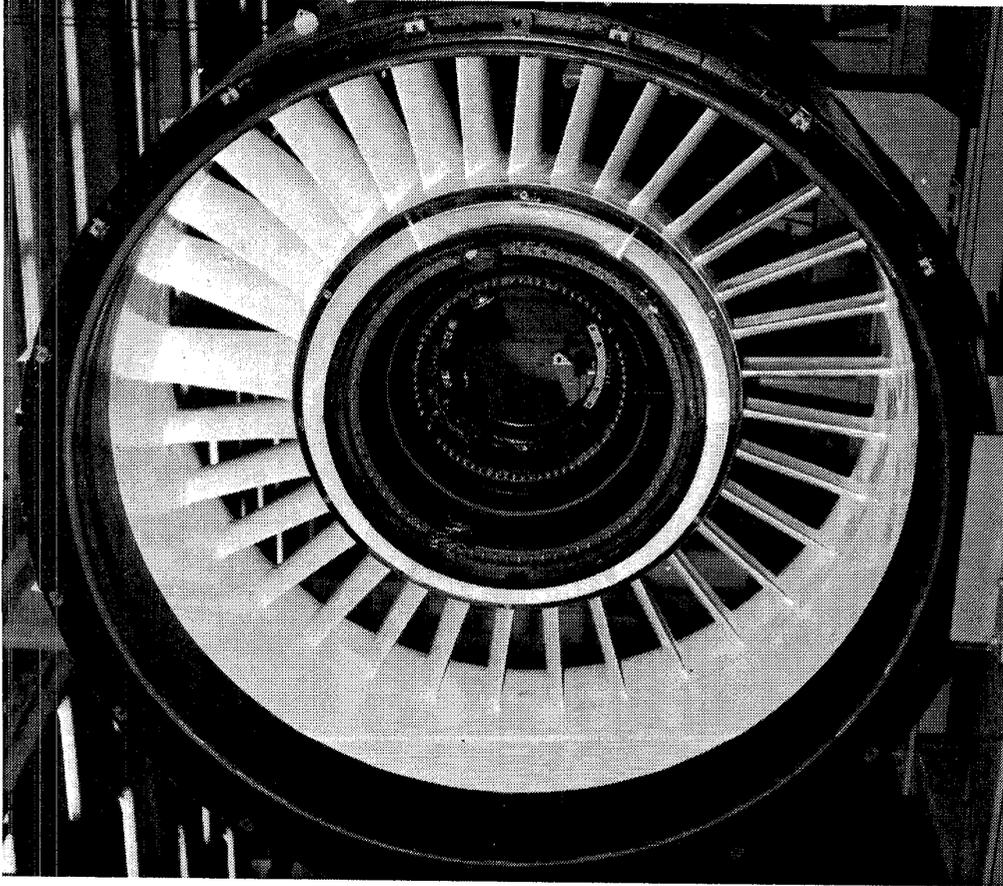


Figure 65. QCSEE Fan Frame.

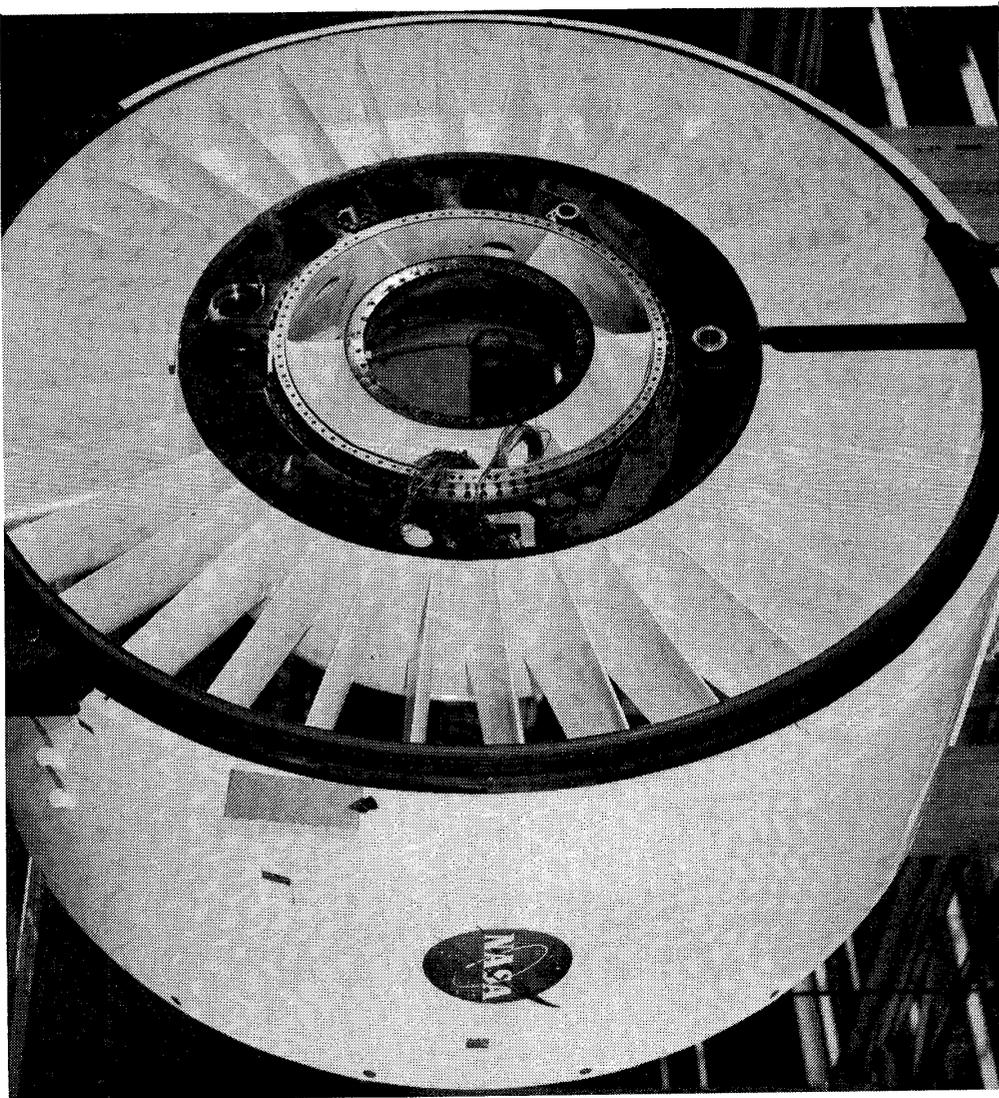


Figure 66. QCSHE Fan Frame.

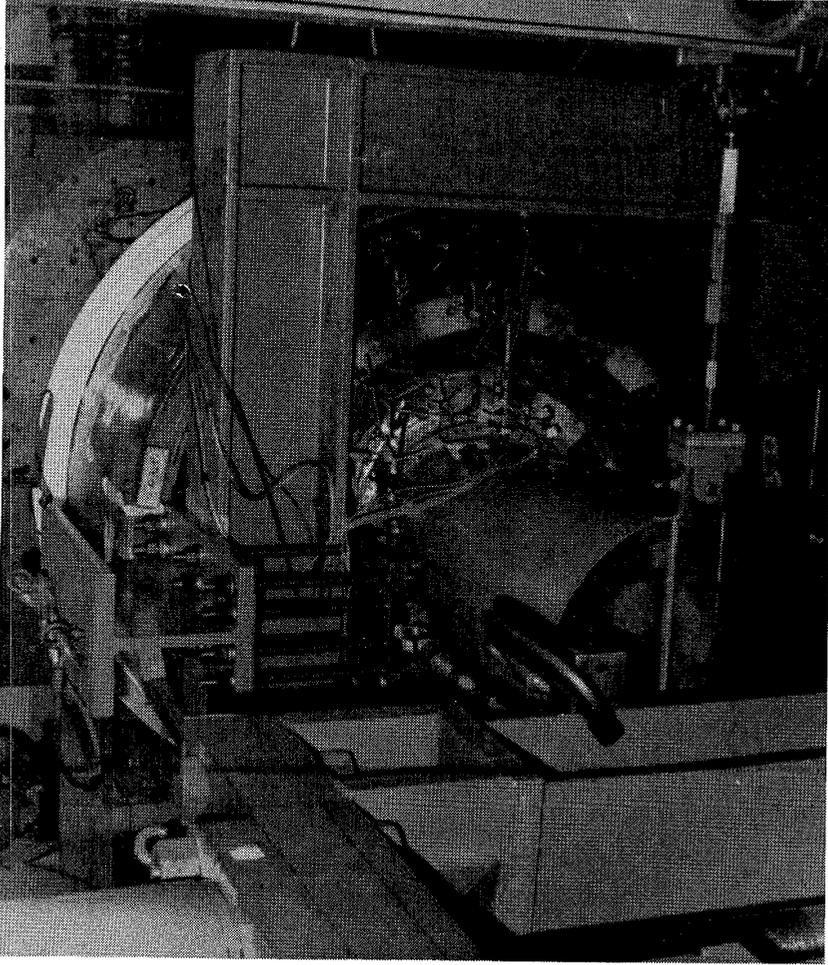


Figure 67. Static Test Setup.

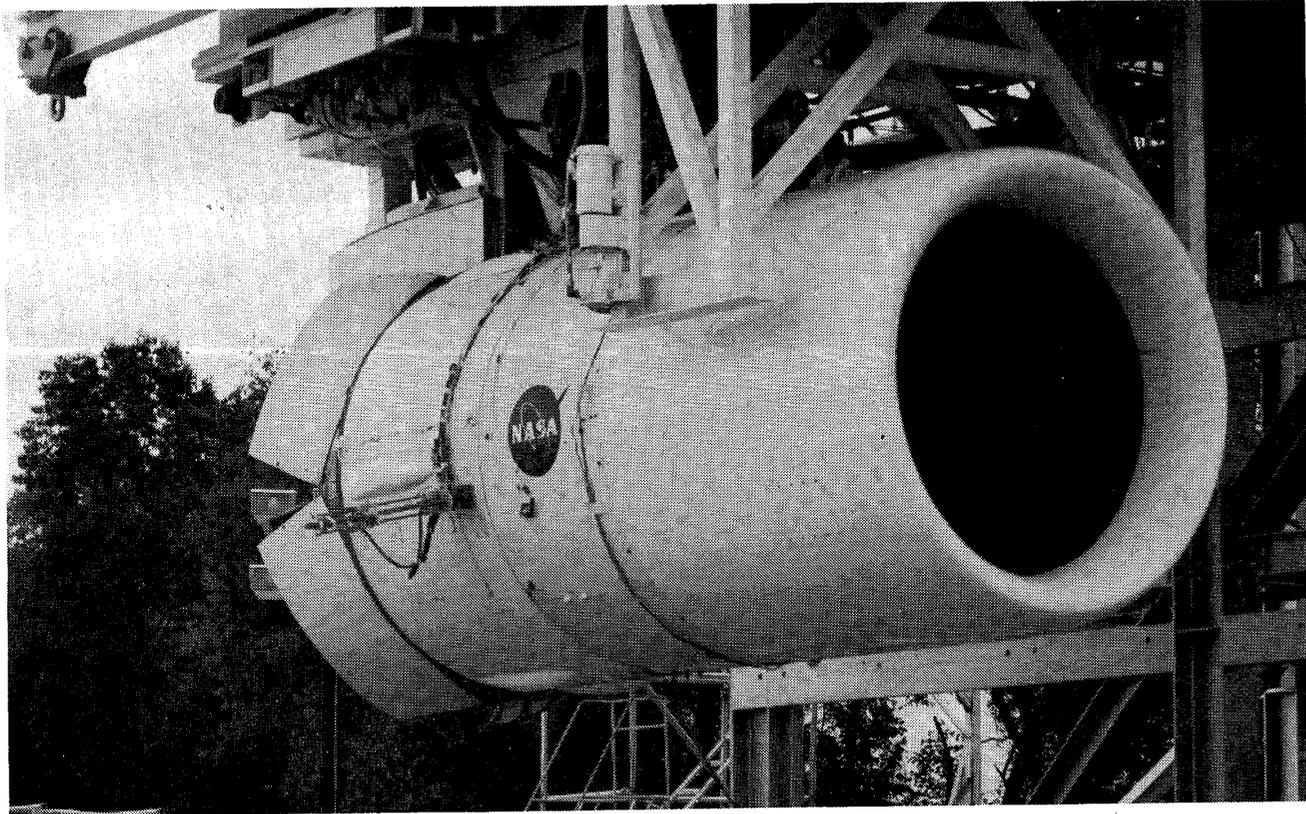


Figure 68. UTW Composite Nacelle.

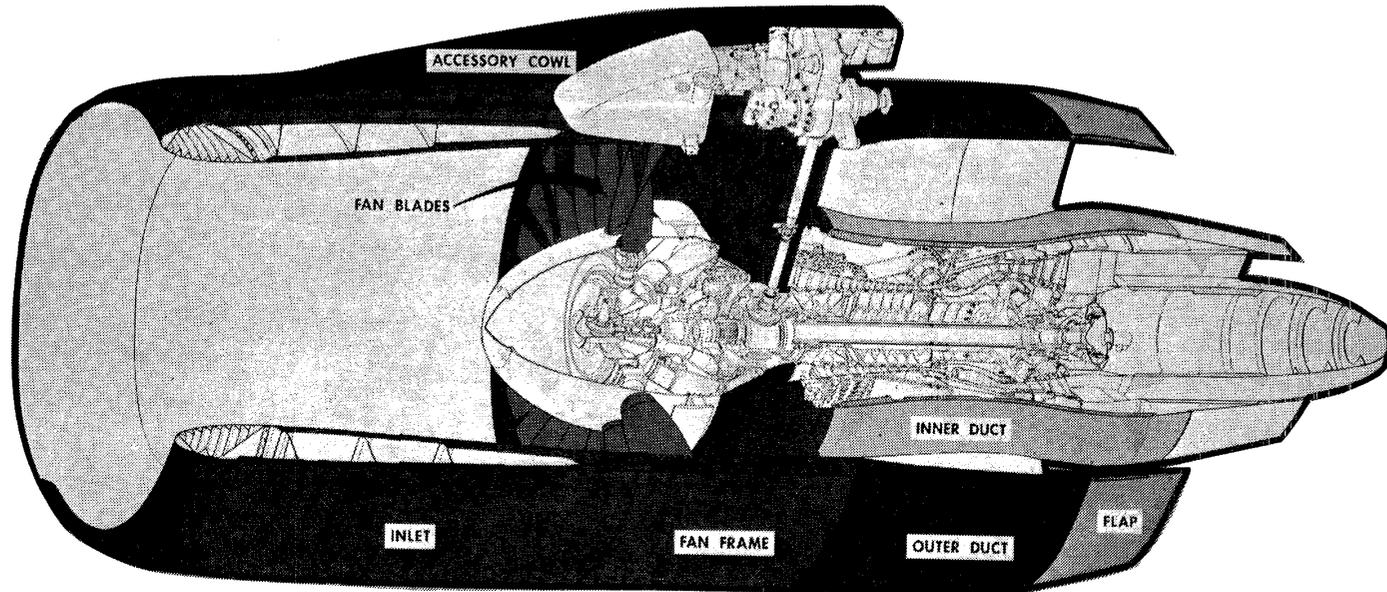


Figure 69. Composite Applications.

the integral acoustic treatment with a 10% open-area face sheet on the inner flowpath. The depth of the honeycomb core on the inner barrel varies as dictated by acoustic requirements. The porosity is molded into the face sheet as it is cured; this is now the practice in making CF6 fiberglass sound panels. The outer barrel is the primary load path. Both barrels are additionally supported by composite ring stiffeners. The leading edge was made from glass/epoxy for the QCSEE demonstrator but would be titanium for a flight engine due to anti-icing requirements. The critical inlet loads result from a 3-g stall in combination with a dynamic landing. Typical stresses, deflections, and margins of safety are shown in Table XVII.

The inlet is attached to the fan casing by 16 rotating latches. These points are the only critical local loads applied to the inlet; therefore, a subcomponent test, see Figure 70, was conducted of this area. The latch-housing failure was within 1% of the rated latch capability. Analysis indicates that six consecutive latches would have to be open before failure would occur at maximum load.

3.7.2 Outer Cowl and Fan Nozzle

Both of these components were fabricated in the same manner as the inlet, using the same materials. They are of full-depth honeycomb-sandwich construction with Kevlar/epoxy outer skin, aluminum-honeycomb flex core, and graphite/epoxy inner skin and structural rings. The only purpose for using graphite for the inner skins was the 15% to 20% porosity required for acoustics. At that time, it was felt that this porosity could best be obtained by laser drilling, and the initial attempts at laser drilling Kevlar/epoxy had not been as successful as laser drilling graphite/epoxy.

The pressure loading of these components is shown in Figure 71. Typical stresses resulting from this loading are shown in Table XVIII along with the allowable stresses obtained from coupon testing. Several critical joint areas were also checked by subcomponent tests.

The fabrication of these components was reasonably straightforward; both were built-up on male tooling. The outer cowl is shown in Figure 72 as the outer surface of the honeycomb is being machined prior to bonding on the outer skin - the last major operation. The nozzle-actuator housing pans can be seen as well as the tunnels for routing the hydraulics and sync cables to the actuators. The completed outer cowl is shown in Figure 73. The piano hinge which attaches the cowl to the pylon can be seen. The external fairings for the actuators can also be noted.

The only difference in construction of the fan nozzle was in inclusion of spring-loaded seals in the ends of the nozzle flaps which sealed the flaps against leakage in the forward-flight nozzle position. These seals separated when the nozzle was in the reverse-thrust position as shown in Figure 74.

Table XVII. Inlet Stresses and Deflections at Maximum Load Conditions.

3g Stall Plus Dynamic Landing

Type	Stress		Safety Factor	Deflection cm (in.)
	Calculated N/cm ² (psi)	Allowable N/cm ² (psi)		
Compression	1400 (2034)	12,377 (17,950)	7.8	0.058 (0.023)
Tension	1583 (2296)	27,097 (39,300)	16.1	
Shear	378 (584)	6033 (8750)	14.1	0.414 (0.163)
Burst	1806 (2620)	27,097 (39,300)	14.0	
Crush	3910 (5672)	12,377 (17,950)	2.2	

Table XVIII. Typical Outer-Cowl Stresses.

Component	Mode	Calculated Stress/Load	Allowable Stress/Load
Outer Skin	Buckling	18,450 N/cm ² (26,760 psi)	45,330 N/cm ² (65,740 psi)
Forward Ring	Compression	165 N/cm ² (240 psi)	910 N/cm ² (1320 psi)
Aft Ring	Bending	23,277 N/cm ² (33,760 psi)	77,221 N/cm ² (112,000 psi)
Piano Hinge Fast.	Bearing	10,782 N (2,424 lb)	52,698 N (11,847 lb)

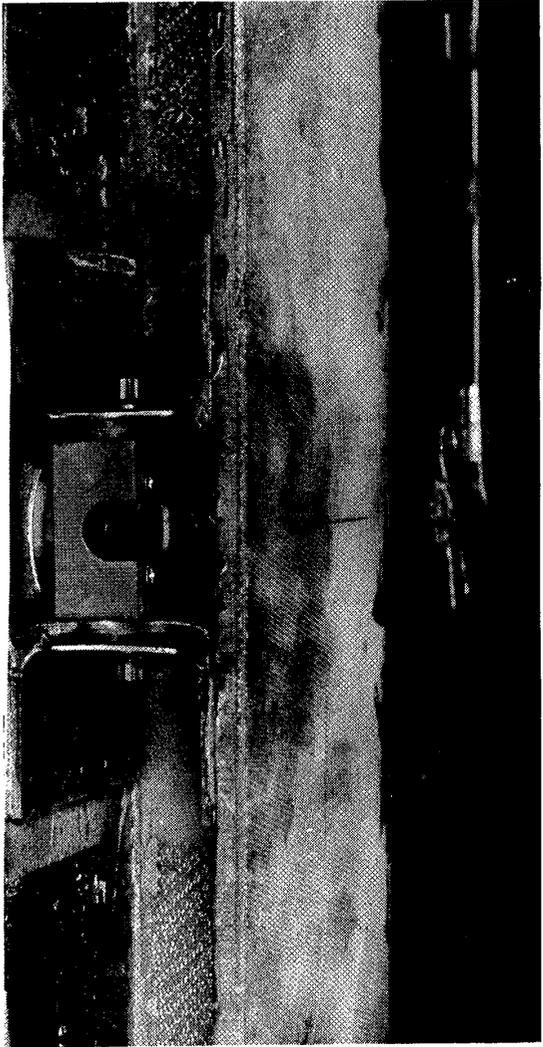


Figure 70. Inlet-to-Frame Attachment Test.

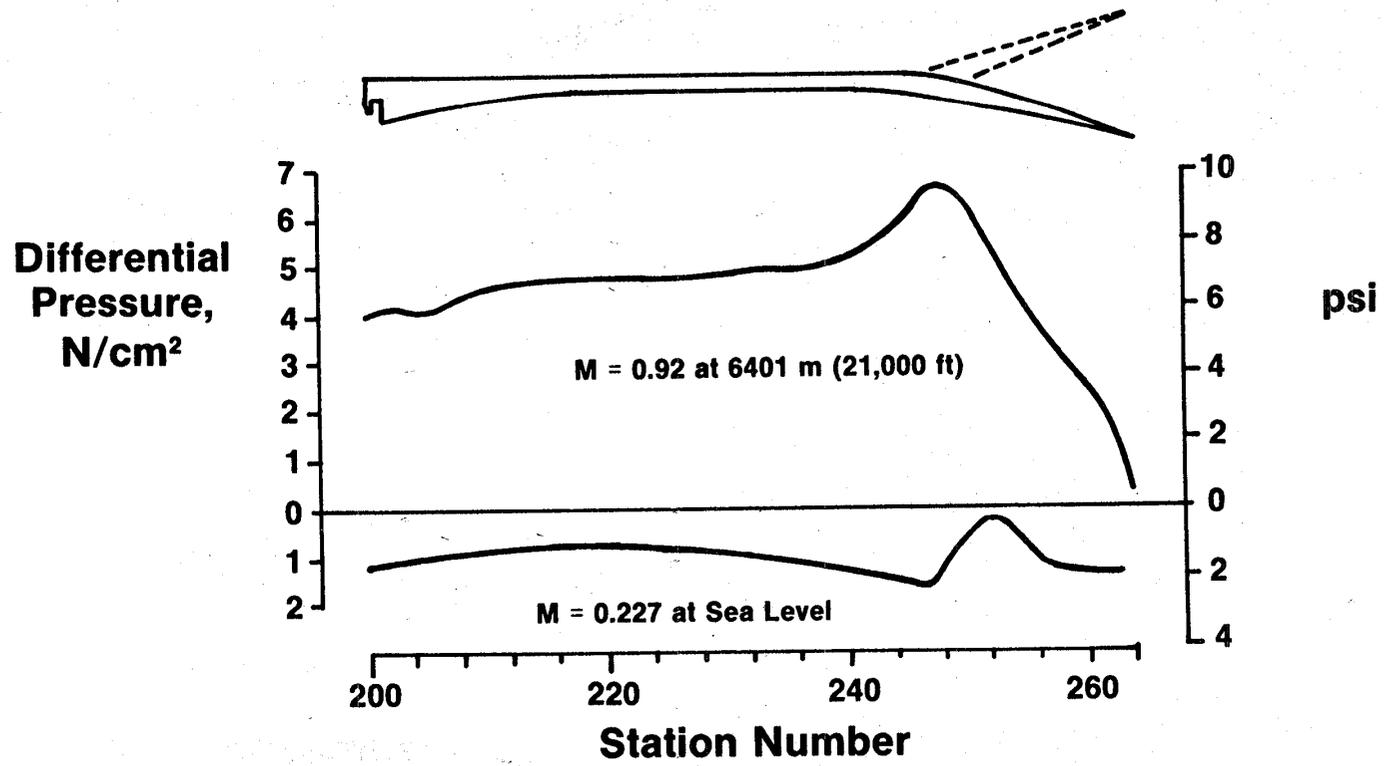


Figure 71. Differential Pressures.

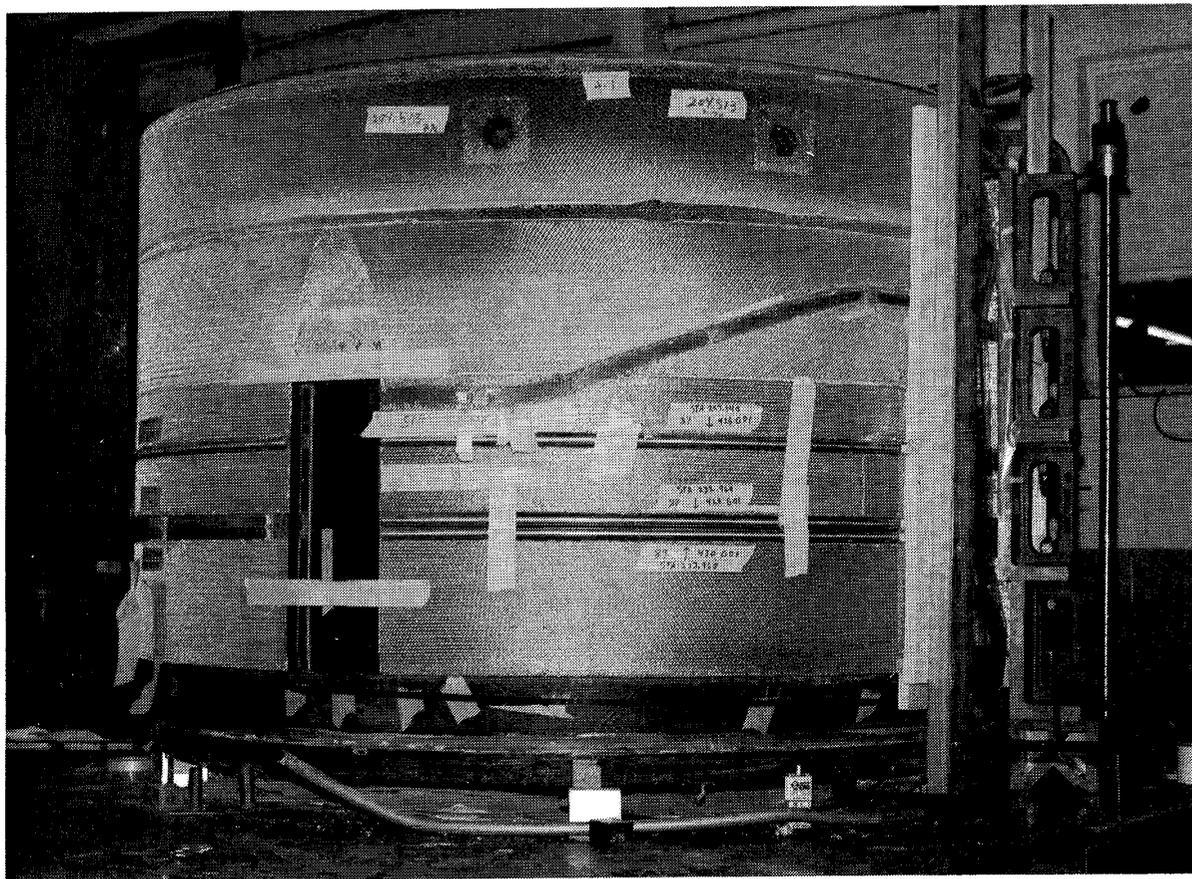


Figure 72. Outer Cowl Fabrication.

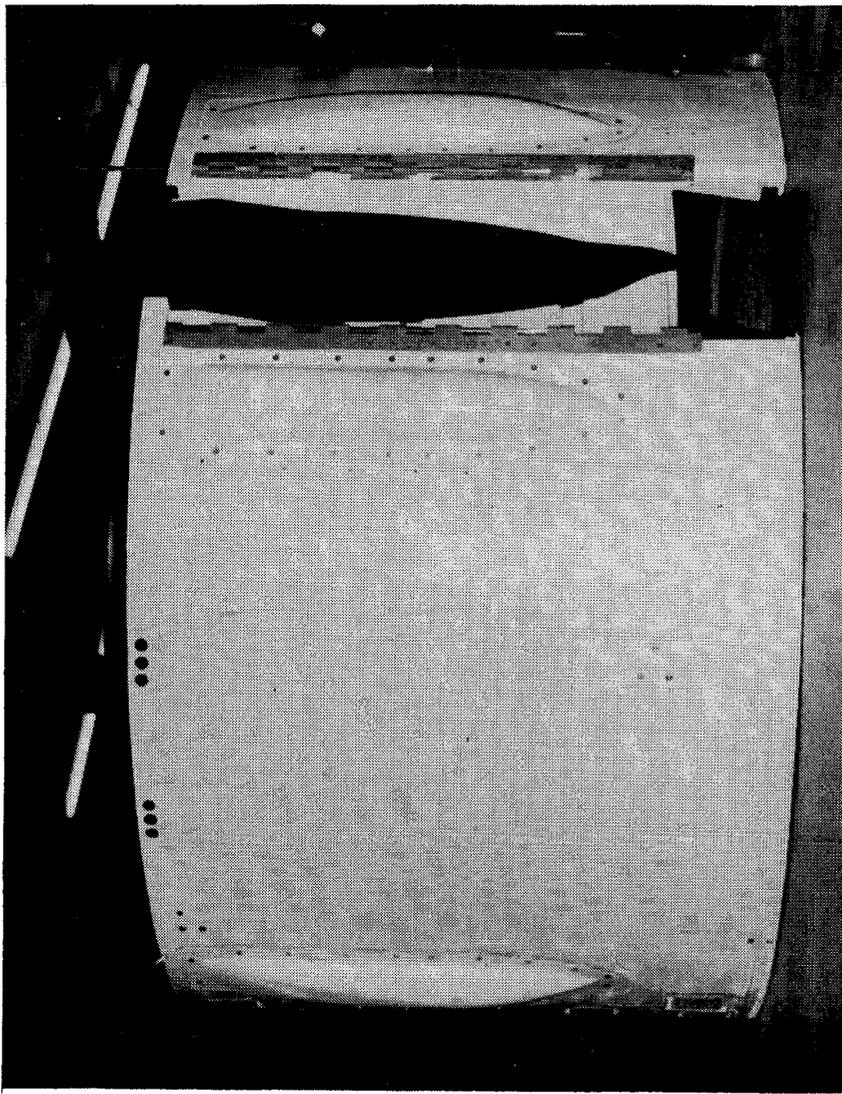


Figure 73. Completed Outer Cowl.

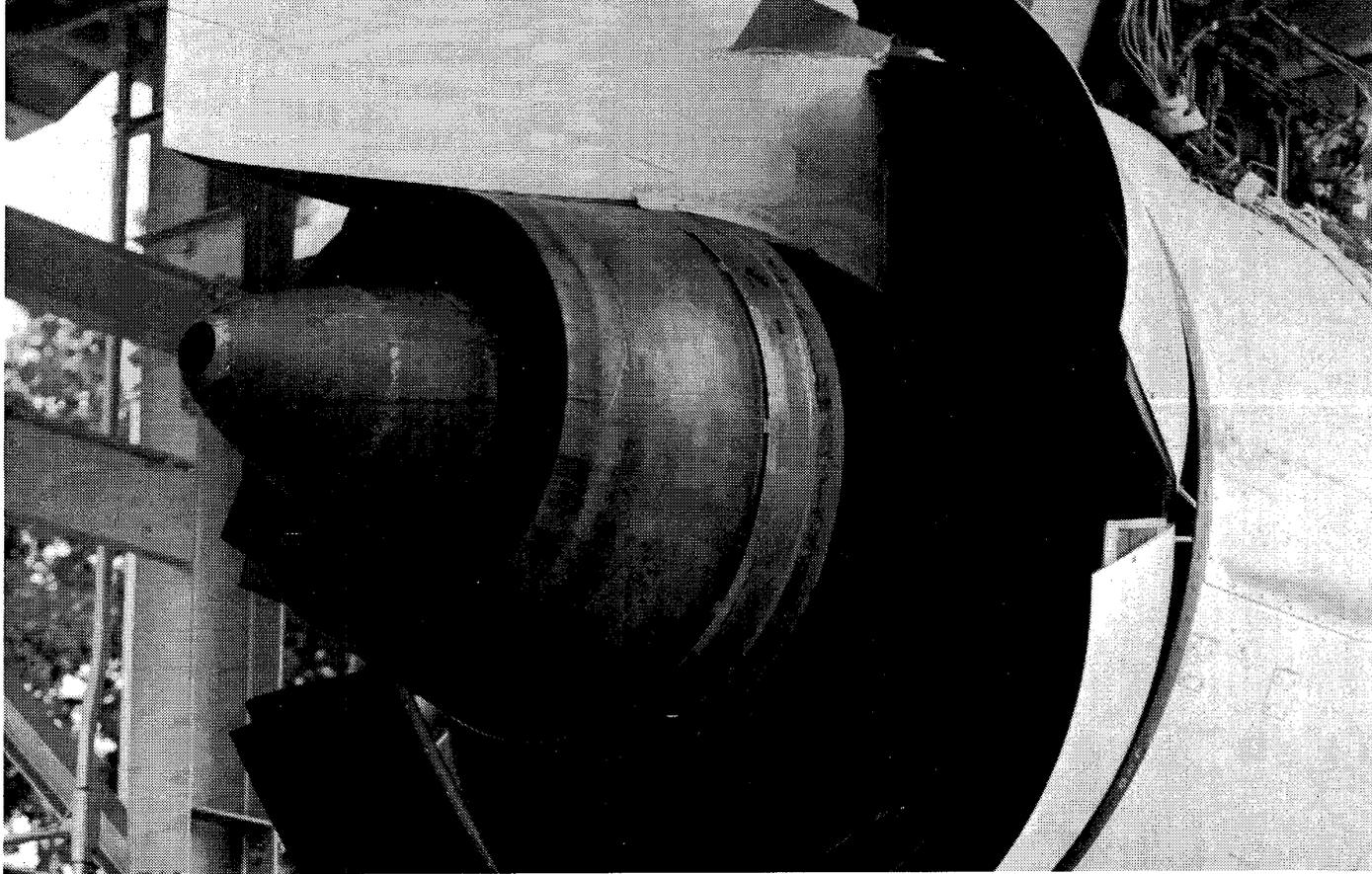


Figure 74. Fan Nozzle.

The most critical area in the outer-cowl/fan-nozzle system was the hinge ring in the back end of the outer cowl which supports the fan nozzle. This area was proof-tested satisfactorily in the test shown in Figure 75.

3.7.3 Inner Cowl

The most ambitious application of composites to the QCSEE nacelle-type hardware was in the area of the cowl; temperatures precluded the use of the familiar reinforced-epoxy materials. Even with a typical heat shield installed, the operating-temperature requirements were beyond epoxy capabilities, as shown in Figure 76.

Based on this information, it was decided to employ the NASA-developed PMR 15 polyimide type resin system. This system not only met the temperature requirements but is relatively easy to process and produces low-void-content laminates. Woven graphite T300 cloth was chosen as the reinforcement because it provided the needed stiffness and was easier to fabricate with than tape. This is particularly true when using the PMR system because of its lack of tack compared to epoxies. This material could also be laser drilled to get the 15% to 25% porosity required for acoustic treatment in this component. The HRH 327 fiberglass/polyimide core was used because of temperature considerations.

Using these materials, a core-cowl design was developed that resulted in a structure with typical ultimate calculated applied stresses as shown in Table XIX. Coupon-test results were used to determine the allowable stresses in the table. The completed core cowl is shown in Figure 77. The steel aft ring that forms the slip joint with the outer side of the core nozzle can be seen along with the hinges that attach the core cowl to the pylon. Each half of the core cowl was fabricated in two pieces due to the size of the laboratory autoclave; this would not be necessary in production. The split line can be seen in the photograph. An interior view of the core is shown in Figure 78. The flight-weight core cowl would incorporate a standoff heat shield (steel) in the aft portion of the cowl. This heat shield was not built for the demonstrator engine, so a heat blanket was installed in its place and shop air introduced in sufficient quantities to keep the core-cowl temperature at the levels they would have been if the heat shield had been installed.

3.8 DIGITAL CONTROL SYSTEM

A digital control was specified for the QCSEE propulsion system in anticipation that this technology would be required for an advanced, short-haul, aircraft system. This anticipated need, in conjunction with the general trend toward the use of digital computation in aircraft controls, led to the requirement that the control be engine mounted for exposure to the vibratory and thermal environment. As a result of this development effort, a digital control technology base has been established for the application of digital controls on many kinds of future aircraft-propulsion systems.

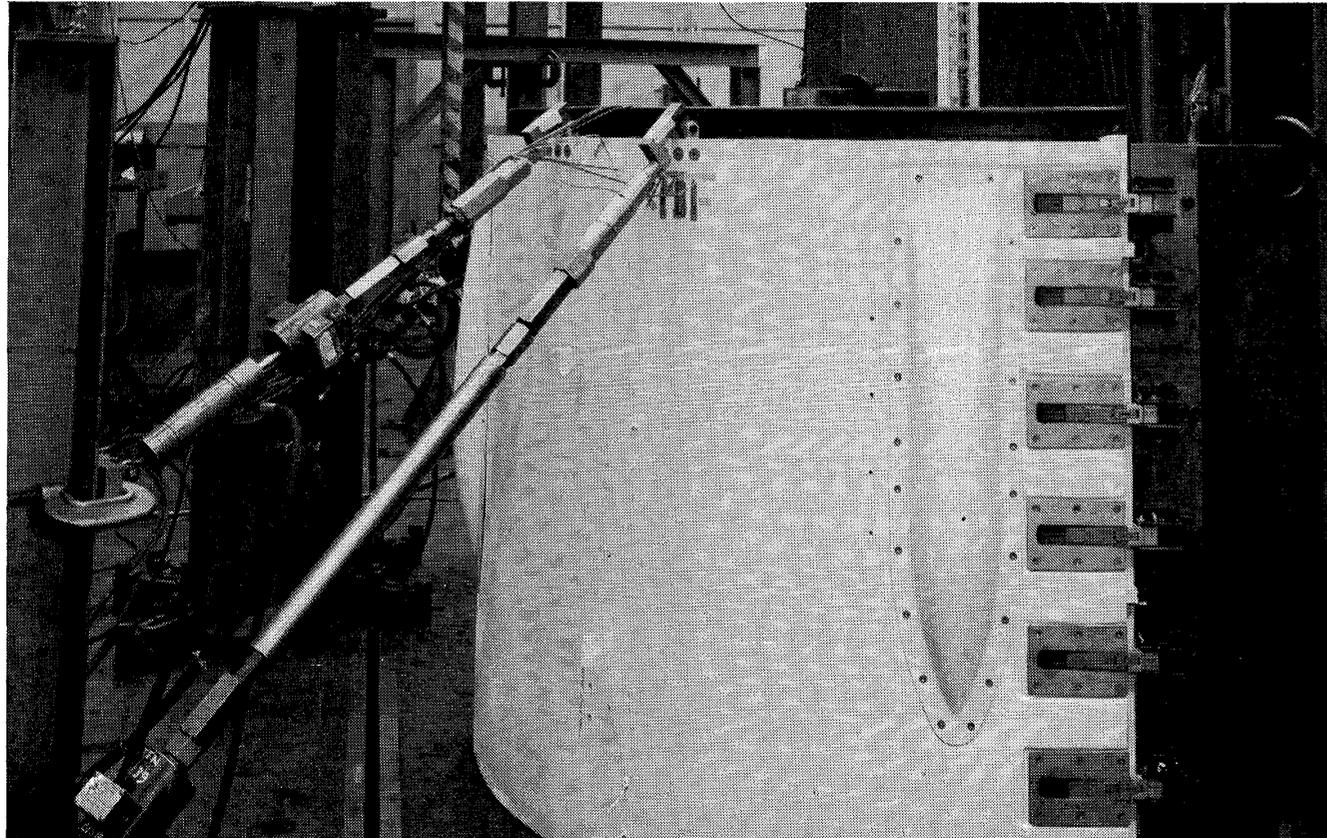


Figure 75. Outer Cowl Static Load Test.

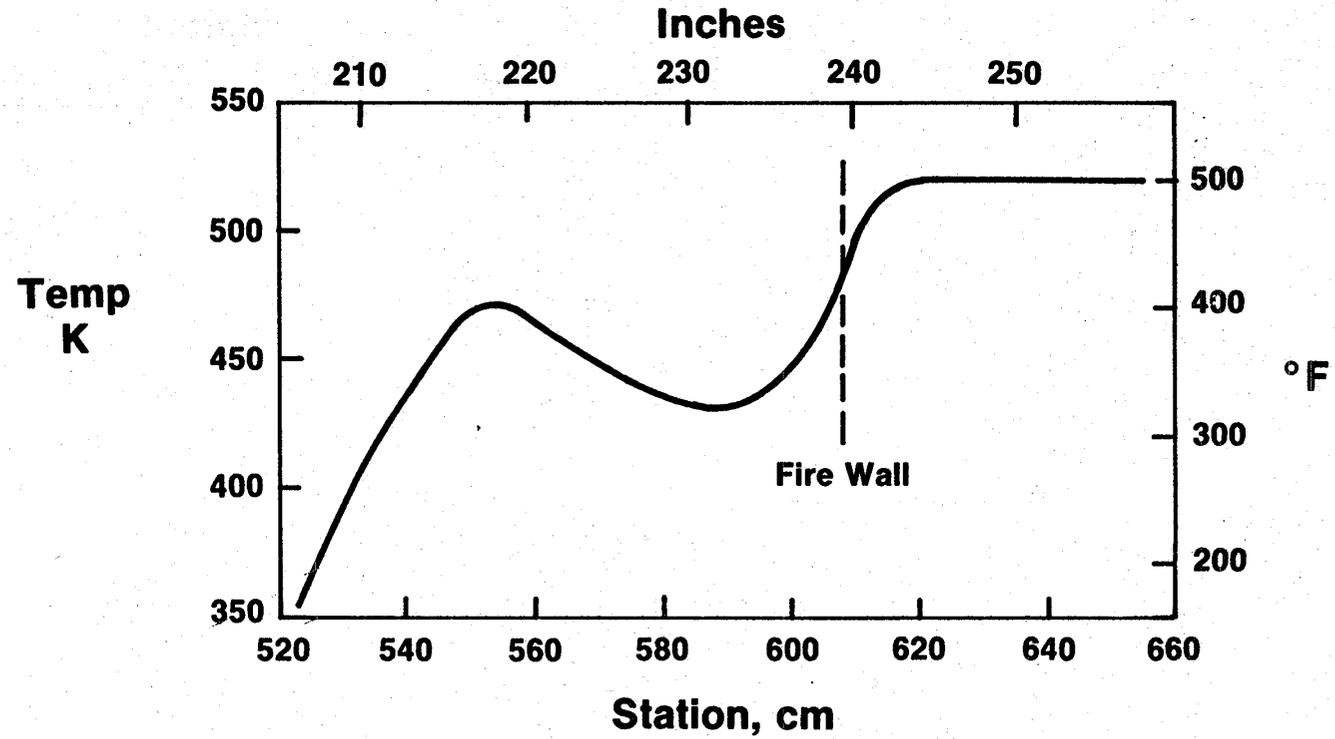


Figure 76. Inner Core Cowl Estimated Temperatures (Heat Shield Installed).

Table XIX. Typical Core-Cowl Stresses.

<u>Load Condition</u>	<u>Component</u>	<u>Ultimate Calc. Stress N/cm² (psi)</u>	<u>Allowable Stress N/cm² (psi)</u>
Forward Thrust	Outer Face Sheet	8480	19,240
	Tension	(12,300)	(27,900)
Reverse Thrust	Outer Face Sheet	2290	12,480
	Compression	(3324)	(18,100)
Forward Thrust	Inner Face Sheet	11,420	29,990
	Compression	(16,560)	(43,500)

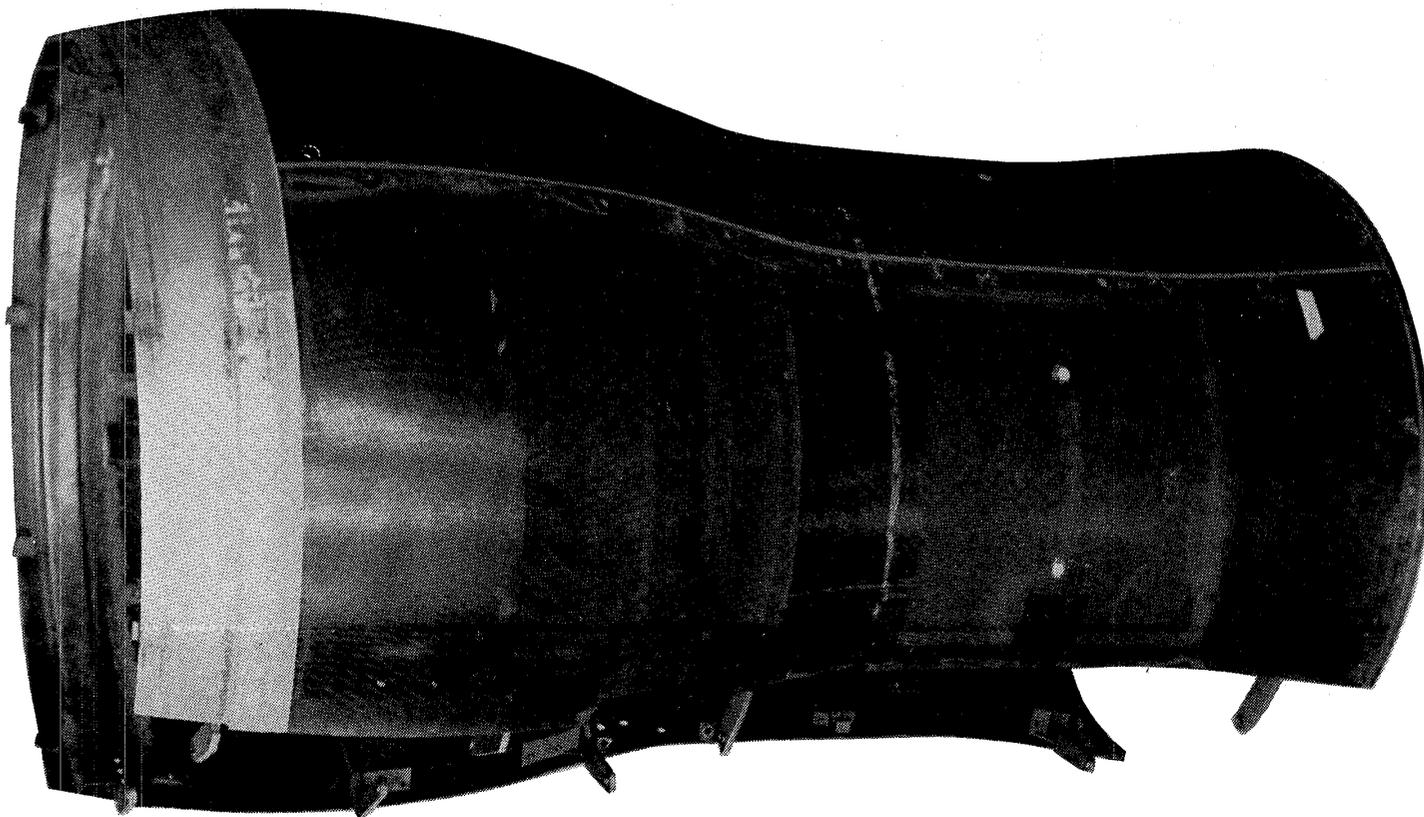


Figure 77. Completed Core Cowl.

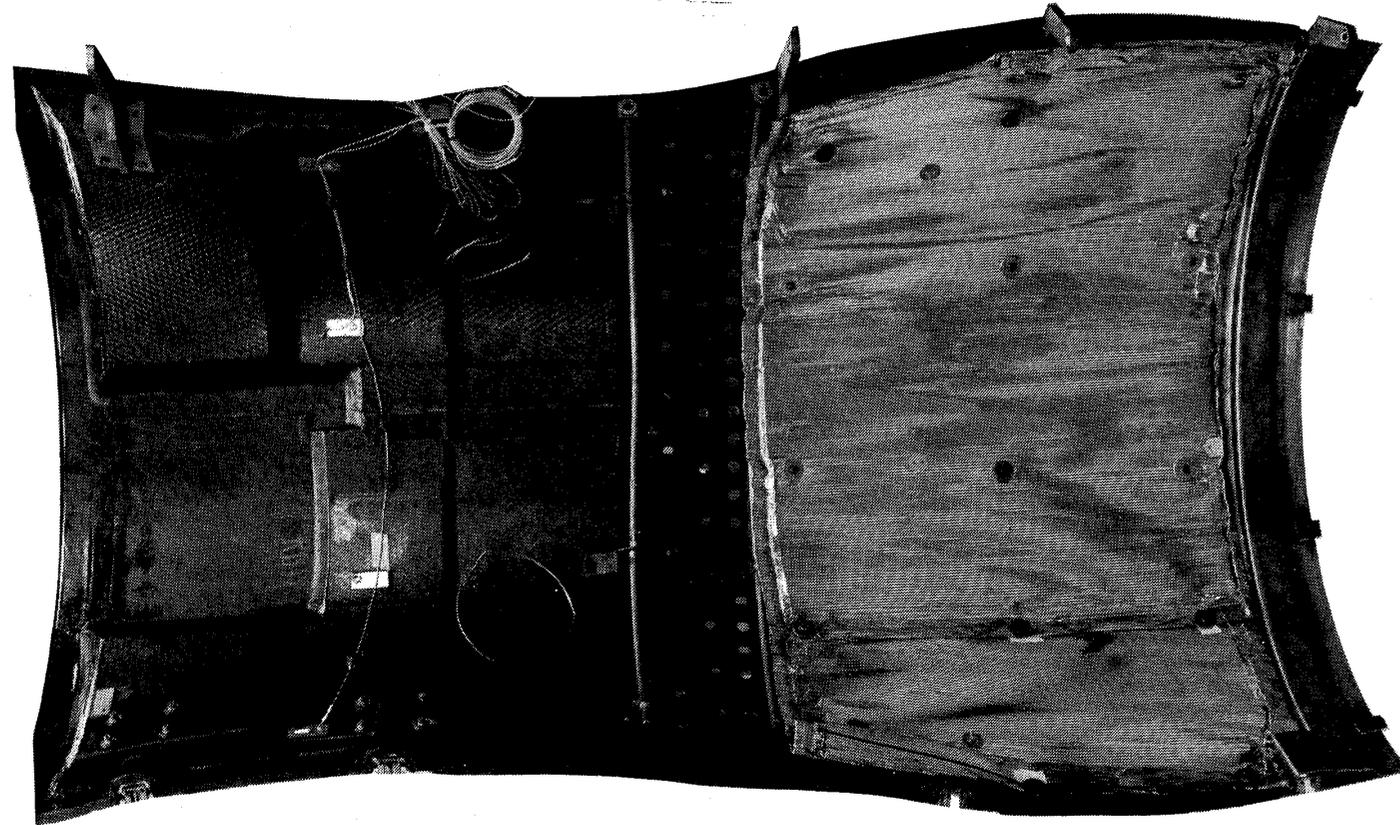


Figure 78. Core Cowl Interior View.

3.8.1 UTW Design Requirements

The control system design was based on a set of control-system requirements developed from the needs of a short-haul aircraft system. The primary control-system requirements are:

- Set Percent Rated Thrust
- Maintain Engine Safety Limits
- Reduce Pilot Work Load
- Control Inlet Mach Number
- Provide Rapid Thrust Response
- Facilitate Engine-Condition Monitoring
- Interface with Aircraft Digital Computer

One of the primary functions of the propulsion control is to manipulate the engine variables to achieve the design thrust levels. The use of a digital control allowed the development of control-system logic that related engine thrust to measurable engine parameters. These parameters were integrated and scheduled so that cockpit power-lever position (percent power setting) was directly related to percent of rated thrust. The thrust parameter selected for the UTW engine was propulsion system pressure ratio: compressor-discharge static pressure divided by free-stream total pressure (P_{S3}/P_{T0}). The basic pressure ratio schedule was biased by engine inlet and aircraft operating conditions to achieve a relationship between rated thrust and cockpit power-lever position over the flight envelope.

To achieve safe operation over the flight envelope, the control system was designed to automatically maintain engine operation within normal physical limits. The control system incorporated logic to prevent engine overspeed or overtemperature. The specific mechanization of the limits will be discussed later.

Since operation of a short-haul aircraft into intercity airports could place heavy demands upon the pilot, it was required that the system design should attempt to reduce pilot work load. To accommodate this objective the system was designed to automatically integrate the propulsion-system variables and engine safety limits.

One of the primary objectives of the QCSEE program was the development of noise-reduction technology. Previous experiments have shown that operation with a high inlet-throat Mach number provides a substantial reduction in fan noise. To achieve this noise-reduction benefit, it is necessary to provide automatic control of inlet-throat Mach number at high power settings, and demonstration of this capability was a UTW engine control requirement.

Studies by NASA prior to initiating the QCSEE program revealed that short-haul aircraft require rapid thrust response to achieve a safe go-around in the event of an engine failure during landing approach. As a result of these studies, the propulsion system was required to provide a thrust change from 62% to 95% in one second. This thrust-response rate is approximately twice as fast as current engines.

Digital computers have the inherent capability to process and transmit massive amounts of data rapidly. It was decided to utilize this capability, and the QCSEE digital control was designed to collect and transmit 48 engine-condition parameters such as speeds, pressures, temperatures, and operating modes. The data were stored and displayed in the engine control room. With appropriate integration of the engine and aircraft digital controls, a comprehensive condition-monitoring system could be provided to provide maintenance-action information.

To be utilized effectively, a propulsion-system digital control should have the capability to interface with an aircraft digital control system. Propulsion-system commands from the aircraft and propulsion-system operational data would be transmitted through this interface. Recognition of this need led to the requirement for a digital interface and transmission system between the experimental propulsion system and the engine control room.

3.8.2 UTW System Description

Figure 79 is a simplified schematic of the UTW propulsion control system. The UTW engine incorporated four manipulated variables: fan nozzle area, fan pitch angle, engine fuel flow, and core stator angle. The system to control these variables can be divided into three functional groups: the system sensors, represented by the engine sensors and digital commands from the control room; the computer, represented by the digital control; and the system power, represented by the system actuators. The digital control is the heart of the system; hence, it incorporates all of the control laws and logic to regulate the variables from engine idle to takeoff thrust. The other major components in the system are: fuel pump, hydromechanical control, and hydraulic pump.

In this control system, the fan nozzle and fan-pitch actuators were manipulated solely by the digital control. Fuel flow was varied as programmed by the digital control; however, the hydromechanical control had the authority to override the digital control, and it also schedules the core stator-angle position. This mechanical override capability was incorporated for several reasons: development program cost, digital control memory size, and experimental engine safety. A secondary electromechanical power-demand link to actuate the fuel stopcock and set a core-speed limit was also implemented for experimental engine safety.

The command and data link was a serial, time-multiplexed, data-transmission system consisting of digital serializers, optical isolators, line

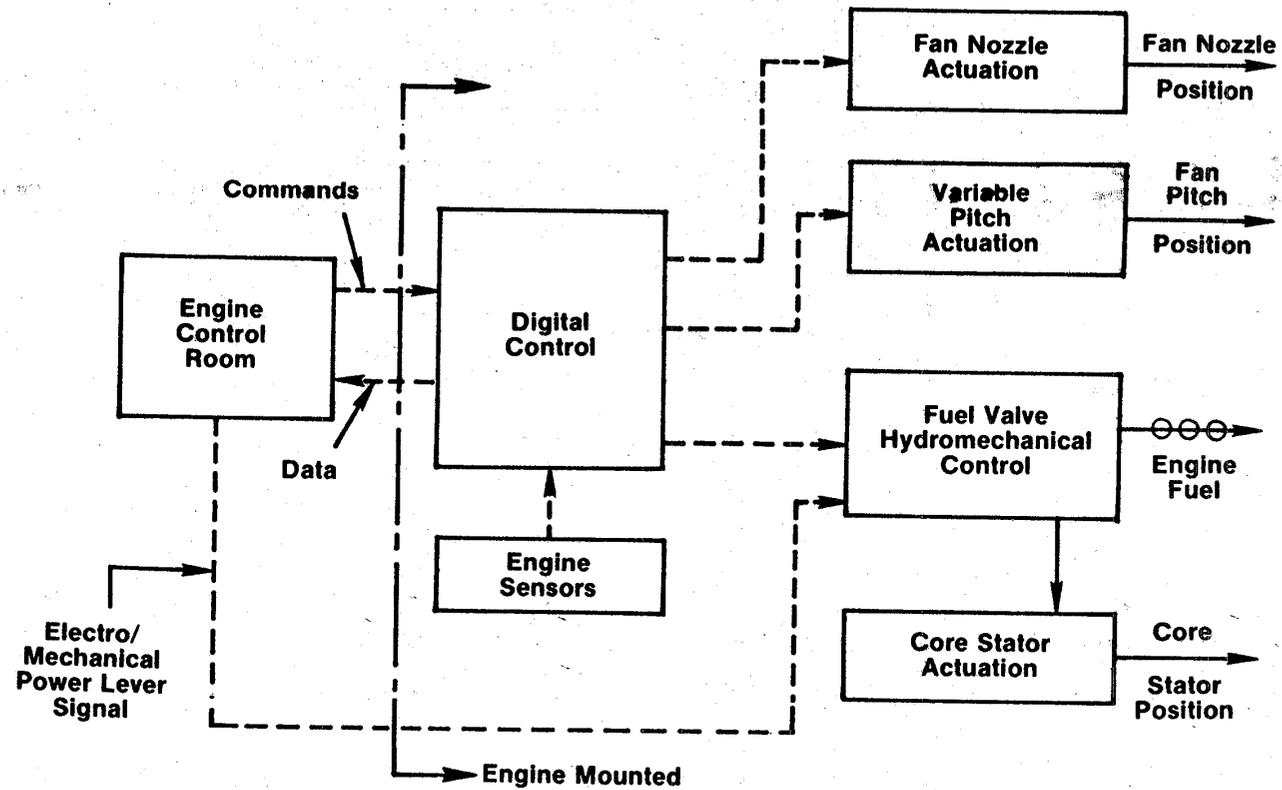


Figure 79. UTW Control System Schematic.

drivers, and line receivers. Data were transmitted and received at a one-megahertz rate. The command and data-transmission process was regulated by the engine-mounted digital control.

An engine-driven, accessory-gearbox-mounted, F101 engine fuel pump was utilized for fuel system pressurization and fuel delivery. The pump incorporates a fixed-displacement vane element and a centrifugal boost element to charge the intake of the vane element. Rated pump speed is 6690 rpm; at this speed it has a capacity of 2.7 dm³/sec (42.8 gpm) with a pressure rise of 6.93 MN/m² (1000 psi). The pump was designed and manufactured by Sperry-Vickers.

A modified F101 engine fuel control was used for fuel metering. This control uses a constant metering head and incorporates a servo-operated bypass valve to accommodate excess pump flow. The control incorporates hydromechanical devices for speed governing and for fuel and core stator scheduling and provides a fuel-system interface with the digital control. The control was designed and constructed by Woodward Governor Company.

The UTW engine incorporated an engine-driven, piston-type, pressure-compensated, hydraulic pump as a power supply for variable nozzle and variable fan-pitch actuation. The pump supplies a constant-pressure, variable flow to the system servovalves - which are regulated by the digital control. The pump capability at 100% speed is 3.08 dm³/sec (48.8 gpm) with a pressure rise of 23.6 MN/m² (3350 psi). This relatively large flow capacity was required to provide rapid variable-pitch actuation at low engine speeds. The pump was designed and manufactured by Abex Corporation.

Figure 80 shows a photograph of the engine-mounted digital control. The package shown in the figure incorporates pressure transducers for sensing the pressures used in engine control, a separately powered analog control for limiting fan overspeed, and the digital control. The unit is powered by a variable-frequency, variable-voltage, engine-driven alternator. Power dissipation is in the order of 100 watts and is handled by air cooling. The cooling-air source is free-stream total pressure, and the pressure sink is the fan inlet.

The digital control integrates the following functions: sensor excitation and signal conditioning, data acquisition, digital-to-analog conversion, output-signal conditioning, power-supply regulation, and special-purpose digital computation. The digital computer is composed of five major sections: program memory, read/write memory, clock, central processor, and input/output unit. The computer has the capability to add, subtract, multiply, divide, and branch upon command. The machine data word is 12 bits in length. The computer instruction set consists of 31 different instructions.

The program memory incorporates instructions that define the control laws and logic. The UTW QCSEE control memory incorporates 3071 instructions to define the complete control strategy. Each instruction in the program memory

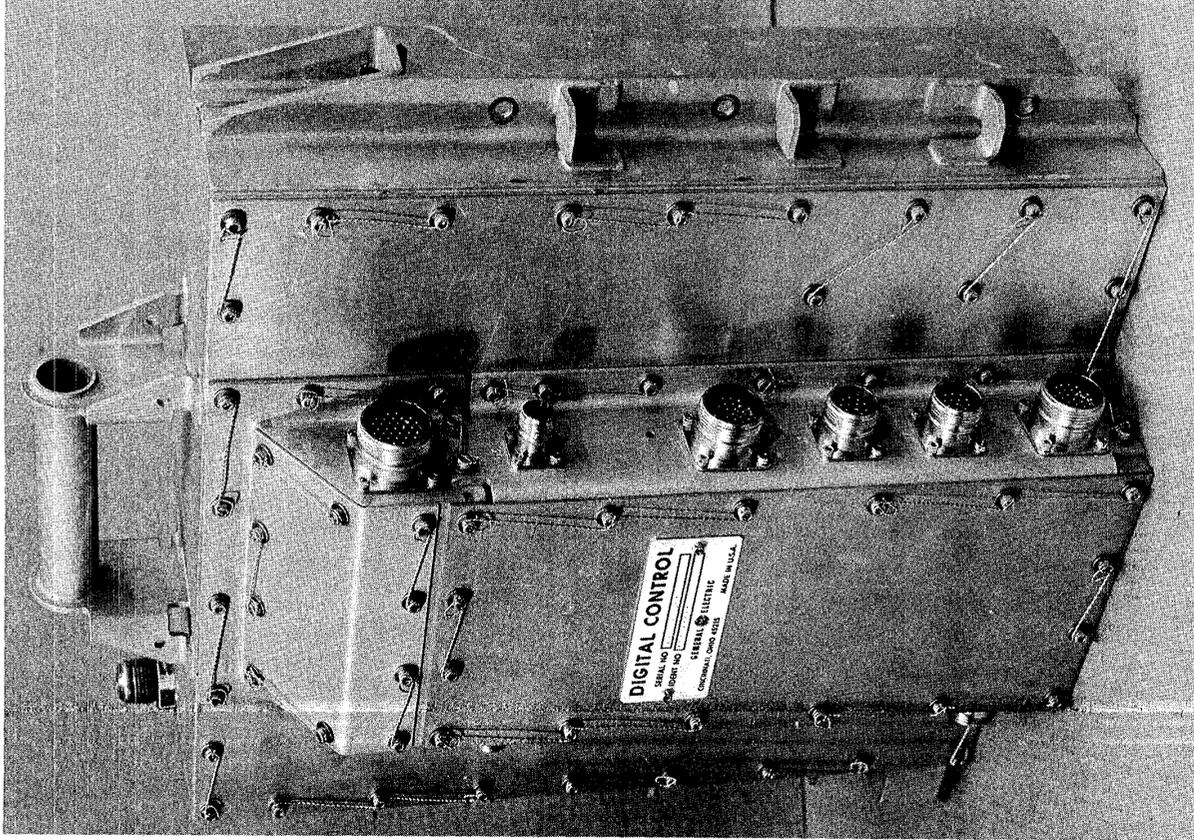


Figure 80. UTW QCSEE Digital Control.

is sequentially transmitted to the central processor for execution. The timing for instruction execution is controlled by the central processor. Execution time for the UTW QCSEE program is 7.46 milliseconds. Hence, the program repeats 134 times per second.

The electrical components in the digital control consist of a combination of discrete and medium-scale integrated components. A type of logic called the low power Schottky TTL was selected for digital components. These devices were selected because they offer the best speed-power product. The digital control was designed and fabricated by the General Electric Company.

Figure 81 is a schematic of the UTW engine showing the control system sensors. All of the measured parameters, except core stator angle and core inlet temperature, were collected by the digital control and used in the propulsion control logic. In addition, they were subsequently transmitted to the control room for display.

Fan inlet total temperatures and free-stream total pressures were measured to evaluate flight conditions and used for power-control scheduling.

Inlet static pressure was combined with free-stream total pressure and used as a representation of inlet Mach number. The static pressure was measured at the 40% axial station in the inlet duct. This was done to eliminate pressure variations due to crosswinds. An empirical equation was used to convert the measured pressure ratio to average inlet-throat Mach number.

Free-stream total pressure was also used along with measured compressor-discharge pressure to establish propulsion system pressure ratio - which is related to system thrust.

Fan pitch angle, fan nozzle area, and core stator angle were measured to allow for a loop closure in the control logic.

Fuel flow, compressor discharge temperature, and pressure were measured for use in the computation of turbine inlet temperature.

Core inlet temperature, core speed, and low pressure turbine speed were measured for use in physical speed limits, corrected speed limits, acceleration schedules, and core stator schedule computations.

All of the sensors used in the system were current, state-of-the-art-type devices.

3.8.3 UTW Operating Characteristics

One fundamental task performed in designing an automatic control system was to define the system control mode. This control-mode-definition process relates the engine cycle variables (speeds, pressures, temperatures, etc.) to the available manipulated variables (fuel flow, fan pitch, nozzle area) to

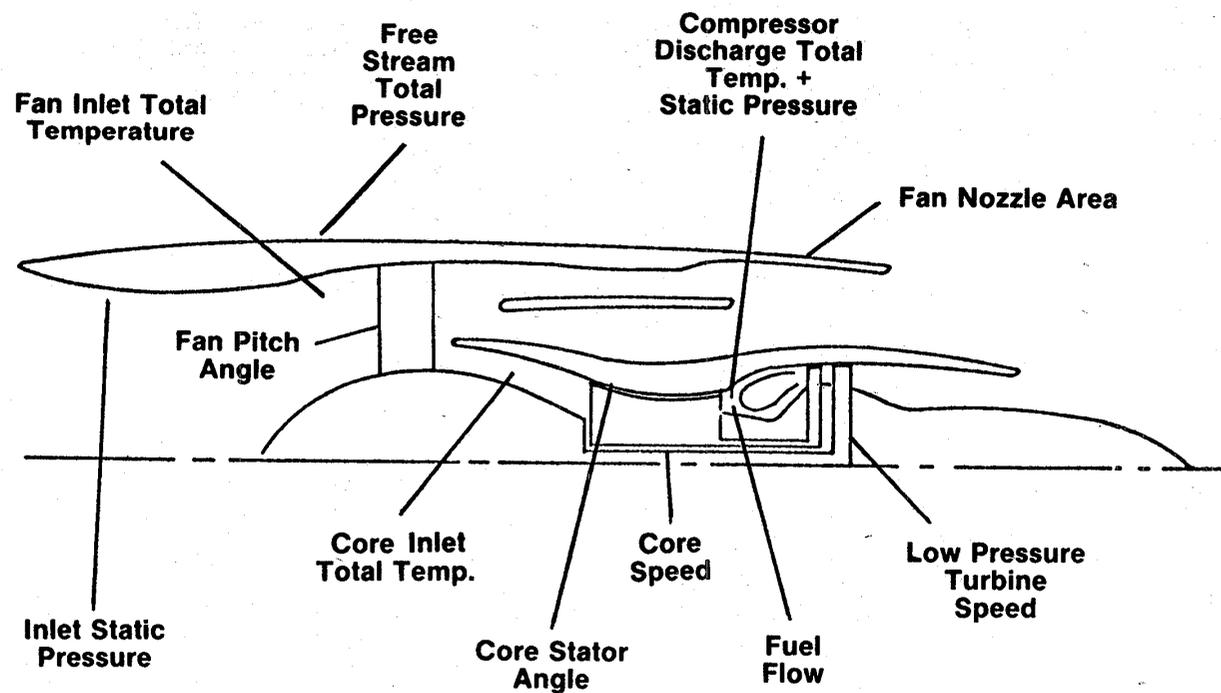


Figure 81. UTW Control System Sensors.

achieve control of the vehicle and to obtain the desired operating characteristics. The objective of the analysis is to choose practical combinations of cycle parameters and manipulated variables which result in small variations in the engine-cycle-dependent variables (i.e., thrust, sfc, stall margin) at important operating conditions. The analysis process involves the comparison of potential control modes on the basis of accuracy, schedulability, stability, response, and other performance considerations.

The UTW QCSEE incorporated three prime manipulated variables: fuel flow, fan pitch, and fan nozzle area. During the mode-selection process these variables were paired with many combinations of engine cycle variables. The analysis resulted in selection of engine pressure ratio (P_{S3}/P_{T0}), fan speed, and inlet Mach number as controlled variables. These variables were paired with fuel flow, fan pitch, and fan nozzle area.

As a result of this pairing of variables, selection of a percent power setting through movement of the power lever causes the following: engine fuel flow is varied to hold a scheduled engine pressure ratio, fan pitch is varied to hold a scheduled fan speed, and fan nozzle area is varied to hold a scheduled inlet Mach number. The above actions are implemented through the digital control. This variation of the manipulated variables is constrained by both physical limits and cycle considerations. For example, maximum fan nozzle area was limited to 1.87 m² (2900 in.²) because at this point the fan nozzle exit area became larger than the fan duct area, and nozzle variations no longer affected inlet Mach number. Fan pitch was limited to 10° closed from nominal due to actuator mechanical limits.

Figure 82 shows the relationship between fan nozzle area, inlet Mach number, and percent power demand at sea level conditions. Over the complete power setting range, the digital control tries to position the fan nozzle to maintain an inlet Mach number of 0.79. However, in the lower percent power setting region (<70%) the nozzle is scheduled to the maximum area, and inlet Mach number varies as a function of power setting. As the power demand is increased beyond approximately 70% the fan nozzle area begins to close to maintain a constant inlet Mach number.

Figure 83 shows the relationship between fan blade pitch angle, corrected speed, and percent power setting at sea level standard conditions. In the lower power-setting region fan speed varies with percent power setting because the fan pitch is closed to its minimum position. As the percent power setting is increased beyond approximately 55%, the fan pitch begins to open toward the takeoff position to hold fan speed constant at approximately 95% - the scheduled fan speed for takeoff power. The fan speed is held constant at the higher power settings for transient-response reasons which will be discussed later.

3.8.4 UTW Automatic Safety Limits

As noted earlier, one of the primary control-system functions is to prevent the engine from exceeding speed or temperature limits. To meet this

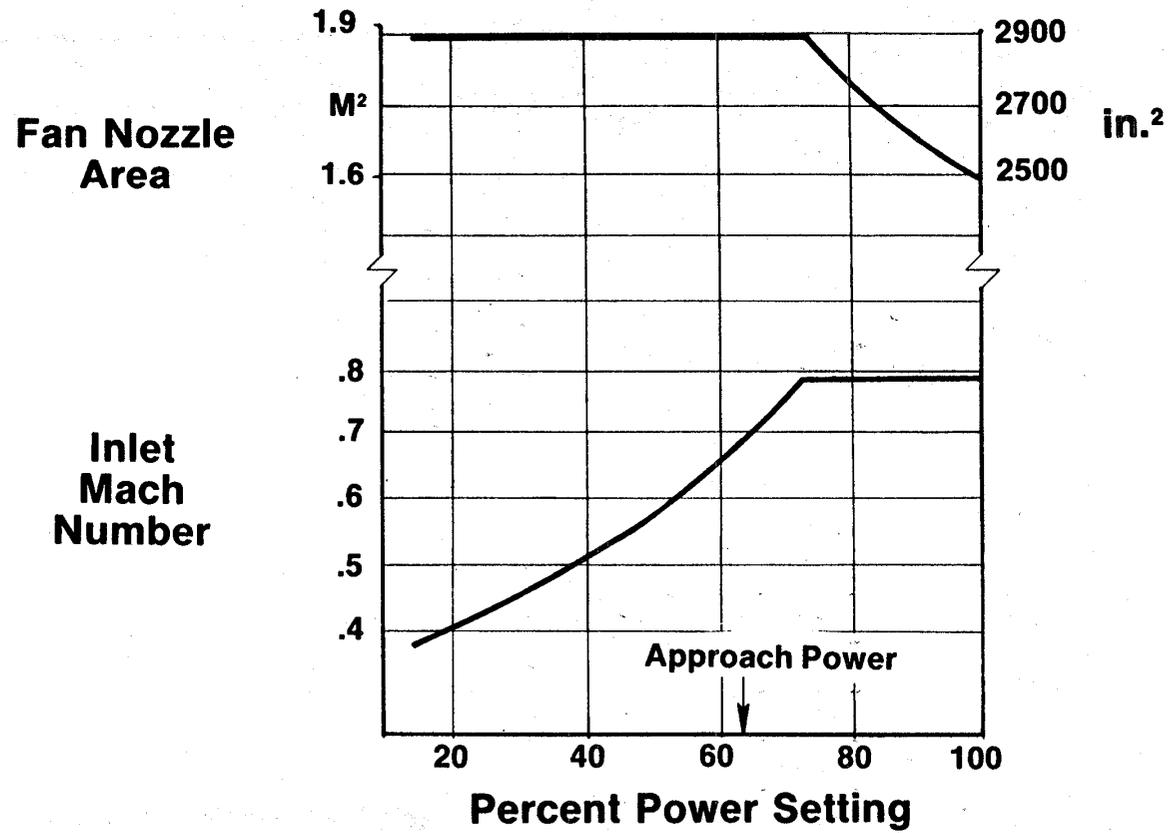


Figure 82. UTW Fan Nozzle Control Characteristics.

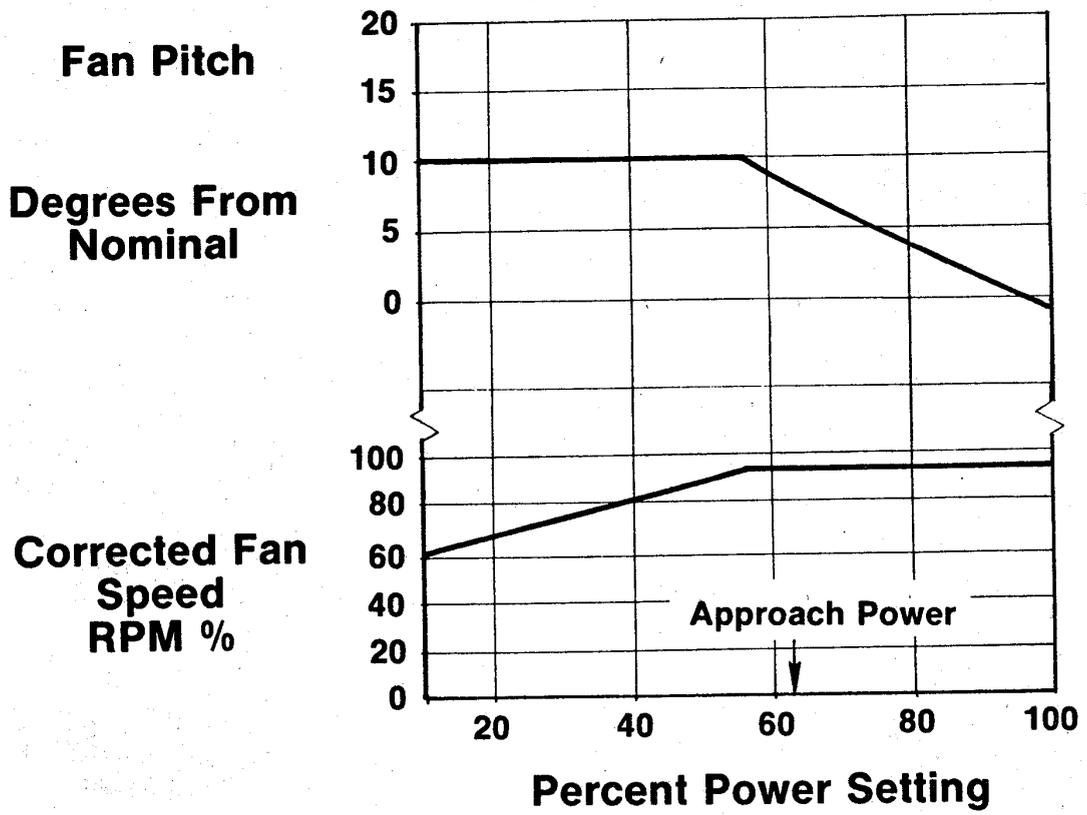


Figure 83. UTW Fan Pitch Control Characteristics.

requirement, limiting functions were incorporated in the hydromechanical and digital controls. The hydromechanical control incorporated a full-range, fly-ball governor on core speed; this would override the digital control input and reduce fuel flow if core speed attempted to exceed the scheduled value. The digital control memory incorporated fan speed and core speed limits which would cut-back fuel flow if the speed limit was reached. The digital control unit also incorporated a separate analog control to cut-off fuel flow on the experimental engine if overspeed occurred in the low pressure turbine due to loss of load. Loss of load could occur with a reduction gear failure or an extreme closure of the fan pitch at high power.

Turbine temperature was limited by a digital control function. The control memory incorporated an equation that calculated turbine inlet temperature as a function of fuel flow, compressor discharge pressure, and temperature. The control compared the calculated turbine inlet temperature with a limit and acted to cut-back fuel flow to prevent operation beyond this limit. The digital control received fan-case vibration signals from test facility instruments. The control program memory incorporated logic to automatically retard the experimental engine to idle power if vibration signals exceeded a safe level.

3.8.5 UTW Transient Response

As noted earlier, the QCSEE's were required to have rapid thrust-response capability. The specific requirement was to achieve a thrust change from 62% to 95% thrust in one second. Figure 84 shows the results of a study using a transient model of the UTW engine. The QCSEE requirement is noted on the figure. The dashed line shows the response of a conventional turbofan in which fan speed and core speed are both varied with fuel flow. The required response could not be achieved, with a conventional system, due to compressor stall and turbine inlet temperature considerations.

The solid line on Figure 84 shows the predicted thrust response with fan speed held constant through variation in the fan pitch angle. Holding fan speed constant results in the achievement of the required response since acceleration of the fan rotor is not required, and changes in fan pitch angle result in rapid changes in fan airflow.

3.8.6 OTW Design Requirements

The control-system requirements for the OTW engine were essentially the same as the UTW engine. However, the inlet Mach number control requirement was eliminated because the exhaust nozzle was manually varied, and two new requirements were added. These new requirements were:

- Failure indication and corrective action
- Full authority digital control

**Time to 95%
Net Thrust,
Seconds**

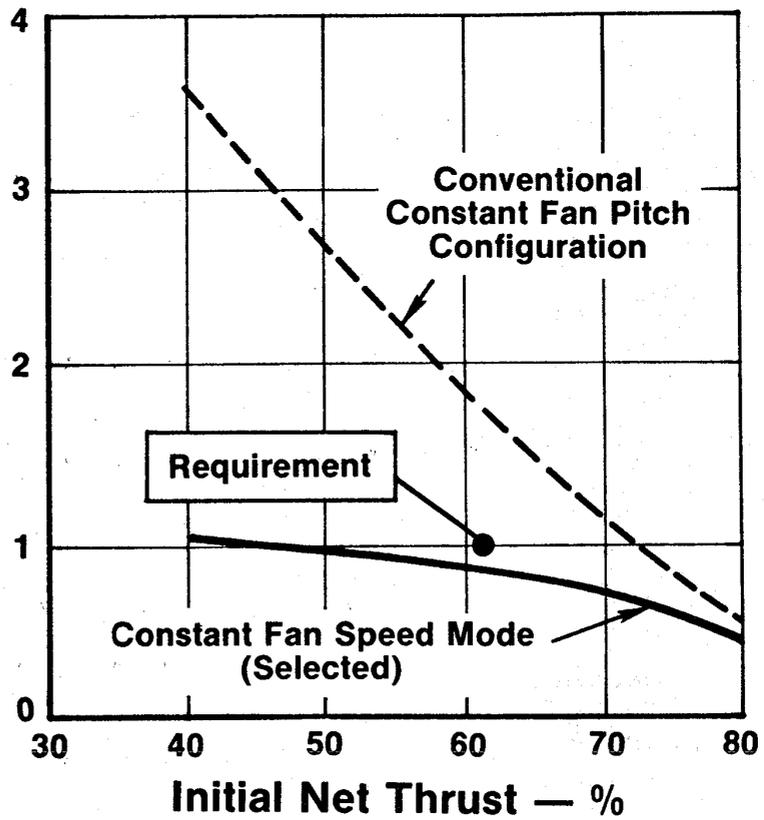


Figure 84. UTW Predicted Transient Response.

The first of these requirements is associated with a concept which allows continued operation after failure of an engine control-system sensor. The second requirement was added to allow further development of engine digital-control-system technology. The manner in which these requirements were implemented and demonstrated is discussed in the following sections.

3.8.7 OTW Control System Description

Figure 85 is a simplified schematic of the OTW propulsion control system. The experimental engine incorporated two manipulated variables: engine fuel flow and core compressor stator angle. The system to control these variables can be divided into three functional groups. These are the system sensors, the digital control, and the system actuators. The digital control is the heart of the system; it incorporates all of the control laws and logic to regulate the variables from engine start to maximum thrust. The digital control is identical to the UTW control except the control program memory has been revised to incorporate the OTW engine characteristics. The other major components in the system are the fuel pump, hydromechanical control, and core stator actuators. These components are the same as on the UTW engine except for functional changes in the hydromechanical control. On the OTW engine, the hydromechanical functions associated with acceleration fuel and core stator scheduling were eliminated. These important functions were incorporated into the full-authority digital control program memory.

Figure 86 is a schematic of the OTW engine and shows the control system sensors. The schematic is similar to the UTW system except for the following: the fan pitch and fan nozzle sensors have been eliminated, the core stator angle is sensed with an electrical transducer, and the core inlet temperature is calculated from fan inlet temperature, fan speed, and a fan-efficiency function. This calculated value of core inlet temperature is used in a subsequent calculation by the digital control to establish corrected core speed.

3.8.8 OTW Operating Characteristics

A control system analysis similar to the UTW engine effort was performed to select the controlled- and manipulated-variable pairs. Since the OTW experimental engine incorporated only one primary manipulated variable (fuel flow), the analysis process was less complicated. The analysis resulted in the pairing of corrected fan speed with engine fuel flow. Corrected fan speed was chosen because of its close correlation with turbofan thrust. Furthermore, the analysis resulted in the decision to schedule the core compressor stators with corrected core speed because this relationship provides good control of compressor stall margin. As a result of the above selection, movement of the percent-power-demand selector causes the digital control to vary fuel flow to hold a scheduled corrected fan speed and to schedule the core stator angle as a function of corrected core speed.

The digital control also incorporates the engine acceleration fuel schedule. This acceleration fuel limit is composed of two primary schedules.

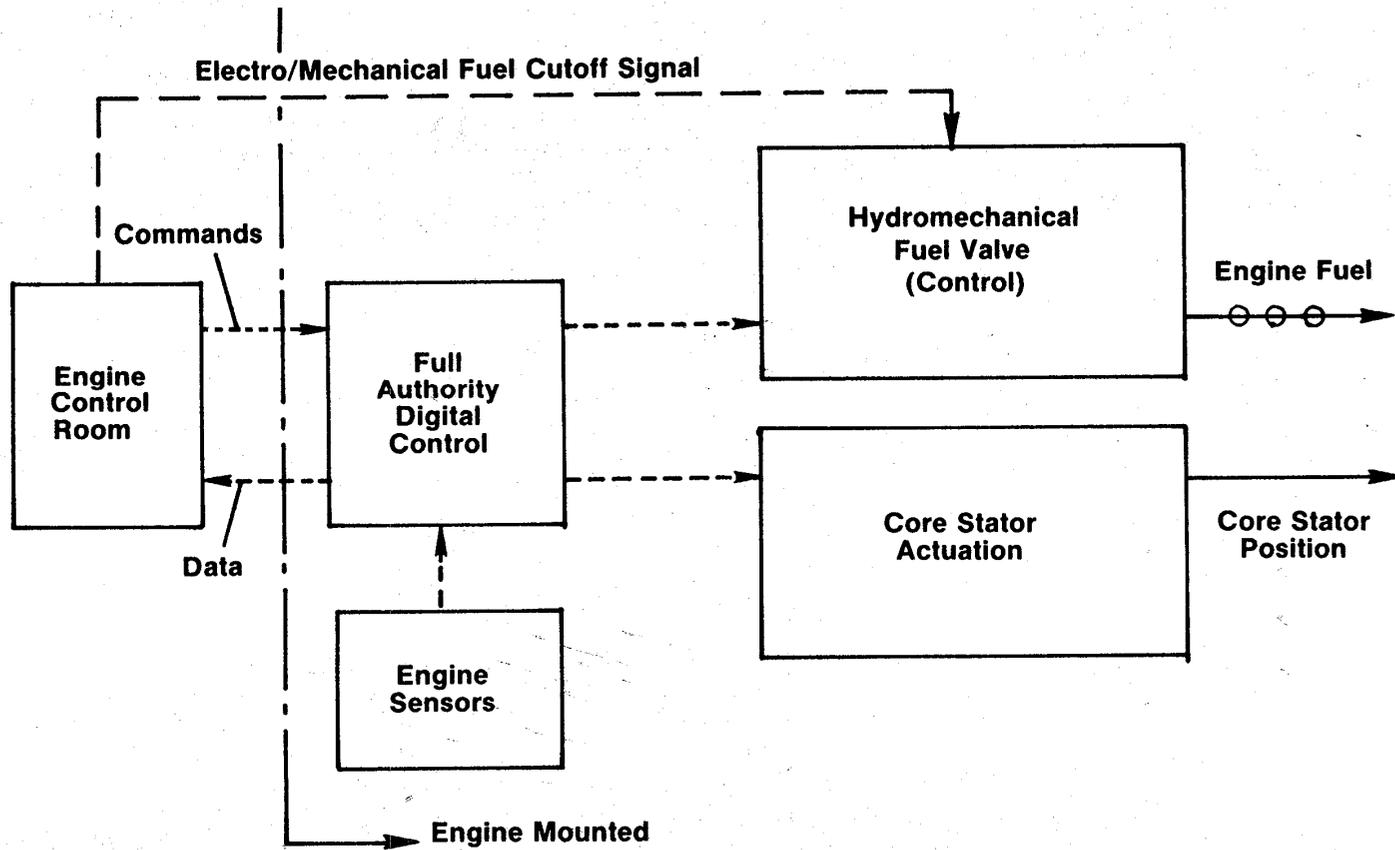


Figure 85. OTW Control System Schematic.

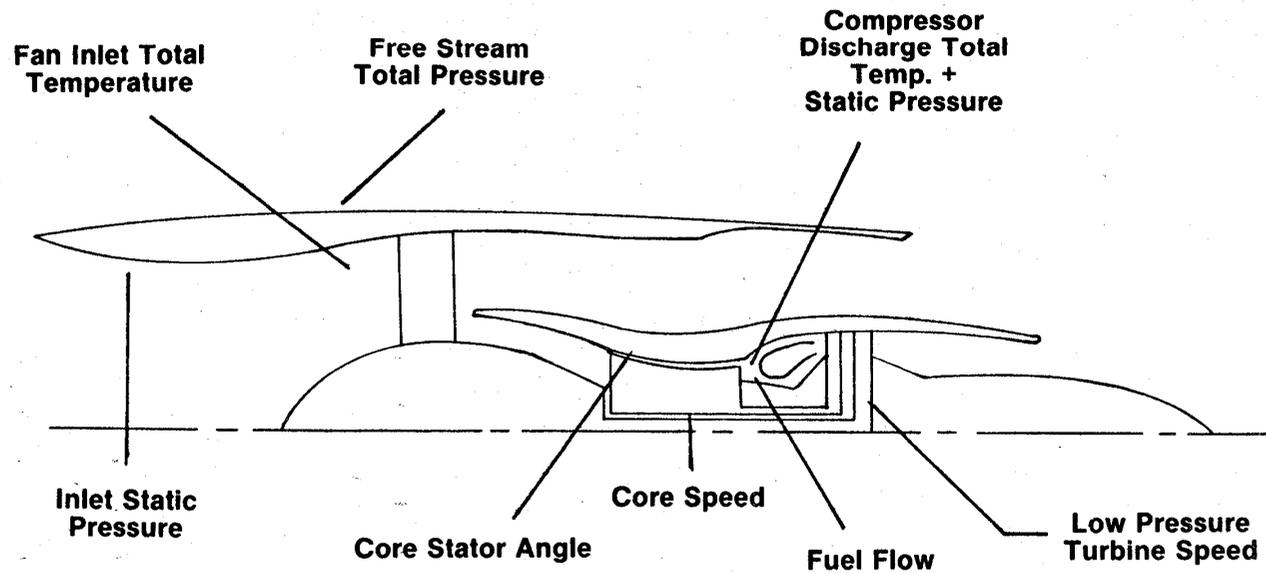


Figure 86. OTW Control System Sensors.