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ABSTRACT

A description of the overall QCSEE (Quiet Clean Short-haul Experimental Engine) Program is presented. The design of the two experimental engines in the program is essentially completed. The engine designs are described and projections of their performance presented. And finally, the advanced technology elements being incorporated into the engines are discussed.

INTRODUCTION

This paper presents a review of the QCSEE (Quiet Clean Short-haul Experimental Engine) Program. The overall objective of the program is to develop advanced propulsion system technology suitable for future short-haul aircraft. Recognizing that future aircraft will be required to be lower noise and pollution generators, advanced technology related to quiet and clean propulsion systems is an important aspect of the program. In the past, significant propulsion system noise improvements have been compromised by added performance losses and increased weight which ultimately result in increased aircraft operational costs. Accordingly, the QCSEE Program has the added objective of reducing, if not eliminating, operational cost penalties associated with the significant noise reduction goal of the program. This will be accomplished by developing noise reduction concepts that are less costly in terms of performance losses, as well as by introducing new technology into the propulsion system that is related to performance improvement exclusively. In view of the current interest in energy conservation this aspect of the program takes on added significance.

The QCSEE program review to be presented here will include a description of the overall program including the objectives, scope, and schedule. A description of the design and projections of the performance of the two experimental engines in the program will be presented. And finally, some discussion of the advanced technology items being incorporated into the engines will be presented.

BACKGROUND

The interest in short-haul aircraft propulsion in the QCSEE program results from studies which suggest that there is a potential market for new aircraft of this type in the 1980's and beyond. A desired feature for short-haul aircraft is the ability to be able to operate out of small airports, with corresponding short runways, in order to serve a wider market. This short runway operational capability can best be obtained by using deflected flow from the engines to help provide the additional aircraft lift that is required for this type of operation. This concept is often referred to as powered-lift.

Currently, the two preferred methods of obtaining powered-lift are the under-the-wing (UTW) and over-the-wing (OTW) blown flap concepts. An example of each concept is shown in figures 1 and 2 for the UTW and OTW engine installations respectively. There are advantages and disadvantages to each approach. The UTW concept results in a more conventional and simpler engine installation from an aerodynamic and mechanical standpoint While the OTW engine installation is less conventional, it offers the advantage of lower noise. The lower noise is a result of the shielding benefits provided by the large wing surface which is in the propogation path between the engine exhaust noise and ground observers. Because of the interest in both approaches, the QCSEE program is developing technology related to each approach.

OVERALL QCSEE PROGRAM

The objectives of the QCSEE program are as follows. The first objective is to develop short-haul propulsion technology which is environmentally and economically acceptable and is suitable for power-lift applications. The technology will be developed and demonstrated using full-scale engines. The second objective is to provide the Government with data on the environmental acceptability of the concepts investigated which could then serve as the basis for future Government rule making. And finally, there is the objective to provide industry with data so that the new technology can be incorporated into future engine development programs with a reduced amount of technical risk.

The primary technical requirements established for the QCSEE engines are given in table 1. As can be seen, the noise requirement for the engines is quite low. From a pollution standpoint, the designs use the EPA 1979 emission standards (which are directed towards the current conventional take-off and landing type of aircraft) as a general emission requirement because of the absence of any proposed standards for the short take-off and landing (STOL) aircraft. Because of the large effort in combustor emissions reduction technology in other programs, the QCSEE program for the most part, is relying on these other programs to provide the technology needed to meet the required emission levels. The installed thrust requirements of the UTW and OTW engines are 17 400 and 20 300 pounds, respectively. For short-haul aircraft, a 35 percent reverse thrust capability appears adequate.

A challenging requirement of the QCSEE engines is the relatively high installed thrust to weight ratios. The installed thrust-to-weight ratio is used here because this parameter not only includes engine performance but it recognizes the installation effects on thrust and weight. One of the important aspects of the QCSEE Program is to reduce the installation penalties. The installed thrust-to-weight of a modern engine such as the CF-6 used in the DC-10 aircraft is about 3.5 which illustrates the improvement being sought in the program. Finally, short-haul, power-lift aircraft will require improved engine dynamic response because of operation from short runways and the use of engines for providing lift.

The QCSEE engines contain a wide range of advanced technologies which include:

High bypass ratios engines
Variable pitch fan

Variable area fan nozzle

Advanced acoustic suppression (high-Mach-number inlet and acoustic linings)

Digital electronic controls

Reduction gearing

Composite components (fan blades, fan frame, and nacelle)

These new technologies contribute to either reduced engine noise or improved performance, and in some cases they help in both areas. Although the QCSEE program is directed toward short-haul, powered-lift aircraft, most of the new technology items shown here would also be beneficial if applied to engines of more conventional aircraft.

Design studies of low fuel consumption short-haul aircraft (ref. 1) indicate that significant reductions in fuel consumption can be made by modest reductions in aircraft speed in conjunction with wing aerodynamic refinements, such as higher aspect ratio and supercritical wings, and the use of low pressure ratio (high bypass ratio) propulsion systems. Fan pressure ratios in the range of 1.35-1.40 were found to be optimum for the anticipated future fuel prices. The QCSEE cruise fan pressure ratios arewithin this range, and accordingly, the fan technology being developed in QCSEE along with those technology elements that reduce propulsion system weight, should be of value to future low fuel consumption aircraft developments. Alltold, the technology being developed in the QCSEE program has the potential for benefitting a wide range of future aircraft developments. A more detailed discussion of these advanced technologies will be presented later.

An overall QCSEE program schedule is shown in figure 3. The major part of the program is being done under contract. A contract was awarded to the General Electric Company on January 1, 1974 to design, fabricate, and test two QCSEE engines. At this time, General Electric has completed the UTW and OTW engine designs and is deeply into the engine fabrication phase. Fabrication of the UTW and OTW engines and the boilerplate and composite nacelles will be completed in 1976. Following the engine and nacelle tests at General Electric, which completes the contracted effort, both propulsion systems will be delivered to NASA late in 1977. NASA tests will include acoustic evaluation of the engines with wing and flap sections installed to simulate the powered-lift condition. This testing will be followed by altitude performance tests in one of the altitude test chambers at the Lewis Research Center.

UTW PROPULSION SYSTEM DESIGN

A cross-section view of the UTW propulsion system is shown in figure 4. Also indicated in the figure are the advanced technology features incorporated in the engine. An F101 engine core is employed. The F101 engine is being developed by the General Electric Company for use in the Air Force B-1 bomber.

The acoustic requirements for the propulsion system have a major impact on the propulsion system design. The acoustic design considerations are shown in table 2. Since the most difficult acoustic requirement is the takeoff noise condition, this becomes the design point. The two major noise sources for the takeoff condition are jet/flap interaction noise and fan noise. However, core noise becomes a noise source to control when the two primary noise sources are reduced. Jet/flap interaction noise is caused by the engine exhaust impinging on the wing flaps. At this time, the only known method of its control is to reduce the velocity at which the exhaust impinges on the wing flaps, or in effect, to reduce the fan pressure ratio. Accordingly, the UTW fan pressure ratio is limited to 1.27 at takeoff. Thus, the reduction of jet/flap interaction noise had a major affect on the overall engine cycle, requiring a low fan pressure ratio and a corresponding high engine bypass ratio.

Unlike jet/flap interaction noise, there are several techniques available for reducing fan noise. The techniques incorporated into the UTW design are listed in table 2. The high-throat-Mach-number inlet (0.79 design Mach number) and wall acoustic treatment are used to suppress fan inlet noise. Acoustic treatment on the fan exhaust duct walls and a splitter ring are used to suppress fan aft noise. Wall acoustic treatment is contained in the core nozzle for core noise suppression.

Projections of aircraft noise levels using the UTW propulsion system characteristics indicate that all the noise requirements described earlier can be met, with the possible exception of the reverse thrust noise which appears to be a rather difficult-to-achieve requirement. Estimates of aircraft footprint area for 95 EPNdB noise contours show that footprint area will approach one-quarter square mile, which is well within the one-half square mile requirement. This footprint area is significantly lower than that of the quietest commercial aircraft in service today - by about a factor of ten - and, therefore, represents a significant noise improvement.

The major engine characteristics that were found necessary to meet the acoustic and performance requirements of the engine are presented in table 3. At takeoff, the relatively high bypass ratio of the engine is due to the relatively low (1.27) fan pressure ratio, which as previously indicated, is a result of acoustic considerations. Because of the low fan pressure ratio, the fan tip speed is reduced in order to reduce fan source noise. The engine overall pressure ratio is relatively low. Commercial engines usually employ higher overall cycle pressure ratios to improve propulsive performance. This could be accomplished in the UTW engine as well as in the OTW engine by adding booster stages. However, this was not done because it would not contribute significantly to the technology being developed and it would add considerable cost to the program.

In order to achieve maximum cruise thrust with the engine with airflow limited by the near-sonic inlet, the fan pressure ratio can be raised to greater than 1.35 for the cruise condition. This is done by reducing the fan nozzle area in conjunction with a two-degree closing of the fan blade pitch.

OTW PROPULSION SYSTEM DESIGN

Having reviewed the design of the UTW propulsion system, the next subject is a similar look at the OTW propulsion system. A cutaway view of the OTW engine and nacelle is shown in figure 5 and again, the advanced technology features incorporated are indicated. An F101 engine core is also used in the OTW propulsion system. For over-the-wing engine installations, a target type thrust reverser is more practical than the variable-pitch fan approach. The reasons are: the higher fan pressure ratio; the mixed core and fan flows; and the over-the-wing reverse flow discharge capability. In order to reduce program costs the fan blades and nacelle are not made of composite materials and, as a result of this, they are not flight-weight designs. A developed engine would use composite materials in the blades and nacelle in much the same manner as they are used in the UTW propulsion system.

The characteristics of the OTW propulsion system are presented in table 4. For comparison, those of the UTW propulsion system are also included. The OTW propulsion system has a lower bypass ratio than the UTW engine because of the higher fan pressure ratio (1.34) selected for the engine. A higher pressure ratio can be used in this engine without exceeding the noise goal because of the shielding of the jet/flap interaction noise provided by the over-the-wing engine installation. The higher fan pressure ratio improves the engine cruise performance and is, therefore, the motivation for increasing the fan pressure ratio. The higher fan pressure ratio requires a higher fan tip speed.

The relatively higher thrust of the OTW engine is not significant but is simply a result of the higher fan pressure ratio and the desire to have similar airflow capability for both engines. A common engine airflow was desired to permit using nearly identical fan frames and engine inlets, and thereby, to reduce program costs. During operation at cruise conditions, the fan pressure ratio can be raised to about 1.4 to increase the cruise thrust of this engine. The variable fan nozzle area capability is used to produce the increase in fan pressure ratio. Projection of the acoustic and aerodynamic performance of the OTW engine indicate that it will meet all the requirements established for it.

QCSEE ADVANCED TECHNOLOGY ELEMENTS

This section of the report reviews the more important advanced technology elements that are incorporated into the QCSEE propulsion systems. The discussion includes the benefits that the technology will bring, some of the design details and how the technology fits into the propulsion system designs.

Variable pitch fan. - Studies (ref. 2) have shown that variable-pitch fans have the potential for significantly reducing conventional thrust reverser system weight and cost if the fan pressure ratio is lower than about 1.30. This is the primary reason for incorporating the variable-pitch fan concept in the UTW propulsion system. However, there are other side benefits (which could be more important in some applications) such as the ability to vary the blade pitch during operation at takeoff, approach, idle, and cruise conditions in order to improve, as required, either the propulsion system noise, pollution, performance or engine thrust response characteristics. For example, engine pollutants at idle generally are a difficult problem. The variable-pitch fan feature can possibly help reduce these pollutants by operating the fan at idle thrust in a manner (flat pitch) that will improve the combustor inlet conditions. The advantages of this concept will be evaluated in the engine test program.

Figure 6 illustrates how the blade pitch variation capability will be used in the operation of the UTW engine. Shown in the figure are portions of a predicted UTW fan map where the solid lines are the predicted constant speed lines for the nominal (design) blade pitch. Also shown is the fan stall line. Changing the blade angle, opened (towards stall) or closed, results in a completely new fan map. A few non-nominal blade pitch setting speed lines are indicated in the figure by the dot-dashed lines. It can be seen that as the blade pitch is closed or opened at a given speed that there is respectively a marked reduction or increase in airflow. Due to acoustic considerations, the takeoff fan pressure ratio was limited to 1.27; however, the cruise pressure ratio (1.39) is kept as high as possible to improve cruise performance while maintaining adequate stall margin. The aerodynamic design point of the fan was a point about mid-way between the cruise and takeoff pressure ratios and at a slightly higher airflow.

The fan operates, for much of its operating range, as a constant airflow machine. The reason for this is the high-throat-Mach-number inlet In the region of the takeoff fan pressure ratio, a fixed value of airflow is desired because of the dependence on the inlet throat Mach number (0.79) to limit fan inlet noise propagation. Because the inlet is close to the choking airflow at a 0.79 Mach number, the airflow is not allowed to increase as it normally does at cruise because of a large increase in inlet pressure loss as the throat Mach number approached 1. Such pressure losses would result in significant performance penalties. The fan operating line is shown by the dashed line in the figure.

The operating line pressure ratios and airflow rates are obtained by a combination of fan nozzle area, blade pitch and engine corrected speed variations. The fan nozzle area change between takeoff and cruise points is 25%. Blade pitch is set at one degree open at 95 percent speed for takeoff to help establish the fan flow required to maintain the 0.79 Mach number at the inlet throat. At cruise, the blade pitch is closed one degree and the speed is increased to 105% of design. This blade pitch is chosen for the best combination of performance and stall margin.

Below a fan pressure ratio of 1.17, the fan nozzle has reached its open area limit, and the airflow and, therefore, inlet throat Mach number can no longer be held constant. For approach thrust (65% of design), the blade pitch is set at a two-degree closed position at 95% of design speed. This pitch setting is used to allow the fan speed to remain at the takeoff speed so that the engine thrust can be increased rapidly to the takeoff level. The transition to takeoff thrust is accomplished by rotating the fan blades, closing the fan nozzle to the proper area and increasing the fuel valve setting. All this can be done in less than a second because of the relatively low inertia of the components involved. Normally, if the engine has no variable blade pitch capability, the thrust increase is obtained by increasing the fan rotational speed, and because of the high inertia of the fan spool, the time is much longer. The QCSEE type of thrust transient, however, presents a more complex control problem, and the digital system in the engine is an important part of this feature. The digital control will be discussed later.

Although the previous discussion was based on predicted fan performance, recent aerodynamic tests of a 20-inch scale model of the UTW variable-pitch fan have confirmed that it will be capable of operating much in the manner described. However, there probably will be relatively minor changes in blade pitch and possible speed in order to obtain the desired fan pressure ratio at the various operating points in both forward and reverse thrust modes.

Because of the importance of the variable pitch feature in the QCSEE program, two different approaches to mechanizing the system are being investigated. One is being designed and built by Hamilton Standard under contract to General Electric Company. This variable pitch mechanism is schematically illustrated in figure 7. This design features the use of a cam-harmonic drive mechanism. It also employs a flexible cable which permits placing some of the electrical components in a more convenient location for easier maintenance. The no-back locks the blades in place when they are not being actuated and prevents movement that would result from the aerodynamic and mechanical forces acting on the blades.

The second variable pitch machanism, which is being built by General Electric, is shown in figure 8. This system features a ball screw - ball spline drive machanism which turns the blades through a ring and pinion gear arrangement. Much experience on aircraft engines has been obtained with ball screw devices which have been used as thrust reverser actuator machanisms.

Composite blades. - The use of composite fan blades offers the advantage of reducing the weight and cost of the engine. In addition, since the weight of the fan blade affects to a large degree the loads on the variable pitch actuation system, the use of composite blades reduces the weight and complexity of the variable pitch actuation system. A photograph of a QCSEE blade is shown in figure 9. The blade is 22.3 inches long from the tip to the base of the dovetail. The chord lengths at the blade tip and hub are 11.8 and 5.8 inches, respectively.

The blade is made of epoxy resin and graphite fibers with smaller quantities of glass and boron fibers added for developing the structural characteristics required in the blade. Although this blade design has proved adequate for the engine test program, its foreign-object-damage (FOD) resistance has been less than desired. Accordingly, the blade development program has been augmented to improve the QCSEE blade FOD resistance. Recent related results have been encouraging. It is expected that an acceptable design will result from the augmented blade development effort. The improved FOD resistant blades may eventually be incorporated into the engine to demonstrate their engine operational capability.

Composite fan frame. - The composite frame represents a significant technology advancement in the QCSEE program. The use of composite materials in the frame is expected to reduce the frame weight by about one-third over that of the usual metal frame and also to significantly reduce the frame cost. A cut-away view showing the frame structural arrangement is shown in figure 10. The main structural elements are the three wheels that are indicated in the figure. The nacelle structure, fan bypass vanes and fan bypass and core channels are built-in as an integrated structure. The front engine and nacelle inertia loads and the engine thrust are carried through the fan frame. The frame is built primarily of graphite fibers and an epoxy resin. In addition, aluminum honeycomb and Kevlar fibers are used to some extent in the formation of the airflow channels. Construction of the initial frame, which contains some 2300 individual pieces that subsequently are bonded together into one continuous structure, is well underway. A photograph of the fabricated aft wheel is shown in figure 11. The large size of the frame is evident.

Composite nacelle. - Another area where the use of composite materials is expected to significantly improve propulsion system weight and cost is in the nacelle. The nacelle (fig. 4) composite components consist of the inlet duct, the fan duct outer wall, the acoustic splitter and the core cowl. The acoustic treatment in the nacelle is built-in or integral with the structure, and it therefore serves the dual functions of acoustic suppression and structural load-carrying. This type of construction contributes to the lightweight and low cost characteristics of the design. The nacelle is built of Kevlar fibers, aluminum honeycomb, and epoxy resin except in the hot core cowl areas where graphite fibers and a polyimide resin system are used. Estimates indicate that the potential weight saving due to the use of composite materials to construct the nacelle can be in the area of 25%.

Combustor. - As indicated previously, the plan in the combustor emissions reduction area was to incorporate NASA Clean Combustor Program technology, as appropriate, into the QCSEE engines. The Clean Combustor Program has identified several combustor designs that produce emission levels that are significantly lower than those of combustors in use today. The combustor design that appears most suited to the QCSEE engines, considering both emission levels and adaptation to the engine, is the double annular dome type. A cross-section of the double annular combustor design, which has been sized and adapted to fit into the space available in the QCSEE engine is illustrated in figure 12. One of the main features of this design is the double annular row of swirl cup fuel injectors which allow the combustion to be staged. The outer row of injectors is used for low power settings while both rows are used for high power settings. The advantage of this approach is that each row of injectors can be designed and is operated over a much narrower range of conditions so that emission levels are improved.

Because of the relatively short length available for the combustor in the QCSEE engines and the smaller size of the engines, it is anticipated that some modifications to the basic double annular combustor design which was evolved in the Clean Combustor Program will have to be made in order to adapt it to the QCSEE engines. Accordingly, a combustor-rig test program will be initiated to investigate the effect and determine the modifications necessary to apply the double annular combustor technology to the QCSEE engines.

Reduction gears. - Low pressure ratio fans, such as the QCSEE fans, operate at relatively low rotational speeds. In order to keep the speed of the turbine that drives the fan high and, therefore, its size and weight down, speed reduction gears were incorporated into both the engines. Thus, the incorporation of light-weight reduction gears into the engines is expected to reduce overall propulsion system weight.

The gear sets for both engines are arranged in an epicyclic configuration with an input sun gear, an output ring gear, and stationary star gears supported on spherical roller bearings. A cross-section of the UTW reduction gear is shown in figure 13. Also included in the figure are some of the characteristics of both the UTW and OTW units. Of interest is the relatively light-weight design for the high horsepower transmission. The experimental unit weights shown could be reduced by about 8% in a flight application. The additional weight of the experimental units is in the static structure which results from attempts to simplify construction and reduce program costs.

Digital control. - There are a number of potential advantages associated with the use of a digital control system. Some of these are: reduced pilot work load through automatic thrust and safety limit control; ability to control more complex engines; health monitoring of the engines and automatic corrective action; and the ability to operate the engine more efficiently. A schematic layout of the UTW engine control system is illustrated in figure 14. There are four engine variables that need to be controlled: the fuel valve setting; the core stator angle; the fan blade pitch, and the fan nozzle area. The three engine performance parameters that the engine mounted digital control system will control are thrust, inlet throat Mach number and fan speed. A control mode analysis, which considered both control accuracy and stability, indicated that the engine thrust should be controlled through an engine pressure ratio parameter. For rapid thrust response, fan pitch was selected to control fan speed, and fan nozzle area was selected to control inlet Mach number. In addition, the digital control will automatically limit a number of engine parameters and also provide access to a quantity of engine performance data. Finally, the control system will incorporate a feature which will allow it to continue to function in the event of a failure of one or more of the engine sensors that are used in the engine control system.

CONCLUDING REMARKS

The design of both QCSEE propulsion systems is essentially completed. Work is now concentrating on the fabrication of engine and nacelle components, and the assembly of the first engine is scheduled to be completed in April of 1976. In the QCSEE program a wide range of advanced propulsion system technology is being investigated. The wide range of advanced technologies being investigated can be grouped into three general areas associated with improvements in propulsion system noise, performance or fuel economy and emissions. Although the major thrust of the program is directed towards providing technology for powered lift, short-haul aircraft, many of the individual technology elements in the program will have application to a much broader range of future aircraft.

REFERENCES

1. M. K. Bowden, H. S. Sweet, and M. H. Waters, "Design of Short-haul Aircraft for Fuel Conservation," Paper 750587, presented at SAE Air Transportation Meeting, Hartford, Conn., May 1975.

2. R. Neitzel, R. Lee, and A. J. Chamay, "QCSEE Task 2: Engine Installation Preliminary Design," NASA CR-134738, 1975.

TABLE 1. - QCSEE TECHNICAL REQUIREMENTS

Noise, 500 ft sideline:	
Takeoff & approach, EPNdB	95
Reverse, PNdB	100
Footprint, 95 EPNdB contour, sq mi	<0.5
Pollution	EPA 1979 emission levels
Installed thrust:	
Forward UTW, lb	17 400
Forward OTW, lb	20 300
Reverse	35% of forward thrust
Installed thrust/weight:	
UTW	4.3
OTW	4.7
Dynamic response:	
Approach to takeoff thrust, sec	1.0
Reverse thrust, sec	1.5

TABLE 2. - UTW PROPULSION SYSTEM

ACOUSTIC DESIGN FACTORS

[Design point, takeoff.]

Noise sources	Method of reduction
Jet/flap interaction	Reduced fan pressure ratio, 1.27
Fan noise	Low fan tip speed Large rotor/stator spacing Blade/vane ratio Acoustic suppression
Core noise	Acoustic suppression

TABLE 3. - UTW ENGINE

CHARACTERISTICS AT TAKEOFF

Bypass ratio	12.1
Fan pressure ratio	1.27
Fan tip speed, ft/sec	950
Overall pressure ratio	14.3
Thrust, lb	17 400

TABLE 4. - ENGINE

CHARACTERISTICS AT TAKEOFF

	OTW	UTW
Bypass ratio	10.1	12.1
Fan pressure ratio	1.34	1.27
Fan tip speed, ft/sec	1162	950
Overall pressure ratio	17.3	14.3
Thrust, lb	20 300	17 400

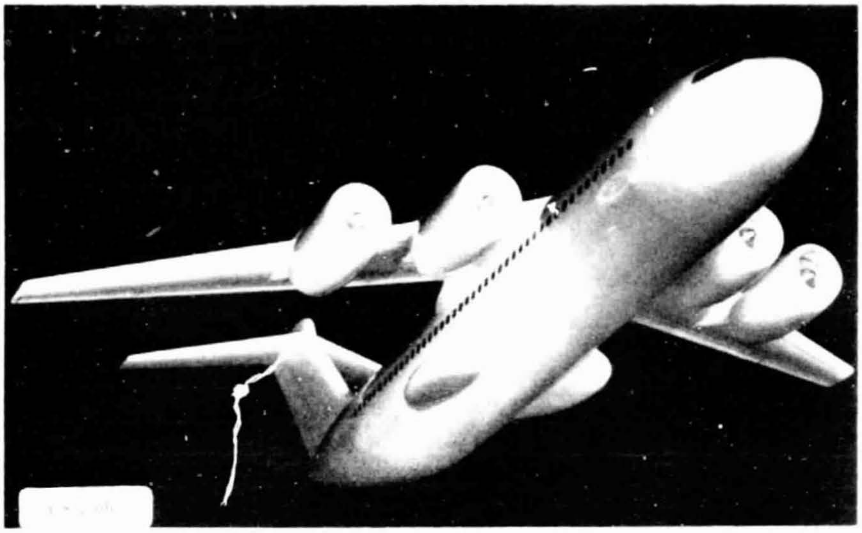

Figure 1. - Conceptual UTW short-haul aircraft.

Figure 2. - Conceptual OTW short-haul aircraft.

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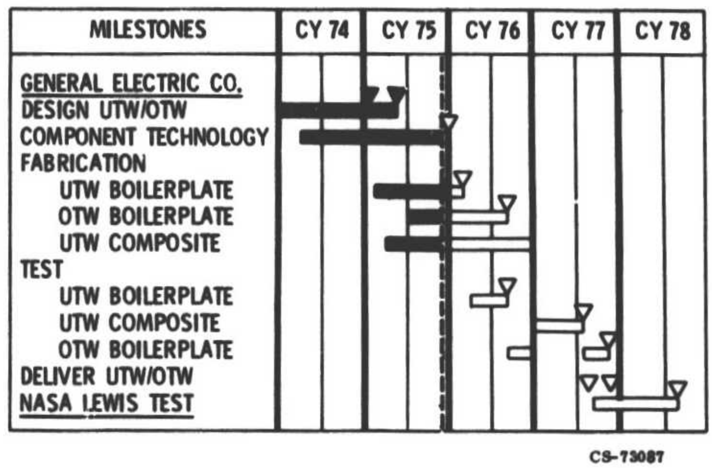


Figure 3. - QCSEE project schedule.

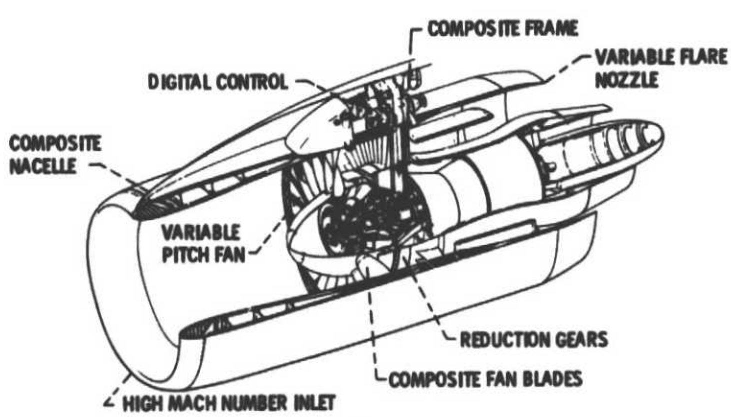


Figure 4. - QCSEE UTW engine.

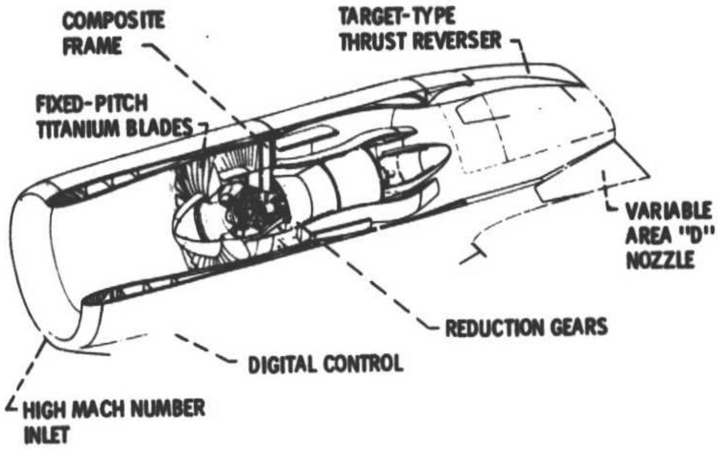


Figure 5. - QCSEE OTW engine.

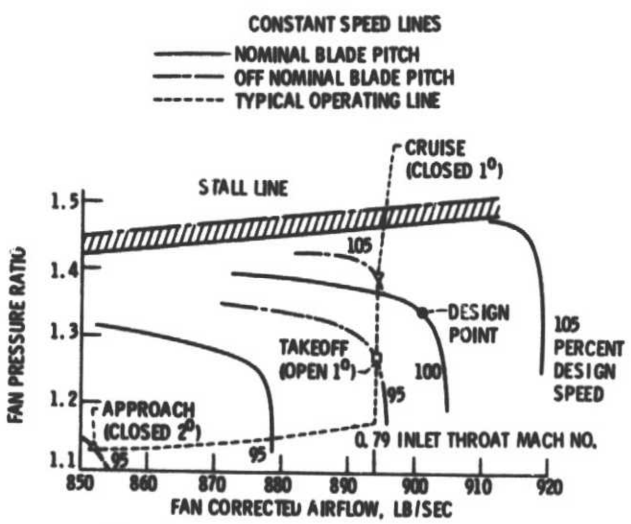


Figure 6. - Predicted UTW variable pitch fan map.

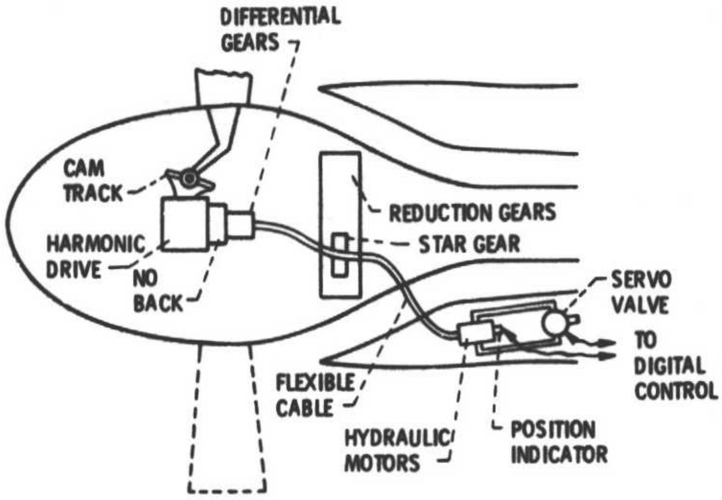


Figure 7. - Hamilton standard variable pitch mechanism.

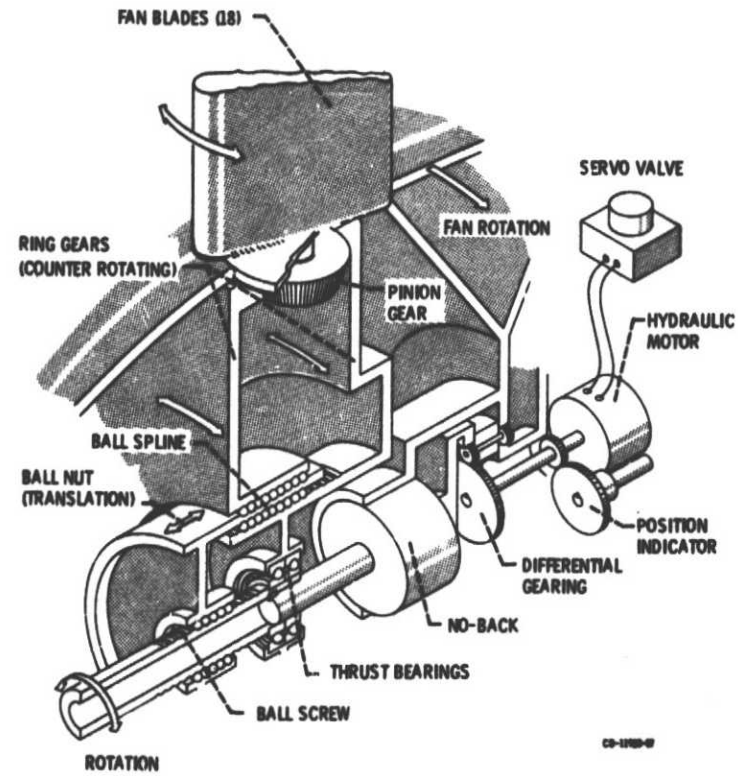


Figure 8. - General Electric Co. variable pitch mechanism schematic.

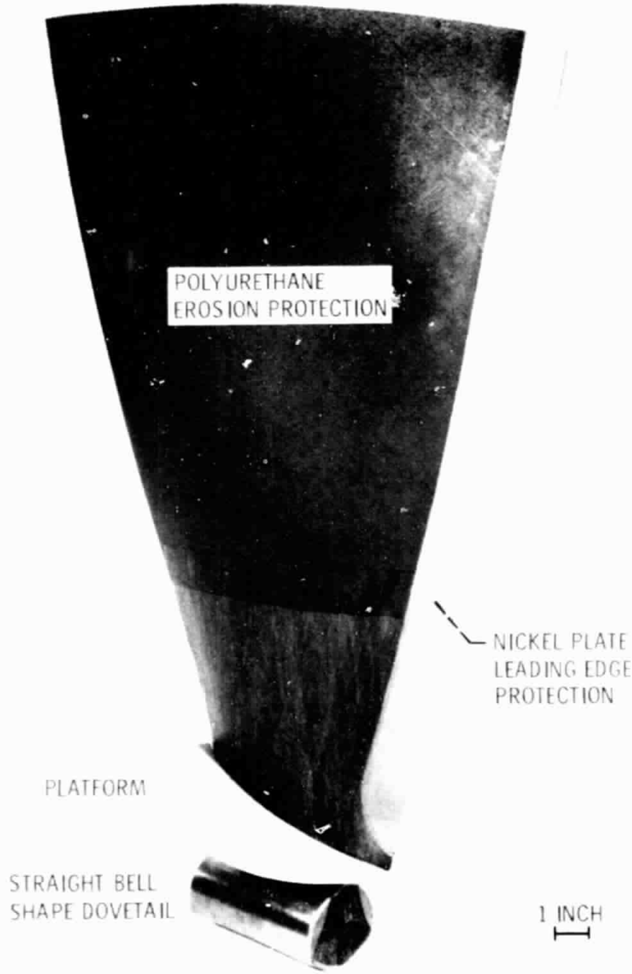


Figure 9. - UTW engine composite fan blade.

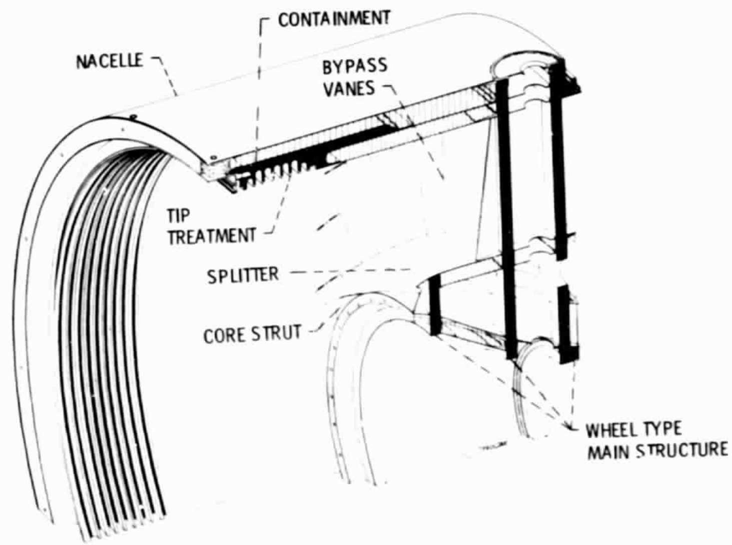


Figure 10. - Composite fan frame.

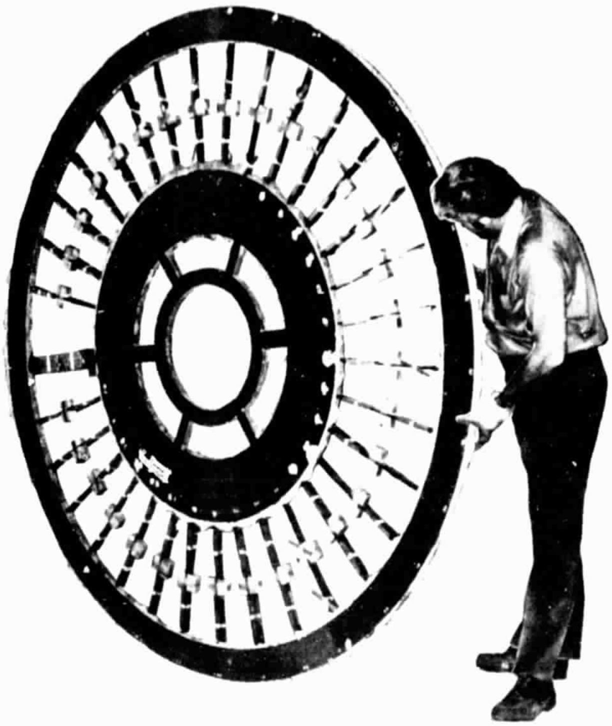


Figure 11. - Assembled composite fan frame wheel.

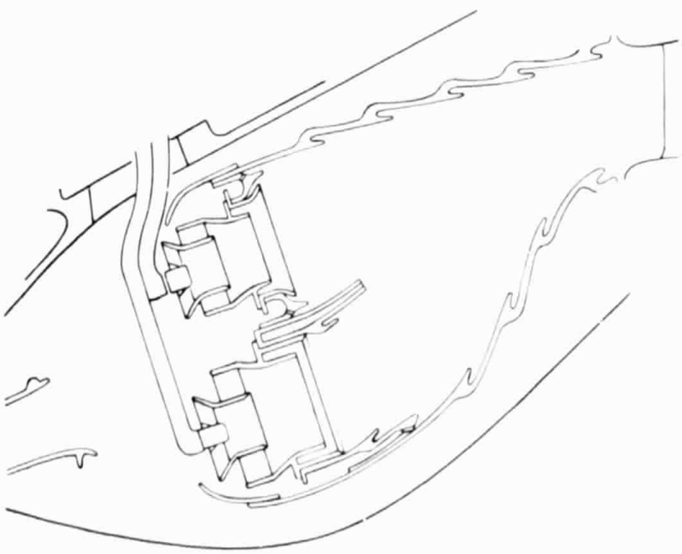
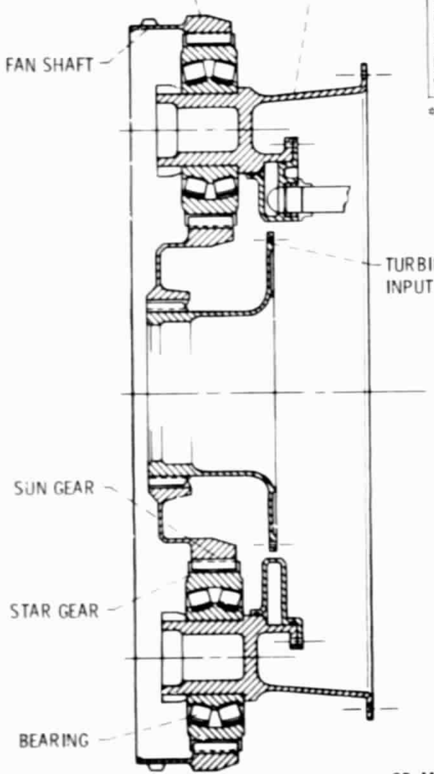


Figure 12. - Double annular combustor in QCSEE envelope.



	UTW	OTW
GEAR RATIO	2.465	2.062
HORSEPOWER*	13256	17183
SUN SPEED RPM	7747	7962
NO. STARS	6	8
STAR SPEED RPM*	10577	14998
EFFICIENCY*	99.3	99.1
WEIGHT	204	198

*TAKE-OFF CONDITIONS

CD-11921-07

Figure 13. - Reduction gears.

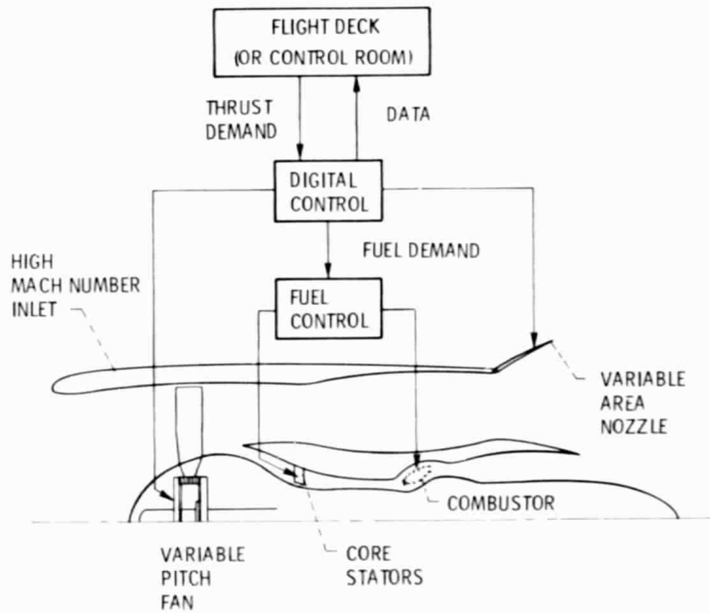


Figure 14. - QCSEE control system.