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OVERVIEW OF NASA PTA PROPFAN FLIGHT TEST PROGRAM

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SUMMARY

During the last several years, high-speed propellers have made the transition from a wind tunnel curiosity to a very likely near-term, fuel-efficient propulsion system that could revolutionize the subsonic commercial air transport industry. A key ingredient in this remarkable progress is the advanced turboprop program. Working together, NASA and industry have developed and flight-tested two propeller propulsion systems to provide answers to key technical questions and concerns. An industry team is currently developing a third propeller propulsion system for flight testing early in 1988. This report covers, in particular, the progress of the NASA-sponsored Propfan Test Assessment (PTA) flight test program. Lockheed-Georgia is the prime contractor for PTA with Allison, Hamilton Standard, Rohr, Gulfstream, and Lockheed-California serving as major subcontractors. In PTA, a 9-ft-diameter propfan has been installed on the left wing of a Gulfstream GII executive jet and is undergoing extensive flight testing at Dobbins Air Force Base to evaluate propfan structural integrity, near- and far-field noise, and cabin interior noise characteristics. This research testing includes variations in propeller tip speed and power loading, nacelle tilt angle, and aircraft Mach number and altitude. As a result, extensive parametric data will be obtained to verify and improve computer codes for predicting propfan aeroelastic, aerodynamic, and acoustic characteristics. Over 600 measurements are being recorded for each of approximately 600 flight test conditions.

INTRODUCTION

The major elements of the NASA-sponsored Advanced Turboprop (ATP) program, as shown in figure 1, are the Large-Scale Advanced Propeller (LAP) contract with Hamilton Standard, the Propfan Test Assessment (PTA) contract with Lockheed-Georgia, the Unducted Fan (UDF) contract with General Electric, and the Advanced Gearbox Technology contracts with both Allison and Pratt & Whitney.

In the LAP contract, Hamilton Standard designed, built, and ground-tested an eight-bladed, 9-ft-diameter, advanced single-rotation SR-7 propeller. Before delivery of the two SR-7 assemblies to PTA, Hamilton Standard conducted thorough bench tests at their research facilities, static tests with facility power at Wright Patterson Air Force Base, and wind tunnel tests at the Onera 26-ft tunnel in Modane, France. In the Modane tests, depicted in the photo on the left in figure 2, the propfan blades were instrumented to measure both steady and unsteady blade pressure distributions. Up to six of the eight blades were removed in the Modane tunnel testing in order to properly simulate

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the correct power loading per blade with the limited facility power available. These unique data are currently being used to validate and improve propfan aerodynamic and acoustic performance prediction codes. One of the completed SR-7 assemblies for delivery to the PTA program is shown in the right-hand photo of figure 2.

The Unducted Fan program was a cooperative NASA-GE program to design, build, and static-test an 11-ft-diameter gearless counterrotating propeller propulsion system. The GE ground static test at Peebles, Ohio, is shown in the top photo of figure 3. In this 25 000-lb-thrust demonstrator engine, the propeller blades are mounted directly to the frames of a counterrotating turbine, eliminating the need for a high-horsepower gearbox. The UDF was static tested in August 1985 and later flight tested on the Boeing 727 and Douglas MD-80 aircraft. These two UDF flight-test configurations are shown in the two lower photos of figure 3. Flight-test results with both an 8 by 8 and 10 by 8 blade configuration indicate that a product UDF can meet the stringent FAR-36 noise standards, provide a quiet cabin environment, and burn from 40 to 50 percent less fuel than the low-bypass turbofans in use today in narrow-body aircraft such as the 727 and DC-9.

Both Allison and Pratt & Whitney were involved in the early phases of the NASA Advanced Gearbox Technology program. However, because of funding problems, only Allison (with their own funds) completed gearbox testing. Allison's 13 000-hp gearbox design used an in-line differential planetary gear system. In nose-to-nose rig tests at Allison's new gearbox test facility, shown in figure 4, an efficiency of over 99 percent was verified. Test results also indicated that the durability goal of 30 000-hr mean time between removals is achievable. Allison is using these results to build the flightweight gearbox for the 578-DX counterrotating propeller drive system being developed jointly by Pratt & Whitney and Allison. Hamilton Standard has designed and built a counterrotation propeller assembly for the 578-DX which draws upon SR-7 (LAP) technology and the results of counterrotation model testing of similar configurations. Testing of the 578-DX on the Douglas MD-80 will begin in 1989.

In just a few years, the propfan has made the transition from small-scale wind tunnel models to the flight test of several large-scale systems, as illustrated in the series of photographs in figure 5. The balance of this paper will focus on the NASA-sponsored PTA flight test program.

OBJECTIVES AND PROGRAMMING ASPECTS OF PTA PROGRAM

The PTA program focused on two fundamental concerns: propfan structural integrity and noise, as detailed in figure 6. NASA had to be sure that the thin, highly swept propfan blades would behave aeroelastically as predicted and that propfan-generated noise was not a problem. Source noise, cabin noise, community noise, and en route noise were investigated.

Figure 7 shows how the PTA program has progressed from its inception in August 1984. The Allison model 570 industrial gas turbine engine and T56 gearbox were modified and checked out by early 1986 for the static testing at Rohr's Brown Field test site in June 1986. Following the Rohr test, the propfan was installed on the left wing of the Gulfstream GII executive jet, and flight testing began in March 1987. In support of the flight test, several scale-model wind tunnel tests were conducted to verify predicted aircraft flutter, performance, stability and control, and handling characteristics. The flight research testing was completed with the test of an advanced, lightweight, acoustically-treated interior in March 1988.

Figure 8 shows the team responsible for implementing the PTA program. Lockheed-Georgia, prime contractor to NASA for PTA, led a team consisting of five major subcontractors: Allison for the turboshaft engine and gearbox to power the propfan, Hamilton Standard for the SR-7 propfan, Rohr for the QEC or forward nacelle, Gulfstream for all aircraft modifications, and Lockheed-California for their expertise in the acoustic arena. All contractors did a remarkable job of pulling together as a team to make the total program a success.

AIRCRAFT MODIFICATION AND SUPPORT ACTIVITIES

Although installing the propfan on the wing of an aircraft may sound simple, it was actually very complex. Almost all of the aircraft systems (fuel, hydraulic, air conditioning, electrical, control, and so forth) had to be modified. The modifications made to the G-II airplane to convert it to the PTA testbed are summarized in figure 9. Of particular note is the over-2000-lb static balance boom added to the right wing to offset the 6500-lb propulsion system on the left wing. A dynamic boom was installed on the left wing to assure adequate wing flutter margin. Wing structural beef-up involved adding doublers to the front and rear beams, adding a rib near the nacelle attach point, and adding doublers to the ribs and skin. It should also be noted that, in addition to these modifications, a 700-lb armor plate of 3/8-in. stainless steel was installed on the fuselage during the early part of the flight testing to protect the crew in the event of a blade failure.

Because of the research objectives of the PTA flight test effort, it was necessary to highly instrument the airplane, as indicated in figure 10, thus adding to the complexity of the modification effort. Over 600 research and operational parameters were added for this test, including microphones, accelerometers, pressures, temperatures, fuel flow rates, propfan strains, and aircraft and propfan operation conditions. All parameters were continuously recorded by on-board recorders. In addition, propfan stresses were monitored in real time by an on-board Hamilton Standard engineer whenever the propfan was powered. A telemetry system also sent selected key parameters to a ground recording system.

To verify propfan integrity, the propfan had to be tested over a range of conditions including forward speed, altitude, and inflow angle of attack. Speed and altitude were easy to control, but the propfan inflow angle was more difficult. The variation in aircraft weight due to fuel burnoff during testing did not provide a sufficient angle-of-attack change. Lockheed came up with a unique way of solving this problem - a tiltable forward nacelle. With this system, which is illustrated in figure 11, tilt was adjustable from 2° up, to 3° down, simply by changing the forward-to-aft nacelle mounts. With tilt adjustment, the desired range of inflow conditions was attainable over a range of flight operating conditions. Figure 12 shows how nacelle tilt, combined with aircraft weight change (i.e., weight changing as fuel is burned off during flight), gives the desired range of a propfan flow parameter called excitation factor. Excitation factor is a measure of flow nonuniformity and in its simplest form is the product of propfan inflow angle and the flow dynamic head. Shown in figure 12 are three representative flight conditions: Mach 0.3 at sea level, Mach 0.6 at 20 000-ft altitude, and Mach 0.8 at 30 000-ft altitude. In each case, an excitation factor range of about 2 to 4 is possible.

In support of the PTA design modification and analysis effort, several ground and wind tunnel tests were conducted. The models are shown installed in the test facilities in figure 13. These tests provided the data necessary to confirm predictions, verify analytical models, reduce program risk, and allow the proper interpretation of flight test data. Testing included a 1/3-scale inlet diffuser test to evaluate inlet recovery and distortion characteristics, a 1/9-scale full-span aeroelastic model test in NASA Langley's 16-ft transonic dynamics tunnel to verify aircraft flutter margins, a 1/9-scale full-span model test in two tunnels (NASA Langley's 16-ft transonic tunnel and 4- by 7-m low-speed tunnel to evaluate aircraft stability, control, and performance), and a 1/9-scale semi-span model in the NASA Lewis 8- by 6-ft wind tunnel to obtain data on the flow field coming into the propfan. This flow field information is needed for interpreting the propfan stress data obtained in flight.

The drive system for the SR-7 propfan consisted of an extensively modified Allison T-56 gearbox and a somewhat modified Allison model 570 industrial gas turbine engine. The model 570 is a ground-based version of the XT701 experimental engine developed by Allison for the Army heavy lift helicopter. Because this is one-of-a-kind hardware, the gearbox and engine were thoroughly ground tested before being combined with the Hamilton Standard SR-7 propfan and static tested at Rohr's static test stand in Chula Vista, California. The gearbox and engine testing at the Allison plant in Indianapolis are shown in the photos on the left in figure 14, while the Rohr test configuration is shown on the right. The 50-hr propulsion system checkout test over simulated flight conditions at Rohr was a real surprise, as it went almost exactly according to plan with only minor adjustments required before proceeding with the flight test program.

In figure 15 are shown a few photos of the Gulfstream GII airplane during various stages of modification. In the upper left-hand photo is the serial number 118 GII as purchased by Lockheed in May 1986. Wing beef-up, the attachment of the wing to the fuselage, and the nacelle installation on the wing are also shown in this series. The lower right-hand photo clearly shows the split line between the forward and aft nacelle assemblies. It is in this region that the attachment mounts are changed to adjust nacelle tilt angle.

FLIGHT TESTING

Figure 16 shows the completed PTA airplane as it was first tested in April 1987 with the propfan installed. Previous aircraft checkout testing without the propfan installed started in March. Note the static balance boom on the right wing, the microphone boom and flutter boom on the left wing, the Rosemount aerohead boom on the nose, the fuselage protective shield in the plane of the propfan, and of course the SR-7 propfan and nacelle on the left wing. The top photograph shows that the propfan was not operated and that the blades were in the feather position during takeoff because of structural restrictions on allowable flap hinge moments. The Allison propfan engine is air started after takeoff with bleed air from the Spey engines at an altitude of about 5000 ft.

The flight test program was sequenced as shown in figure 17 to keep risk to a minimum. All systems were carefully checked out on the ground before going to flight testing. In flight, the complete flight research envelope (and beyond, to provide a safety margin) was systematically cleared before proceeding with the flight research testing. The initial airworthiness flight test phase was conducted with the protective armor plate installed on the fuselage until confidence was gained in the structural integrity of the propfan over the extremes of the operating conditions to be encountered in the test effort. The airworthiness tests consisted of evaluations of aircraft/propfan propulsion systems, flight flutter, and handling characteristics. The objective of the flight research phase was to verify propfan structural integrity, to determine propfan source noise, to obtain community and en route noise characteristics, to define cabin noise environment, and to determine lateral noise attenuation characteristics. Approximately 80 percent of the total flight time was devoted to flight research testing.

Over 500 high-altitude test conditions were recorded over the flight envelope shown in figure 18. The large number of test points is a result of the parametric approach to obtaining data. Nacelle tilt, propfan tip speed, and propfan power were all varied independently for the altitudes and speeds shown. In addition, baseline acoustic data were obtained with the propfan removed at most of these flight conditions so that propfan noise at various conditions could be compared with similar baseline conditions without the prop. The program emphasis was on getting good research data for verifying computer prediction codes. These codes can then be used by industry in the design of future propfan propulsion systems.

Figure 19 is a closeup photo of the installed SR-7 propfan with the spinner removed. Note the strain gages on each of the blades. Forty six strain gages were installed on the blades and blade root area. As mentioned earlier, key gages were continuously monitored during flight, and 32 were recorded.

Figure 20, which is representative of in-flight measured propfan blade inboard bending stress data, shows that these stresses were consistently below the infinite life limit criterion set by Hamilton Standard. These data show that although nacelle tilt angle variations affect blade stressing in a predictable manner, the trends vary as a function of airspeed. The results also show that blade stress increases with decreasing rotational speed (closed versus open symbols) because of increased 2-per-rev response as a critical speed is approached at the lower rotational speed.

The fuselage surface has been instrumented with a total of 44 microphones which are concentrated near the plane of propfan rotation, as shown in figure 21. This microphone placement allows mapping of the propfan noise contours in the area where they are likely to maximize. Internal cabin noise microphones at analogous locations will allow an assessment of the acoustic attenuation due to the cabin wall. The acoustic boom located near the wing tip contains five microphones at axial stations identical to five of the fuselage microphone planes. The boom is located at the same distance from the propfan as the closest points on the fuselage. The boom microphones will show the acoustic impact of rotation directionality, when the results are compared with the output from the analogous fuselage microphones. This is because the propfan blades on the inboard side are rotating upward with the flow due to circulation over the wing, whereas on the outboard side the blades are moving downward against the circulatory flow.

Figure 22 compares fuselage-surface blade passing tone for measured flight test noise data, prediction, and Lewis 8- by 6-ft wind tunnel data acquired with a subscale propfan model. As can be seen, there is good correlation of the measured flight data with both the prediction and the corrected model test data. The peak surface noise occurs slightly downstream of the propfan plane and in magnitude is slightly below that obtained with the prediction and the wind tunnel data.

Community noise testing at the NASA Wallops Flight Facility was completed in October 1987. Twelve flights of about 2 hr each were flown over the microphone array shown to obtain a matrix of data at several altitudes (from 850 to 1600 ft), propfan tip speeds, power settings, and nacelle tilt angles. Acoustic baseline data with the propfan blades removed were also obtained. As shown in figure 23, sideline microphones beyond the normal 1476-ft distance required by FAR-36 were located at intervals out to a distance of 8100 ft from the flight path in order to assess lateral noise attenuation characteristics of the propfan in addition to the usual community noise measurements. A quick-look analysis of the acoustic data from each of the seven microphone sites was performed after each flight, and the data quality appears to be excellent. Detailed analysis of this data is now in progress.

After completion of the Wallops low-altitude noise tests, the PTA airplane returned to Dobbins Air Force Base in Marietta, Georgia, for maintenance and preparation for high-altitude en route noise testing, which was completed in November 1987. The en route noise testing was a joint effort with the FAA, which was primarily interested in verifying an analytical code for the prediction of atmospheric acoustic attenuation. In addition, NASA was interested in determining the acoustic characteristics for the propfan propulsion system from the standpoint of an observer on the ground when the airplane is in high-altitude flight. To assess the atmospheric acoustic attenuation characteristics, it was necessary to measure the propfan noise near the source as well as on the ground. The Lewis Learjet, equipped with wing-tip and fuselage microphones and special video and still camera equipment for distance measuring, was used for the acquisition of source noise data. The FAA installed a line of microphones on level ground at five stations beneath and perpendicular to the flight path, as shown in figure 24. To quantify atmospheric conditions during these flights, the Air Force launched weather balloons four times each day. Because it was necessary for the Learjet to fly beneath and close to the PTA at locations where pilot visibility of the other aircraft was restricted, the NASA T-38 chase plane was also flown on these formation flights to assure adequate separation between the two aircraft. Analysis of the data acquired in this testing is now in progress. Data quality appears to be excellent.

An advanced cabin acoustic treatment enclosure was fabricated under a NASA-Langley contract by Lockheed-California for flight test in the PTA testbed aircraft in March 1988. The enclosure, located as shown in figure 25, consists of tuned Helmholtz resonator panels attached to a framework, which was mounted to the cabin floor through vibration isolators. A comparison will be made between the interior noise levels with the advanced treatment and that obtained in the earlier flight tests of the same airplane with bare, untreated cabin walls. These flight tests complete the currently planned PTA flight test program.

CONCLUDING REMARKS

The PTA flight testing was completed with the cabin acoustic enclosure testing in March 1988. The results obtained thus far are preliminary because analysis of the massive quantities of data acquired in this program will not be completed until late 1988. The PTA flight test effort is summarized as follows:

1. Over 600 measurements recorded
2. Over 500 high-altitude flight test conditions, including propfan tip speed from 600 to 840 ft/sec, propfan power from minimum to 100 percent, three nacelle tilts (to vary excitation factor), speed to Mach 0.89, and altitudes from 2000 to 40 000 ft
3. Community noise data obtained at NASA Wallops Flight Facility
4. En route noise data obtained

Resulting conclusions and status of the program are highlighted as follows:

1. Propfan structural and aeroelastic response in good agreement with predictions
2. Measured near-field noise trends were consistent with predictions and data acquired in wind tunnel tests on subscale models
3. Community noise test data being analyzed by NASA and Lockheed
4. FAA and NASA using en route noise data to validate atmospheric attenuation codes
5. Interior noise tests completed in March 1988

In the high-altitude research tests, over 600 data parameters were recorded at more than 500 flight conditions. The effects of propfan tip speed and power level on blade stress and acoustics were recorded over a spectrum of flight conditions. A spectrum of inflow conditions was obtained over the flight Mach number/altitude matrix by varying nacelle tilt. A further perturbation to inflow conditions was obtained by a limited variation in yaw angle. Research data were acquired for a flight envelope extending from near the low-speed stall region to a flight speed of Mach 0.85 at altitudes up to 40 000 ft. Airworthiness testing verified that the aircraft was free of flutter up to Mach 0.89. For the wide range of inflow and flight conditions investigated for the propfan in this flight test program, blade stresses were always well within the limits specified by Hamilton Standard for unlimited fatigue life. The source noise measured on the fuselage in the high-altitude research testing was close to analytical prediction and wind tunnel model data. The peak noise at the fuselage surface occurred slightly downstream of the propfan plane.

Additional data were acquired in a series of low-altitude community noise evaluation flights at NASA Wallops in September and October, 1987. In addition to normal community noise measurements, lateral noise attenuation characteristics were also evaluated. Community noise data from Wallops is of good quality and is now being analyzed. Subsequently, high-altitude en route noise testing was performed over northern Alabama in conjunction with the FAA to verify an atmospheric attenuation model and to determine the general characteristics of propfan noise measured on the ground. A preliminary look at the data indicated that it is of good quality, with the stable weather conditions necessary for code verification.

The final flight testing in PTA was a test of the advanced cabin acoustic treatment enclosure in March 1988. These tests allowed a direct comparison to be made between noise levels in flight with the treatment and with a bare-wall cabin. Because of the extensive source noise data acquisition throughout this research program, the propfan source noise will be well understood and will be beneficial in understanding any further treatment improvements which may be desired after analysis of the test results.

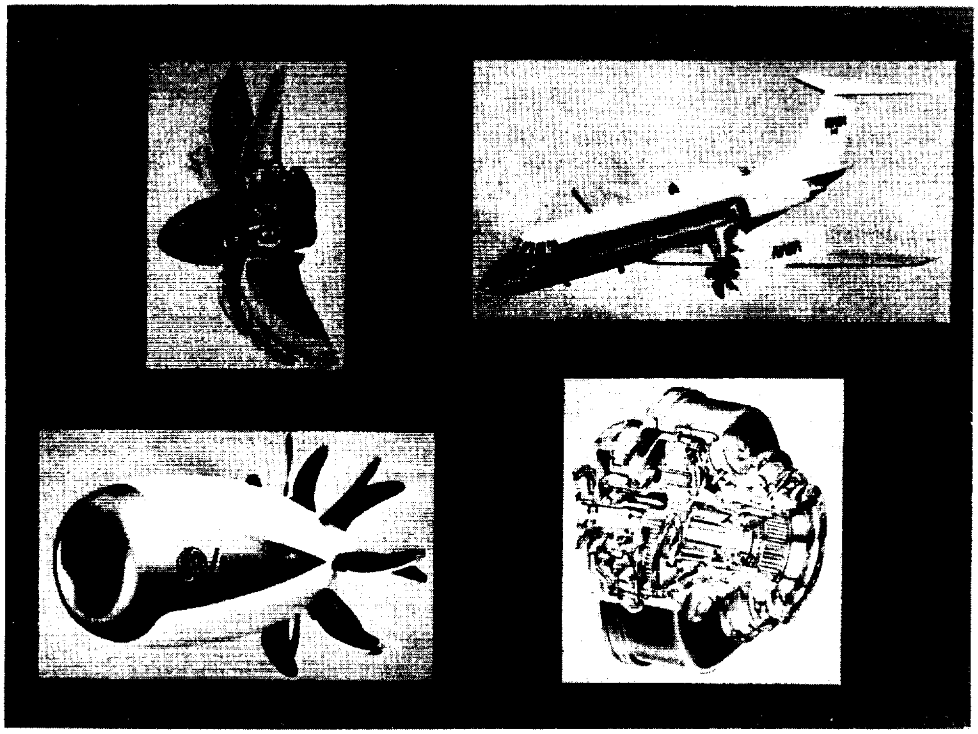

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Figure 1. - Major contractual elements of ATP.

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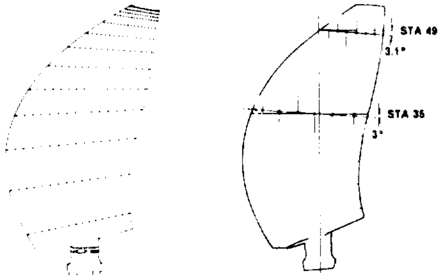
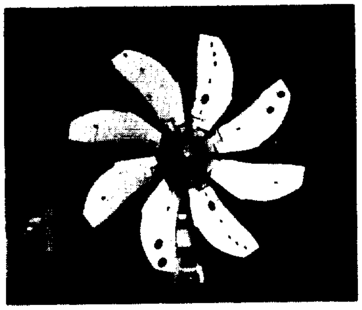
TWO-BLADE SR-7 IN MODANE, FRANCE, WIND TUNNEL

TRANSDUCER LOCATIONS



STEADY PRESSURE **UNSTEADY PRESSURE**

INSTRUMENTATION FOR MODANE TESTING



TWO SR-7 ASSEMBLIES DELIVERED TO PTA

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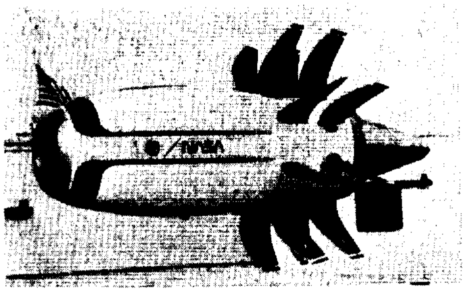
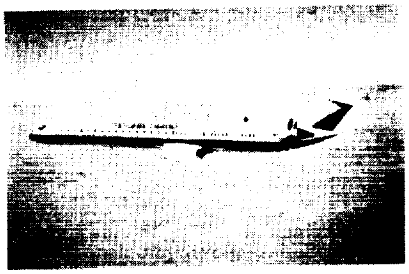
Figure 2. - LAP project.



GE STATIC TEST AT PEEBLES, OHIO

BOEING 727 FLIGHT TEST



DOUGLAS MD-80 FLIGHT TEST

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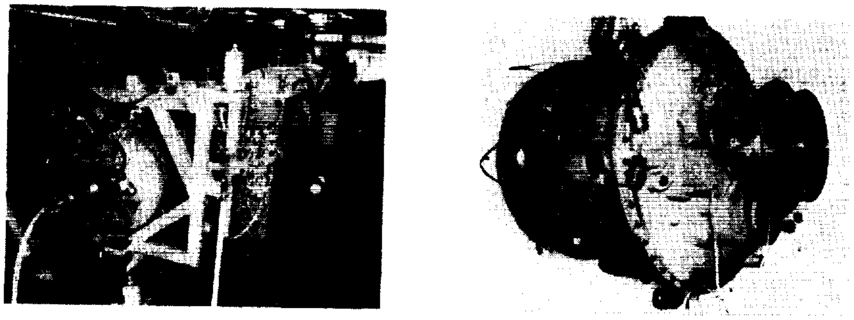
Figure 3. - NASA/GE unducted fan (UDF).



- **ALLISON CONTRACT**
- **COUNTERROTATING IN-LINE DIFFERENTIAL PLANETARY GEAR SYSTEM**
- **13 000-shp CLASS**
- **99 PERCENT EFFICIENCY**
- **DURABILITY GOAL OF 30 000-hr MTBR**

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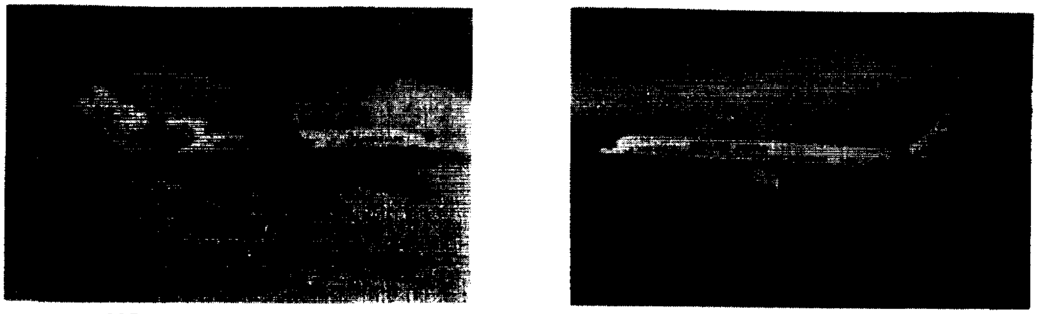
Figure 4. - Advanced counterrotation gearbox systems.

PTA/GULFSTREAM GII



UDF/BOEING 727

UDF/MD-80 AND 578DX/MD-80

CD-87-28794

Figure 5. - Flight testing of advanced turboprops.

EVALUATE THROUGH THE DEVELOPMENT OF A FLIGHTWORTHY DRIVE SYSTEM AND SUBSEQUENT GROUND AND FLIGHT TESTING OF A LARGE-SCALE PROPFAN

- **PROPFAN STRUCTURAL INTEGRITY**
- **PROPFAN SOURCE NOISE**
- **ASSOCIATED PROPFAN-RELATED CABIN NOISE AND VIBRATION**
- **FAR-36 COMMUNITY NOISE**
- **ENROUTE CRUISE NOISE (GROUND)**

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Figure 6. - Propfan Test Assessment (PTA) objectives.

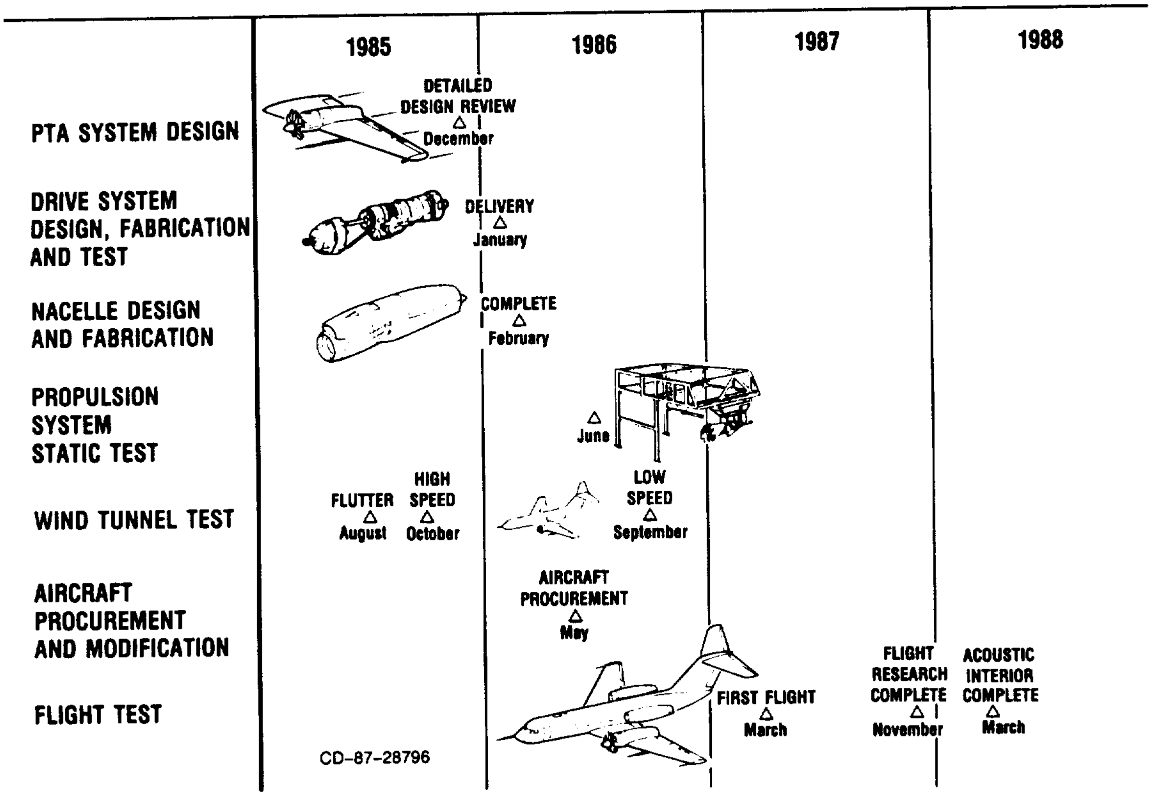

Figure 7. - PTA schedule.

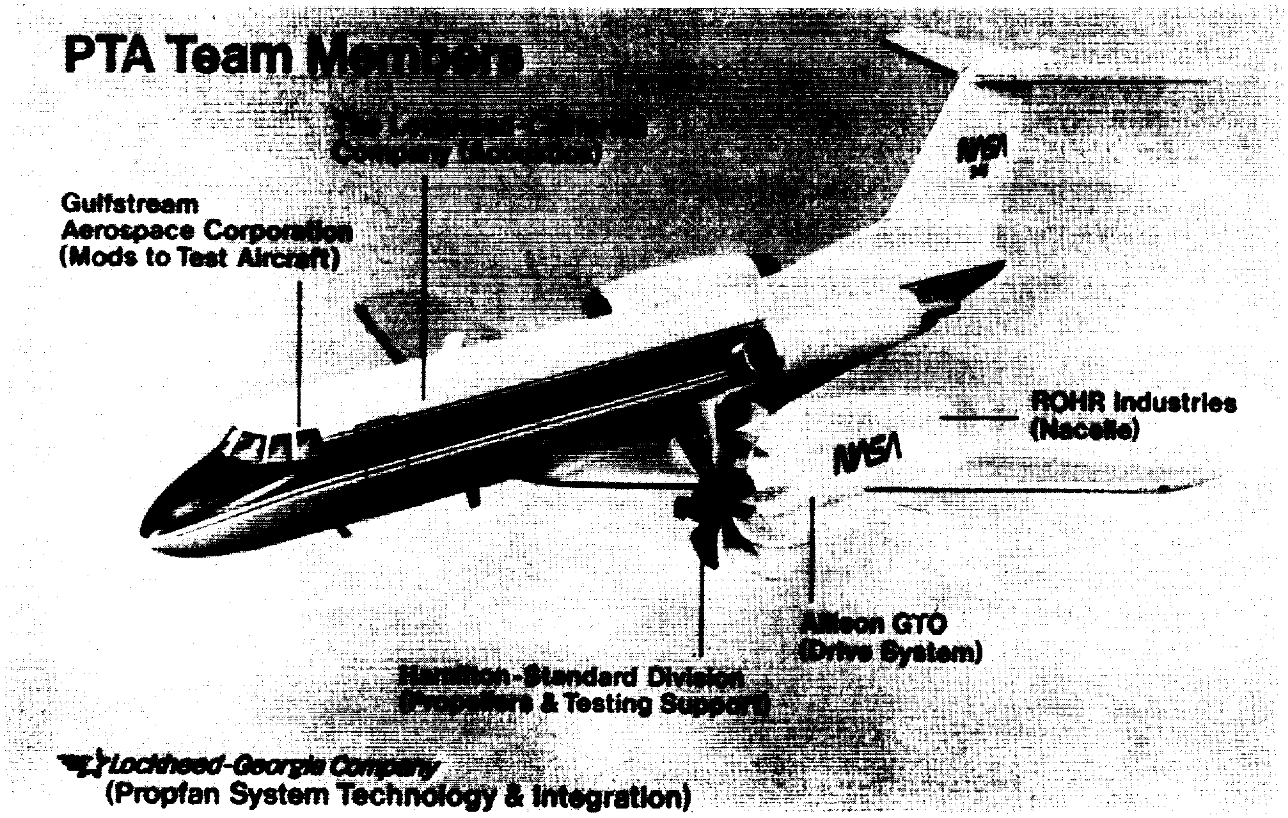

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Figure 8. - PTA team members.

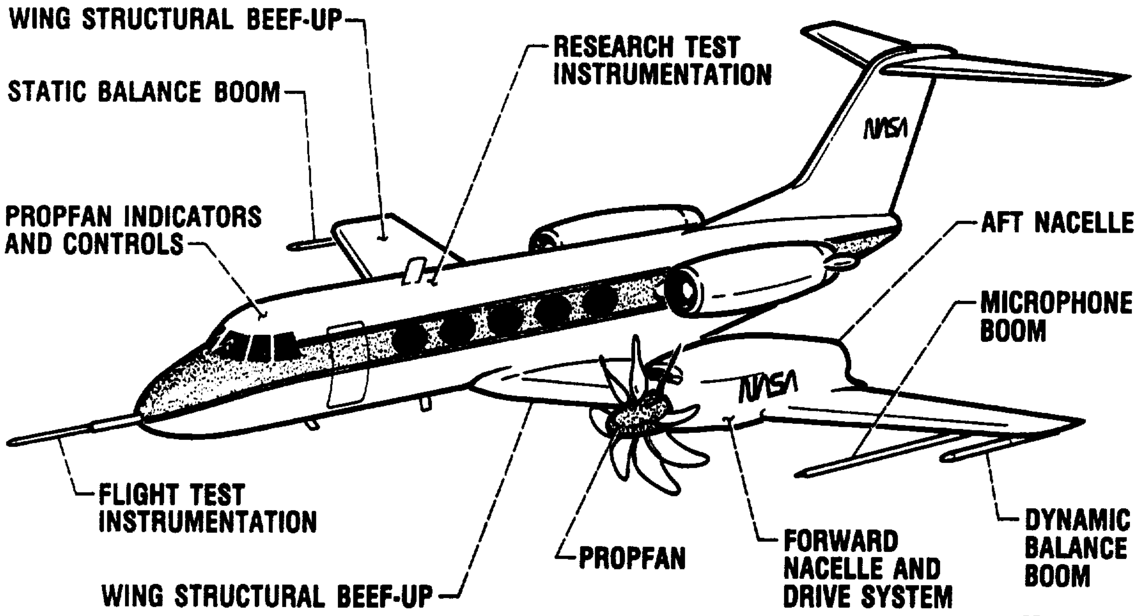

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Figure 9. - Aircraft modifications.

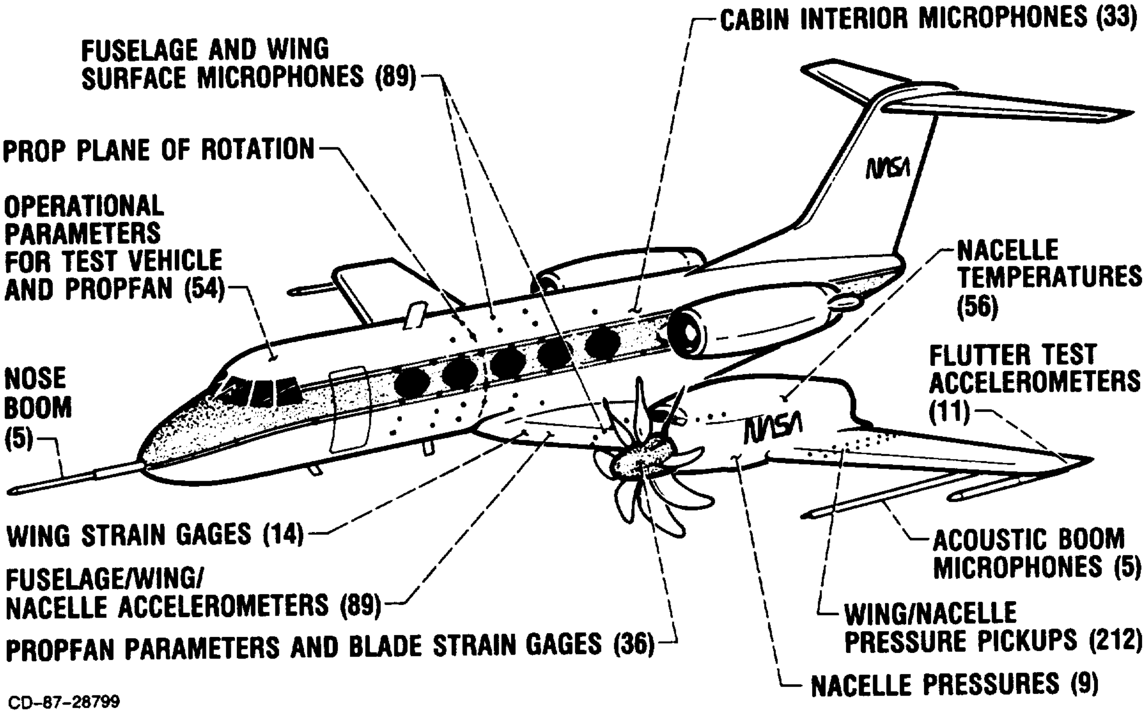

Figure 10. - Research instrumentation (613 parameters).

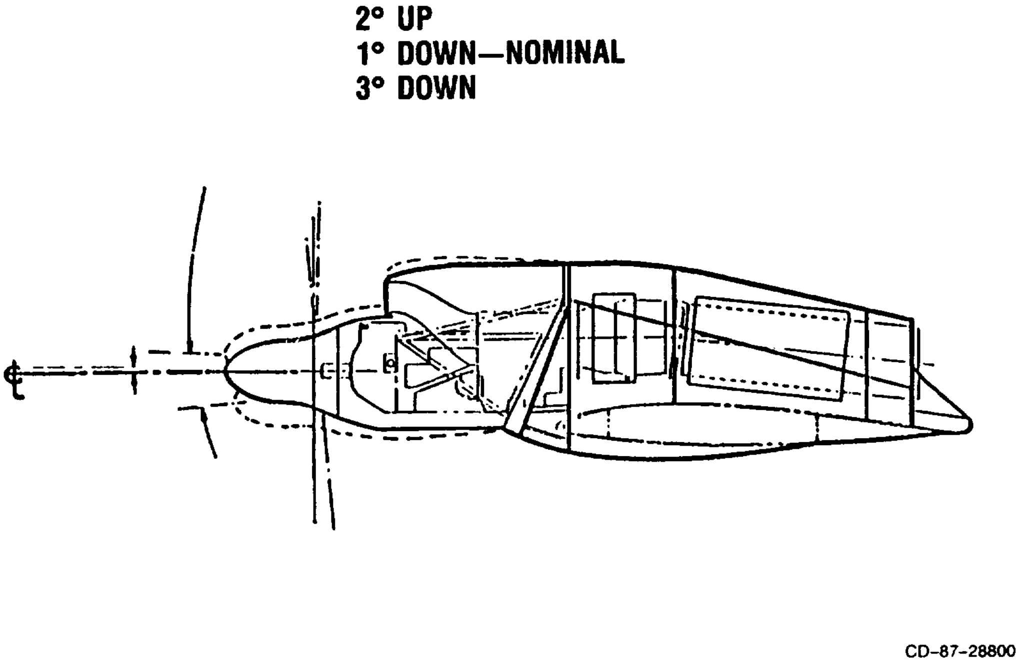

Figure 11. - Nacelle tilt range.

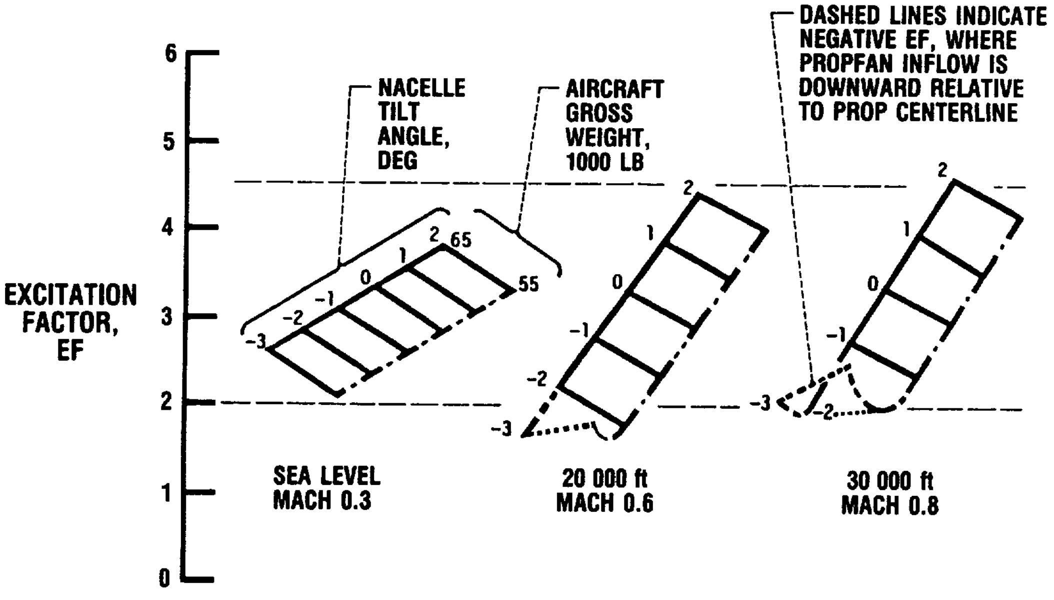

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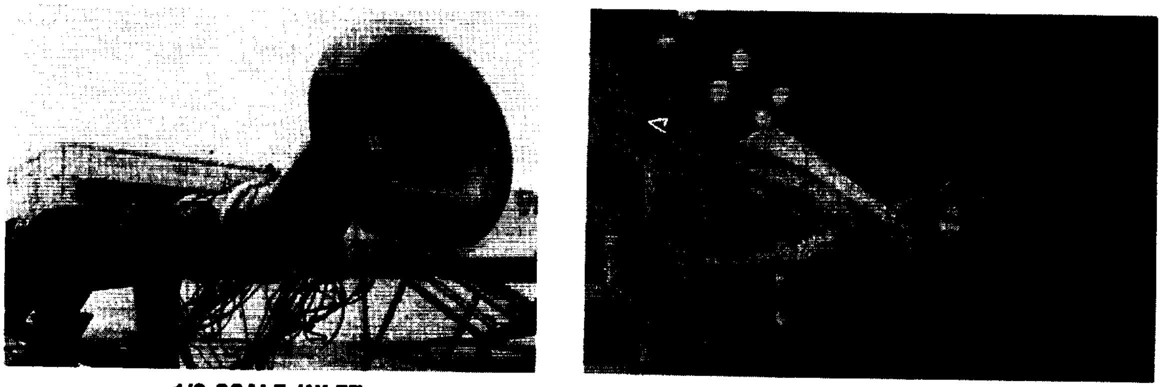
Figure 12. - Predicted propfan excitation factors.



1/3-SCALE INLET

1/9-SCALE FLUTTER

1/9-SCALE STABILITY, CONTROL, AND PERFORMANCE

1/9-SCALE PROP FLOWFIELD

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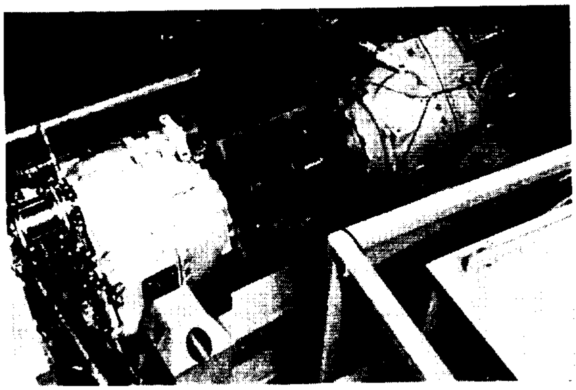
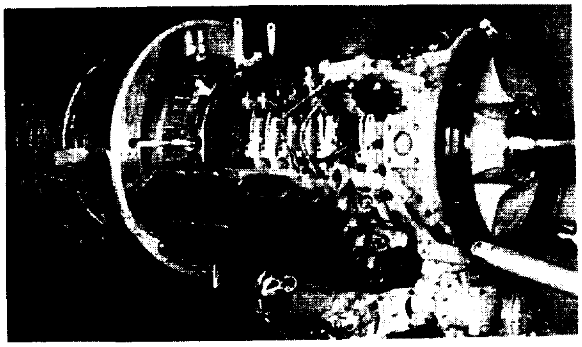
Figure 13. - Scale-model testing.



GEARBOX ENDURANCE



ENGINE DURABILITY

PROPULSION SYSTEM STATIC TEST

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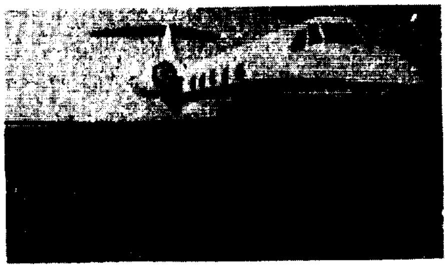
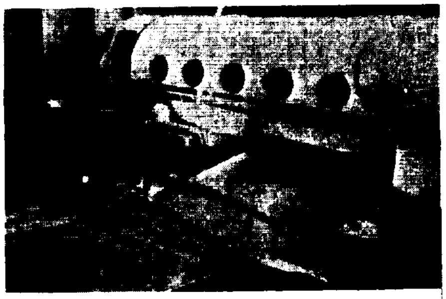
Figure 14. - Ground testing.

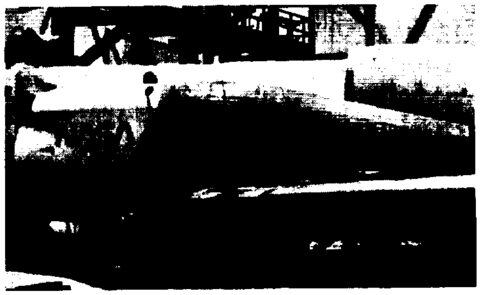


SERIAL NO. 118 GII

WING BEEF-UP



WING-TO-FUSELAGE ATTACHMENT



NACELLE ON WING

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Figure 15. - Aircraft and stages of modification.

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Figure 16. - PTA flight testing begun in March 1987.

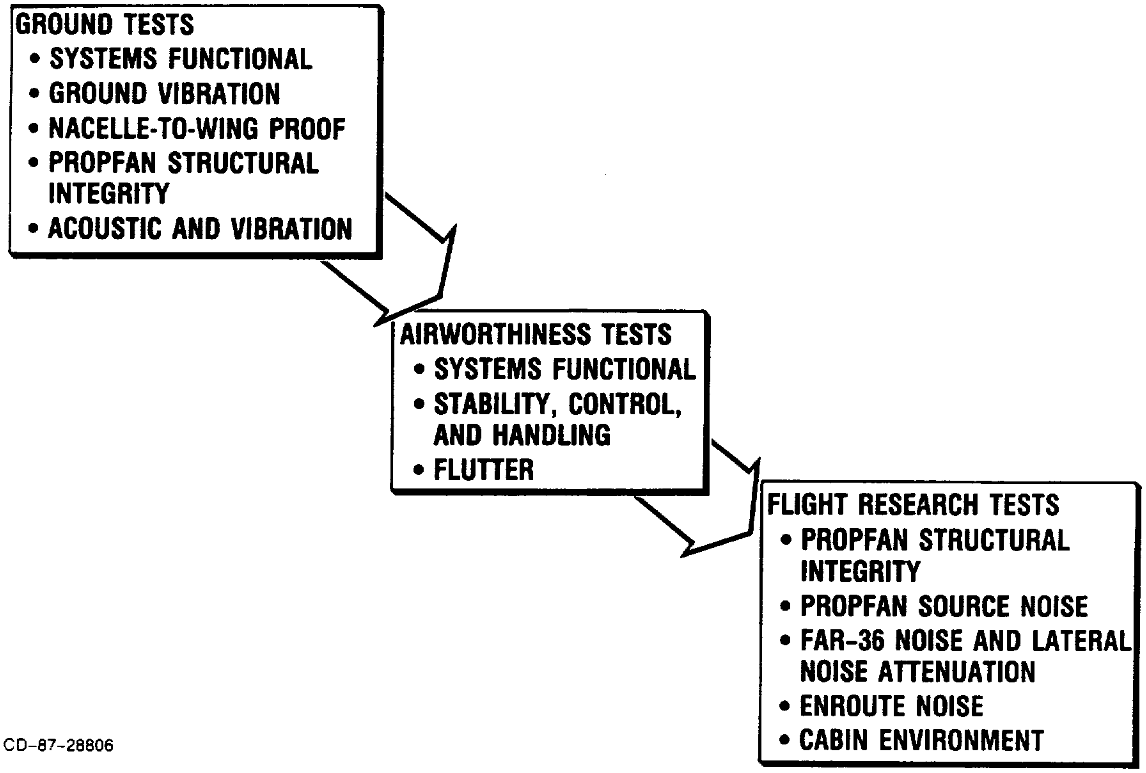

Figure 17. - PTA flight test program.

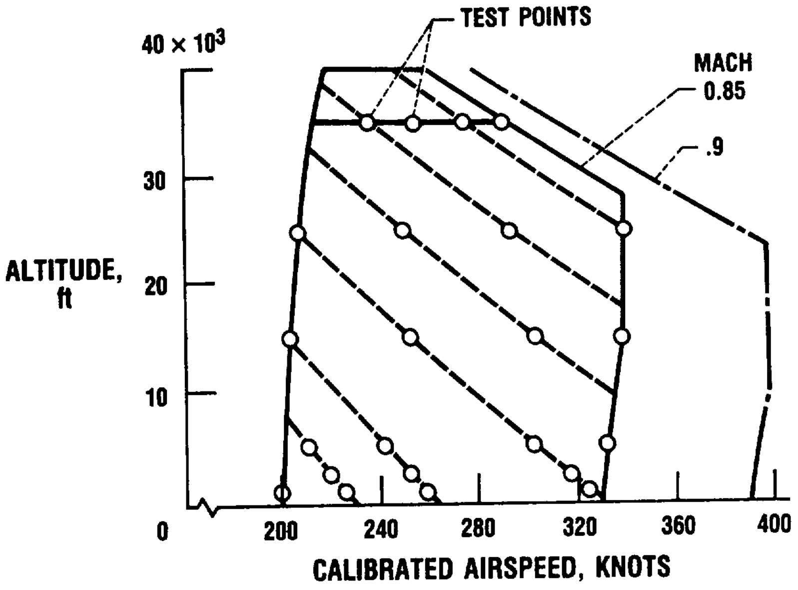

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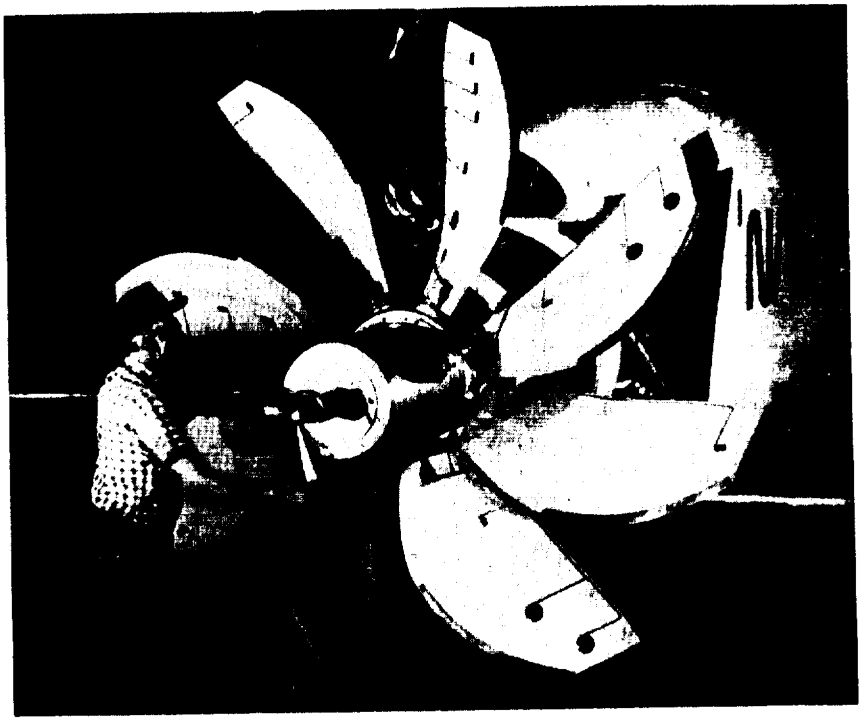
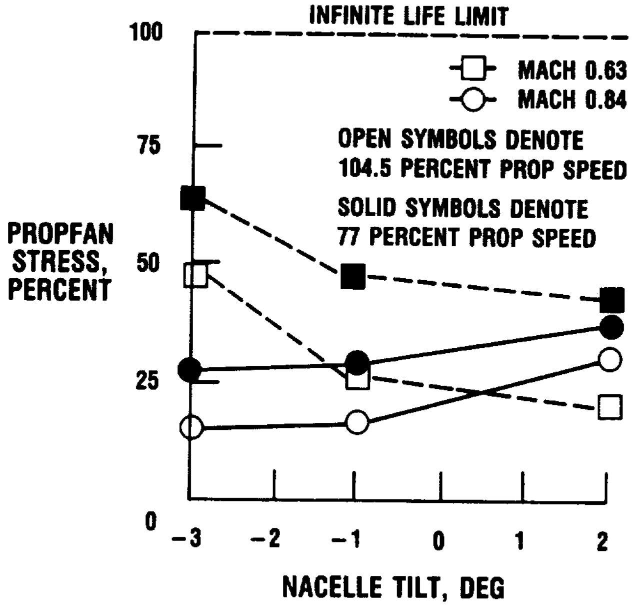
Figure 18. - Flight test envelope.



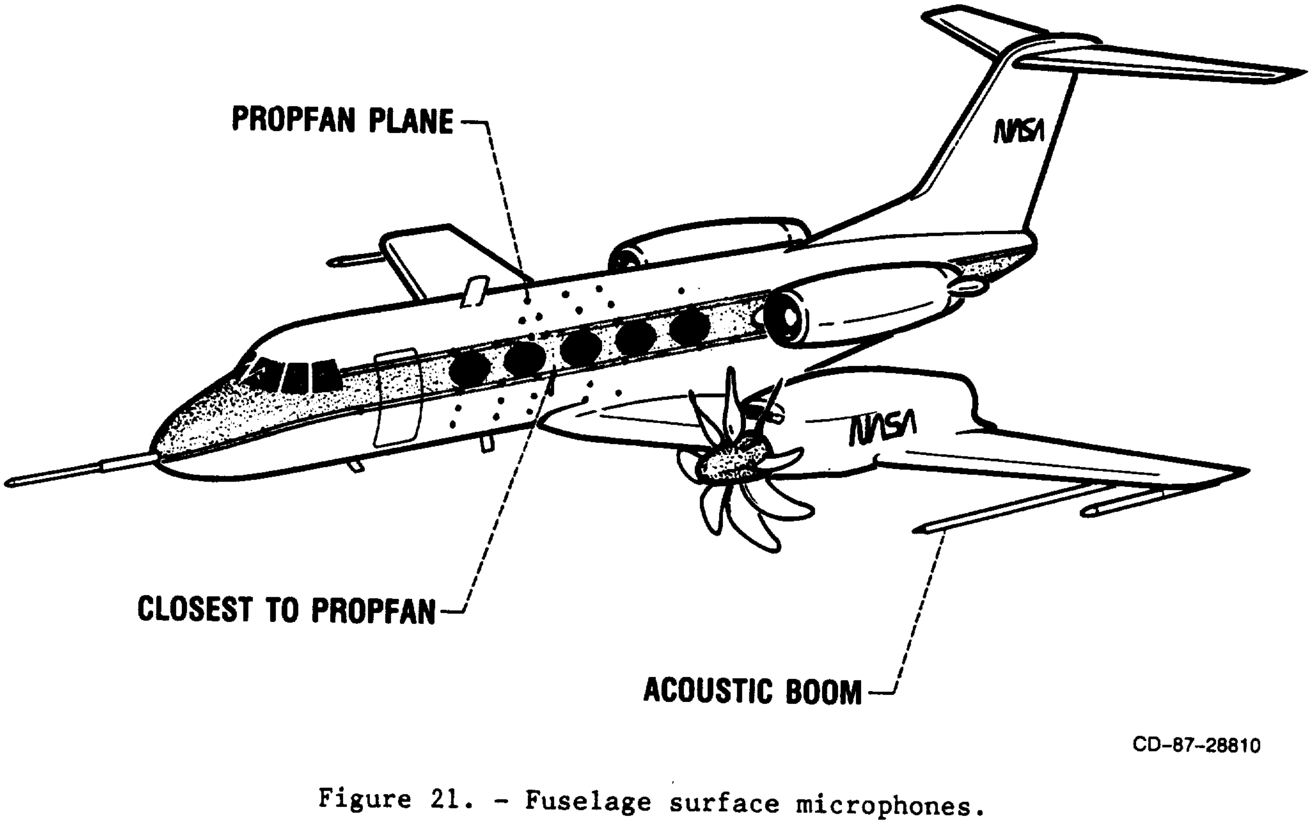
CD-87-28808

Figure 19. - Installed SR-7 propfan.



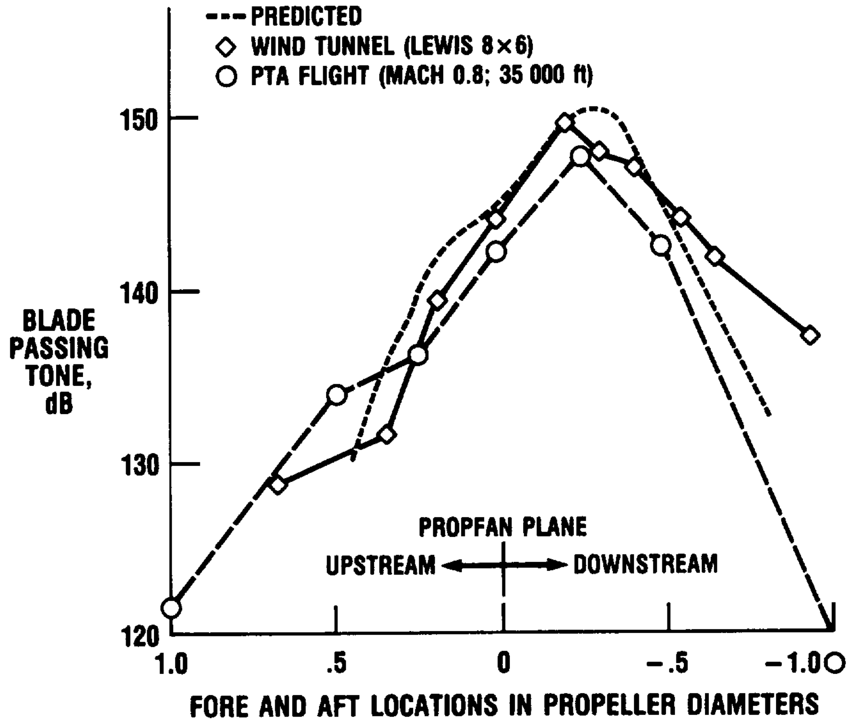
CD-89-40051

Figure 20. - Propfan in-flight stress (altitude, 27 000 ft).



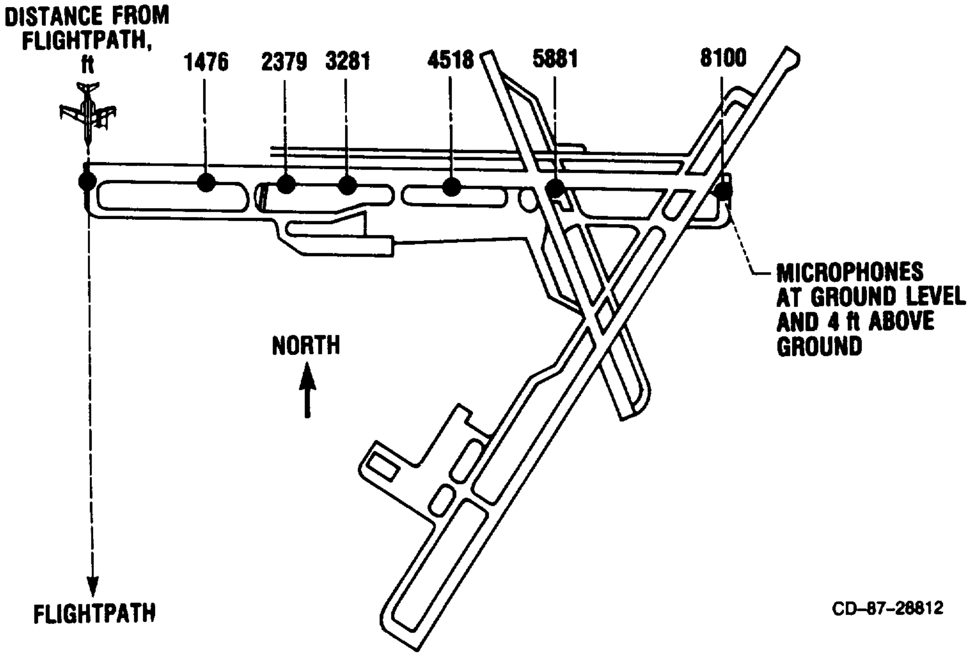
CD-87-28810

Figure 21. - Fuselage surface microphones.



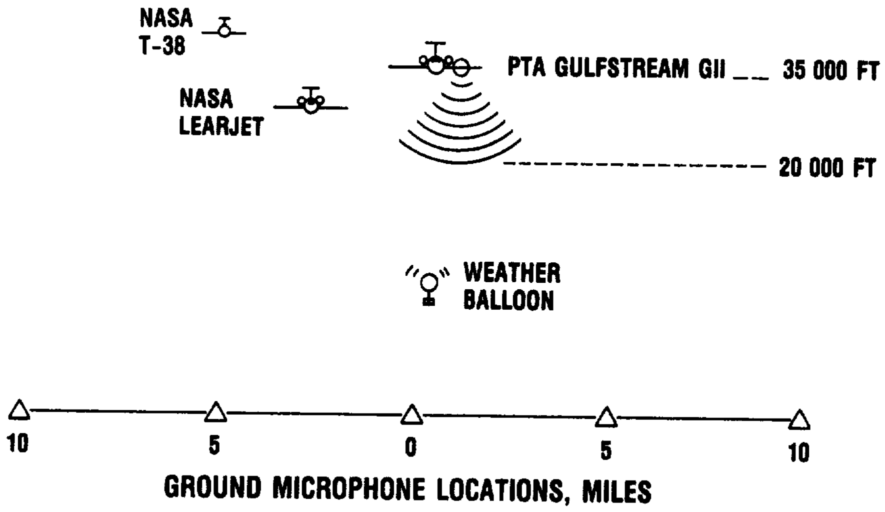
CD-87-28811

Figure 22. - Fuselage exterior noise.



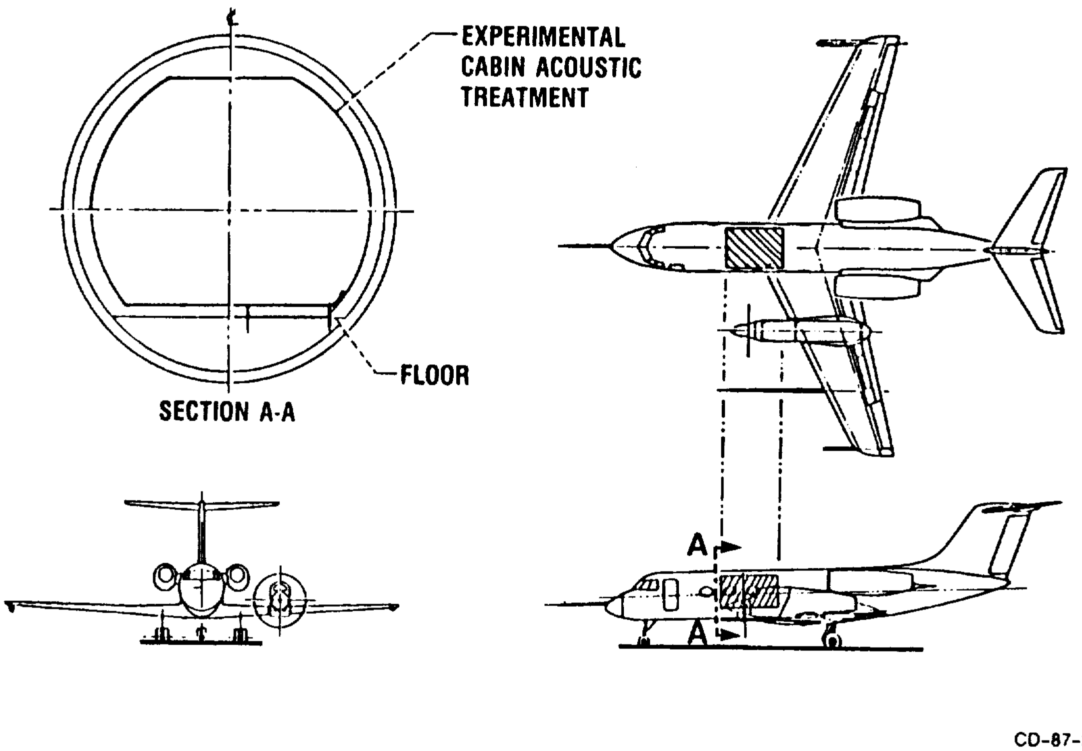
CD-87-28812

Figure 23. - Community noise testing, NASA Wallops Flight Facility.



CD-87-29512

Figure 24. - En route noise testing (cooperative NASA/FAA program).



CD-87-28813

Figure 25. - Cabin noise testing.