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ENGINE COMPONENT IMPROVEMENT— PERFORMANCE IMPROVEMENT PROGRAM

JT9D - 7 3.8 ASPECT RATIO FAN

by

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FOREWORD

The development and demonstration effort described in this report was conducted by the Commercial Products Division of Pratt & Whitney Aircraft Group, United Technologies Corporation, under sponsorship of the National Aeronautics and Space Administration - Lewis Research Center. This JT9D Performance Improvement effort is part of the Engine Component Improvement (ECI) Project, which is part of the NASA Aircraft Energy Efficiency (ACEE) Program. The JT9D-7 3.8 AR Fan Program was conducted from January, 1978 through February 1979.

This report was prepared by William O. Gaffin, Pratt & Whitney Aircraft Program Manager, with the assistance of William J. Olsson. The technical data presented in the report was compiled with the cooperation of a large segment of Engineering personnel. This report has been assigned the Commercial Products Division, Pratt & Whitney Aircraft Group Internal Report Number PWA-5515-114.

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SUMMARY

The objective of the JT9D-7 3.8 Aspect Ratio (AR) Fan program was to demonstrate the performance, stability and acoustic effects of the concept. Preliminary analysis during the feasibility studies predicted an average cruise thrust specific fuel consumption improvement of 1.3 percent and exhaust gas temperature improvements of 3° and 7°C at takeoff and climb for the concept relative to the Bill-of-Material fan.

To accomplish these improvements, the JT9D-7 fan section was redesigned to increase its aerodynamic efficiency. Features of the redesign, which will be referred to as the 3.8 AR fan, include elimination of a blade part span shroud, updating of the blade airfoil technology, increasing the blade chord, and reducing the number of blades and fan exit guide vanes.

Four series of back-to-back engine comparison tests were run to demonstrate the performance and operational characteristics of the 3.8 AR fan. A performance test in our altitude test facility at simulated cruise conditions was run to demonstrate the thrust specific fuel consumption improvement attributable to the fan. A flight test series was run to determine the effects of the fan on engine performance, stability and operational suitability. Steady state and vibratory stresses in the fan blades and vanes were also measured as part of this series. A series of static engine tests was run with variable area fan discharge nozzles to determine the response of the 3.8 AR fan to inlet flow distortions and increased fan blade tip clearances. Finally, a standard engine acoustic test was run on a static stand to determine the noise characteristics of the fan.

The 3.8 AR fan demonstrated an average cruise thrust specific fuel consumption improvement of 1.3 percent over the Bill-of-Material fan, as predicted. The exhaust gas temperatures at takeoff and climb were approximately equal to the Bill-of-Material fan in each case, compared to the 3° and 7°C improvements predicted. The 3.8 AR fan demonstrated stability, operational suitability and noise characteristics equal to or better than the Bill-of-Material fan. Measured stresses were all within acceptable limits except for one location on the blade, which was corrected by a minor design modification.

Updating the airline acceptability analysis to reflect the demonstrated performance of the 3.8 AR fan resulted in airline payback periods of 1.3 and 14 years for new engine purchases and retrofit of existing engines, respectively. The new buy payback period is well within the acceptable limit of 6 years and the retrofit payback period is well

beyond the limit, which was also the case in the original evaluation. Consequently, the estimated airline acceptability of the 3.8 AR fan is as predicted. The cumulative fuel saving estimate for the concept, assuming that it goes into production, is 2650 million liters (700 million gallons) which is within three percent of the original estimate. However, a decision has been made by P&WA, independent of the demonstration program, to suspend further development of the 3.8 AR fan. A more advanced fan is being developed for the JT9D-7R4 engine which will realize the potential efficiency advantage of the single shroud fan while providing increased total airflow and allowing increased overall engine pressure ratio for higher thrust capability.

2.0 INTRODUCTION

National energy demand has outpaced domestic supply, creating an increased U.S. dependence on foreign oil. This increased dependence was dramatized by the OPEC oil embargo in the winter of 1973-74. In addition, the embargo triggered a rapid rise in the cost of fuel which, along with the potential of further increases, brought about a changing economic circumstance with regard to the use of energy. These events, of course, were felt in the air transport industry as well as other forms of transportation. As a result of these experiences, the government, with the support of the aviation industry, initiated programs aimed at both the supply (sources) and demand (consumption) aspects of the problem. The supply problem is being investigated by looking at increasing fuel availability from such sources as coal and oil shale. Efforts are currently underway to develop engine combustor and fuel systems that will accept fuels with broader specifications.

An approach to the demand aspect of the problem is to evolve new technology for commercial aircraft propulsion systems which will permit development of a more energy efficient turbofan, or the use of a different propulsive cycle such as a turboprop. Although studies have indicated large reductions in fuel usage are possible with advanced turbofan or turboprop engines (e.g., 15 to 40 percent), any significant fuel savings impact of these approaches is at least fifteen years away. In the near term, the only practical fuel savings approach is to improve the fuel efficiency of current engines. Examination of this approach has indicated that a five percent fuel reduction goal, starting in the 1980-82 time period, is feasible for current commercial engines. Inasmuch as commercial aircraft in the free world are using fuel at a rate in excess of 80 billion liters of fuel per year, even five percent represents significant fuel savings.

Accordingly, NASA is sponsoring the Aircraft Energy Efficient (ACEE) Program, which is directed at reduced fuel consumption of commercial air transports. The Engine Component Improvement (ECI) Program is the element of the ACEE Program directed at reducing fuel consumption of current commercial aircraft engines. The Engine Component Improvement (ECI) Program consists of two parts: Engine Diagnostics and Performance Improvement. The Engine Diagnostics effort is to provide information to identify the sources and causes of engine deterioration. The Performance Improvement effort is directed at developing engine components having performance improvement and retention characteristics which can be incorporated into new production and existing engines.

The Pratt & Whitney Aircraft Performance Improvement effort was initiated with a Feasibility Analysis, which identified engine performance improvement concepts, and then assessed the technical and economic merits of these concepts. This assessment included a determination of airline acceptability, the probability of introducing the concepts into production by the 1980 to 1982 time period, and their retrofit potential. Since a major portion of the present commercial aircraft fleet is powered by the JT8D and JT9D engines, performance improvements were investigated for both engines. The study was conducted in cooperation with Boeing and Douglas aircraft companies, and American, United and Trans World Airlines, and is reported in reference 1.

In the Feasibility Analysis, the JT9D-7 3.8 AR Fan performance improvement concept was selected for development and evaluation, because of its fuel savings potential and attractive airline payback period. The analysis predicted an average cruise thrust specific fuel consumption improvement of 1.3 percent, and exhaust gas temperature improvements of 3° and $7^{\circ}C$ at takeoff and climb for the 3.8 AR fan relative to the JT9D-7 Bill-of-Material fan.

3.0 FAN DESIGN CHARACTERISTICS

The Bill-of-Material fan for the JT9D-3A/7 family of engines was originally designed in 1966 using the "J" airfoil configuration that was state-of-the-art at that time. The fan was designed with an unusually high blade aspect ratio (4.6) in the interest of saving weight, resulting in a 46 blade rotor. Structural considerations dictated the use of two part span shrouds for the high AR blades. The number of fan exit guide vanes was set at 108 to provide the absolute minimum level of rotor-stator interaction noise, and the vane chord and thickness were established by structural considerations. This combination results in vane blockage greater than optimum, causing a small performance penalty.

In designing the 3.8 AR fan, the blade chord was increased substantially as shown in Table 3-1, allowing a reduction in the number of blades from 46 to 38 with the same gap-chord ratio, elimination of one shroud with the same structural strength margins, and reduction in the number of fan exit guide vanes with essentially the same blade-stator interaction noise characteristics. Additionally, the more advanced Multiple Circular Arc airfoil was used in the blade design to reduce shock losses. Compared to the Bill-of-Material fan, the 3.8 AR fan was designed to produce slightly higher airflow and pressure ratio at equal rotor speeds, as shown in Table 3-1. A photograph of the Bill-of-Material and 3.8 AR fan blades is presented in Figure 3-1, showing the wider chord and single part-span shroud of the 3.8 AR fan blade. A lightweight hollow hub was designed for use with the 3.8 AR fan to compensate for the

TABLE 3-1

JT9D-7 BILL-OF-MATERIAL AND 3.8 AR
FAN DESIGN PARAMETERS

	Bill-of-Material Fan	3.8 AR Fan
AR	4.6	3.8
Number of Blades	46	38
Airfoil Series	J	Multiple Circular Arc
Blade Root Chord Length, cm (in.)	15.32 (6.030)	18.44 (7.262)
Blade Tip Chord Length, cm (in.)	19.66 (7.740)	25.77 (10.148)
Shroud Location, % of span	50 & 85	68
Number of Fan Exit Guide Vanes	108	86
Corrected Fan Rotor Speed, RPM	3306	3306
Fan Pressure Ratio	1.482	1.496
Total Corrected Airflow, kg/s (lb/s)	710 (1566)	718 (1584)
Equivalent Fan Efficiency, %	Base	+2.6
Engine Weight, Kg (lb)	Base	+20 (45)

higher weight of the 3.8 AR fan blade set, maintaining the total weight of the assembly approximately the same as the Bill-of-Material. Figure 3-2 is a photograph of the Bill-of-Material and 3.8 AR fan rotors in a side by side comparison. Other changes required with the 3.8 AR fan included a modified fan speed electronic transmitter to compensate for the different number of fan blades; a redesign of the fan containment case to contain the heavier, longer chord blades, and a recontoured nose spinner to match the root flowpath of the new blade. Figure 3-3 is a cross-section of the JT9D-7 engine, showing the differences in the 3.8 AR fan package from the Bill-of-Material fan package.

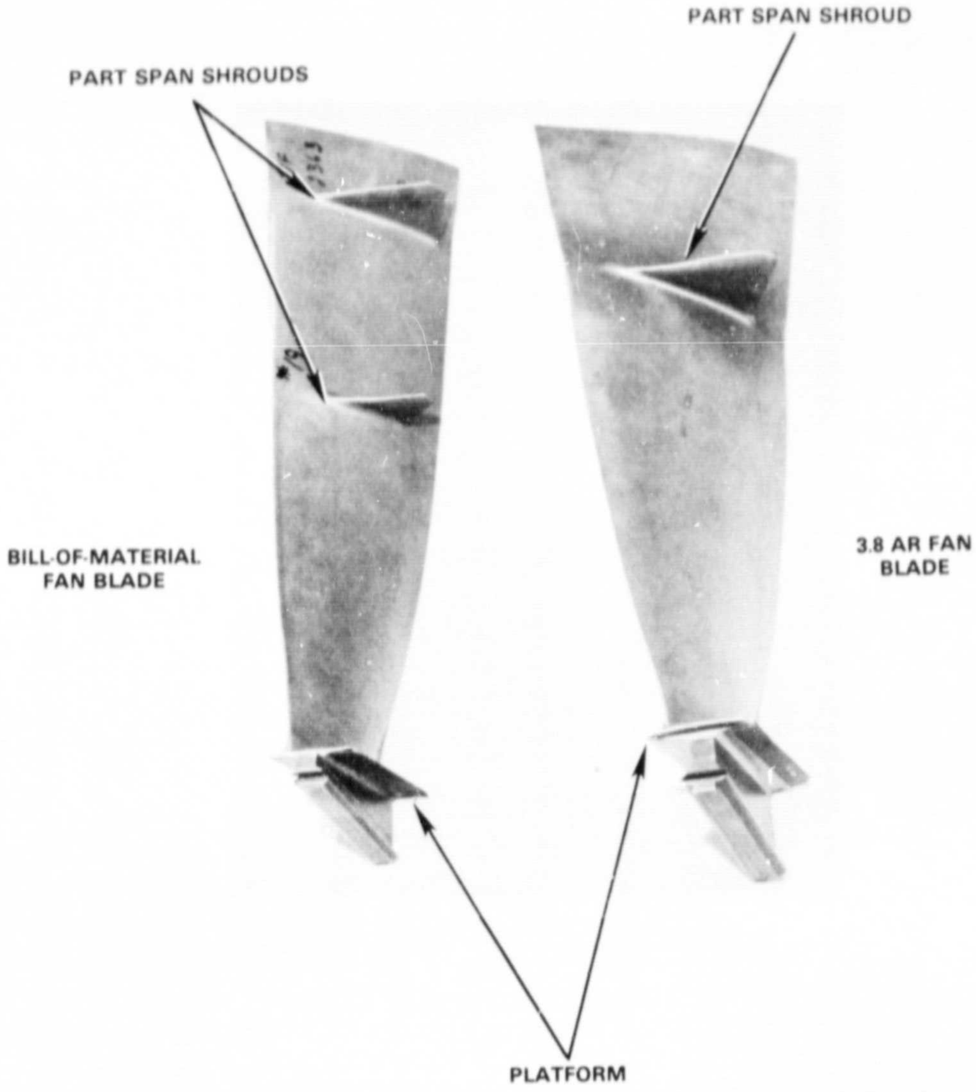
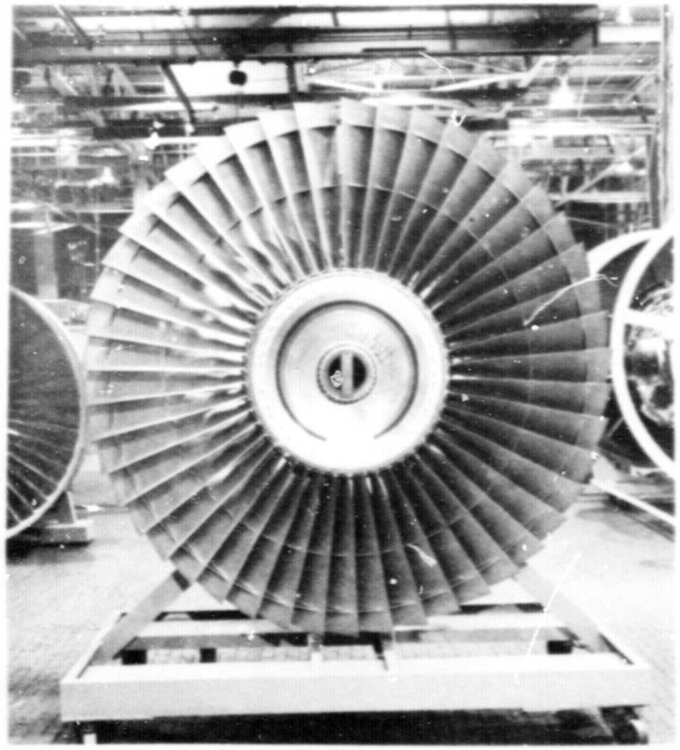
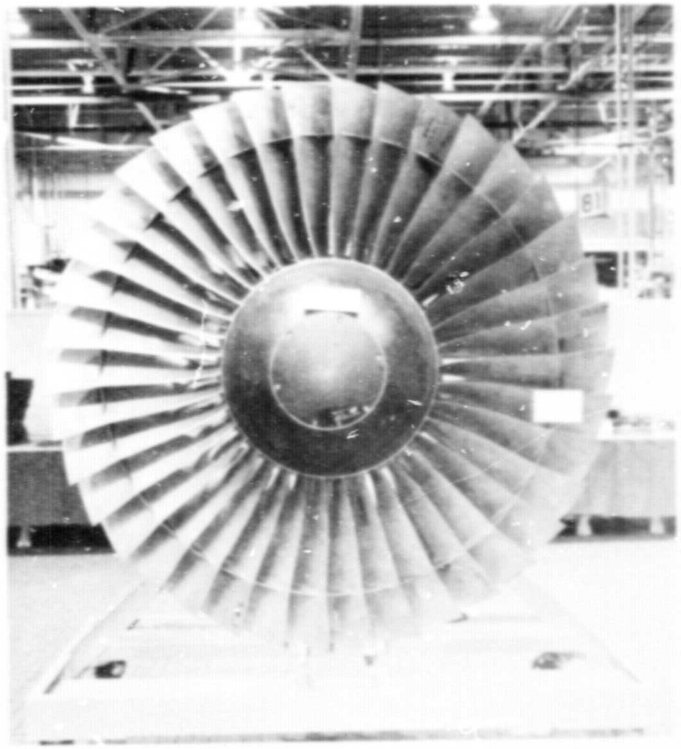


Figure 3-1 Comparison of JT9D-7 Bill-of-Material and 3.8 AR Fan Blades. The 3.8 AR fan blade has a wider chord than the Bill-of-Material blade, and one part span shroud instead of two.



4.6 AR BILL-OF-MATERIAL FAN



3.8 AR FAN

Figure 3-2 Comparison of JT9D-7 Bill-of-Material and 3.8 AR Fan Rotors. The 3.8 AR fan rotor has 38 blades compared to 46 in the Bill-of-Material fan.

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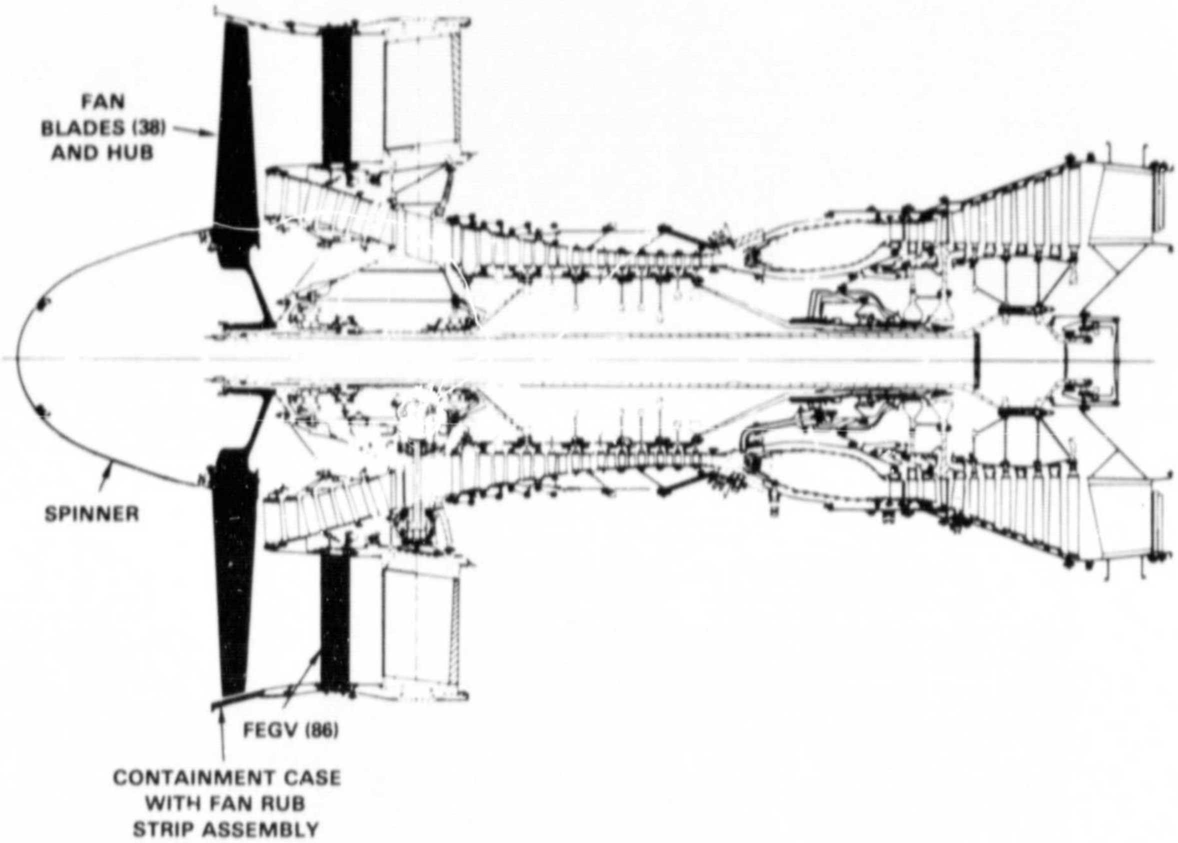

Figure 3-3 JT9D-7 Engine with 3.8 AR Fan System. Labelled parts are different from the equivalent Bill-of-Material parts.

4.0 TEST PROCEDURE AND EQUIPMENT

Four separate test programs were conducted to evaluate the JT9D-7 3.8 AR fan, including simulated altitude engine performance tests in our altitude facility, engine flight tests, engine ground stability tests and engine acoustic tests. Each of the four test programs was conducted by testing a JT9D-7 experimental engine with the 3.8 AR fan and current JT9D-7 4.6 AR Bill-of-Material fan installed back-to-back. A photograph of a JT9D-7 engine with the 3.8 AR fan installed is shown in Figure 4-1. Test facilities, engine test configurations, instrumentation, and test procedures are discussed in the subsequent paragraphs of Section 4.0. The test results are presented and discussed in Section 5.0.

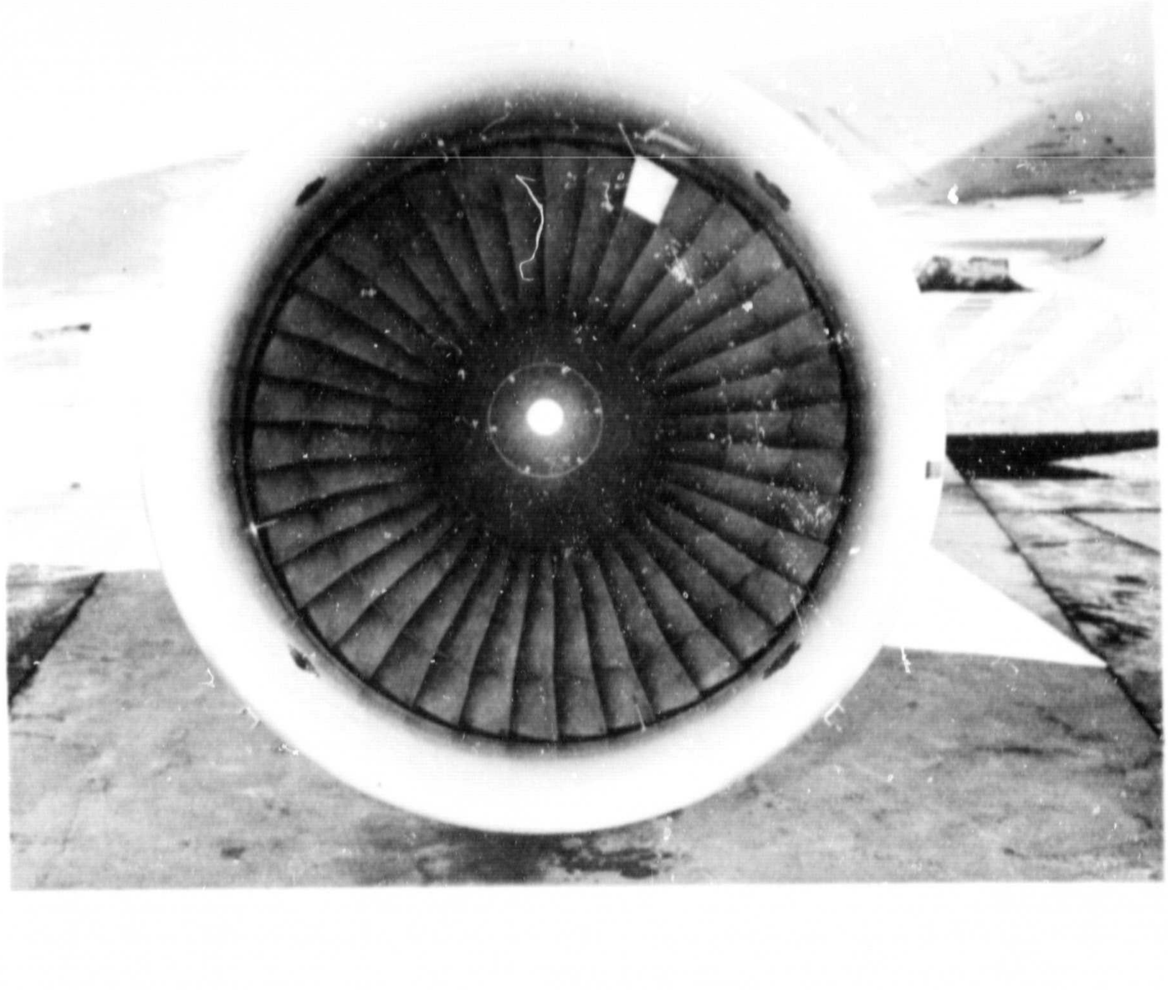

Figure 4-1 JT9D-7 Engine with 3.8 AR Fan Installed. The engine is mounted on the wing of the B-52 flying test bed.

4.1 Simulated Altitude Engine Performance Test

The objective of the engine performance test was to determine the thrust specific fuel consumption improvement of the 3.8 AR fan relative to the JT9D-7 4.6 AR Bill-of-Material fan at realistic cruise operating conditions. The two fans were tested back-to-back on the same engine at cruise flight conditions of 9,906 m (32,500 ft) altitude, 0.84 Mach number. Standard performance calibration test procedures were used with each fan to determine performance over a thrust range from 60 percent cruise to maximum climb.

The test vehicle was a JT9D-7 experimental engine (X-618). The engine was equipped with standard production instrumentation plus the special experimental instrumentation listed on Table 4-1.

TABLE 4-1

SPECIAL INSTRUMENTATION FOR SIMULATED ALTITUDE ENGINE PERFORMANCE TEST

Parameter	Description
Total Pressures at:	
Fan Inlet	8 pitot-static probes
Fan Exit	8 rakes/8 sensors per rake
LPC Exit	4 rakes/5 sensors per rake
HPC Exit	4 rakes/3 sensors per rake
HPT Exit	3 probes
Total Temperatures at:	
Fan Exit	8 rakes/8 sensors per rake
LPC Exit	4 rakes/5 sensors per rake
HPC Exit	4 rakes/3 sensors per rake

The test was conducted in an altitude test facility using a test stand (X-217, Figure 4-2) which is capable of testing a JT9D engine over its full power range at simulated flight conditions of from 3,048 m to 10,210 m (10,000 to 33,500 ft) altitude and 0 to 0.84 Mach number. The facility provides inlet and exhaust conditions to the engine which duplicate these encountered inactual flight, allowing direct demonstration of engine and component performance with realistic air temperatures. The stand consists of an enclosed test cell containing an altitude chamber, within which a test engine can be suspended from an overhead mounting system. The mounting system provides for direct thrust measurement and flow meters provide direct fuel flow measurements, allowing accurate definition of thrust specific fuel consumption values at the simulated flight conditions. The stand is also equipped with instrumentation for monitoring the temperature, pressure, and flow of the engine air supply and ejector systems.

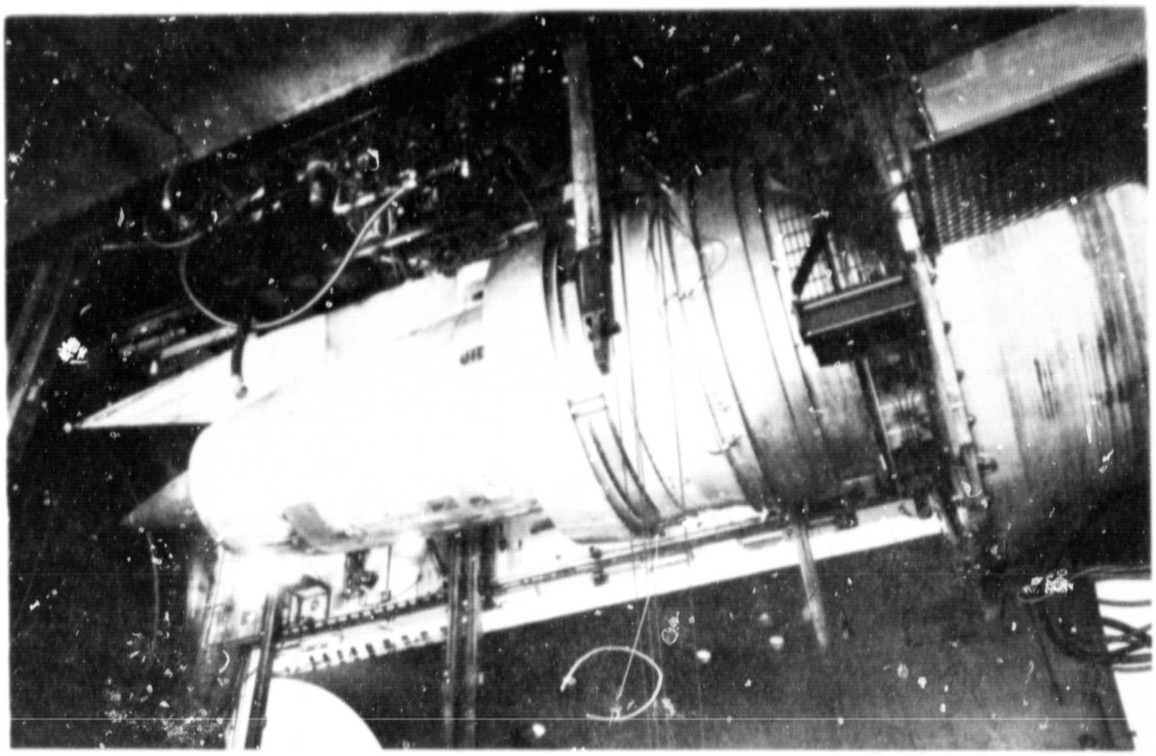

Figure 4-2 JT9D-7 Experimental Engine in Simulated Altitude Test Stand. This facility allows performance testing at realistic cruise operating conditions.

4.2 Engine Flight Test

The objective of the engine flight test was to compare the low pressure compressor stability, fan stability, adverse wind sensitivity, flight operational suitability, and fan stress characteristics of the 3.8 AR fan with the Bill-of-Material fan. The two fans were tested back-to-back on the same JT9D-7 engine (X-618) in a Boeing 747-200 nacelle mounted on a flying testbed.

The test facility was a Boeing B-52 airplane which had been modified to accept a JT9D test engine and nacelle at the right inboard engine pylon location (see Figure 4-3). The airplane is equipped with a comprehensive instrumentation and data acquisition system to measure and record steady state and transient data from the engine under test. The data is displayed on a scope for monitoring and is recorded on magnetic tape in analog and digital form. Instrumentation used in the test is listed in Table 4-2.

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Figure 4-3 B-52 Flying Test Bed. Airplane modifications allow the mounting of an experimental JT9D engine on the right inboard pylon for flight testing.

4.2.1 Low Pressure Compressor Stability Test

Low pressure compressor stability was evaluated during B-52 aircraft flight tests by using engine transient rematch characteristics during snap decelerations to force the match point of the low pressure compressor into the surge region. The engine control system was modified for this test to allow abnormally fast deceleration and to deactivate the low pressure compressor surge protection bleed system.

In normal control system operation, the bleed system opens either at the beginning of or at some point during the deceleration, depending on the rate at which the power lever is retarded. Additionally, the fuel control limits the rate at which fuel flow is reduced during a fast deceleration. Together, the two control functions keep the low pressure compressor transient operating conditions well below the surge line, as illustrated in Figure 4-4. For the low pressure compressor stability test, the bleed control system was deactivated so the bleeds remained closed, and the fuel control deceleration schedule was adjusted to allow a much faster reduction in fuel flow. With these modifications, the low pressure compressor transient operating line is forced into the surge region by a snap deceleration. By measuring engine data during the transient excursion and identifying the point of surge, it is possible to determine the low pressure compressor operating characteristics at surge. Repeating this process during a series of snap decelerations from starting points at the different power settings produces a locus of surge points, defining the low pressure compressor surge line.

TABLE 4-2

B-52 3.8 AR FAN MEASURED PARAMETERS

Parameter	Description
LPC Rotor Speed	2 Tachometers
HPC Rotor Speed	3 Tachometers
Fuel Flow	2 Flowmeters
Total Pressure at Engine Face	4 Sensors
Static Pressure at Engine Face	4 Sensors
Total Pressure Forward of Fan Exit Guide Vanes	8 Rakes With 8 Sensors/Rake
Total Pressure Aft of Fan Exit Guide Vanes	6 Manifolded Rakes With 10 Sensors/Rake
Total Pressure Aft of LPC	4 Rakes With 5 Sensors/Rake
Total Pressure Aft of LPC, Mach Number Probe	1 Manifolded Source, 4 Transducer
Static Pressure Aft of LPC, Mach Number Probe	1 Manifolded Source, 3 Transducers
Total Pressure Minus Static Pressure, Mach Number Probe	1 Sensor
Total Pressure Aft of HPC	4 Rakes With 3 Sensors/Rake
Burner Pressure	2 Sensors
Burner Pressure To Bleed Control	2 Sensors
Burner Pressure to Fuel Control	2 Sensors
Burner Pressure (Low Range)	2 Sensors
Static Pressure Burner Liner	1 Sensor
HPC Start Bleed Control Pressure	1 Sensor
Starting Bleed Signal From Fuel Control	1 Sensor
Total Pressure at HPT Inlet	1 Sensor
Altitude Ambient Pressure	2 Sensors
Total Pressure at HPC Inlet	1 Sensor
Total Pressure Aft of LPT	1 Manifolded Source, 4 Transducers
HPC Variable Vane Actuator Pressure Open	1 Sensor
HPC Variable Vane Actuator Pressure Closed	1 Sensor

TABLE 4-2

B-52 3.8 AR FAN MEASURED PARAMETERS (Cont'd)

Surge Bleed Override Actuator Pressure	1 Sensor
Static Pressure at OD of 4th Stage, LPC	2 Sensors
Static Pressure, LPC Bleed Exit	2 Sensors
Fuel Pressure at T_{T2} Sensor	1 Sensor
Primary Fuel Manifold Pressure	1 Sensor
Secondary Fuel Manifold Pressure	1 Sensor
HPC Bleed Pressure 9th Stage	1 Sensor
3.5 Bleed Actuator Pressure, Closed	1 Sensor
3.0 Bleed Control Pressure, Open	1 Sensor
Pressure, 3.0 Bleed Control Closed	1 Sensor
3.5 Bleed Actuator Pressure	1 Sensor
Total Temperature at Engine Face	4 Thermocouples
Fuel Temperature	2 Thermocouples
Total Temperature Aft of LPC, Mach Number Probe	1 Thermocouple
Total Temperature Aft of LPC	4 Rakes With 5 Thermocouples/Rake
Total Temperature Aft of HPC	4 Rakes With 3 Thermocouples/Rake
Total Temperature LPT Inlet	6 Probe Average
Total Temperature Aft of LPT	6 Thermocouples
Total Temperature Aft of LPT	6 Probe Average
Total Temperature Aft of LPT	6 High Response Thermocouples
Outside Air Temperature	2 Thermocouples
Air Temperature at Fan Blade Rubstrip	4 Thermocouples
Temperature, LPC Bleed Exit	1 Thermocouple
Engine Power Lever Angle	1 Sensor
Engine Condition Lever Angle (Fuel On-Off)	1 Sensor
Variable HPC Vane Angle	1 Sensor
Wind Direction (Ground)	1 Sensor
Wind Direction (Ground	1 Sensor
Vibration, Inlet	1 Sensor
Vibration, Diffuser	1 Sensor
Vibration, Burner	1 Sensor
Vibration, Rear Case	1 Sensor
Total Pressure Forward of Fan Exit Guide Vanes	12 High Response Sensors
LPC Bleed Actuator Travel	1 Sensor
LPC Ble[illegible] Cavity Static Pressure	2 High Response Sensors
LPC Bleed Exit Static Pressure	2 High Response Sensors
Splitter ID Static Pressure	2 High Response Sensors
Splitter OD Static Pressure	2 High Response Sensors
Fan Duct OD Static Pressure	2 High Response Sensors
Fan Exit Guide Vane Stress	11 Strain Gages
LPT Shaft Stress	1 Strain Gage
Flame Detectors (on/off)	4 Sensors

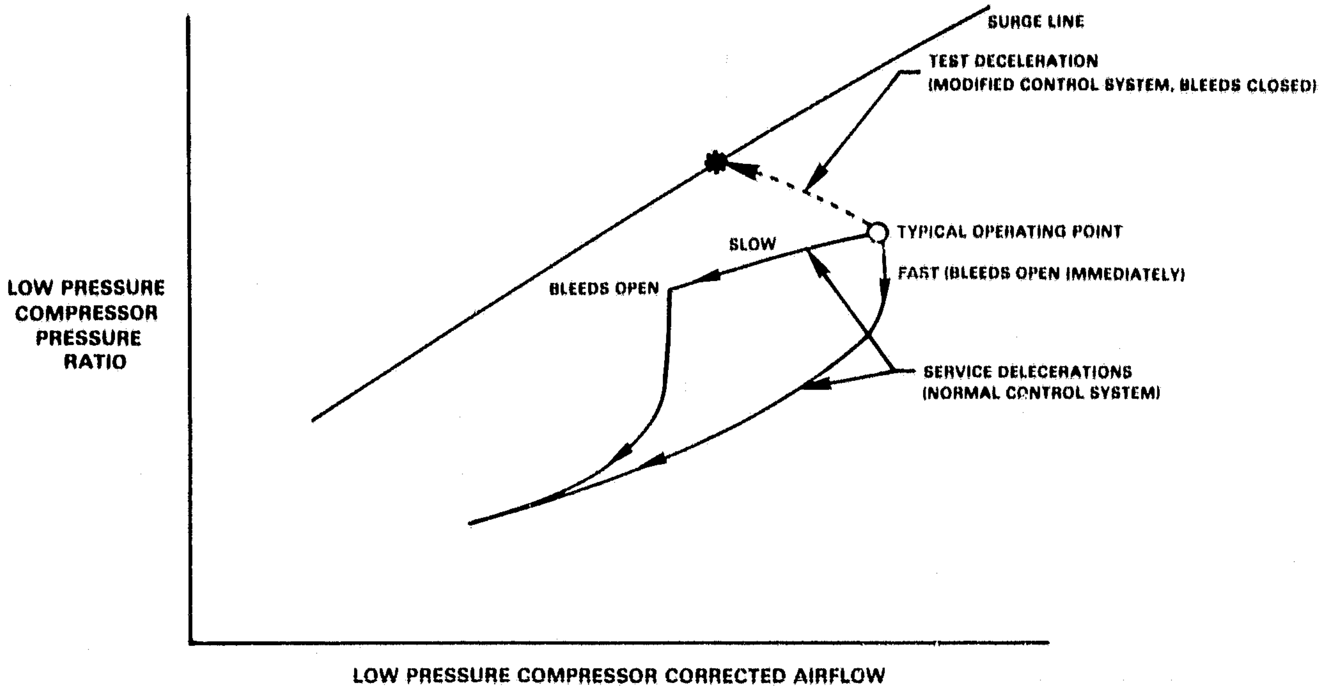

Figure 4-4 Low Pressure Compressor Transient Operation. A modified engine control system allows the use of deceleration rematch effects to map the low pressure compressor surge line.

Snap decelerations were initiated at 19 engine power settings from just above idle to maximum climb power, with the B-52 testbed aircraft at 0.8 Mach number and 10,668 m (35,000 ft.), the stability bleeds initially closed, the bleed system deactivated and the engine stabilized for at least four minutes before each test.

The test was conducted with the JT9D-7 4.6 AR Bill-of-Material fan, the initial 3.8 AR fan configuration, and two variations of the 3.8 AR fan blades. The first variation had longer part span shrouds than the initial configuration, which forced the outer diameter portion of the blade span into a more closed stagger (about 1.6°) as shown in Figure 4-5. The second variation had the same part span shroud length as the initial configuration, but the inner diameter portion of the blade span (as shown in Figure 4-6) was modified to reduce its camber. Testing of all four fan configurations was done with the circumferentially grooved fan rubstrip (Figure 4-7), which is the JT9D-7 Bill-of-Material configuration.

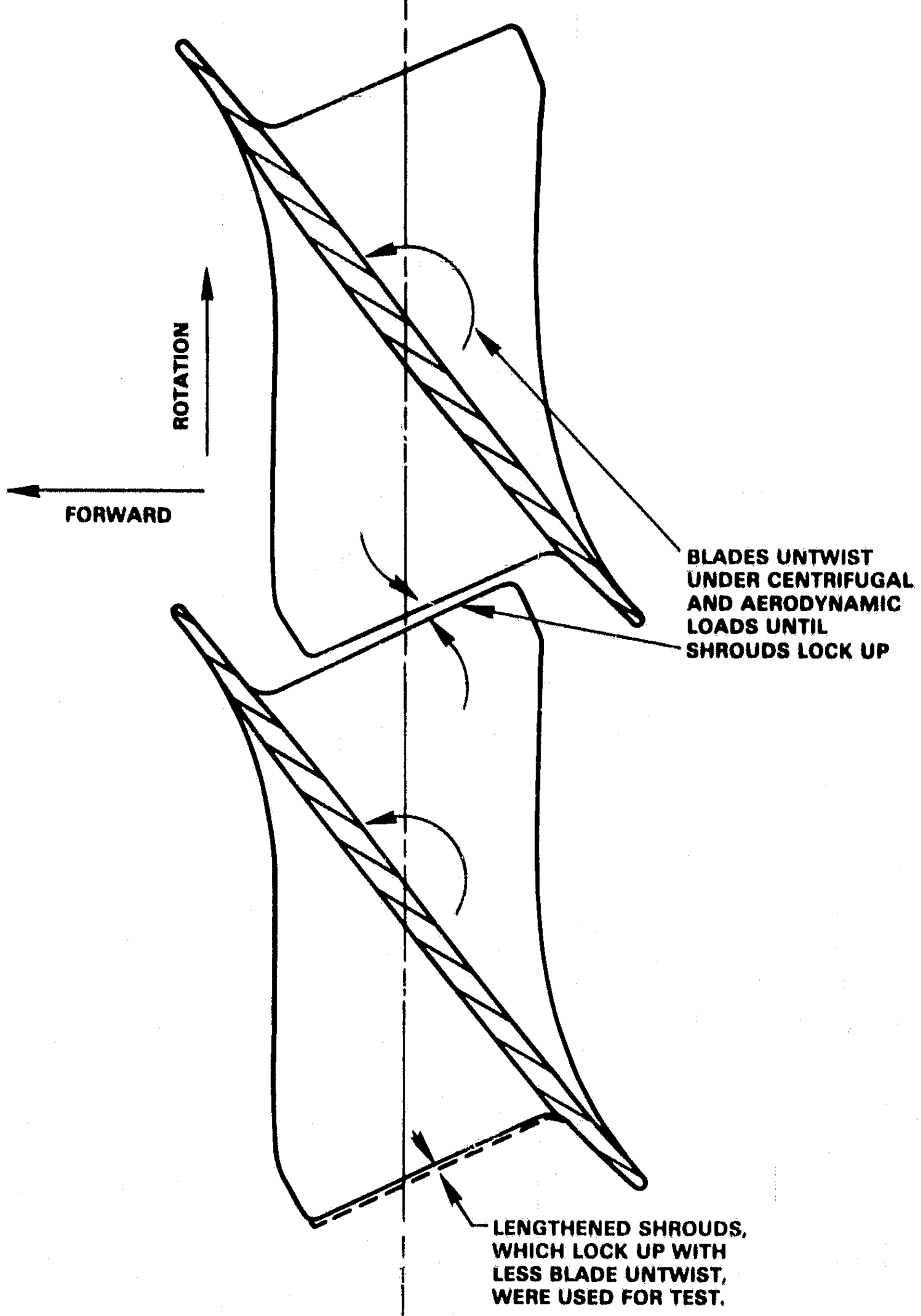

Figure 4-5 Lengthened Part Span Shrouds. The lengthened shrouds reduce blade untwist by 1.6°, and were used on the first variation of the 3.8 AR fan blade.

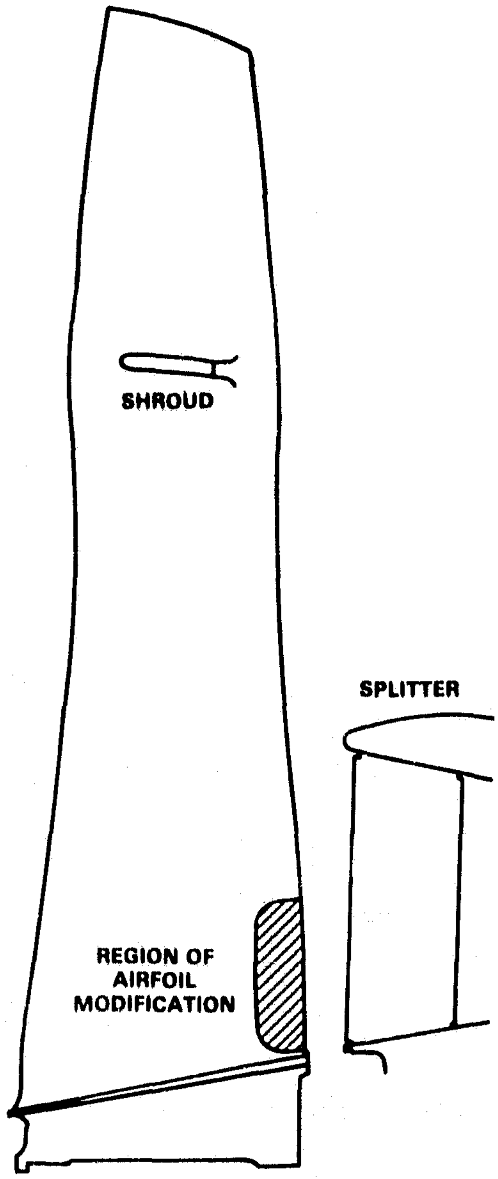

Figure 4-6 Region of Reduced Camber. Blade camber was reduced in the indicated region for the final 3.8 AR fan configuration.

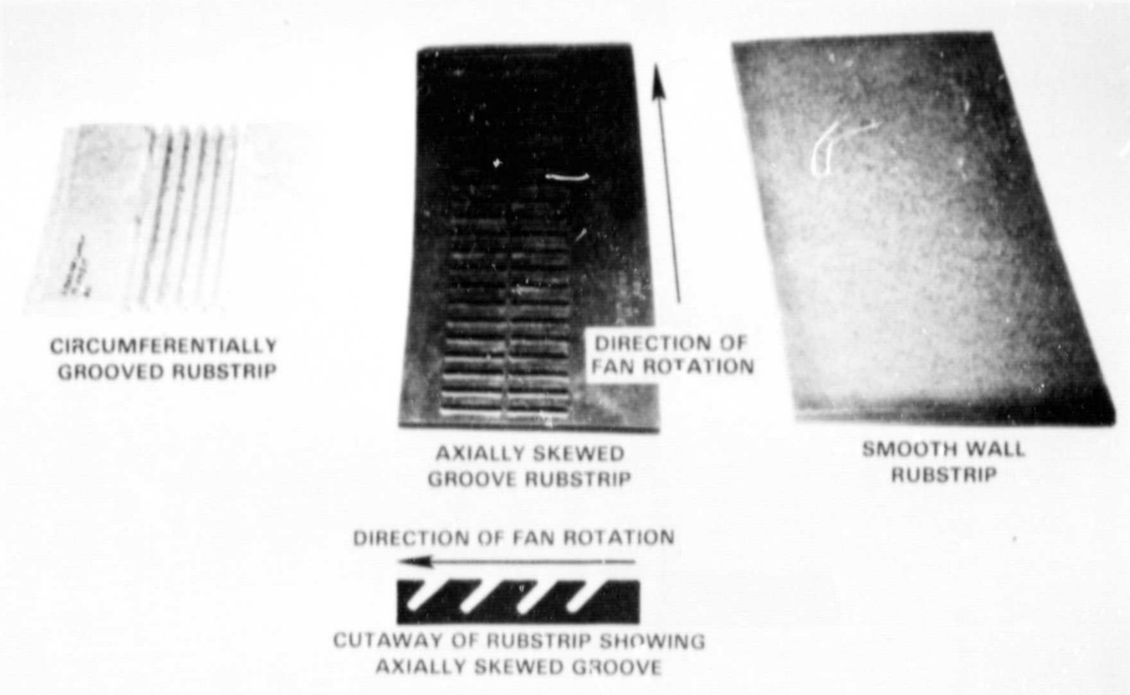

Figure 4-7 JT9D Fan Rubstrip Configurations. The circumferentially grooved rubstrip is the JT9D Bill-of-Material configuration. The axially skewed groove rubstrip and a smooth surface rubstrip were also tested to explore their effect on stability.

4.2.2 Fan Stability Test

A static ground test with the engine installed on the B-52 aircraft was conducted to evaluate the effect of fan blade tip clearance variations on fan stability. Fan blade tip clearance was increased incrementally until nacelle vibration was visually observed as the engine was accelerated into the higher power ranges. Experience indicates that these vibrations signal the onset of fan tip stall.

Tip clearance was increased up to about 0.254 cm (0.100 in) above the Bill-of-Material production clearance by shimming the fan rotor forward relative to the conical fan case as shown in Figure 4-8. Further clearance increases were obtained by offset machining the inner diameter of the fan rubstrip. The same offset machining technique that is used in setting the Bill-of-Material rubstrip/blade tip clearances was used for the test, except the offset was increased as the clearance was increased. This approach, which is illustrated in Figure 4-9, simulates the wear pattern found in actual operation, which is more pronounced at the bottom because of fan case motion induced by air loads on the inlet cowl during high angle of attack operation. As indicated in the figure, the Bill-of-Material (B/M) rubstrip is machined as two circles, one concentric with the rotor centerline and the second offset downward by 0.101 cm (0.040 in). When larger clearances were machined for this test, the downward change was increased by an amount equal to the radial clearance increase Δ , so the maximum circumferential clearance increase occurs at the bottom centerline.

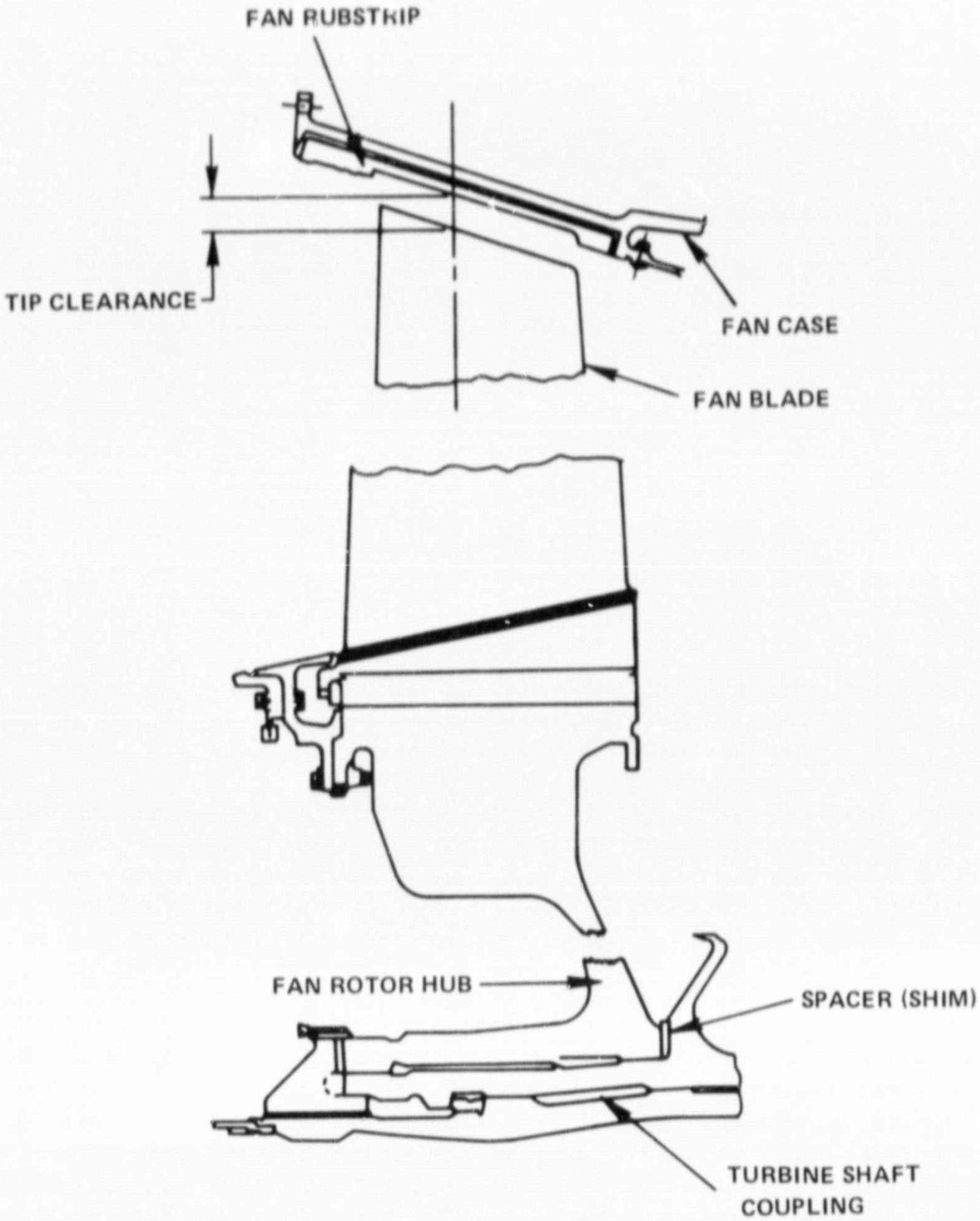

Figure 4-8 Fan Blade Tip Clearance Adjustment Method. Fan blade tip clearances are set by using different sized spacers (shims). The spacer moves the fan blade forward or backward relative to the conical case.

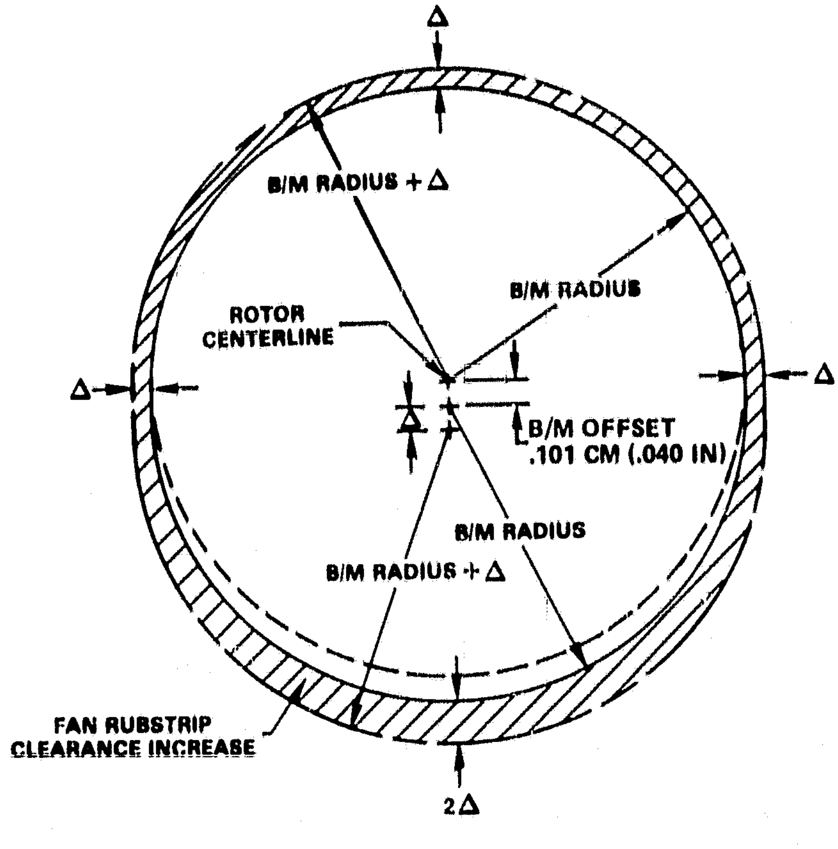

Figure 4-9 Offset Machining of Fan Rubstrip. Fan rubstrip clearance was varied circumferentially to simulate field wear patterns for the stability tests.

Tests were run with the Bill-of-Material fan and the 3.8 AR fan configuration back-to-back on the same engine. The basic fan stability testing was conducted with the Bill-of-Material circumferential groove rubstrip. Some additional 3.8 AR fan testing was conducted with the axially skewed groove (Figure 4-7) and smooth surface rubstrips.

4.2.3 Operational Suitability Test

Operational suitability of a JT9D-7 engine with the 3.8 AR fan was evaluated relative to the Bill-of-Material fan on the wing of the B-52 aircraft in ground and flight tests. Adverse wind sensitivity tests were conducted to define engine stability in airline ground handling situations, such as taxiing, start of takeoff, and engine control trimming. Flight transient suitability tests were conducted to evaluate engine stability in airline flight operations, such as engine and airplane accelerations and decelerations, and airplane maneuvers.

Adverse wind sensitivity tests were conducted to determine the maximum engine power setting that could be reached with various crosswind and tailwind velocities before encountering engine surge. Tests were conducted with the engine and nacelle mounted on the testbed airplane to provide realistic installation effects. Steady wind speeds up to 80 km/hr (50 mph) were generated by using the propeller wash from a Convair 240 twin-engine airplane to augment natural winds. Wind direction was controlled by positioning the testbed airplane relative to the natural or augmented wind.

The test was conducted using the Bill-of-Material circumferential groove rubstrip. The rubstrip was machined to set the blade tip clearance at the field wear limit using the offset machining technique described in Section 4.2.2. This is the "worst case" for fan stability in operational engines.

The engine power range from minimum idle to takeoff was divided into five steps for each wind velocity setting. The engine was allowed to stabilize for three minutes at each step, starting with minimum idle and increasing until takeoff power was reached or a surge occurred.

The flight transient suitability test was conducted by observing engine performance through a series of engine excursions and airplane flight maneuvers which simulate the range of normal in-flight service operation. Tests were conducted with the testbed airplane in flight at altitudes from 4,267 m to 13,716 m (14,000 to 45,000 ft) at Mach numbers from 0.22 to 0.8. Back-to-back engine acceleration and deceleration tests were run with the 3.8 AR fan and Bill-of-Material fan. Windmilling engine starts and airplane transient and maneuver tests were run with the 3.8 AR fan only, since the Bill-of-Material fan had previously passed the same tests. Each segment of the test series is described below.

Engine snap decelerations to idle, starting from 19 different power settings spaced between maximum climb and minimum idle power, were conducted at the following flight condition:

Altitude, m (ft)	Speed
10,668 (35,000)	Mach 0.8

Engine interrupted decelerations starting from maximum climb power, with the turnaround from deceleration to acceleration varied in small steps between maximum climb and minimum idle power, were conducted at the following flight conditions:

Altitude, m (ft)	Speed
11,887 (39,000)	Mach 0.77
13,716 (45,000)	min. flight

Engine accelerations to maximum climb power, starting from minimum idle, flight idle, and three other low power settings, were conducted at the following flight conditions:

Altitude, m (ft)	Speed
4,267 (14,000)	Mach 0.22
10,668 (35,000)	Mach 0.8
13,716 (45,000)	Mach 0.8

Windmilling engine starts were performed at the following flight conditions:

Altitude, m (ft)	Speed
10,668 (35,000)	Mach 0.8, 0.7, 0.6, 0.5
6,096 (20,000)	Mach 0.6
3,048 (10,000)	463 km/hr (250 knots)

Airplane descent, with the engine operating at minimum idle, was performed between the following altitudes:

	Altitude, m (ft)
Start	7924 (26,000)
End	5486 (18,000)

Airplane accelerations from minimum flight speed to maximum flight speed, with the engine operating at maximum cruise power, were performed at the following altitudes:

Altitude, m (ft)
3,048 (10,000)
13,716 (45,000)

Three different airplane maneuvers, a 45 degree banked turn, a maximum yaw to the left, and a maximum yaw to the right, were performed at the following conditions:

Altitude, m (ft)	Speed	Engine Power
10,668 (35,000)	Mach 0.8	Max. climb
10,668 (35,000)	Mach 0.8	Max. cruise

4.2.4 Fan Stress Test

Steady state and vibratory stress levels in the blades and vanes of the 3.8 AR fan system were measured by strain gages at locations on the parts where maximum stresses were expected. The measurements were taken with the engine installed on the B-52 aircraft operating both on the ground and in flight.

In the ground test, the engine was accelerated slowly from minimum idle to maximum fan rotor speed, and then decelerated slowly back to idle to find the rotor speeds at which maximum vibratory stress occurred in the blades and the vanes. The engine was then operated for five minutes at each of these maximum stress speeds. Steady state and vibratory stresses were recorded during normal and snap accelerations and decelerations.

In the flight test, vibratory stresses were recorded during airplane takeoff with the engine operating at takeoff power, and during slow engine accelerations and decelerations with the airplane flying at the following conditions:

Altitude, m (ft)	Speed
4,572 (15,000)	Mach 0.45
10,972 (36,000)	Mach 0.81

4.3 Engine Ground Stability Test

The objective of the engine ground stability test was to define the stability characteristics of the 3.8 AR fan relative to the Bill-of-Material fan with variations in inlet flow distortion and fan blade tip clearance. The two fans were tested back-to-back on the same JT9D-7 experimental engine (X-547), which was equipped with a variable flow area fan discharge nozzle system as shown in Figure 4-10. This system allows the fan discharge area to be varied while the engine is running. The tests were conducted by stabilizing the engine operation with the normal fan nozzle area, then slowly reducing the area to force the fan pressure ratio above the normal operating line to define the stall point.

The test was conducted in an enclosed facility (X-236) capable of testing a JT9D engine up to its maximum takeoff thrust capability. The stand provides sea level static inlet and discharge pressure conditions with the option of heating the inlet air up to 120°F. Inlet and discharge flow is silenced to permit around the clock operation. The test engine is supported from an overhead thrust measuring platform.

Normal production engine instrumentation was augmented with special inlet and fan discharge instrumentation for recording inlet flow distortion. Fan inlet wall high response thermocouples, located 12.7 mm (0.5 in.) forward of the fan leading edge, were used to monitor fan tip stall. This special instrumentation is described in Table 4-3, and shown in Figure 4-11.

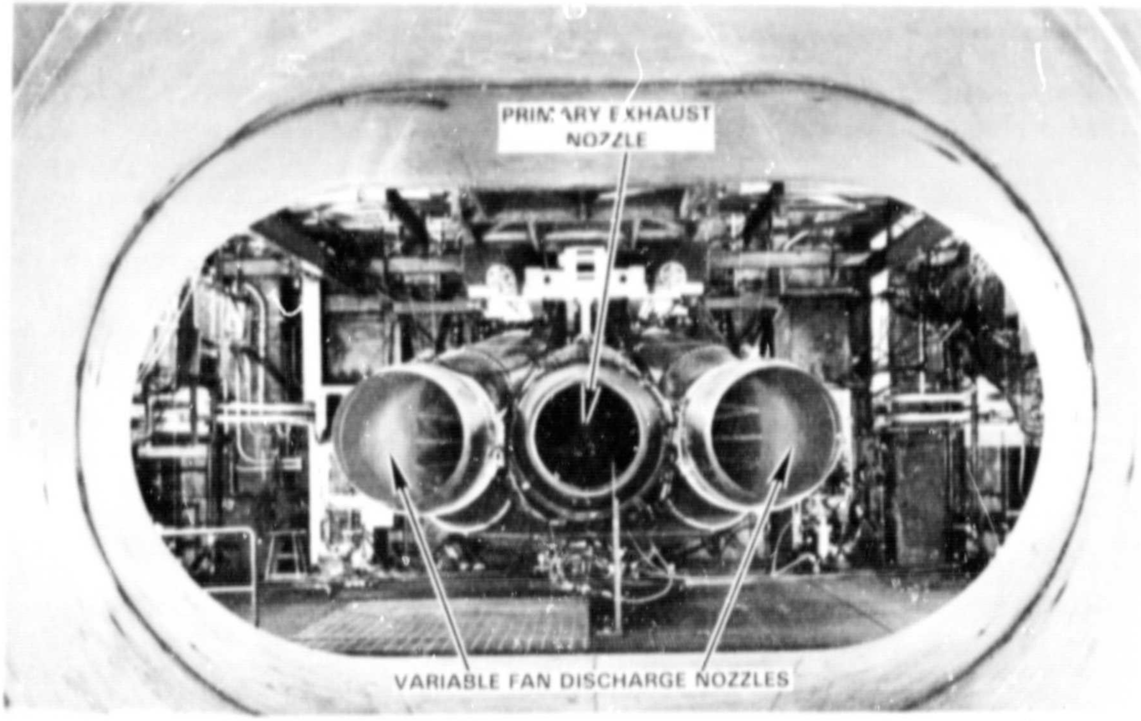

Figure 4-10 JT9D-7 Experimental Engine with Variable Fan Discharge Nozzles. Variable area fan nozzles allow the fan pressure ratio to be increased during engine operation, so that the fan stall line can be mapped.

TABLE 4-3

SPECIAL INSTRUMENTATION FOR ENGINE GROUND STABILITY TEST

Parameter	Description
Fan Inlet Total Pressure	8 rakes/10 sensors per rake at fan face, spaced every 45°
Fan Inlet Total Temperature	4 thermocouples at fan face 1.27 mm (0.5 in.) forward of fan leading edge and 0.63 mm (0.25 in.) from wall OD located at 0°, 90°, 180° and 270°
Fan Discharge Total Pressure	8 rakes/8 sensors per rake with kiel heads
Fan Discharge Total Temperature	8 rakes/8 sensors per rake
Fan Discharge Area	Calibration of variable fan nozzles in square feet.

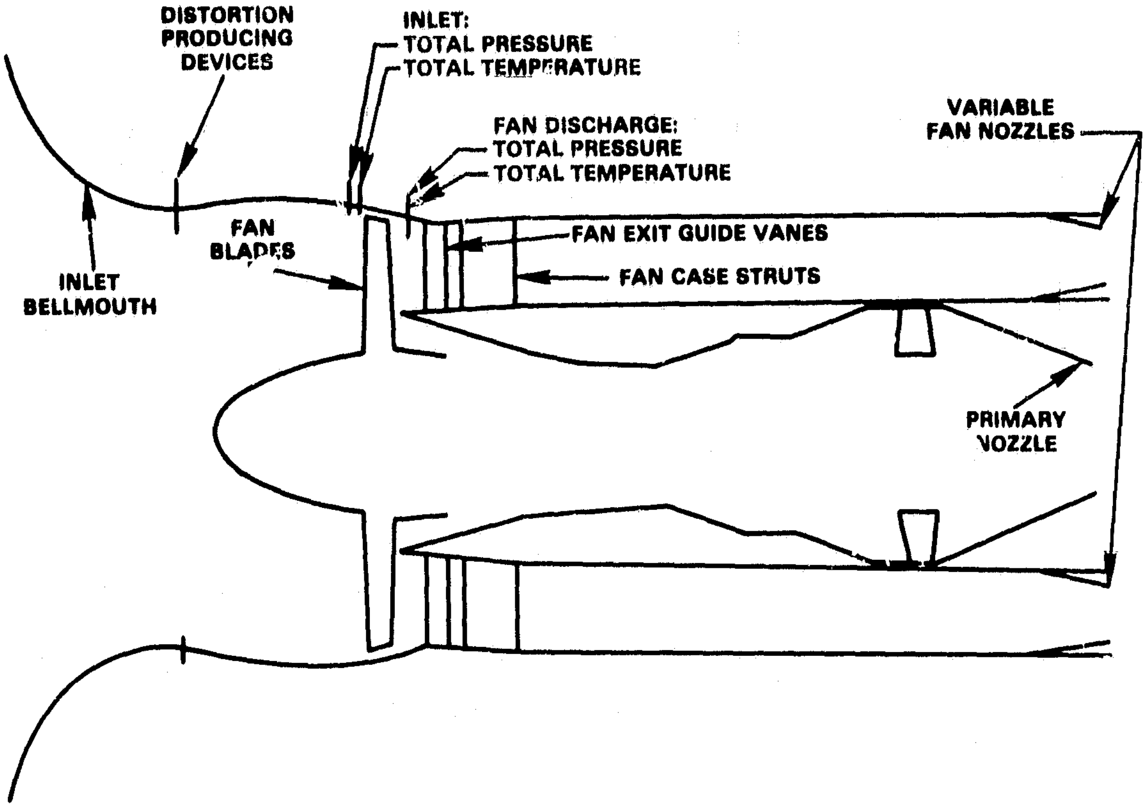

Figure 4-11 Axial Locations of Special Equipment for Fan Stability Test. This test equipment was used to generate and monitor various fan stall conditions.

The JT9D-7 experimental engine was tested with a clean bellmouth inlet, and with two inlet flow blockages to simulate operational inlet distortions.

Two 0.63 cm (0.25 in) diameter rods, formed into full rings, were installed in the inlet bellmouth, as shown in Figure 4-12. The two rings were located axially at the throat of the bellmouth inlet. One ring was attached directly to the inlet wall, while the second was supported 2.5 cm (1.0 in) away from the wall. Previous testing with this system has shown that it provides a good simulation of the boundary layer build-up in the long inlet of a center engine installation, such as the McDonnell-Douglas DC-10 airplane.

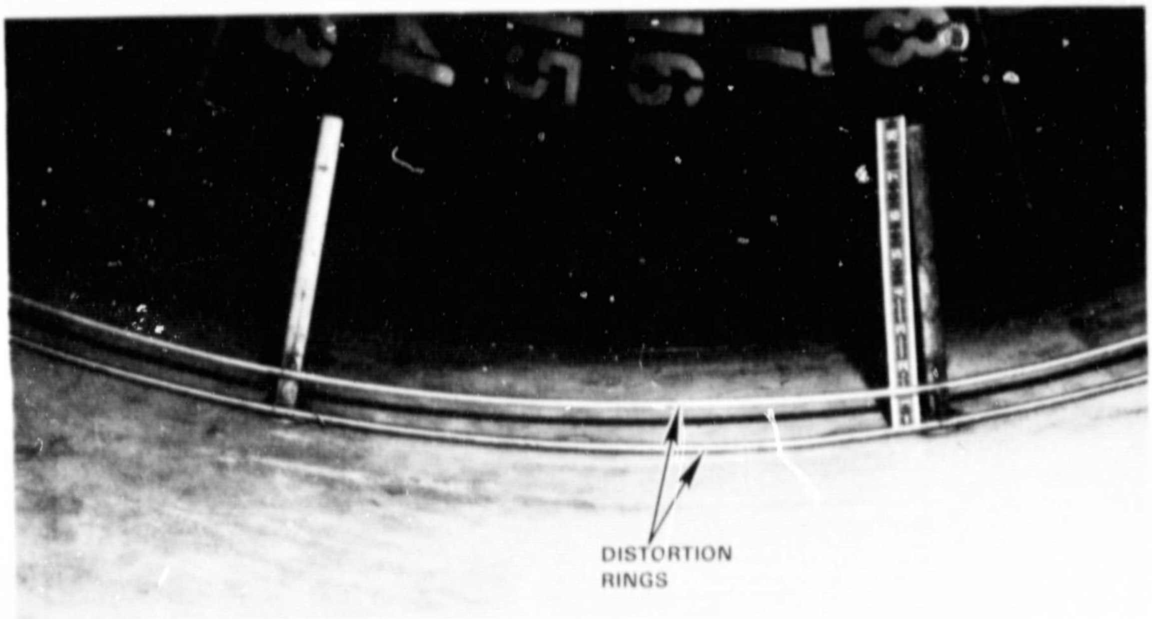

Figure 4-12 Inlet Distortion Rings. Flow blockage induced by the full circumference rings simulates the boundary layer buildup in the long inlet of a center engine installation, such as the McDonnell-Douglas DC-10.

Four layers of screen were installed in the lower quadrant of the inlet, as shown in Figure 4-13. The large screen has a 2.5 x 2.5 cm (1 x 1 in) mesh, covers a 135° arc, and extends 28.57 cm (11.25 in) radially from the inlet wall. The largest of the overlay screens has a 1.27 x 0.63 cm (0.5 x 0.25 in) mesh, and the two smaller screens have a 0.63 x 0.63 cm (0.25 x 0.25 in) mesh. The screen array is located axially at the throat of the bellmouth inlet. Previous testing has shown that this system simulates the distortion encountered by a wing mounted installation when the airplane is rotated to an extremely high angle of attack. Such a maneuver, which can occur in emergency takeoff situations, produces the maximum inlet distortion that an engine is likely to encounter in airline service.

The Bill-of-Material fan was tested with the Bill-of-Material circumferentally grooved rubstrip, and with the tip clearance set at the field wear limit of 6.8 mm (0.270 in.). The 3.8 AR fan was tested with the same rubstrip configuration, but its tip clearance was varied from the Bill-of-Material new engine clearance of 4.5 mm (0.175 in.) to well beyond the field wear limit. The offset rubstrip machining technique described in Section 4.2.2 was used to set tip clearance with both fans. The test results were correlated against the maximum static tip clearance, which occurs at the bottom centerline. The 3.8 AR fan was also tested with the axially skewed groove rubstrip configuration (Figure 4-7) to determine its response.

Figure 4-13 Inlet Distortion Screens. Flow blockage induced by these screens simulates the flow distortion that a wing mounted engine would experience at extreme angles of attack.

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To evaluate each of the test configurations, the engine was started and the power set at 1600 rpm corrected fan rotor speed with the variable area fan nozzles in the maximum open position (approximately normal fan nozzle area). After a five minute stabilization, performance data was recorded. Then, the fan nozzle area was decreased by 0.093 m^2 (1 ft^2) and a data point recorded. The fan nozzle area was decreased by additional 0.093 m^2 (1 ft^2) increments until a stall occurred. Fan inlet wall thermocouples were the prime indicators of fan stall.

The fan nozzles were opened and fan rotor speed was subsequently increased to 2400, 3000, and 3200 rpm (takeoff power). The stabilization and stall initiation procedure was repeated for each power setting. Fan rubstrip condition was documented and fan tip clearance re-measured at the completion of the test for each configuration.

4.4 Engine Acoustic Test

The objective of the engine acoustic test was to compare the noise characteristics of the 3.8 AR fan to the Bill-of-Material fan. This was done by testing each fan in a JT9D engine and recording the noise characteristics generated at various power settings at a radius of 45.7 m (150 ft) from the test stand.

The test engine, (X-618), was built to approximate the performance characteristics of a JT9D-7A production engine. The engine was equipped with standard flight instrumentation for this test. A Boeing 747-200 nacelle inlet, fan reverser sleeves, core cowl, and tailpipe were installed on the engine. The engine was mounted on the outdoor test stand as shown in Figure 4-14. A large inlet screen was installed as shown in Figure 4-15 to reduce the turbulence of the inlet flow with minimal attenuation of inlet noise. This system simulates the noise characteristics of an engine on a moving aircraft.

The test stand (Rohr B-150) and its surrounding field are designed for acoustic testing of engine/nacelle systems. The test stand is a cantilever type structure, which supports the engine from above, and is open on one side so that it will not affect noise measurements aft, forward, or towards the open side. The stand is surrounded by a surface of trap rock, to provide for uniform reflected noise. Figure 4-16 is an aerial schematic of the acoustic test facility, showing the cantilever test stand, trap rock apron and the location of microphones used to record the engine noise. The stand is also equipped to measure ambient air temperature, pressure and relative humidity, wind speed and direction, and engine thrust and fuel flow. Data collected from this instrumentation and the engine flight instrumentation was stored, processed and reduced by a high speed digital computer system.

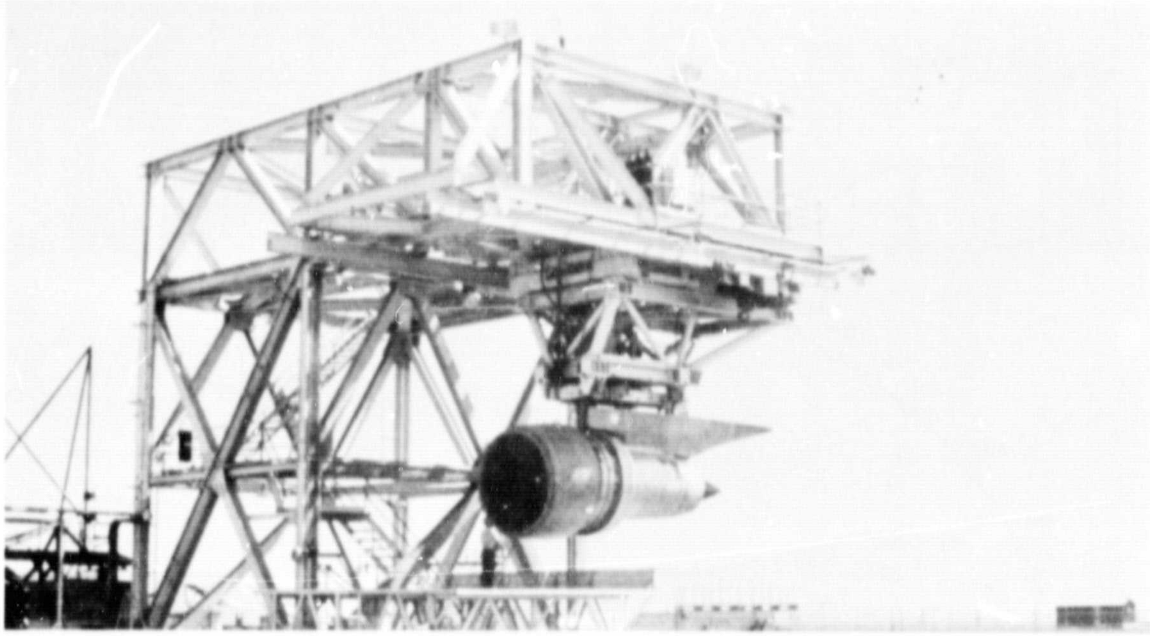

Figure 4-14 JT9D-7 Engine Installed in Acoustic Test Facility. Absence of obstructions forward, aft, and to one side facilitates acoustic testing.

Figure 4-15 JT9D-7A Engine Installed in Acoustic Test Stand. The inlet screen assembly reduces turbulence to simulate the inlet flow conditions of an engine mounted on a moving aircraft.

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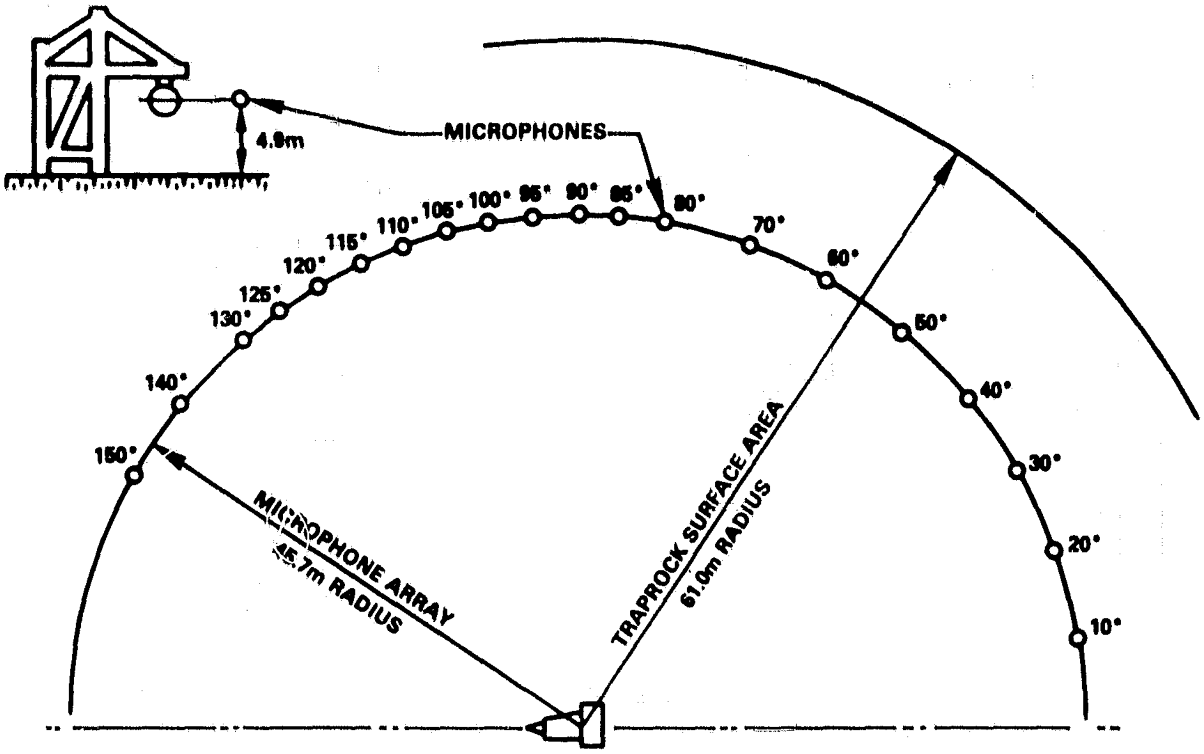

Figure 4-16 Schematic of the Acoustic Test Facility. Twenty microphones are located in a 45.7 m (150 ft.) radius around the test stand.

Before each test series, the noise measurement system was calibrated using a white noise source. The trap rock apron surrounding the test stand was raked and leveled to provide a uniform surface and reduce the possibility of unwanted acoustic effects. Acoustic tests were conducted only when atmospheric conditions were within the accepted "test window" shown in Figure 4-17 and defined in FAR Part 36 amendment 9. Before and after each engine test, microphones were calibrated using a pistonphone directly traceable to the National Bureau of Standards.

Both fan configurations were run at the data points shown in Table 4-4. The engine was allowed to stabilize for three minutes at each data point before data was taken. The test data point sequence was run twice for each fan configuration.

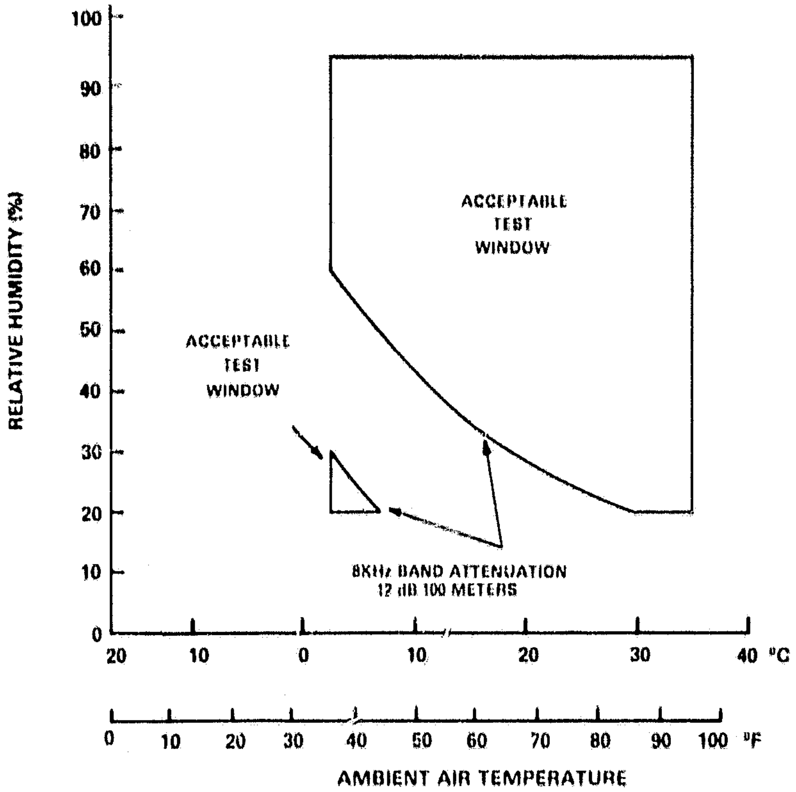

Figure 4-17 FAR Part 36, Amendment 9 Acceptable Test Conditions. The test window shown here was used for the 3.8 AR fan acoustic tests.

TABLE 4-4

ACOUSTIC TEST DATA POINTS

Data Point Sequence	Corrected Fan Rotor Speed (RPM)
1	1750
2	1930
3	2100
4	2260
5	2400
6	2670
7	3020
8	3120
9	3230
10	3275
11	3370
12	3440

5.0 RESULTS AND DISCUSSION

The 3.8 AR fan installed in a JT9D-7A engine demonstrated an average cruise thrust specific fuel consumption improvement of 1.3 percent over the Bill-of-Material fan in the altitude engine performance tests. Engines using the 3.8 AR fan also demonstrated takeoff and climb exhaust gas temperature margins, fan and low pressure compressor stability, inlet distortion and cross-wind tolerance, and noise levels equal to or better than the Bill-of-Material fan in the flight stability tests, ground stability tests, and acoustic tests. Strain gage measurements in the fan blade, hub and fan exit guide vanes taken during the flight stability tests showed the stresses to be equal to or lower than in the Bill-of-Material parts in all locations except one. The exception was in the fan blade airfoil/platform intersection, where the stresses were slightly higher than in the Bill-of-Material blade. This deficiency has been corrected by a design modification which increases the fillet radius in this location.

These above results are discussed in the subsequent paragraphs of Section 5.0. The test facilities, engine test configurations, instrumentation, and test procedures which led to these results are discussed in the corresponding paragraphs of Section 4.0.

5.1 Simulated Altitude Engine Performance Test

In back-to-back engine performance tests in our altitude test facility at realistic cruise conditions (described in Section 4.1) the 3.8 AR fan showed a maximum thrust specific fuel consumption improvement of 2.5 percent over the Bill-of-Material fan at the maximum climb thrust rating of the engine. Figure 5-1 shows that the improvement varies with power setting, decreasing to 0.5 percent improvement at 60 percent maximum cruise thrust. The thrust specific fuel consumption improvement of 1.3 percent at 90 percent cruise thrust is exactly equal to the improvement predicted for the economic evaluation of the concept in Reference 1. This 1.3 percent TSFC improvement is equivalent to a fan efficiency increase of about 2.6 percentage points.

5.2 Engine Flight Tests

The following results were obtained from the B-52 ground and flight tests described in Section 4.2.

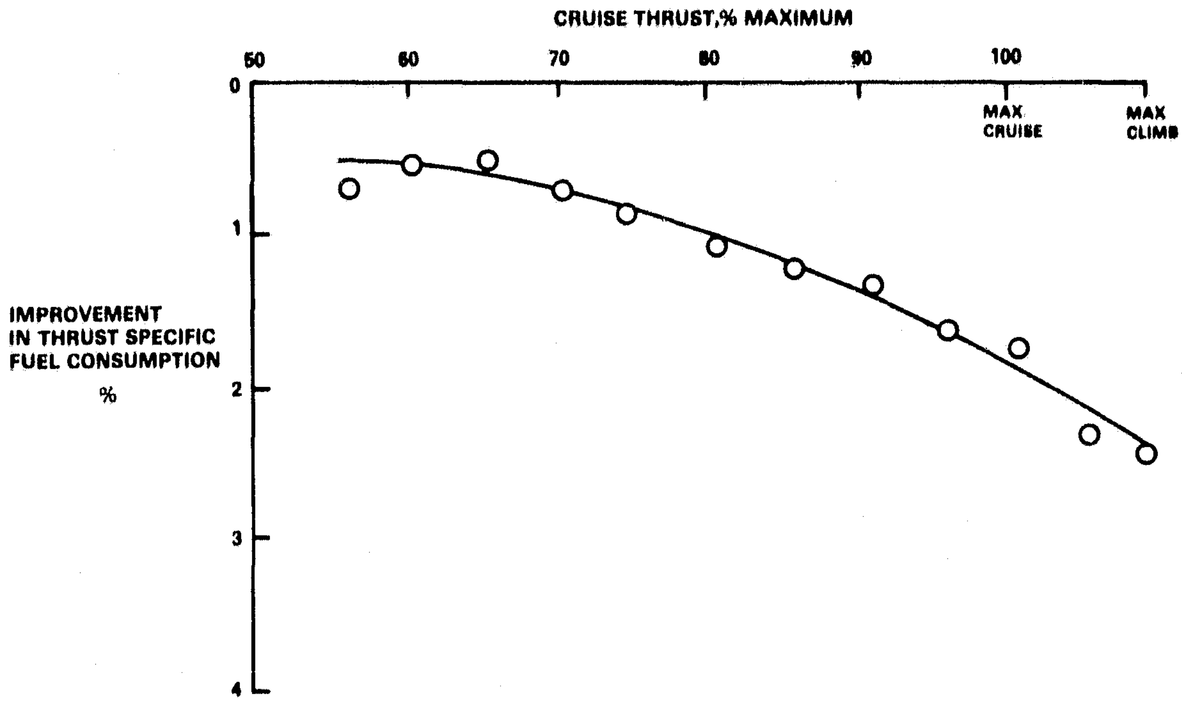

Figure 5-1 Thrust Specific Fuel Consumption Improvement of the 3.8 AR Fan Relative to the JT9D-7 Bill-of-Material Fan. These results are for a simulated altitude of 9,906 m (32,500 ft) and a Mach number of 0.84.

5.2.1 Low Pressure Compressor Stability

The low pressure compressor surge margin of the three different 3.8 AR fan configurations (described in Section 4.2.1) at cruise flight conditions are presented in Figure 5-2 relative to that with the 4.6 AR Bill-of-Material fan. The initial 3.8 AR fan configuration showed a surge margin loss relative to the Bill-of-Material fan of about two percentage points maximum at the lower airflows. The first variation of the 3.8 AR fan, which had the blade tip stagger closed 1.6°, showed a further loss in low pressure compressor surge margin. This result indicated that the low pressure compressor surge margin loss could not be corrected by shifting work to the inner diameter portion of the blade. The final 3.8 AR fan configuration, which had a modified blade trailing edge inboard of the flow splitter, resulted in a low pressure compressor surge margin equal to the Bill-of-Material system at low power, increasing to five percentage points better than the Bill-of-Material configuration at design airflow.

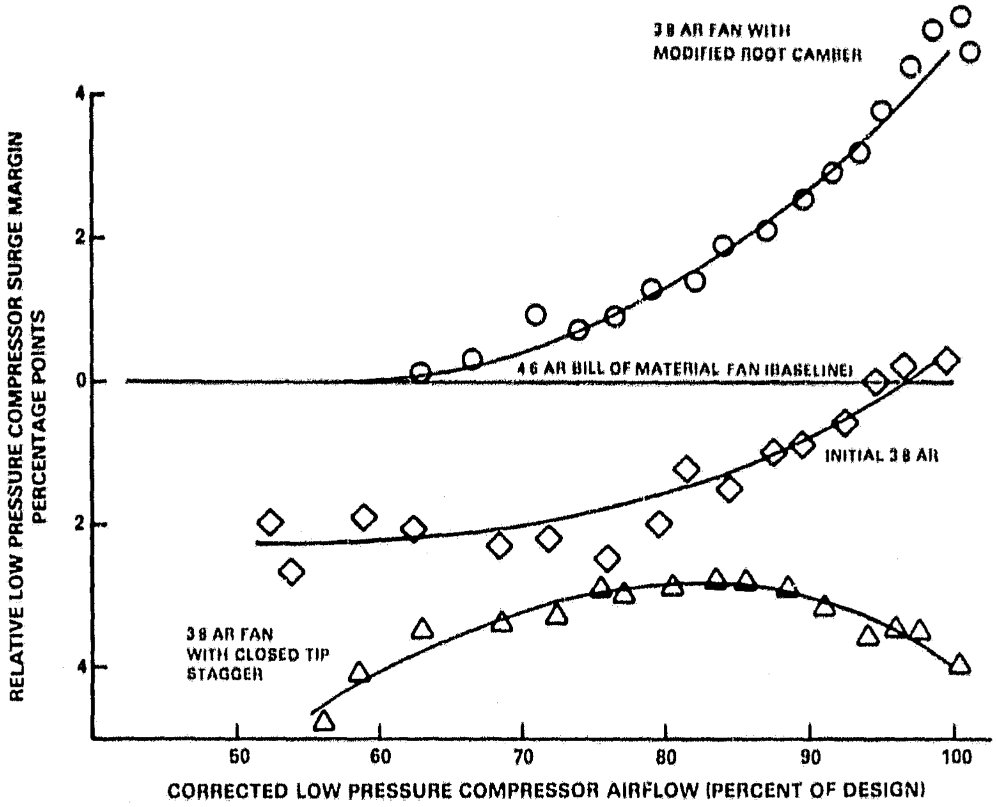

Figure 5-2 Effect of the 3.8 AR Fan on Low Pressure Compressor Surge Margin. The final 3.8 AR fan with a modified root airfoil provides a low pressure compressor surge margin equal to or better than the Bill-of-Material fan.

Subsequent engine performance checks with the final fan configuration showed an exhaust gas temperature reduction of 1°C at takeoff conditions and an increase of 1°C at climb conditions compared to the 4.6 AR Bill-of-Material fan. The estimated net effect of these differences is no change in engine maintenance requirements. This is acceptable, but the results are less beneficial than the 3°C and 7°C reductions predicted in Reference 1 for takeoff and climb, respectively.

5.2.2 Fan Stability

Fan stability test results are presented in Table 5-1 as the maximum tip clearance achievable with stall-free operation. The 3.8 AR fan demonstrated the ability to operate with 0.076 cm (0.030 in) larger tip clearance than the 4.6 AR Bill-of-Material fan before fan tip stall occurred in a static test on the B-52 airplane. This result was obtained using the Bill-of-Material circumferential groove rubstrip configuration. The 3.8 AR fan with the axially skewed grooved rubstrip tolerated an additional 0.228 cm (0.090 in) clearance increase (the maximum tested) without stalling. When the 3.8 AR fan was tested with a smooth surface rubstrip, it lost 0.177 cm (0.070 in) clearance tolerance relative to the circumferential groove rubstrip. The Bill-of-Material fan was not tested with the alternate rubstrips in this program, but previous tests have shown effects similar to those with the 3.8 AR fan.

TABLE 5-1

EFFECT OF RUBSTRIP CONFIGURATION ON FAN STABILITY

Rubstrip Configuration	Maximum Stable Tip Clearance, cm (in) — Bill-of-Material Fan	Maximum Stable Tip Clearance, cm (in) — 3.8 AR Fan
Circumferentially Grooved	Base	+ 0.076 (0.030)
Axially Skewed Groove	--	+ 0.304 (0.120)
Smooth	--	- 0.101 (0.040)

5.2.3 Operational Suitability

The 3.8 AR fan is equal to the Bill-of-Material fan in terms of tolerance to adverse winds during airline ground handling situations. The wind speed required to cause engine surge in the ground test of the flying test bed installation is plotted against wind direction in Figure 5-3. The cluster of data points at each wind direction represent variations in engine power level. No surges were experienced at wind directions of 45^{o} and below. As shown in Figure 5-4, there is considerable scatter when the data is plotted against engine power setting, but a definite trend toward higher wind tolerance at lower power settings can be identified. In fact, no surges were recorded at engine idle power with adverse wind speeds up to the maximum tested (about 80 km/hr or 50 mph). The adverse wind limits that are specified for control trimming of the Bill-of-Material JT9D-7 engine in Pratt & Whitney Aircraft maintenance manuals are superimposed on Figure 5-3. Note that the 3.8 AR fan equipped engine has a comfortable margin of wind speed tolerance above the trim limits.

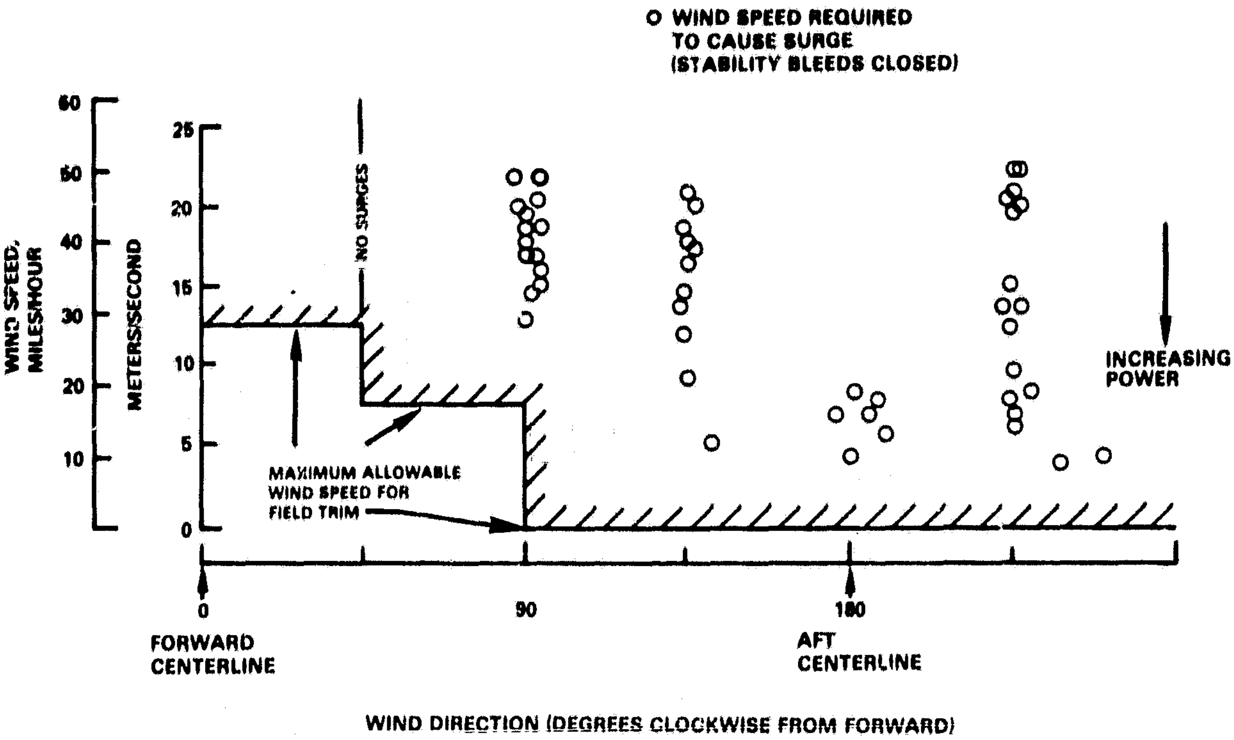

Figure 5-3 Comparison of 3.8 AR Fan Adverse Wind Tolerance with Bill-of-Material Trim Limits. The 3.8 AR fan shows a comfortable tolerance margin above the trim limits.

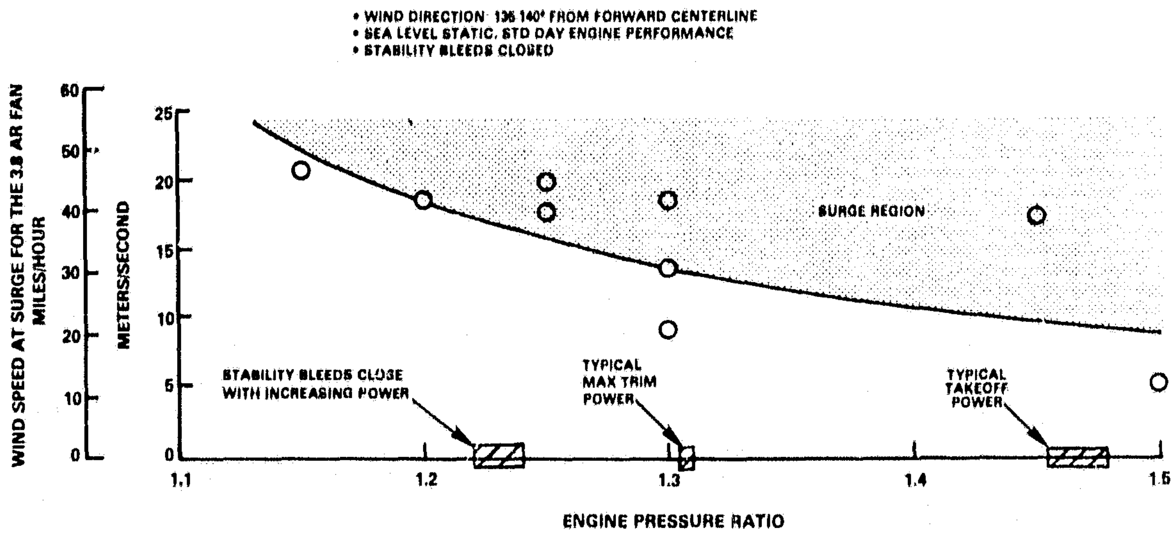

Figure 5-4 3.8 AR Fan Adverse Wind Sensitivity versus Engine Power Settings. A trend toward higher tolerance at lower power settings is apparent.

Other airline ground handling situations are not affected by adverse winds as greatly as control trimming since they do not require high engine power and zero forward speed simulataneously. For example, taxiing involves low power operation only, while takeoff is normally toward the prevailing wind and significant forward speed is attained before the engines reach takeoff power.

Data scatter shown on Figure 5-4 is attributable to the lack of accurate control of wind speeds and direction, and to secondary disturbances in the outdoor test environment. However, the results are still significant since similar variations around the nominal wind conditions also occur in airline operation.

The 3.8 AR fan engine responded normally to each of the transients and maneuvers imposed during the in-flight suitability test. The flight speeds required for windmilling engine starts were the same as the Bill-of-Material. Engine acceleration and deceleration times were essentially equal to those of the Bill-of-Material engine at the same flight conditions. The engine operated satisfactorily under the maximum angle of attack, turn, yaw and flight speed accelerations and decelerations that were generated with the testbed airplane.

5.2.4 Fan Stress

Peak vibratory stresses in the 3.8 AR fan blades and fan exit guide vanes were substantially lower than in the Bill-of-Material system, as shown on Figures 5-5 and 5-6. Note also on Figure 5-5 that the most significant resonance condition (3E) occurs at a lower rotor speed with the 3.8 AR fan putting it below the normal cruise operating range.

Steady state stresses in the 3.8 AR fan system were also lower than in the Bill-of-Material fan, with one exception. The exception was in the fan blade airfoil/platform intersection, where the results of the B-52 tests confirmed earlier test results that the steady stress was 10 percent higher than desired. In order to ensure that the long service life established by the Bill-of-Material blades is not compromised with the 3.8 AR fan, the fillet radius in this area has been increased from 0.30 inch to 0.35 inch in a design modification which will reduce the stress by an estimated 10 percent.

5.3 Engine Ground Stability Test

The results of the static engine tests with variable fan discharge nozzles (described in Section 4.3), indicate that the 3.8 AR fan has a larger tip stability margin than the Bill-of-Material fan. The improvement amounts to two to five percent in terms of additional fan nozzle area reduction required to precipitate stall when compared to the Bill-of-Material fan at equal tip clearances. The variation depends on inlet distortion, as shown in Figures 5-7, 5-8, and 5-9. These figures compare the 3.8 AR fan and Bill-of-Material fan at a typical takeoff power condition, where fan tip stability is most important. The comparative results were similar at other power settings.

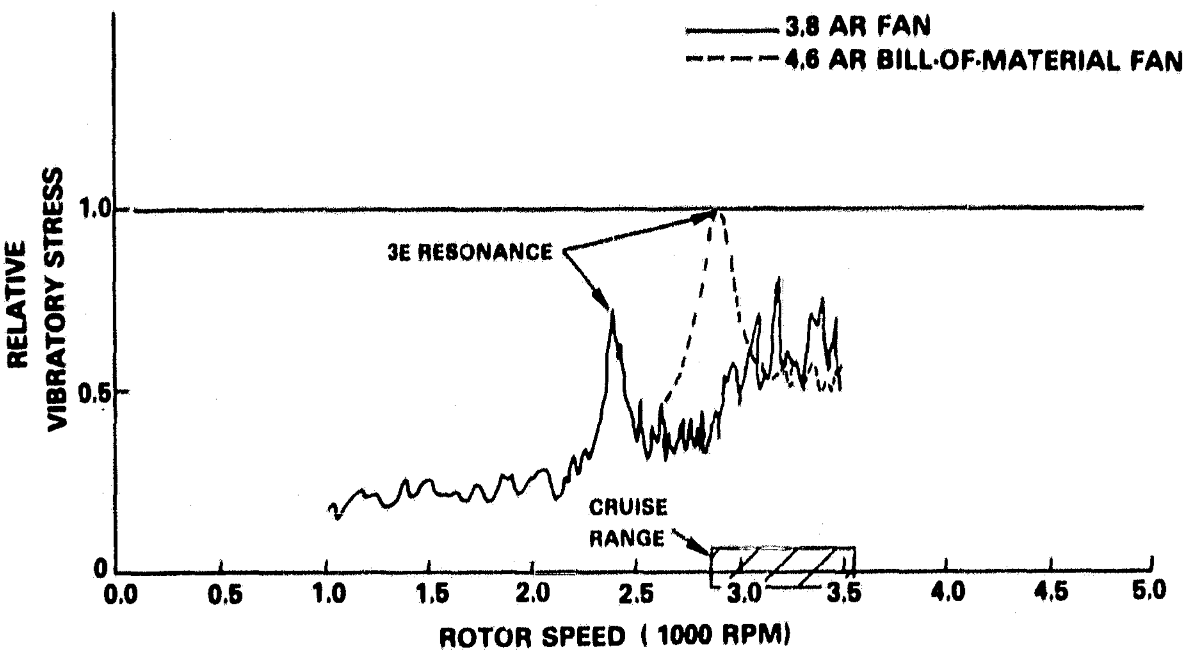

Figure 5-5 Comparison of Vibratory Stresses in the Fan Blade Root Leading Edge. The 3.8 AR fan blade has a lower peak vibratory stress, and the peak occurs below the normal cruise operating range.

The results can only be compared to the Bill-of-Material fan at one value of fan tip clearance at each inlet distortion because of the limited data available on the Bill-of-Material fan. However, the trends shown by the 3.8 AR fan are interesting, and similar trends would be expected with the Bill-of-Material fan. Note for the clean inlet case (Figure 5-7) that the fan nozzle area reduction required to precipitate stall decreases as fan tip clearance is increased, implying a loss of stall margin with increasing clearance, as would be expected. However, with the inlet distortions represented in Figures 5-8 and 5-9 the variation with clearance occurs only in the lower clearance range. There is apparently an interactive effect between tip clearance and inlet distortion, but this effect has not been explained.

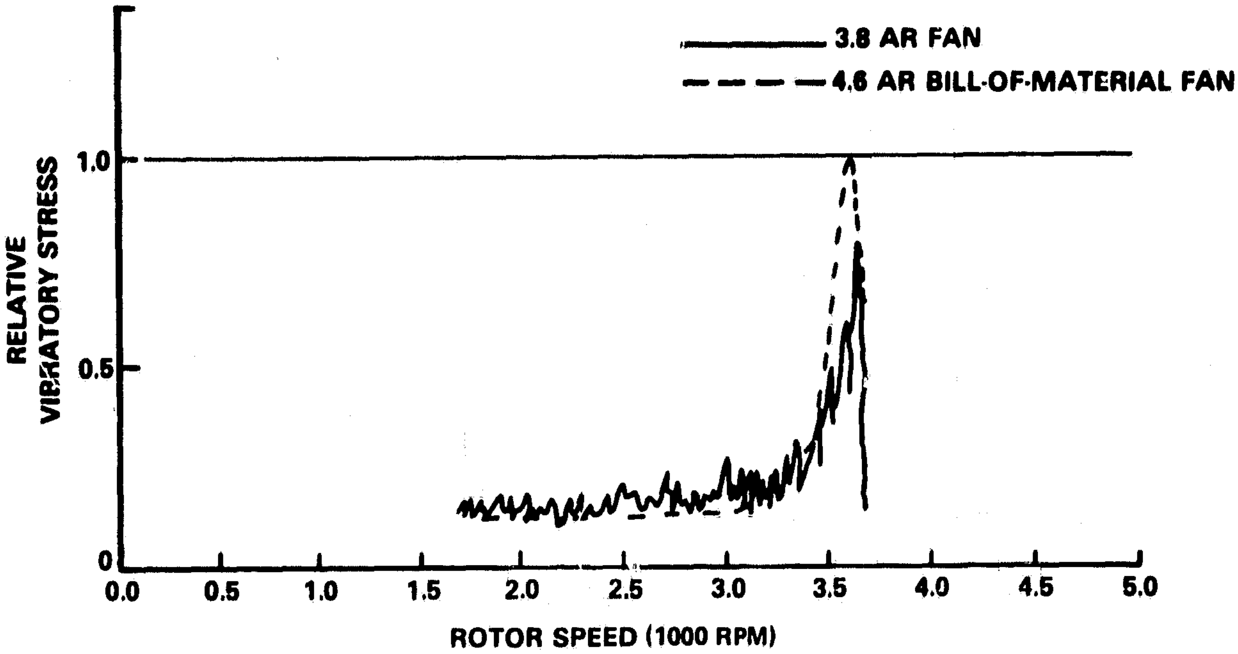

Figure 5-6 Comparison of Vibratory Stresses in the Fan Exit Guide Vane Mid-Span Maximum Thickness Section. The 3.8 AR fan exit guide vane has a lower peak vibratory stress.

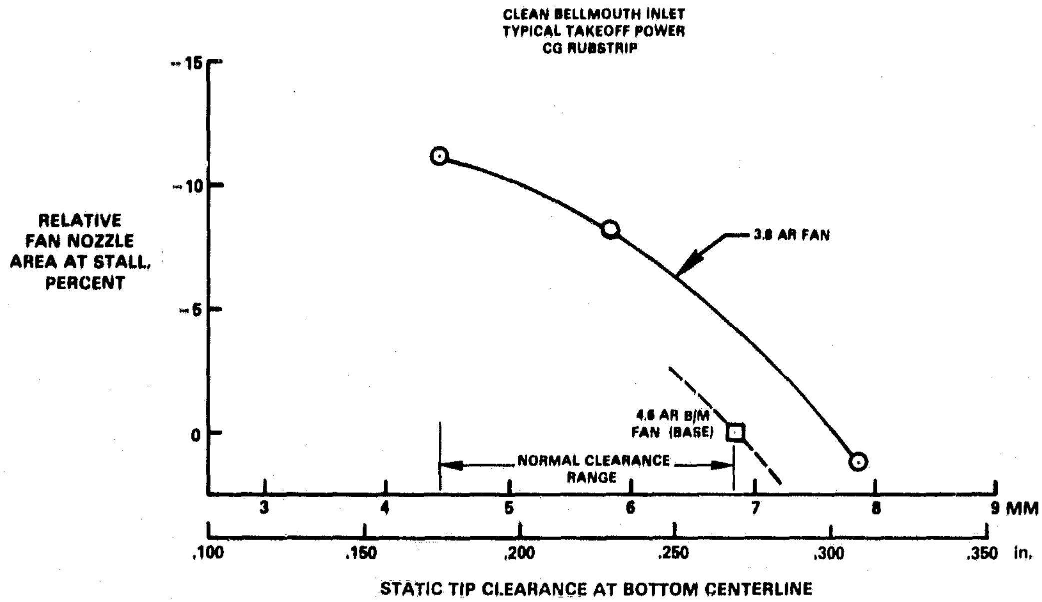

Figure 5-7 Comparison of Fan Tip Stability with Clean Inlet. The 3.8 AR fan has more stability margin than the Bill-of-Material fan at equal tip clearances. Note the rapid variation with clearance.

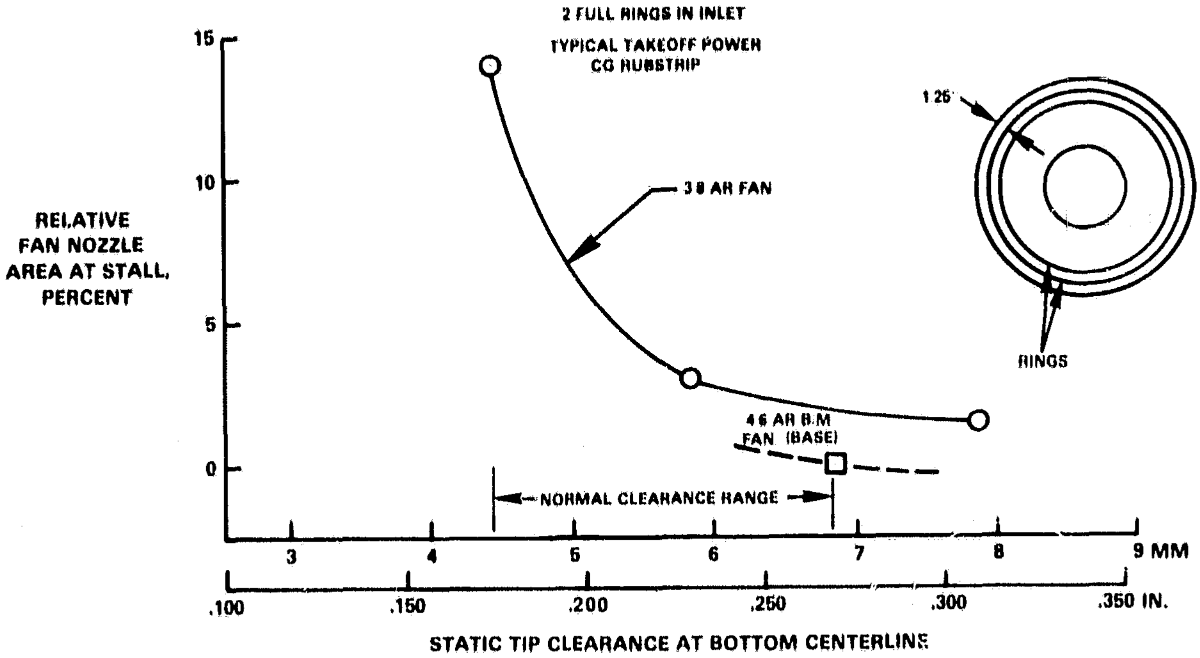

Figure 5-8 Comparison of Fan Tip Stability with Simulated Center Engine Installation. The 3.8 AR fan has more stability margin than the Bill-of-Material fan at equal tip clearances. Note the decreasing variation at higher clearances.

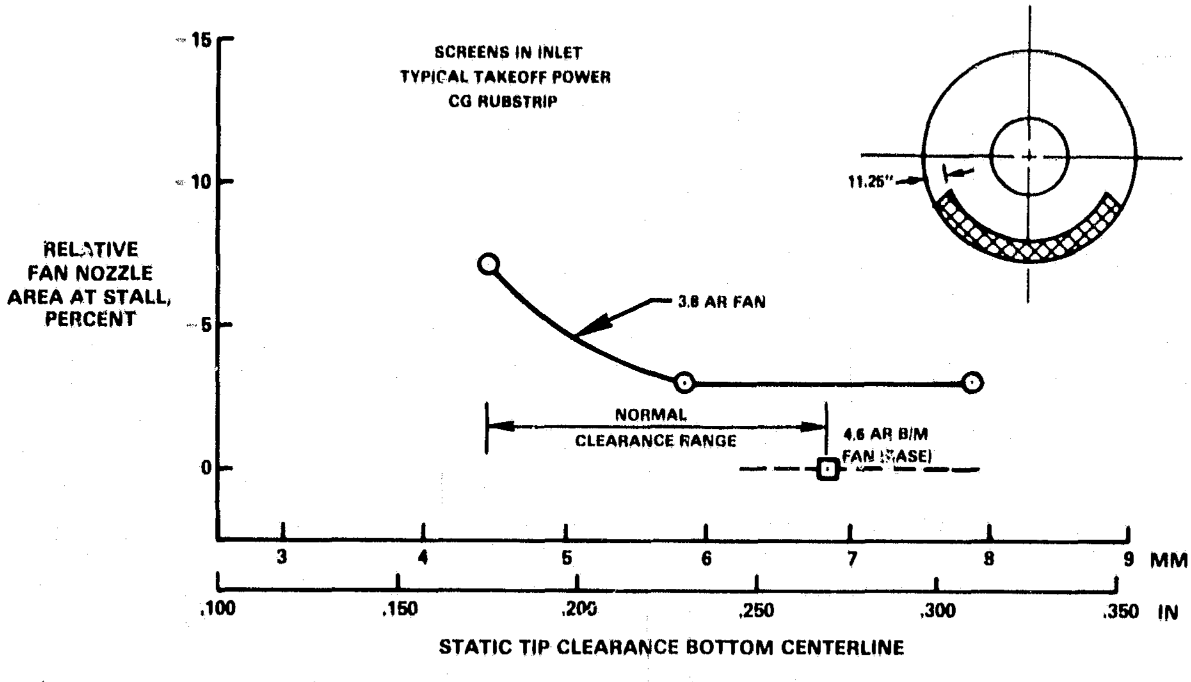

Figure 5-9 Comparison of Fan Tip Stability with Simulated Distortion due to Over-Rotation. The 3.8 AR fan has more stability margin than the Bill-of-Material fan at equal tip clearances. Note the small variation with clearance.

The above results were obtained with the circumferentially grooved (CG) rubstrip for both fans (The CG rubstrip is the configuration used in JT9D-7 Bill-of-Material engines). The 3.8 AR fan tip stall margin increased with the axially skewed groove rubstrip. Previous tests of the Bill-of-Material fan with this rubstrip have shown a similar increase.

5.4 Engine Acoustic Test

Based on the back-to-back engine acoustic test described in Section 4.4, the 3.8 AR fan has essentially the same noise level as the Bill-of-Material fan within the accuracy that noise data can be recorded and interpreted. Peak value of perceived noise level obtained in the forward and aft directions are compared for the two fans in Figures 5-10 and 5-11, respectively. A direct comparison at each rotor speed shows the 3.8 AR fan noise to be slightly lower than the Bill-of-Material fan at most rotor speeds, but the difference is too small to be significant. Note that the lower rotor speed points on these figures are corrected to a 370 ft. distance to correspond to the altitude over the FAR-36 1-mile measuring station on approach, while the higher rotor speed points are corrected to 800 feet to approximate the altitude over the 3.5 mile measuring station on takeoff. Variation in noise through the forward and aft quadrants is also similar for the two fans, as shown at two representative rotor speeds in Figures 5-12 and 5-13.

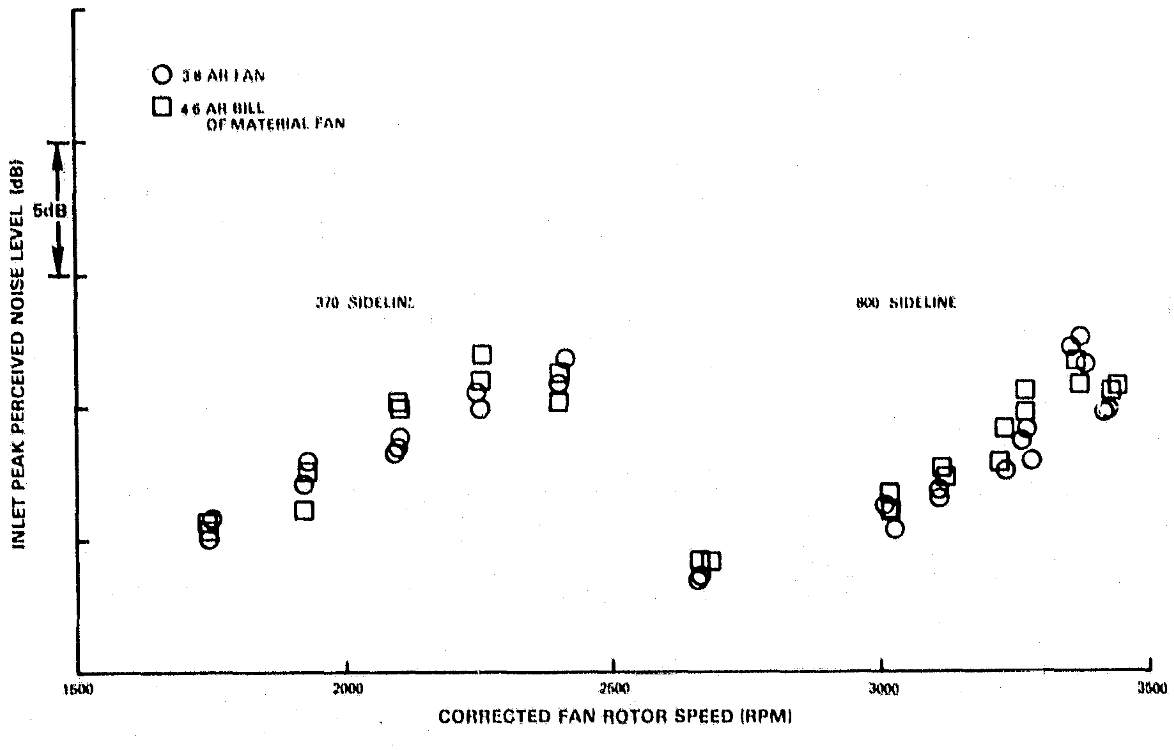

Figure 5-10 Comparison of Inlet Peak Perceived Noise Levels. Engine noise levels of both fans are approximately equal.

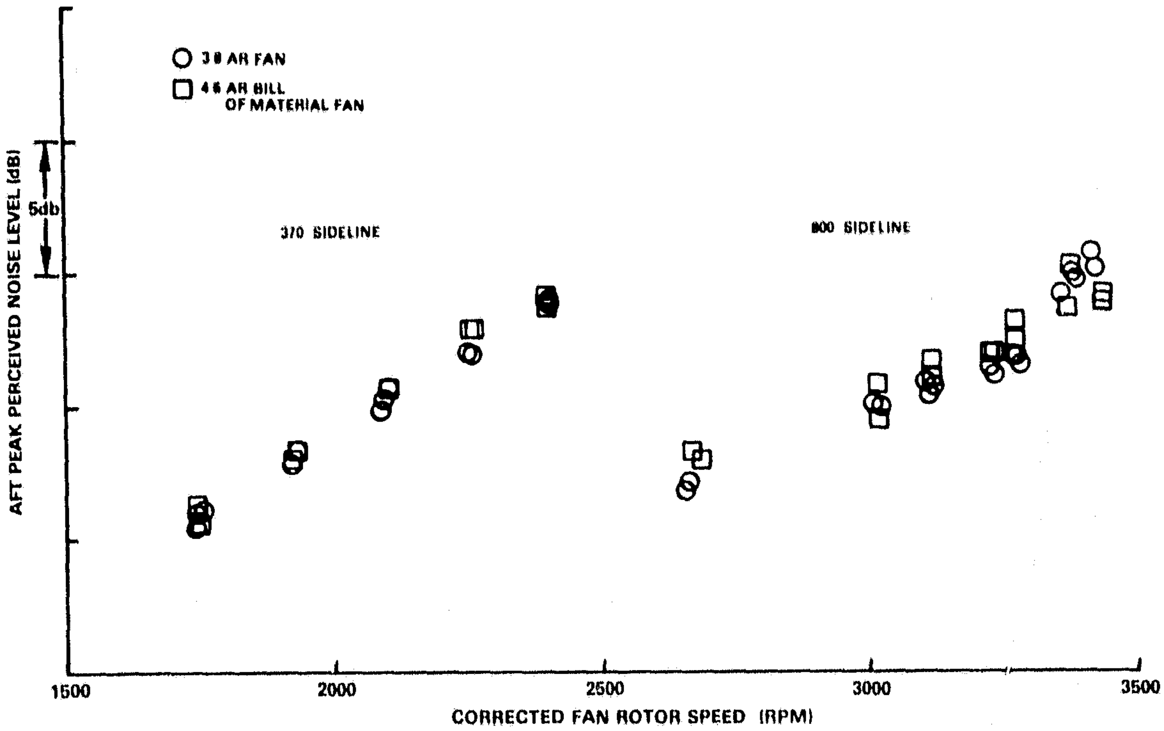

Figure 5-11 Comparison of Aft Peak Perceived Noise Levels. Engine noise levels of both fans are approximately equal.

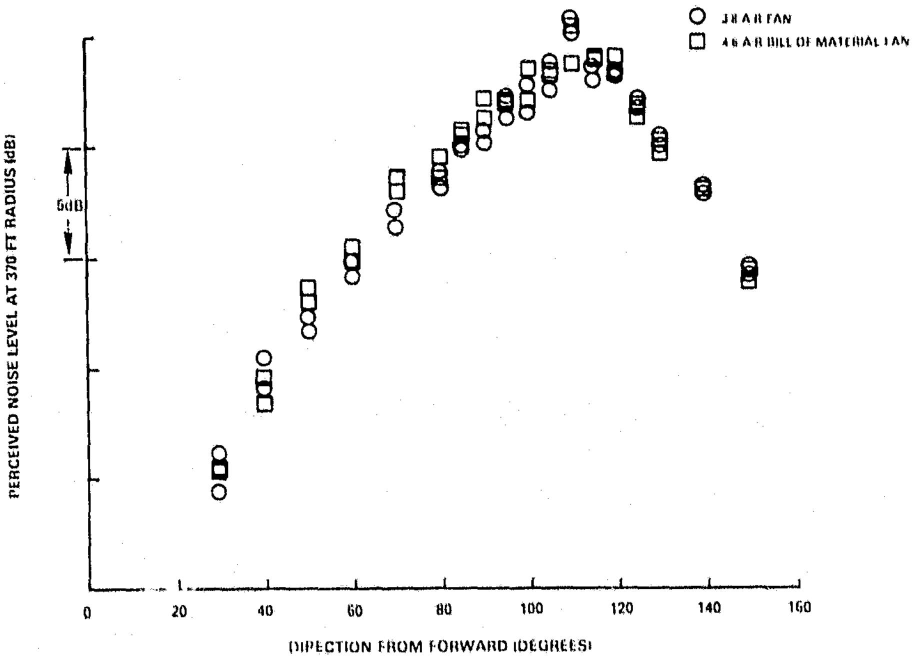

Figure 5-12 Comparison of Noise Directivity at 2400 RPM Corrected Fan Rotor Speed. Engine noise levels and directivity of both fans are approximately equal.

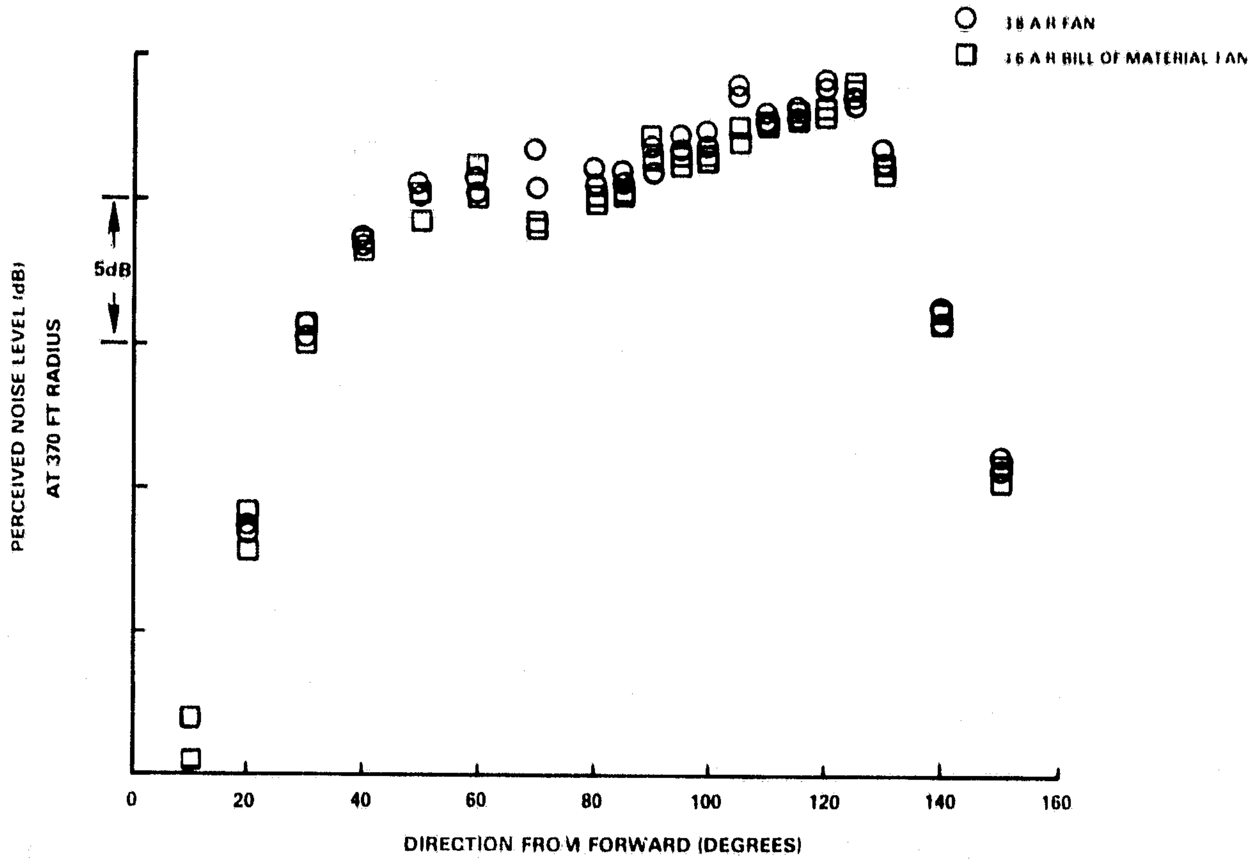

Figure 5-13 Comparison of Noise Directivity at 3400 RPM Corrected Fan Rotor Speed. Engine noise levels and directivity of both fans are approximately equal.

The above comparisons were made at equal rotor speeds because this is the most direct way to present and interpret the data, which was taken as a function of rotor speed. Similar comparisons at equal thrust levels would product the same results, since the thrust-rotor speed relationship of the two fans is essentially equal except at very high rotor speeds, as shown in Figure 5-14.

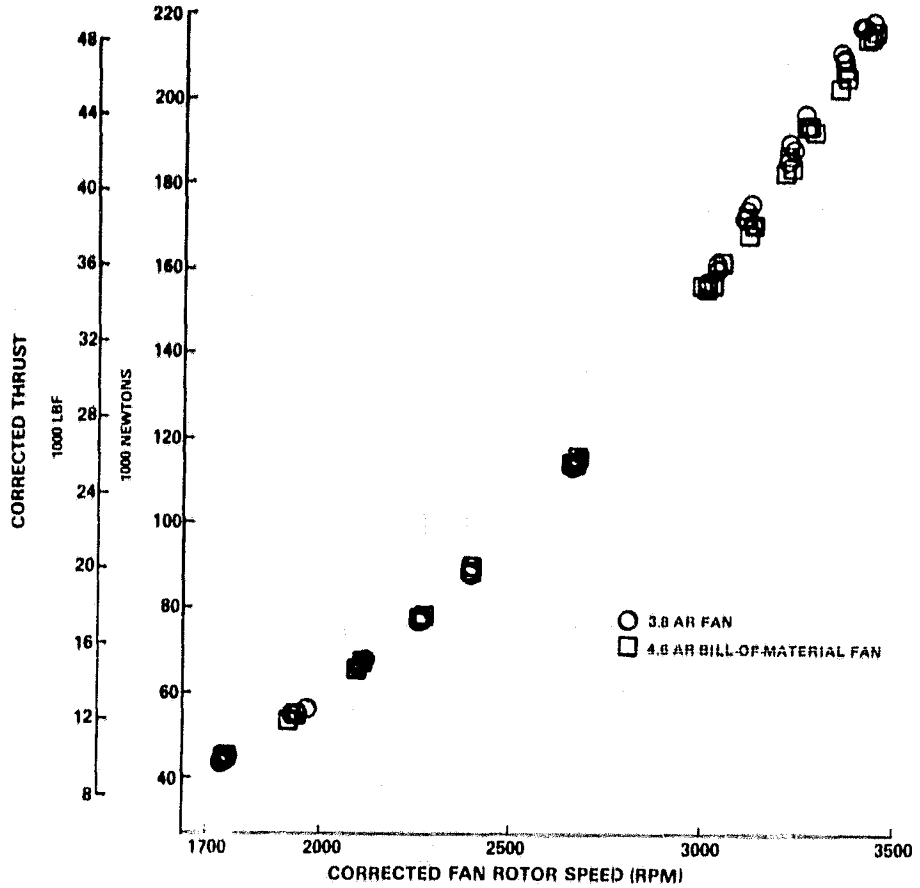

Figure 5-14 Comparison of the Engine Thrust/Fan Rotor Speed Relationship. The relationship is essentially unchanged except at very high rotor speeds, where the 3.8 AR fan gives slightly higher thrust.

6.0 ECONOMIC EVALUATION

The 3.8 AR fan concept was evaluated as part of the Engine Component Improvement - Performance Improvement Task 1 Feasibility Analysis effort (Reference 1) in 1977. Objectives of the analysis were to determine airline company acceptability and to estimate the cumulative fuel savings that would result if the 3.8 AR fan were incorporated on JT9D-7 production engines. This evaluation was based on analytical estimates of the effects of the 3.8 AR fan on engine performance, weight, and cost. These early estimates are shown in the first column of Table 6-1, 6-2 and 6-3. It was on the basis of this original evaluation that the 3.8 AR fan concept was chosen for demonstration under the ECI-PI program.

TABLE 6-1

JT9D-7 3.8 AR FAN
PREDICTED ENGINE EFFECTS (PER ENGINE)

	Original Evaluation	Revisions Based On Test Results
Thrust Specific Fuel Consumption Improvement, percent		
Takeoff	0.6	0.1
Climb	2.1	1.8
Cruise, avg.	1.3	1.3
Hold	0.6	0.2
Exhaust Gas Temperature Change, °C		
Takeoff	-3.0	-1.0
Climb	-7.0	+1.0
Weight Change, kg (lbm)	+20(45)	
Price Change, $	+25,500	
Kit Price, $ (non-attrition basis)	+300,600	
Maintenance Cost Change, $/Oper. Hr.		
Materials	+0.20	
Labor @$30 per Man-Hr.	-3.10	0
Start of Service Date	1980	

TABLE 6-2

JT9D-7 3.8 AR FAN
AIRLINE COST EVALUATION (PER 747-200 AIRPLANE)

	Original Evaluation	Revisions Based On Test Results
Total Operating Cost Change, $/Yr.	-181,120	-121,560
Required Airline Investment Change, $		
New Buy	+ 157,300	
Retrofit	+1,722,400	
Payback Period, Years		
New Buy	0.9	1.3
Retrofit	9.6	14.2
DOC Change, Percent	-0.8	-0.5

TABLE 6-3

JT9D-7 3.8 AR FAN
FUEL SAVINGS EVALUATION (WORLD FLEET
OF JT9D-7 POWERED 747 AIRPLANES)

	Original Evaluation	Revisions Based On Test Results
No. of Engines Affected		
New Buy	1050	1050
Retrofit	0	0
Total	1050	1050
Cumulative Fuel Saved, 10^6 Liters (10^6 gal)		
New Buy	2725 (720)	2650 (700)
Retrofit	0	0
Total	2725 (720)	2650 (700)
Fleet Fuel Saved, percent	1.5	1.5

The second column of Table 6-1 shows the engine performance effects that were obtained from the engine test program. The demonstrated average cruise thrust specific fuel consumption improvement of 1.3 percent was the same as the original estimate, while the improvements at other flight conditions are somewhat less than estimated. The exhaust gas temperature effects at takeoff and climb were less beneficial than originally estimated, resulting in less advantage in maintenance cost, as shown in Table 6-1.

Results of the economic evaluation are corrected in the second column of Tables 6-2 and 6-3 to reflect the demonstrated performance changes. The net effect of the thrust specific fuel consumption revisions is such a small change in fuel usage that it falls within the rounding of the percent fuel saving value, as shown on Table 6-3. This effect is small because the cruise fuel consumption, which was the same as predicted, predominates in the fuel usage calculation. The only significant effect on the economic evaluation is the maintenance labor cost revision, which accounts for most of the total operating cost revision shown on Table 6-2. This revision increases the payback periods as shown. However, the payback period increases have no effect on the acceptability of the concept, as reflected in the number of engines affected (see Table 6-3). This is due to the fact that the revised new buy payback period is still well within the acceptable limit of 6 years established in Reference 1, while the retrofit payback period was originally unacceptable and remains so with the revision. Since the total number of engines affected by the concept remains unchanged, the revised cumulative fuel saved estimate of 2650 million liters (700 million gallons) is within three percent of the original estimate, reflecting only the small revision in percent fuel saving, as discussed above.

Note that the estimates of engine weight and price effects, and the projected start of service date have not been updated, since the demonstration program provided no information on these parameters. However, a decision has been made by P&WA, independent of the demonstration program, to suspend further development of the 3.8 AR fan. A more advanced fan is being developed for the JT9D-7R4 engine which will realize the potential efficiency advantage of the single shroud fan while providing increased total airflow and allowing increased overall engine pressure ratio for higher thrust capability.

7.0 CONCLUDING REMARKS

Engine testing of the JT9D-7 3.8 AR fan demonstrated an average cruise thrust specific fuel consumption improvement of 1.3 percent relative to the Bill-of-Material fan.

Engine testing also showed the 3.8 AR fan to be equal to or better than the Bill-of-Material fan in exhaust gas temperature margins, fan and low pressure compressor stability, inlet distortion and adverse wind tolerance, in-flight operational suitability, and noise levels.

Strain gage measurements on the 3.8 AR fan system showed all stresses to be within acceptable limits, except for one location in the fan blade, which has been corrected by a minor revision of the local fillet radius.

The demonstrated cruise thrust specific fuel consumption improvement is the same as the estimate used in the ECI Feasibility Analysis evaluation of the concept. The exhaust gas temperature improvement is somewhat less than the earlier estimate, which results in revisions of the airline maintenance cost savings and payback period. However, the predicted acceptability of the concept is unchanged. The revised cumulative fuel saving estimate of 2650 million liters (700 million gallons) is within three percent of the original estimate.

A decision has been made by P&WA, independent of the demonstration program, to suspend further development of the 3.8 AR fan. A more advanced fan is being developed for the JT9D-7R4 engine which will realize the potential efficiency advantage of the single shroud fan while providing increased total airflow and allowing increased overall engine pressure ratio for higher thrust capability.

APPENDIX A

PRODUCT ASSURANCE

INTRODUCTION

The Product Assurance system provided for the establishment of quality requirements and determination of compliance with these requirements, from procurement of raw material until the completion of the experimental test. The system ensures the detection of nonconformances, their proper disposition, and effective corrective action.

Materials, parts, and assemblies were controlled and inspected to the requirements of the 3.8 AR Fan Program. A full production-type program requires inspection to the requirements indicated on the drawings and pertinent specifications. On experimental programs Engineering may delete or waive noncritical inspection requirements that are normally performed by Experimental Quality Assurance.

Parts, assemblies, components and end-item articles were inspected and tested prior to delivery to ensure compliance to all established requirements and specifications.

The results of the required inspections and tests were documented as evidence of quality. Such documents, when requested, will be made available to designated Government Representatives for on-site review.

Standard P&WA Commercial Products Division Quality Assurance Standards currently in effect and consistent with Contractual Quality Assurance Requirements were followed during execution of this task. Specific standards were applied under the contract in the following areas:

1. Purchased Parts and Experimental Machine Shop
2. Experimental Assembly
3. Experimental Test
4. Instrumentation and Equipment
5. Data
6. Records
7. Reliability, Maintainability and Safety

1. PURCHASED PARTS AND EXPERIMENTAL MACHINE SHOP

Pratt & Whitney Aircraft has the responsibility for the quality of supplier and supplier-subcontractor articles, and effected its responsibility by requiring either control at source by P&WA Vendor Quality Control or inspection after receipt at P&WA. Records of inspections and tests performed at source were maintained by the supplier as specified in P&WA Purchase Order requirements.

Quality Assurance made certain that required inspections and tests of purchased materials and parts were completed either at the supplier's plant or upon receipt at P&WA.

Receiving inspection included a check for damage in transit, identification of parts against shipping and receiving documents, drawing and specification requirements, and a check for Materials Control Laboratory release. Positive identification and control of parts was maintained pending final inspection and test results.

The parts manufactured in Pratt & Whitney Aircraft Experimental Machine Shop were subject to Experimental Construction procedures to ensure that proper methods and responsibilities for the control of various quality standards were followed.

Drawing control was maintained through an engineering drawing control system. Parts were identified with the foregoing system. Quality Assurance personnel are responsible for reviewing drawings to ensure that the proper inspection requirements are indicated.

Non-conforming experimental articles involved in this program were detected and identified by Experimental Construction, by vendors, or by Experimental Quality Assurance. Non-conforming articles were reviewed by Engineering and Experimental Quality Assurance personnel in deciding disposition. Records of these decisions, including descriptions of the non-conformances were maintained by Experimental Quality Assurance and reviewed by the cognizant Government Quality Assurance Representative.

2. EXPERIMENTAL ASSEMBLY

In Experimental Assembly engines were assembled for evaluation of engine performance, stability and noise under the program. Established Experimental Construction procedures were employed to perform the work and to ensure that proper responsibilities and methods for the control of various quality standards were followed.

3. EXPERIMENTAL TEST

The performance and stability tests were performed under Experimental Test Department procedures which cover sea level testing in X-236 stand, and flight testing in the B-52 testbed airplane. Instrumentation was provided by the Instrumentation Development Department. All equipment was monitored and controlled by Experimental Test Procedures.

The acoustic test was conducted under the experimental procedures of Rohr Industries, which conform to the requirements of the Pratt & Whitney Aircraft Experimetal Test Department.

4. INSTRUMENTATION AND EQUIPMENT

Instrumentation and equipment were controlled under the P&WA Quality Assurance Plan which includes controls on the measuring and test equipment in Experimental Test to specific procedures. All testing and measuring equipment carries a label indicating its status (controlled, monitor or calibrated) and, when applicable, the date of calibration and next due date.

The accuracy of gages and equipment used for quality inspection functions was maintained by means of a control and calibration system. The system provided for the maintenance of reference standards, procedures, records, and environmental control when necessary. Gages and tools used for measurements were calibrated utilizing the aforementioned system.

Reference standards were maintained by periodic reviews for accuracy, stability, and range. Certificates of Traceability establish the relationship of the reference standard to standards in the National Bureau of Standards (NBS). Calibration of work standards against reference standards was accomplished in environmental-controlled areas.

Initial calibration intervals for gaging and measuring equipment were established on the basis of expected usage and operating conditions. The computerized gage control system provided a weekly listing of all gages and equipment requiring calibration, highlighting overdue items.

5. DATA

Engine performance and stability data from X-236 stand was recorded on the Steady State Data System. Engine performance, stability and stress data from the B-52 flight test was recorded on the Airborne Data Acquisition System. Both of these systems are certified to procedures which specify calibration intervals for the components requiring laboratory certification. During each data acquisition, the system recorded certified reference parameters which provided an "on-line" verification that the systems were performing properly.

This "confidence" data was reviewed at the time of the run and was later analyzed to provide an overall assessment of the system operations.

The Rohr Industries data acquisition system used for recording engine performance and noise data is certified to procedures similar to the Pratt & Whitney Aircraft systems.

6. RECORDS

Quality Assurance personnel ensured that records pertaining to quality requirements were adequate and maintained as directed in Experimental Quality Assurance procedures and in accordance with contractual requirements.

Engine build and operating record books were maintained in accordance with Engineering Department requirements. In addition, a consolidated record of operating times for each rig or component test article used in the experimental program was maintained.

7. RELIABILITY, MAINTAINABILITY AND SAFETY

Standard production engine design techniques and criteria, which consider product reliability and maintainability in context with all other requirements (such as performance, weight and cost), were used in defining the parts for the 3.8 AR Fan Program. The significant stress areas of the modified parts were analyzed to ensure that their structural margins were equal to or better than those of the Bill-of-Material parts. Parts designed in this manner would be expected to have far greater reliability than necessary for the relatively short term tests conducted under the under the subject program, and no reliability problems were encountered. Strain gages, used in selected locations on the unique parts in some of the tests, verified the acceptability of the stress levels, with one minor exception. This exception was corrected by a local design modification, as described in the Results Section of this report.

The 3.8 AR fan is designed with the same maintainability features as the Bill-of-Material fan, including provisions for individual fan blade replacement with the engine installed on the airplane. However, these features were not demonstrated as part of the subject program.

The safety activities at Pratt & Whitney Aircraft are designed to fully comply with the applicable sections of the Federal Aviation Regulations, Part 33 Air Worthiness Standards: Aircraft Engines, as established by the Federal Aviation Administration.

APPENDIX B

REFERENCES

1. Gaffin, W. O. and Webb, D. E., "JT8D and JT9D Jet Engine Performance Improvement Program - Task I Feasibility Analysis - Final Report", NASA CR-159449, April 1979