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JT8D-15/17 HIGH PRESSURE TURBINE ROOT DISCHARGE BLADE PERFORMANCE IMPROVEMENT

by

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16. Abstract

The JT8D high pressure turbine blade and seal were modified, using a more efficient blade cooling system, improved airfoil aerodynamics, more effective control of secondary flows, and improved blade tip sealing. Engine testing was conducted to determine the effect of these improvements on performance.

The improvements included a two pass cooling system dicharging at the root of the blade into the rear disk rim cavity, the extension of the honeycomb seal land to cover the spoiler of the lighweight shroud, reduced blade trailing edge thickness, an extended vane platform to reduce seal cooling air mixing with the hot gaspath air, feather seals between the vane platforms, elimination of the blade shroud notch, material substitution and cooling air control in the seal support ring to improve thermal growth characteristics.

The modified turbine package demonstrated significant thrust specific fuel consumption and exhaust gas temperature improvements in sea level and altitude engine tests. Inspection of the improved blade and seal hardware after testing revealed no unusual wear or degradation.

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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 JT8D Performance Improvement effort is part of the Engine Component Improvement (ECI) Project, which is part of the NASA Aircraft Energy Efficiency (ACEE) Program. The JT8D-15/17 HPT Root Discharge Blade Program was conducted from September, 1978 through July 1980. Mr. J. A. Ziemianski and Mr. T. N. Strom of the NASA Lewis Research Center were the Project Manager and Project Engineer respectively for the contract.

This report was prepared by A. S. Janus under the direction of William O. Gaffin, Pratt & Whitney Aircraft Program Manager, and with the assistance of E. J. Sceggel and C. S. Vickery. 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-5515-138.

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1.0 SUMMARY

Under the JT8D-15/17 Root Discharge Blade program, an improved high pressure turbine for cooled-turbine models of the JT8D engine was designed and demonstrated as part of the NASA sponsored Engine Component Improvement - Performance Improvement (ECI-PI) program. This improved turbine, called the Root Discharge Blade Package, is based on a proven concept used successfully in JT9D engines.

The root discharge blade package demonstrated a thrust specific fuel consumption improvement of 1.8% at average (90% of maximum) cruise power at Mach 0.8, 9,144 m (30,000 ft) altitude, and exhaust gas temperature improvements of 18°C at takeoff and climb conditions in back to back engine testing with a Bill-of-Material high pressure turbine. Preliminary analysis during the ECI-PI feasibility studies in 1977 predicted an average cruise thrust specific fuel consumption improvement of 1.4% and exhaust gas temperature improvements of 12°C and 9°C at takeoff and climb for the concept.

These performance improvements were the result of a number of design changes relative to the Bill-of-Material high pressure turbine. A two-pass cooling system was used for the high pressure turbine blades instead of a single-pass, along with a modified blade tip sealing arrangement. These changes were combined with feather seals and extended platforms on the high pressure turbine vanes, improved control of the high pressure turbine outer air seal cooling and thermal response, and high pressure turbine aerodynamic refinements to form the Root Discharge Blade Package that was tested.

The long term performance retention of the blade tip seal configuration has been thoroughly demonstrated by engine endurance testing and controlled field service evaluation experience by a major operator of JT8D-9 engines. The durability of the complete package has been demonstrated by engine endurance and certification testing in the JT8D-217 development program. A modified version of the root discharge blade, with further aerodynamic improvements in the airfoil and other improvements throughout the engine, is under development for the JT8D-15A, 17A, and 17AR engine models. These engines are improved fuel economy versions of the current service JT8D-15, 17 and 17R models, and are scheduled for production in 1982.

Airline acceptance of the root discharge blade concept has been demonstrated by orders for the JT8D-217 and JT8D-15A, 17A, and 17AR models. Based on a recent projection of the market for these engines and conversion kits through the year 1990, the performance improvement of the root discharge blade package will result in a cumulative airline fuel saving through the year 2005 of 2.6 billion liters (685 million gallons). This saving may be compared to the estimate of 1.5 billion liters (397 million gallons) from the 1977 study.

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 still many 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 (based on a congressional request), 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.

The study resulted in the selection of two sequential concepts for the JT8D-15/17 high pressure turbine, the Revised Cooling and Outer Air Seal concept and the Root Discharge Blade Concept. At the time of the study, it was envisioned that the outer air seal portion of the first concept would be retained in the later development of the Root Discharge Blade Concept. However, the design evolution of the root discharge blade package made it necessary to alter the outer air seal configuration (as described later) and the Revised High Pressure Turbine Cooling and Outer Airseal Concept was abandoned. Because of this change, this report presents the performance of the root discharge blade package relative to the original JT8D-15/17 turbine, rather than relative to the interim concept as in the Feasibility Analysis report. The predicted performance of the Root Discharge Blade concept relative to the Bill-of-Material engine, obtained by adding the predicted effects of the two concepts, is an average cruise thrust specific fuel consumption improvement of 1.4 percent, and exhaust gas temperature improvements of 12° and 9°C at takeoff and climb.

The results of the Root Discharge Blade program are discussed herein. Section 3.0 is a description of the concept and its design evolution. Section 4.0 describes the test equipment, facilities, and procedures that were used to determine the performance improvement of the concept. Section 5.0 provides the results obtained from testing, Section 6.0 estimates the energy impact of the concept, and Section 7.0 explains what was learned and the future course of action that will be taken on the concept.

3.0 ROOT DISCHARGE BLADE DESIGN AND EVOLUTION

3.1 Design Features of the Root Discharge Blade

The objective of the Root Discharge Blade Program was to improve on the efficiency of the JT8D Bill-of-Material high pressure turbine blade design without sacrificing any of its durability. To accomplish this, a conceptual design was chosen in which the blade cooling air is discharged from the root of the blade into the high pressure turbine disk rear rim cavity, rather than into the blade tip clearance annulus as in the Bill-of-Material design. This concept had already been included in some JT9D engine models, and had proven successful.

Figure 3-1 compares the Bill-of-Material and root discharge high pressure turbine blade cooling paths. The figure shows that the Bill-of-Material blade tip sealing is limited by the outlet required to discharge the cooling air into the blade tip clearance annulus. The root discharge blade employs a two-pass cooling airflow path that discharges instead from the blade root attachment into the downstream disk rim cavity allowing the use of an outer air seal system superior to the original Bill-of-Material seal. In addition, the root discharge blade concept reduces the amount of turbine blade cooling air needed to maintain proper blade temperature because of its more efficient heat transfer characteristics.

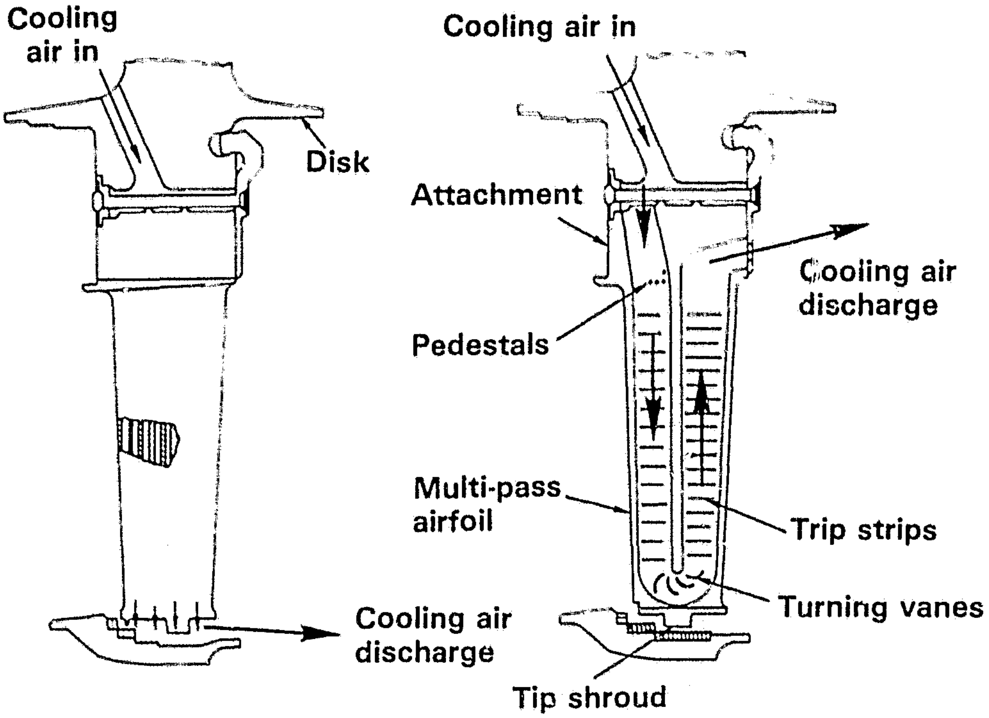

Figure 3-1 Comparison of the Bill-of-Material and Root Discharge High Pressure Turbine Blade Cooling Paths. The root discharge blade uses 40 percent less cooling air because of its more efficient cooling design. (J24342-3)

The following discussion illustrates the root discharge blade features, compared to the Bill-of-Material blade. These features are pointed out in Figure 3-1. Photographs of a complete and cutaway root discharge blade are shown in Figure 3-2. In Section 3.2, the design evolution of the root discharge blade is described.

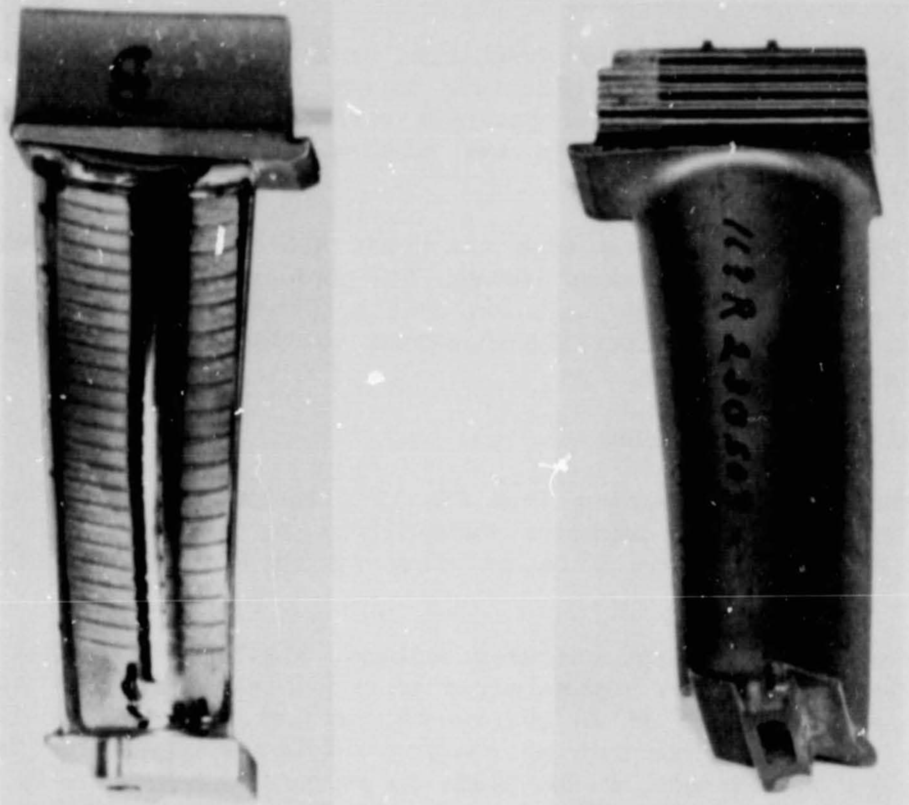

Figure 3-2 Complete and Cutaway Root Discharge Blade. The trip strips and other internal cooling features contribute to the high cooling efficiency of the blade. (80-444-0930-A, 80-441-0450-A)

3.1.1 Aerodynamic and Heat Transfer Improvements

The root discharge blade's two-pass cooling path allows cooling air to be discharged from the blade root. The design has improved heat transfer characteristics, reducing cooling air requirements by 40 percent, while maintaining or reducing blade metal temperatures relative to the Bill-of-Material design. Part of the heat transfer improvement is produced by trip strips in the cooling air flow path. The trip strips quickly trigger the transition from laminar to turbulent flow in the boundary layer along the cooling path wall. The turbulent flow regime transfers heat much more efficiently from the wall, because of turbulent mixing of the hot air from the wall with the cooler free stream air. The trip strips also provide greater surface area for higher heat transfer rates. The trip strips are located so that there are 17 in the leading edge cooling passage and 23 in the trailing edge passage. The greater number of trip strips in the trailing edge increase the heat transfer rate there to compensate for the increased cooling air temperature.

Cylindrical obstructions, or pedestals, were placed at the entrance of the cooling flow path. The pedestals direct flow along the blade leading edge, increasing the heat transfer coefficient there. Turning vanes were put in the 180° bend in the cooling air flow path to maintain proper flow distribution.

Externally, blade trailing edge thickness was reduced 0.060 cm (0.024 inches), reducing turbulence losses. The reduced trailing edge thickness was made possible by improved casting properties of the root discharge blade alloy and variable thickness coating techniques, described in the following section.

3.1.2 Material Improvements

The blade alloy was changed from PWA-1455 (B-1900) to PWA-1447 (MAR-M -247). The new alloy improves castability by reducing porosity and doubles the blade creep life relative to the Bill-of-Material blade alloy.

A combination overlay and diffused coating, PWA-270 NiCoCrAlY over PWA-273 diffused aluminide, was selected to increase sulfidation resistance of the root discharge blade 300 to 400 percent, relative to the Bill-of-Material design. The overlay coating thickness was varied as necessary across the surface of the blade to produce the optimum sulfidation resistance with minimal effect on weight and blade aerodynamics. The coating was thickest at the pressure (concave) side of the blade and the leading edge, where the greatest amount of sulfidation usually occurs. The coating was thinnest at the blade trailing edge, so that trailing edge turbulence losses would be minimized. The coating replaces the combination PWA 73/70 diffused coating used on the Bill-of-Material blades.

3.1.3 Seal Improvements

The high pressure turbine seal was also improved under the root discharge blade program. The honeycomb seal land was extended to cover the spoiler of the lightweight shroud and the knife edge was eliminated, producing a seal that has less leakage than either the Bill-of-Material knife edge seal or the double knife edge seal used in the Revised High Pressure Turbine and Outer Air Seal Program, described in reference 2. The long term performance retention of this blade tip seal configuration has been demonstrated by engine endurance testing and field service evaluation experience with the JT8D-9.

The honeycomb seal was partially filled with porous metal insulating material, which reduces heat transfer to the outer air seal. The insulation reduces the thermal gradient across the seal, minimizing thermal strain. In addition, the outer air seal was made from Hastelloy S, a more durable material that has excellent elongation properties and creep life. It also has a lower coefficient of expansion, which in conjunction with the insulated seal makes seal and rotor growth more compatible, allowing better clearance control.

Other sources of leakage in the high pressure turbine were reduced or eliminated. The shroud notch found in the Bill-of-Material blade was filled in, eliminating leakage through this path. A nickel-graphite coating was also applied to the "fir tree" blade attachments. This produces a more positive fit between the blade root attachment and the disk, and reduces leakage through this area.

Cooling flow across the seal was improved to minimize seal thermal expansion and reduce leakage. The design improvements included an extended platform on the upstream vane row to reduce seal cooling air mixing with hot gaspath flow, feather seals (Figure 3-3) between the vane platforms to reduce leakage there, and improvements to the seal cooling flow distribution. As shown in Figure 3-4, a "piston ring" is used to provide improved flow control outside the outer air seal. A single piece ring ("hammer" ring) between the high pressure turbine outer air seal and the second stage vane was also used to replace the Bill-of-Material sectioned ring, eliminating leakage that was occuring between the sections. The "W" shaped spring loads the high pressure turbine outer air seal against the hammer ring. These leakage reducing features permitted a redistribution of cooling air around the high pressure turbine outer air seal, allowing tighter and more precise control of turbine blade tip clearances.

3.1.4 Other Improvements and Advantages

To compensate for the efficency gains realized by the improvements to the high pressure turbine, the low pressure turbine vane nozzle area was reduced. The reduction was required to maintain compressor match with the root discharge blade package installed.

A dirt purge hole was added at the blade tip to avoid cooling path blockage. The dirt purge hole allows dirt to be expelled from the blade, rather than collecting in the 180° bend in the cooling path.

Despite the large number of improvements and modifications made to the high pressure turbine under this program, the root discharge blade and its outer air seal are compatible with all JT8D-11, 15, 17, and 217 engine models, with minimal modifications.

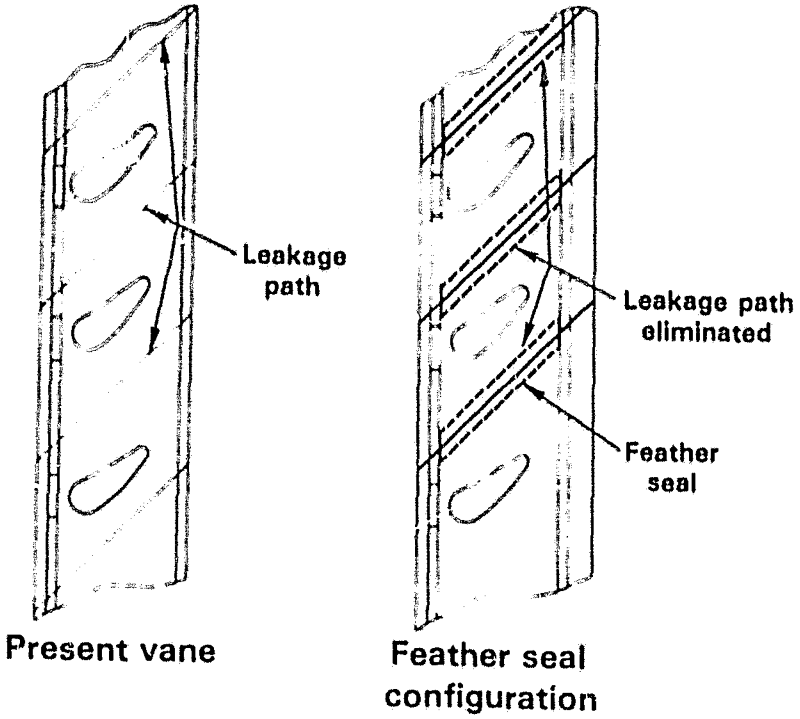

Figure 3-3 Feather Seals. The feather seals reduce leakage between the vane platforms, increasing turbine efficiency. (S-9723-21A)

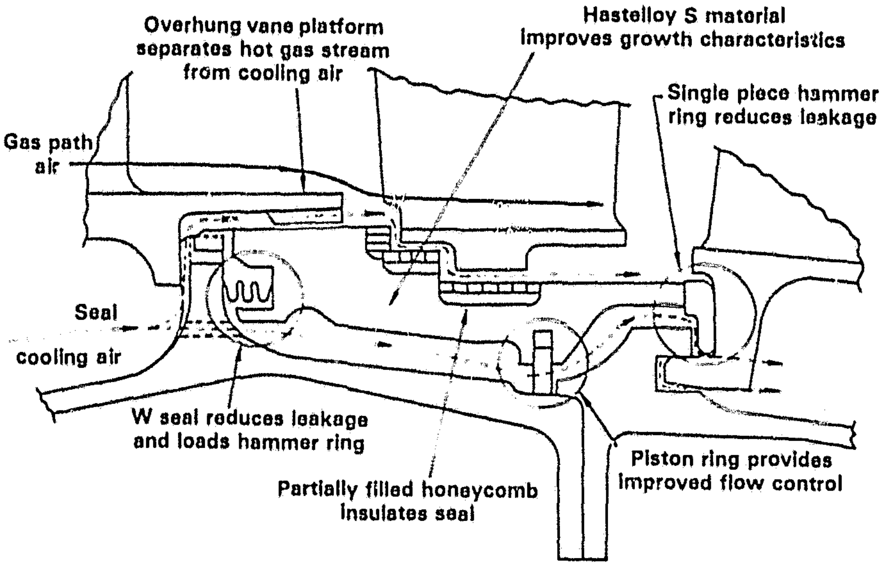

Figure 3-4 Seal Leakage Reducing Features. The leakage reducing features provide better control of cooling flow around the high pressure turbine outer air seal, allowing more precise control of blade tip clearances. (J24143-8)

3.2 Design Evolution

3.2.1 The Starting Point

A conceptual design of the root discharge blade was made as part of the Task 1 Feasibility Analysis (reference 1). This blade incorporated the basic improvements of the root discharge blade, but employed the same seal as the suction side discharge blade concept, designed under the Revised HPT Cooling and Outer Air Seal program (reference 2). This seal was an improvement over the Bill-of-Material seal because it incorporated an additional knife edge on the blade tip shroud and extended the honeycomb seal land to cover the added knife edge and the existing spoiler on the shroud. This double knife edge seal configuration was designed to reduce turbine blade tip leakage further than the single knife edge design of the Bill-of-Material blade. Sketches of the Bill-of-Material, suction side discharge and double knife edge root discharge blades are shown in Figure 3-5.

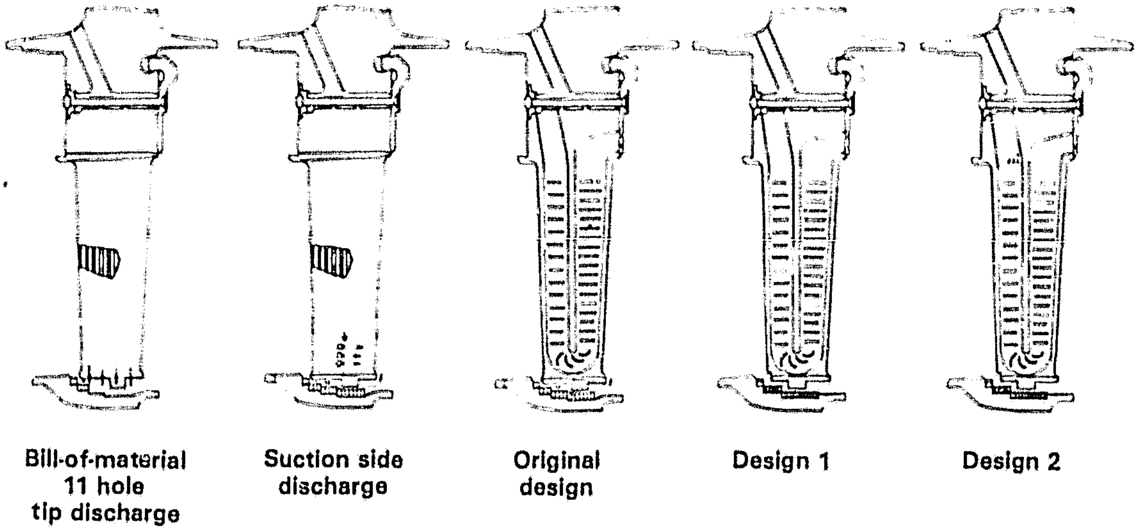

Figure 3-5 Design Evolution of the Root Discharge Blade. Each successive design iteration improved the root discharge blade. The two designs tested under the program are shown on the extreme right. (J24342-12)

3.2.2 The Root Discharge Blade "Package" (Design 1)

During the root discharge blade design effort the double knife edge seal configuration was dropped in favor of a lighter weight blade shroud design. The lighter weight blade shroud design featured lower blade stress levels, a further reduction in blade tip leakage, and long term performance retention that was demonstrated by engine endurance testing and field service evaluation by a major operator of JT8D-9 engines.

A number of other improvements were also included in the high pressure turbine in addition to the root discharge blade during this design iteration. The concept became the root discharge blade "package", because all of these design improvements were related to the redesigned root discharge blade. These improvements, mainly to the seal system and its cooling flow distribution, are described in Section 3.1.3.

This design was used in the sea level engine performance test, described in Section 4.1. To simplify terminology, the root discharge blade and outer air seal design described here will be called "design 1", and is shown in Figure 3-5.

3.2.3 Improved Durability (Design 2)

Although the root discharge blade design 1 has greater low cycle fatigue resistance than the Bill-of-Material high pressure turbine blade due to its superior material properties, it is still limited to the same life as the Bill-of-Material blade. This is because sulfidation can be a life limiting factor for both blades when subjected to the most severe environments that some airlines operate in. To further improve the durability of the root discharge blade, an overlay coating was added, blade wall thicknesses were increased, and the core was redistributed to compensate for the increased wall thicknesses. Preliminary water flow rig testing also revealed a low cooling flow area at the leading edge of the new blade design. Pedestals were added to the cooling path entrance to redirect cooling air towards the leading edge, improving the heat transfer coefficient there and reducing the possibility of thermal cracking. This blade design is shown as the last of the series in Figure 3-5, and is the design described in Section 3.1.

This design was used in the altitude engine performance test, and will be referred to as design 2. Designs 1 and 2 were intended to be aerodynamically identical, and demonstrated the same performance in back to back sea level engine performance testing (results of which are presented in Appendix A).

4.0 TEST EQUIPMENT AND PROCEDURE

4.1 Sea Level Test

The purpose of the sea level test was to assess the performance and stability of the high pressure turbine root discharge blade and its redesigned outer air seal at sea level conditions. This was done by testing Bill-of-Material high pressure turbine hardware in an experimental JT8D-17 engine to obtain baseline performance, and then replacing the Bill-of-Material hardware with the root discharge blade package and repeating the test.

4.1.1 Test Equipment and Facilities

An experimental JT8D engine (X-372) was used as the test vehicle. The engine was built to a JT8D-17 Bill-of-Material configuration, but was instrumented to a much greater degree than a production engine. A cross section of the engine is given in Figure 4-1.

The type and quantity of instrumentation installed in the engine is given in Table 4-1. This instrumentation measured rotor speeds, airflow, fuel flow, pressures and temperatures used for performance calculations and assessment.

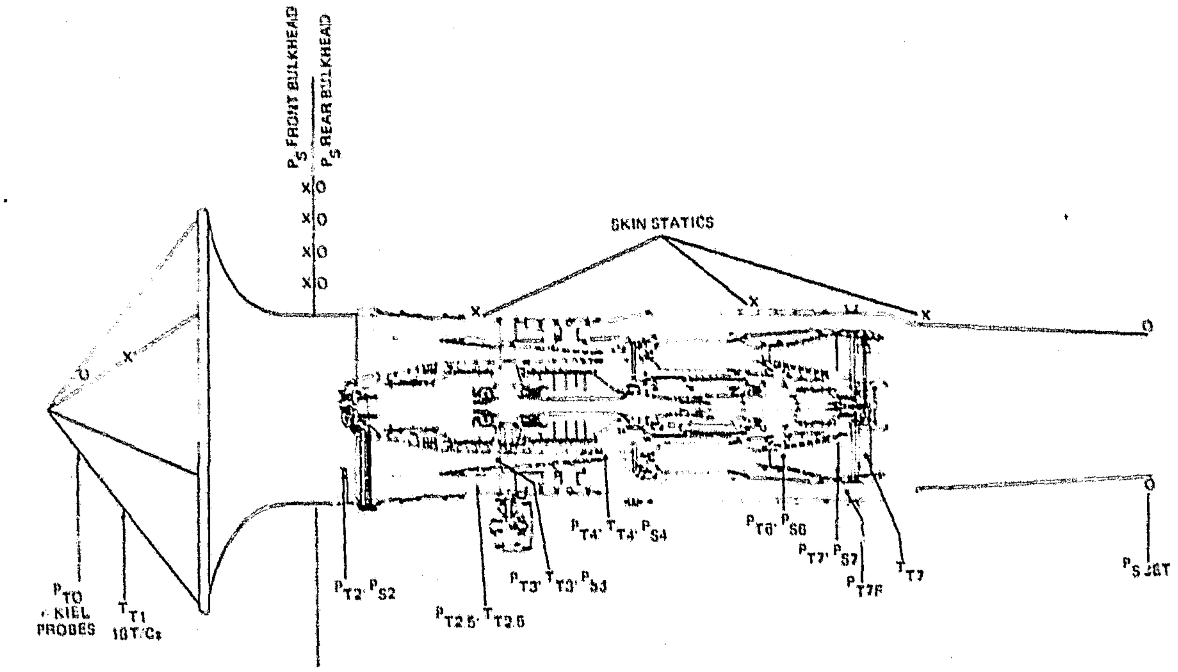

Figure 4-1 Cross Section of the Test Engine. The diagram shows the axial locations of the engine instrumentation used to calculate performance.

TABLE 4-1

CALIBRATION INSTRUMENTATION

Engine Station or Location	Parameter	Description
0.0	Bellmouth Screen Total Pressure	4 Kiel Probes
Front of Test Stand Bulkhead	Static Pressure	4 Taps (transducers)
Rear of Test Stand Bulkhead	Static Pressure	4 Taps (transducers)
1.0	Bellmouth Screen Total Temperature	12 Calibrated Thermocouples
2.0	Forward of Inlet Guide Vanes Total/Static Pressure	6 Pitot Static Probes
2.5	Fan Exit Guide Vanes Total Pressure	4 Pole Rakes With 5 Readings Per Rake
2.5	Fan Exit Guide Vanes Total Temperature	16 Individual Temp. Probes with Calibrated Thermocouples
3.0	LPC Exit Total Pressure	4 Rakes With 5 Readings Per Rake
3.0	LPC Exit Total Temperature	4 Rakes With 5 Readings Per Rake
4.0	HPC Exit Total Pressure	3 Rakes With 4 Readings Per Rake
4.0	HPC Exit Total Temperature	2 Rakes With 4 Readings Per Rake
Diffuser case	Combustor Static Pressure	1 Pressure Transducer
Diffuser case	Bleed Cavity Turbine Cooling Air Static Pressure	1 Pressure Transducer
7.0	LPT Exit Total Pressure	1 Manifolded Reading From 6 Probes With 6 Samples Per Probe

TABLE 4-1 (Cont'd)
CALIBRATION INSTRUMENTATION

Engine Station or Location	Parameter	Description
7.0	LPT Exit Total Temperature	8 Rakes With 1 Average Per Rake
7.0	Fan Exit Total Pressure	6 Individual Pressure Probes
External Edge of Tail Pipe	Static Pressure	4 Taps (transducers)
Rear of Fan Duct	Total Pressure	1 Manifolded Reading From 6 Probes With 6 Samples Per Probe
Fuel Line	Fuel Flow	2 Turbine Meters
Flow Meters	Fuel Temperature	2 Probes
Thrust Bed	Net Thrust	2 Strain Gage Load Cells
	Low Pressure Rotor Speed	1 Tachometer
	High Pressure Rotor Speed	1 Tachometer

In addition to the general instrumentation installed in the test engine to monitor performance, special temperature and pressure instrumentation was installed in the Bill-of-Material and Root Discharge Blade high pressure turbine sections, as shown in Figures 4-2 and 4-3. Instrumentation identified by numbers 1 through 8 was used to measure the temperatures and pressures of the outer air seal cooling air. Numbers 9 through 11, 31, 32, 33, 35 and 36 were used for high pressure turbine efficiency calculations. Numbers 12 through 15 were used to measure the properties of the cooling air supplied to the root discharge blade. Numbers 21 through 25 were used to record the seal response to changes in the cooling airflow and to measure absolute seal temperature levels. Numbers 32 and 33 were also used to measure the temperature and pressure of the boundary layer behind the outer air seal. Numbers 34 and 36 were used to determine the temperature and pressure of the cooling air discharged from the root discharge blade. Numbers 37 through 41 were used to measure the temperature of the case to determine if the cooling air temperature had changed significantly from the Bill-of-Material, causing thermal stresses. Tables 4-2 and 4-3 give the circumferential locations for the special instrumentation.

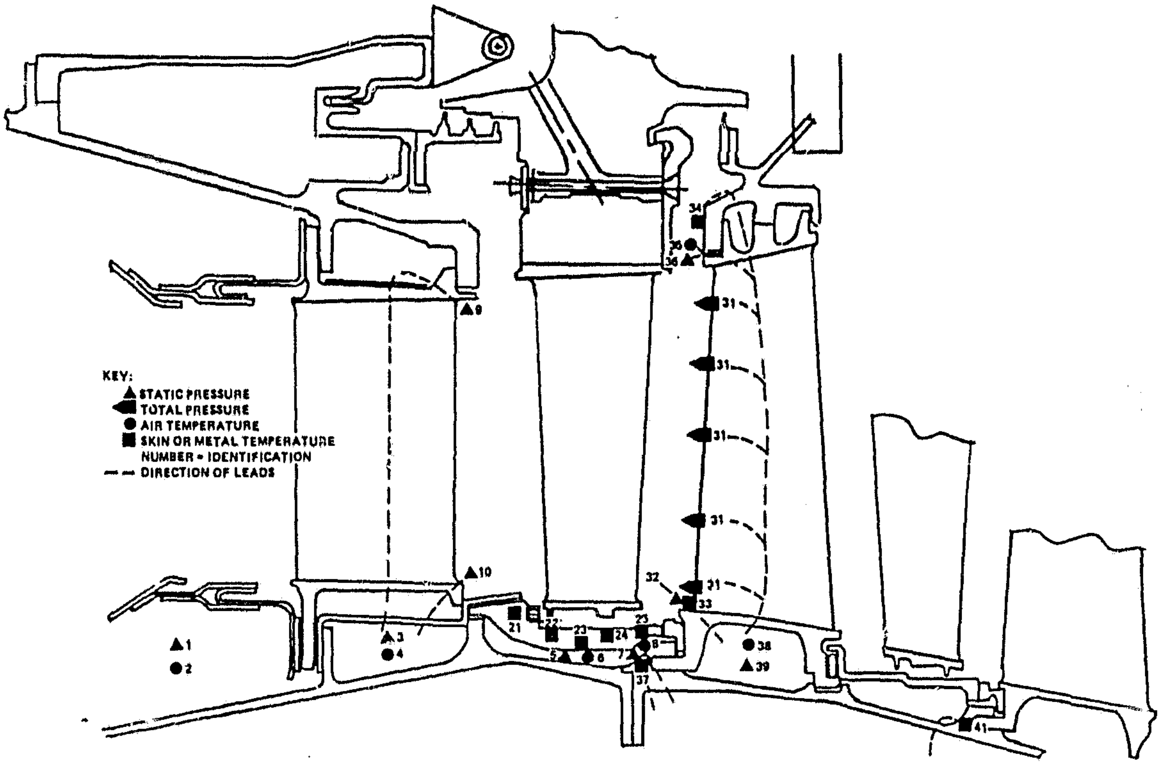

Figure 4-2 Baseline Configuration Special Temperature and Pressure Instrumentation. This instrumentation was installed in the Bill-of-Material high pressure turbine configured test engine to specifically monitor its performance.

The test facility was a sea level test stand (X-235) located in Pratt & Whitney Aircraft's Willgoos Test Facility. The stand is a gas turbine engine test facility designed to test full scale turbojet and turbofan engines, including the JT8D, at sea level static inlet and discharge pressure conditions. The test engine is supported from an overhead thrust measuring platform with a load cell and readout system capable of measuring thrust directly. Fuel flow, inlet air flow, temperatures and pressures can also be measured on the stand, allowing accurate definition of thrust specific fuel consumption. Maximum stand airflow capability is 250 kg/s (550 lbm/s). A 1.98 x 10^{14} W (52 million BTU/hr) heater is available to simulate hot day conditions up to 49°C (120°F). A photograph of the test engine mounted in the test stand is provided in Figure 4-4.

Test data is recorded automatically and processed by an on-line computer. On demand, the system can process approximately 600 parameters, and print out "quick look" calculations within three minutes on a printer located in the control room. Digital magnetic tape is also used to store data for more complete analysis later.

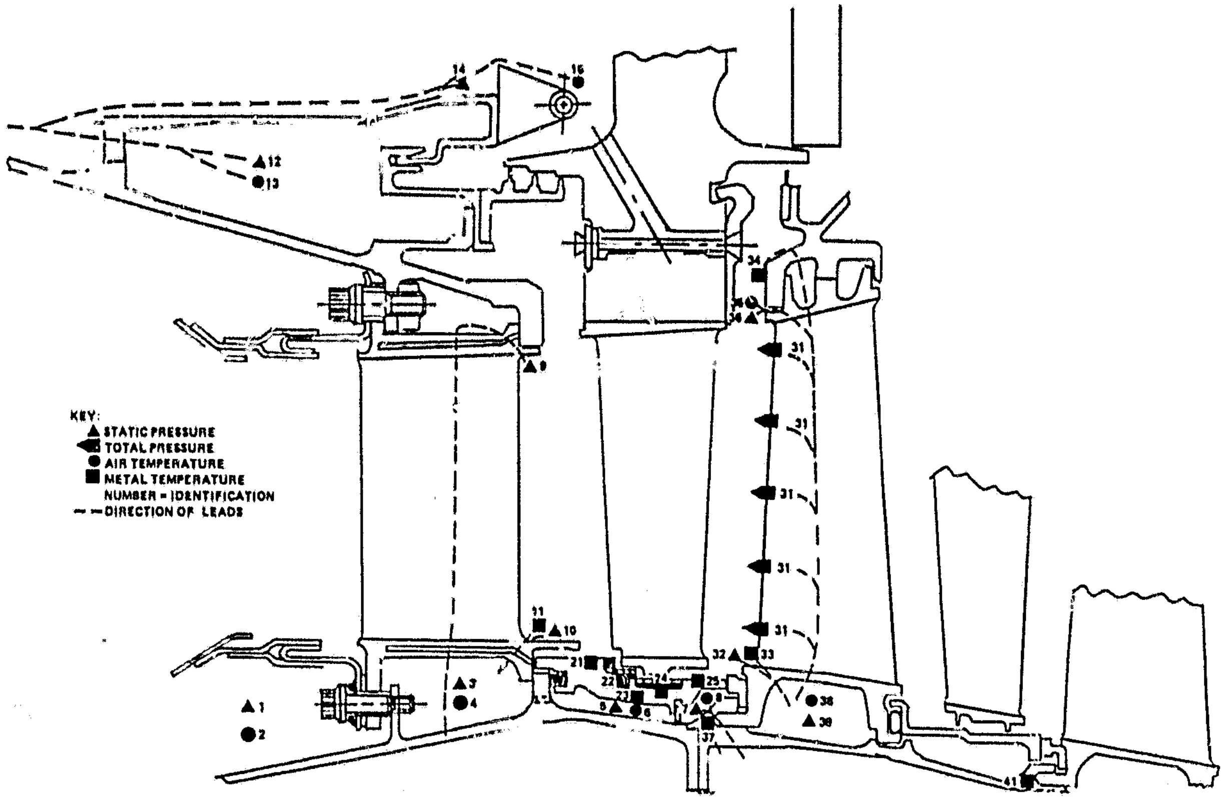

Figure 4-3 Root Discharge Blade Package Special Temperature and Pressure Instrumentation. This instrumentation was installed in the Root Discharge Blade Package configured test engine to specifically monitor its performance.

4.1.3 Test Procedure

The following general rules and specifications were used during the test program to ensure the accuracy and repeatability of the data.

- A thrust meter adjusted calibration was required prior to testing and after any remount or module change. "As is" thrust meter calibrations were taken immediately after each performance calibration (while the stand was still warm).

- The two turbine-type fuel meters were calibrated before use. Post-test "as is" calibrations were also done.

- Fuel samples were taken before and immediately after each performance calibration. The samples were tested for specific gravity and lower heating value. A fuel sample was taken during a calibration if a long shutdown was required.
- An instrumentation and data recording systems check was made at idle and at 45,000 N (10,000 lbf) observed thrust before high power performance data was acquired.
- Each performance calibration power setting was stabilized for three minutes before data was acquired, except for the first power setting of the data acquisition run, which was stabilized for five minutes. Each calibration was performed in order of decreasing power.

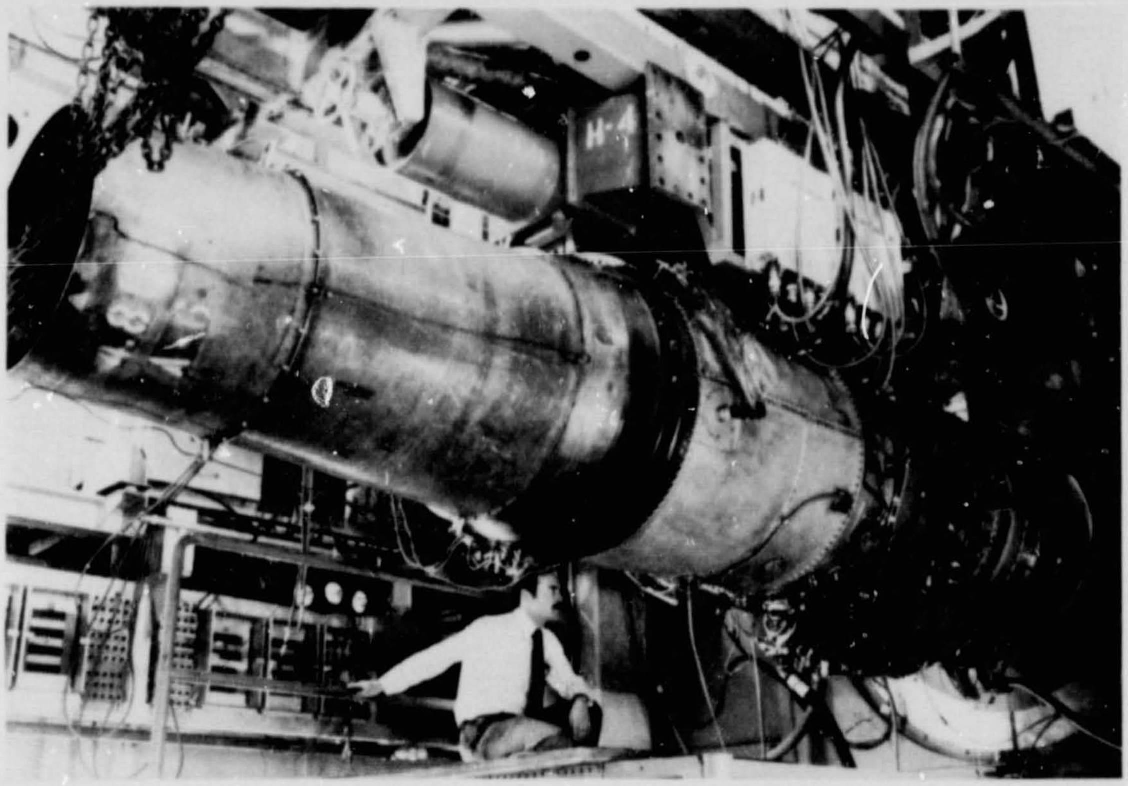

Figure 4-4 Experimental Engine Mounted in the Sea Level Test Stand (X-235). This test setup was used to generate sea level performance data. (J23929-91)

TABLE 4-2

JT9D-17 BILL-OF-MATERIAL CONFIGURATION INSTRUMENTATION CIRCUMFERENTIAL LOCATIONS

Identification Number (Figure 4-2)	Type	Circumferential Locations
High Pressure Turbine Area		
1	Static Pressure	39, 204 and 298°
2	Air Temperature	"
3	Static Pressure	"
4	Air Temperature	"
5	Static Pressure	"
6	Air Temperature	"
7	Static Pressure	"
8	Air Temperature	"
9	Static Pressure	"
10	Static Pressure	"
High Pressure Turbine Outer Air Seal Area		
21	Metal Temperature	39, 294 and 298°
22	"	"
23	"	"
24	"	"
25	"	"
Low Pressure Turbine Area		
31	Total Pressure	0, 60, 120, 180, 240, 300°
32	Static Pressure	0, 180 and 240°
33	Skin Temperature	"
34	Skin Temperature	"
35	Air Temperature	"
36	Static Pressure	"
37	Metal Temperature	0, 60, 120, 180, 240 & 300°
38	Air Temperature	39, 204 and 298°
39	Static Pressure	"
40	Air Temperature	"
41	Metal Temperature	0, 60, 120, 180, 240 & 300°

TABLE 4-3

JT8D-17 ROOT DISCHARGE BLADE CONFIGURATION INSTRUMENTATION CIRCUMFERENTIAL LOCATIONS

Identification Number (Figure 4-3)	Type	Circumferential Locations
High Pressure Turbine Area		
1	Static Pressure	39, 204 and 298°
2	Air Temperature	"
3	Static Pressure	"
4	Air Temperature	"
5	Static Pressure	"
6	Air Temperature	"
7	Static Pressure	"
8	Air Temperature	"
9	Static Pressure	0, 180 and 240°
10	Static Pressure	"
11	Skin Temperature	"
12	Static Pressure	"
13	Air Temperature	"
14	Static pressure	"
15	Air Temperature	"
High Pressure Turbine Outer Air Seal Area		
21	Metal Temperature	39, 204 and 298°
22	"	"
23	"	"
24	"	"
25	"	"
Low Pressure Turbine Area		
31	Total Pressures	0, 60, 120, 180, 240, 300°
32	Static Pressure	0, 180 and 240°
33	Skin Temperature	"
34	Skin Temperature	"
35	Air Temperature	"
36	Static Pressure	"
37	Metal Temperature	0, 60, 120, 180, 240 & 300°
38	Air Temperature	39, 204 and 298°
39	Static Pressure	"
40	Air Temperature	"
41	Metal Temperature	0, 60, 120, 180, 240 & 300°

To acquire performance data on the Root Discharge Blade Package relative to the Bill-of-Material high pressure turbine, the Bill-of-Material configured engine was installed in the test stand. A standard vibration survey was performed to ensure that the engine was balanced properly and no unacceptable vibrations would be encountered when the engine was brought up to power. A leak check was performed, and then a snap deceleration was run to wear in the engine seals.

Ten data points at 4,448 N (1000 lbf) thrust decrements from 75,619 to 35,586 N (17,000 to 8000 lbf) were taken, observing all engine operating limits (8800 RPM low pressure rotor speed, 12,600 RPM high pressure rotor speed, 650°C (1202°F) exhaust gas temperature, and 1.8 x 10^6 Pa (266 psig) burner pressure). The engine was then shut down and a fuel sample was taken, along with an "as is" thrust meter calibration. The data acquisition, fuel sample and thrust meter calibration were then repeated as an additional assurance of accuracy.

Following this second data acquisition, the Bill-of-Material hardware was replaced with the root discharge blade package and the entire test procedure repeated.

Stability margin was also evaluated during the sea level test. Stability margin was determined by using engine transient rematch characteristics during snap accelerations to force the match point of the high pressure compressor into the surge region. A special fuel control was used for the test to allow abnormally fast accelerations. The transient relationship between fuel flow/burner pressure ratio and high pressure rotor speed was recorded during the accelerations from various initial power settings.

4.2 Altitude Test

The purpose of the JT8D-17 High Pressure Turbine Root Discharge Blade altitude test was to assess the performance of the root discharge blade package under realistic flight conditions. This was done by testing the root discharge blade package in an experimental JT8D-17 engine, and then replacing the root discharge blade package with Bill-of-Material hardware and repeating the test to obtain baseline performance. The same experimental test engine (X-372) was used as in the sea level test.

4.2.1 Test Facilities and Equipment

Experimental engine instrumentation was unchanged from the sea level test, and is described in Table 4-1. Special root discharge temperature and pressure instrumentation available from the previous sea level test was still in the test engine. However, this instrumentation was not monitored for the altitude test.

The test facility was an altitude test stand located in Pratt & Whitney Aircraft's Willgoos Test Facility (X-209). The stand is designed for testing of full scale turbojet and turbofan engines, including the JT8D-15/17 model used to test the root discharge blade concept, at realistic flight conditions.

The stand is an enclosed test cell, containing an altitude chamber equipped with a moveable thrust measurement platform. The engine inlet is sealed to an inlet chamber, and the engine exhaust is ejected through a duct exiting through the opposite end of the chamber. Air required to operate the test engine can be drawn directly from the atmosphere, throttled to a lower pressure, or supplied under pressure from the laboratory air compressor units. In addition, inlet air can be cooled to as low as -48°C (-55°F) by passing the air through the laboratory air refrigeration system, or heated to as high as 329°C (625°F) by passing the air through air heater units located adjacent to the test cell. Engine exhaust gas can be discharged directly to the atmosphere or to the laboratory exhauster units. Use of the exhauster units allows control of the pressure at the engine exhaust and within the test chamber, simulating operation of the engine over a wide range of altitudes. Through controlled use of the laboratory compressors, air heaters and refrigeration systems, in coordination with the exhauster units, altitude and flight speed conditions were reproduced so that the performance of the test engine could be determined accurately under realistic flight conditions. A photograph of the engine being mounted in the test chamber is shown in Figure 4-5.

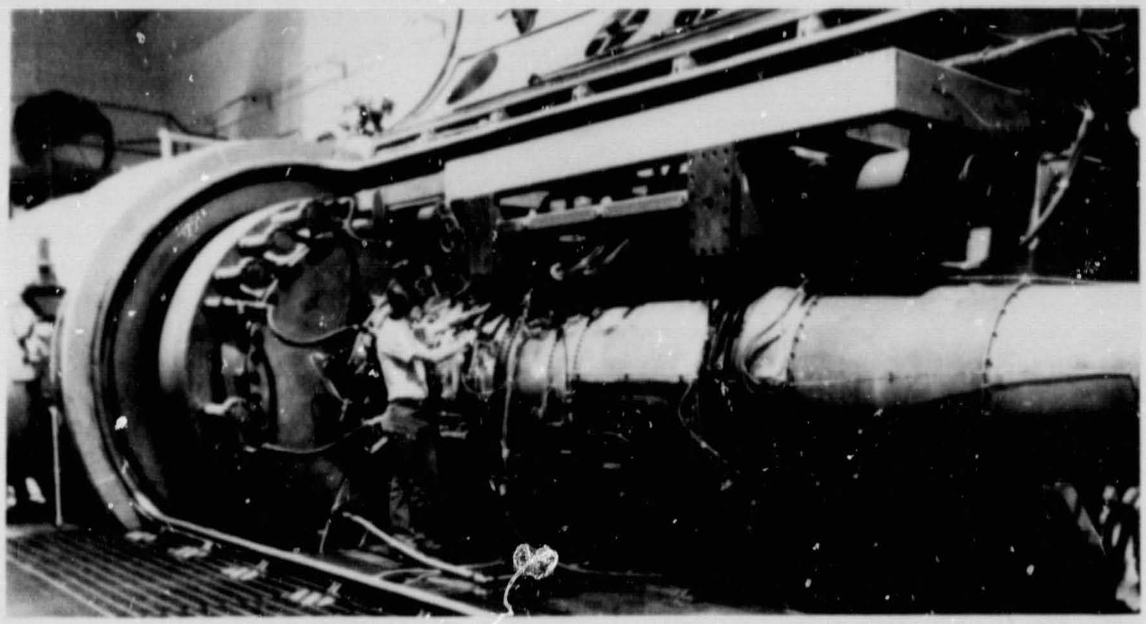

Figure 4-5 Experimental Engine Being Mounted in the Altitude Test Stand (X-209). The engine is enclosed in a sealed test chamber designed to reproduce almost any altitude and flight speed condition it may operate at. This permits the performance of the test engine to be determined accurately under realistic flight conditions. (J23929-90)

The thrust measurement system consisted of a strain gage load cell and a flexure mounted thrust platform. The system is designed to measure thrust up to 111,205 N (25,000 lbf). A load cell rated at 44,482 N (10,000 lbf) was used for this test since the thrust of the engine at altitude is reduced from full sea level ratings. As in the sea level test, data was acquired and reduced by computer.

4.2.2 Test Procedure

Before the engine assembly and test, checks were made on the various engine components, including the root discharge blade. Flow tests of the individual design 2 root discharge blades and the rotor/blade assembly indicated higher cooling air flows than the design values by 15%. To reduce the modified root discharge blade flow to the value measured in the design 1 root discharge blade, two of the sixteen tangential on board injection (TOBI) nozzles were plugged, as shown in Figure 4-6. The TOBI nozzles supply cooling air to the turbine blades. The amount of cooling flow to be blocked off was determined by analytical means. Cooling air supply pressure measured during the engine test verified that this change reduced the cooling air flow to the design value.

The test engine was mounted in a sea level test stand (X-235) to calibrate the engine and ensure that its performance still correlated with the results obtained in the earlier sea level test. Following this calibration, the engine was installed in the altitude test stand. A preliminary test was run at 4,572 m (15,000 ft), 0 Mach number conditions in the altitude stand to correlate performance to the sea level test. Finally, the cruise performance test was run at 9144 m (30,000 ft), 0.8 Mach number conditions.

General rules and specifications used to ensure the accuracy and repeatability of the data are listed below.

- The cold exit area of the tailpipe was measured immediately prior to the test. Ambient temperature was also noted during the measurement.

- A thrust meter adjustment calibration was done before testing and after any remount or module change. "As is" thrust meter calibrations were taken immediately after each performance calibration (while the stand was still warm). A calibration adjustment was required whenever an "as is" calibration was out of limits ± 53 N (±12 lbf) average, ± 53 N hysteresis.

- Thrust meters had to agree within 44 N (10 lbf) during data sampling, and test point thrust variations within the data point sample were re-run if the thrust varied by more than 89 N (20 lbf).

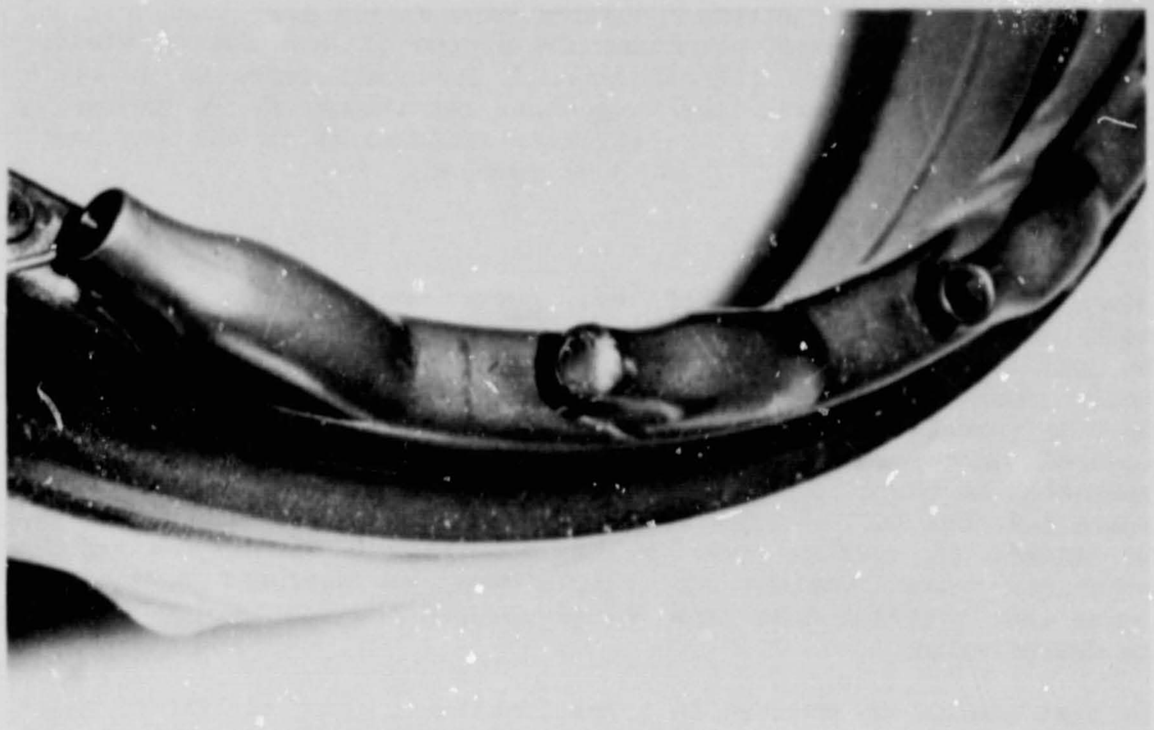

Figure 4-6 Plugged Tangential On Board Injection (TOBI) Nozzles. Two of the sixteen TOBI nozzles were plugged to provide the proper cooling flow through the root discharge blades. The blades and nozzles will be properly matched in the production engines. (80-444-0436-B)

- Fuel samples were taken before and immediately after each performance calibration. The samples were analyzed for specific gravity, lower heating value, and viscosity. A fuel sample was taken during a calibration if a long shut down was required.
- A check was made at idle and at around 6500 rpm observed low pressure rotor speed to check instrumentation and data recording systems before acquiring high power performance data.
- Each performance calibration power setting was stabilized for seven minutes before the acquisition of data.
- A calibration was not conducted when critical instrumentation was inoperative.
- The two fuel meters used in the sea level calibration were also used in the altitude test. These meters were calibrated before and after testing. Agreement of ±0.1 percent

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fuel flow and ± 0.27°C (± 0.5°F) fuel temperature was required between the two calibrations.

- Each performance data acquisition was performed in a sequence of decreasing power.

- Venturies were choked (the ratio of venturi total pressure to plenum total pressure was greater than 1.2) for each data point.

After mounting and before testing began, a corrected thrust meter calibration was performed over a range from -13,345 to +53,378 N (-3000 to +12000 lbf). An idle leak check was made for a time period of about 20 minutes, which also served to clear old fuel from the lines. An instrumentation check was performed at 6500 rpm low pressure rotor speed, the engine shut down, and instrumentation and leaks were repaired as necessary.

Performance data was taken in a decreasing power sequence, defined by setting low pressure rotor speed. The initial test sequence with the root discharge blade package, shown on Table 4-5, covered the range from 2.5% above maximum rated power to ground idle at both flight conditions. Each test was later repeated at rotor speeds interspersed between the initial points, as shown in the "Repeat" columns of Table 4-5.

TABLE 4-5

JT8D-17 CALIBRATION DATA POINTS
ROOT DISCHARGE BLADE HIGH PRESSURE TURBINE PACKAGE

Altitude, m (ft)	4,572 m (15,000)		9,144 m (30,000)	
Mach No.	0		0.8	
Inlet Temp. °C	-14.1 ± 2.7		-15 ± 2.7	
Inlet Pressure mm Hga	428.90		344.01	
Ejector Press. mm Hga	428.90		225.67	
Test Run	Initial	Repeat	Initial	Repeat
Low Pressure Rotor Speed Sequence, RPM:	8430		8350	
		9140		8200
	7860		7990	
		7580		7660
	7340		7340	
		7100		7040
	6950		6760	
		6750		6470
	6530		6180	
		6250		5890
	5775		5695	
		5300		5345
	4545		5130	
		4025		4920
	3410		4670	
				4450

The initial test sequence with the Bill-of-Material high pressure turbine, shown on Table 4-6, covered the range from 2.5% above maximum rated power to 28% of maximum cruise power. The test at each flight condition was later repeated with the rotor speed interspersed as with the root discharge blade package test.

TABLE 4-6

JT8D-17 CALIBRATION DATA POINTS
BILL-OF-MATERIAL HIGH PRESSURE TURBINE

Altitude, m (ft)	4,572 m (15,000)		9,144 m (30,000)	
Mach No.	0		0.8	
Inlet Temp. °C	-14.1 ± 2.7		-15 ± 2.7	
Inlet Pressure mm Hga	428.90		344.01	
Ejector Press. mm Hga	428.90		225.67	
Test Run	Initial	Repeat	Initial	Repeat
Low Pressure Rotor Speed Sequence, RPM:	8320		8230	
		8038		8080
	7770		7870	
		7500		7570
	7280		7290	
		7070		7000
	6910		6720	
		6720		6440
	6500		6150	
		6200		5870

5.0 TEST RESULTS

Summary of Results

The root discharge blade package exceeded all Feasibility Analysis predicted performance estimates (reference 1). At 90 percent of maximum cruise power thrust specific fuel consumption improved 1.8 percent relative to the Bill-of-Material blade, compared to the predicted improvement of the concept of 1.44 percent. At 80 percent maximum cruise power the thrust specific fuel consumption improvement was even better, reaching 2.4 percent.

Exhaust gas temperature decreased 18°C (33°F) at sea level takeoff conditions, improving upon the predicted temperature reduction by 6°C (11°F), as shown in Table 5-1. The stability margin of the engine was unchanged, and the acceleration time of the engine from idle to sea level takeoff showed a small improvement. The predicted and actual performance improvement of the concept is summarized in Table 5-1. Note that the demonstrated thrust specific fuel consumption improvement is significantly better than predicted at typical cruise (90 percent maximum cruise) conditions, and that the difference is even more favorable at takeoff, climb, and hold (40 percent maximum cruise) conditions. The demonstrated thrust specific fuel consumption improvements, when evaluated in the typical airline route structure defined in Reference 1, results in an estimated fleet fuel saving of 1.8%. For comparison, the predicted thrust specific fuel consumption values resulted in an estimated fleet fuel saving of only 1.15%.

TABLE 5-1

ROOT DISCHARGE BLADE PACKAGE PERFORMANCE IMPROVEMENT RELATIVE TO THE BILL-OF-MATERIAL HIGH PRESSURE TURBINE

Altitude, m (ft)	Mach Number	Power Level	Thrust Specific Fuel Consumption Improvement, %		Exhaust Gas Temperature Improvement, °C (°F)	
			Predicted	Demonstrated	Predicted	Demonstrated
Sea Level	0	Takeoff	0.58	1.9	12 (22)	18 (33)
7,925 (26,000)	0.7	Max. Climb	0.66	1.4	9 (16)	18 (33)
9,144 (30,000)	0.8	80% Max. Cruise	-	2.4		
9,144 (30,000)	0.8	90% Max. Cruise	1.44	1.8		
3,050 (10,000)	0.45	40% Max. Cruise	0	2.5		

5.1 Sea Level Test Results

Performance Improvement

The root discharge blade package produced significant performance improvements at sea level static conditions, relative to the Bill-of-Material high pressure turbine. A plot of the thrust specific fuel consumption improvement is given in Figure 5-1, and the exhaust gas temperature improvement is shown in Figure 5-2. The performance figures shown are corrected to standard day conditions.

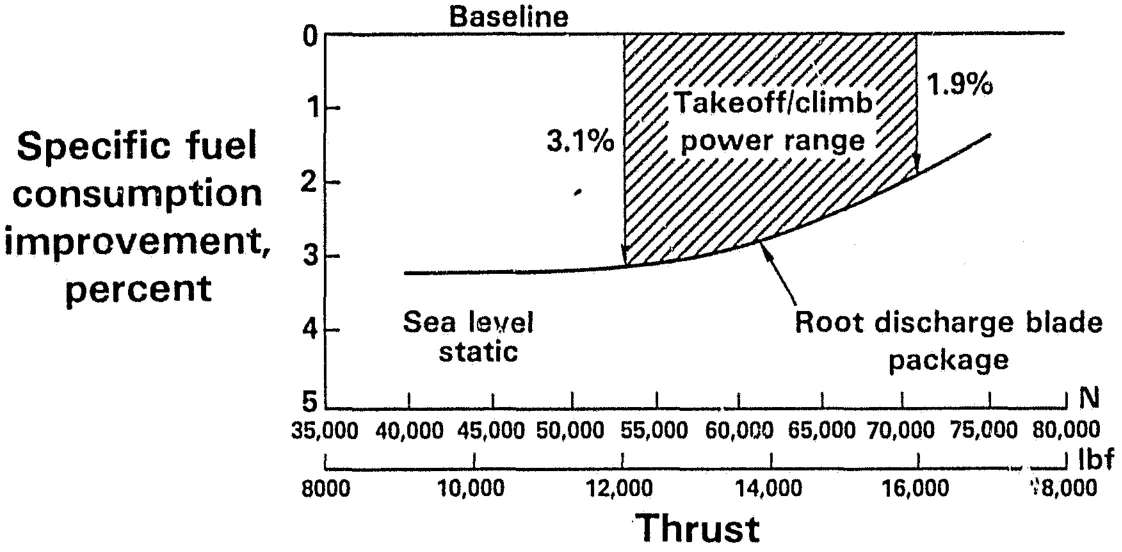


Figure 5-1 Sea Level Exhaust Gas Temperature Improvement. The data was taken at sea level static conditions. (J24143-13)

Stability and Operational Characteristics

The low power surge margin of the root discharge blade package equipped engine was essentially unchanged from that of the Bill-of-Material high pressure turbine engine, as shown in Figure 5-3. Low power surge margin was evaluated by using engine transient rematch characteristics during snap accelerations to force the match point of the high pressure compressor into the surge region. A special fuel control was used for this test to allow abnormally fast accelerations. The transient relationship between fuel flow ratio (fuel flow/burner pressure) and high pressure rotor speed was recorded during accelerations from various initial power settings. The results are presented in terms of the increase in acceleration fuel flow that the engine can tolerate relative to the normal fuel control limit. The differences between the lowest point of each curve shown on Figure 5-3 are within instrumentation accuracy, indicating that engine surge margin was not affected significantly by the root discharge blade package.

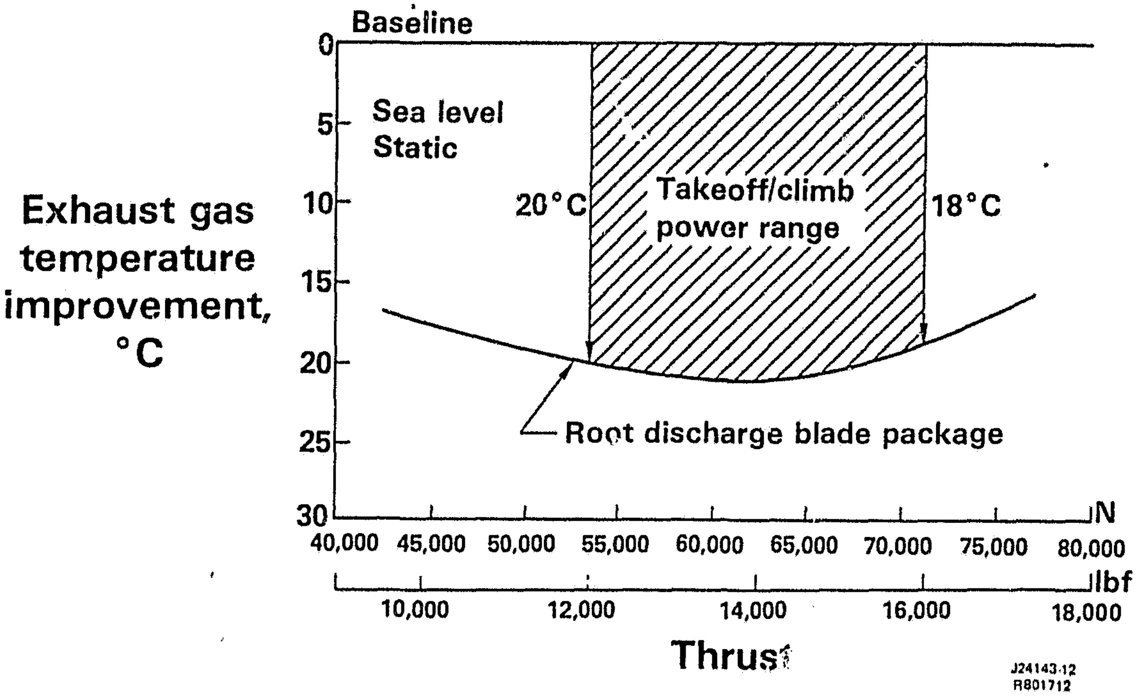


Figure 5-2 Sea Level Thrust Specific Fuel Consumption Improvement. The data was taken at sea level static conditions. (J24143 -12)

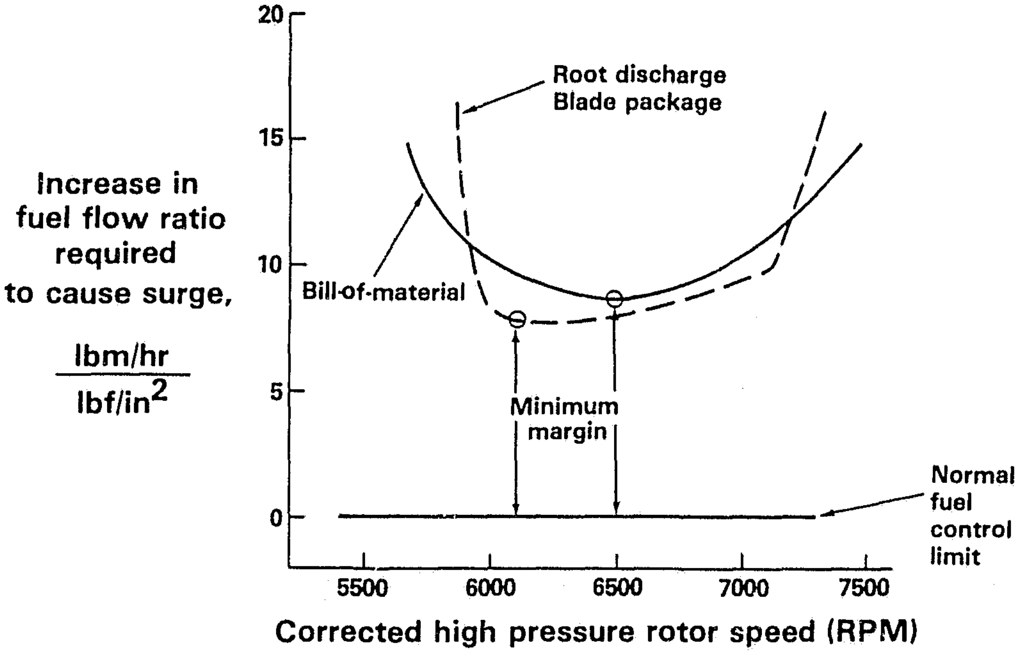


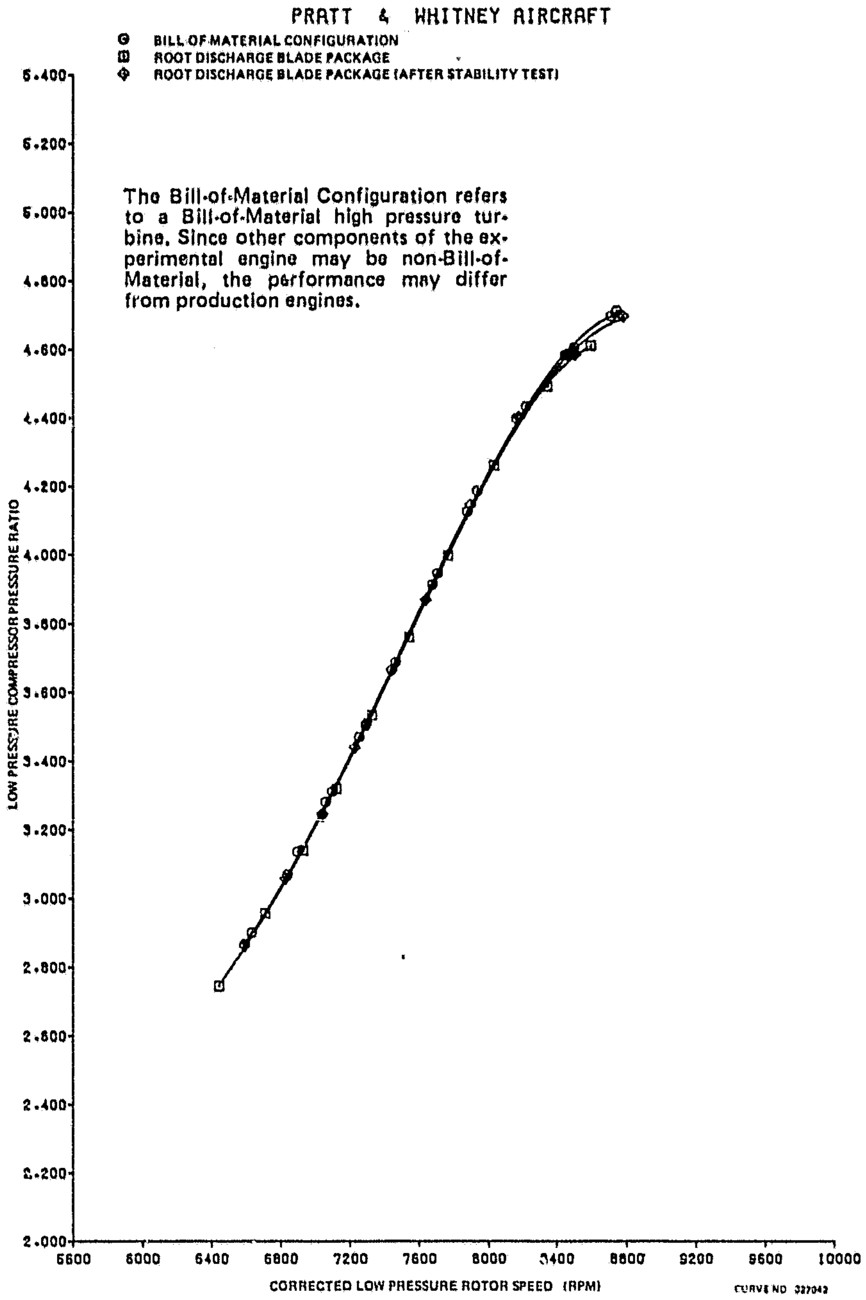
Figure 5-3 Surge Margin. Response of the engine to abnormally fast accelerations was essentially unchanged, indicating the margin of the Bill-of-Material high pressure turbine equipped engine had been maintained. The differences between the two curves are within instrumentation accuracy. (J24342-11)

The turbine nozzle vane area change compensated for the effect of the efficiency increase of the root discharge blade package, because the low and high pressure compressor operating lines showed essentially no change, as shown in Figures 5-4 and 5-5. This is consistant with the results of the sea level stability test which indicated that the surge margin of the engine tested with the root discharge blade package was equal to that of the Bill-of-Material high pressure turbine configured engine. If the operating line had shifted, a significant change in surge margin would have been observed.

Engine pressure ratio versus thrust was unaffected, as shown in Figure 5-6. This is important because engine pressure ratio is the parameter used by airlines to set thrust levels. If the curve shifted, new thrust scheduling procedures would have to be implemented. However, a shift in the engine pressure ratio versus thrust relationship was not anticipated, and the test results of the root discharge blade package support this prediction within measurement accuracy.

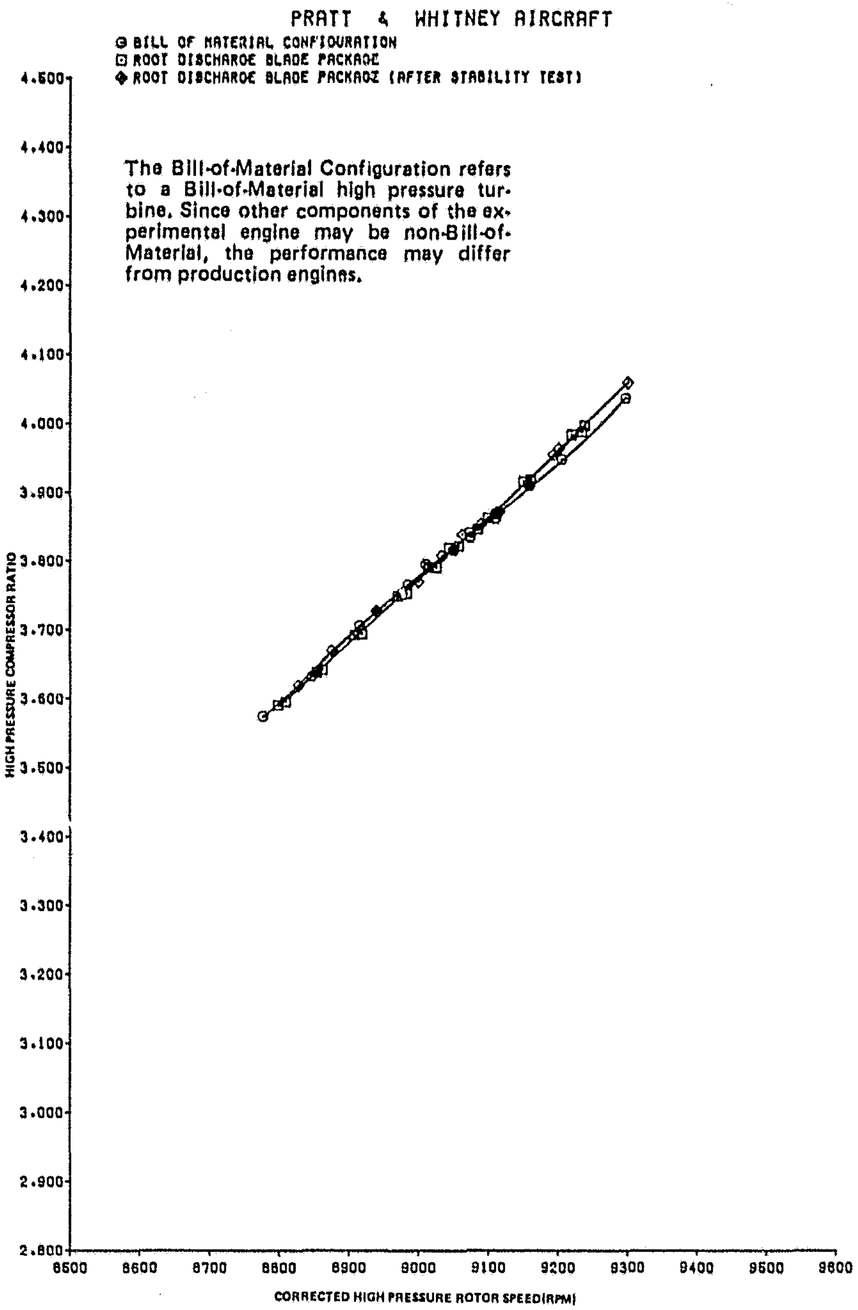
A small reduction in the time required for the engine to accelerate from ground idle thrust was noted with the root discharge blade package. This change results from the turbine efficiency increase which makes more turbine power available for rotor acceleration.

Low pressure rotor speed increased especially at the higher thrust levels, as shown in Figure 5-7. This is a result of the substantial exhaust gas temperature reduction, which demands increased total airflow through the engine to satisfy nozzle choking requirements. The low pressure rotor speed must increase to enable the fan to meet this demand for more airflow. A new fan inlet case with increased flow capacity has been designed and tested as part of a total performance improvement package for JT8D-15/17/17R engine models, as described in Section 6, "Energy Impact". The new inlet case corrects the low pressure rotor speed increase and provides further exhaust gas temperature and fuel consumption improvements as well.



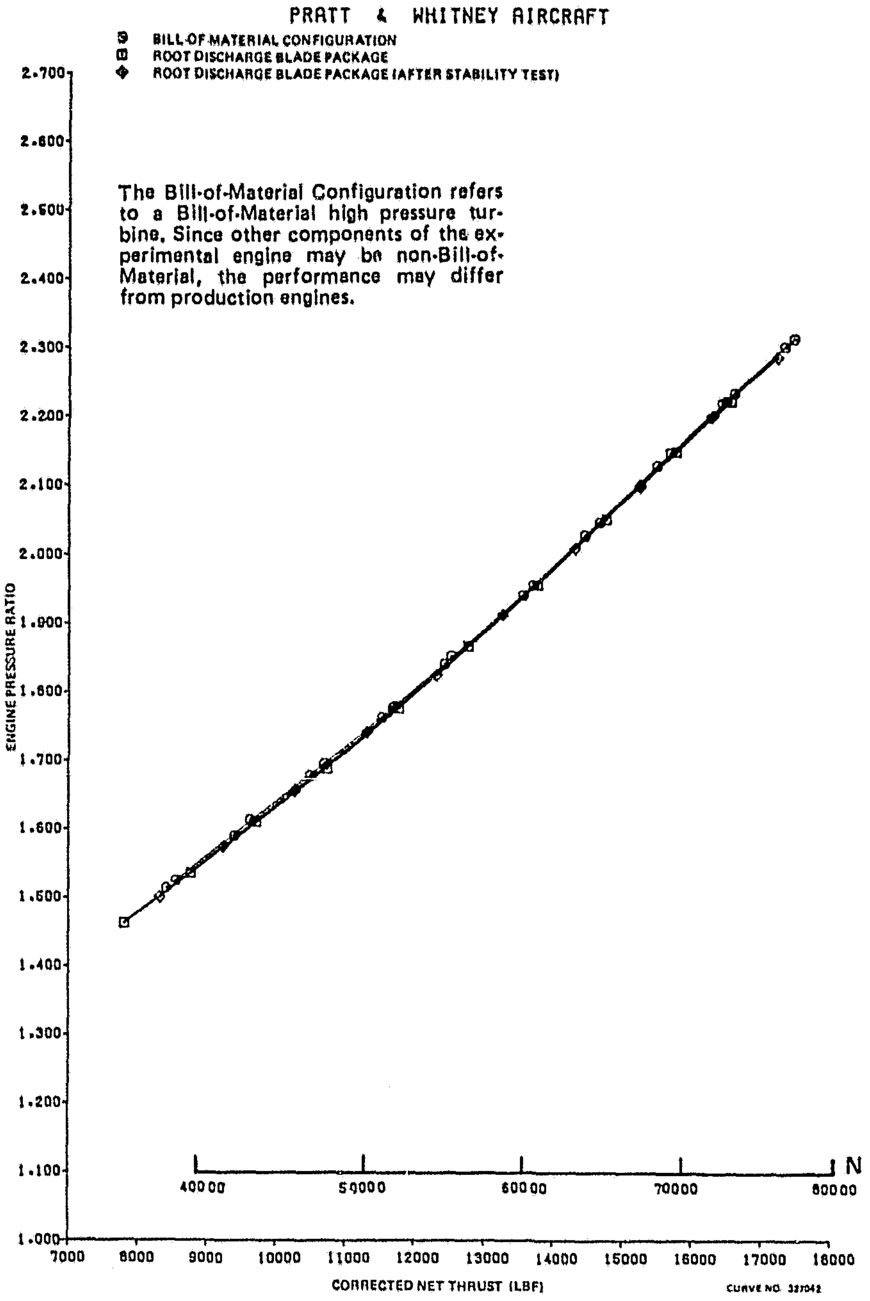
The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-4 Comparison of Root Discharge Blade Package and Baseline Low Pressure Compressor Operating Lines. The curves are essentially the same, so that no change in the operating guidelines is required. The data was taken at sea level static conditions. (327042)



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-5 Comparison of Root Discharge Blade Package and Baseline High Pressure Compressor Operating Lines. The curves are essentially the same, so that no change in the operating guidelines is required. The data was taken at sea level static conditions. (327042)



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-6 Comparison of Root Discharge Blade Package and Baseline Engine Pressure Ratio Variation with Thrust. The two curves are almost identical, allowing the pilot to set the same engine pressure ratios as the Bill-of-Material high pressure turbine equipped engines. The data was taken at sea level static conditions. (327042)

5.2 Altitude Test Results

Performance Improvement

As in the sea level test, the root discharge blade package produced significant performance improvements at cruise flight conditions. A plot of the thrust specific fuel consumption improvement is given in Figure 5-8, and the exhaust gas temperature improvement is shown in Figure 5-9. The performance figures shown were taken at 9,144 m (30,000 ft), 0.8 Mach number, standard day conditions.

Operational Characteristics

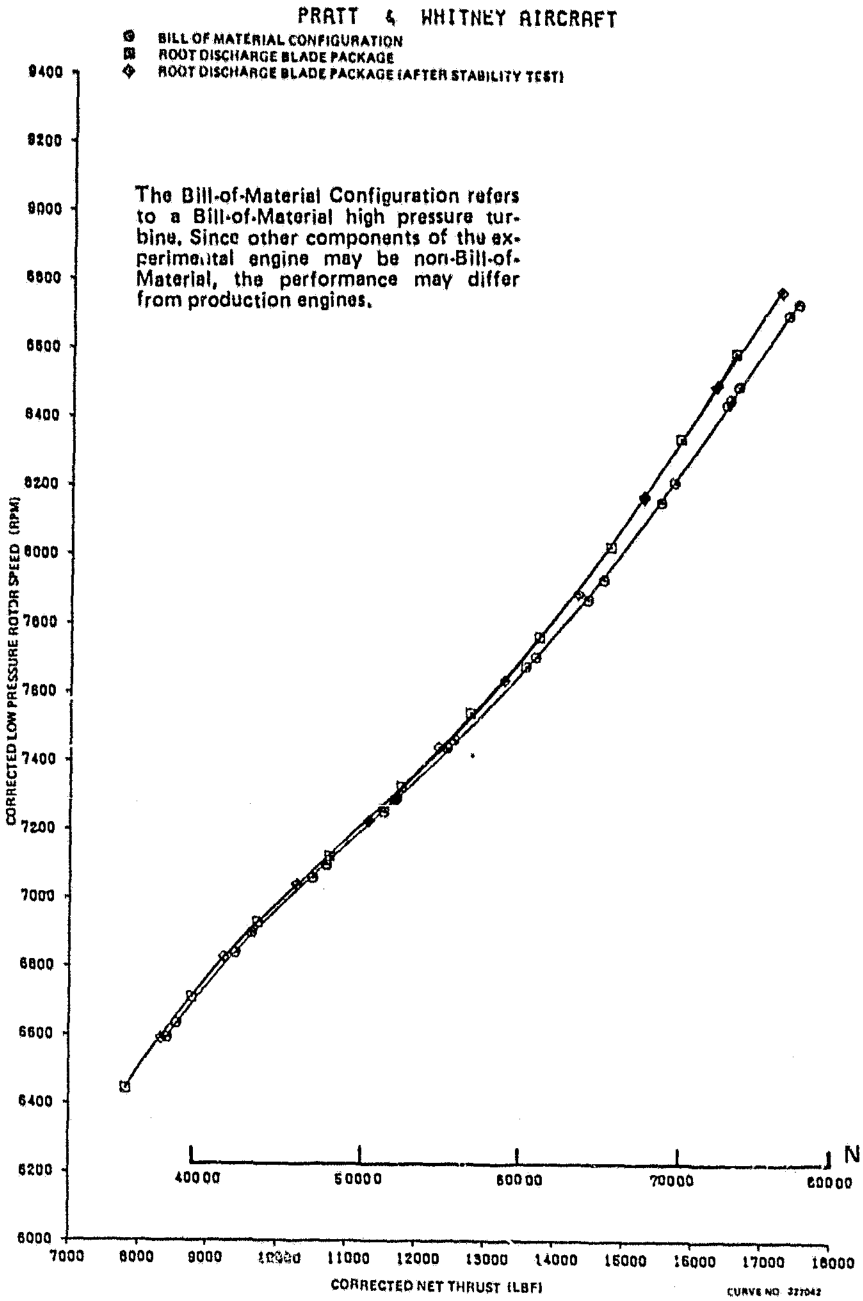
The low and high pressure compressor operating lines showed essentially no change at altitude conditions, as shown in Figures 5-10 and 11. This verifies that the turbine nozzle vane area change compensated for the effect of the efficiency increase of the root discharge blade package. As in the sea level test, the low pressure rotor speed increased for all values of thrust (Figure 5-12).

5.3 Condition of Hardware

The post-test condition of all of the root discharge blade package hardware was excellent despite the severity of the test program, which included engine surges and transient operations not normally encountered in airline service.

Very light rubbing was observed on the blade tip surfaces and the honeycomb seal, as shown in Figure 5-13. The light rubs that were experienced, 0.3 mm (0.012 inch), were caused by a hot acceleration run (which is an operation of the engine rarely performed in normal airline operation) during the sea level stability test program. The rub is illustrated in Figure 5-14, which is a graph of the transient blade tip clearance. The graph shows the hot acceleration of the engine was performed three minutes after a snap deceleration to idle from steady-state take-off power. A three minute period at idle does not allow the massive turbine disk, which is mostly sealed from the gas stream, to transfer the heat it acquired under take-off conditions. When the engine is quickly accelerated to full take-off power, the centrifugal stretch imparted on the blades causes an interaction with the cooled and shrunken honeycomb seal assembly. This condition exists until the honeycomb seal ring responds to the gas temperature rise and grows away from the blade tips. The cold build tip clearances used during the engine performance evaluation were set to loose relative to normal airline practice, and can be set tighter to further improve thrust specific fuel consumption.

Sea level thermocouple measurements revealed that the high pressure turbine outer air seal temperature decreased 25^{o}C (45^{o}F) at sea level take-off. As stated in Section 3.0, the lower seal temperature helps to better control blade tip clearances and seal leakage, and prolong the life of the outer air seal.



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-7 Low Pressure Rotor Speed versus Thrust. Low pressure rotor speed increased over all thrust levels, as a result of the exhaust gas temperature improvement. A new fan inlet case will be offered with the root discharge blade package to increase fan airflow and reduce the rotor speed back to the design point. The data was taken at sea level static conditions. (327042)

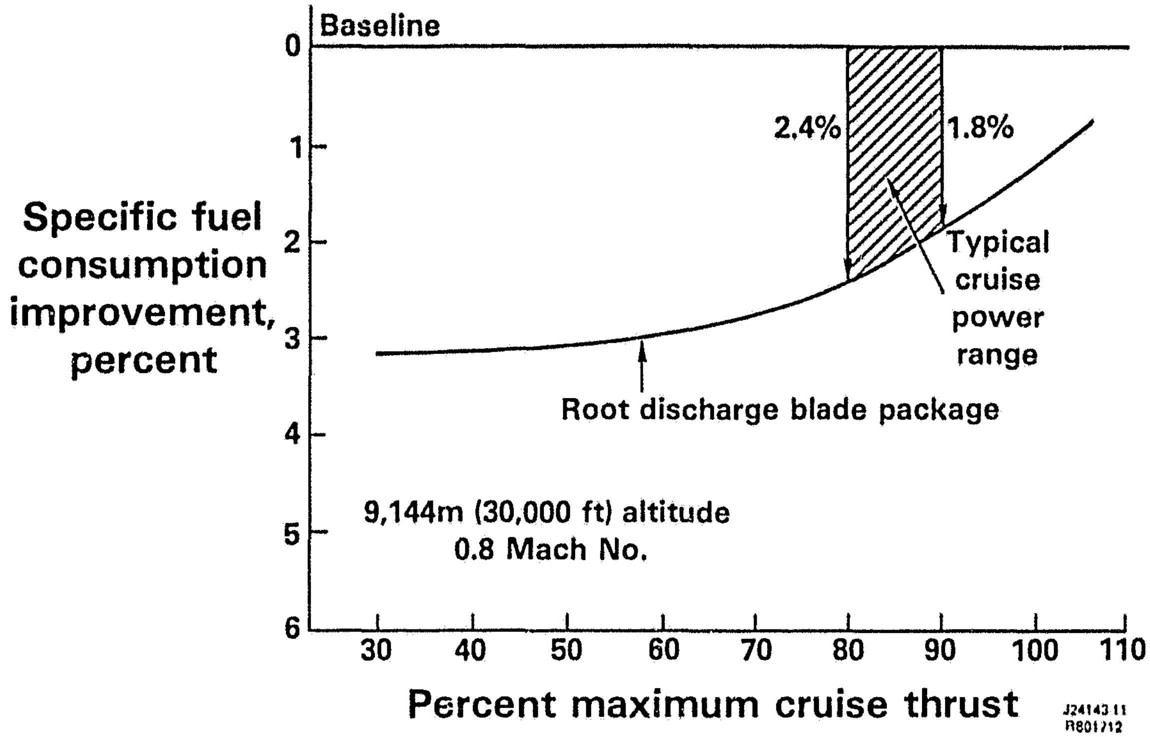


Figure 5-8 Altitude Thrust Specific Fuel Consumption Improvement. The data was taken at 9144 m (30,000 ft) altitude, 0.8 Mach number conditions. (J24143-11)

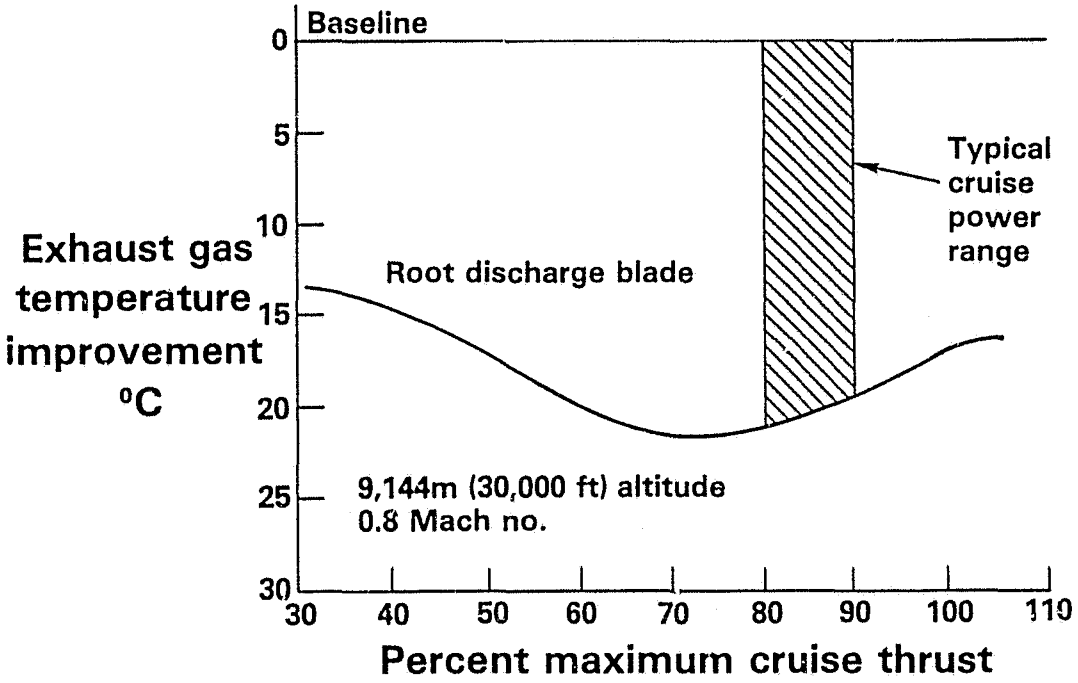
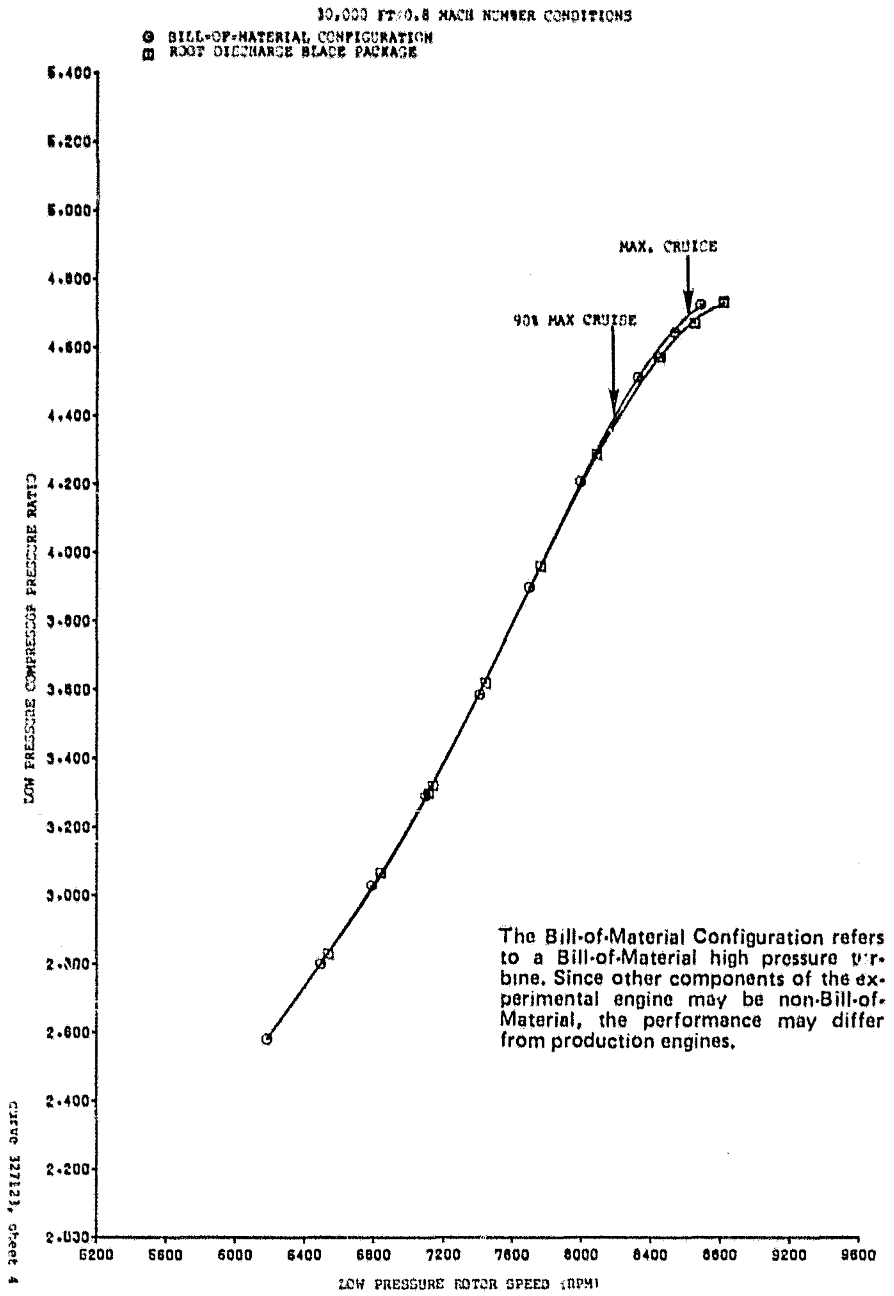
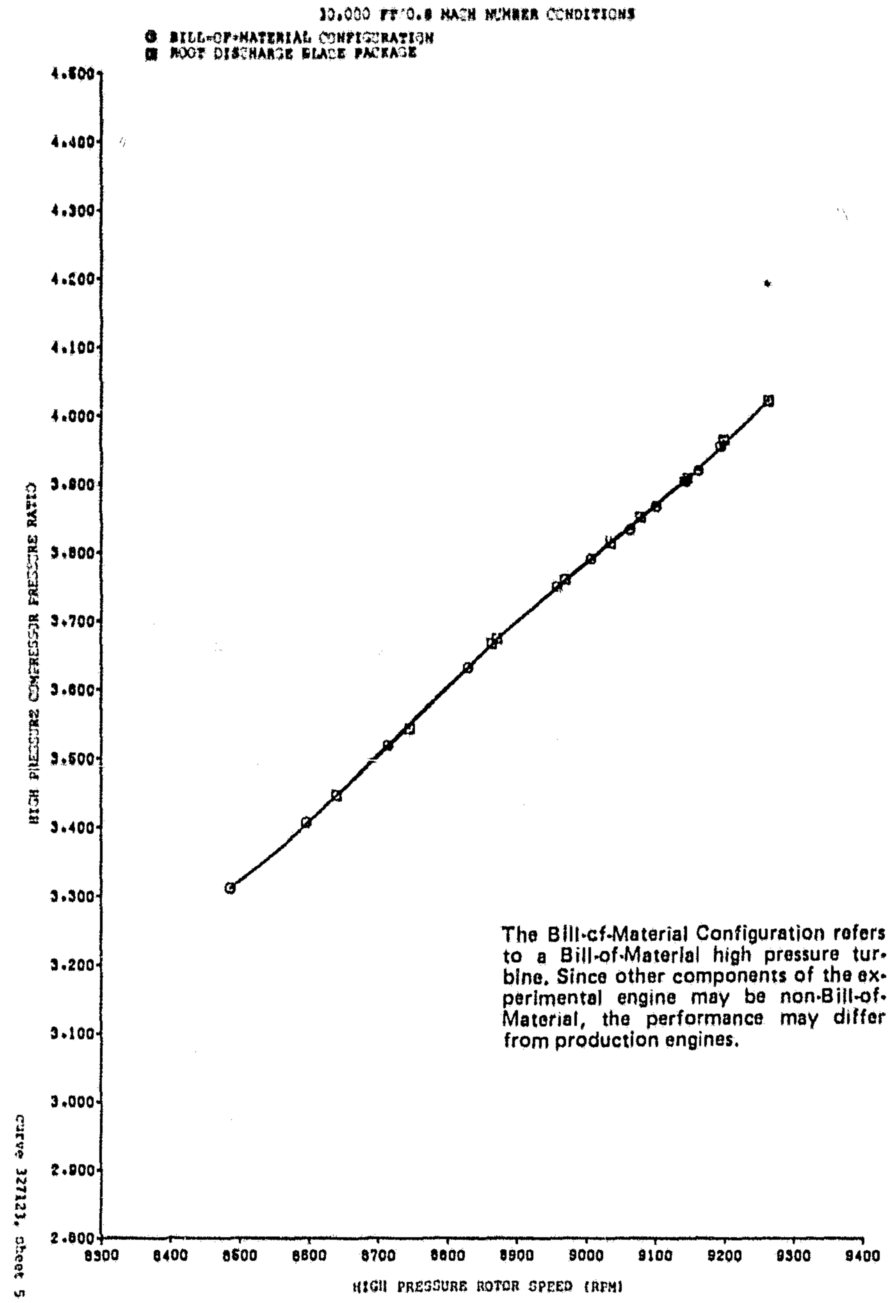


Figure 5-9 Exhaust Gas Temperature Improvement. The data was taken at 9144 m (30,000 ft) altitude, 0.8 Mach number condi- tions. (J24342-2)



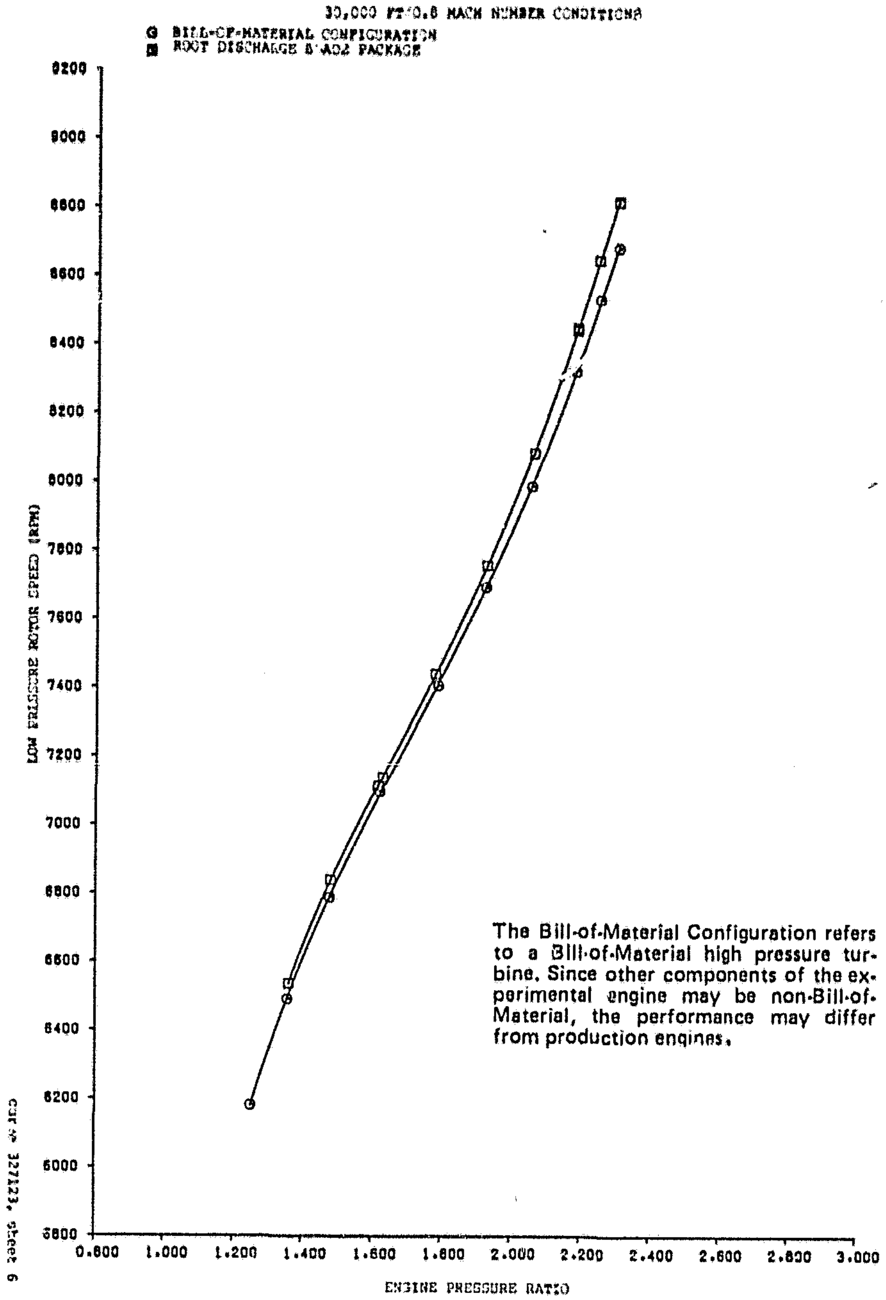
The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-10 Comparison of Root Discharge Blade Package and Baseline Low Pressure Compressor Operating Lines. The data was taken at 9144 m (30,000 ft) altitude, 0.8 Mach number conditions. (Curve 327123-4)



The Bill-cf-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-11 Comparison of Root Discharge Blade Package and Baseline High Pressure Compressor Operating Lines. The data was taken at 9144 m (30,000 ft) altitude, 0.8 Mach number conditions. (Curve 327123-5)



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure 5-12 Low Pressure Rotor Speed versus Engine Pressure Ratio. Low pressure rotor speed increased over all thrust levels, as a result of the exhaust gas temperature improvement (see Figure 5-8). The data was taken at 9144 m (30,000 ft) altitude, 0.8 Mach number conditions. (Curve 327123-6)

Figure 5-13 Condition of Root Discharge Blade Tips and Seal After Testing. Only very light rubbing was observed on the blade tip surfaces and the seal. The excellent condition of the hardware shown here was typical of the entire set of blades and the seal. (80-444-057-B,C)

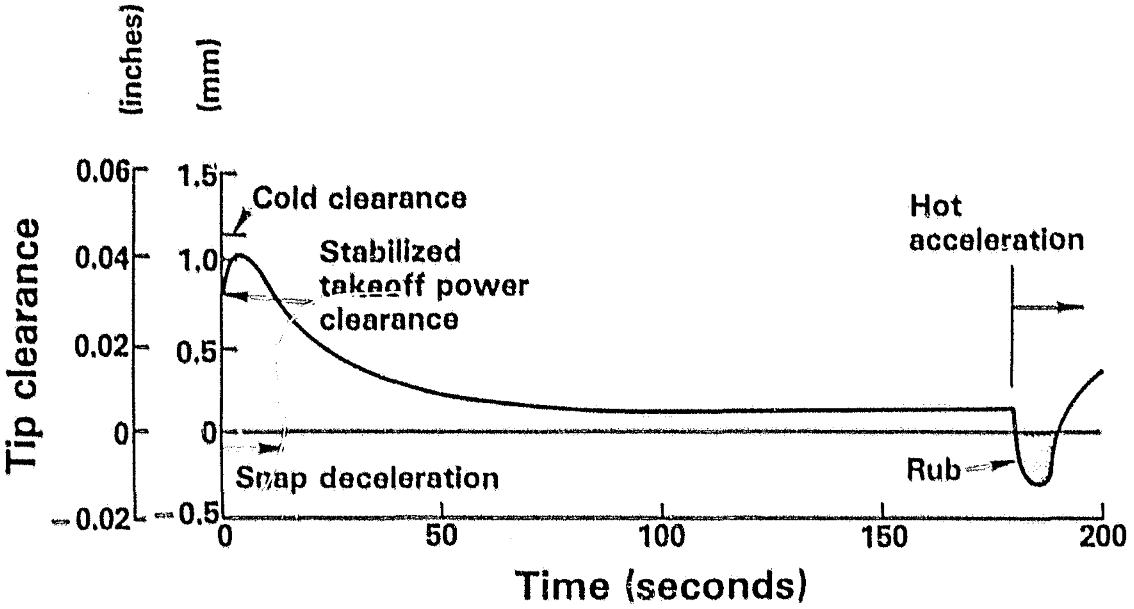


Figure 5-14 Blade Tip Clearance Diagram. Even though a hot acceleration was run, as shown above, only light rubs were observed on root discharge blade seal hardware. (J24342-10)

6.0 ENERGY IMPACT

The performance improvement demonstrated with the Root Discharge Blade Package provides the potential for a major reduction in energy consumption, but to realize this potential, the concept must be accepted by the airlines.

The ECI-PI Feasibility Analysis conducted in 1977 (Reference 1) predicted that the concept would be very acceptable to the airlines both in new engines and as a retrofit for existing engines based on performance, economics and market forecasts available at that time. The actual performance benefit has now been demonstrated to be greater than the 1977 estimate, and the economic and marketing factors have also changed in the direction to encourage airline acceptance of the concept. Consequently, an update of the acceptability analysis is in order.

The Root Discharge Blade Package has already been incorporated in the JT8D-217 engine model. Deliveries of this model began in November, 1980 to fill airline orders for the McDonnell-Douglas DC9-80 airplane. The Root Discharge Blade Package was accepted by the airlines in this case as an integral part of the overall performance and economic advantages of the JT8D-217/DC9-80 engine/airplane combination. An evaluation of the acceptability of the isolated Root Discharge Blade concept in this application would be meaningless, but the fuel saving contribution of the concept is real and will be included in the cumulative fuel saving estimate presented later.

A major aerodynamic redesign of the JT8D high pressure turbine, which affects the first vanes and the low pressure turbine as well as first stage blades, was recently completed and engine testing has started. This redesign retains all of the cooling and sealing features of the demonstrated Root Discharge Blade Package while providing additional performance improvement by reducing aerodynamic losses in the primary gas flowpath. This aerodynamically redesigned high pressure turbine is part of a total performance improvement package for the JT8D-15/17/17R engine models, which also includes the modifications described on Table 6-1. This total package adds the "A" designation to the JT8D-15A/17A/17AR engine models, improving their performance as shown on Table 6-2.

The specific fuel consumption improvements of the "A" package will result in a fuel saving of 5.7% in the typical airline operation of the JT8D powered DC9, 727 and 737 airplanes. The exhaust gas temperature reduction will result in longer times between engine shop visits and in longer engine part lives. One feature of the package, the carbon seal system for the No. 4 bearing compartment, is expected to reduce engine oil consumption by 30%, which will result in a saving of about $1000 per year for each engine in typical airline operation.

TABLE 6-1

"A" Engine Designation Performance Package

Fan	Increased airflow inlet case Improved blade aerodynamics Recambered first stator
Low Pressure Compressor	Recambered second stator
High Pressure Compressor	Sermetel^R coated stators
Diffuser Case Bearing Compartment (No. 4)	Carbon seal
High Pressure Turbine	Root discharge blade package Improved blade and vane aerodynamics
Low Pressure Turbine	Honeycomb airseals Improved blade and vane aerodynamics

TABLE 6-2

Estimated Performance Effects of "A" Package

Thrust Specific Fuel Consumption Improvement, percent	
Takeoff	5.2
Climb	5.6
Cruise, 80% maximum cruise	5.5
90% maximum cruise	4.9
Hold	6.3
Takeoff Exhaust Gas Temperature Reduction, °C	53
Oil Consumption Reduction, percent	30

A payback period evaluation of this package for conversion of the earlier engine models was conducted using the method described in Reference 1, but with the updated economic assumptions shown on Table

6-3. The net airline investment required to convert an existing JT8D -15, -17, or -17R engine to the "A" designation was estimated to be $350,00 per installed engine. This net investment accounts for the initial purchase of a $440,000 kit for the installed engine, required rework and spares as well as routine parts purchase that are avoided by purchasing the kit. The payback calculation was based on the fuel saving benefit only, with the beneficial effects of the exhaust gas temperature reduction and the oil consumption reduction neglected for conservatism. The results are presented on Figure 6-1 as a function of fuel price and aircraft utilization. Typical airline operation would show a payback period of about 3.5 years. These results may be judged against the acceptability criteria established by Pratt & Whitney Aircraft with the assistance of five major U.S. airlines in the Reference 1 study. The maximum acceptable payback period for an engine conversion program was defined as a function of the remaining economic life of the engine, as shown in Figure 6-2. Based on this criteria, the "A" package at 3.5 years payback period is attractive for conversion of JT8D-15/17/17R engines whose operation is expected to continue for at least five years after conversion. This includes nearly all such engines that will be in service when the package becomes available in 1982. Its acceptability has been demonstrated by airline orders for the conversion kits.

The payback period for the "A" package in a new engine was not evaluated, but it would be significantly better than the conversion case because the incremental investment is much smaller for the same fuel benefit.

The cumulative fuel saving attributable to the demonstrated Root Discharge Blade Package portion of the total performance improvements in the JT8D-217 and JT8D-15A/17A/17AR engine models was calculated based on a recent proprietary projection of the market for these engines through the year 1990. Each engine was assumed to have an operational life of 15 years for estimating the number of engines to be retrofitted and the number of years over which the fuel saving applies. The resulting cumulative fuel saving is 2.6 billion liters (685 million gallons), which can be compared to the estimate of 1.5 billion liters (397 million gallons) from the 1977 Feasibility Analysis of the concept.

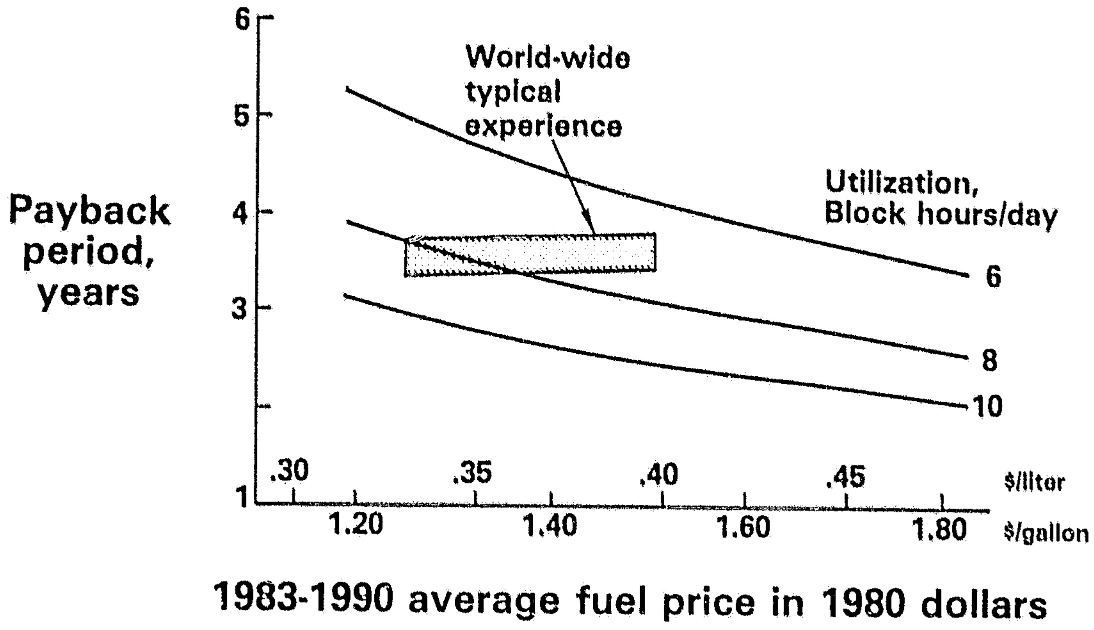


Figure 6-1 "A" Package Payback Period. Conversion of existing JT8D-15/17/17R engines to the "A" designation will pay for itself in about 3.5 years. (J24143-29)

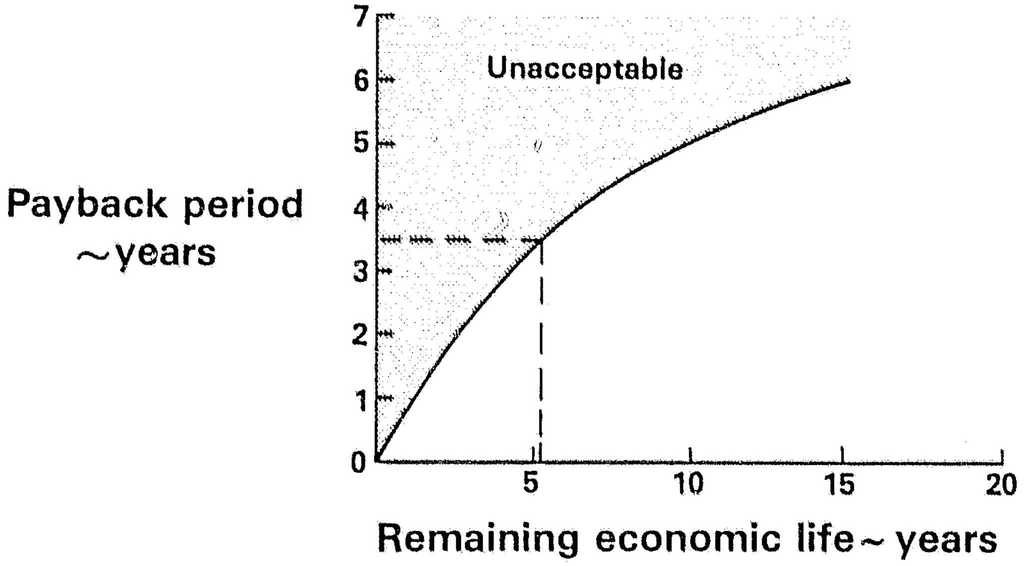


Figure 6-2 Economic Acceptability of Retrofit. JT8D-15/17/17R engines with five or more years of economic life left can benefit from the installation of the "A" package. (J24143-23)

TABLE 6-3

Revised Assumptions for Payback Period Evaluation

	Ref. 1	Revised
Year Dollars	1977	1980
Current fuel price, $/gallon ($/liter)	0.35 (0.092)	Variable
Fuel price escalation above general inflation, percent/year	0	3
Salvage value/catalog value, percent	0	10
Spares/active engines, percent	Variable	15
Aircraft recertification charge, $/Engine	0	30,000
Engine shop labor reduction per °C exhaust gas temperature reduction, $/Engine Operating Hours	0.21	0
Aircraft utilization, Block Hr./Day		
DC-9	7.98	Variable
727	8.92	Variable

7.0 CONCLUDING REMARKS

The root discharge high pressure turbine program was successful in that the technical objectives were met or exceeded and immediate application to production and retrofit of JT8D engines has resulted from its attractive fuel saving benefit.

Performance Expectations Exceeded with Root Discharge Blade Package

The performance improvement provided by the root discharge blade package was better than the original predictions. At 90 percent maximum cruise power, thrust specific fuel consumption improved 1.8 percent relative to the Bill-of-Material blade, compared to the predicted improvement for the concept of 1.44 percent. Exhaust gas temperature decreased 18°C (33°F) at sea level takeoff conditions, improving on the predicted temperature reduction by 6°C (10°F). The stability margin of the engine was unchanged, and the acceleration time of the engine from ground idle to sea level takeoff improved slightly.

Root Discharge Blade Package Included in New JT8D-200 Series Model - October 1980 Delivery

A version of the root discharge blade package tested under this program was adopted for the JT8D-217 engine model. Development testing has been completed, confirming the root discharge blade package benefits under realistic flight conditions. The durability has also been demonstrated in the variety of cyclic endurance tests at limiting speed and overtemperature conditions required for engines in the FAA certification process.

"Aero Redesign" Root Discharge Blade Package is Key Feature of Total "A" Package in JT8D-15A/17A/17AR Engines

A package of performance improvements which will improve the cruise thrust specific fuel consumption of the JT8D-15/17/17R engine models by 5.5% (adding an "A" to the engine designations) has been designed and testing has been started. Approximately half of this performance improvement is attributable to an aerodynamically redesigned root discharge blade package.

The aerodynamic redesign updates the airfoil shapes and reduces the solidity of the high pressure turbine blades and vanes, while retaining the cooling and sealing advantages of the root discharge blade package described in this report. The "A" package will be delivered in new engines and as conversion kits for existing engines starting in 1982.

APPENDIX A

Comparison of Design 1 and Design 2 Blade Performance

The Design 1 Root Discharge Blade (see Section 3.2.2) was used in the sea level static engine performance test. The Design 2 Root Discharge Blade (see Section 3.2.3) was used in the altitude performance test of the same engine several months later. This altitude test was immediately preceded by a brief sea level static test with the Design 2 blades in the engine, allowing a performance comparison of the two root discharge blade designs. The measured thrust specific fuel consumption and exhaust gas temperature differences between the two were very small as shown on Figures A-1 and A-2. Additionally, the gas generator parameters showed little or no shift, as shown on Figures A-3 through A-6. Since the two blade designs are aerodynamically identical, the small differences in measured performance are believed to be due to combination of measurement inaccuracies and a shift in the baseline engine performance with time.

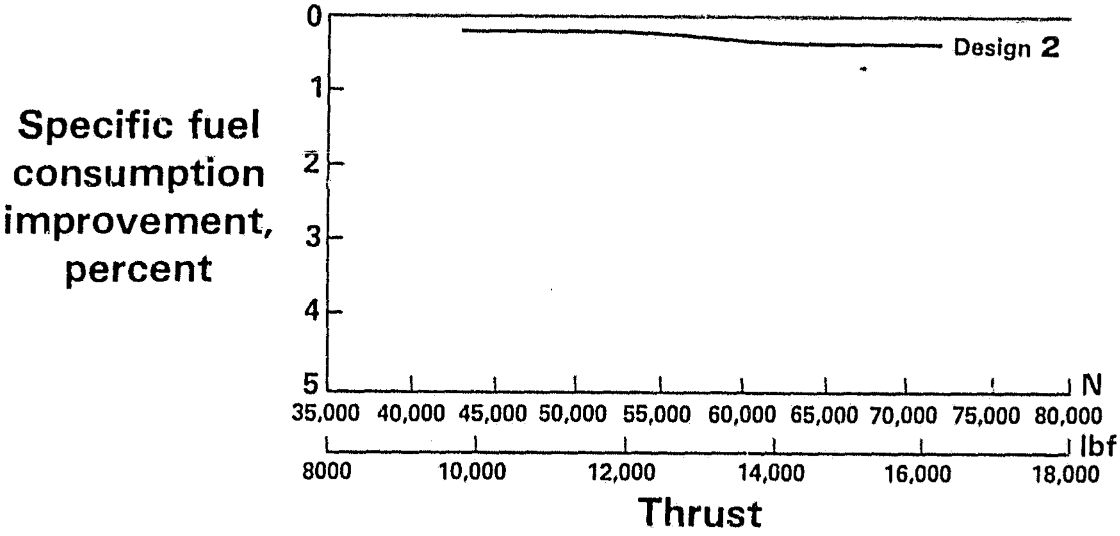


Figure A-1 Comparison of Root Discharge Blade Design 2 Thrust Specific Fuel Consumption Relative to Design 1 at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the thrust specific fuel consumption remained virtually the same, within instrumentation accuracy. (J24342-13)

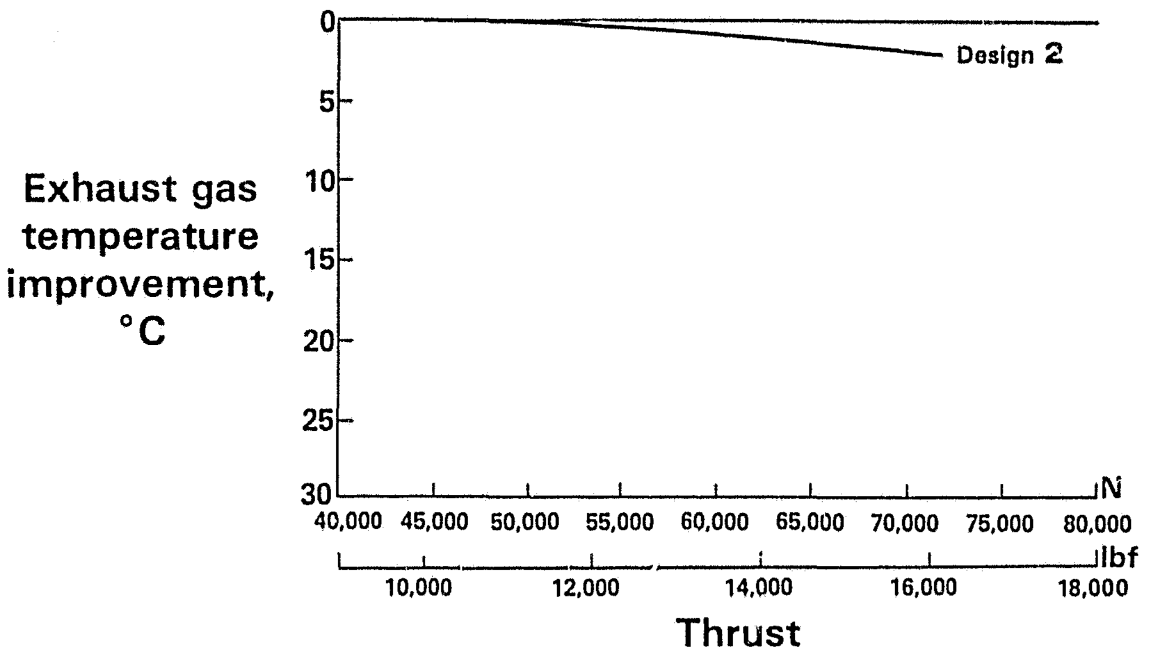
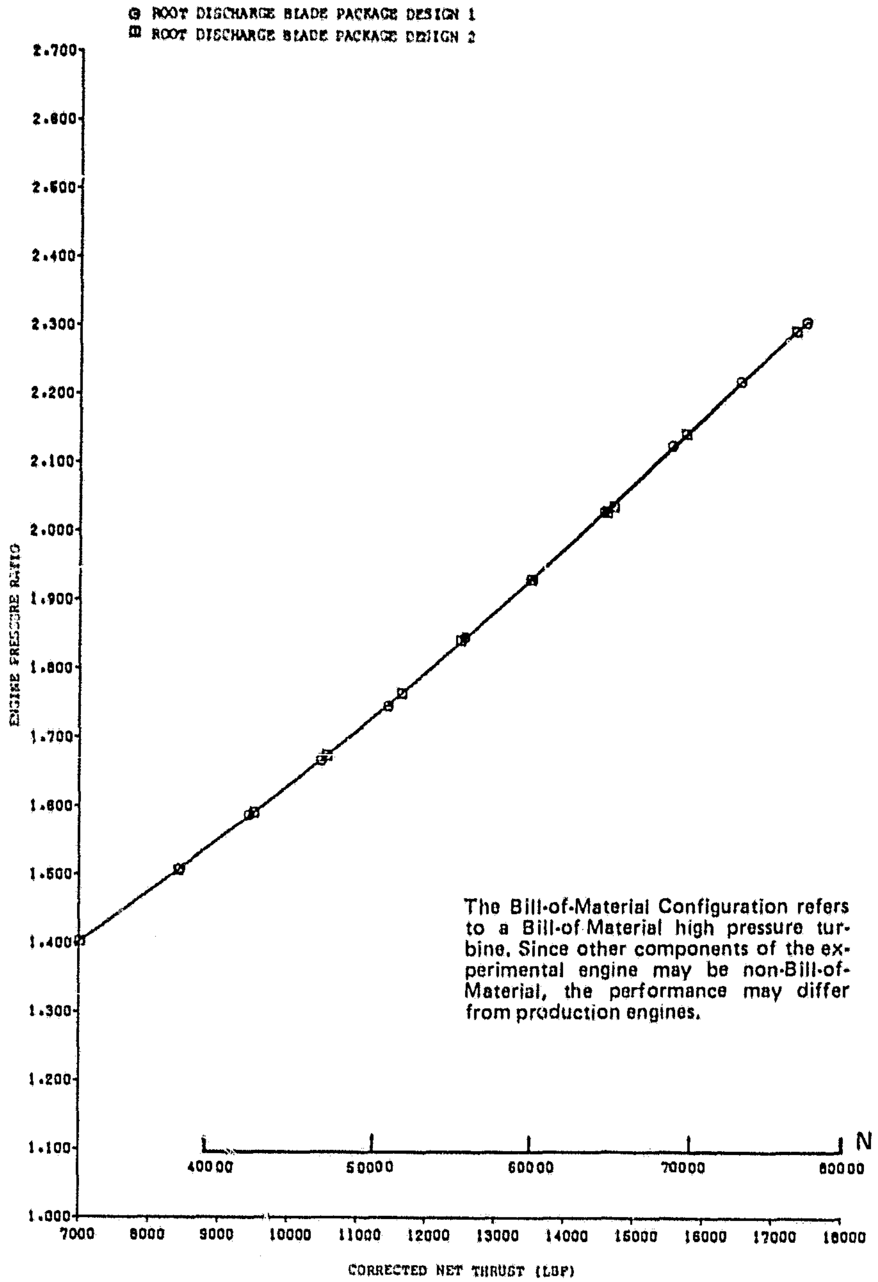
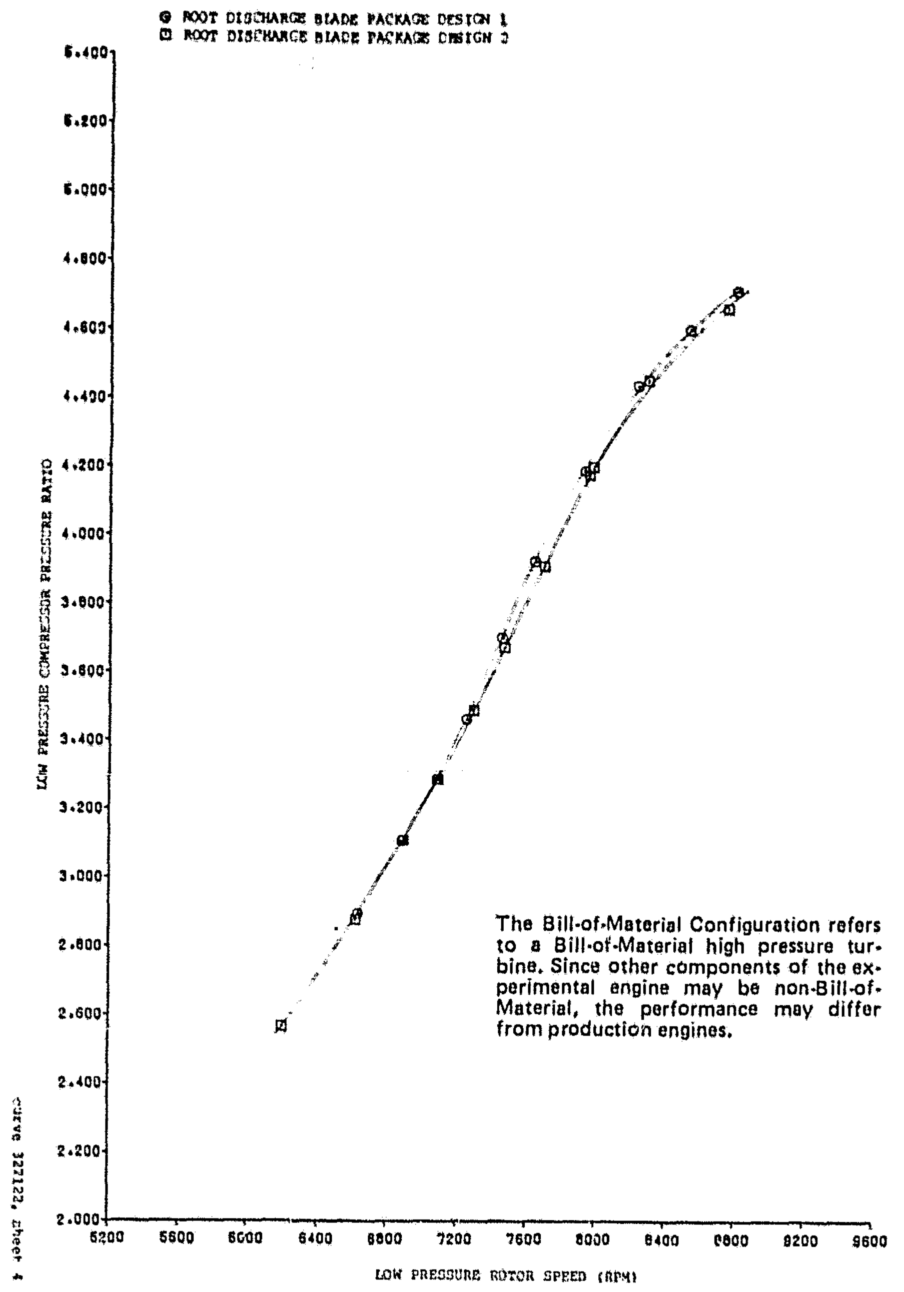


Figure A-2 Comparison of Root Discharge Blade Design 2 Exhaust Gas Temperature Relative to Design 1 at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the exhaust gas temperature remained virtually the same, within instrumentation accuracy. (J24342-14)



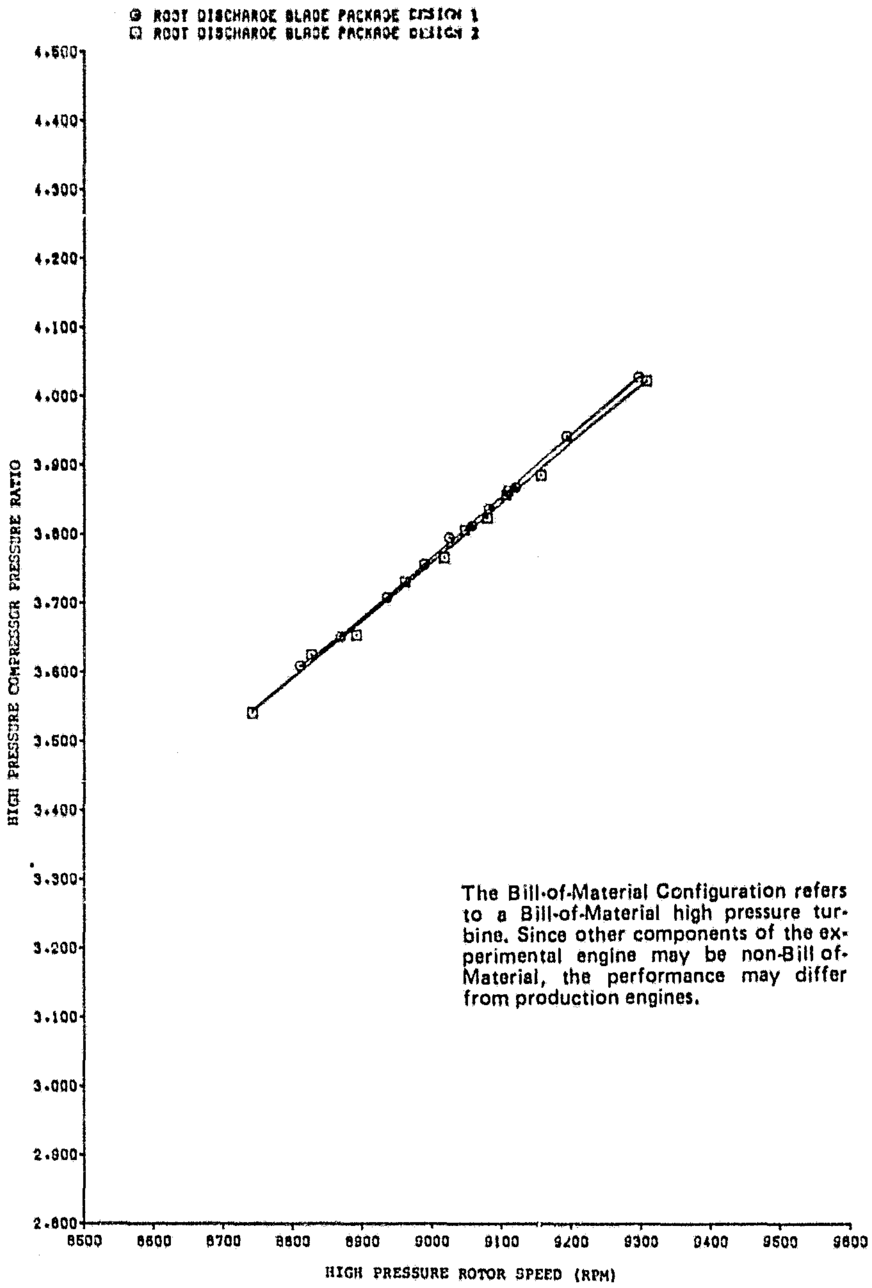
The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure A-3 Comparison of Root Discharge Blade Designs 1 and 2 Engine Pressure Ratio at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the engine pressure ratio remained virtually the same, within instrumentation accuracy. (Curve 327122-3)



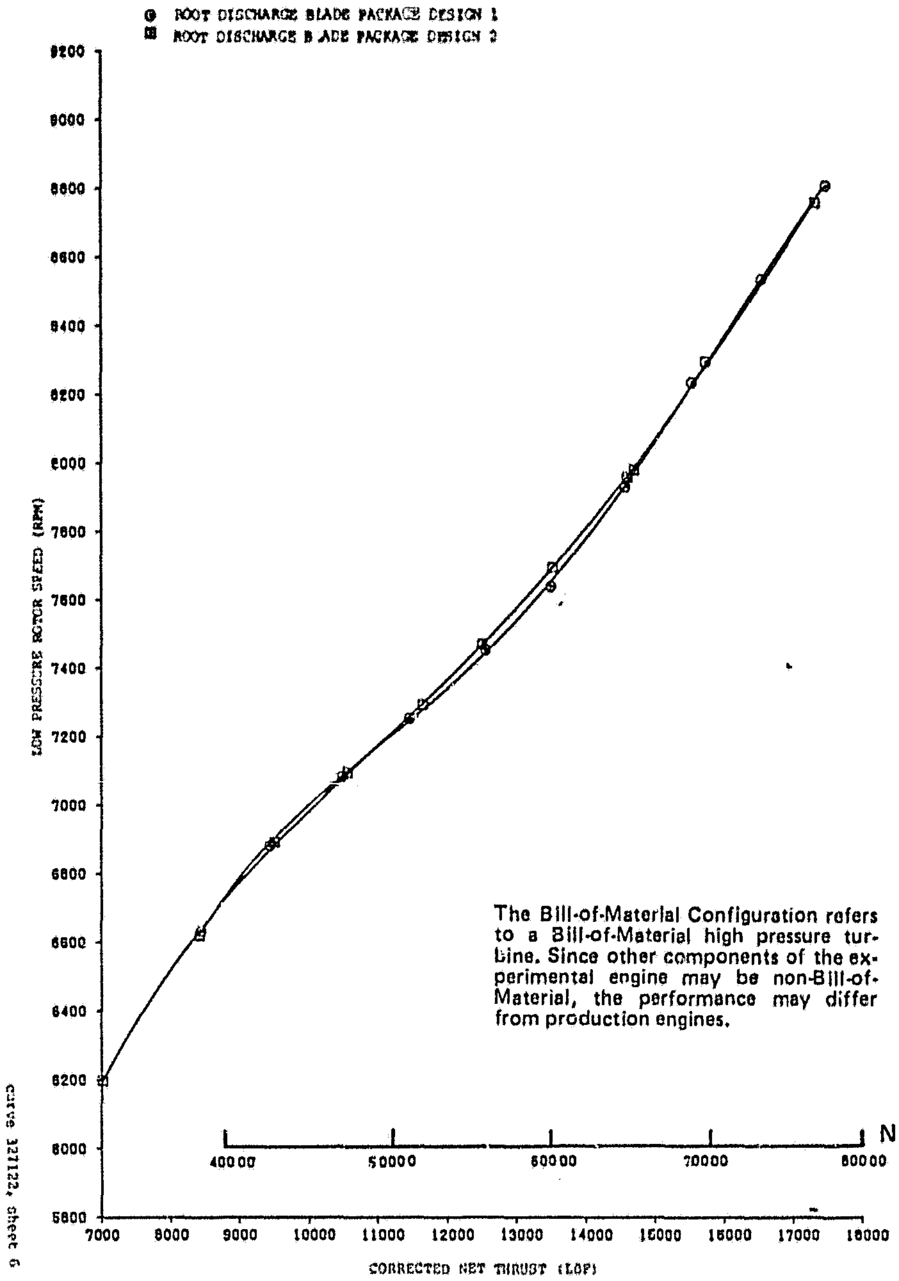
The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure A-4 Comparison of Root Discharge Blade Designs 1 and 2 Low Pressure Compressor Pressure Ratio at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the low pressure compressor pressure ratio remained virtually the same, within instrumentation accuracy. (Curve 327122-4)



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill of-Material, the performance may differ from production engines.

Figure A-5 Comparison of Root Discharge Blade Designs 1 and 2 High Pressure Compressor Pressure Ratio at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the high pressure compressor pressure ratio remained virtually the same, within instrumentation accuracy. (Curve 327122-5)



The Bill-of-Material Configuration refers to a Bill-of-Material high pressure turbine. Since other components of the experimental engine may be non-Bill-of-Material, the performance may differ from production engines.

Figure A-6 Comparison of Root Discharge Blade Designs 1 and 2 Low Pressure Rotor Speed at Sea Level Static Conditions. The blades' external aerodynamics were identical, so the low pressure rotor speed remained virtually the same, within instrumentation accuracy. (Curve 327122-6)

APPENDIX B

PRODUCT ASSURANCE

INTRODUCTION

The Product Assurance system for this program provided for the establishment of quality, reliability, safety, and maintainability requirements and determination of compliance with these requirements, from the design stage through the procurement of hardware 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 quality requirements of the Root Discharge Blade 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, were made available to designated Government Representatives for on-site review.

Standard Pratt & Whitney Aircraft 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 Pratt & Whitney Aircraft Vendor Quality Control or inspection after receipt at Pratt & Whitney Aircraft. Records of inspections and tests performed at source were maintained by the supplier as specified in Pratt & Whitney Aircraft 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 Pratt & Whitney Aircraft.

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 the test engine was assembled for evaluation of engine performance in accordance with the program requirements. 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 and altitude stand testing. Instrumentation was provided by the Instrumentation Development Department. All equipment was monitored and controlled by Experimental Test Procedures.

4. INSTRUMENTATION AND EQUIPMENT

Instrumentation and equipment were controlled under the Pratt & Whitney Aircraft 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.

5. DATA

Engine performance and stability data from the sea level and altitude stands were recorded on the Steady State Data System. This system is certified to procedures which specify calibration intervals for the components requiring laboratory certification. During each data acquisition the system recorded certified reference parameters, providing an "on-line" verification that the systems were performing properly.

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

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 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 Root Discharge Blade 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 subject program, and no reliability problems were encountered.

The root discharge blade was designed with maintainability features similar to the Bill-of-Material high pressure turbine blade. However, these features were not demonstrated as part of the subject program.

The safety activities at Pratt & Whitney Aircraft and as considered on this program 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.

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 (PWA-5515-38)

2. Gaffin, W. O., "Revised HPT Blade and Outer Air Seal", NASA CR-159551, March 21, 1979 (PWA-5515-77)