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EXECUTIVE SUMMARY REPORT

JT9D JET ENGINE DIAGNOSTICS PROGRAM

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Pratt & Whitney Aircraft Group
Commercial Products Division

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16. Abstract

The NASA JT9D Jet Engine Diagnostics Program was a five-year effort to identify and quantify the various engine deterioration phenomena that affect JT9D performance retention and identify approaches to improve performance retention of current and future engines. The program included surveys of historical data, monitoring of in-service engines, ground and flight testing of instrumented engines, analysis, and analytical modeling. The Boeing Commercial Airplane Company, Douglas Aircraft Company, Trans World Airlines, Pan American World Airways, and Northwest Airlines participated as subcontractors in various phases of the program. Historical data were provided also by American Airlines. The studies showed that performance deterioration is made up of both short- and long-term modes, both of which are flight-cycle related phenomena. Short-term deterioration occurs primarily during airplane acceptance testing prior to delivery to the airline. This effect is caused by flight-load and power induced clearance closures and engine deflections with resulting rubbing of airfoils and seals. Long-term deterioration is caused by erosion of airfoils and gas-path seals during ground operation and take-off and by cyclic induced thermal distortion of the high-pressure turbine airfoils. Studies of possible remedial approaches have shown that performance retention within 1 to 2 percent of initial revenue service performance can be achieved with a proper program of hot section and cold section maintenance.

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PREFACE

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SUMMARY

The NASA JT9D Jet Engine Diagnostics Program* has been a five year effort to identify and quantify the various engine deterioration phenomena that affect JT9D performance retention and identify approaches to improve performance retention of current and future engines. The program has included surveys of historical data, monitoring of in-service engines, ground and flight testing of instrumented engines, analysis, and analytical modeling. The Boeing Commercial Airplane Company, Douglas Aircraft Company, Trans World Airlines, Pan American World Airways, and Northwest Airlines participated as subcontractors in various phases of the program. Historical data were provided also by American Airlines.

The initial studies established that performance deterioration is made up of short- and long-term modes, both of which are flight cycle related phenomena. The later efforts provided additional data and refined and expanded on the initial conclusions.

The short-term deterioration occurs primarily during airplane acceptance testing prior to delivery to the airline. Therefore, it has little effect on revenue service performance retention. The long-term deterioration continues throughout engine life with a negative effect on performance retention.

Short-term deterioration results from an increase in gas-path running clearances with resultant decreases in engine module efficiencies. This short-term effect is caused by flight-load and power induced clearance closures and engine deflections with resulting rubbing of airfoils and seals. Rubs occur for the most part prior to revenue service during the various airplane maneuvers associated with the production acceptance testing of the airplane. This flight-load induced wear occurs in all modules with the low-pressure compressor and high-pressure turbine performance most affected.

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* This work was conducted by Pratt and Whitney Aircraft for the National Aeronautics and Space Administration under Contract NAS3-20632. This contract was managed by the Lewis Research Center.

Long-term performance deterioration is also a flight cycle related phenomenon. It is caused by erosion of airfoils and gas-path seals during ground operation and take-off and by cyclic induced thermal distortion of the high-pressure turbine airfoils. Erosion primarily affects cold section efficiencies by blunting the blade leading edges, reducing airfoil chords, and further opening running clearances. Thermal distortion in the turbine results from high-temperature cycling with resultant gas-path leakage, loss of optimum airfoil shape, and further rubbing of seals. The effect of the long-term deterioration mode for the JT9D-7A engine is shown on Figure 1. An increase of 2 percent in cruise thrust specific fuel consumption is typical after 2000 flight cycles of revenue service due to performance loss in unrepaired engines.

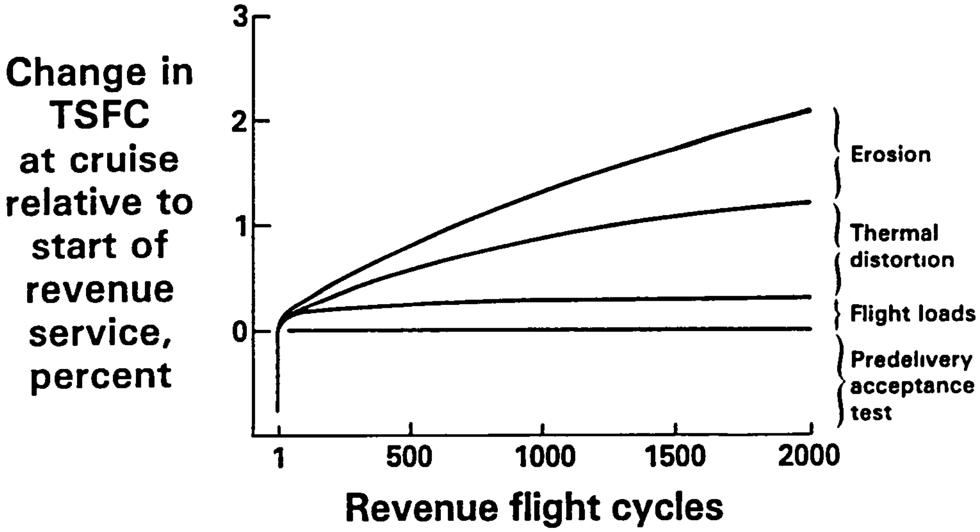


Figure 1 JT9D-7A Engine Long-Term Performance Deterioration at Altitude Cruise Conditions Relative to Start of Revenue Service. (J21216-21)

This NASA-sponsored program has identified possible approaches to reduce the short-term performance loss. It has also shown that performance retention within 1 to 2 percent of initial revenue service performance can be maintained with a proper program of hot section and cold section maintenance, as shown on Figure 2.

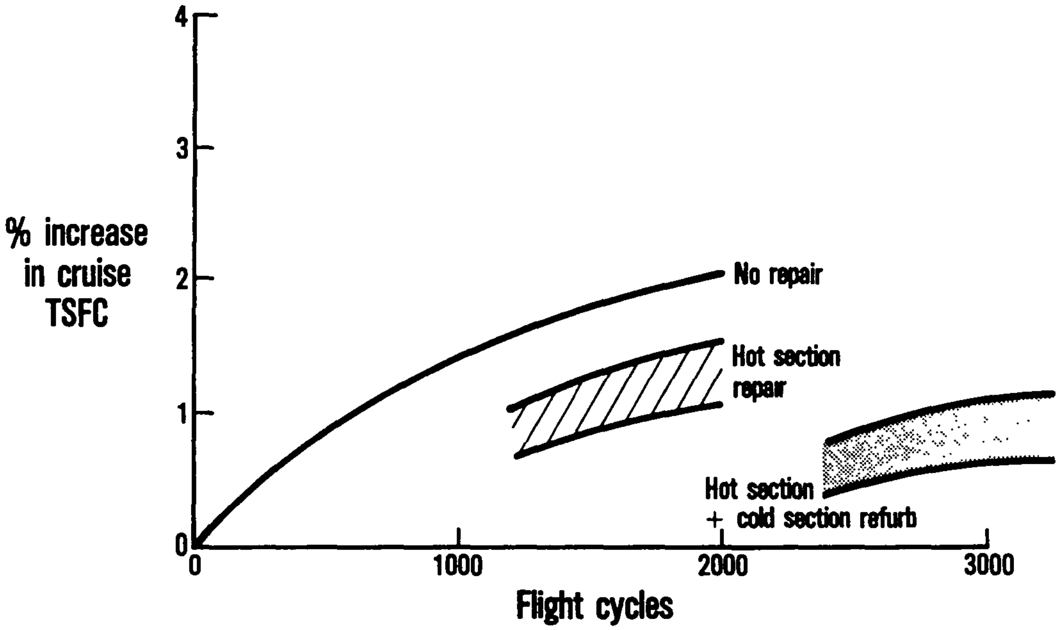


Figure 2 Effect of Repair on JT9D-7A Engine Cruise Thrust Specific Fuel Consumption. (J24603-24)

SECTION 2.0

INTRODUCTION

The National Aeronautics and Space Administration JT9D Jet Engine Diagnostics Program had the objectives of identifying and quantifying the causes and sources of performance deterioration in the JT9D turbofan engine and developing basic information which will be applied to minimize performance degradation of current and future engines. NASA Contract NAS3-20632 defined the work to be accomplished by the Pratt and Whitney Aircraft (P&WA) Group and its subcontractors to achieve these objectives. Specifically, this program:

- o Defined the extent and magnitude of JT9D engine performance deterioration and established statistical trends;
- o Identified and quantified the sources and causes of JT9D short-term and long-term engine performance deterioration;
- o Determined the sensitivity of component performance to deterioration of engine parts;
- o Developed and periodically refined an analytical model of JT9D-7A engine performance deterioration which represents a statistical average, or typical, thrust specific fuel consumption (TSFC) loss associated with individual parts or components; and
- o Recommended operational and maintenance procedures and development items to improve performance retention of current and future engines.

These objectives were accomplished by the work performed under the folowing tasks:

- o Task I consisted of the collection and documentation of historical data from airframe manufacturers and airlines on performance deterioration of JT9D-3 and JT9D-7A engines (Reference 1).
- o Task II provided an accumulation of in-service ground and flight performance and maintenance data from a controlled sample of JT9D-7A engines on the Pan American fleet of Boeing 747 Special Performance (SP) airplanes. The data covered a time period from predelivery testing through revenue service (Reference 2).
- o Task III was divided into two parts. Task IIIA consisted of the controlled testing of a low-time service engine and related analytical work to document the sources and causes of short-term deterioration (References 3, 4, and 5). Task IIIB consisted of the testing of an engine under simulated flight aerodynamic and thrust load conditions to correlate performance loss with these loads (Reference 6)

- Task IV, the objective of which was to determine the sources and causes of long-term deterioration, was deleted during fact-finding prior to contract negotiation. However, Pratt & Whitney Aircraft agreed to provide, on an informal basis, data from its in-house programs related to long-term deterioration.

- Task V consisted of a special flight test program to measure flight-induced loads such as gravitational ("g"), gyroscopic (gyro), and inlet aerodynamic loads and their impact on engine clearances and performance during typical airplane acceptance flights and revenue service maneuvers. The flight test data was supplemented by engine data taken during ground testing (References 7 and 8).

- Task VI covered all data reduction and analysis related to Tasks I, II, III, and V.

- Task VII provided for management and report preparation activities related to the program.

SECTION 3.0

APPROACH

The JT9D-7A engine was selected for the study since various models had been operating for a long time, and some of these models were still in production; as a result, both ample high-time and new engine data were available. Thus, the reported performance deterioration causes and rates may already have been corrected in the latest model JT9D engines.

The first task was the collection of available historical data. These data included:

- o Pratt & Whitney Aircraft production performance records to establish a base level.
- o Airframe manufacturers certification records to show early changes in performance.
- o Airline and Pratt & Whitney Aircraft prerepair and postrepair calibration test results and hardware inspection results to explain long-term changes.

Based on the analysis of these data, some preliminary conclusions were drawn:

- o There are three generic causes of engine performance deterioration, namely: 1) blade-to-seal rub-induced clearance changes; 2) erosion of fan and compressor airfoils and seals; and 3) thermal distortion of hot section parts.
- o Performance deterioration trends may be divided into two distinct time periods: short-term and long-term deterioration. The prime causes of short-term deterioration are flight load- and engine power-induced rubs which open gas-path clearances, thus reducing module efficiencies and influencing airflow. The analysis of the historical data as seen on Figure 3 showed an initial increase in thrust specific fuel consumption at sea level in the first few flights conducted by the airframe manufacturer, prior to delivery of the airplane to the airlines.
- o The long-term performance deterioration then occurs at a slower rate with the dominant causes being erosion in the cold section and thermal distortion of airfoils and seals in the hot section, Figure 4. Both these effects are also cyclic functions.
- o Erosion of cold section airfoils and seals is due to ingestion of abrasive materials during ground operation, take-off, and landing. Erosion causes wear of airfoil surfaces, blunting of leading edges, and further opening of running clearances with resulting decreases in both module efficiency and airflow. It also contributes to changing flow patterns which, in turn, contribute to hot section deterioration.

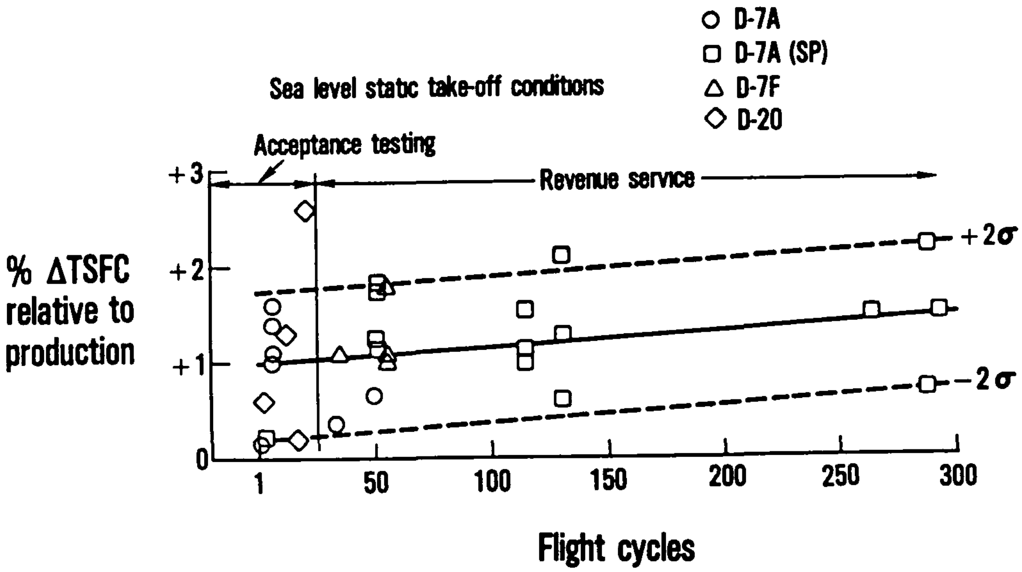


Figure 3 Historical Short-Term Deterioration Data. (J24873-4)

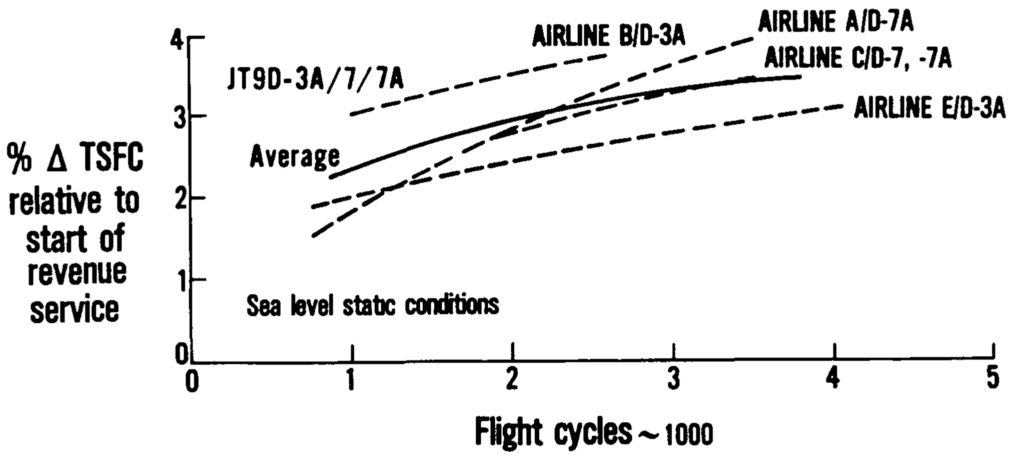
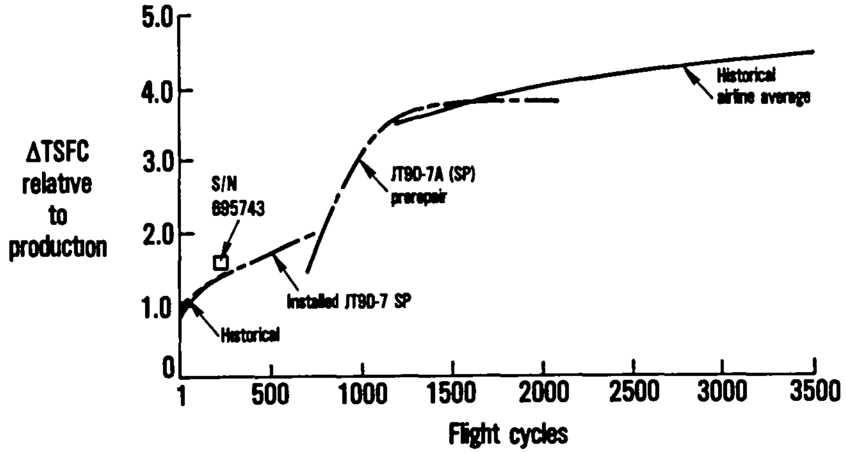


Figure 4 Historical Long-Term Deterioration Data for Unrepaired Engines. (J24603-8)

- Thermal distortion of hot section airfoils is caused by the higher temperatures at take-off power and by the changing gas flow patterns which in turn are caused by deterioration in the compressor and combustor modules. The thermal distortion of vanes and structure reduces airfoil efficiency, increases secondary flow leakage, and contributes toward load-induced rubs.

o Turbine performance can be recovered by hot section refurbishment; however, cold section refurbishment not only recovers compressor efficiency and flow but also retards the deterioration of the higher-cost hot section components. A comparison of the fleet historical prerepair and postrepair calibration data showed an average performance recovery of 1 percent in sea level take-off thrust specific fuel consumption with a potential for up to 2 percent recovery with increased cold section and hot section refurbishment.

The first task of the program provided an abundance of information (Reference 1), but it left numerous gaps in the data. The second task, an in-service engine performance study, conducted jointly with Pan American World Airways, expanded the data base significantly by allowing the monitoring of a controlled sample of 28 JT9D-7A engines in the Pan American 747SP airplane fleet from preflight testing of the engines at Boeing through 2100 flight cycles of operation (Reference 2). The data collection included: installed-engine ground calibrations before the first airplane flight and periodically during subsequent revenue service; in-flight engine calibrations during the flights immediately following the ground calibrations; a complete set of crew-collected engine condition-monitoring data from the fleet; prerepair and postrepair calibrations; and repair histories on each of these engines that came into the shop (Reference 3). The data also included an expanded instrumentation calibration and a complete analytical teardown of one of the engines (S/N 695743) after 141 flight cycles (see Figure 5).



- Installed ground test from 0 – 1100 flight cycles
- Expanded testing and analytic teardown at 141 cycles
- Pre and post repair calibrations

Figure 5 Pan American 747SP/JT9D-7A In-Service Engine Performance Data. (J24873-6)

The results of this effort firmly established that the load-induced short-term deterioration occurs in the first few flights prior to revenue service. The study provided data for the refinement of the various engine module deterioration prediction models which were first developed on the basis of the historical data. Finally, the study provided a correlation between performance retention at flight cruise conditions and performance change as measured by ground calibrations. The quality of the flight performance data was less than that of the ground tests due to the limitations of available instrumentation systems. However, the data sample was large enough that statistical trends could be established. One such set of data is 747SP engine condition monitoring (ECM) fuel flow data shown in Figure 6. The data were recorded at cruise altitudes between 32,000 and 40,000 feet and corrected to 35,000 feet and constant engine pressure ratio (EPR). A trend line through the 1398 data points shows a 1.7 percent increase in fuel flow rate after 1500 revenue flight cycles from the start of airline service on engines with no repairs.

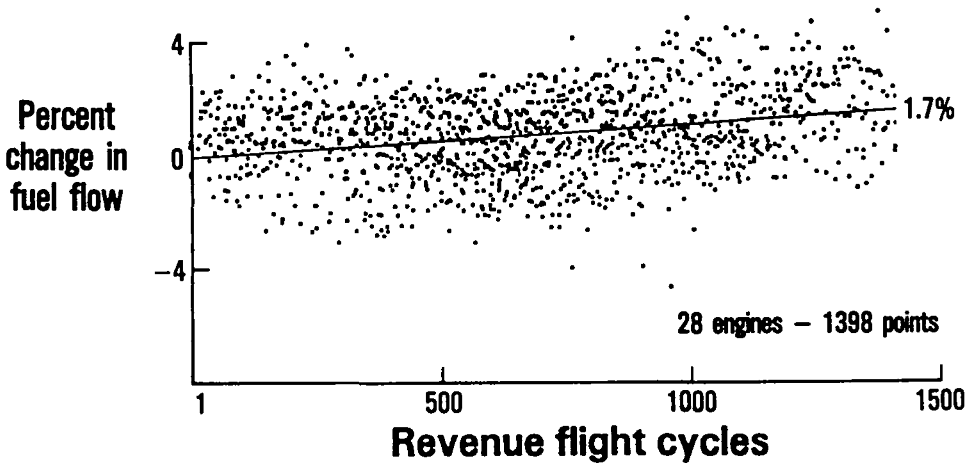


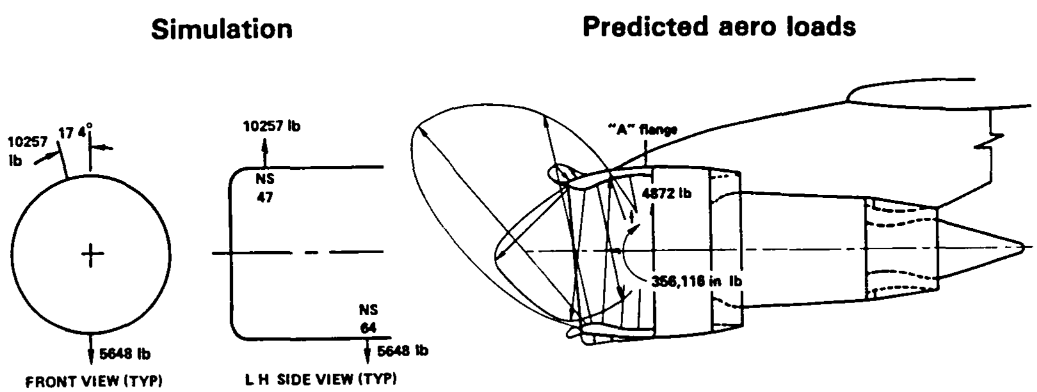
Figure 6 Cruise Fuel Flow Trend with Usage for Pan American 747SP/JT9D-7A Unrepaired engines. (J24873-7)

An analytical model (Reference 4) was developed to predict performance deterioration due to the cumulative clearance closures and rubs caused by quasi-steady (slowly varying with time) mechanical loads. The loads considered were aerodynamic loads on the inlet, maneuver-induced "g" and gyro loads, and thrust loads. Using Boeing-supplied load inputs, the model identified aerodynamic loads as a prime cause of short-term rub-induced deterioration.

A similar analytical study considered the effects of dynamic loads, as might occur due to a sudden gust in flight or a hard landing, on running clearances and possible rubs. The results of this effort (Reference 5) indicated that with the possible exception of the once-in-a-lifetime hard landing, dynamic loads do not contribute to engine performance deterioration.

The short-term load-induced performance loss, though not significantly contributing to revenue service wear, does present a challenge. If it can be eliminated or significantly reduced, the new airplane could be delivered to the airline with up to 1.1 percent improved sea level thrust specific fuel consumption which is equivalent to 0.8 percent improved cruise thrust specific fuel consumption.

The final two data-gathering tasks of the JT9D diagnostics program were test programs directed toward a better understanding of this load-induced wear. The first of these tasks was the Simulated Aerodynamic Loads Test conducted in a Pratt & Whitney Aircraft test stand. The objectives of this test program were to determine the changes in engine operating clearances and performance under: 1) thrust and thermal loads, 2) static simulated aerodynamic flight loads (Figure 7), and 3) the combination of thrust, thermal and static aerodynamic loads during engine operation. Test results were expected to permit validation of the levels, module distribution, and causes of short-term performance losses. In addition, the test program would validate or permit refinement of previous analytical study results on the impact of aerodynamic flight loads on performance losses. To accomplish these objectives, a JT9D-7 engine was analytically rebuilt with average production clearances and new seals as well as extensive instrumentation to monitor performance, case temperatures, and clearance changes. A special loading device was designed and constructed to permit application of Boeing-predicted moments and shear forces to the engine by the use of cables placed around the flight inlet. These loads simulated Boeing's estimated aerodynamic pressure distributions that occur on the 747 airplane inlet in various important segments of a typical airplane flight.



Maximum resultant at "A" flange

	Simulated	Predicted
Moment	356,288	356,116

Figure 7 Inlet Air Loads at Take-Off Rotation. (J21704-193)

The test engine and loading device were installed in the Pratt & Whitney Aircraft X-Ray Test Facility, shown on Figure 8, to permit the use of X-ray techniques in conjunction with laser probe clearance measuring instrumentation to monitor important engine clearance changes under both steady state and transient engine operating conditions. Upon completion of the Simulated Aerodynamic Loads Test program, the test engine was analytically disassembled, and the condition of gas-path parts and final clearances were extensively documented.

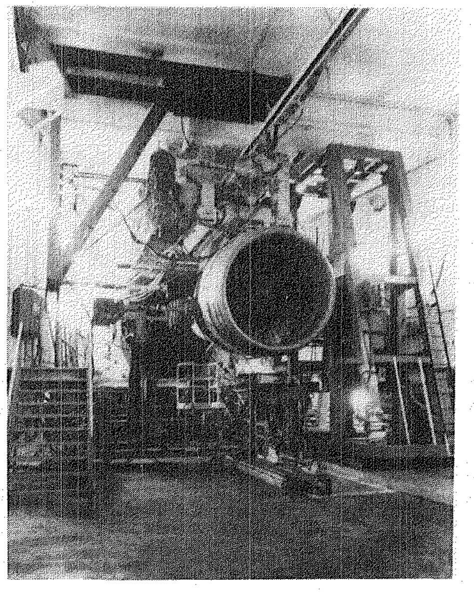


Figure 8 X-Ray Facility with Test Engine Installed. (J24603-15)

The performance monitoring calibrations between tests indicated that the engine lost 1.1 percent in sea level take-off thrust specific fuel consumption due to permanent clearance changes caused by the application of these inlet loads, thus validating the short-term deterioration results of the prior phase of the diagnostics program.

The overall engine performance loss was distributed among all modules; however, the low-pressure compressor and high-pressure turbine rub-induced efficiency loss and flow capacity changes were the major contributors to short-term performance loss.

Transient testing, conducted after completion of the simulated aerodynamic loading, indicated no additional performance losses associated with transient engine operation.

The Flight Loads Test was the final phase of the JT9D Diagnostics Program. It was conducted as a joint effort with the Boeing Commercial Airplane Company. Boeing, under contract with NASA-Langley, provided the test airplane and measured the flight loads on the instrumented engines. Pratt & Whitney Aircraft, under contract with NASA-Lewis, provided the instrumented engines and measured the effects of the flight loads on the engines. The Flight Loads Test was conducted to verify the simulated aerodynamic loads used in the X-ray Load Test program and to further expand on the flight conditions and flight load effects measured in that program. Specifically, the flight loads test objectives were to:

- o Measure the flight loads (aerodynamic, inertial, and gyroscopic) typical of acceptance test and revenue service;

- o Explore the effects of airplane gross weight, sink rate, pitch rate, and various maneuvers on flight loads applied to engine and nacelle;

- o Simultaneously measure engine running clearances, closures, and performance changes resulting from these maneuvers; and

- o Analyze the results, refine the performance deterioration prediction models, and develop recommendations to improve performance retention of the propulsion system.

The Flight Loads Test program utilized the Boeing RA001 test 747 airplane with two partially refurbished and instrumented JT9D-7A engines (Figure 9). Most of the instrumentation was placed on engine 3. It was believed that the inboard engine was subjected to higher angles of attack than the outboard engine because wing bending reduced the incidence of the outboard nacelle and because the outboard nacelle was less affected by upward airflow induced by the wing flaps. Therefore, the inboard nacelle was expected to sustain greater flight loads and was chosen for a more detailed survey.

Instrumentation included pressure taps on the fan inlets to continuously map the pressure flow field, accelerometers and rate gyros to measure inertia loads on engine and airplane, laser clearance measuring probes to monitor fan and high-pressure turbine running clearances, thermocouples to monitor turbine case temperatures, and engine and airplane performance monitoring instrumentation. All instrument systems were recorded continuously by time-synchronized systems to permit subsequent matching of flight loads and their effects on the engine.

The planned test program began with a production airplane acceptance flight (Figure 10) to document the predelivery performance loss. In subsequent flights, conditions with more stringent aerodynamic and inertial loads typical of revenue service were flown. These conditions included variations in take-off gross weight, flap setting, and power level plus high-"g" turns. Data were also recorded in two conditions outside the normal flight envelope. These conditions were a high gross weight, high sink rate landing and an airplane stall.

Figure 9 Boeing-Owned 747 Test Airplane. (J24018-5)

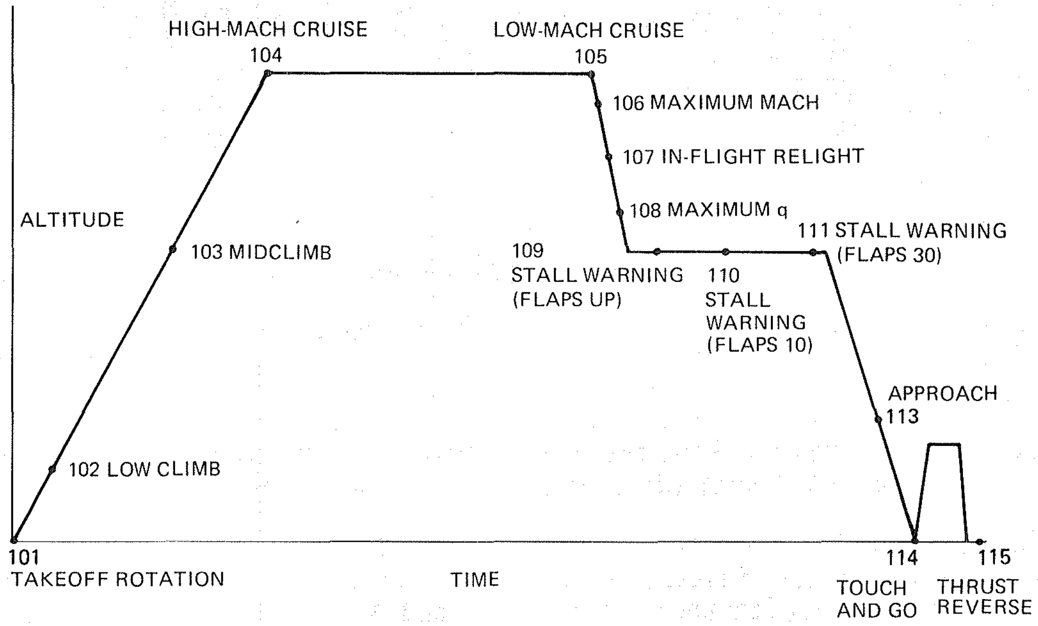


Figure 10 Production Airplane Acceptance Flight Profile.

Analysis of these load and clearance closure data verified the importance of aerodynamic loads and added new information to the short-term deterioration evaluation. Aerodynamic loads were shown to be a function of the airflow into the engine inlet and the degree of bending of that air stream to enter the inlet. These aerodynamic loads were found to be larger than predicted. Thus, maximum aerodynamic loads occurred under conditions combining high power and high airplane angle of attack. The aerodynamic load was the dominant effect on fan clearance; thus, the critical fan operating condition was at take-off. Figure 11 shows the change in fan clearance during ground idle, acceleration to full power, rolling down the runway, take-off, and climb for each of the four laser clearance-measuring probe locations. The initial acceleration causes greater closure at the bottom of the engine since the centrifugal and thrust bending effects are additive.

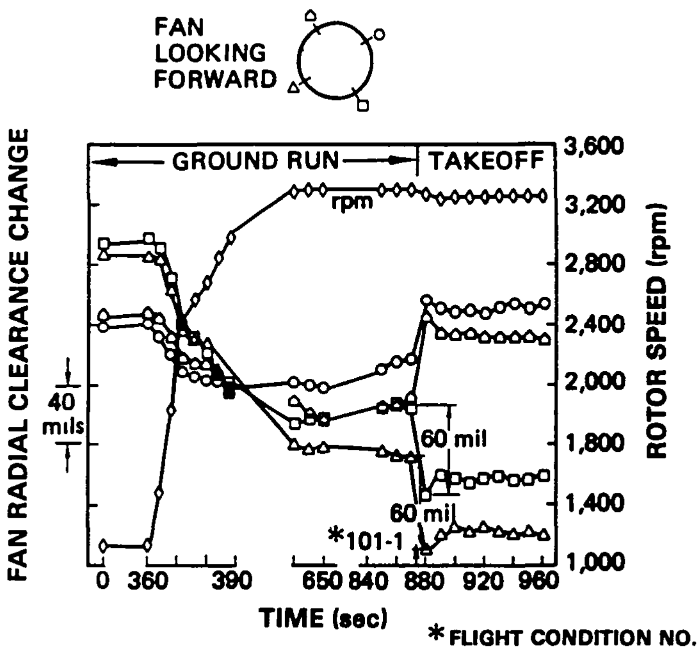


Figure 11 Change in Fan Running Clearance from Stabilized Idle to Take-Off at 612,000 pounds TOGW with 20-degree Flaps.

At take-off rotation the aerodynamic load builds up causing an upward deflection of the inlet, resulting in further closing of clearances at the bottom and clearance opening at the top. Closure was greater at take-off with 10-degree flaps and at high gross weights as a result of the higher aerodynamic loads.

The maximum clearance closure in the high-pressure turbine was shown to be the result of a combination of effects. Centrifugal expansion, thrust and aerodynamic load-induced case bending, and differential thermal expansion all combined to close down running clearances. Thus, during the typical revenue flight cycle, maximum turbine clearance closure occurred during early climb when the aerodynamic loads were still reasonably high and thermal equilibrium had not been reached. Figure 12 shows that centrifugal expansion, thrust loading, and blade and case thermal expansion initially closed the running clearance as power was increased. Aerodynamic loads at take-off closed the clearance an additional 5 mils at the bottom of the engine. However, the slow thermal expansion of the rotor disk continued the axisymmetric closure for an additional 4 minutes. The maximum closure increased slightly with greater take-off gross weight.

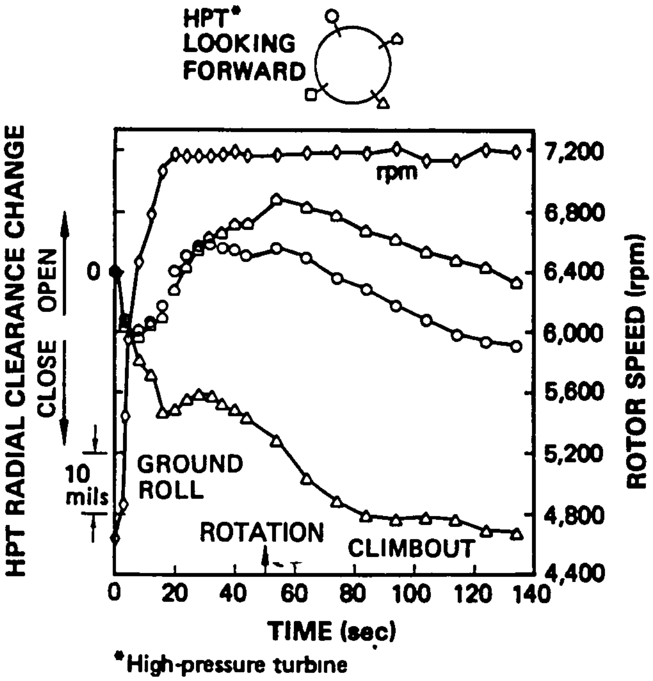


Figure 12 Change in High-Pressure Turbine Clearance from Ground Roll to Take-Off at 571,000 pounds TOGW with 10-degree Flaps.

SECTION 4.0

ENGINE PERFORMANCE RETENTION PREDICTION MODELS

One of the major objectives of this program has been the development and refinement of analytical models for predicting the deterioration with engine usage of both the complete JT9D engine and the individual modules. These models consist of families of curves which define the changes in the performance parameters (efficiency, flow capacity) with usage for each of the engine modules. These parameter changes are applied to the JT9D performance analysis program to determine the predicted performance change with usage of an average engine. The preliminary models were prepared based on analysis of the performance, engine usage, and replaced-parts condition data collected during the first phase of the program. All the in-service data collected on the Pan American 747SP fleet was used for the first refinement of the models. This effort was followed by a second and third refinement based on the results of the simulated and actual flight test results.

Figure 13 shows the analytical-model predicted performance deterioration at sea level for an average JT9D-7 engine, by module contribution and by cause. The model includes the production acceptance test loss which occurs prior to airplane delivery. The model also assumes no engine repairs with the exception that the high-pressure turbine has been stabilized at a constant level after 1000 flight cycles by a hot section maintenance program. As seen, the low-pressure compressor and high-pressure turbine are most sensitive to early rub-induced deterioration. Erosion of airfoils and seals is the prime contributor to long-term deterioration in the engine cold section as shown on Figure 13, while thermal distortion is the prime contributor in the hot section.

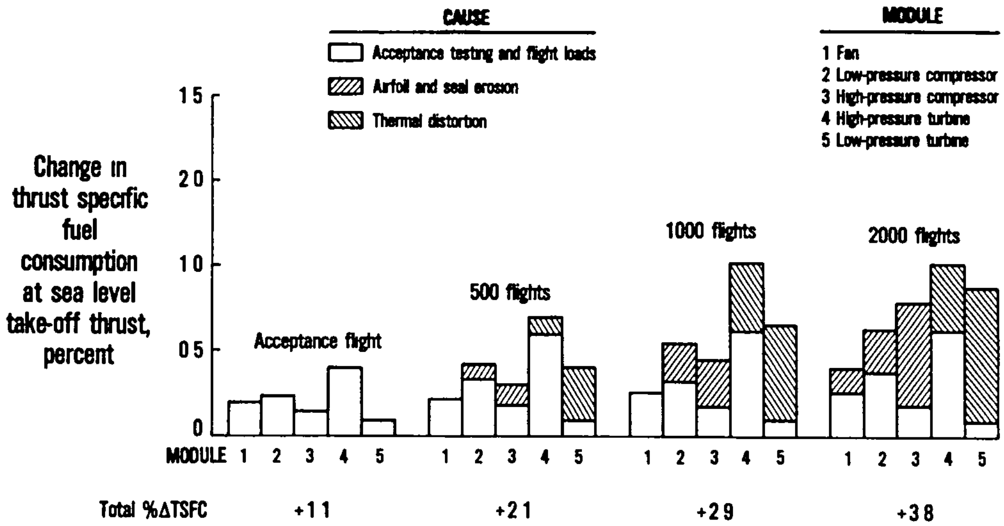


Figure 13 Predicted Performance Deterioration at Sea Level Relative to Production Engines by Module Contribution and by Cause. (J26090-15)

To validate the models at cruise conditions, it was first necessary to establish actual in-flight average performance. The engine condition monitoring data, as shown in Figure 6, and in-flight calibration data, collected on unrepaired Pan American 747SP/JT9D-7A engines from start of revenue service to 1500 flight cycles, provided this performance data. Performance at cruise conditions was determined to be less sensitive to component deterioration than performance at sea level. This reduced sensitivity results from the fact that the ram pressure ratio increases the nozzle pressure ratio at cruise and, thus, makes performance less sensitive to gas generator losses. This effect has also been demonstrated in the Pratt & Whitney Aircraft (Willgoos) altitude test facility. The result is that the increase in cruise thrust specific fuel consumption due to component deterioration is about 75 percent of the increase at sea level. The JT9D performance retention model supports the results and was used to develop the curves on Figures 1 and 2.

SECTION 5.0

CONCLUSIONS

Performance deterioration in the JT9D is made up of short-term and long-term effects, all of which are flight cycle sensitive. Short-term deterioration is caused by blade and seal rubs which open running clearances in all modules, thus reducing efficiencies and changing flow rates. Short-term deterioration occurs primarily during predelivery airplane acceptance testing, influencing the initial performance more than the performance retention. Long-term deterioration is caused by erosion in the cold section and thermal distortion in the hot section. Erosion of airfoils and seals is a continuing effect which blunts and wears airfoils, thus reducing their efficiency and opening running clearances with resultant reduction in module efficiency and change in airflow. Thermal distortion of turbine vanes and structure reduces vane efficiency, increases secondary coolant leakage, and contributes to further airfoil seal rubs in the turbine.

Short-term rub-induced deterioration occurs primarily during take-off and climb when aerodynamic and power-induced loads are at a maximum. Erosion occurs during take-off, landing, and ground operation when foreign object ingestion is greatest. Thermal distortion occurs at high power when turbine temperatures are highest. Thus the JT9D engine deterioration is a flight cycle phenomenon.

Performance retention within 1 to 2 percent of initial revenue service performance can be maintained with a proper program of hot section and cold section maintenance.

SECTION 6.0

RECOMMENDATIONS

The JT9D Engine Diagnostics program established a number of approaches for the improvement of JT9D performance retention. These approaches fall into the following three categories: operator action, airframe manufacturer action, and engine manufacturer action.

Operator Action

- Use take-off with 20-degree flaps whenever conditions permit to reduce the maximum aerodynamic load, thereby reducing cold section seal rubs.

- Use take-off at derated power whenever conditions permit to reduce hot section thermal distortion.

- Minimize extended high power operation immediately prior to start of take-off to prevent turbine rub due to combined effect of maximum thermally-induced and mechanically-induced clearance closures.

- Allow time for rotor temperature to stabilize following deceleration and prior to next power acceleration, whenever possible, to minimize rubs induced by a hot rotor/cold case interaction; see Reference 2.

- Follow the modular maintenance recommendations listed in Reference 2 and adhere to the build standards in the Pratt & Whitney Aircraft JT9D Overhaul and Repair Manuals.

Airframe Manufacturer Action

- Modify the production airplane acceptance test to use take-off with 20-degree flaps rather than 10-degree flaps and reduce power level during test maneuvers involving high angle of attack such as stall warnings to reduce aerodynamic load-induced rubs and subsequent performance loss during acceptance testing.

Engine Manufacturer Action

- Continue development of gas-path clearance control systems and abradable rub strips to provide closer running clearances.

- Investigate the extent and cause of thermally-induced closures in the high-pressure turbine with the goal of minimizing nonsymmetric closures.

- o Develop improved erosion resistant coatings and materials for the cold section of the engine.
- o Develop designs to reduce ingestion of erosive materials into the compressor section of the engine.
- o Develop designs to reduce hot section temperature profile shifts and the resultant thermal distortion of gas-path parts.
- o Include clearance monitoring in the development testing of new engines.

Joint Airframe Manufacturer/Engine Manufacturer Action

- o Investigate methods of structurally integrating the engine and the nacelle to reduce the asymmetric closure due to aerodynamic and thrust loads.

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