# JT9D JET ENGINE DIAGNOSTICS PROGRAM*

W. J. Olsson and W. J. Stromberg
Pratt & Whitney Aircraft Group

## SUMMARY

The NASA JT9D Engine Diagnostics Program has been a four-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, 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 was 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 small effect on revenue service performance retention. The long-term deterioration continues throughout engine life with a negative effect on performance retention.

The combined effect of the short- and long-term deterioration modes for the JT9D-7 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.

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 induced engine deflections with resulting rubbing of airfoils and seals. Wearing of blades and seals occurs 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. The results show a 0.8 percent increase in flight thrust specific fuel consumption during the predelivery airplane acceptance testing and an additional 0.3 percent increase during early revenue service.

Long-term performance deterioration is also a flight cycle related phenomenon. It is caused by erosion of airfoils and gas-path seals during

* This work was conducted by Pratt & Whitney Aircraft for the National Aeronautics and Space Administration under Contract NAS3-20632.

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 chord, and further opening running clearances. Thermal distortion of airfoils results from high-temperature cycling of the airfoils with resultant gas-path leakage and loss of optimum airfoil shape.

The diagnostics program has shown that performance retention within 1 to 2 percent of initial revenue performance can be maintained with a proper program of hot section and cold section maintenance as shown on figure 2.

## INTRODUCTION

The NASA JT9D Engine Diagnostics Program is a part of the NASA sponsored Engine Component Improvement (ECI) Project which is directed toward improving the fuel consumption of selected current high bypass ratio turbofan engines and their derivatives by 5 percent over the life of these engines. The ECI project is divided into two subprojects: Performance Improvement and Engine Diagnostics. Performance Improvement is directed toward developing fuel saving component technology which may be applied to current engines and their derivatives. Engine Diagnostics is directed toward identifying and quantifying engine performance losses that occur during the engine's service life and developing criteria for minimizing these losses, as shown on figure 3. The JT9D Jet Engine Diagnostics Program, which is now nearing completion, has successfully identified and quantified the various causes of JT9D performance deterioration and the possible approaches toward improved performance retention.

This paper will briefly describe the various approaches used in this project and the results and conclusions that have been reported to date.

## APPROACH

The ideal approach for determining the cause and extent of engine deterioration would consist of tracking a large number of individual engines from production testing through extended revenue service, monitoring their flight performance with expanded instrumentation, closely tracking their maintenance histories, then correlating specific maintenance events, performance shifts, and operational history. For numerous reasons this procedure was not feasible. Therefore, we took the following 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; thus, both ample high-time and new engine data were available.

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.

- o In-flight engine monitoring data to establish the relation between ground performance and cruise performance changes.

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

- o There are four generic causes of engine performance deterioration, namely: 1) flight-load induced clearance changes; 2) erosion of fan and compressor airfoils and seals; 3) thermal distortion of hot section parts; and 4) variations in airline repair standards.

- o Performance deterioration trends may be divided into two distinct time periods: short-term and long-term deterioration. The prime cause of short-term deterioration is flight-load induced rubs which open gas-path clearances, thus reducing module efficiencies and influencing airflow. The analysis of the historical data as seen on figure 4 showed a 1 percent 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 Performance deterioration then occurs at a slower rate dominated by erosion of cold section airfoils and seals, with resulting blunting of airfoils and further opening of running clearances. This erosion and thermal cycle induced distortion of hot section airfoils results in loss of airfoil efficiency and increased secondary flow leakage. The historical data showed the sea level thrust specific fuel consumption to have increased to about 4 percent above production levels after acceptance testing and 3000 revenue flight cycles of an unrepaired engine operation as seen on figure 5.

- o The deterioration of the turbine airfoils and seals results from changes in their environment. These changing temperature and flow patterns are caused by deterioration in the compressor and combustor modules. Thus, more frequent cold section maintenance pays off in reduced deterioration in the higher priced hot sections.

- o 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 2 percent recovery with increased cold section and hot section refurbishment.

The first phase of the program provided an abundance of information but left numerous gaps in the data. The second phase, or in-service engine performance study, conducted jointly with Pan American World Airways, expanded the data base significantly by allowing us to monitor a controlled sample of 28 JT9D-7A engines in the Pan Am 747SP airplane fleet from preflight testing of the engines at Boeing through 2100 flight cycles of operation. 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 flight condition monitoring data from the fleet; prerepair and postrepair calibrations and repair histories on each of these engines that came into the shop; and an expanded instrumentation calibration and complete analytical teardown of one of the engines after 141 flight cycles (see figure 6).

The results of this effort firmly established that the flight-loads induced short-term deterioration occurs in the first few flights prior to revenue service. It provided ample data for the refinement of the various engine module deterioration prediction models which were first developed on the basis of the historical data. Finally, it 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 available instrumentation systems. However, the data sample was large enough that statistical trends could be drawn. One such set of data is 747SP engine conditioning monitoring (ECM) fuel flow data shown on figure 7. 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.

The short-term flight-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 percent improved sea level thrust specific fuel consumption which is equivalent to 0.8 percent improved cruise thrust specific fuel consumption. Previous studies have estimated that more than 80 percent of the flight-load induced damage is caused by aerodynamic (pressure) loads applied to the fan cowl, and the remaining damage is caused by inertia loads from gusts and hard landings plus maneuver-induced gyroscopic loads.

The final two data gathering tasks of the JT9D diagnostics program were test programs directed toward a better understanding of this flight-load induced wear. The first of these 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 8; and (3) the combination of thrust, thermal, and static aerodynamic loads during engine operation to permit validation of the levels, module distribution, and causes for 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, an engine was analytically built 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 known moments and shear forces to the engine by the use of cables placed around the flight inlet. These loads simulated the estimated aerodynamic pressure distributions that occur on the inlet in various important segments of a typical airplane flight.

The test engine and loading device were installed in the Pratt & Whitney Aircraft X-Ray Test Facility, shown on figure 9, 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 flight-load test program, the test engine was analytically disassembled and the condition of gas-path parts and final clearances was extensively documented.

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. Another 0.2 percent change in thrust specific fuel consumption was produced by an increase in airfoil surface roughness in the low-pressure compressor and thermal distortion in the high-pressure turbine. This additional 0.2 percent was a result of the experimental nature of this test program and does not occur in early revenue service. Prior to the test program, the change in sea level performance due to clearance changes was predicted to be 0.9 percent. Therefore, the agreement between measured and predicted performance is considered to be satisfactory.

The overall engine performance loss was distributed among all modules; however, the low-pressure compressor and high-pressure turbine contributed the major portion of the loss. The major permanent clearance changes (seal rubs) occurred in the fan, high-pressure compressor, and high-pressure turbine and were found to be the direct result of the loads imposed. Table I compares these results with previous comparisons of module contribution to sea level performance changes with early usage.

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 as listed on figure 10.

The test approach was to install an analytically built and instrumented engine in position No. 3 on the Boeing test 747 (RA001) airplane and an analytically built and instrumented fan case on the position No. 4 engine, figure 11. The analytically built engine was calibrated at Pratt & Whitney Aircraft before delivery and then again after installation in the aircraft, prior to flight testing.

A series of flight tests was conducted with progressively increasing flight loads. Continuous, simultaneous measurements with all data systems were recorded to accurately document the cause and effect relationship of flight loads to engine deterioriation. Performance and fan clearances were documented after each flight by calibrations and rub measurements to determine the effect of increasing loads.

A final postflight calibration at Pratt & Whitney Aircraft and an analytical teardown of the analytically built engine was conducted following the flight program to quantify the effects of the flight loads, figure 12.

Instrumentation included pressure taps on the positions No. 3 and 4 nacelles to measure the aerodynamic loads, accelerometers on both engines to measure inertia loads, and rate gyros on both engines to measure gyroscopic loads. Clearance closures were monitored by laser probes on the high-pressure turbine of the position No. 3 engine and on both fans. Thermocouples on the high-pressure turbine of the position No. 3 engine measured the transient and steady state thermal effects on the running clearances. Finally, expanded performance instrumentation on position No. 3 engine permitted closer performance monitoring since it was the prime data source. The position No. 4 engine was instrumented sufficiently to identify clearance and load differences due to its position on the wing.

The flight loads testing was successfully completed, and the test data analysis is now in process. The clearance closures at actual flight conditions generally repeated the measured closures in the X-ray load test program under simulated flight loads, see figure 13. This program also confirmed that aerodynamic loads occurring during high power operation, that is, take-off rotation, airplane power-on stalls, and high G maneuvers, are the prime cause of fan performance deterioration. In addition, the preliminary analysis indicates that the combination of mechanical loads and transient thermal expansion during the extended high power climb is the prime cause of short-term deterioration in the high-pressure turbine.

The final report of the flight test program will be issued this fall and will include a final refinement of the performance deterioration models, including analytical results of the X-ray load test and the flight load test.

## ENGINE PERFORMANCE RETENTION PREDICTION MODELS

One of the major objectives of this program has been the development and refinement of analytic 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 various 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 in 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 just-completed second refinement of the short-term deterioration predictions based on the X-ray load test results. Table I compares representative results from the different data sources. Figures 14 and 15 show the thrust specific fuel consumption changes at sea level for an average engine versus usage as predicted by the latest model. For that model, it was assumed that high-pressure turbine performance had been stabilized at a constant level after 1000 flight cycles and the low-pressure turbine after 2000 cycles by a hot section maintenance program. Figure 14 subdivides the predicted deterioration by module. As seen, the low-pressure compressor and high-pressure turbine are most sensitive to early flight-load induced deterioration. Erosion of airfoils and seals is the prime contributor to long-term deterioration in the cold section as shown on figure 15, while thermal distortion is the prime contributor in the hot section. One more refinement of these models will be made after completion of the flight loads test data analysis.

To validate the models at cruise conditions, it was first necessary to establish actual in-flight average performance. The engine condition monitoring 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 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 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. Evaluation of cruise performance data from the flight loads test will permit a further refinement of the cruise performance retention model.

## CONCLUSIONS

Performance deterioration in the JT9D-7 is a flight sensitive phenomenon caused by a short-term and two long-term wear modes. The short-term deterioration occurs primarily during airplane acceptance testing and, therefore, does not affect airline operation. The long-term wear takes place continuously over the engine life so that the performance loss can be minimized by a sound maintenance program. Short-term deterioration is primarily due to flight-load induced blade and gas-path seal wear which result in increased gas-path running clearances. The wear occurs in all engine modules but has the most deleterious effect on the low-pressure compressor and high-pressure turbine performance. The wear occurs during conditions that combine minimum axisymmetric running clearances and maximum engine distortion or asymmetric closure.

Minimum axisymmetric clearance occurs during high power operation due to the combined effect of centrifugal forces and high metal temperatures. Maximum asymmetric closure is caused by airplane maneuver induced aerodynamic loads and thrust induced engine bending loads. Thus, short-term deterioration is a cyclic effect in that it occurs during take-off and climb and other maneuvers which combine high aerodynamic loads and high engine power. Cruise, approach, and landing do not contribute to short-term deterioration.

Long-term deterioration is also flight cycle dependent. It is caused by erosion of the airfoils and seals, which cause airfoil roughness, bluntness, chord loss, and increased gas-path clearances, and by thermal distortion of turbine airfoils which reduces their efficiency and increases leakage.

Ingestion of foreign matter during taxi, take-off, and landing operations is the primary cause of erosion. Changing gas-flow patterns caused by erosion plus thermal cycling of the engine are the prime causes of thermal distortion of the turbine airfoils. The split of deterioration by module on figure 14 shows the increasing importance of high-pressure compressor and low-pressure turbine in long-term deterioration.

The refined performance deterioration prediction model shows a 2.1 percent increase in cruise thrust specific fuel consumption in the first 1500 revenue flight cycles. The program results also show that a good program of both hot section and cold section maintenance can maintain cruise performance between 1 and 2 percent of that at start of revenue service.

## RECOMMENDATIONS

Based on the results of the completed phases of the JT9D Diagnostics Program and the preliminary results of the Flight Loads Test Program, the following recommendations, summarized on figure 16, are made toward improved performance retention in current and future propulsion systems.

Performance retention in current engines can best be maintained by following improved maintenance practices which have been developed jointly with the airlines, based on the early findings of this and industry-sponsored programs. These improved practices provide both cold-section and hot-section refurbishment, and the potential results are summarized on figure 17.

Performance retention in future propulsion systems will benefit from the following:

- o Performance deterioration caused by flight loads and thrust-induced loads will be minimized by integrated engine and nacelle designs that consider the effects of both flight loads and thrust loads.

- Further development of gas-path clearance control systems and abradable rub strips will provide closer running clearance control in the high-pressure turbine.

- Erosion effects on cold section airfoils and seals will be minimized by improved coatings and materials and the consideration of refined gas-path designs for reducing the ingestion of erosive material.

- Erosion effects on hot section airfoils and seals will be minimized by improved high temperature materials.

- Thermal distortion effects will be minimized by refined gas-path designs and improved maintenance programs that reduce temperature profile shifts.

TABLE I

COMPARISON OF MODULE CONTRIBUTION TO
SEA LEVEL TSFC DETERIORATION

| | Historical Data Analysis (149 Cycles) | In-Service Engine Analysis (150 Cycles) | P&WA Testing of P-695743 (141 Cycles) | Simulated Aero-dynamic Loads Test of P-662211 |
|---|---|---|---|---|
| | Change in TSFC (%) at Sea Level Static Take-Off Thrust | | | |
| Fan | +0.1 | +0.2 | +0.1 | +0.2 |
| Low-Pressure Compressor | +0.2 | +0.4 | +0.4 | +0.3 |
| High-Pressure Compressor | +0.3 | +0.2 | +0.3 | +0.2 |
| High-Pressure Turbine | +0.4 | +0.4 | +0.6 | +0.5 |
| Low-Pressure Turbine | +0.5 | +0.1 | +0.1 | +0.1 |
| TOTAL | +1.5 | +1.3 | +1.5 | +1.3 |

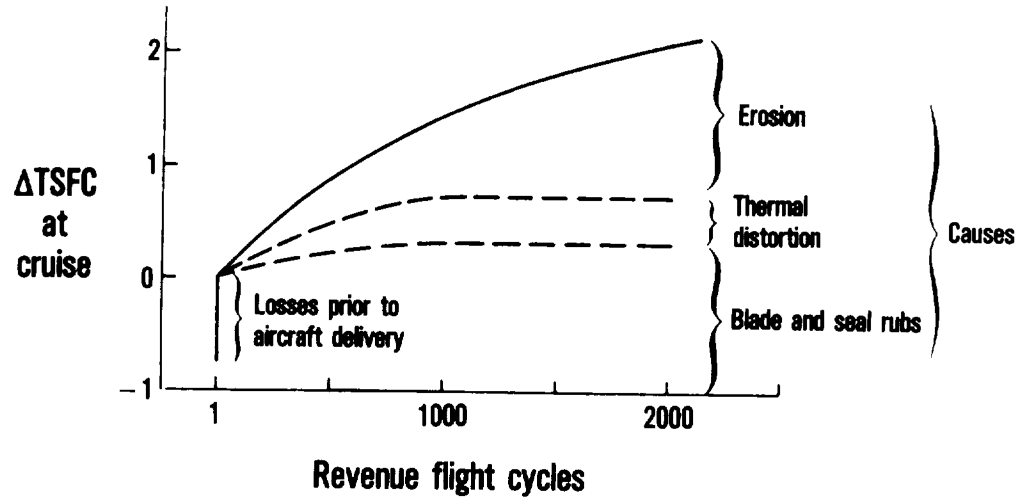



Figure 1 JT9D-7A In-Service Engine Performance Deterioration at Altitude Cruise Conditions. (J24873-2)

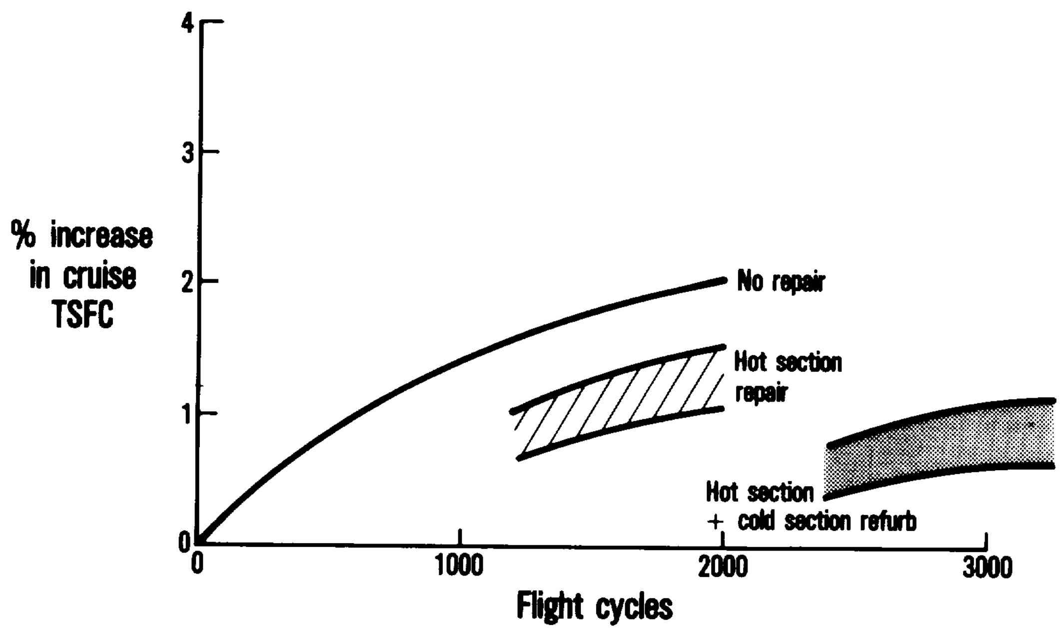



Figure 2 Effect of Repair on JT9D-7A Engine Cruise Thrust Specific Fuel Consumption. (J24603-24)

1. **Define scope of JT9D performance deterioration**
2. **Identify and quantify sources of JT9D performance deterioration**
3. **Determine sensitivity of component performance to engine parts deterioration**
4. **Develop analytical model of JT9D performance deterioration**
5. **Recommend performance retention techniques for current and future engines**

Figure 3 JT9D Diagnostics Program Objectives. (J23878-4)

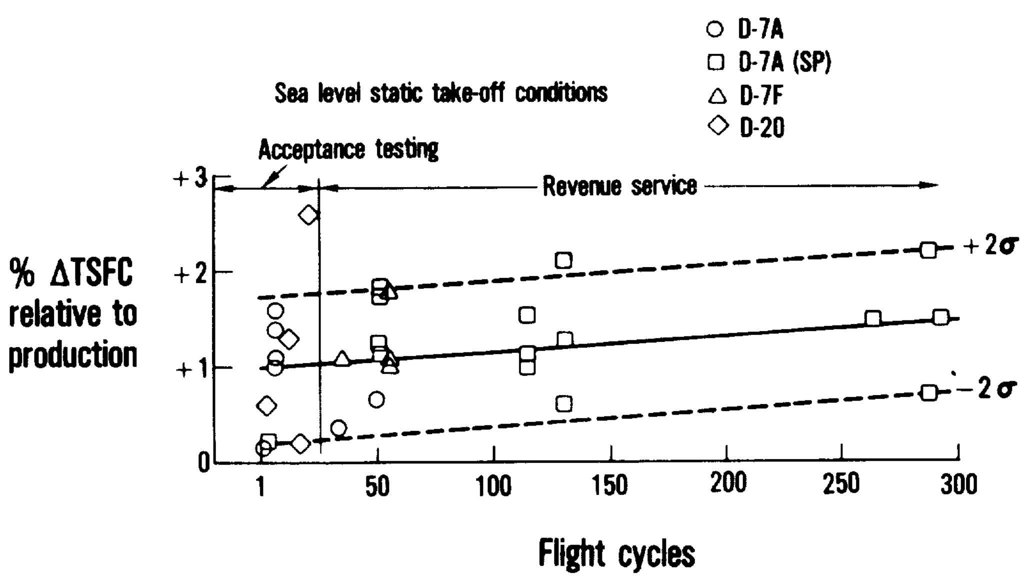



Figure 4 Historical Short-Term Deterioration Data. (J24873-4)

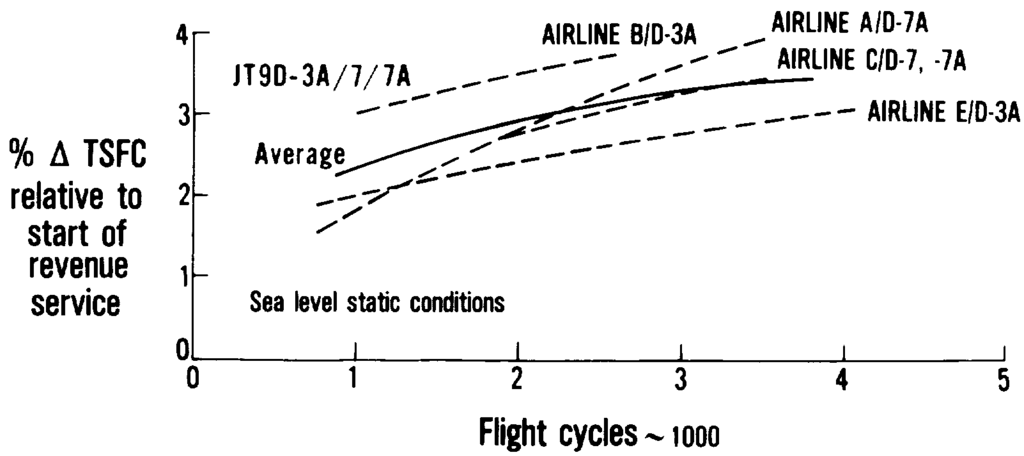
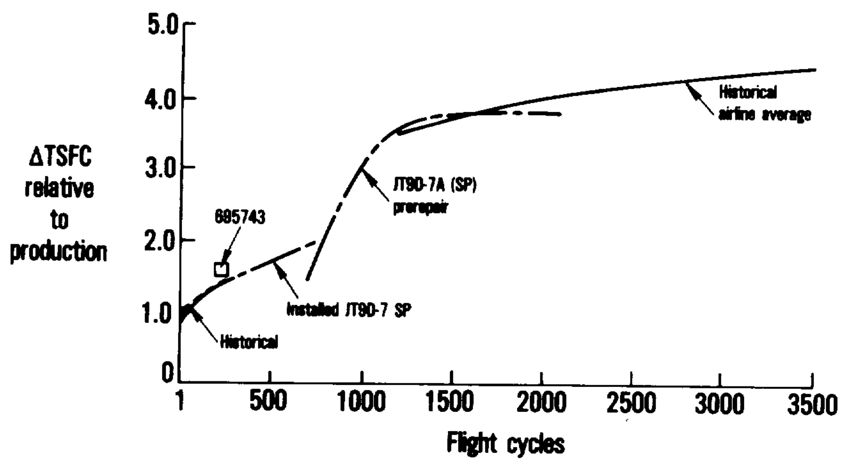



Figure 5  Historical Long-Term Deterioration Data for Unrepaired Engines.
(J24603-8)




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

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

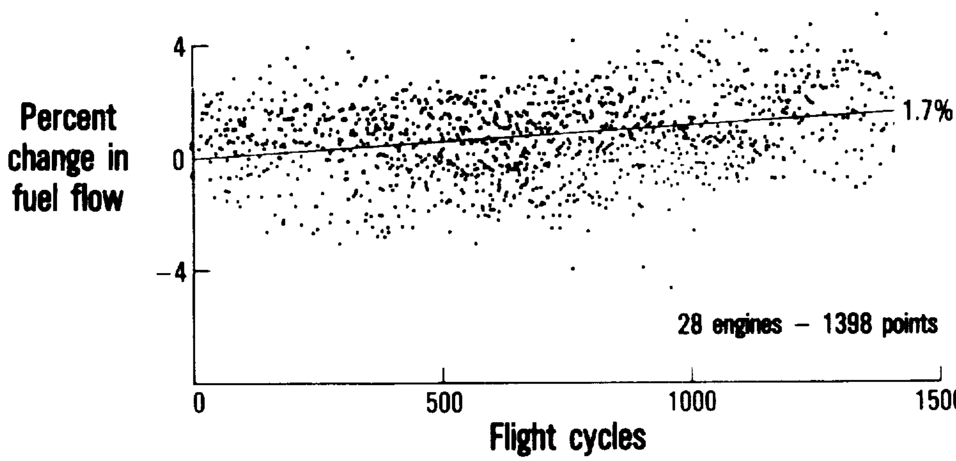
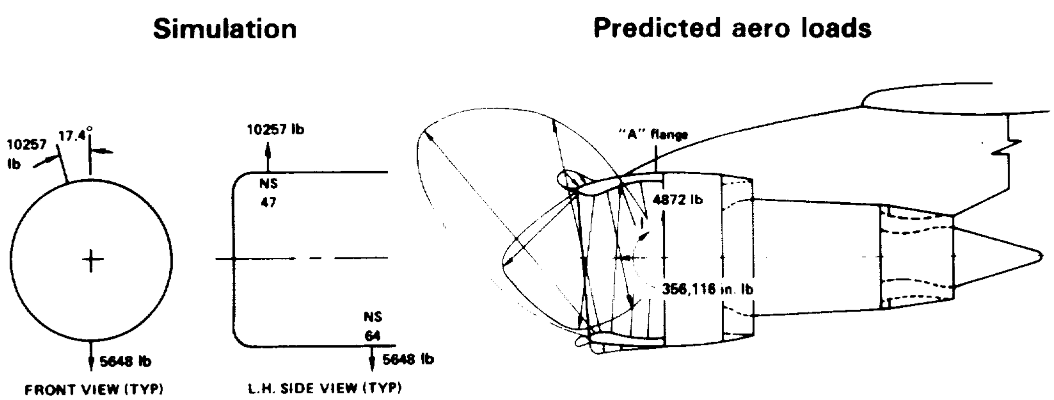



Figure 7 Cruise Fuel Flow Trend with Usage for Pan American 747SP/JT9D-7A Unrepaired Engines. (J24873-7)




**Maximum resultant at "A" flange**

| | Simulated | Predicted |
|---|---|---|
| Moment | 356,288 | 356,116 |

Figure 8 Inlet Air Loads at Take-Off Rotation. (J21704-193)

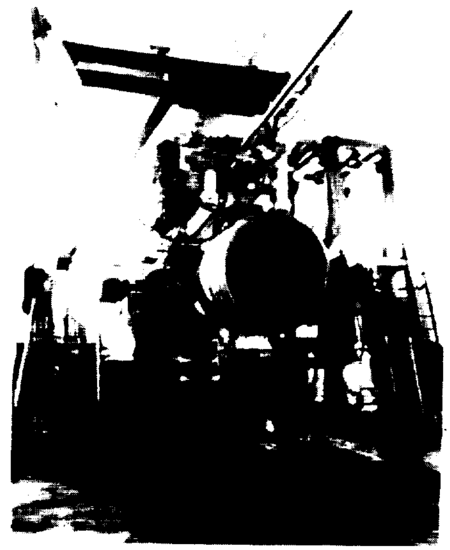


Figure 9 X-Ray Facility with Test Engine Installed. (J24603-15)

- **Measure typical aerodynamic and inertia loads during acceptance test and revenue service**
- **Explore effects of gross weight, sink rate, pitch angle, and maneuvers on nacelle loads**
- **Measure engine clearance closures and engine performance resulting from the airplane maneuvers**
- **Provide data for improved propulsion system designs**

Figure 10 Flight Loads Test Program Objectives. (J24603-3)

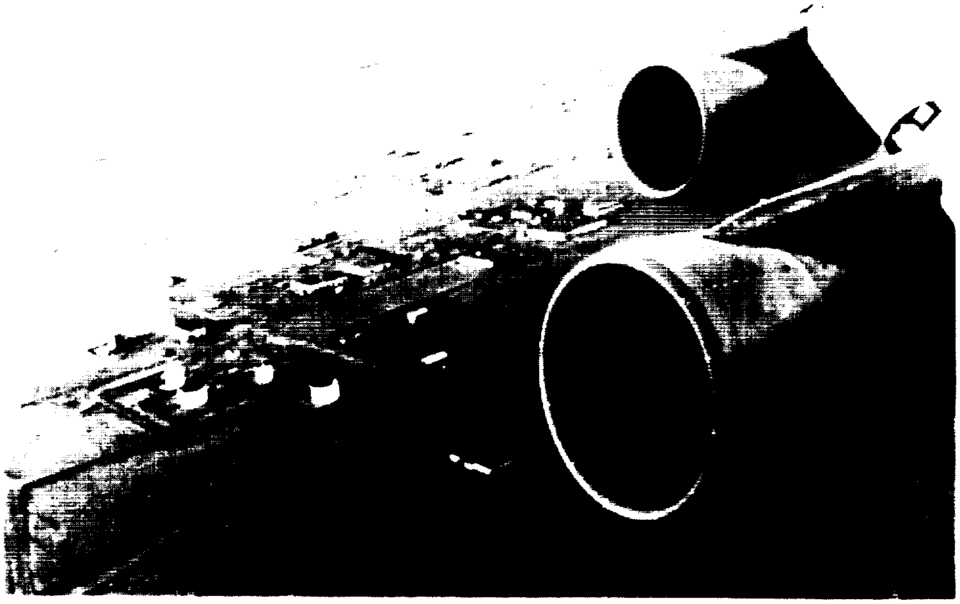


Figure 11 Instrumented JT9D-7A Engine Installed on RA001 Airplane for Flight Loads Test. (J24603-22)

- Analytical build of instrumented fan and high pressure turbine
- Initial engine calibration in test cell
- Installed engine ground calibration
- Production acceptance test flight at 550,000 lb takeoff gross weight
- Installed engine ground calibration
- Wind-up turns to 2Gs
- Installed engine ground calibration
- Heavy gross weight takeoff, maximum dynamic pressure and maximum Mach number
- Installed engine ground calibration
- Final engine calibration in test cell
- Analytical teardown of fan and high pressure turbine

Figure 12 Test and Inspection Sequence for Flight Loads Test Program. (J24018-6)

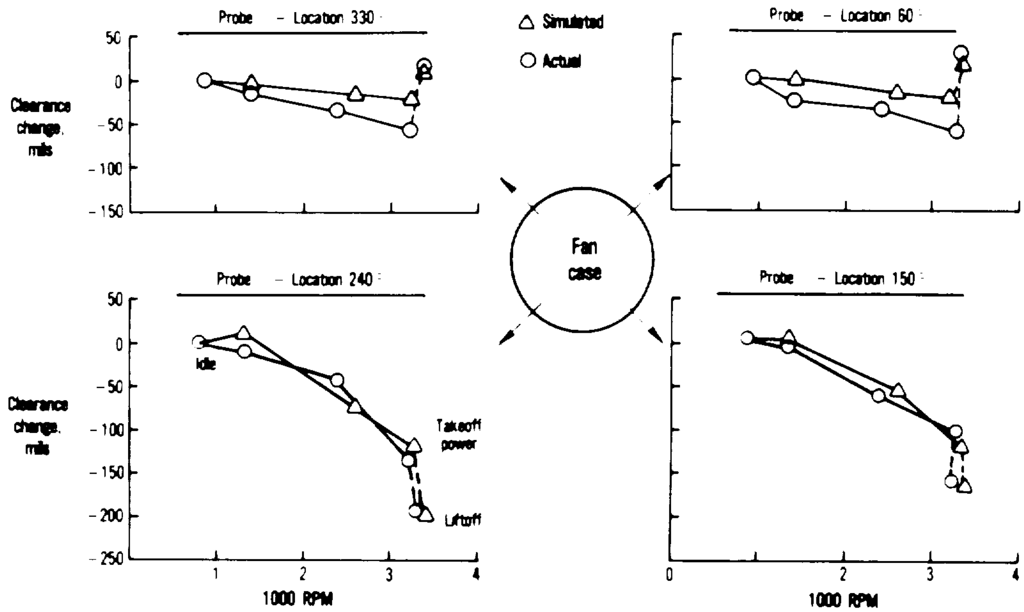



Figure 13 Comparisons of Simulated and Actual Flight Test Fan Closures; Acceleration to Take-Off. (J24873-10)

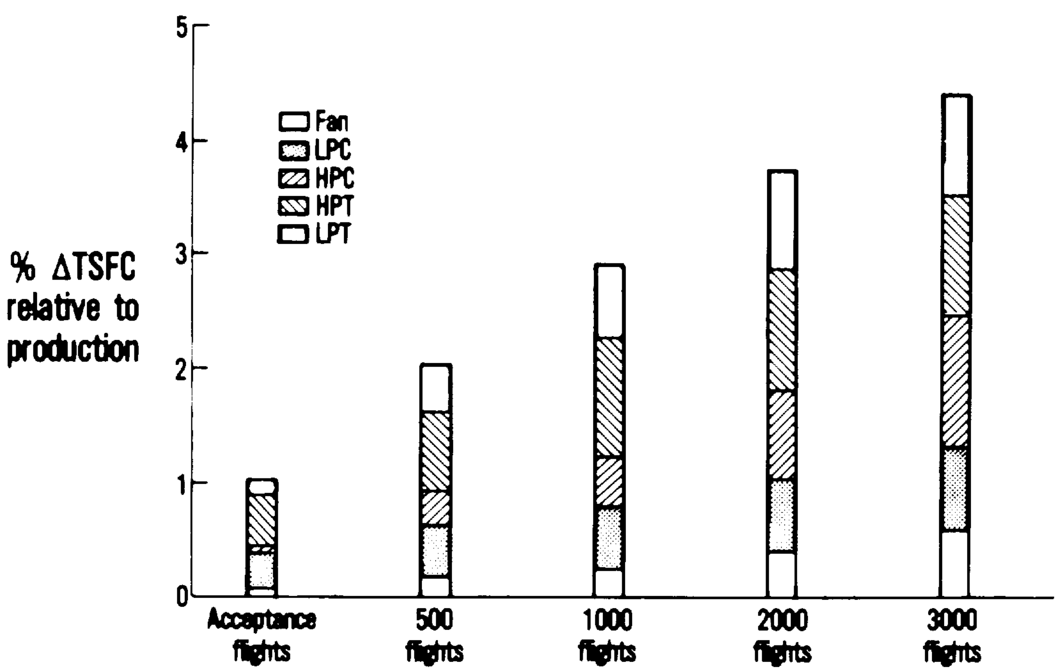



Figure 14 JT9D-7 Sea Level Perfomance Deterioration Distribution by Engine Module. (J24603-21)

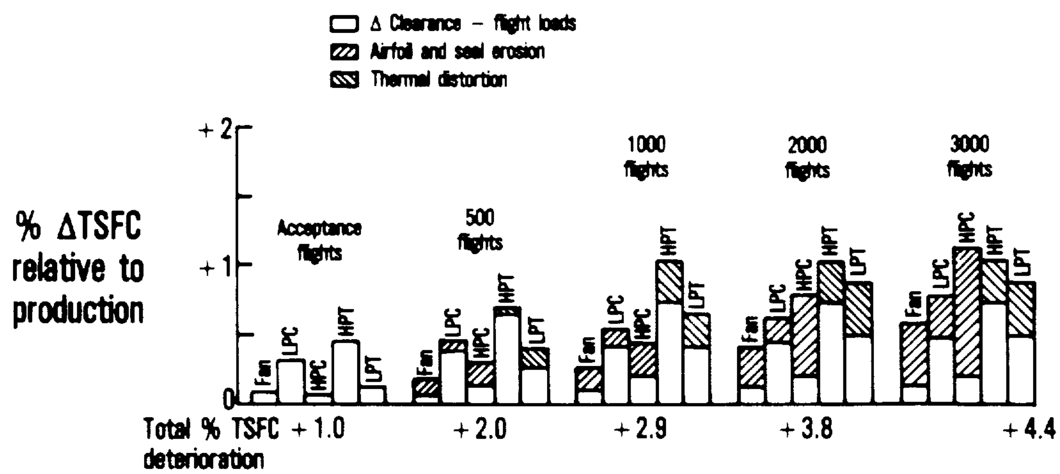



Figure 15 JT9D-7 Sea Level Performance Deterioration Distribution by Cause. (J24603-23)

**Current engines:**

- Cold section refurbishment

**Future engines:**

- Flight-load resistant propulsion systems
- Erosion resistant design and materials
- Thermal distortion resistant design and materials

Figure 16 Flight Loads Test Program Recommendations. (J24765-17)

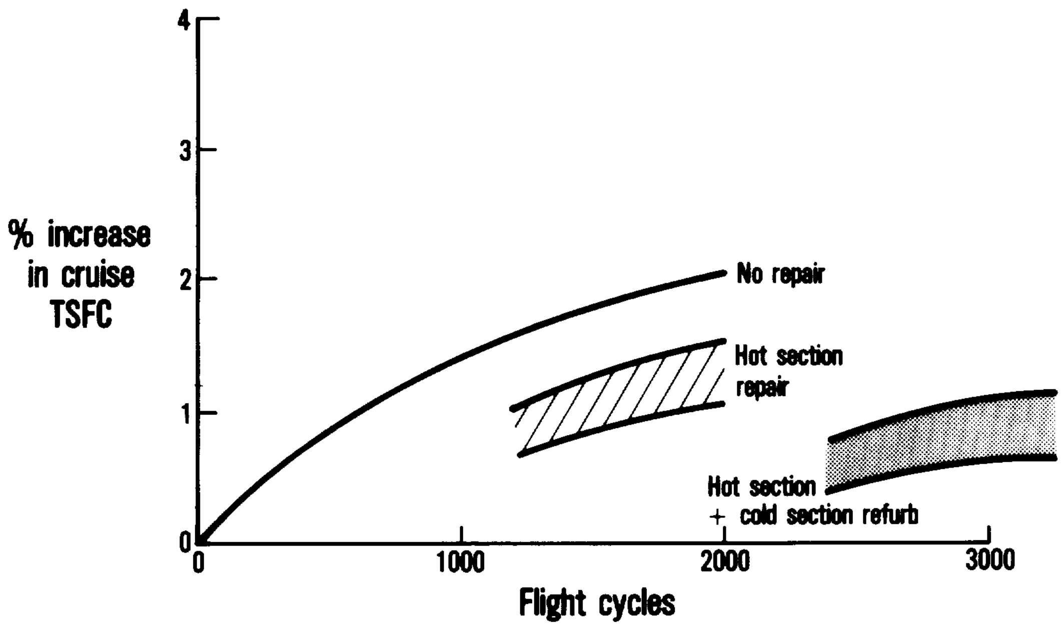



Figure 17 Effect of Repair on JT9D-7A Engine Cruise Thrust Specific Fuel Consumption. (J24603-24)