JT8D ENGINE PERFORMANCE RETENTION

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SUMMARY

The attractive performance retention characteristics of the JT8D engine are described. Because of its moderate bypass ratio and turbine temperature, and stiff structural design, the performance retention versus flight cycles of the JT8D engine sets a standard that is difficult for other engines to equal.

In addition, the significant benefits of refurbishment of the JT8D engine are presented. Cold section refurbishment offers thrust specific fuel consumption improvements of up to 2 percent and payback in less than a year, making a very attractive investment option for the airlines.

INTRODUCTION

The ability of an aircraft powerplant to retain its marketed performance is one of the primary considerations in its development or selection. Escalating price of fuel during the last decade has placed greater emphasis on defining the performance retention characteristics of current, as well as new powerplants. Any performance loss can be directly related to increased operating costs, and fuel is an ever increasing portion of those operating costs.

The Pratt & Whitney Aircraft JT8D engine is a first generation turbofan engine, i.e., a low bypass ratio, dual spool, axial flow turbofan that enjoys the distinction of being the most widely used engine in commercial service. To date, over 10,000 units have been delivered and power more than 3,000 aircraft for 175 airline operators worldwide. To assist these operators in minimizing fuel costs and maximizing time on-wing, Pratt & Whitney Aircraft has conducted an extensive analysis of the JT8D engine in order to define the industry potential for performance recovery, the modes of performance loss within the component modules and cost effective means of recovering that lost performance.

PERFORMANCE CHARACTERISTICS

Quantifying performance losses as a function of engine service time has been an industry problem since the initiation of commercial service. Manufacturer development processes include many tests with cyclic power adjustments that provide advanced notice of problems arising from thermal distress and fatigue. They do not have the means of accelerating the normal erosion process that the gas path hardware is subjected to daily in commercial service.

However, operators have all these conditions occurring continuously, but usually do not have the facilities, manpower, financial commitment or time to do the extra testing that would provide this basic knowledge.

Reams of inflight cruise monitoring data could be reviewed. Almost all airlines require the flight crew to record one data point during cruise on each engine during each flight leg. Five performance parameters are recorded: engine pressure ratio, high and low spool rotor speeds, fuel flow and exhaust gas temperature. The data quality suffers due to the use of aircraft instrumentation. The principal use of the data is to monitor the engine parameters for abrupt changes that would signal a potential incidence of part failure. Data scatter is significant. Considerable massaging is required to smooth out the data enough to generate trending information that will identify a severe deviation thereby making the identification of small performance losses very difficult. It was, therefore, decided to base the on-wing (pre-repair) deterioration characteristic on ground engine cell data acquired from engines run prior to repair.

Figure 1 provides the average performance retention characteristics of the JT8D engine and the individual sea level static data points used as the basis for this curve. The average curve is described by a second order curve fit through all the data, and is considered representative for all JT8D-1 through JT8D-17 models.

Figure 2 shows this characteristic in relation to the industry average post repair performance levels. Three levels of performance are shown that exist in commercial service today. The uppermost curve represents the average on-wing (pre-repair) deterioration. Individual operators may experience deterioration rates significantly different from this curve, either better or worse, since there are a multitude of factors that can influence the deterioration rate. These factors will be discussed in the later paragraphs.

Average industry performance levels after repair are represented by the middle curve. Industry repair practices have reflected the philosophy of on-condition maintenance, which were directed at minimizing engine maintenance cost. Cheap fuel prices and known operating limits have allowed operation under this maintenance philosophy. Engines are operating today that have accumulated operating times in the 30,000 hour or cycle region with periodic hot section repair and only occasional minor cold section work to repair airfoil damage from Bill of Material or foreign objects. Refurbishment of the compressors to recover performance loss (particularly specific fuel consumption) was dismissed by operators as not being cost effective. These components were generally refurbished only when incidences of compressor surge were encountered.

This curve then reflects the results of on-condition maintenance philosophy with an implied penalty because of limited cold section repair. The curve flattens to a relatively constant loss resulting from the imposition of the operating temperature limit. Gas path deterioration and increasing exhaust gas temperature coexist. Generally, the JT8D engine has not had a problem with the exhaust gas temperature measuring system indicating temperatures that are falsely high or low. Therefore, as the gas path deteriorates, the exhaust gas temperature limit restricts takeoff power setting, forcing the engine back to the repair shop. The practice of minimum repair then manifests itself in ever shorter periods of operation between repair cycles and exhaust gas temperature limiting operation.

Fuel shortages and the continuing escalation of fuel prices have refocused the industry emphasis on fuel economy, both in operation and maintenance. Practices that were not cost effective a few years ago, now have reasonable payback periods.

In the interest of identifying effective refurbishment, Pratt & Whitney Aircraft funded a JT8D Engine Maintenance Technology study to define the primary modes of deterioration in the engine, identify the modules where maximum performance restoration could be attained and develop cost effective methods of recovering that lost performance. Cooperation of four major airlines (three domestic and one foreign), two years of studying hardware, scrap records and available data, and an in-house testing program using a loaned high time service engine, have identified and demonstrated that significant performance could be recovered through fan and high pressure compressor refurbishment.

The lower curve (Figure 2) represents the average level of performance attainable through a revised maintenance philosophy that recognizes periodic cold section refurbishment as a major part of performance recovery.

It would appear that a significant improvement is still available, since the average remains approximately 2.0 percent above the new engine baseline. The curve should not be interpreted to conclude that refurbishment to the "as new" performance level cannot be achieved. A few of the engines came within 0.5 percent of their production acceptance levels. Current production performance levels were used as a consistent base for all the post repair tests and the average engine performance has improved over the years. This would tend to make the difference appear larger than it actually was. Realistically, achievement of "as new" performance can be accomplished through refurbishment. Although material lost to erosion cannot be restored, airfoil shape and surface finish, which are the prime performance factors, can be restored with only a residual reduction in performance life.

FACTORS INFLUENCING PERFORMANCE RETENTION

Assuming large amounts of usable data were available to define the performance retention characteristics for each operator, a wide variation in operator average retention and engine to engine variations about each average could be expected. Engine deterioration rates are dependent on many factors other than engine to engine differences of gas path geometry and cycle matching. Of major influence are operational environment, operational philosophy and maintenance philosophy, which are particular to each individual airline.

Gaspath Geometry

The JT8D engine is a first generation turbofan engine, i. e. , a dual spool, axial flow, low bypass turbofan. It is constructed with a full length annular fan duct that directs fan air rearward to mix with primary air in a common convergent exhaust nozzle. This results in rigid case construction so the installed engine is not adversely affected by the axial bending forces exerted by inlet air loads during aircraft rotation and maneuvering.

In comparison to more current state of the art engines, the gas path is built with relatively loose clearances between rotating and stationary parts, therefore, compressor and turbine airfoil tip rub is not a factor. The primary forms of performance loss are hot section thermal distress, compressor airfoil roughness and compressor airfoil erosion.

Airfoil roughness is the result of environmental contamination and generally occurs in the first 1,000 hours of operation after installation or cleaning. Contamination is the minor mode of compressor performance loss that appears to reach its maximum and then remains relatively constant throughout the operational phase.

High gas velocities and thinner airfoils in the high pressure compressor account for a large measure of the performance impact. In addition to the leading edge erosion exhibited in the fan and low pressure compressor, blade pressure side erosion also occurs. Both leading edge and pressure side erosion occur concurrently until approximately 4.0 percent chord is lost near the blade tip. At this point, the blade trailing edge has become excessively thin and begins to tear away. Figure 3 graphically shows the relative performance loss of each deterioration mode and the accelerated rate for performance loss that takes places when the trailing edge shreds.

Operational Environment

Operational route structure and geographical area have a definite impact on the deterioration rate. The JT8D engine is used in the short to medium range segment of the industry. Aircraft cyclic times, the time between takeoff and landing, vary between 20 minutes to two hours per cycle. The industry average is about one hour per cycle, which is considerably shorter than the typical long range aircraft which run four to seven hours per cycle.

Hot section distress, the primary mode of engine performance loss in all engines, is cyclic dependent. Time at high temperature is the key parameter in determining turbine hardware lives. Since maximum temperature is achieved during takeoff, deterioration as a function of engine cycles becomes most significant. On this basis, the JT8D engine performance retention characteristic is very attractive.

Cold section airfoil erosion, the principal mode of performance loss in the compressor, is cyclic dependent, and also dependent on geographical area. A Middle East operator typically exhibits more airfoil erosion due to sand ingestion, in 2,000 cycles than a large domestic operator may see in 30,000 cycles. Figure 4 illustrates the variation in erosion rates by assuming that the rates are linear.

Other geographical areas have their own particular problems, although not as severe as the desert operations. Operators in Alaska also have an erosion problem with volcanic ash and operators near salt water or highly industrialized areas have problems with corrosion and sulphidation.

Operational Philosophy

Power setting procedures that reduce the impact of hot section thermal shock during takeoff have been defined by engine and airframe manufacturers and are available to the operators. The procedures simply require the flight crew to compute the required power necessary to get airborne based on the ambient temperature, aircraft gross weight and runway length. Dependent on these variables, reduced power may be used instead of the full rating. This results in the engine operating at a lower turbine inlet temperature. A significant reduction in turbine distress and, consequently, a reduced deterioration rate can be realized if reduced power takeoffs are used whenever possible.

Figure 5 shows an analytical assessment of maintenance material cost resulting from reduced power takeoffs. The relative cost is shown as a function of engine time per cycle with lines of constant percentage of power reduction. Maintenance material savings are directly related to a reduction in turbine distress. Similar savings can be realized by using reduced climb power whenever aircraft loading and routing permit.

Maintenance Philosophy

Maintenance policy has been an evolving process as illustrated in Figure 6. During the early years of operation, maintenance was on a hard time basis. Engines were removed, inspected and repaired at specific intervals. As confidence in the hardware integrity became proven, the time intervals were extended based on operator experience.

Logical progression led to on-condition maintenance. This was considered at one time to be the ultimate policy. Engines stay on-wing until removal is forced by a fault or the inability to set power because of reaching an operational limit. Some parts still retain hard time limits based on maximum cycles for useful life, but generally these are long term limits. All interim maintenance is based on a problem developing or the engine reaching the exhaust gas temperature limit prior to meeting the power setting requirement. This was an acceptable maintenance policy during an era where fuel cost was a small portion of total airline operating cost.

Minimal maintenance results in increased fuel consumption and turbine temperature levels. Turbine distress occurs with increasing regularity and is readily evident during disassembly. Compressor deterioration is not as apparent, therefore, the extent of cold section maintenance was to blend repair obvious Bill of Material and foreign object damage.

The tightened world supply of fuels and strategic materials highlighted the need to change philosophies. Fuel became a major part of the airline operating cost and the maintenance emphasis was redirected toward reducing fleet fuel consumption. The impact of the cold section, fan and high pressure compressor particularly, became more obvious, forcing maintenance philosophy to swing back towards scheduled cold section refurbishment.

PERFORMANCE OPTIMIZATION

With the maintenance philosophy shift towards scheduled compressor refurbishment, the next logical progression is towards complete engine maintenance management. The deterioration rates of each module, and the potential to recover lost performance are recognized in this concept. This utilizes a cost effective mix of repair techniques and new parts to attain a service goal.

This also must address on-wing maintenance to retain the performance recovered through refurbishment for as long as possible. Periodic engine water wash and fuel nozzle cleaning should be included in any engine management program.

Compressor airfoil roughness has been found to occur in the first 1,000 hours of operation. Experience has shown that long term water washing is not very effective in removing compressor contamination. However, short term periodic washing (250 hour intervals) has demonstrated that performance loss due to contamination can be held off for 4,000 to 5,000 cycles. Intervals recommended for compressor water wash have been in 1,000 hour increments or less, but as more data is accumulated, the most significant results are associated with the shorter time interval wash procedures.

Considerable data from hot section inspections have correlated burned turbine nozzle vanes and streaked combustion chambers with coked fuel nozzles. Non-uniform fuel flow from plugged nozzles results in excessive temperature and burned vanes. On-wing fuel nozzle cleaning procedures have been proven effective in eliminating moderate coke deposits. Therefore, periodic cleaning in the recommended 1,000 hour intervals will maintain coke free operation and optimize turbine hardware performance.

PERFORMANCE RETENTION MODELING

In order to determine more cost and fuel efficient maintenance practices, an accurate model of engine performance loss must be constructed. This model can be used to quantify performance loss for a particular engine model as a function of usage. Additionally, a complete model will identify losses both by module and cause, such as erosion of airfoils, thermal distortion of hot section parts, and clearance increases between rotating and stationary parts due to erosion or rubs.

To begin the process of model construction, appropriate data sources must be selected. Inflight monitoring data is available, but its usefulness as a primary source is limited. The quality limitations of flight data have been discussed previously; large amounts of data must be trended in order to be meaningful. In addition, flight data furnishes far fewer parameters than the number of module losses to be defined. In particular, the lack of thrust measurement makes determination of low spool losses very difficult. Finally, flight data is affected by aircraft systems, particularly the pneumatic system, which makes analysis of the data even more difficult.

Two data sources were used to construct the JT8D engine performance retention model. The first of these was pre-repair data obtained from airline test cell runs. Because of the nature of airline operations, particularly with a well-proven engine like the JT8D and prevailing on-condition maintenance practices, pre-repair data is not normally obtained. However, there is a limited amount of first run data available. This data is relatively accurate and furnishes pressure ratios and thrust, in addition to more accurate definition of those parameters measured inflight. By comparing the pre-repair data for a particular engine to its production run data, it is possible to use a computer simulation of the engine to calculate efficiency and flow capacity change for every module. This analysis depends on use of known relationships between cold sections efficiency and flow capacity changes, referred to as "coupling" relationships.

The other data source used for the model was teardown inspection data. Used parts with known service times were collected and analyzed to determine performance changes from the new part configuration. Such data furnishes knowledge of the causes, as well as the magnitude of module performance loss. From the estimates of individual module performance changes from new, total engine performance change from new can be synthesized with the engine computer simulation. The results of this analysis can then be compared to the pre-repair analysis and then both analyses can be iterated until reasonable closure is obtained, as shown in Figure 7. Since each analytical approach has its limitations, such iteration enhances the validity of the solution.

This process was performed for the JT8D-9 engine. Figure 8 shows a comparison of increase in sea level takeoff exhaust gas temperature from production as predicted by the model, compared to the pre-repair data. Figure 9 shows the same comparison for thrust specific fuel consumption. Reasonably good correlation between the average of the data and the model is shown. The used part analysis showed that the component deterioration for a typical operator was most strongly related to flight cycles for reasons previously discussed. However, there can be considerable operator-to-operator variation associated with operating environment differences.

Modules losses at 4,000 and 8,000 cycles that result from the analysis are shown in Figure 10. Cold section losses are dominated by erosion and roughness damage, while hot section losses occur primarily in the high pressure turbine and are largely the result of thermal distortion (vane bow). There are no module losses due to clearance increases. The low bypass ratio of the JT8D engine minimizes thrust bending loads, and the long, stiff one piece fan duct effectively isolates the internal engine cases from nacelle aerodynamic loads. These features, plus the moderate hot section temperatures, result in a standard of performance retention that is difficult for other engines to equal.

Figures 11 and 12 show the overall impact of cold section versus hot section losses on exhaust gas temperature and thrust specific fuel consumption, measured at sea level takeoff conditions. The hot section dominates exhaust gas temperature increase, while cold section losses have greater thrust specific fuel consumption impact. Historically, engine overhaul has been directed primarily toward restoring exhaust gas temperature margin, and airline efforts were accordingly concentrated on hot-section repair. However, in the current era of constantly escalating fuel prices, Figure 12 shows the importance of periodic cold section refurbishment to minimize fuel burned.

In order to analyze the potential benefits of performance restoration on fuel burned, fuel consumption at altitude conditions must be evaluated. This can be done with the engine computer simulation. Analysis shows that there is an effect of both flight condition and power setting on thrust specific fuel consumption change due to component performance changes. A weighted thrust specific fuel consumption change has been defined which combines both climb and cruise thrust specific fuel consumption at typical altitude conditions, in proportion to the fuel consumed during a typical mission. For the JT8D engine in a typical 727 application, the weighted thrust specific fuel consumption change is approximately the average of climb and cruise changes.

Takeoff exhaust gas temperature and weighted thrust specific fuel consumption increases are shown by module and cause in Figures 13 and 14. Exhaust gas temperature increase is primarily controlled by the high pressure turbine; however, high pressure compressor losses also contribute significantly. Thrust specific fuel consumption increases are dominated by the fan and high pressure turbine; the high pressure compressor again contributing significantly.

The performance retention model can also be used to predict the impact of hot section repair, and project performance losses for multiple run engines. Figures 15 and 16 show the impact of hot section repair only. Typical first removal is shown at about 6,000 cycles, which would probably be for foreign object damage or hot section inspection. At this point, a change in high pressure turbine outer airseal from bill-of-material knife edge to honeycomb (typical airline practice) is shown. Erosion of the replacement outer airseal plus worse bow for repaired vanes results in more rapid exhaust gas temperature and thrust specific fuel consumption increase with flight cycles, so that an exhaust gas temperature-limited condition may be encountered at about 10,000 cycles. The effect of hot section only repair is that the interval between the exhaust gas temperature-limited shop visits decreases with successive shop visits. This is because of the underlying cold section damage which has not been corrected.

IMPACT OF COLD SECTION REFURBISHMENT

The assumed workscope for cold section restoration is shown in Figure 17. If cold section refurbishment is accomplished at "soft" time intervals of 12,000 to 17,000 cycles (nearest convenient time when the engine is in the shop), the model predicts the results of Figure 18. Fan and low pressure compressor restoration are accomplished at 13,500 cycles, along with high pressure turbine repair. At 17,000 cycles, the high pressure compressor and turbine are repaired. The benefits in improved thrust specific fuel consumption are readily apparent.

A number of studies have illustrated the cost-effectiveness of cold section refurbishment for the JT8D engine. Figure 19 illustrates summary results from one study. The study showed fan and low pressure compressor refurbishment to be most cost effective (earliest payback). Refurbishment of fan, low pressure compressor and high pressure compressor combined, resulted in 1.6 percent weighted thrust specific fuel consumption recovery at refurbishment, $21^{\circ}F$ exhaust gas temperature recovery and payback in less than a year for a typical operator, based on 50 cents per gallon of fuel. Current fuel costs would further enhance cost effectiveness of cold section refurbishment, notwithstanding increased labor and parts costs since this study was conducted.

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2. 1980 JT9D Engine Regional Engineering and Maintenance Conference, Pratt & Whitney Aircraft Group, Commercial Products Division.
   October 1980, Zurich, Switzerland and Washington, D.C.
   November 1980, San Diego, California and Singapore

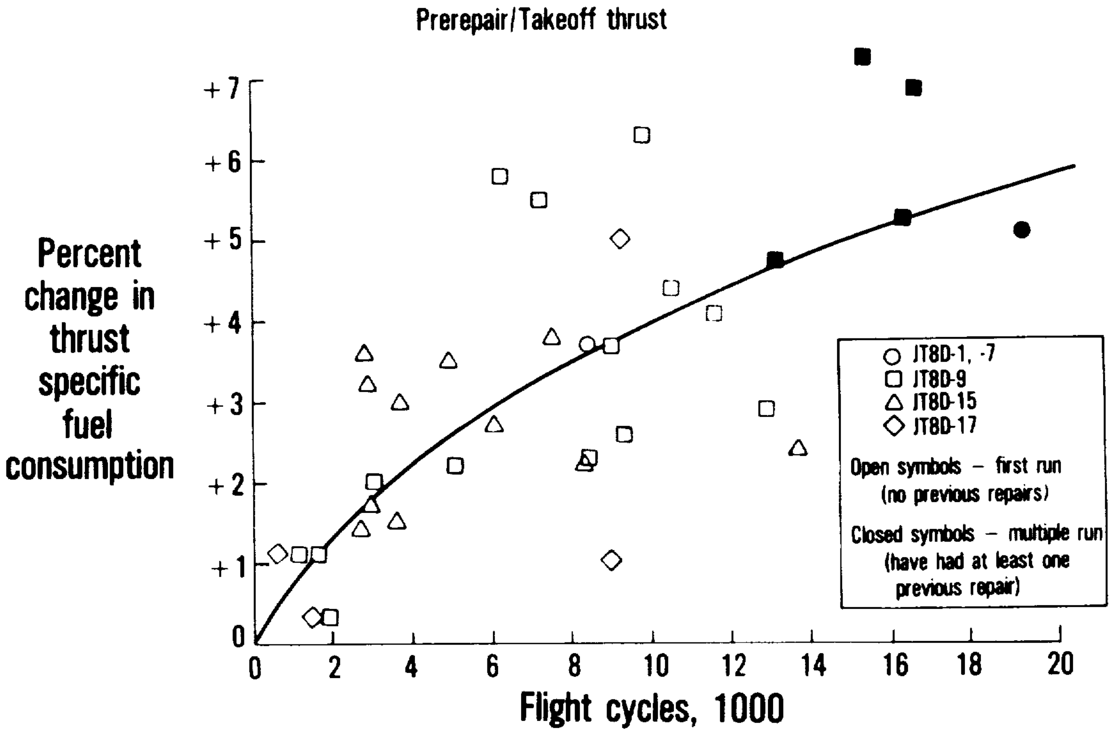


Figure 1 Sea Level Static Test Cell Data JT8D Engine Performance Retention

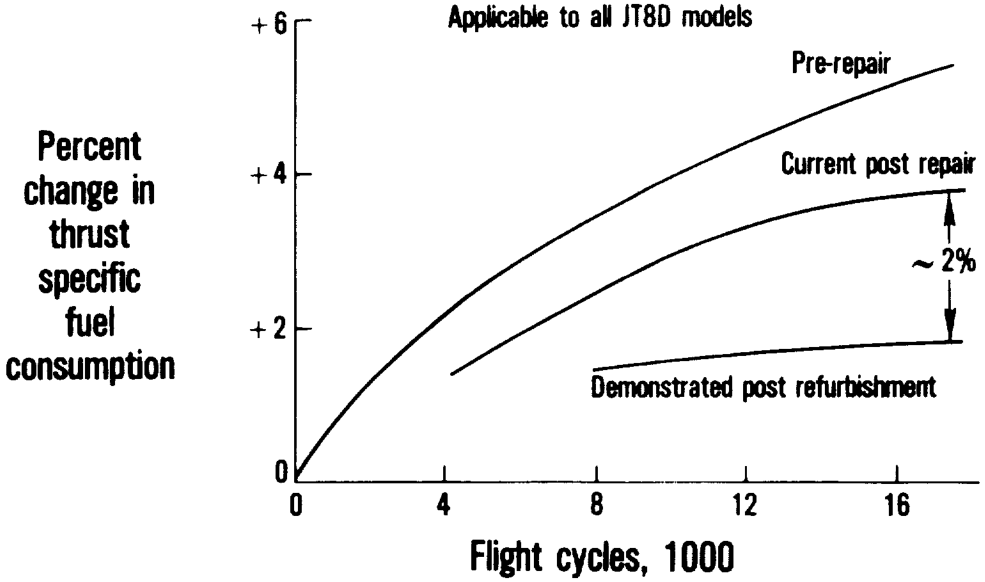


Figure 2 Industry Average Post Repair Level Shows Significant Potential for Performance Recovery

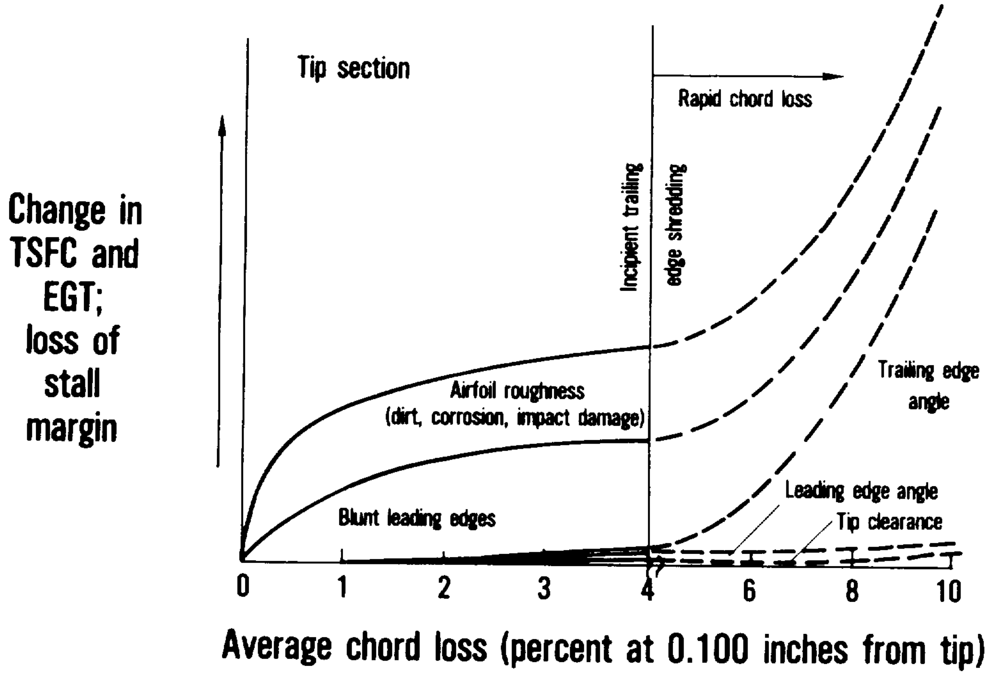


Figure 3 High Pressure Compressor Performance Retention Directly Related to Chord Loss

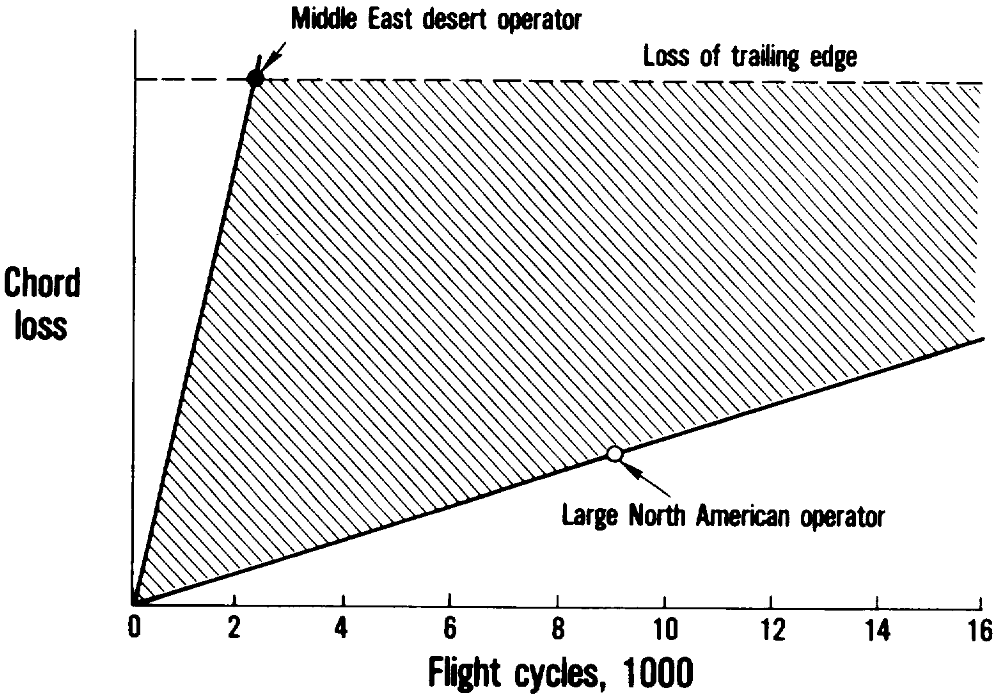


Figure 4 High Pressure Compressor Blade Chord Loss Rate Varies Greatly Between Operators

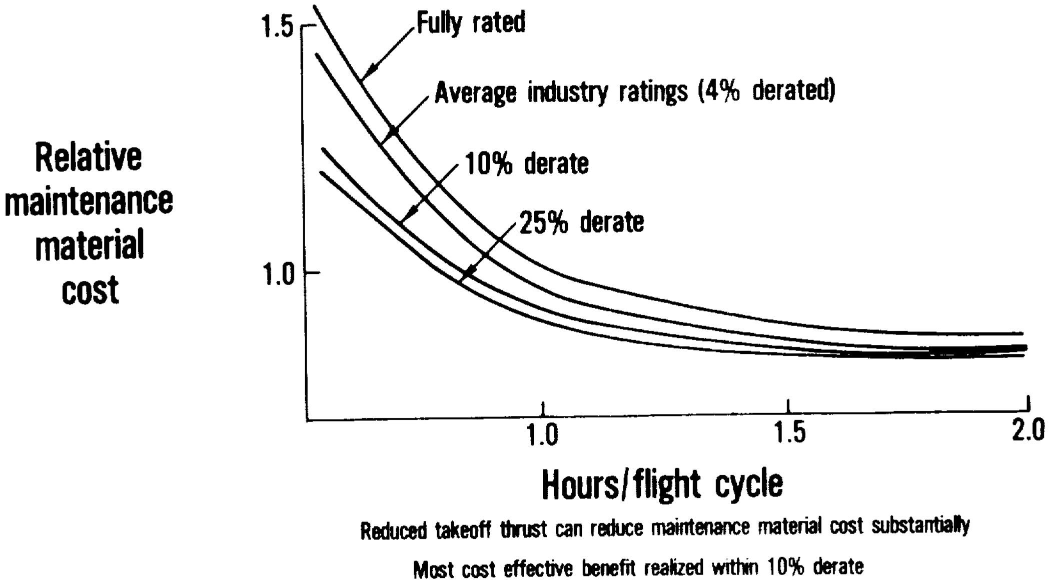


Figure 5 Maintenance Cost Reduced by Thrust Derate Procedures

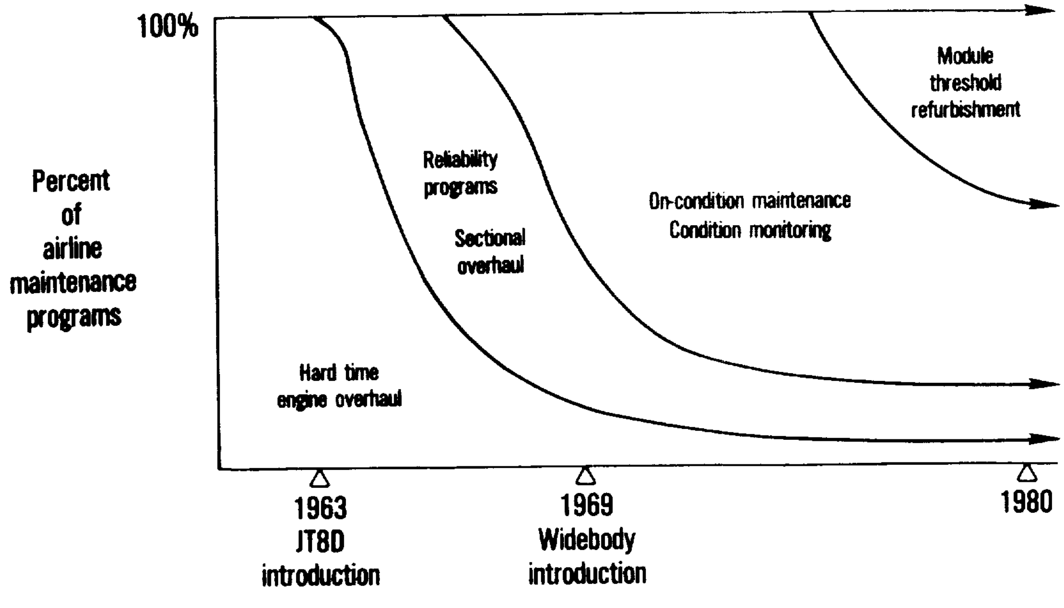


Figure 6 Engine Maintenance Concepts are Changing

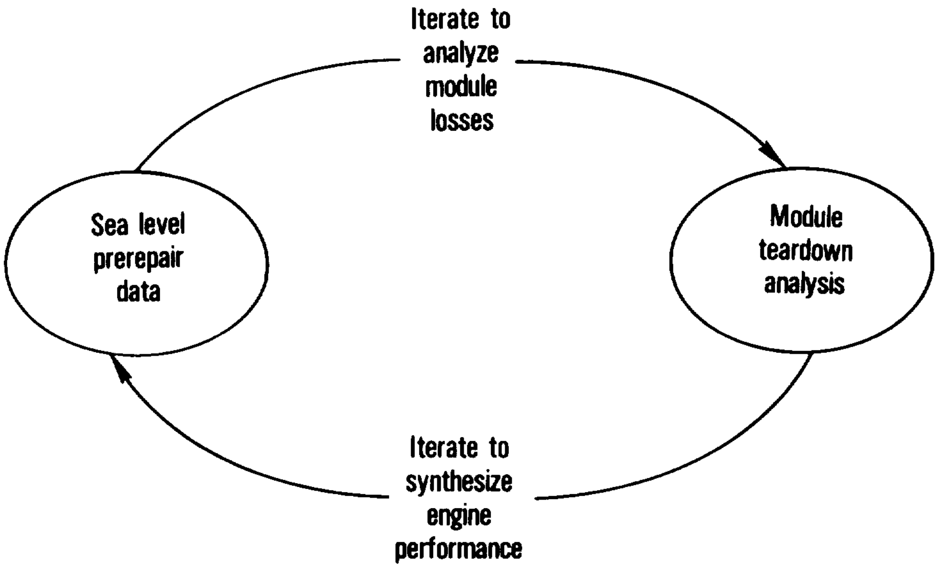


Figure 7 JT8D Engine Performance Retention Model-Approach

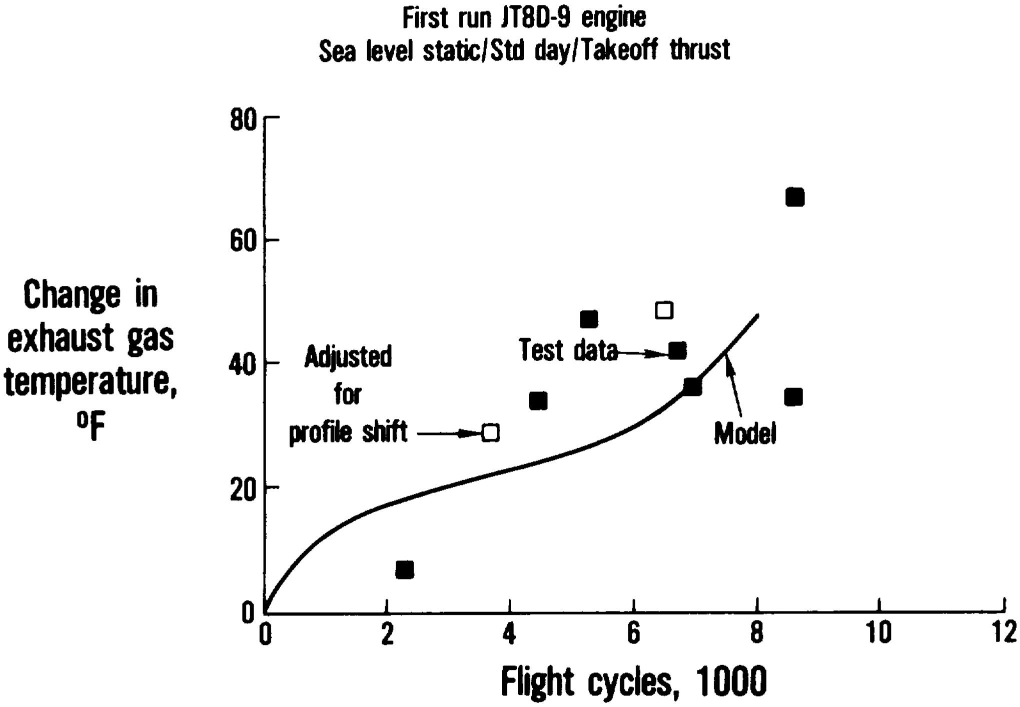


Figure 8 Model Agrees with Test Data

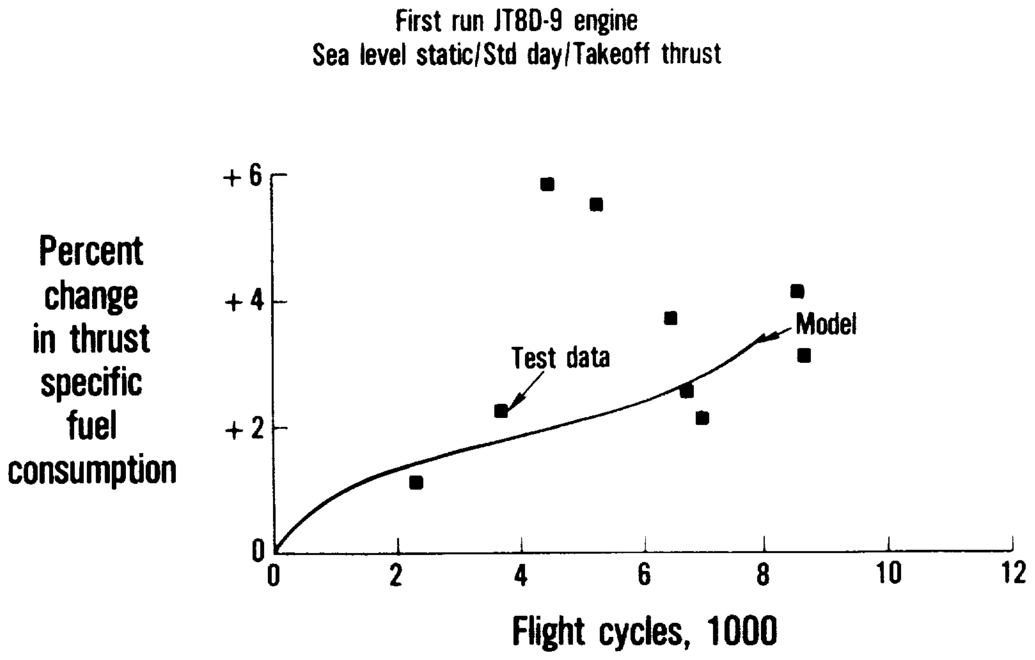

First run JT8D-9 engine
Sea level static/Std day/Takeoff thrust

Figure 9 Model Agrees with Test Data

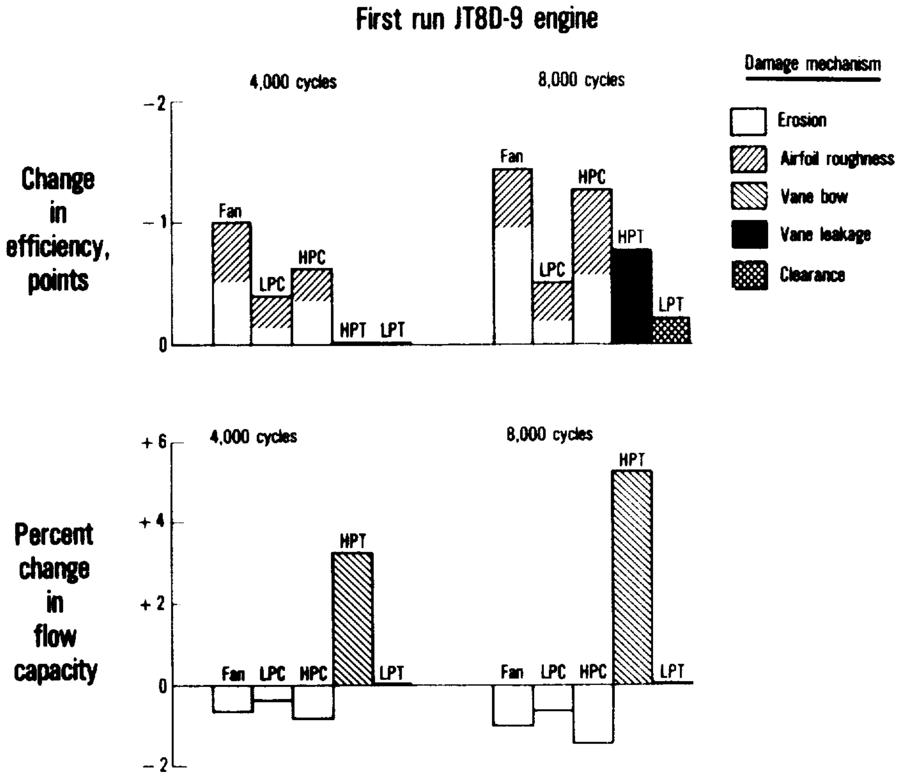

First run JT8D-9 engine

Figure 10 Model Losses Derived from Teardown Data

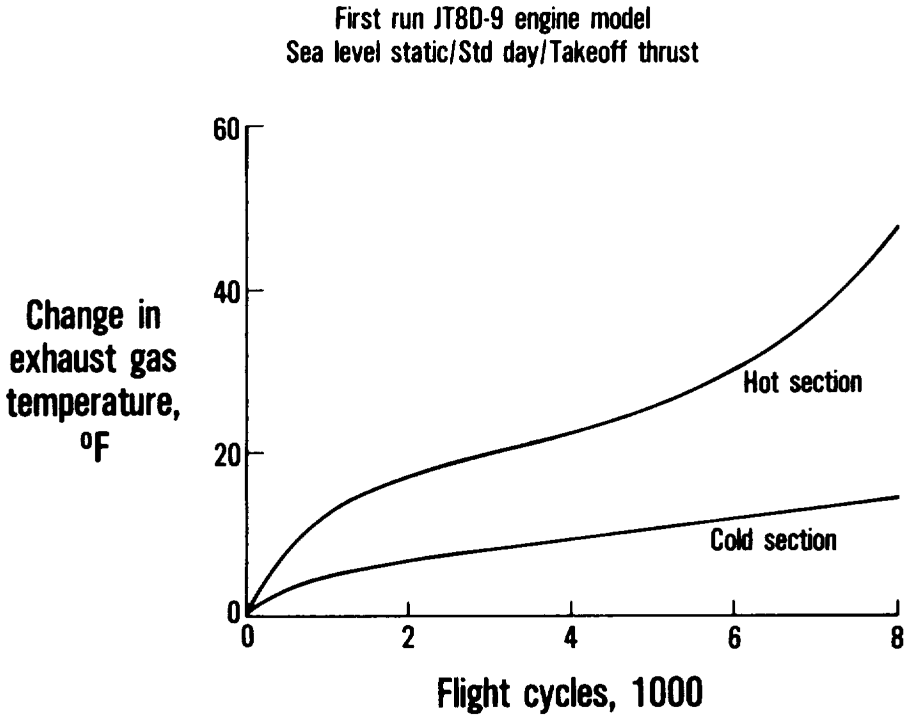

First run JT8D-9 engine model
Sea level static/Std day/Takeoff thrust

Figure 11 Exhaust Gas Temperature Increase Dominated by Hot Section

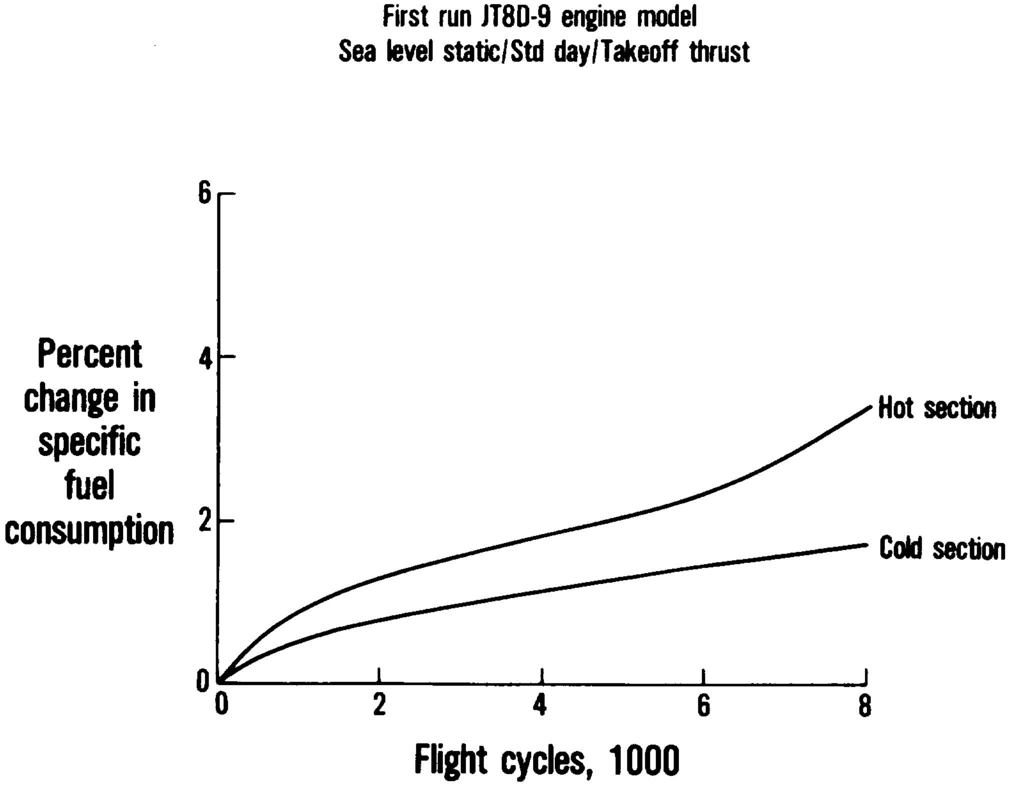

First run JT8D-9 engine model
Sea level static/Std day/Takeoff thrust

Figure 12 Thrust Specific Fuel Consumption Increase Controlled by Cold Section

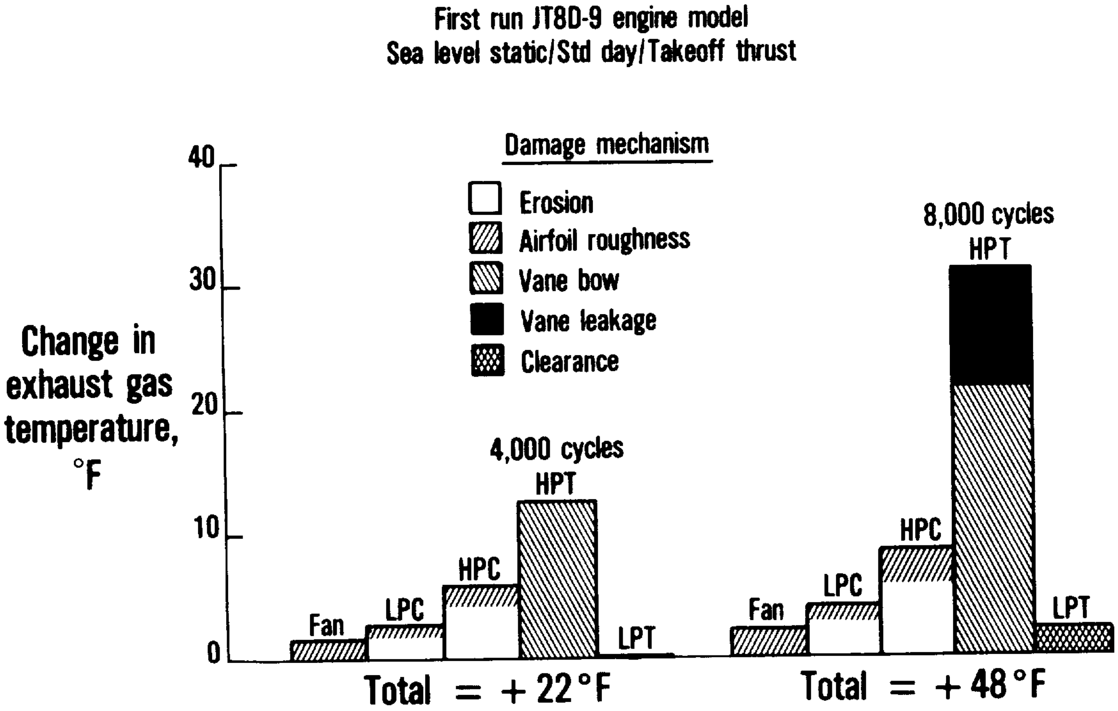


Figure 13 High Pressure Turbine Losses Major Cause of Exhaust Gas Temperature Increase

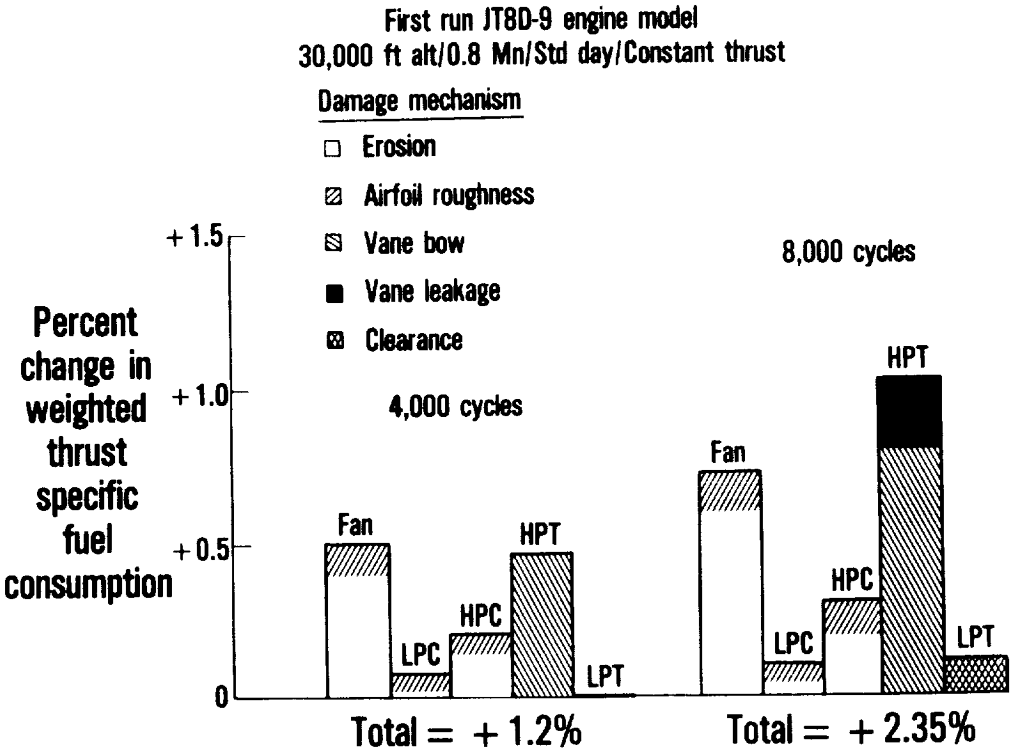
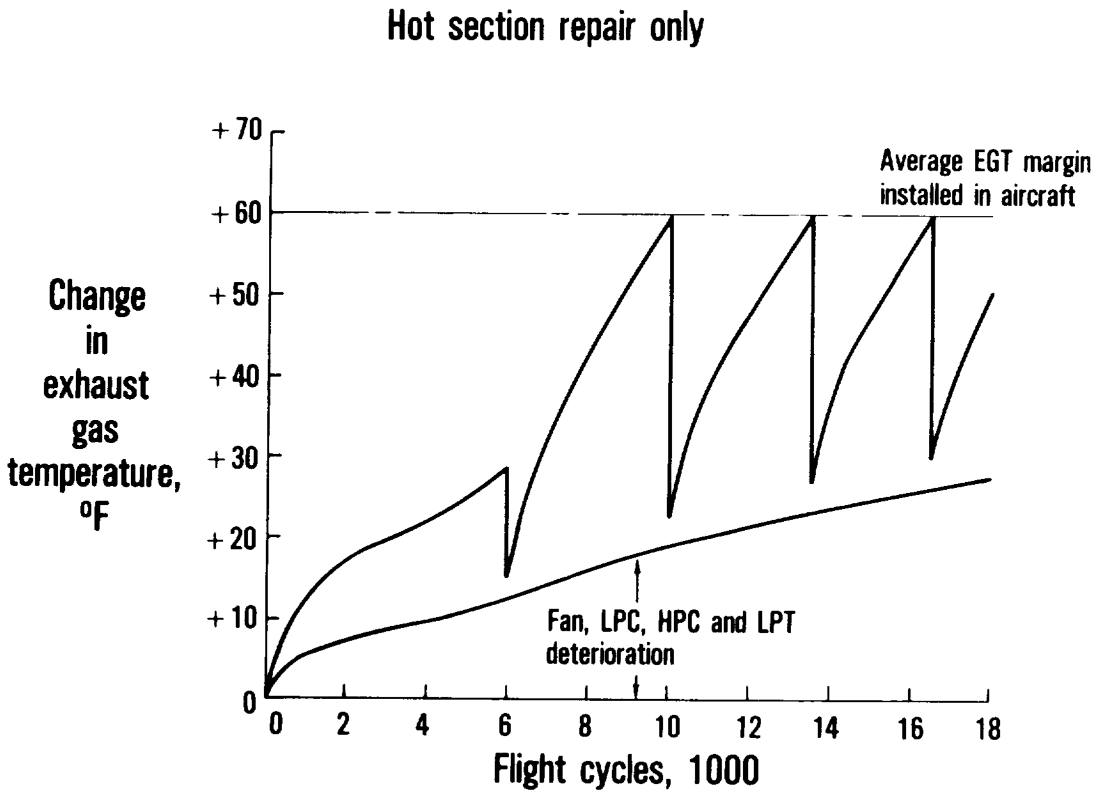
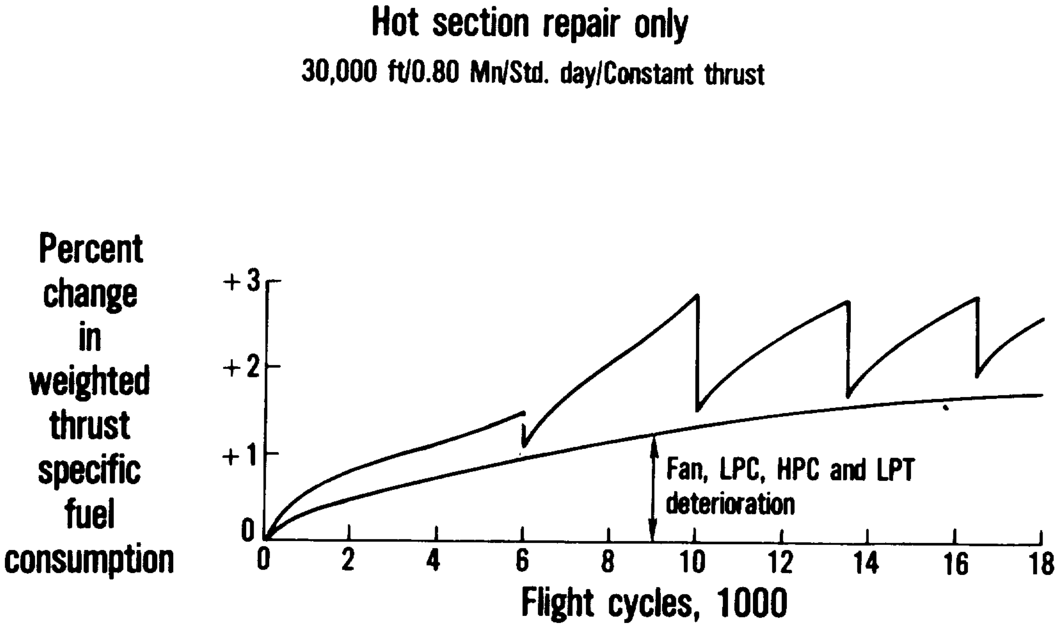


Figure 14 Cold Section Erosion and High Pressure Turbine Vane Bow Major Causes of Thrust Specific Fuel Consumption Loss



Hot section repair only

Figure 15 JT8D-9 Engine Multi-Run Model Projects Realistic Exhaust Gas Temperature-Limited Removals



Hot section repair only

30,000 ft/0.80 Mn/Std. day/Constant thrust

Figure 16 JT8D-9 Engine Multi-Run Model Shows Importance of Cold Section Losses

Module	Workscope
Fan	– All blades – SWECO clean, chamfer cut
Low pressure compressor	– All blades – SWECO clean, chord check, leading edge radius restoration, replace as necessary – All stators – vapor clean, check vane angle, re-angle as necessary
High pressure compressor	– All blades – SWECO clean, chord check, leading edge radius restoration, replace as necessary – All stators – vapor clean, check vane angle, re-angle as necessary

Figure 17 Assumed Workscope for Compressor Restoration

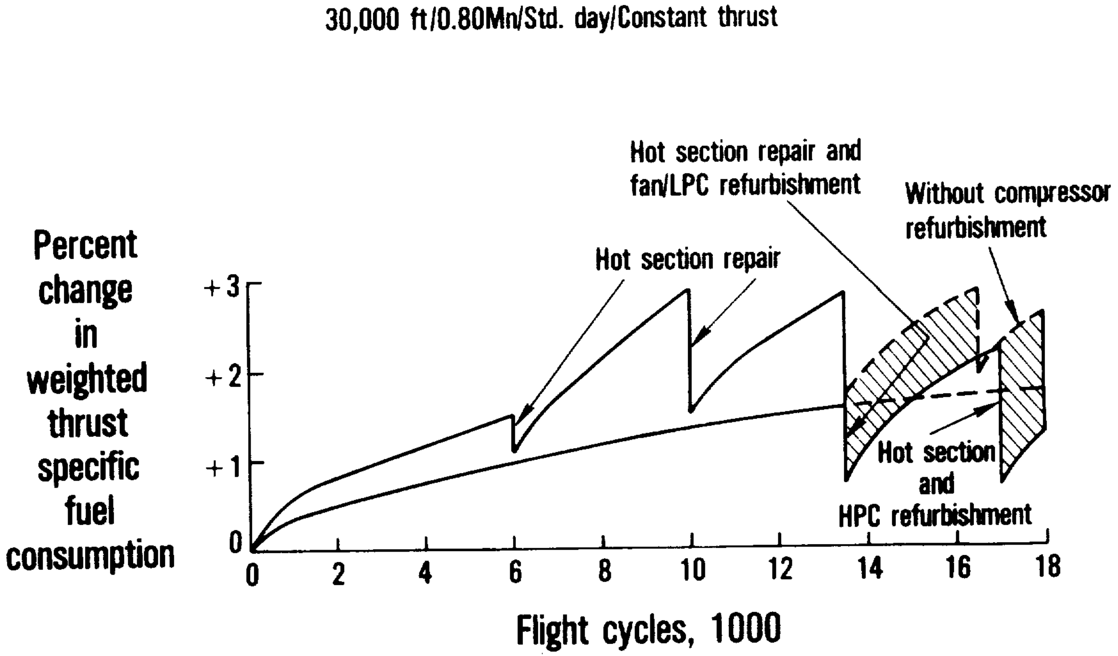


Figure 18 JT8D-9 Engine Multi-Run Model Shows Benefits of Cold Section Refurbishment

- **Weighted TSFC recovery at refurbishment = 1.6%**
- **EGT recovery at refurbishment = 21°F**

Fan, LPC, HPC only

- **Payback period less than one year (typical operator)**

Figure 19 Cold Section Refurbishment Cost Benefit Analysis