JT9D JET ENGINE PERFORMANCE DETERIORATION*

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SUMMARY

Escalating fuel costs and the need to meet national energy conservation goals have led to a new industry awareness of the importance of maintaining good fuel consumption throughout the life-cycle of an engine. However, higher fuel consumption is only part of the overall engine deterioration picture which consists of reduced surge margin, higher exit gas temperature, and other hot section distress. Engine deterioration characteristics can, in general, be divided into two time periods. The first, called short-term deterioration, occurs in less than 250 flights on a new engine and in the first few flights following engine repair. Engine deterioration in the second time period, characterized as long-term, involves primarily hot section distress and compression system losses which occur at a somewhat slower rate than short-term deterioration.

It is generally accepted that the causes for short-term deterioration are associated with clearance changes which occur in the flight environment. In this paper, the analytical techniques utilized to examine the effects of flight loads and engine operating conditions on performance deterioration are presented. The role of gyroscopic, gravitational and aerodynamic loads are shown along with the effect of variations in engine build clearances. These analytical results are compared to engine test data along with the correlation between analytically predicted and measured clearances and rub patterns. Conclusions are drawn and important issues are discussed.

INTRODUCTION

The current and projected high cost of fuel for gas turbine engines places a premium on incorporation of design features which increase the operating efficiency of aircraft propulsion systems. One such feature, universally recognized to be of major importance, is the maintenance of tight operating clearances between static and rotating components of flowpath seals. In practice, this is rather difficult to accomplish since the individual seal components and their supporting structures experience wide excursions in temperatures, rotational speeds, and other loadings at different points in the flight cycle which give rise to relative deflections that can lead to contact, wear, and increased clearances between seal parts. Early gas turbine designs (turbojets and low bypass ratio turbofans) accounted for these time varying loads and associated deflections as part of the standard process and attempted to tune rotor and case growths such that tight clearances (maximum efficiency) would occur during steady-state operation (climb, cruise) without introducing damaging rubs during transient conditions (takeoff, landing). In view of the ready availability of inexpensive fuel and other

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factors, designs which dropped a few percent in efficiency after a year or two in service were considered adequate at that time.

Today's situation is quite different as a consequence of two factors. First, fuel costs have more than doubled in the past few years and are expected to continue to rise, and second, higher bypass ratio engines are more susceptible to structural deformations which can cause tight seal clearances to be degraded by rubs. The second factor follows from the larger size (increased thrust and air loads) and increased thrust-to-weight ratio (lightweight, flexible structures) characteristics of the turbofan engines which power current commercial transports. In order to define powerplant configurations which will meet the more stringent performance retention requirements of tomorrow's marketplace, today's designer must have at his disposal a more advanced set of analytical tools with which to anticipate the response (deflections) of an engine to its flight environment (loads) than was previously necessary.

This paper describes progress that has been made toward development of a comprehensive analytical procedure for predicting the effects of flight loads on short-term gas turbine performance deterioration (fig. 1). The damage mechanism considered is wear of flowpath outer airseals due to interference of rotating (blade tip) and stationary (rubstrip) seal components. Wear behavior of inner airseals is more complex and has been omitted from the current study. Other mechanisms such as erosion and contamination which decrease engine efficiency more gradually than seal rubs are deemed to be of secondary importance in short-term deterioration and have been excluded.

SYMBOLS

Values are given in SI units. The measurements and calculations were made in U.S. Customary Units.

M_n	Engine inlet Mach number
% Δ TSFC	Percent change in engine thrust specific fuel consumption
V_S	Airplane stall velocity
ζ_{ij}	Performance influence coefficient for stage j, condition i
$\bar{c}_j$	Average clearance change for stage j

ANALYTICAL MODEL

This section provides a general description of the analytical procedure employed to assess the effects of steady flight loads on short-term performance deterioration of the JT9D-7/747 propulsion system. In essence, the model provides a vehicle for predicting blade tip rub damage caused by structural deformations which occur during flight operation and relates the corresponding enlarged seal clearances to increases in engine thrust specific fuel consumption (TSFC).

Flight Profile Definition

The starting point for all deterioration predictions to be discussed in this paper is a description of the sequence of operating conditions or events which comprise an engine mission or flight profile. The cycle may be relatively simple in terms of power level changes and exposure to external loads, as is the case for standard "green runs" and engine acceptance tests on the ground, or may encompass load spectra from runway roughness to clear air turbulence which are commonly encountered by commercial airlines. Each such cycle is constructed from a series of time segments (start-up, taxi, takeoff, climb, cruise, descent, approach, landing, shutdown), the end points of which can be characterized by unique combinations of aircraft and engine operating parameters (gross weight, altitude, attitude, Mach number (Mn), rotor speeds, temperatures, pressures, flows) that serve to define boundary conditions for subsequent aerodynamic, thermodynamic and structural analyses. For this paper, attention has been primarily focused on the airplane acceptance test flight (figs. 2, 3) chiefly because the profile is well defined and secondly, test data defining the magnitude of the change in TSFC is available for a number of engines covering the flight cycle range of interest. Ground tests and fleet service which precede and follow the flight acceptance test, respectively, have also been included but in somewhat less rigorous fashion. Quantitative information on idealization of these cycles for the JT9D-7 engine is discussed later.

Loads and Structural Deflections

Temperature, pressure and centrifugal force fields play an important role in determining internal seal clearances. These are always present during engine operation. Perhaps, the most convenient feature of this set is the common assumption that circumferential variations in these fields are small and, for the purposes of deflection analysis, can be neglected. The second important characteristic is that each field varies appreciably in response to changes in power level and requires a transient analysis for proper representation. Specialized computational procedures have evolved to perform the secondary flow, heat transfer, and other analyses that define temperature, pressure, and rotor speed time histories for desired flight profiles. These loads are input to axisymmetric structural analysis programs which generate histories of relative deflections (gap closures) between static and rotating components. Combination of the axisymmetric closures with values for the initial build clearances (cold gaps, also assumed to be uniform) then provides the sought after hot clearances as functions of time. Since they essentially indicate the gaps available for accommodation of additional deflections due to external flight loads, plots of these data will hereafter be referred to as baseline clearance curves.

A second set of structural deformations is related to loads which are not uniformly distributed with respect to the engine centerline. Generally, this set arises from external motions or restraints imposed by the flight environment and is composed of airloads (inlet lift), maneuver loads (g's, gyros), and thrust (including thrust reverse). As would be expected, consideration of these loads and their contribution to the performance deterioration problem presents a greater challenge than was the case for the previous group. A NASTRAN finite element model of the JT9D-7/747 was required to simulate the engine's response to external loads (figs. 4, 5.).

The burden of defining cowl pressure distributions (airloads) and maneuver load factors for candidate flight missions has traditionally been borne by the airframe manufacturers. Since these data are usually supplied to Pratt & Whitney Aircraft (P&WA) only in gross form (force/moment resultants, design limits/envelopes), provision was made for Boeing Commercial Airplane Company (BCAC) to generate detailed pressure load descriptions. Conversion of internal and external pressure distributions into appropriate descriptions of thrust and thrust reverse loads was also performed by P&WA and BCAC, respectively. Nodal forces consistent with inlet cowl pressure distributions, internal thrust build-up, maneuvers, and thrust reverse loadings were applied to the NASTRAN model and corresponding rotor/case displacement solutions obtained.

Blade-Tip/Rub-Strip Damage Calculation and Performance Deterioration

The process whereby structural deflections are translated into blade-tip/rubstrip damage involves calculations for a sequence of time points selected from a given flight profile. For each time point, the effects of axisymmetric loads (baseline clearances), engine offset grinds, and rub damage from previous time points are combined to establish the circumferential variation of clearance that is available for accommodation of non-axisymmetric structural deformations. Asymmetric rotor/case deflections are then introduced and when the relative closures exceed the available gap, the extent of local interference is recorded. Finally, wear characteristics of the contacting materials are considered to determine the trade-off between blade-tip/rub-strip damage due to the interference. Gap changes caused by shortened blades and the worn rubstrip are in turn carried forward to appear as increased initial clearances for the next time point. At the end of the cycle, the accumulated damage for each rub-strip is circumferentially integrated and added to blade-tip wear to provide the average clearance change for the stage.

The final step to be taken involves conversion of permanent clearance changes for the total cycle to increases in TSFC under standard performance conditions. This is accomplished by simply summing the contributions from each stage, or,

$$(\% \, \Delta \, \mathrm{TSFC})_i = \sum_{\substack{\text{all} \\ \text{stages}}} \zeta_{ij} \, \bar{c}_j$$

The influence coefficients (ζ) are unique to a particular engine model.

ENGINE DETERIORATION SIMULATION

Airplane Flight Acceptance Test

The production flight acceptance test was selected for simulation because every 747 off the assembly line is tested this way, according to a routine that is kept as standard as possible. The purpose of the flight acceptance test is to check out airplane internal systems. Airplane takeoff gross weight, airspeed, and throttle setting vary somewhat from one test to another because pilot instructions are given in terms of obtaining a signal from a warning or control instrument rather than in terms of achieving a specified flight condition.

Operating conditions to be considered as part of the flight test are defined in terms of rotor speeds, pressures, and temperatures from engine performance tables along with flight-related parameters such as attitude, altitude, inlet Mach number, airplane weight, and fuel distribution in the wing. Airloads present on the inlet are described for the flight acceptance profile. Thermal, pressure and centrifugal loadings are accounted for by the use of baseline clearance curves. These curves describe axisymmetric clearances between rotating and stationary seal components as functions of time for the flight acceptance profile. Inertia (g's) and gyroscopic effects as a function of time are also characterized for the acceptance profile.

The computer simulation of the flight acceptance test incorporates the proper combination of nacelle loadings, engine thrust, inertia and gyroscopic effects, baseline clearances, and engine airseal/blade abradability factors. Exposure to thrust and maneuver loads results in deformation of propulsion system structural members and leads to relative motion between static and rotating components of flowpath seals. If the motions are larger than can be accommodated by the available clearances, rubs and wear will occur and hence a loss in performance. This simulation covers 16 conditions along the mission profile as shown in figure 2. A summary of relevant flight parameters is given in figure 3.

JT9D-7/747 Service Experience

In the simulation of the 747 service experience, the previously defined flight acceptance test was refined to include only those maneuvers which are typical of a revenue flight. For the simulation, relative values of the loads remain unchanged, but the absolute values are increased to account for the probability of encountering larger loads during the life of the airplane.

The simulation of 747 service experience, as well as airplane acceptance, has been accomplished at several discrete times (after 500, 1000, etc., flights) in the lifetime of the airplane. In the lifetime of the airplane an ever-increasing chance of exposure to increasing load levels causes engine deterioration. Results from the model strongly reinforce the conclusion that flight induced seal rubs are the primary cause of short-term (250 flights or less) engine performance deterioration and they are a significant contributor to the additional deterioration accumulated over the long term. As part of this simulation, it has been shown that certain engine components are particularly sensitive to certain types of loads. In figure 6, it can be seen that the fan stage is very sensitive to gyroscopic loadings and relatively insensitive to varying gravitational (g) loading levels. It can also be seen that the high pressure turbine (HPT) stages are relatively insensitive to gyros but sensitive to g loadings.

Effects of Engine Build Clearance Tolerances

Ultimately an engine's rate of deterioration is a function of its design. An engine built with open clearances deteriorates at a slower rate than an engine with tight clearances. An engine with loose clearances has a high initial fuel consumption, but shows little deterioration from load effects with time. An engine with tight clearances has a low initial fuel consumption, but exhibits a much greater initial short-term deterioration rate. Modeling studies have shown that although an engine built with tight clearances deteriorates at a greater rate, it still exhibits better fuel consumption than a nominally built engine over its life cycle. This is true, in part, because rubs are local and the stage is still tighter on the average.

The effects of build clearance tolerances were investigated by using company standard engine build tolerance values in conjunction with the previously mentioned baseline clearance curves. Figure 7 depicts the results obtained from this investigation. From the figure, it is obvious that an engine built with open clearances shows less deterioration with time than an engine built with tight clearances. In this figure, however, no attempt has been made to bias the curves due to initially higher fuel consumption or initially lower fuel consumption. Correlation of predicted % Δ TSFC ranges with short-term engine deterioration data is shown in figure 8. The predicted values bracket the engine data quite well.

The trend in predicted changes in % Δ TSFC of the JT9D-7 from loads versus time was found to be in good agreement with 747 fleet experience trends as shown in figure 9. Figure 10 suggests that beneficial effects of module reoperation or replacement (where only build clearances are restored) are only temporary and, as the engine re-enters service and encounters flight loadings, the airseals in the restored module (HPT or LPT) once again experience rub damage and deterioration within a short-term time frame.

Analysis of the results from the simulation reveals that calculated average clearance changes for the individual stages also correlate well with the JT9D-7 experience. Except for the fan stage (fig. 11), however, predicted and observed circumferential rub damage distributions do not compare satisfactorily. Figure 12 depicts 1st-stage HPT outer airseal damage as a function of angular location for both a NASTRAN prediction and measured data on an engine that was torn down and measured in-house. A significant point to make with respect to this correlation is that the rub pattern exhibited by this engine is not typical of data measured on several other engines. In each case, the NASTRAN predicted values of average damage are in agreement with measured engine data. Figure 13 reinforces the conclusion that the trend in change of turbine tip clearance is increasing with time.

CONCLUSIONS

An analytical procedure for assessing the effects of flight loads on engine performance deterioration has been developed and applied to predict short- and intermediate-term changes in TSFC for the JT9D-7/747 installation. Good correlation between predicted and observed values for Δ TSFC serves to confirm the basic assumption that load-induced seal rubs have a significant effect on short-term performance deterioration.

The correlation between analytical prediction and measured clearance change is acceptable, but further refinements are desirable to explain specific rub pattern variations.

The analytical procedure provides for the detailed description of loads and deflections as they vary with time for arbitrary flight profiles and thereby permits the effects of individual loads to be isolated for evaluation. For the JT9D-7, studies of this kind indicate that airloads (inlet lift) are the dominant factor, maneuver loads (g's, gyros) are of secondary importance, and thrust loads do not contribute to performance losses after the engine acceptance test.

Usefulness of this procedure as a diagnostics tool for understanding the major causes of early performance deterioration (rub-induced clearance changes) has been demonstrated. At the same time, potential usefulness of the procedure as a design tool which can be used to minimize these effects in the future through use of load-sharing nacelles, active clearance control, optimum bearing placement, etc., has also been inferred. Better in-flight load predictions will be needed for future engine design clearance optimization for active clearance control systems.

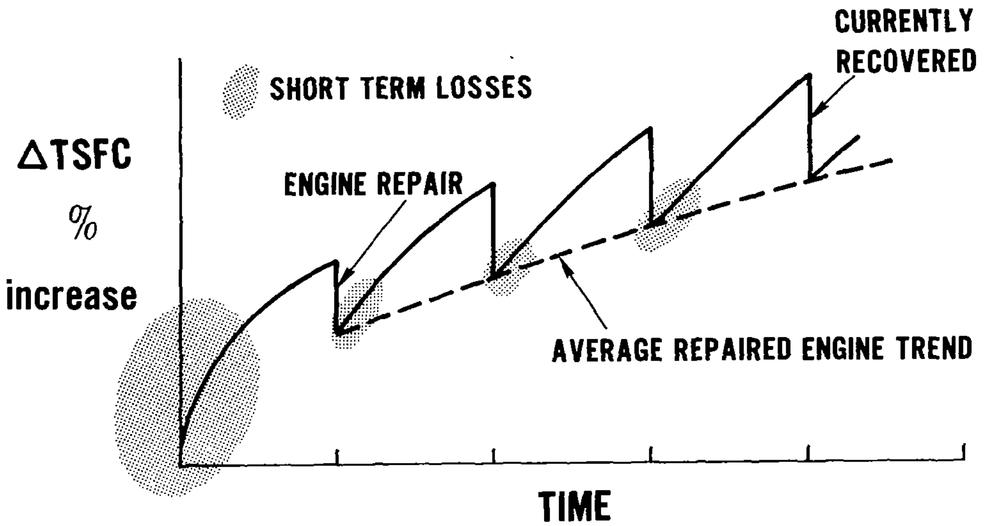
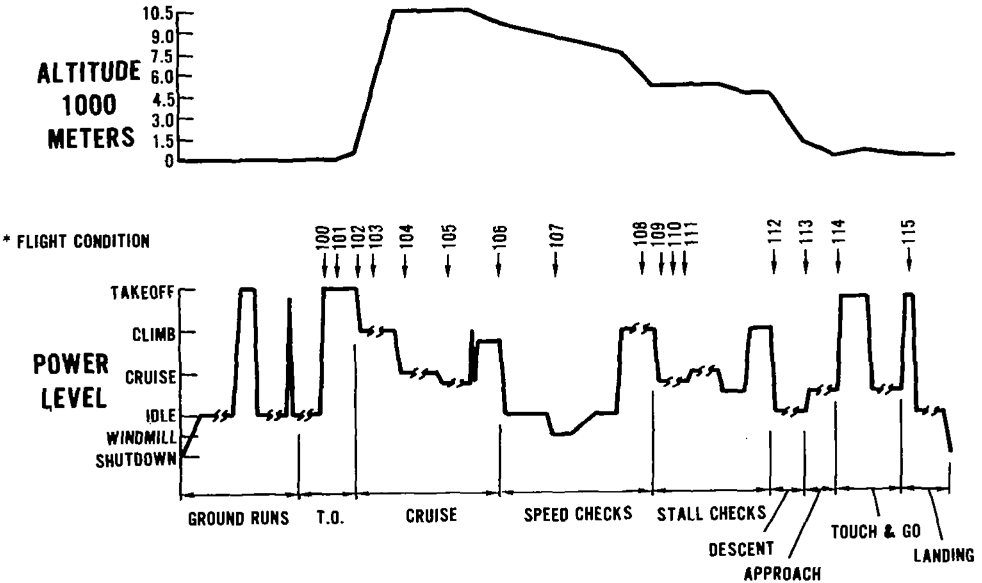


Figure 1.- General characteristic of TSFC performance deterioration trends.



*SEE FIGURE 3

Figure 2.- Airplane acceptance test flight profile.

FLIGHT CONDITION	DESCRIPTION	ALTITUDE (M)	AIRSPEED M_N
100	TAKEOFF ROLL	0	0.186
101	TAKEOFF ROTATION	0	0.214
102	EARLY CLIMB	914	0.401
103	MID CLIMB	5,330	0.617
104	HIGH MACH CRUISE	10,670	0.860
105	LOW MACH CRUISE	10,670	0.770
106	MAXIMUM MACH	9,750	0.920
107	IN-FLIGHT SHUTDOWN	8,380	0.720
108	MAXIMUM SPEED	6,100	0.830
109	1.3 VS. 0° FLAPS	5,180	0.340
110	1.3 VS. 10° FLAPS	5,180	0.340
111	1.3 VS. 30° FLAPS	5,180	0.340
112	EARLY DESCENT	5,180	0.440
113	APPROACH, 20°FLAPS	914	0.240
114	TOUCHDOWN	0	0.271
115	THRUST REVERSE	0	-

Figure 3.- Airplane acceptance test flight profile parameters.

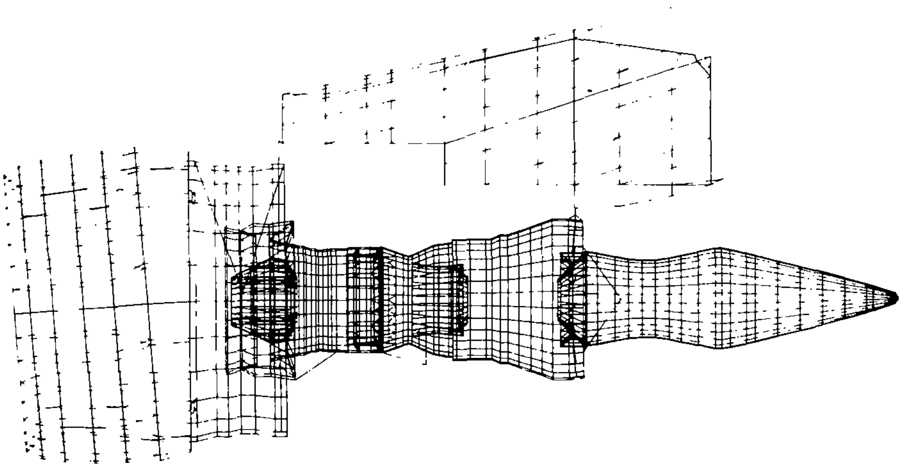


Figure 4.- JT9D-7/747 integrated NASTRAN structural model.

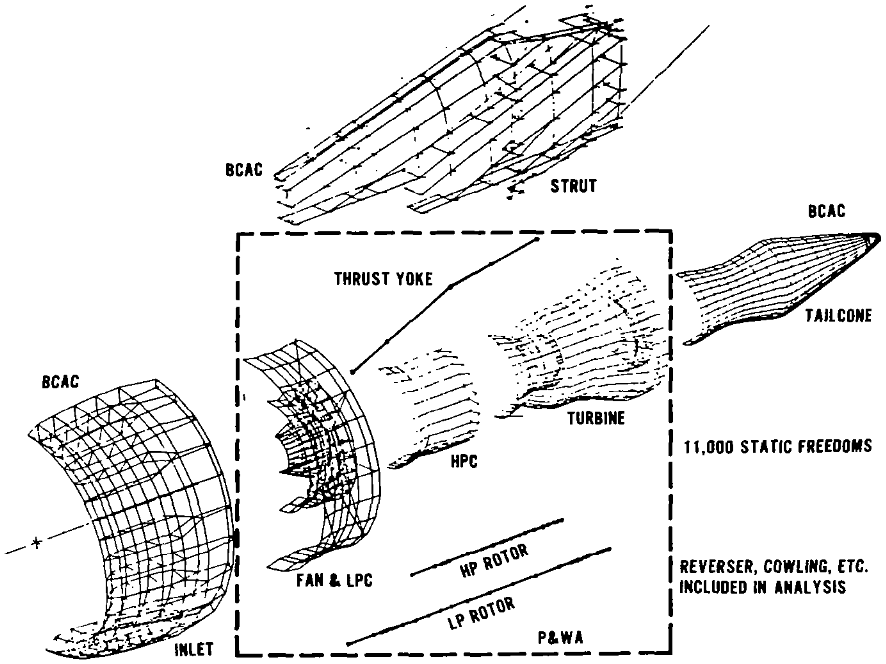


Figure 5.- JT9D-7/747 propulsion system substructures.

		AVERAGE DAMAGE (MM)	
STAGE	1/150 FLIGHTS THRUST AND AIR LOADS	1/150 FLIGHTS THRUST, AIR AND G LOADS	1/150 FLIGHTS THRUST, AIR, G AND GYRO LOADS
FAN	0.508	0.508	0.787
2 LPC	0.025	0.051	0.102
3 LPC	0.381	0.381	0.381
4 LPC	0.584	0.584	0.584
3 LPT	0.025	0.025	0.025
4 LPT	0.076	0.076	0.076
5 LPT	0.127	0.127	0.127
6 LPT	0.254	0.254	0.254
ALL HPC	—	—	—
1 HPT	0.127	0.178	0.178
2 HPT	0.305	0.356	0.356
%ΔTSFC (SSLTO)	1.5	1.61	1.65

Figure 6.- JT9D engine average damage.

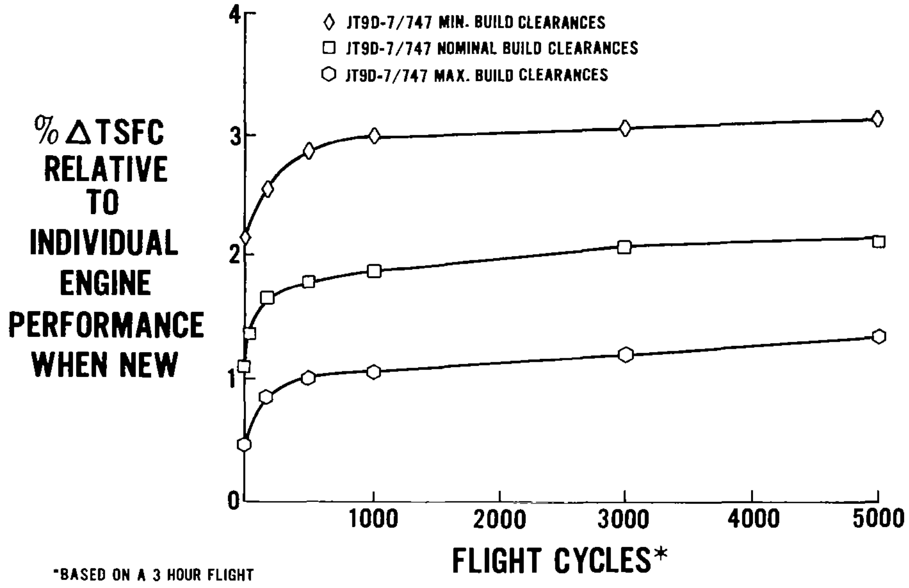


Figure 7.- Predicted effect of build clearance on short and long term deterioration.

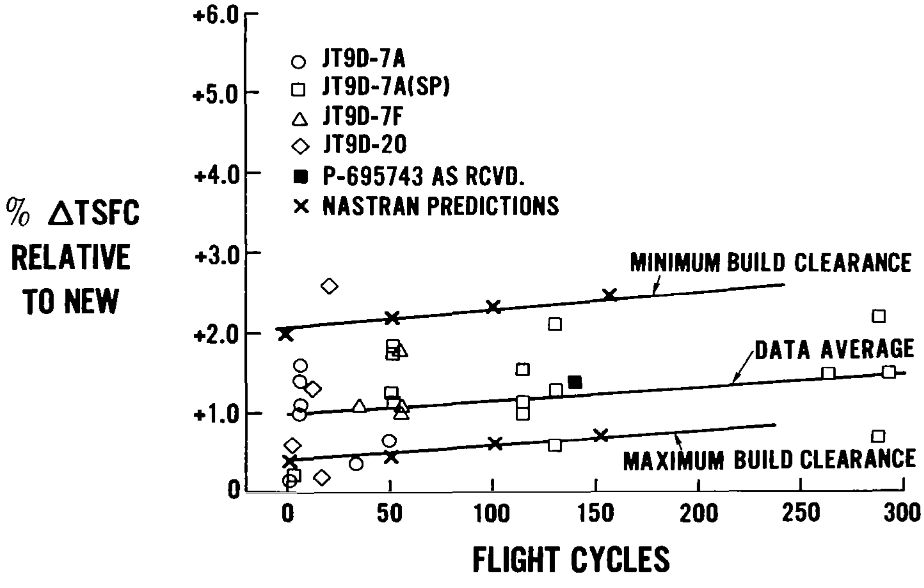


Figure 8.- Short term deterioration predictions bracket engine data.

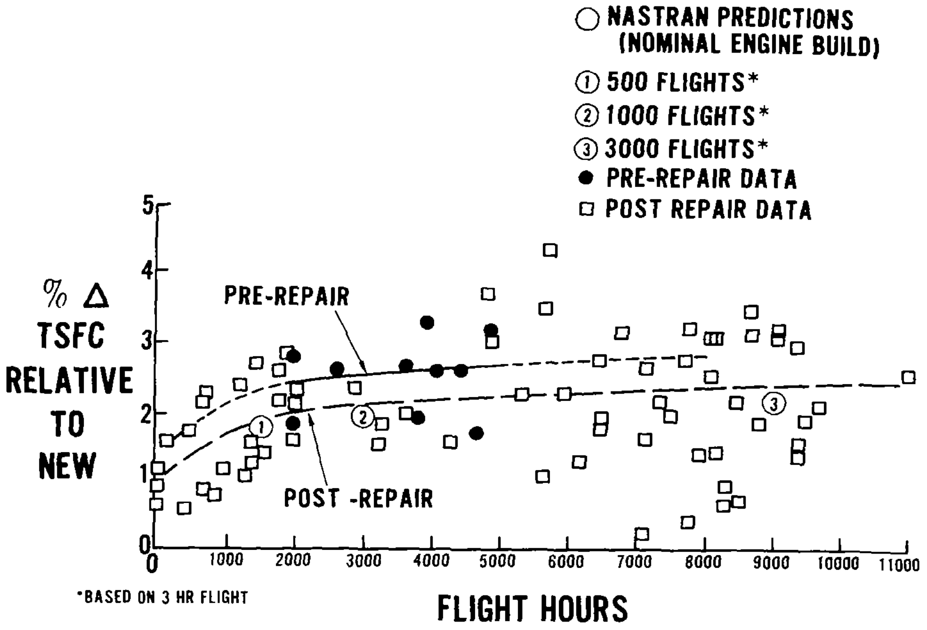


Figure 9.- Long term deterioration predictions are in good agreement with fleet experience.

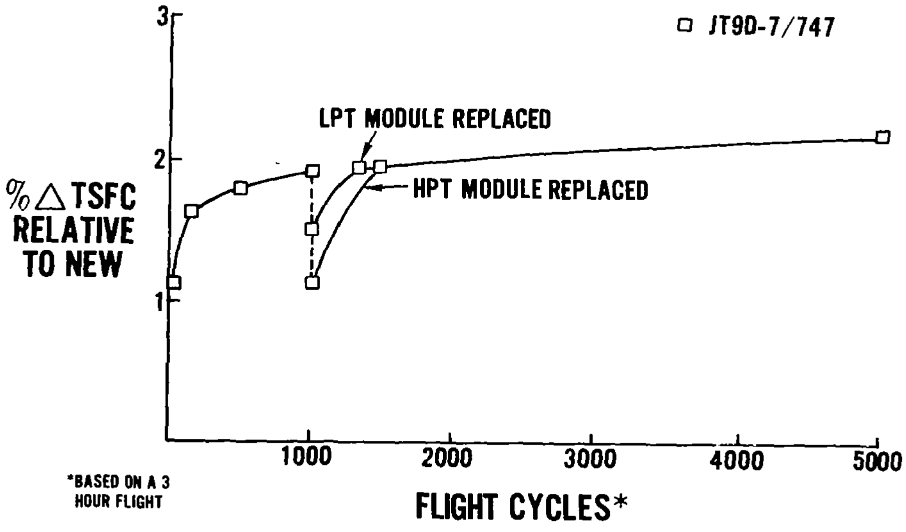


Figure 10.- Effects of turbine module replacement and subsequent deterioration.

ANALYTICAL/EXPERIMENTAL CORRELATION

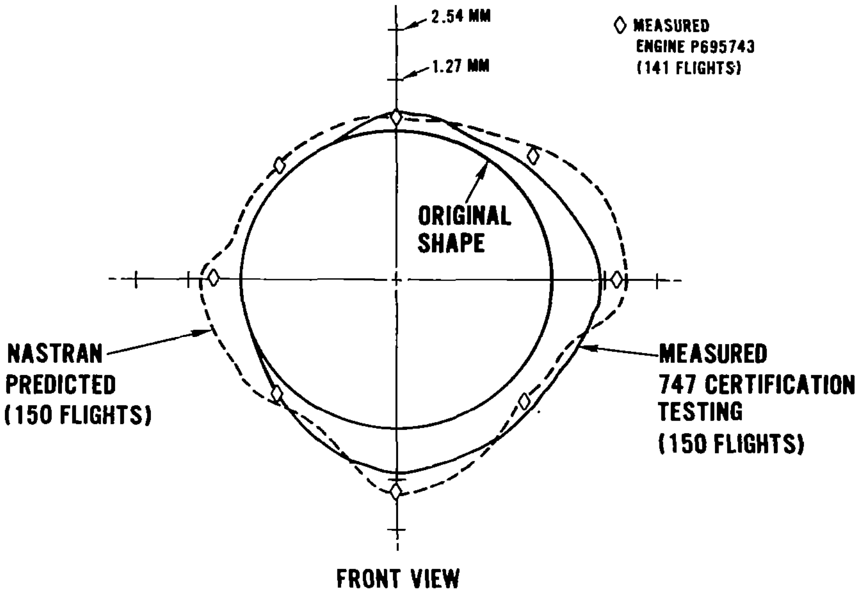
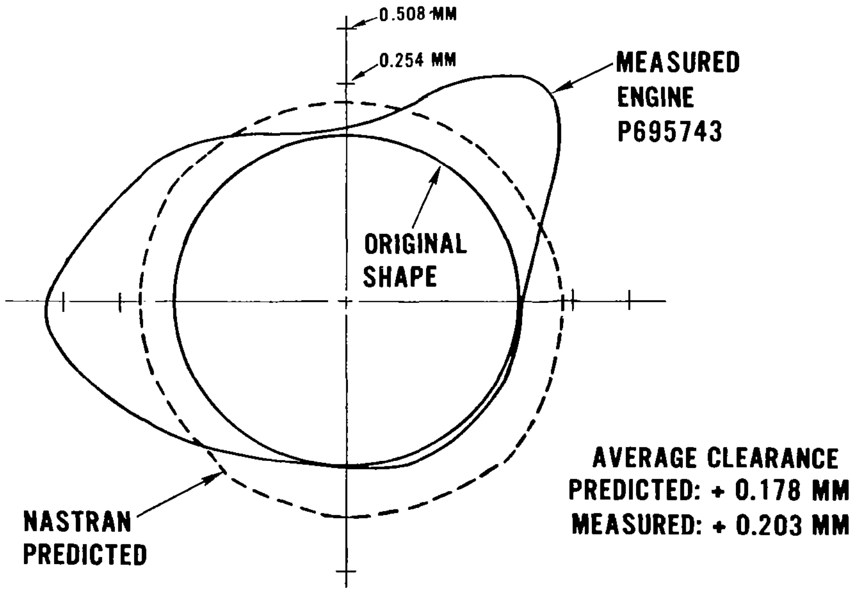


Figure 11.- Predicted fan rub patterns compared to measured data.

PREDICTED FOR 150 FLIGHTS VERSUS MEASURED DATA AT 141 FLIGHTS



AVERAGE CLEARANCE
PREDICTED: + 0.178 MM
MEASURED: + 0.203 MM

Figure 12.- Predicted first HPT outer airseal rub damage compared to measured data.

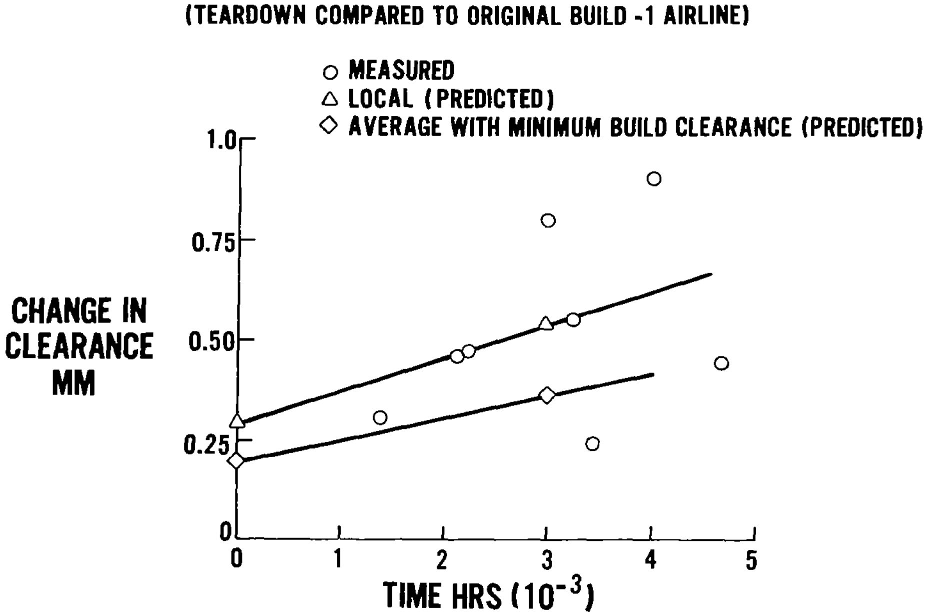


Figure 13.- JT9D-7 high pressure turbine tip clearance change with time.