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CF6 JET ENGINE DIAGNOSTICS PROGRAM

SUMMARY REPORT

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

Cockpit cruise recordings and test cell data in conjunction with hardware inspection results from airline overhaul shops were analyzed to define the extent and magnitude of performance deterioration of the General Electric CF6 high bypass turbofan engines. These studies successfully isolated the magnitude of Short-Term deterioration from the Long-Term, and identified the individual damage mechanisms that were the cause for the majority of the performance deterioration. Unrestored losses, that is, performance deterioration which remains after engine refurbishment, represent over 70 percent of the total performance deterioration at engine shop visit. A large percentage of the unrestored losses are cost effective to restore, and if implemented could reduce fuel consumed by CF6 engines - for example, about 50 million gallons in 1981.

General Electric has already applied the findings of this program to reduce the performance deterioration of new CF6 engines, resulting in a reduction of deterioration of over 50 percent.

The clearance sensitivity evaluations identified a potential for reduction in compressor clearance and a potential for improvement in turbine roundness, which corresponds to cruise SFC reductions of 0.38 and 0.36 percent, respectively.

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FOREWORD

The work was performed by the Evendale Product Engineering Operation of General Electric's Aircraft Engine Group, Aircraft Engine Engineering Division, Evendale, Ohio. The program was conducted for the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, under the CF6 Jet Engine Diagnostics Program, Contract Number NAS3-20631. The CF6 Jet Engine Diagnostics Program is part of the Engine Component Improvement (ECI) Project, which is part of the NASA Aircraft Energy Efficiency (ACEE) Program. The NASA Project Engineer was R. P. Dengler. The program was initiated in 1977 and completed in 1981.

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1.0 SUMMARY

The overall objective of the Engine Diagnostic effort was to conduct studies and tests of current high-bypass ratio turbofan engines to identify and quantify the sources and causes of performance deterioration with respect to operating time (both short-term and long-term), and to develop basic data which can be applied to minimize performance degradation of current and future engines.

Data analysis, engine tests and hardware inspections were conducted in order to define the deterioration characteristics and the causes of deterioration modes, and to increase the understanding of sensitivities of tip clearance changes on engine performance. Cost effective performance retention was identified as a means of significant fuel savings. Based on expected revenue service flight time, it was estimated that application of the cost effective items described for the CF6 family of engines could reduce fuel consumption by 50 million gallons in 1981, and proportionate amounts in subsequent years. General Electric has already applied the findings of this program to reduce the performance deterioration of new CF6 engines. The current CF6-50 engines show an improvement of over 50 percent relative to the engines which formed the baseline for the Diagnostic Program.

The high pressure compressor (HPC) and high pressure turbine (HPT) clearance sensitivity evaluations verified the importance for retention of tip clearance and quantified the performance sensitivities from real-time measurements in CF6 engine tests. A potential reduction in compressor clearance in the aft stages of 1.0 mm (0.040 in) was identified, equivalent to a compressor efficiency increase of 0.78 percent, which translates to a cruise SFC improvement of 0.38 percent. Also, a potential improvement in turbine roundness was established in the order of 0.38 mm (0.015 in.), equivalent to 0.86 percent in turbine efficiency, which translates to a cruise SFC improvement of 0.36 percent.

2.0 INTRODUCTION

An Engine Diagnostics Program to identify and quantify the causes of performance deterioration which increase fuel consumption for the General Electric CF6 family of turbofan engines has been completed. The energy demand in the early seventies outpaced fuel supplies, creating an increased United States dependence on foreign oil. This increased dependence, accentuated by rapid price increases in 1973/74 due to the OPEC embargo, brought about a changing economic environment in all sectors of the transportation industry.

As a result, the Government initiated programs in 1975 aimed at both the supply and demand aspects of the problem. Programs to determine the fuel availability from new sources such as coal and oil shale, with concurrent programs to develop aircraft engine components to accept these broader specification fuels were established in an effort to increase supply. Reduced fuel consumption was the approach selected to reduce demand within the Air Transport Industry. Accordingly, NASA established and sponsored the Aircraft Energy Efficient (ACEE) Program, which was directed toward reducing fuel consumption for commercial air transports.

The long range effort to reduce fuel consumption required the evaluation of new technology for more efficient turbofans or improved propulsion cycles, such as that used for turboprops. It was expected that a significant reduction in fuel consumption by the incorporation of these new and improved state-of-the-art propulsion systems could not be achieved within the next 10-15 years. Therefore, the only practical approach to reducing fuel consumption in the near term was to improve the fuel efficiency of current engines, since these will continue to be the significant fuel users for the next 10-15 years. This was accomplished through the Engine Component Improvement (ECI) Program, one of six programs under the ACEE Program.

Included in the ECI Program was the Performance Improvement element directed toward improving the fuel efficiency of the current engines by incorporating improved designs or modifications in existing designs. The other major element of the ECI Program was the Engine Diagnostics effort to identify and understand the sources and causes of deterioration for high bypass ratio turbofan engines. It is this effort on the General Electric CF6 engines that is summarized in this report.

This effort was directed at identifying and quantifying the sources and causes of engine performance deterioration of the CF6 engine and its derivatives. Performance deterioration is considered to be a result of short-term and long-term effects. Short-term performance deterioration occurs during an engine's initial checkout test prior to delivery to the airlines and in the early fleet operation by the airlines. Most of the short-term deterioration is suspected to occur within the first 100 hours of its operational life. Long-term performance deterioration occurs over an engine's life cycle over and beyond the described short-term operational period.

The specific objectives were:

1. Define the extent and magnitude of CF6 engine performance deterioration and establish statistical trends.

2. Identify and quantify the sources and causes of CF6 short-term engine performance deterioration.

3. Determine sensitivity of component performance to deterioration of engine parts.

4. Develop an analytical model which represents a statistical average or typical SFC loss associated with deterioration for parts of each major component in the engine.

5. Recommend areas where performance retention items can be applied to current and future engines.

This Engine Diagnostics Program investigated performance deterioration characteristics for the CF6 family of engines, specifically the CF6-6D and CF6-50 model engines. The CF6-6D engine is currently utilized on the DC-10 Series 10 while the CF6-50 engine is utilized on the A300B, B747, and the DC-10 Series 30 aircraft. Independent programs were established to investigate each model engine, but all efforts were totally interrelated within the overall program. The program consisted of:

1. Collection and analysis of historical data.

2. Special engine tests including inbound and outbound tests at overhaul shops.

3. Compressor and turbine clearance sensitivity investigations.

3.0 APPROACH

The program to define the deterioration levels and modes for the CF6 family of engines involved four distinct phases: analysis of inbound engine tests results, analysis of airline cruise data, analysis of airline test cell data resulting from testing of refurbished engines and inspection of engine hardware. In addition, the sensitivity of compressor and turbine tip clearances was evaluated in instrumented engine tests.

3.1 INBOUND ENGINE TESTS

Testing of engines removed from aircraft after extensive revenue service, was conducted in order to define, on a specific engine basis, how much the specific fuel consumption had increased and to provide some insight into which components were the prime contributors to the observed deterioration.

Through the CF6-6 and CF6-50 phases of the program, 15 inbound engine tests were conducted. One of these tests, conducted as part of the CF6-6 Program, was specially accomplished to identify short-term losses.

For each of the inbound engine tests, sufficient instrumentation was installed to measure overall engine deterioration and to indicate the magnitude of deterioration of each major component. After the inbound tests had been conducted, three of the engines were subjected to a detailed teardown inspection by design engineers to relate hardware condition to inbound tests results.

3.2 AIRLINE CRUISE DATA

In addition to the inbound tests conducted on specific engines, an analysis of fleet performance data accumulated during flight was conducted to better define the deterioration characteristics of the typical CF6 engine in revenue service.

Data from many airlines are supplied to General Electric on a periodic basis. These data are supplied in many forms from logs recorded by flight engineers in the cockpit to data recorded via automatic data acquisition systems. These data, which are generally recorded during every flight of an aircraft, were used to define the deterioration characteristics of individual engines during the life of the engines over a given installation period. The process to define the performance trend was to compare the performance indicating parameters (fuel flow and exhaust gas temperature level) to a reference engine parameter level at the flight condition and power setting.

Data from five airlines using CF6-6D engines and from nine airlines using CF6-50 engines were reviewed. In all, data from 239 CF6-6D engines and 263 CF6-50 engines were analyzed in defining deterioration rates of initial installation and multiple installation engines in revenue service.

General Electric also obtained and analyzed data recorded at cruise during initial aircraft checkout flights conducted by the aircraft manufacturer to determine if performance degradation occurred within an engine prior to initial revenue service. Data from 82 CF6-6D engines and data from 111 CF6-50 engines were analyzed in order to determine the magnitude of any "Short-Term" deterioration of engine performance prior to airline receipt of the aircraft and engines. As will be discussed in more detail later, it was concluded after this analysis that significant deterioration did occur during these aircraft checkout activities.

A CF6-6D engine that was removed from a DC-10 aircraft and subjected to an inbound performance run verified that the indicated loss based upon cruise data analysis was indeed real and non-reversible. As mentioned, this engine was disassembled and critically inspected by a team of General Electric engineers to define the area of performance degradation. Another engine, removed early after entrance into revenue service due to vibration problems, was also tested inbound and similarly confirmed that the short-term loss of performance was real.

3.3 AIRLINE TEST CELL DATA

An important part of the analysis effort to understand airline fleet engine performance levels centered around the definition of basic engine performance levels after overhaul in the airline shops.

Performance levels were reviewed for engines outbound after overhaul at a major airline overhaul facility during the CF6-6D Program and at one consortium central agency and five other overhaul facilities during the CF6-50 Program. Engine performance levels obtained at these facilities were compared to new engine performance levels obtained in the General Electric Production Facilities in order to define the effectiveness of typical engine workscopes in restoring performance by refurbishment to new engine levels.

3.4 INSPECTION OF ENGINE HARDWARE

The modes of deterioration were identified through actual observations of service hardware by General Electric teams. Teams of Mechanical and Aerodynamic Design personnel visited various maintenance facilities and conducted detailed inspections of the various engine modules in the disassembled stage to assess the condition of component parts relative to the condition of new hardware. Observations of rotor clearances, surface finish of the airfoils, cleanliness and smoothness of various static structures and potential air leakage paths were reviewed and estimates of component performance relative to a non-deteriorated component were assessed.

Hardware from each major module at various stages of engine life was observed, thus allowing estimation of the deterioration associated with any module deterioration mechanism as a function of time and cycles.

The trends of performance deterioration for each engine module were generated from a review and analysis of all the deterioration trends established for specific degradation mechanisms with regards to the respective module. Based upon these module trends, and applying appropriate knowledge of the engine cycle, the overall engine deterioration characteristics were then established. In all cases throughout both the CF6-6 and CF6-50 Programs, the estimates of engine deterioration established based upon hardware examinations showed excellent agreement with the overall deterioration rates established by cruise and test cell data analysis.

3.5 HP COMPRESSOR AND HP TURBINE TIP CLEARANCE SENSITIVITY INVESTIGATIONS

Two instrumented engine tests were conducted to measure compressor and turbine tip clearances and to evaluate the sensivitity of these clearances on engine performance.

The compressor clearance sensitivites were evaluated in an instrumented core engine test in which airfoil tip clearances were controlled by varying the compressor rotor bore cooling air flow at steady state operating conditions. To investigate potential improvements for engine operation with tighter clearances, a number of transient test runs were made which included engine power throttle bursts and chops and hot rotor power throttle rebursts.

The high pressure turbine tip clearance and stator out-of-roundness conditions were measured in an instrumented fan engine test. The testing included both steady-state and transient engine operating conditions. The data were analyzed to determine the effect of HP turbine clearance changes on engine performance and to investigate potential improvements for engine operation with decreased tip clearances.

4.0 DISCUSSION OF RESULTS

The results of the analysis of inbound engine tests, airline cruise data and airline test cell data from testing of refurbished engines are discussed under the heading of Performance Deterioration Characteristics. The details of the hardware inspection are described under the heading of Hardware Inspection Details. The results of the hardware inspection are presented under the heading of Component Deterioration Mechanisms. Finally, the results of the compressor and turbine clearance sensitivity investigations are presented under the heading of HP Compressor and HP Turbine Clearance Sensitivities.

4.1 PERFORMANCE DETERIORATION CHARACTERISTICS

Figure 1 shows the resulting assessment of CF6-6D performance deterioration characteristics for the typical engine through its initial installation of revenue service and for a similar typical engine after several multiple installations. Elements of deterioration and restoration/unrestored performance are presented. This figure indicates the equivalent cruise specific fuel consumption increases that occur relative to a new production engine. The deterioration characteristics for an initial installation is shown on the left. During aircraft acceptance testing, engines incur an average nonreversible short-term loss of 0.9 percent prior to revenue service. This short-term SFC deterioration has already been accounted for when performance guarantees are issued to customers. During their initial installation of revenue service, the SFC increases an additional 1.7 percent based on the typical 4000-hour duration of the initial installation. The total increased SFC of the deteriorated engine after the initial installation is thus 2.6 percent from that of the new production engine. Insufficient data was available to accurately determine the amount of performance restoration during the first shop visit, but it is estimated to be between 0.6 to 0.8 percent.

The deterioration characteristics for multiple installation engines are shown on the right-hand side of Figure 1. From the second to the "nth" installation, the serviceable engine re-enters revenue service after a shop visit with an average unrestored cruise SFC loss of 2.1 percent. Then, during the subsequent revenue service period, the cruise Δ SFC of this multiple-build engine increases by 0.9 percent for the typical 3000-hour duration of multiple-installation engines. The total increased SFC of this deteriorated engine at 3000 hours was 3.0 percent from new. On the average, 0.9 percent of the cruise Δ SFC loss is restored during a shop visit. It is clear from the figure that for any subsequent installation, an average revenue service deterioration of 0.9 percent Δ SFC is incurred. On the average, this same amount is restored during a shop visit for maintenance purposes and the cycle is repeated. The observed trend, then, of a constant level of deterioration for all periods of installation can be primarily attributed to the modular maintenance concept employed to refurbish or repair engines. Though engine-to-engine variations for this cycle are significant, the data presented reflect the typical or average engine deterioration characteristic for the CF6-6D engine.

Figure 2 shows the deterioration characteristics resulting from cruise data analysis of data obtained for the CF6-50 engine on various aircraft. General findings of the program were that the engine short-term losses, which occurred during the airframer checkout of the aircraft, tended to be the same for operation on all three aircraft. Also, the unrestored performance level of the multiple-build engine as refurbished by the various airlines was essentially the same. It can be noted from Figure 2 that the deterioration rate shown during typical B747 operation was lower than observed with DC-10 and A300 operations. The same relationship holds for both the initial and multiple installations. The unrestored SFC of the typical engine re-entering revenue service after airline shop visits is 1.8 percent higher than the new engine baseline for the CF6-50 engine as compared with the 2.1 percent determined in the CF6-6D analysis.

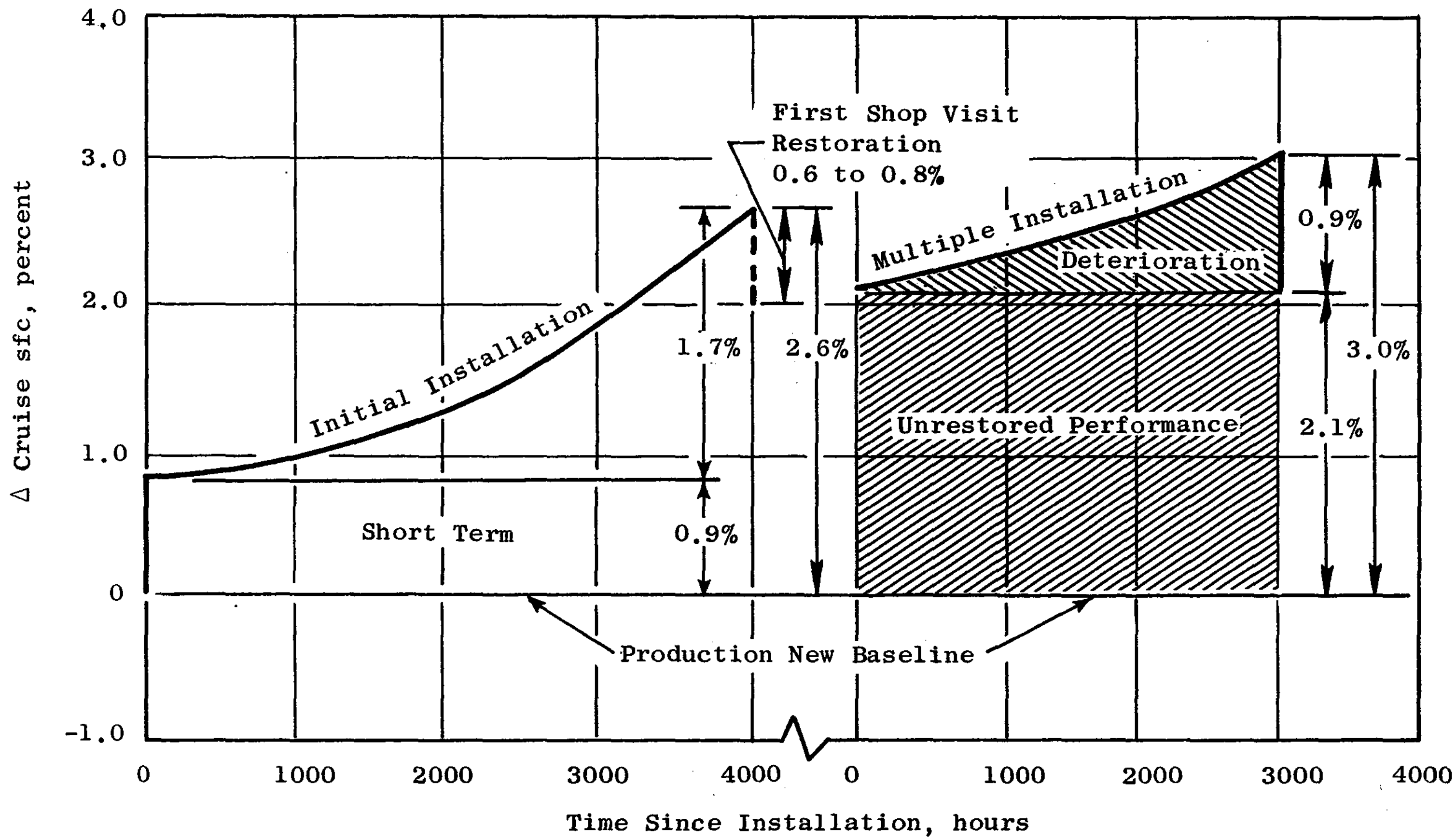
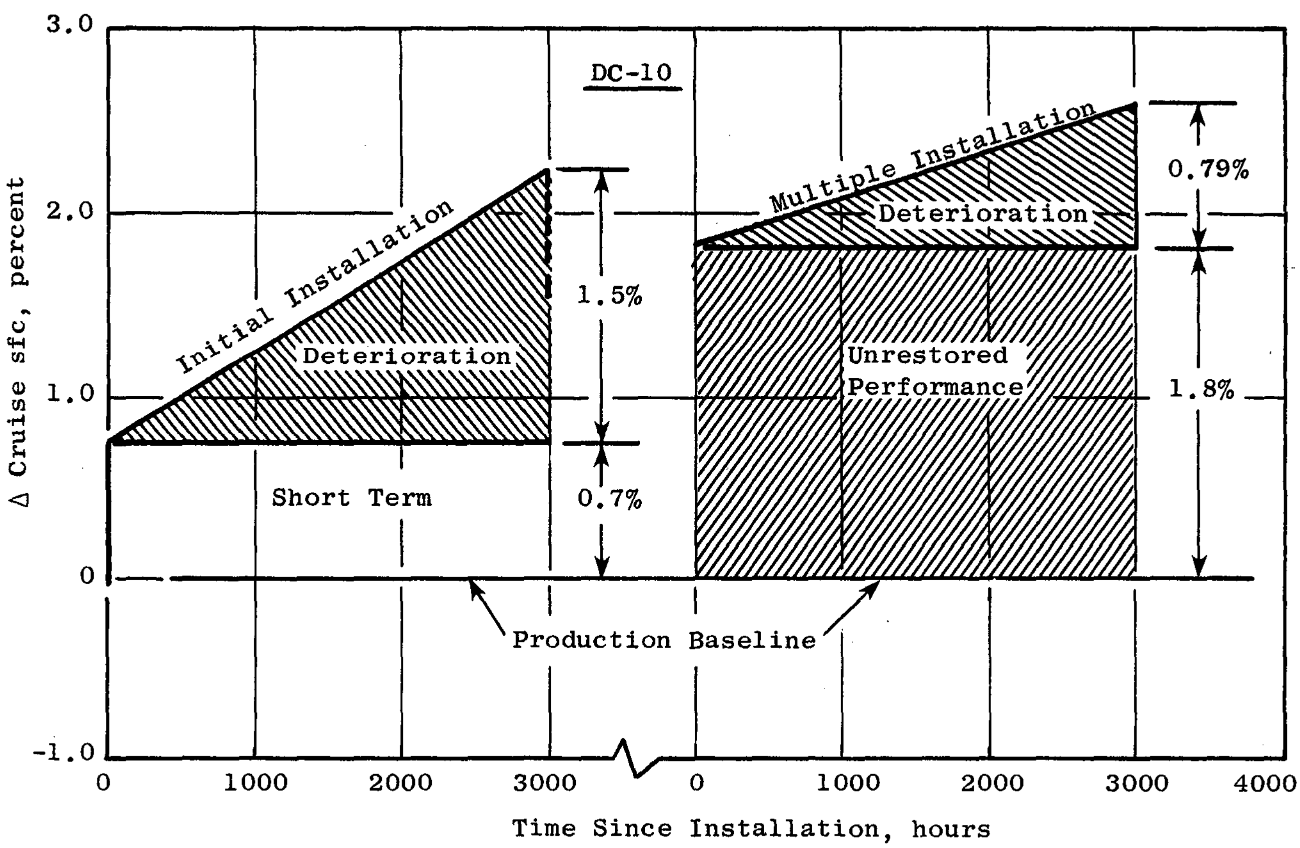


Figure 1. Typical CF6-6D Performance Deterioration Characteristics.

	DC-10	B-747	A300
Short-Term Loss, percent	0.7	0.7	0.7
Typical Time to Removal, Initial Installation, hours	3000	4000	2000
Initial Flight Cycle Length, hours	3.4	5.2	1.5
Initial Installation sfc Loss, percent	1.5	1.6	1.1
Typical Time to Removal, Multiple Installation, hours	3000	3850	2000
Multiple Installation Flight Cycle Length, hours	3.9	5.5	1.3
Multiple Installation sfc Loss, percent	0.79	0.95	0.79
Unrestored sfc, percent	1.8	1.8	1.8

(a) Engine Performance Deterioration Characteristics for Various Aircraft



(b) Deterioration Characteristics for DC-10 Aircraft with Respect to Time

Figure 2. Deterioration Characteristics.

The deterioration rates shown on Figures 1 and 2 are presented as a function of flight hours since installation. As part of the CF6-50 program, an analysis was conducted to understand the variability in deterioration rates which resulted from analysis of DC-10, B747 and A300B data. The conclusion was that deterioration rates for the data surveyed were strongly influenced by the average flight length per cycle and the amount of derate, or reduced power, being used by the individual operators. Table 1 shows the data from Figure 2 translated into the deterioration rate per 1000 cycles basis. The conclusion is that while the DC-10 and B747 data are reasonably consistent and show approximately the same deterioration rate per 1000 cycles, the A300B data shows a much lower deterioration rate per 1000 cycles. Since the A300B data studied as part of this program were consistent with flight cycle lengths of approximately 1.9 hours, the lower deterioration rate per 1000 cycles suggests that deterioration rates are not only influenced by the numbers of cycles but also by the time at temperature.

4.2 HARDWARE INSPECTION DETAILS

The prime modes of deterioration within each module were established primarily through hardware inspections by design personnel at two major CF6-50 overhaul facilities and at one major CF6-6 overhaul facility. The details of the findings of these inspections are reported in References 1 through 7, including identification of the amounts of cruise SFC increase associated with each deterioration mechanism. However, some general statements concerning the more significant deterioration mechanisms are in order.

4.2.1 FAN DETERIORATION

The major areas of performance degradation within the fan section for both engine models were: 1) increases in tip clearance due to shroud erosion and the current maintenance philosophy which requires controlling only minimum clearance; this can result in local grinding and,

Table 1. CF6-50 Deterioration in 1000 Cycles.

Installation	A/C Type DC-10	B-747	A300
Initial Installation Δ SFC	1.71%	2.07%	0.83%
Multiple Build Installation Δ SFC	1.03%	1.36%	0.51%

in turn, results in increased shroud out-of-roundness and increased average clearance, 2) fan blade leading edge bluntness due to erosion and 3) fan bypass OGV erosion and leading edge bluntness due to loss of the polyurethene protective coating. During typical shop visits, the leading edge contours of the stage one blades are typically restored (with approximately 75 percent frequency). However, the "on-condition" maintenance philosophy, requiring only durability repairs, generally results in very little refurbishment to restore to new engine average clearance or to restore the OGV surfaces to the as-new condition.

4.2.2 HP COMPRESSOR DETERIORATION

The major deterioration modes of the CF6 engine high pressure compressors are: 1) increases in airfoil tip clearances, 2) degradation of airfoil surface finishes and leading edges and 3) creation of air flow leakage paths primarily through the variable stator vane bushings. With increased time in revenue service, the assembly of engine compressor stator cases (as engine parts are interchanged during shop visits) develop significant tendencies toward out-of-roundness. The maintenance philosophy in matching rotors and stators is to establish a minimum clearance. Thus, any tendency of the stator case to distort inward creates the requirement for short rotor blades (with resulting increased average clearance) and locally short stator vanes. The eventual result is increased airfoil tip clearances and associated deteriorated performance. Casing distortion and design changes which will result in a reduction in casing distortion are described in detail in References 8 and 9.

4.2.3 HP TURBINE DETERIORATION

The primary modes of deterioration detected in the high pressure turbine during revenue service were (1) the increase in blade tip-to-shroud clearances resulting from rubs which produce some losses in performance due to increased gas flow leakage and (2) airfoil surface finish degradation.

It has been found that tip clearances for both stages of the CF6-50 high pressure turbine typically increase during the first 1500 hours of operation and then appear to increase at a much lower rate. At 4000 hours, the average increase in tip clearances is 0.013 inch on stage 1 and 0.011 inch on stage 2, which corresponds to a 0.55 percent increase in cruise specific fuel consumption. These rubs and resulting clearance changes are primarily due to shroud support distortion, shroud swelling and bowing, shrinkage of the shroud supports and thermal mismatch between rotating and static structures during engine transients. Shroud distortion is discussed in detail in References 9 and 10.

4.2 4 LP TURBINE DETERIORATION

As in the case of the HPT, increases in blade tip clearances and interstage seal clearances result in the major portion of deterioration occurring within the low pressure turbine in service. Degradation of airfoil surface finish is another contributor but results in very little performance loss. The increase in clearances was found to be primarily due to wear of the stationary surfaces which result from engine axial mismatches during different phases of engine operation. While there is little loss of material from the rotating components, the wear of the tip shrouds and interstage seals results in approximately 0.4 percent loss in cruise SFC after 4000 hours of operation with both the CF6-6 and the CF6-50 turbines.

4.3 COMPONENT DETERIORATION MECHANISMS

Figure 3 illustrates the results of the hardware inspection analyses and the resulting deterioration model compared to the performance-data-derived deterioration level for the initial installation of CF6-6D engines. It shows that the largest portion of the 0.9 percent short-term SFC loss resulted from a loss in HPT performance. This loss was due largely to HPT clearance increases during the initial checkout phases of the airplane. During this initial operation of the aircraft by the aircraft

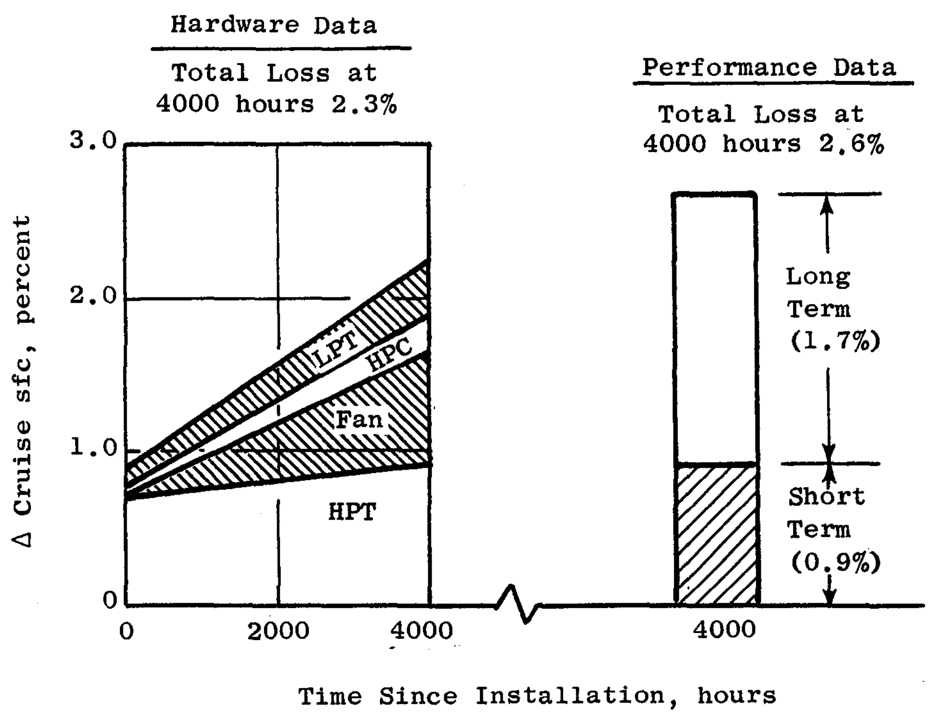


Figure 3. CF6-6D Initial Installation Performance Deterioration.

manufacturer, there is little accompanying loss in the fan, high pressure compressor and low pressure turbine. The combined performance deterioration level, as obtained from hardware inspection assessments, was created from a stackup of the individual component deterioration losses at 4000 hours. The resulting 2.3 percent total performance degradation from the "as new" condition compares well with the 2.6 percent level which resulted from the performance data analysis.

Figure 4 shows the deterioration mechanisms as assessed by hardware inspection for the CF6-6D multiple-build engines. The major deterioration of a multiple-build engine is within the HPT module. Typically, HPT performance is restored during every shop visit while fan, HP compressor and LPT performance levels are not. Therefore, each engine as it re-enters revenue service after an overhaul shop visit has new HPT hardware and somewhat deteriorated fan, HPC, and LPT performance levels. It can be noted again from Figure 4 that the results of the hardware inspection show 3.3 percent performance loss at 3000 hours on multiple-build engines compared to the performance data analysis level which indicated 3.0 percent. Again, the agreement is good. Similar findings resulted for losses associated with the initial installation and the multiple installations of CF6-50 engines, as reported in Reference 6.

Based on hardware inspections, the unrestored loss for the typical CF6-6D engine coming out of the overhaul shop was 2.08 percent in terms of cruise SFC as compared to the 2.1 percent unrestored performance level identified by performance data analysis. Figure 5 illustrates the unrestored performance levels in various components for both the CF6-6D and CF6-50 engine models and compares the overall level as shipped from the airline overhaul facilities, to that of the new engine performance level. Of the 2.1 percent unrestored performance for the CF6-50 engine, it indicates that a large portion of this is due to lack of performance restoration in the fan area. Somewhat lesser amounts of unrestored performance is associated with the high pressure compressor and the LP

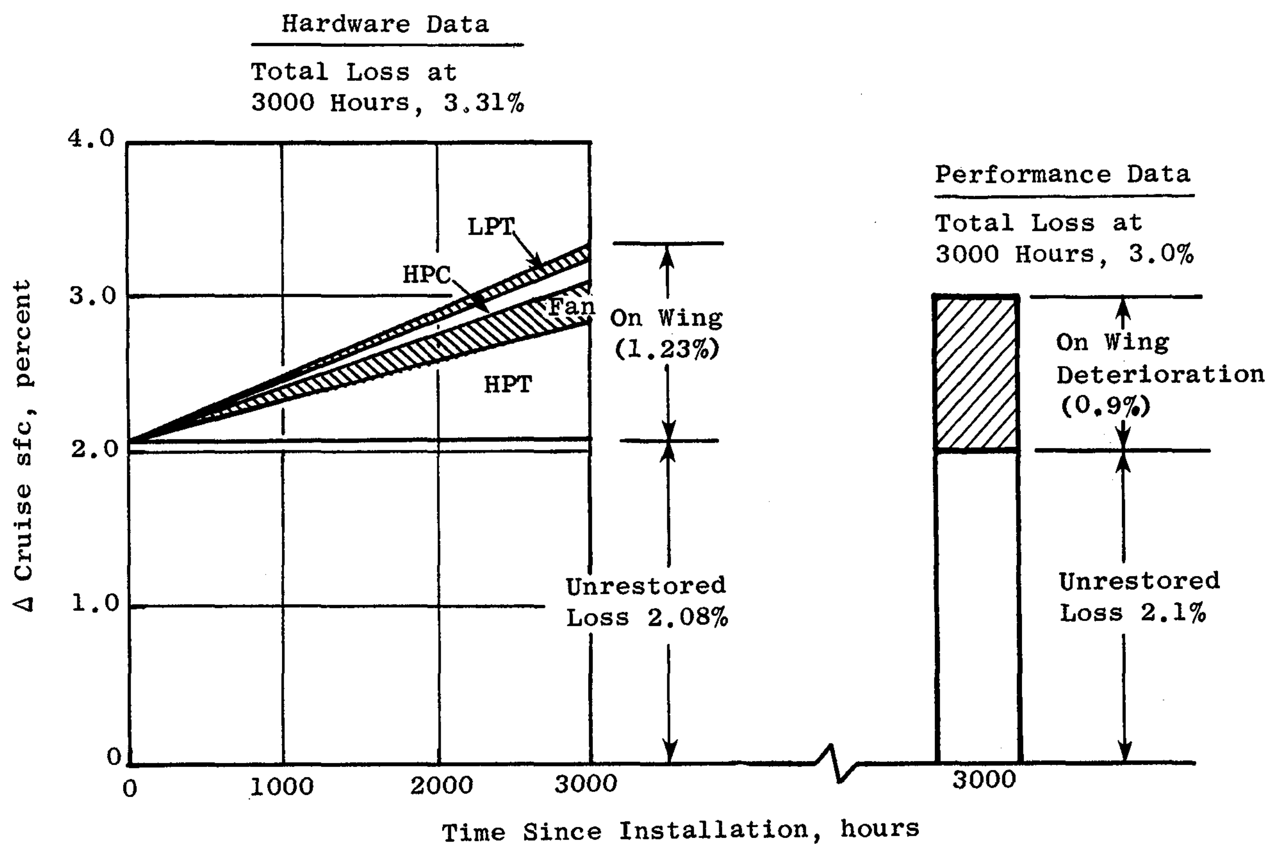


Figure 4. CF6-6D Multiple Build Engine Performance Deterioration.

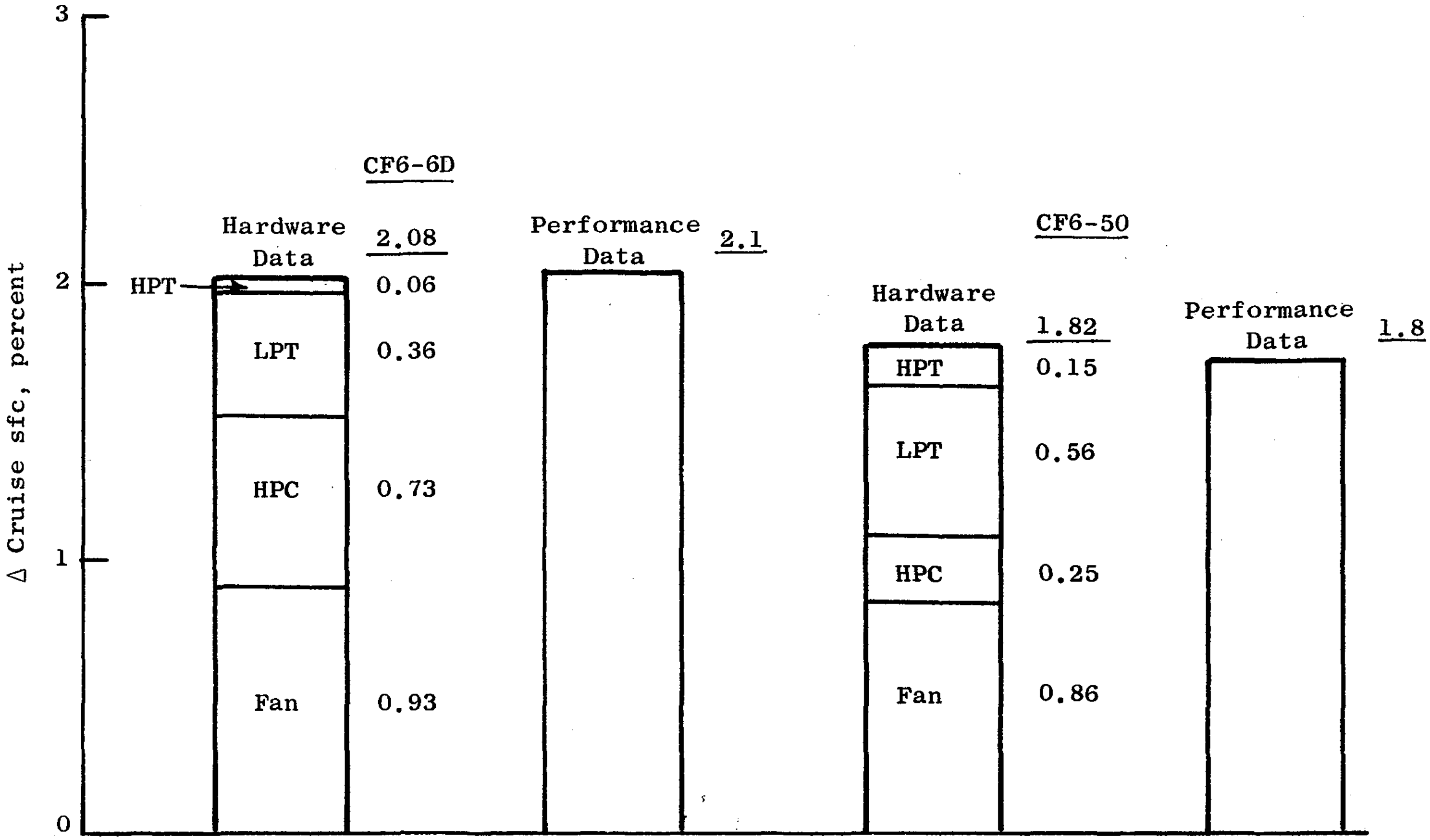


Figure 5. Unrestored Performance – Hardware Inspection Summary Compared to Performance Summary.

turbine. Note that there is very little unrestored performance in the HPT area because the HP turbines of outbound engines are, typically, completely refurbished during shop visits. Again, the hardware inspection data and the performance data show excellent agreement.

The unrestored performance identified in Figure 5 represents a significant potential in terms of fuel and dollars savings to the airlines, if it can be reduced on a cost effective basis. The presence of large amounts of unrestored performance, associated with performance degradation of the fan module, HPC module and the LPT module, relative to new modular performance levels, is due to early workscope definitions. These airline shop overhaul work scope definitions were primarily aimed at maintaining reduced EGT levels and at restoring the condition of the hardware primarily from a reliability standpoint. The engine modules which have the most direct impact on EGT margin are primarily associated with the hot section of the engine, i.e., the combustor and high pressure turbine areas. Larger efforts (dollars and manhours) are required to achieve a similar amount of EGT margin restoration in the LP system components. In the early 1970's, it was concluded that it was not cost effective to do significant performance restoration in the fan and LPT areas with fuel prices at the 30 cents per gallon level of cost. With current and projected fuel prices, the cost effectiveness of doing performance restoration work in all of the engines' major components must be re-examined.

4.4 HP COMPRESSOR AND HP TURBINE CLEARANCE SENSITIVITES

4.4.1 HP COMPRESSOR CLEARANCE EVALUATION

Results of the steady-state power calibration tests of the HP Compressor Clearance Evaluation revealed that a one percent change in the normalized average clearance (summation of tip clearance changes in percent of airfoil length over all stages, divided by the number of stages) produced a one percent change in compressor efficiency (Figure 6). The corresponding

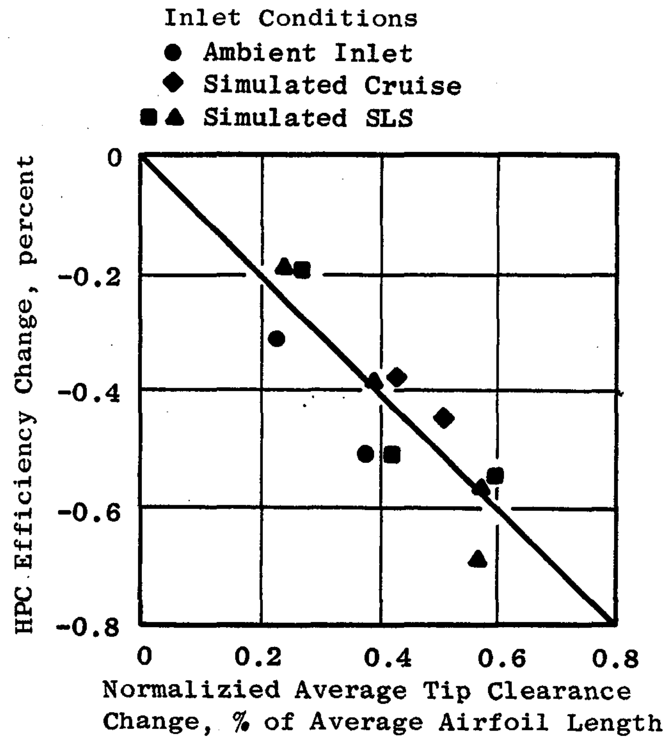


Figure 6. Compressor Efficiency Change Versus Airfoil Tip Clearance Change.

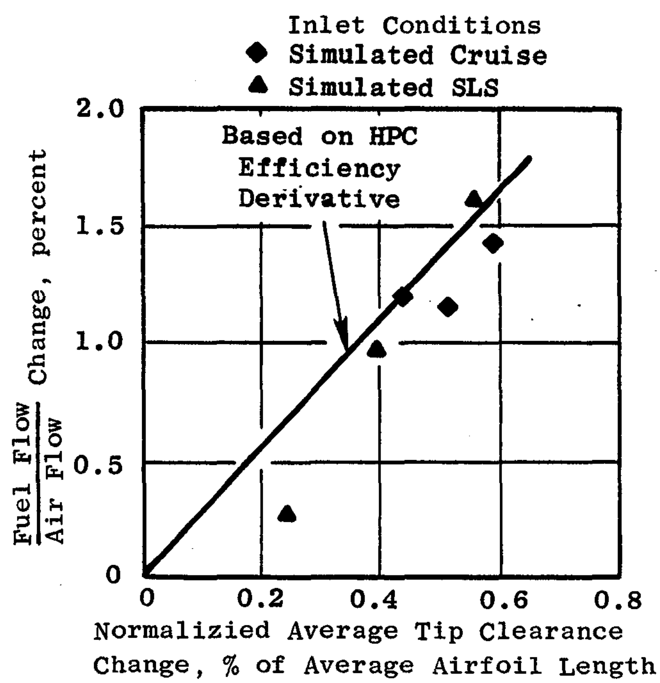


Figure 7. Fuel Flow Change Versus HPC Airfoil Tip Clearance Change.

core engine fuel flow change was about 2.8 percent for a one percent clearance change (Figure 7). The method of obtaining clearance changes by varying the cooling air flow proved to be effective and accurate. The correlation of the measured and calculated clearances, based on measured temperatures, was very good.

The results obtained from the transient tests are summarized in Figure 8 which shows clearance variation in a typical power throttle maneuver which included burst to takeoff, steady-state at takeoff and chop to ground idle. Figure 9 shows calculated clearance variations during a similar power throttle maneuver for the CF6-50 compressor i.e. for an uninsulated INCO 718 stator casing and an uncooled rotor. It will be noticed that cooling of the rotor bore, insulating of the stator casing together with a smaller thermal coefficient of expansion of the casing, produces significantly reduced clearance variations during engine transients and, therefore, permits much smaller compressor buildup and running clearances. Calculations indicate that these clearances can be reduced by 1.0 mm (0.040 in) in the aft stages of the compressor relative to the current CF6-50 compressor clearances. A reduction in clearance on the order of 1.0 mm (0.040 in) for stages 10 through 14 would produce a reduction of 0.78 percent in the average normalized clearance. Using the derivative obtained in this investigation, the corresponding increase in compressor efficiency amounts to 0.78 percent which results in a SFC reduction of about 0.38 percent for a turbofan engine (see References 8 and 9).

4.4.2 HP TURBINE CLEARANCE EVALUATIONS

The results of testing for the HP Turbine Clearance Evaluation have provided accurate clearance response curves and turbine roundness maps. Measurements taken have allowed the correlation of clearance with respect to time, speed, thrust, various operating pressures, and various operating temperatures. Measurements at eight circumferential locations allows for fairly accurate relationships with respect to turbine roundness.

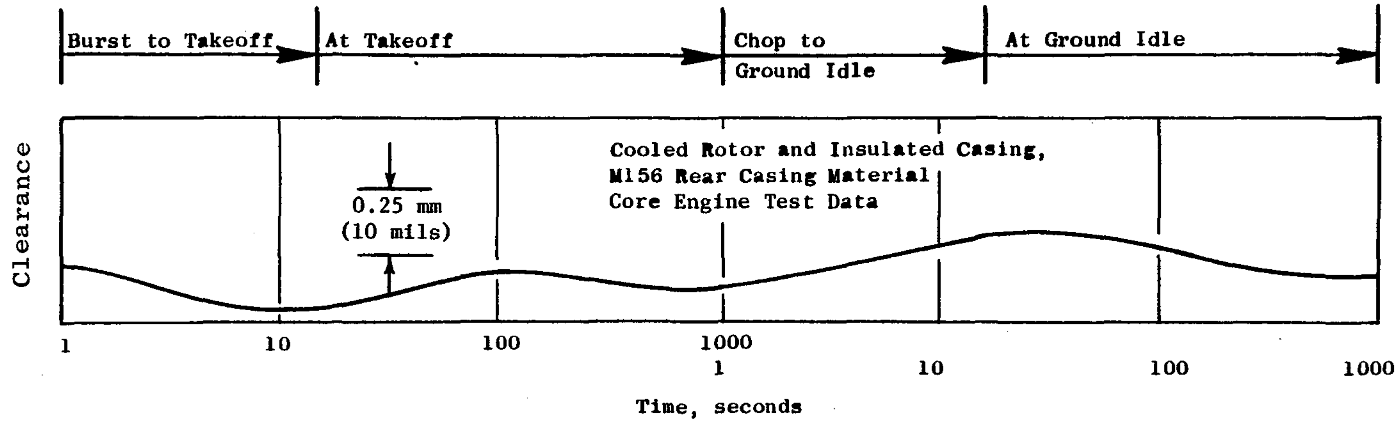


Figure 8. Improved Clearance Variations in Stage 13 of HPC After Burst and Chop Power-Throttle Movements.

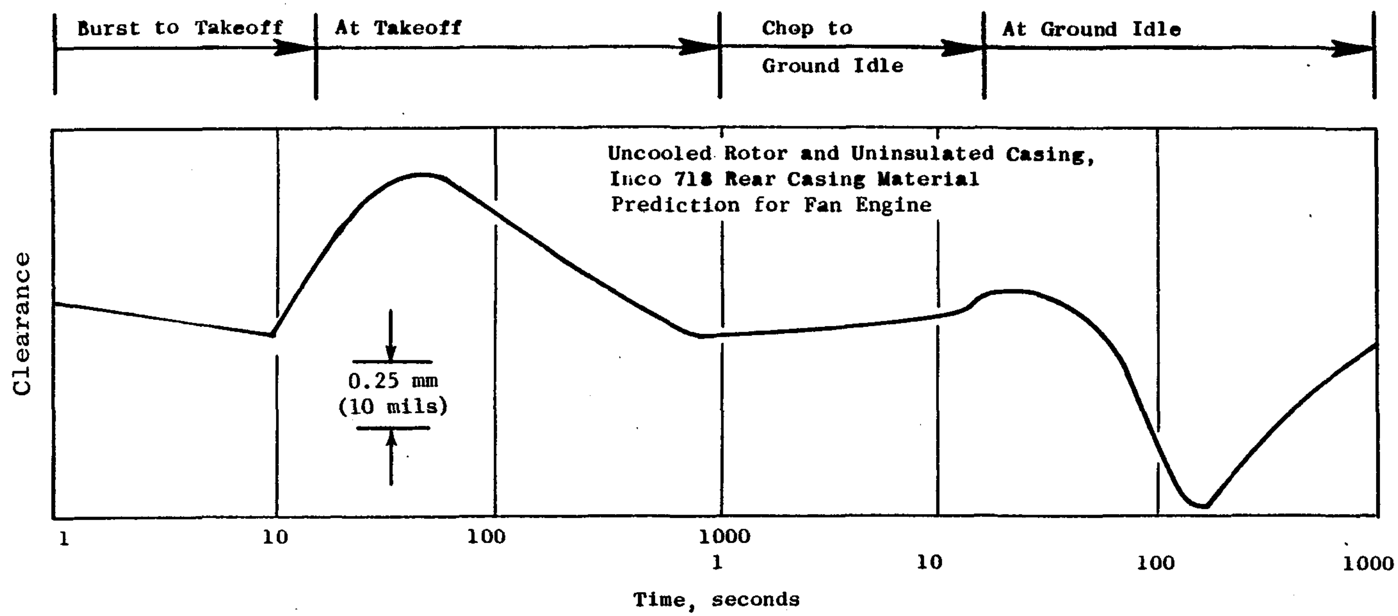


Figure 9. Current Clearance Variations in Stage 13 of HPC After Burst and Chop Power-Throttle Movements.

The results indicated a good correlation of the analytical model of round engine clearance response with measured data (Figures 10 and 11). The stator out-of-roundness measurements verified that the analytical technique for predicting mechanically-caused loads and distortions is correct, whereas the technique for calculating the effects of certain circumferential thermal gradients requires some modifications. This investigation established that the potential for improvements in roundness is in the order of 0.38 mm (0.015 in) equivalent to 0.86 percent in turbine efficiency, which translates to a cruise sfc improvement of 0.36 percent.

4.5 PERFORMANCE RETENTION

As a direct result of knowledge gained from the Diagnostics Programs, a Performance Improvement and Performance Retention Improvement Program has been identified for the CF6 family of engines. The complications of introducing new performance retention features into an existing engine arises from limitations on changes to aircraft power management and functional interchangeability. However, some features are currently planned by General Electric for introduction into the CF6-50 engine production models and which will also be retrofittable within the current fleet. Items being considered which can be included into the current fleet of engines include: smooth solid shrouds in booster stages 1, 2, and 3, which result in reduction in shroud erosion and better clearance control; a modified front engine mount and steel front compressor casing which reduce bending deflections and locally reduce rub potential; improved surface finishes on high pressure compressor blades and vanes; replacement of three stages of titanium stator vanes and four stages of HPC rotor blades with steel which increases erosion resistance; and incorporation of new VSV bushings in the compressor stator case to increase durability and reduce leakage.

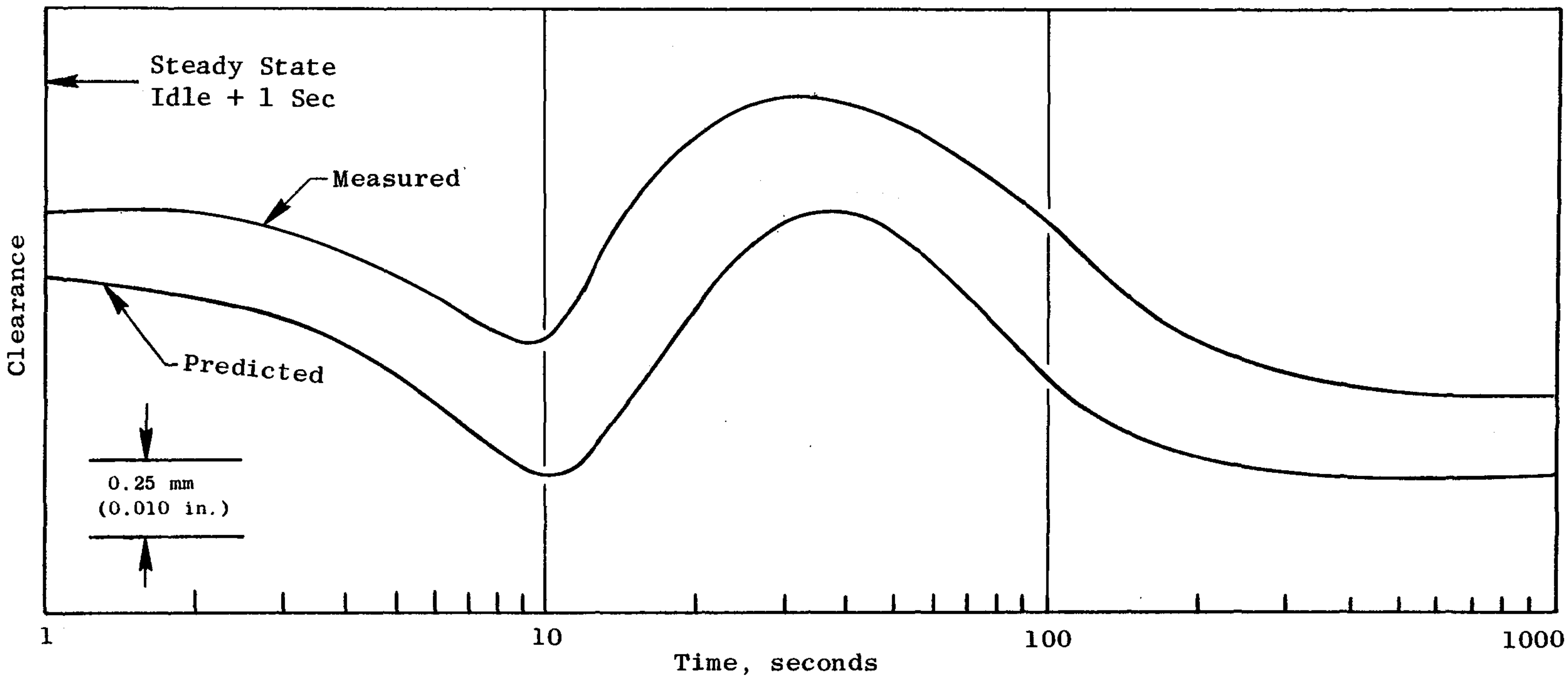


Figure 10. HPT Blade-to-Shroud Clearance As a Function of Time During An Accel.

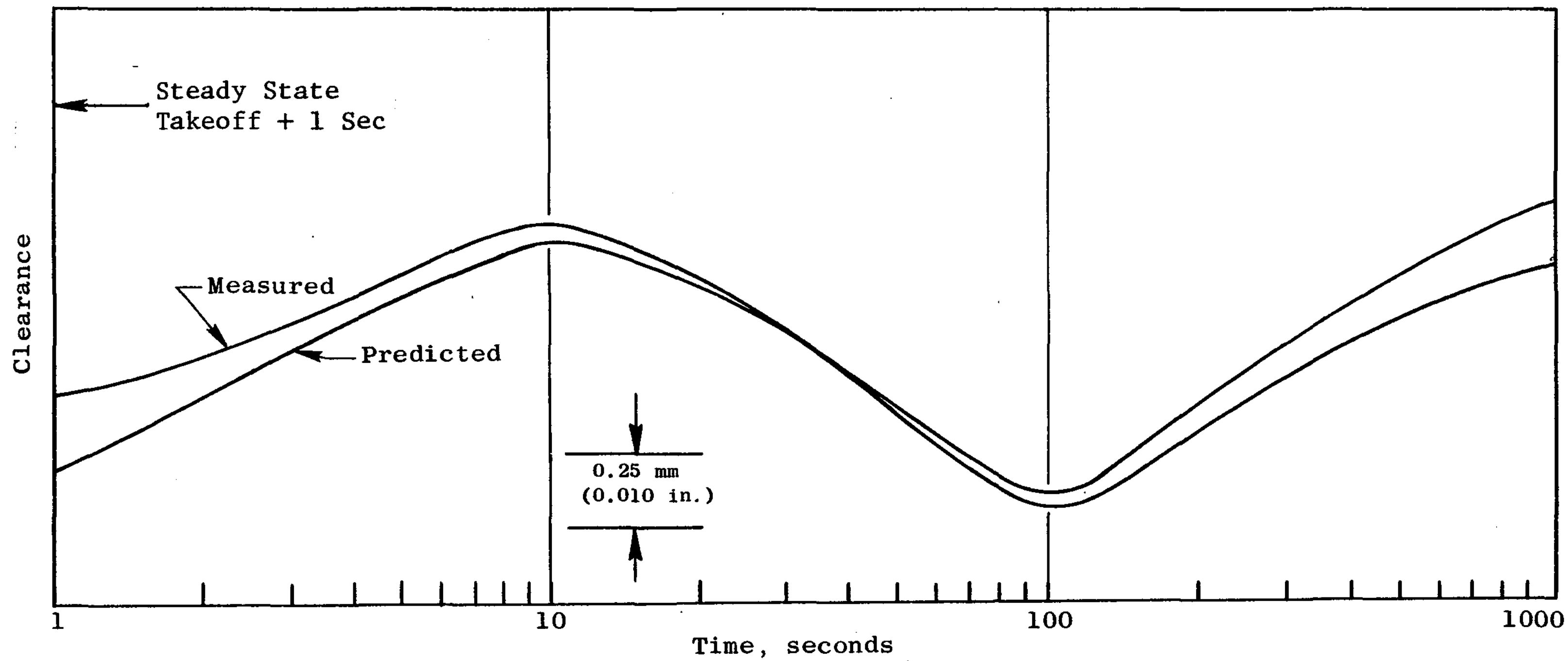


Figure 11. HPT Blade-to-Shroud Clearance As a Function of Time During a Decel.

Other performance retention features are also being incorporated into the production configuration of the CF6-80 family of engines in addition to the performance retention items just mentioned. The HPC casing is a stiffer, two-piece case with insulated rear stages which provides reduced deflections and better roundness thereby reducing rubs. The HPC rotor is cooled by introducing fan air into the bore, resulting in better matching of rotors and stators which again reduces rubs during transients. There will be an improved HPT shroud support system and improved HP turbine shrouds which reduce distortion and blade tip rubs. A passive cooling system for the HP turbine stator is being utilized which will provide a better match with the rotor and reduce blade rubs. Also to be included is an active clearance control system in the LP turbine which will produce close clearances at cruise and larger clearances at takeoff to reduce shroud rubs and prevent deterioration. The deterioration portion of the Diagnostics Program also verified that the performance retention features being designed into the Energy Efficient Engine (E^3) Program will have a definite payoff. These performance retention features include: a low tip speed, wide-chord, rugged fan blade; a short stiff compressor case; ruggedized fan OGV's; and active clearance controls on the high pressure compressor, the high pressure turbine and the low pressure turbine.

4.6 IMPROVED ENGINE WORK SCOPES

The most immediate reduction in fuel usage by today's CF6 fleet which can be achieved as a result of information gained during the NASA Engine Diagnostics Program, lies in the definition of improved engine work scopes during engine shop visits by individual airlines. An integral part of the Engine Diagnostics Program with both the CF6-6D and CF6-50 engines were studies conducted to define how much of the unrestored performance losses, associated with the typical engine as currently shipped from the overhaul test cells, could be restored on a cost effective basis. The results of these studies were intended to be used as guidelines for improved definition of modular work scopes at the overhaul facilities.

As part of these studies, assumptions were made which included: material cost as defined by either repair cost or replacement hardware cost established in the General Electric catalogues; estimates of the cost of doing work based upon General Electric experience; performance gains and the life of the gain consistent with the deterioration rates established as part of the Engine Diagnostics Program; and typical missions assumed consistent with DC-10-10 and DC-10-30 operation. Fuel price for these studies was assumed to be one dollar a gallon.

Based upon these studies, it was concluded that approximately 60 percent of the unrestored performance currently existing on engines being shipped from the various overhaul test sites could be restored on a cost effective basis for the typical engine. Table 2 shows the results of the cost effectiveness feasibility study conducted by General Electric for the CF6-50 engine based on typical overhaul test cell performance levels. It is noted that the greatest potential for cost effective refurbishment exists in restoring fan performance. This restoration includes the effective maintenance on surface finishes, leading edges, and blade tip-to-shroud clearances. Cost effective performance restoration is also achieveable on the HP compressor and some small additional cost effective gains are achieveable on the HP turbine. Based on studies conducted for both engine models, performance restoration of the LPT module, however, is only cost effective when the module has already been disassembled for other reasons.

A word of caution is in order for those who want to use the results of these studies for their own purposes. These studies were based upon a typical or average engine as it is shipped from the various overhaul facilities. Some of the restoration work recommended in these cost effective studies is currently being done by some airlines on a part-time basis. Not all engines that are shipped from the overhaul facilities are equivalent (low) in performance as the typical engine identified and used as part of this study. The cost effectiveness study for an average engine can be misleading on an individual engine basis. The key point to emphasize is

Table 2. CF6-50 Cost Effective Performance Refurbishment.

	% CRUISE SFC	
	UNRESTORED PERFORMANCE	COST EFFECTIVE REFURBISHMENT
FAN SECTION		
FAN BLADE TIP CLEARANCE	0.38	0.38
FAN BLADE L.E. CONTOUR	0.12	0.12
FAN BLADE SURFACE FINISH	0.01	0.01
SPLITTER LEADING EDGE	0.07	0.07
BYPASS OGV - L.E.	0.06	0.06
BYPASS OGV - SURFACE FINISH	0.18	0.18
BOOSTER TIP CLEARANCE	0.03	0
BOOSTER AIRFOIL ROUGHNESS	0.01	0
HP COMPRESSOR		
BLADE & VANE TIP CLEARANCE	0.16	0.16
AIRFOIL LEADING EDGE BLUNTNESS	0.05	0
AIRFOIL SURFACE FINISH	0.03	0
CASING/SPOOL SURFACE FINISH	0.01	0
HP TURBINE		
STAGE 1 NOZZLE DISTORTION	0.05	0
AIRFOIL SURFACE FINISH	0.10	0.10
LP TURBINE		
BLADE TIP CLEARANCE	0.30	0
INTERSTAGE SEAL CLEARANCE	0.22	0
AIRFOIL SURFACE FINISH	0.04	0
TOTAL	1.82	1.08 (1)

NOTE:
(1) 60% OF UNRESTORED PERFORMANCE CAN BE RESTORED ON A COST EFFECTIVE BASIS.

that each airline should conduct its own cost effectiveness studies based on individual practices, labor rates and work scopes to define the actual fuel and dollars savings available. General Electric's conclusions concerning the actual deterioration mechanisms within each module which contribute to the overall module deterioration are established and documented in extreme detail within the referenced NASA reports. These deterioration mechanisms can be used as a basis for each airlne to conduct its own cost effectiveness refurbishment study. The implications of these studies are overwhelming. General Electric believes that potential savings of 50 million gallons of fuel could be realized in a one year time period (1981) based upon the current CF6-6 and CF6-50 fleet of engines.

4.7 IMPACT OF ENGINE OPERATION

Discussions to this point have dealt with what is known about engine deterioration and refurbishment practices in today's operations and what can and is being done to further fuel conservation. There are other factors which must be considered in order not to use excess fuel. Careful attention to operational practices and use of derate power ratings are two such areas.

4.7.1 ENGINE USAGE

Any turbofan engine can be operated in a manner which could result in excessive deterioration. For example, an engine which has been stabilized at high power, then subjected to a reduction in power and subsequently subjected to another accel is exposed to a condition where engine static cases will have cooled faster than the rotor during the down time and could interfere with the hot rotor blades as they expand during the accel thereby resulting in rubs and performance losses. This is known as "hot rotor reburst".

Every engine manufacturer publishes guidelines for engine operation which, if heeded, should result in avoiding the "hot rotor reburst" situation and any other similar situation. Proper discipline by all personnel responsible for any phase of engine operation from line maintenance personnel through flight crews is required in order not to abuse the engine.

4.7.2 USE OF DERATE POWER

It is common knowledge throughout the industry that use of reduced power settings has a strong influence on parts life and maintenance cost.

CF6-50 data analyzed as part of the Engine Diagnostic Program substantiated the fact that a larger amount of derate (reduced power) results in a lower deterioration rate. Figure 12 shows the average deterioration rates of the data from the 9 airlines studied. Shown are the average deterioration rates expressed in terms of EGT (at fan speed) and a percent fuel flow increase (at fan speed) for 1000 hours of operation as a function of average flight cycle length (hours/cycle) for each airline studied. The average of the A300B data, the average of the DC-10-30 data and the average of the B-747 data are used to define a "composite characteristic". The numbers enclosed in parentheses indicate the average percentage thrust derate typically used by the indicated airline. While this summary is not sufficiently accurate to define an exact relationship between deterioration rate and average percentage derate, it does show a correlation between derate usage and reduced deterioration rates.

Although there is considerable scatter of data, it is still fairly clear that continued usage of a given percentage of derate power will result in lower deterioration rates than alternately operating above and below that same percentage of derate. Since lower deterioration rates should result in lower maintenance costs, it follows that maximum derate operation should be encouraged wherever and whenever feasible.

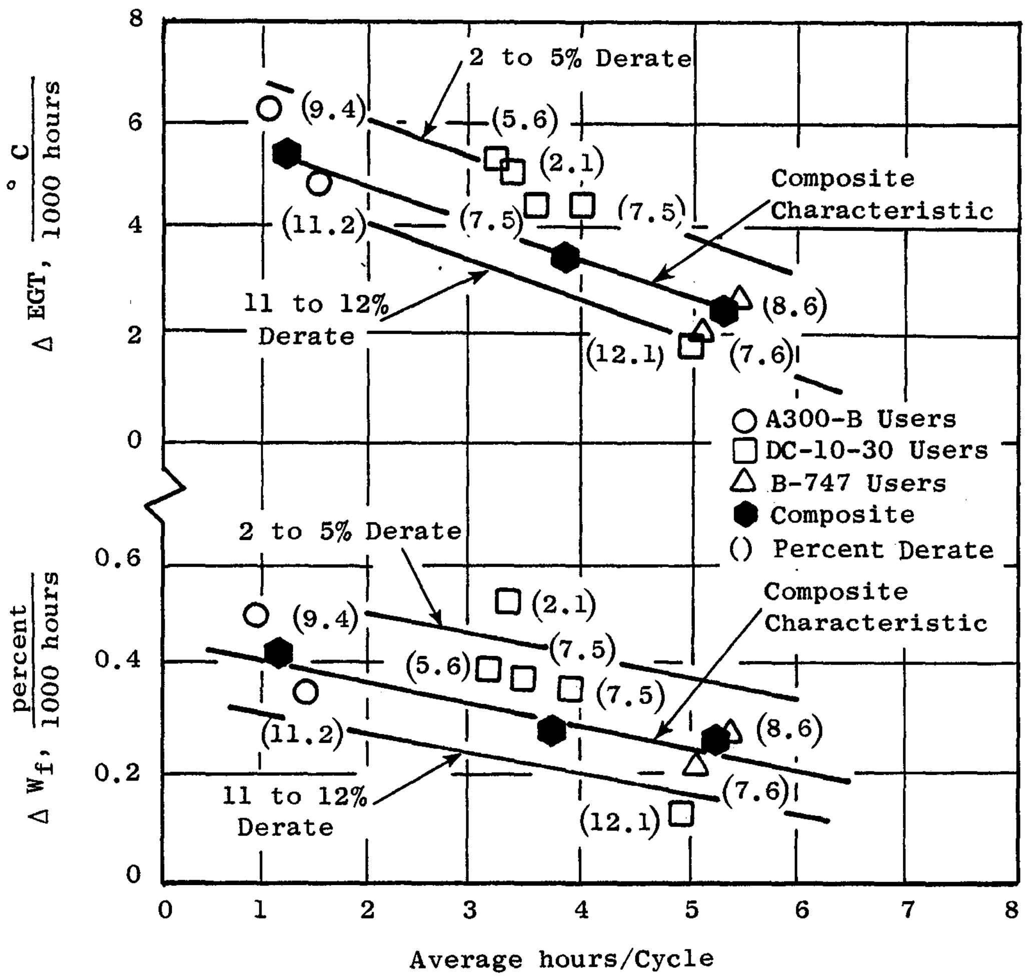


Figure 12. Effect of Flight Cycle Length and Derate on CF6-50 Performance Deterioration.

5.0 CONCLUDING REMARKS

In summary, the NASA Engine Diagnostics Program, aimed at defining CF6 deterioration characteristics, was highly successful. Deterioration rates and modes were identified as were areas of design improvement which can and will result in improved performance retention characteristics. General Electric has already applied the findings of this program to reduce the performance deterioration of new CF6 engines. The current CF6-50 engines show an improvement in deterioration of over 50 percent relative to the engines which formed the baseline for the Diagnostics Program (Figure 13).

Also defined were potential means of fuel conservation with improved cost effective engine performance restoration practices during engine shop visits. Based on expected revenue service flight hours, it was estimated that application of the cost effective items described for the CF6 family of engines could reduce fuel consumption by 50 million gallons while saving the airlines $23 million dollars in 1981. The potential to make a notable impact on energy consumption during the 1980's has been demonstrated.

The HP compressor and HP turbine clearance sensitivity evaluations verified the importance of tip clearance retention and quantified the sensitivities from real-time measurements in CF6 engine tests. A potential reduction of compressor clearances in the aft stages of 1.0 mm (0.040 in) was identified, equivalent to an improvement in compressor efficiency of 0.78 percent which translates to a cruise SFC improvement of 0.38 percent. Also, a potential improvement in turbine roundness was established in the order of 0.38 mm (0.015 in), equivalent to 0.86 percent in turbine efficiency, which translates to a cruise SFC improvement of 0.36 percent.

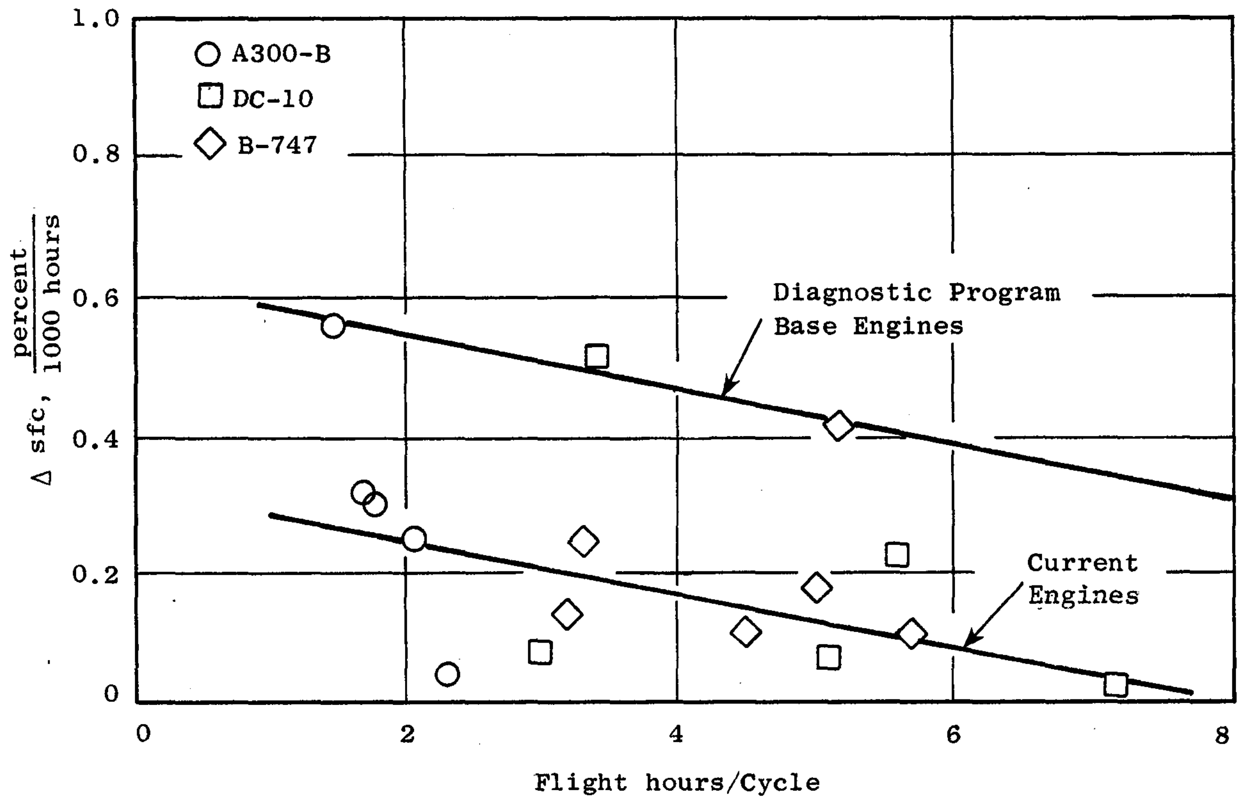


Figure 13. Improvement in CF6-50 Performance Retention for Initial Installations.

APPENDIX A - SYMBOLS

SFC	Specific Fuel Consumption	$\frac{kg}{hr\ daN}$
HPC	High Pressure Compressor	
HPT	High Pressure Turbine	
LPT	Low Pressure Turbine	
EGT	Exit Gas Temperature	^{o}C
OGV	Outlet Guide Vane	
VSV	Variable Stator Vane	
W_f	Fuel Flow	kg/hr

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