CF6 ENGINE DIAGNOSTICS

Ron Stricklin
General Electric Company

INTRODUCTION

The energy demands of the United States far exceed domestic fuel supplies which creates a severe dependence on foreign oil. This dependence was accentuated by the OPEC embargo in the winter of 1973/1974 which triggered a rapid rise in fuel prices. This price rise (Figure 1) further compounded by other inflation factors has brought about a set of changing economic circumstances with regard to the use of energy. As a result, our government, with the support of the Aviation Industry, initiated programs aimed at reducing fuel demands. One such program sponsored by NASA is the Aircraft Energy Efficiency Program which is directed toward reducing fuel consumption for commercial air transports. An integral portion of this program is the Engine Component Improvement (ECI) Program aimed at improving fuel efficiency of current engines. This ECI Program consists of two parts, 1) Performance Improvement and 2) Engine Diagnostics.

General Electric is participating in both parts of the Engine Component Improvement Program. As part of the program, performance deterioration studies for the CF6-6D and the CF6-50 Engine Models have been conducted. The basic objectives of the latter effort were: 1) to determine the specific causes for engine deterioration which increase engine fuel consumption rates, 2) to isolate short term losses from longer term losses and 3) identify potential means to minimize the deterioration effects. The deterioration studies have been completed and final NASA reports published.

To quantify the effect of engine performance deterioration, the fleet statistics for the CF6 family of engines in 1981 were projected. It is anticipated that the CF6-50 family of engines will amass approximately 3.4 million flight hours and the CF6-6 family over one million flight hours in 1981.

An average deterioration in cruise specific fuel consumption of 1 percent over new engine levels will result in excess fuel consumption of approximately 36 million gallons for the CF6 fleet alone. The effects of small amounts of deterioration throughout the fleet are obviously substantial.

This paper presents a summary of the activities which led to defining deterioration rates of the CF6 family of engines, a description of what was learned and an identification of means of conserving fuel based upon the program findings.

HOW DID WE DO THE JOB

The program to define the deterioration levels and modes for the CF6 family of engines involved four distinct phases: analysis of inbound engine test results, analysis of airline cruise data, analysis of airline test cell data resulting from testing of refurbished engines and inspection of engine hardware.

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 specific fuel consumption had increased and 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 specifically 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 test results.

CRUISE DATA ANALYSIS

Inbound engine tests, however, which are conducted on specific engines, yield only limited information concerning the degradation in performance of the average fleet. Recognizing that the intent of the Diagnostics Program was defined to determine the deterioration characteristics of the typical CF6 engine in revenue service, it was concluded that analysis of fleet performance data accumulated during flight was the best means of accomplishing this objective.

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 in general recorded during every flight of an aircraft, were used to define the deterioration characteristics of individual engines during the life of the engines during a given installation period. The process to define the performance trend was to compare the performance indicating parameters (fuel flow level 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 9 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 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.

The CF6-6D engine 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.

AIRLINE CELL DATA ANALYSIS

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 5 other overhaul facilities during the CF6-50 Program.

Performance levels from these facilities were compared to new engine performance levels from the General Electric Production Facilities in order to define the effectiveness of typical engine workscopes in restoring performance by refurbishment to new engine levels.

COMPONENT DETERIORATION MECHANISMS

The actual modes of deterioration were identified by hardware observation 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 finishes of the airfoils, cleanliness and smoothness of various static structures and potential air leakage paths were reviewed and yielded estimates of component performance relative to a non-deteriorated component.

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

Combination of the trends established for each module degradation mechanism yielded module performance deterioration trends. Combination of the module deterioration characteristics using appropriate knowledge of the engine cycle then led to establishing overall engine deterioration characteristics. 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 cell data analysis.

WHAT WAS LEARNED

Figure 2 shows the resulting assessment of CF6-6D performance deterioration characteristics for the typical engine thru its initial installation and experience in review service and for the same typical engine after several multiple installations. Each of the elements of deterioration is presented in Figure 2 for the CF6-6D engine. This Figure shows equivalent cruise specific fuel consumption increases relative to a production new engine. The initial installation is shown on the left. Engines incur an average Short-Term loss of 0.9 percent prior to revenue service. During their initial installation, SFC increases an average of 1.7 percent based on the 4000-hour family of engines. The total increased SFC of the deteriorated engine is thus 2.6 percent from production new. Insufficient data is available to determine the amount of performance restoration during the first shop visit.

During 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. During revenue service, the cruise SFC of this multiple-build engine increases 0.9 percent for the 3000-hour engine. The total increased SFC of this deteriorated engine at 3000 hours was 3.0 percent from new. On the average, 0.9 percent cruise SFC is restored during the shop visit. During the next installation, an average revenue service deterioration of 0.9 percent is incurred. This amount is restored on the average during maintenance and the cycle is repeated.

Though engine-to-engine variations within this cycle are significant, the data presented reflects the typical or average engine deterioration characteristic for the CF6-6D engine.

Figure 3 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 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 3 that the deterioration rate shown during typical 747 operation was lower than observed with DC-10 and A300 operations. The same relationship holds for both the initial and multiple

4

installations. The unrestored SFC of the typical engine re-entering revenue service after airline shop visits is 1.8 percent poorer than the new engine baseline for the CF6-50 engine as compared with the 2.1 percent determined in CF6-6D analysis.

The deterioration rates shown on Figures 2 and 3 are presented as a function of flight hours since installation. An analysis was conducted as part of the CF6-50 program, to understand the variability in deterioration rates which resulted from analysis of DC-10, 747 and A300B data. The conclusion was that deterioration rates for the data surveyed was most strongly influenced by 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 3 translated into the deterioration rate per 1000 cycles basis. The conclusion is that while the DC-10 and 747 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 numbers of cycles but also time at temperature.

Figure 4 illustrates the results of the hardware inspection analyses and the resulting deterioration model compared to the performance-data-derived deterioration level for the CF6-6D initial installation. It shows that the largest portion of the 0.9 percent Short-Term SFC loss resulted from High Pressure Turbine (HPT) performance losses. This loss was due largely to HPT clearance increases during the initial checkout phases of the airplane. During initial operation of the aircraft by the aircraft manufacturer, there is little attendant loss in fan, high pressure compressor and low pressure turbine. It is also to be noted that the combined performance deterioration level created by the stackup of the individual component deterioration losses at 4000 hours shows 2.3 percent total performance degradation from the "as new" condition compared to the 2.6 percent level which resulted from performance data analysis.

Figure 5 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 5 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, agreement is good. Similar findings for losses associated with the initial installation and the multiple installations of CF6-50 engines resulted.

Of prime importance to the program was the finding that the unrestored loss for the typical engine out of the overhaul shop, based on hardware inspections, was 2.08 percent in terms of cruise SFC compared to the 2.1 percent unrestored performance level as identified by performance data analysis.

5

Figure 6 describes the component breakdown for both CF6-6D and CF6-50 engine models as shipped from the airline overhaul facilities compared to the new engine performance levels. It shows that, of the 2.1 percent unrestored performance for the CF6-6D engine and 1.8 percent unrestored performance for the CF6-50 engine, a large portion of these performance losses are due to lack of performance restoration in the fan area with lesser amounts of the performance loss associated with the high pressure compressor and the LP turbines. Note that there is very little performance left to restore in the HPT area for typical outbound engines, again, this is due to the fact that HP turbines are typically completely refurbished during shop visit. Again, the hardware inspection data and the performance data show excellent agreement.

The unrestored performance identified in Figure 6 represents a potential gold mine 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 and direct impact on reliability, are primarily associated with the hot section of the engine, the combustor and high pressure turbine area. Larger efforts (dollars and manhours) are required to achieve the same amount of EGT margin restoration in the LP system components than in the HP 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 a 30 cents per gallon level. 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.

HARDWARE INSPECTION DETAILS

The prime modes of deterioration within each module were established primarily by design team inspections at two major CF6-50 overhaul facilities and at one major CF6-6 overhaul facility. The details of the findings of these inspections are identified in references 1 and 2, 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.

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, 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 and to restore the OGV surfaces to the as new condition.

HPC 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 airflow 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 is the subject of a separate paper at this conference.

HP TURBINE DETERIORATION

The primary mode of deterioration noted in the high pressure turbine during revenue service is the increase in blade tip-to-shroud clearances, resulting from rubs with some losses in performance due to increased airflow leakage and 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 continue to increase, but a a lower rate, thereafter. At 4000 hours, the average increase in tip clearances is 0.013 inch on stage 1 and 0.011 inch on stage 2, which accounts for 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. Again, shroud distortion is the subject of another paper at this conference.

LP TURBINE DETERIORATION

As in the case of the high pressure turbine, increases in blade tip

7

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.

SUMMARY OF DETERIORATED ENGINE

As is evident, a large part of degradation of engine performance in revenue service results from rubs and subsequent increases in clearance in the high pressure compressor, the high pressure turbine and the low pressure turbine.

Considerable effort is being expended by General Electric and the other engine manufacturers to create functional clearance control systems designed to eliminate rubs in these components and to maintain optimum clearances at the required cruise condition to maintain peak engine performance.

USE OF WHAT HAS BEEN LEARNED

The objectives of this part of the Diagnostic Program were to: 1) determine the specific causes for engine deterioration, 2) to isolate Short-Term losses from the longer term losses and 3) to identify potential ways to minimize the deterioration effects. Two potential means are available for minimizing deterioration effects on the current fleet. First is identification of product improvements which will provide better performance retention characteristics in the current engine, and the second is to identify improved engine work scopes which can be used by the airlines to improve performance restoration and, therefore, absolute performance levels of the engines coming out of the airline overhaul shops.

PERFORMANCE RETENTION

As a result of knowledge gained from the Diagnostic 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 will be retrofitable 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.

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 HPT shrouds which reduce distortion and blade tip rubs. A passive cooling system for the HPT 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 LPT 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. Current estimates are that deterioration rate on the E^3 engine should be reduced by 51 percent relative to deterioration rates established for the CF6-50 engine as part of the NASA Diagnostic Program.

IMPROVED ENGINE WORK SCOPES

The most immediate reduction in fuel usage by todays 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 a dollar a

gallon.

It was concluded, based upon these studies, 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 upon 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 surface finishes, leading edges, and maintaining clearances. Cost effective performance restoration is also achievable on the HP compressor, and slight additional cost effective gains are achievable on the HPT. General Electric has concluded to date based upon the studies for both engine models that performance restoration resulting from tearing down the LPT module and restoring performance is not cost effective.

A word of caution, however. These studies are based upon a typical or average engine as it is shipped from the various overhaul facilities. Some of the restoration work used 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 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 airline to conduct its own cost effectiveness refurbishment study. The implications of these studies are overwhelming. General Electric believes that potential savings of between 50 and 60 millions gallons of fuel could be realized in one-year's time period based upon the current CF6-6 and CF6-50 fleet of engines.

WHAT ELSE CAN BE DONE TO SAVE FUEL?

Discussions to this point have dealt with what is known about engine deterioration and refurbishment practices in todays operation and what can and s 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.

ENGINE ABUSE

Any turbofan engine can be operated in a manner which could produce 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 have cooled faster than the rotor during the down time and could interfere with the hot rotor blades as they stretch 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.

USE 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 7 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 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 not implicitly suggested by these data, it is most probably a fact 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. The same is true for maintenance cost. Maximum derate usage is encouraged.

SUMMARY

To summarize, the portion of 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.

Also defined were potential means of fuel conservation today with improved cost effective engine performance restoration practices during engine shop visits.

The potential for additional fuel conservation is there if we make maximum

11

use of this information. The engine manufacturer must design more performance retention into his product; the airlines must analyze and modify engine (and aircraft) maintenance practices.

REFERENCES

1. NASA CR-159786, "CF6-6D Engine Performance Deterioration", RH Wulf, January 1980.

2. NASA CR-159330, "CF6-6D Engine Short Term Performance Deterioration", WH Kramer, JE Paas, JJ Smith, RH Wulf, April 1980.

3. NASA CR-159367, "CF6-50 Engine Performance Deterioration", RH Wulf, November 1980.

4. "CF6 High Pressure Compressor and Turbine Clearance Evaluations", M. Radomski, and L. Cline, Paper Presented at NASA Aircraft Engine Diagnostics Conference, May 6, 1981.

TABLE 1.   CF6-50 DETERIORATION IN 1000 CYCLES

	A/C TYPE		
INSTALLATION	DC10	B747	A300
INITIAL INSTALLATION ΔSFC	1.71%	2.07%	.83%
MULTIPLE BUILD INSTALLATION ΔSFC	1.03%	1.36%	.51%

TABLE 2.   COST EFFECTIVE PERFORMANCE REFURBISHMENT
CF6-50 ENGINE

	% CRUISE SFC	
	UNRESTORED PERFORMANCE	COST EFFECTIVE REFURBISHMENT
FAN SECTION		
FAN BLADE TIP CLEARANCE	.38	.38
FAN BLADE L.E. CONTOUR	.12	.12
FAN BLADE SURFACE FINISH	.01	.01
SPLITTER LEADING EDGE	.07	.07
BYPASS OGV - L.E.	.06	.06
BYPASS OGV - SURFACE FINISH	.18	.18
BOOSTER TIP CLEARANCE	.03	0
BOOSTER AIRFOIL ROUGHNESS	.01	0
HP COMPRESSOR		
BLADE & VANE TIP CLEARANCE	.16	.16
AIRFOIL LEADING EDGE BLUNTNESS	.05	0
AIRFOIL SURFACE FINISH	.03	0
CASING/SPOOL SURFACE FINISH	.01	0
HP TURBINE		
STAGE 1 NOZZLE DISTORTION	.05	0
AIRFOIL SURFACE FINISH	.10	.10
LP TURBINE		
BLADE TIP CLEARANCE	.30	0
INTERSTAGE SEAL CLEARANCE	.22	0
AIRFOIL SURFACE FINISH	.04	0
TOTAL	1.82	1.08

60% OF UNRESTORED PERFORMANCE CAN BE RESTORED ON A COST EFFECTIVE BASIS

13

Fuel Cost History
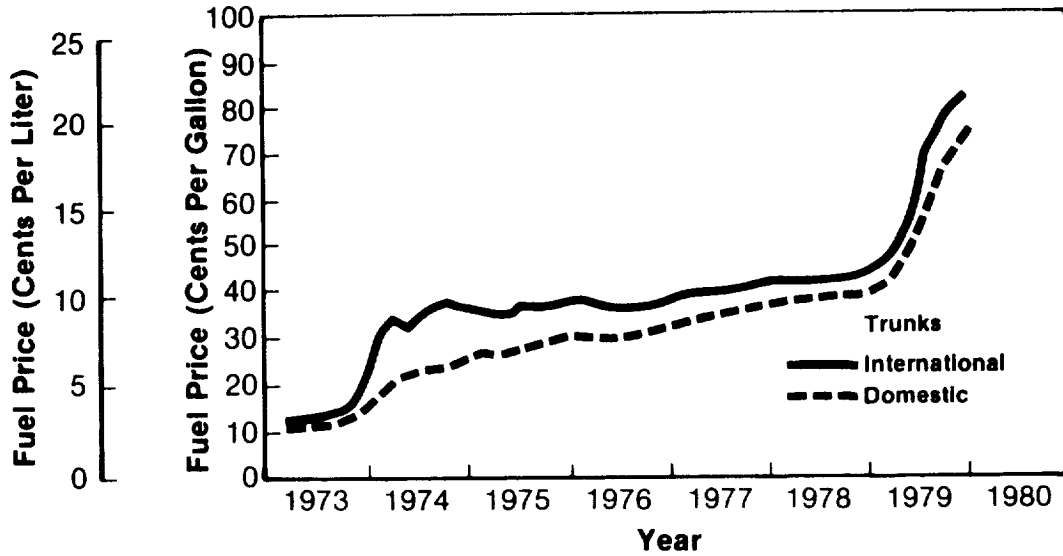## U.S. Airline Jet Fuel Price
Monthly Averages CAB Data

FIGURE 1
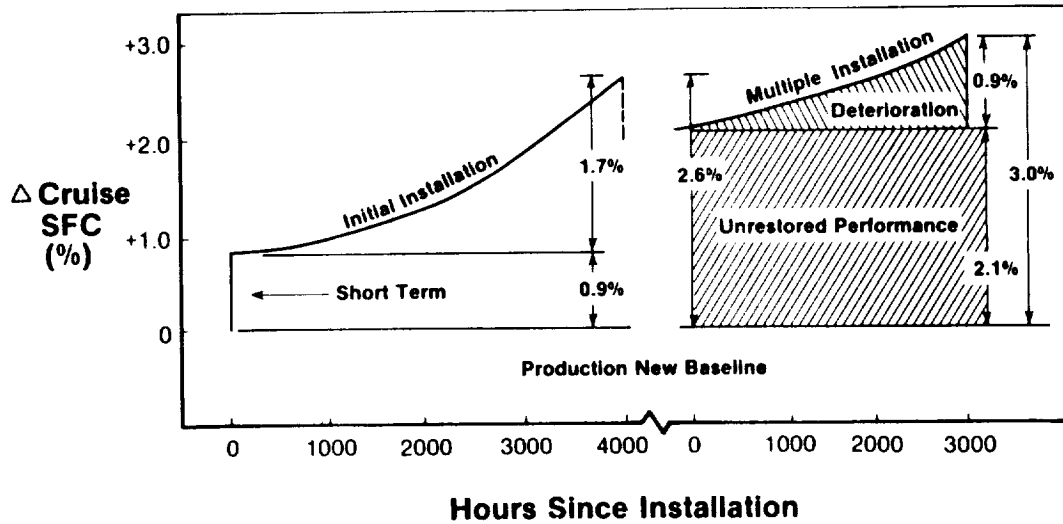
CF6-6D
Performance Deterioration
Characteristics
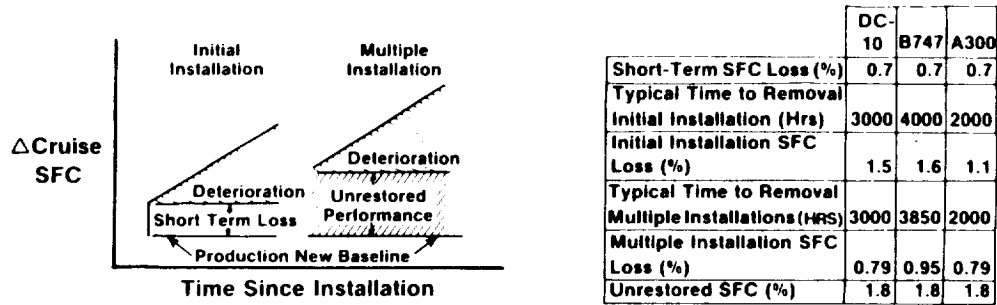

FIGURE 2

14

CF6-50 Deterioration Characteristics

	DC-10	B747	A300
Short-Term SFC Loss (%)	0.7	0.7	0.7
Typical Time to Removal Initial Installation (Hrs)	3000	4000	2000
Initial Installation SFC Loss (%)	1.5	1.6	1.1
Typical Time to Removal Multiple Installations (HRS)	3000	3850	2000
Multiple Installation SFC Loss (%)	0.79	0.95	0.79
Unrestored SFC (%)	1.8	1.8	1.8

FIGURE 3

CF6-6D Initial Installation Performance Deterioration

Hardware 2.3%

ΔCruise SFC at 4000 Hours

Good Agreement!

Performance 2.6%

FIGURE 4

15
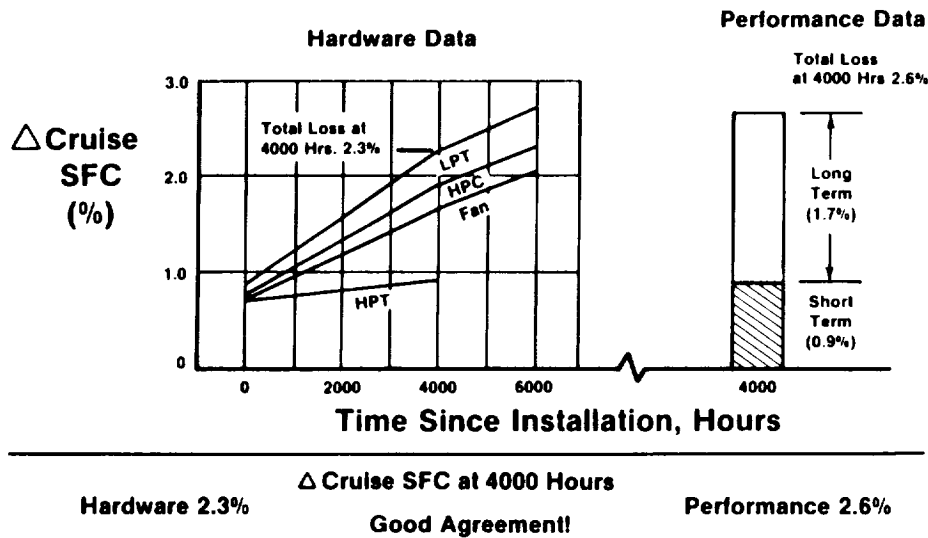
CF6-6D Multiple Build Engine Performance Deterioration
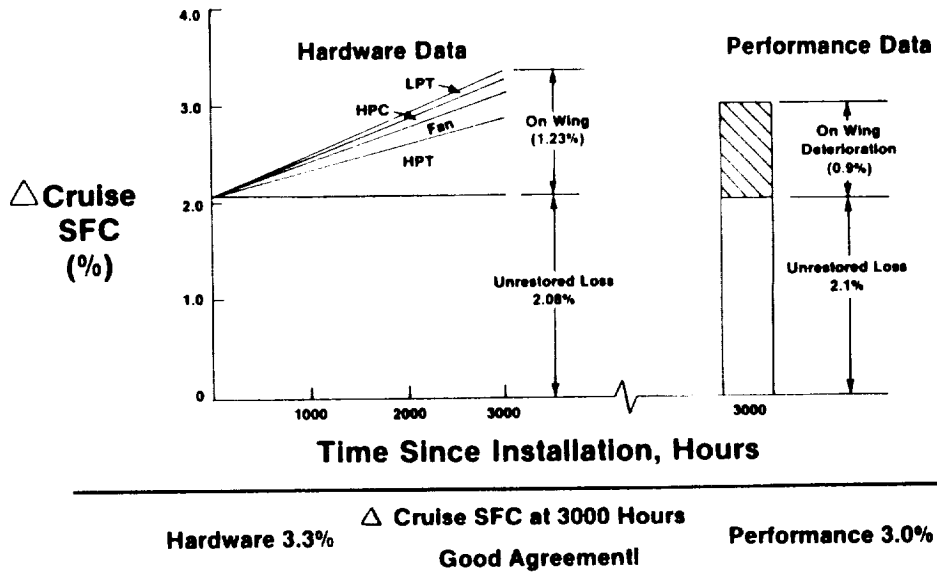
FIGURE 5

Unrestored Performance
Hardware Inspection Summary
Compared to Performance Summary

• **Hardware Inspections and Performance Data Analysis Show Excellent Agreement**

FIGURE 6

16
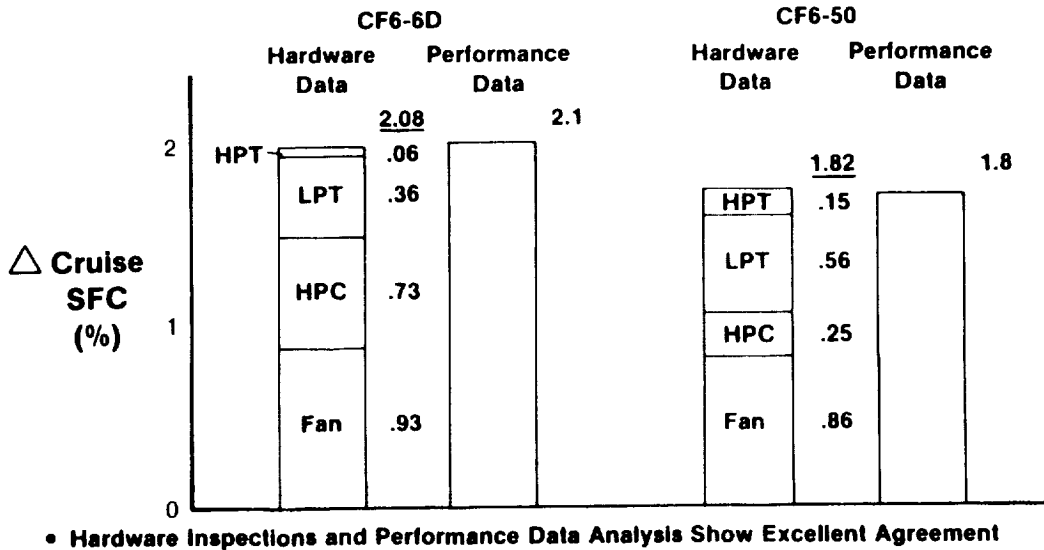
Effect of Flight Cycle Length and Derate on CF6-50 Performance Deterioration

FIGURE 7