# CF6 JET ENGINE PERFORMANCE DETERIORATION RESULTS *

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## SUMMARY

There are many factors which contribute to the performance/deterioration trends of a high bypass-ratio jet engine over a typical life span. In order to identify and effectively introduce fuel conservation measures for such engines, it is necessary to expand information and technology related to these trends. Representative results to-date from an investigation of the General Electric CF6 engines under the NASA Lewis Research Center sponsored "CF6 Jet Engine Diagnostics Program" are reported herein with particular emphasis on the CF6-6D engine model.

Gross measurements of engine performance, such as airline fleet averages, are typically presented as changes relative to a reference baseline. These delta performance levels are the results of not only engine deterioration, but also of design change effects and of performance restoration during airline maintenance.

The revenue service deterioration trends for recent vintage CF6-6D engines have been established for the first installation. The average cruise losses after 4000 flight hours of service are a 2.5% increase in WFM (fuel flow), a 2.0% increase in SFC (specific fuel consumption) and a 17°C increase in EGT (exhaust gas temperature). The rate of deterioration declines with time; for example, the WFM rate is 1.0%/1000 hours for the first 1000 hour period while this rate decreases to 0.5%/1000 hours for the third 1000 hour period.

Modular assessments of deteriorated engines typically indicate that more than 50% of total SFC losses occur in the core hot section. Most of these losses are recovered during normal airline refurbishment. Further, average fleet outbound performance of refurbished engines appears to be stable after the initial (approximately two) shop visits. Moreover, it appears that increased performance restoration can be achieved by added maintenance effort on the low pressure system.

Pre-delivery performance losses occurring during new airplane checkout flights, but before airplane delivery, have also been quantified as a 0.9% increase in SFC. These losses are incurred during the first several flights and have been incorporated in the flight planning manual. Further, the magnitude of these losses has been observed to be less than half when the engines

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enter revenue service as airline spares rather than by normal aircraft delivery.

A number of studies, both experimental and analytical, are currently underway to further define typical CF6 performance and hardware characteristics through an engine life cycle. The information and technology produced from these NASA/General Electric Company studies will be used to reduce fleet fuel usage by minimizing performance deterioration and improving performance restoration for current and future engines.

## INTRODUCTION

By 1990, high bypass-ratio engines such as the CF6 are expected to account for about 75 percent of the total fuel consumed by the U.S. commercial aviation fleet. This aviation fuel, however, is no longer as plentiful and inexpensive as it once seemed to be. Efforts have thus been initiated to determine how to conserve this important resource, especially in relation to its use by these high bypass-ratio engines.

As part of the NASA Aircraft Energy Efficiency (ACEE) program, the Lewis Research Center is conducting an engine diagnostic program on the CF6 engine, with the General Electric Company as the prime contractor. This "CF6 Jet Engine Diagnostics Program" will continue through the end of 1979. The primary objective of this program is to provide additional information and technology which can be used, beginning within the next few years, to minimize the performance deterioration and improve performance restoration of current CF6 engines and their derivatives, thereby realizing significant fuel savings. Emphasis is being placed on the identification and quantification of specific components within the engine which contribute to performance deterioration.

Since this program addresses fuel conservation, the primary interest will be on SFC (specific fuel consumption) performance. This differs from the historical emphasis placed on EGT (exhaust gas temperature) by the airlines and engine companies. EGT, the temperature of the core airstream entering the low pressure turbine of the CF6 engine, is an useful parameter to indicate engine performance in that it can be directly measured by the airlines. On the other hand, SFC must be computed from test cell measurements of thrust and fuel flow or derived from correlations of cruise fuel flow. As such deterioration, impending overhaul requirements and minimum outbound performance have been primarily keyed to EGT prior to this program with little regard for SFC. The emphasis of this investigation on SFC trends should produce advances in the field of fuel conservation.

The CF6 engines provide a good base for this program. These engines are currently installed in large subsonic transports with twin, tri, and quad airplane configurations. Further, these airplanes are produced by various airframe companies and are being used by numerous airlines over a wide variety of route structures.

Engine performance, and changes therein, are complex phenomena involving many diverse factors. This is especially so when considering more than just overall changes in performance. At this time, aspects which are not correlated well include: the sources and causes of deterioration, the relative performance losses of the individual engine modules, and the relation of engine parts condition to performance. Likewise, the effects of variables in the airline utilization of engines, such as length of service versus number of cycles, route structure, usage of derated takeoff power, aircraft type, or engine location are not well understood.

This program addresses the broad scope of engine performance deterioration and restoration through the many facets of a typical engine life cycle. This life cycle includes (for both the CF6-6D & CF6-50 engines) production acceptance testing, flight checkout by the airplane manufacturer, the first installation and refurbishment during airline revenue service, as well as successive revenue service installations and refurbishments. The sources of existing or historical information include: 1) for installed cruise - airline in-service trend data and airplane manufacturer flight checkout data; 2) for test cell data - production acceptance tests, inbound tests prior to maintenance, and outbound tests after refurbishment; and 3) for parts condition - teardown inspection results for special engines and overhaul facility records/experience. In addition, a number of controlled back-to-back tests and hardware inspections are being conducted to provide new information. The combination of refined analyses of existing data with new experimental results will be used to define typical engine performance/hardware characteristics through an engine life cycle.

The initial findings from these studies are presented in this paper. A number of engine performance and restoration aspects are addressed. Statistical trends of CF6-6D performance are shown. Brief discussions of CF6-50 performance trends and of some on-going diagnostic studies are also included. Further, examples of methods to improve overall performance by reducing performance deterioration and improving performance restoration are discussed.

## INSTALLED PERFORMANCE

### Typical Airline Trends

Airlines are very conscientious about tracking the installed performance of the engines powering their airplane fleet. Cruise trend information is recorded regularly for individual engines as a normal operational procedure during revenue service. This information is used to monitor the relative health of each engine, to anticipate normal maintenance requirements of the engines, and to help assess the profitability of the fleet operation.

These cruise data consist of cockpit measurements of significant engine parameters, most notably WFM (fuel flow), EGT and N1 (fan rotational speed), during stabilized operation at altitude. For the CF6 family of engines, fuel flow measurements are compared to values from the Flight Planning & Cruise Control Manual for the same flight condition and N1. This manual (FPM) is a tabulation of baseline reference curves for installed engine performance under various operating conditions. The baseline is representative of the installed performance of early CF6 production engines used in a flight test program to define reference engine performance.

These cruise data, delta WFM and delta EGT from FPM at constant N1, are trended versus operating time for individual engines and versus calendar time for the fleet. The individual engine trends are useful for indicating significant internal engine changes/damage warranting hardware inspections or indicating impending requirements for maintenance. On the other hand (due to inherent large scatter in individual engine trending), fleet average trending is typically used to define engine performance deterioration. Thus, improved engine performance and fuel savings resulting from technology developed during the deterioration studies will be reflected in airline fleet average trends.

## Trend Levels - Basic Factors

A typical airline monthly DC10-10 fleet trend of cruise fuel flow (deltas relative to the airline FPM, ΔWFM) is presented in Figure 1. The average fleet monthly ΔWFM, as well as the data range, are shown for 1973 through 1977. It can be seen that the fuel flow trends increased during the early years of the fleet operation before stabilizing in 1975. These early fleet fuel flow increases of the CF6-6D engines in the DC10-10 fleet resulted from two factors: 1) the deterioration of engines (a majority which had less than 3000 hours of operation in mid-1973), and 2) the introduction of engine design changes into the fleet which resulted in increased average fuel flow levels as well as, in many cases, increased thrust at N1. The fleet installed fuel flow has stabilized in recent years as the effects of these two factors spread through the airline fleets. The hardware improvement item which had the major impact on fuel flow and thrust at N1, namely modified fan blades, had been incorporated into the DC10-10 airline fleets by 1975. Also, the performance level averages stabilized as the fleet matured.

Performance deterioration and engine design changes, plus limited performance restoration, have produced the present fleet fuel flow level relative to the FPM baseline. The effects of these factors on engine performance, such as fuel flow, are shown schematically in Figure 2. Note that, as indicated in the sketch, additional maintenance beyond normal refurbishment would improve the installed performance. The cost effectiveness of this additional maintenance has not, at this time, been determined.

## Design Changes - Effect On Cruise Performance

Design changes were incorporated into the DC10-10 fleet in order to improve CF6-6D performance retention and/or durability after the FPM baseline had been defined by the CF6-6D flight test program. This flight planning manual to which all installed performance is referenced is not normally updated to reflect such engine design changes for an engine model. Since these hardware changes affect the gross measurement of performance, it is thus necessary to identify the magnitude of the associated installed performance changes in order to separate and define the engine operational deterioration.

Both specific design changes and associated changes in performance are presented in Figure 3. (These design changes and the effects are discussed in greater detail in Reference 1.) All of these items have been incorporated in recent vintage engines (i.e. ESN 451-406 & above) during production, while earlier engines had the changes incorporated through factory changes and/or service bulletins. The net effect on cruise performance, relative to the FPM, of all these changes has been to increase net thrust at N1 by 2.5% while producing higher fuel flow at N1 (3.2% increase), EGT at N1 (7.0 °C increase), and SFC at Fn (0.79% increase), while still meeting SFC requirements.

To illustrate the installed performance effects of the design changes on measured fuel flow, initial airline revenue service cruise data have been trended on new engines that had been shipped with these changes. Presented in Figure 4 are these data for the DC10-10 installation of the CF6-6D engine. It can be seen that fuel flow is 3.2% higher than the reference baseline as the engines started revenue service. Again, note that these engines were shipped with acceptable SFC margins.

## Typical Deterioration Trends

Typical installed deterioration trends are established from these cruise data which were recorded for engines prior to any maintenance by three DC10-10 operators during normal revenue service. A curve fit representative of the average CF6-6D cruise fuel flow of post -406 engines is shown in Figure 4. It can be observed that the rate of deterioration was greater early in the life of these engines. During the first 1000 hours of operation, the average cruise deterioration rate was about 1%/1000 hours, while during the third 1000 hours of operation the deterioration rate had decreased to less than half of that rate, being about 0.5%/1000 hours.

The cruise EGT and SFC deterioration trends (not shown) of these same installed engines were similar. About 40% to 45% of the average cruise performance deterioration after 4000 hours of operation was lost during the first 1000 hours of service for these CF6-6D engines. The average change in performance at cruise power during these engines' first 1000 hours was a 7 1/2 °C increase in EGT at N1, and an equivalent 0.8% increase in SFC at Fn based on ΔWFM. It is suspected that the higher early deterioration rate was related to the average rate at which engine clearances (rotating and stationary) opened up. For instance, during initial installation the engine clearances are tighter, thus the likelihood of a rub which will cause a performance loss is higher. The events which result in increased clearances and losses in performance are distributed more heavily in the early operational time.

### Installed Performance Trend Summary

The average installed engine performance levels, relative to the FPM baseline, are thus the sum of the effects of deterioration and of hardware design changes. The delta fuel flow and SFC variations with time of CF6-6D, post ESN 451-406, engines are shown in Figure 5 for a typical first installation of these engines. After 4000 hours of operation, the average level of fuel flow at N1 was 5.7% above the baseline of which 2.5% was due to deterioration and 3.2% was due to engine design changes. Likewise, after 4000 hours of operation, the average cruise SFC at Fn increased 2.0% above the initial service level where the aircraft had acceptable specific range (i.e. measure of airplane specific fuel consumption).

## METHODS TO IMPROVE PERFORMANCE & REDUCE FUEL CONSUMPTION

Two approaches toward improving the performance and reducing fuel consumption of the airline fleets are: 1) reduce performance deterioration, 2) attain additional performance restoration during maintenance. The intent of the current diagnostic studies is to develop a better understanding of engine performance, as well as improve technology. This will be accomplished in order to identify specific and viable actions for both approaches, thereby yielding performance improvements and fuel savings for current and future engines. As part of on-going investigations, not only will overall engine performance (losses and restoration) be considered, but modular performance, as well as the hardware conditions relative to performance changes, will also be examined.

### Reduce Deterioration

There are a number of avenues open when exploring the approach to improved performance by means of reducing deterioration. Design changes can be incorporated in engines to reduce deterioration rates. Operational procedures can be modified, within certain constraints, to reduce the severity of the conditions under which the engines operate. Examples of these avenues will be given. Further, the sources and causes of pre-delivery deterioration (losses occurring during initial flights, particularly during airplane checkout flights) are being investigated to determine what actions might be taken to reduce this loss.

### Design Changes To Reduce Deterioration

Consider first the effect of engine design changes on deterioration rates. As part of engine diagnostic studies, the effect of hardware changes on deterioration, such as the CF6-6D improvements introduced in production with ESN 451-406, will be examined. Such a study will involve accounting for the fleet mix of engines with and without these improvements. At this date a comparison more readily made would be between two CF6 engine models, the -6D and the -50A. The CF6-50, being a derivative of the CF6-6D, incorporated many basic design philosophy changes that were based on mechanical and aerodynamic experience with the CF6-6D. Moreover, typical cruise deterioration histories prior to refurbishment have been established for these engines.

This comparison of the cruise deterioration rates of CF6-6D and CF6-50A engines installed in DC10 airplanes is presented in Figure 6. Losses in performance of these non-refurbished engines relative to their respective FPM baselines are shown at 1000 flight hour intervals. It can be observed that the rate of deterioration is lower for the CF6-50A. In particular, the fuel flow was consistently lower for the CF6-50A through 3000 hours, as were the average SFC and EGT rates of deterioration. In other words, the design changes incorporated in the CF6-50A model resulted in better average performance retention prior to the first refurbishment of the engines. Nevertheless, the deterioration characteristics are similar for both engine models. This similarity generally allows performance improvements designed for one engine model to be applied to the other model.

## Operational Procedures To Reduce Deterioration

Another avenue to achieve deterioration rate reductions is through flight operation procedures, certainly within the constraints of safety. One procedure employed by airlines to reduce deterioration is to operate their engines derated when conditions permit (load factors, airport temperature and altitude considerations). An example is presented in Figure 7 showing for the CF6-50 the average EGT deterioration rate per 1000 hours as a function of the percent of rated CF6-50C thrust. Curves of the average deterioration rate are shown for the first 1000, 2000, and 3000 hours of revenue service operation. As noted, airlines typically operate CF6-50 engines at 7% derated thrust. Based on this preliminary analysis, it can be observed that the effect of derate is to substantially reduce the average performance losses (in this case, EGT) for a CF6-50 engine. For instance, after 1000 hours of operation, the average EGT relative to initial flight levels would be about 9 °C higher without derate. CF6-50 engines operating at derated thrust have better average EGT performance throughout a typical installation. The improved EGT performance is also indicative of improved SFC and fuel flow performance.

## Pre-Delivery Losses

Another aspect of engine performance deterioration must be considered; namely pre-delivery losses, the performance losses prior to initial revenue service. This deterioration becomes evident as a loss in performance after the initial flights, but prior to revenue service of the engine, when compared to predicted performance levels of production test cell calibrations. These losses have been shown for both the CF6-6D and CF6-50 to be real and not reversible when low time engines were recalibrated in test cells after undergoing airplane checkout procedures. These losses are included in the airline reference datum point as defined by initial revenue service and are incorporated in the FPM baseline. Since these losses were also incurred during the flight test program prior to defining the flight planning manual, all of the baseline data to which the engines are now being compared are, therefore, consistent.

Another characteristic of pre-delivery loss which has been observed is that installed performance losses are larger for engines undergoing airplane checkout procedures conducted by the aircraft manufacturer than for those engines entering revenue service as airline spares. As yet, no General Electric engines have been torn down to develop an analytical assessment of the causes of this deterioration. However, an investigation is currently underway to identify and quantify the sources and causes of this deterioration.

During the checkout of a new airplane prior to delivery to an airline, ground run-ups of the engines are made in order to trim the throttle levers and linkages plus several flights are flown to checkout the systems through their full range of operations. Engine cockpit parameters are typically recorded by the airframer during the first flight. The average cruise losses after the airplane checkout for these CF6-6D engines were 1.3% increase of WFM at N1, 0.9% increase of SFC at Fn, and 16°C increase in EGT at N1. As previously noted, these are incorporated in the FPM. Modular assessments of the losses are not complete as part of the diagnostic studies, but it is estimated that the losses were primarily in the HP turbine. The causes of these losses will be investigated as part of the diagnostic studies.

As mentioned earlier, engines going through airplane checkout procedures characteristically experience greater losses than engines entering revenue service as airline spares. A comparison indicating this difference is presented in Figure 8. Average revenue service deterioration of WFM and EGT are shown for the first installation of CF6-6D post ESN 451-406 engines. Even though the data are sketchy, it can be observed that the spare engines entered service with better performance and remained consistently better through the first installation (typically less than 5000 hours). The average difference was about 0.4% WFM at N1, and 9°C EGT at N1. These differences seemingly are the result of the rigorous airplane/engine flight checkout procedures required for aircraft checkout, prior to delivery and entry into revenue service.

## Additional Performance Restoration

Another approach to improve fleet performance and reduce fuel usage is to attain additional performance restoration during maintenance. The key to success for this approach is to identify specific hardware refurbishment with the potential of restoring significant performance losses and to determine the cost effectiveness of such work. An important element in this is the assessment of modular performance losses and the relation of these losses to the hardware condition.

The refurbishment of CF6 engines is generally accomplished on a modular replacement basis; non-serviceable modules are replaced with restored, serviceable modules. The workscope for a particular engine during a particular shop visit is suited to the condition of that engine at that time. The basic objectives of the refurbishment efforts in the overhaul facilities have been to replace damaged or non-serviceable parts and to restore EGT temperature margin (the basic shop measure of overall performance) so that the engine can be returned to revenue service for a reasonably long period of time.

The largest causes of CF6 engine removals are related to the hot section core items; e.g. the HP turbine, the HP turbine nozzle, and the combustor. The refurbishment emphasis, as a result, has been on the hot section to restore core performance as discussed in Reference 2. As outlined in this reference, numerous studies have been conducted to identify cost effective refurbishment activities.

With the normal workscope aimed at the core, the largest potential for additional performance restoration during engine maintenance in the overhaul shop probably lies in the low pressure system. Typically, little work is done on the LP system during a shop visit. The amount of performance that is restorable through cost effective LP refurbishment is being examined as part of the CF6 diagnostics studies.

## Modular Performance Assessment

As part of these studies, two CF6-6D engines have been run inbound in a test cell prior to any maintenance in order to assess the modular contributions to the overall deterioration. The apportionments of the overall SFC losses measured in the test cell for these two engines, ESN 451-380 & 451-479, as well as for two other engines, are presented in Figure 9. This assessment is shown as a percentage of the total SFC loss relative to production acceptance test levels and is divided between the HP compressor, the HP turbine, and the LP system. The losses in the HP turbine are further divided between efficiency changes and cooling flow changes, while the LP system assessment represents the combined losses in the LP turbine and the fan or LP compressor.

For the first three engines, it can be observed that the largest SFC losses, about 65% of the total, have been assessed to be the result of HP turbine deterioration. This assessment illustrates why the typical airline refurbishment emphasis has been directed at the core hot section. HP compressor deterioration has been assessed at 16% to 28% of the total SFC deterioration, while the remaining 7% to 21% have been assigned to deterioration of the LP System. The fourth engine, ESN 451-479, appeared to have an untypically low percentage of SFC deterioration in the HP compressor and LP system.

As part of the CF6 diagnostic studies, ESN 451-380 & 451-479 underwent teardown inspections, after inbound tests, to assess the hardware condition and to determine the major hardware contributors to modular performance deterioration. The major items influencing as-recieved engine performance for each section of the engine were as follows.

TWO SPECIAL DIAGNOSTIC CF6-6D ENGINES

MAJOR HARDWARE CONDITIONS AFFECTING PERFORMANCE

| | |
|---|---|
| HP Compressor | - Airfoil Surface Finish |
| Core Hot Section | - HP Turbine Tip Clearances |
| | - Forward Shaft Seals |
| Low Pressure System | - Stage 1 Fan Blade Cleanliness & LE Contour |
| | - LP Turbine Clearances |

This list notes only the major hardware conditions which result in modular performance deterioration. Numerous dimensions, surface finishes, and general part conditions were recorded throughout these two engines prior to any refurbishment activity. The above items were determined to have the most significant impact on performance based on a combination of the observed wear of these parts and previously developed hardware/performance influence factors. These influence factors relate measured changes in hardware condition to overall performance.

As previously indicated, airline maintenance of deteriorated engines is typically directed toward refurbishment of the core hot section, where the largest performance deterioration usually occurs. This emphasis on core refurbishment can be observed in all overhaul facilities; the workscope for most engine visits includes replacement and/or refurbishment of hot section parts, while only occasionally including work on the low pressure system. The resulting performance restoration of the core can be derived from analysis of test cell measured, overall performance improvements. Since core components have a somewhat larger influence on EGT than LP system components, a percent of core efficiency improvement produces more EGT reduction than a similar improvement in LP system efficiency.

Typical Outbound Performance

Although the amount of restoration attained for individual engines/visits varies substantially, the average outbound performance appears to be stable for a given set of engines. To illustrate this point, histories of outbound SFC and EGT deltas relative to a 10,000 hour average are shown in Figure 10 for twelve refurbished CF6-6D engines through three or more shop visits per engine (74 total outbound tests). While there is a wide data spread, the outbound levels measured in this airline test cell were observed to be steady-to-improving over 10,000 hours of revenue service for this twelve-engine sample. This trend has resulted from an increased maintenance scope to restore EGT margin and performance of older engines.

Further, average sea level SFC and EGT margins (about 2 1/2% below new engine specs and 8°C EGT margin) imply that the average refurbished engine has performance losses remaining in LP efficiency when returning to revenue service. When these outbound margins are compared to average production engine acceptance test cell levels, the performance deltas indicate that the new engines were typically 3% to 3 1/2% better in SFC and 20°C better in EGT. This $\Delta$SFC/$\Delta$EGT combination suggests that the average LP system efficiency of these refurbished engines was on the order of 3% lower than typical production CF6-6D engines (worth 2% in SFC). This observation coincides with typical overhaul facility workscopes which emphasizes core hot section work.

## LP System Restoration Potential

Previous investigations were properly directed toward identifying cost effective refurbishment procedures and techniques for the core because the greatest return on maintenance efforts required to restore EGT within acceptable margins relative to certified limits should be in the core. With escalating fuel prices and dwindling fuel resources, however, efforts must be directed toward obtaining additional performance restoration for the engines during normal maintenance. Since there is typically little refurbishment effort for the LP system and since outbound performance after maintenance suggests significant residual SFC losses in the LP system, it appears that studies are needed to define the amount of performance restoration that might be expected with expanded LP refurbishment activities and the projected cost effectiveness of such activities. As part of the NASA Lewis Research Center sponsored "CF6 Jet Engine Diagnostic Program", a major investigation into LP system performance deterioration is currently underway.

A series of back-to-back engine tests is planned in 1978 to compare the performance of new production low pressure turbine modules to that of typical airline serviceable LP turbine modules which are installed on refurbished outbound engines. These tests should provide results which indicate the degree of LP turbine efficiency which is not regained during normal maintenance. In addition, tests are also planned to measure the amount of performance restoration which can be obtained by refurbishment or replacement of selected LP turbine parts. This investigation should provide deeper insight into the possibilities of additional performance restoration through expanded maintenance procedures.

Improvement of the typical outbound SFC performance margins of refurbished engines, such as shown in Figure 10, will lead directly to fleet fuel savings. If expanded refurbishment efforts can be demonstrated to be cost effective, such practices can be introduced rapidly in the field. As such, fuel savings can be realized for all engines currently in service, as well as for new engines. The important factor in identifying added or revised refurbishment activities which will yield improved performance and lower fuel consumption is understanding the contributions of modular deterioration to overall performance losses, as well as understanding the relation of parts condition on performance. Diagnostic studies are currently proceeding to broaden this understanding, not only for the LP turbine, but for all the major engine modules.

## CONCLUDING REMARKS

The study of jet engine performance over a typical life span is a broad and complex topic. The gross measurements, such as fleet fuel flow levels, of engine performance are impacted by many factors. Factors which produce these levels consist not only of engine deterioration, but also of design change items and the performance restoration of engines during airline maintenance. In order to improve performance and reduce fleet fuel usage, it is necessary to identify the contribution of each of these factors.

The use of the performance baseline from the flight planning manual as a reference to measure changes in cruise fuel flow rates has been discussed. For the CF6-6D engine, the introduction of design changes for performance and durability reasons was seen to introduce an average increment relative to this baseline of 3.2% WFM increase at N1, 2.5% Fn increase at N1, 0.8% SFC increase at Fn, and 7 °C EGT increase at N1, while maintaining sufficient SFC margin of the delivered airplane. The effect of revenue service deterioration and performance restoration relative to the reference was shown to be an adder on top of these design effects.

A schematic of typical CF6-6D performance through revenue service and airline maintenance is presented in Figure 11, in terms of percent cruise SFC relative to an airline datum point (average level upon entering revenue service). The typical changes in SFC margin are shown for airline revenue service through four installations and refurbishments. The relative magnitudes of the changes and frequency of shop visits are representative of post ESN 451-406 engines.

The overall installed performance trends for these engines are well understood through the first installation. These deterioration losses are summarized below relative to the airplane datum point.

AVERAGE CRUISE LOSSES FOR FIRST INSTALLATION

| | ΔWFM @ N1 | ΔSFC @ Fn | ΔEGT @ N1 |
|---|---|---|---|
| 4000 Hour Deterioration | 2.5% | 2.0% | 17 °C |

Further, during the typical airline restoration of the CF6-6D engine more than 50% of the modular losses of a typical inbound deteriorated engine are in the core hot section. Most of these losses are recovered during normal refurbishment. The resulting average outbound performance of these refurbished engines appears to be stable with operational time. Losses typically remain in the LP system after refurbishment, but the amount that is recoverable through additional maintenance has yet to be defined.

Pre-delivery losses occurring before airplane delivery have also been defined in terms of overall performance changes. These average cruise losses after airplane checkout are 1.3% WFM increase at N1, 0.9% SFC increase at Fn, and 16 °C EGT increase at N1. It has also been observed that engines entering revenue service as spare engines display less than half the losses incurred during aircraft checkout flights and the performance of these spare engines remain consistently better through the first installation. The causes of these losses are not fully defined at this point, but they are being carefully investigated in an attempt to improve delivered airplane/engine performance.

The current "CF6 Jet Engine Diagnostic" studies will continue through the end of 1979. To date, test cell and cruise performance data have been examined for both the CF6-6D and CF6-50 engines to establish or confirm statistics and trends of engine performance. As part of the continuing diagnostics program both experimental and analytical studies are currently underway during which 1) overall performance trending and deterioration models will be extended and refined over the complete engine life cycle; 2) modular deterioration rates will be further assessed; and 3) typical hardware conditions will be related to performance losses. The information and technology produced from these studies will be used to reduce fleet fuel usage by minimizing performance deterioration and improving performance restoration for current and future engines.

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## NOMENCLATURE

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

| | |
|---|---|
| Airline Datum Point | aircraft performance reference level as determined during initial revenue service |
| As-Shipped | production acceptance test cell data |
| EGT | exhaust gas temperature, in °C |
| EGT Margin | test cell EGT margin (zero margin in test cell equivalent to 17°C margin on wing) |
| ESN | engine serial number |
| FPM | "Flight Planning & Cruise Control Manual", tabulation of baseline reference curves for installed engine performance under various operating conditions |
| Fn | net thrust, rated CF6-6D takeoff installed thrust = 173 kN (38,900 lbf) |
| HP | high pressure |
| HPT | high pressure turbine |
| LP | low pressure |
| LPT | low pressure turbine |
| N1 | fan rotational speed, rated CF6-6D takeoff fan speed = 3443 rpm |
| SFC | specific fuel consumption, CF6-6D takeoff guarantee level (0.357) |
| SFC Margin | difference between SFC level & guarantee SFC, % |
| SPEC | airplane delivery specification |
| TSO | time since overhaul, in hours |
| TSN | time since new, in hours |
| WFM | fuel weight flow |
| ΔWFM, ΔWf | change in fuel weight flow relative to the FPM reference, in % |

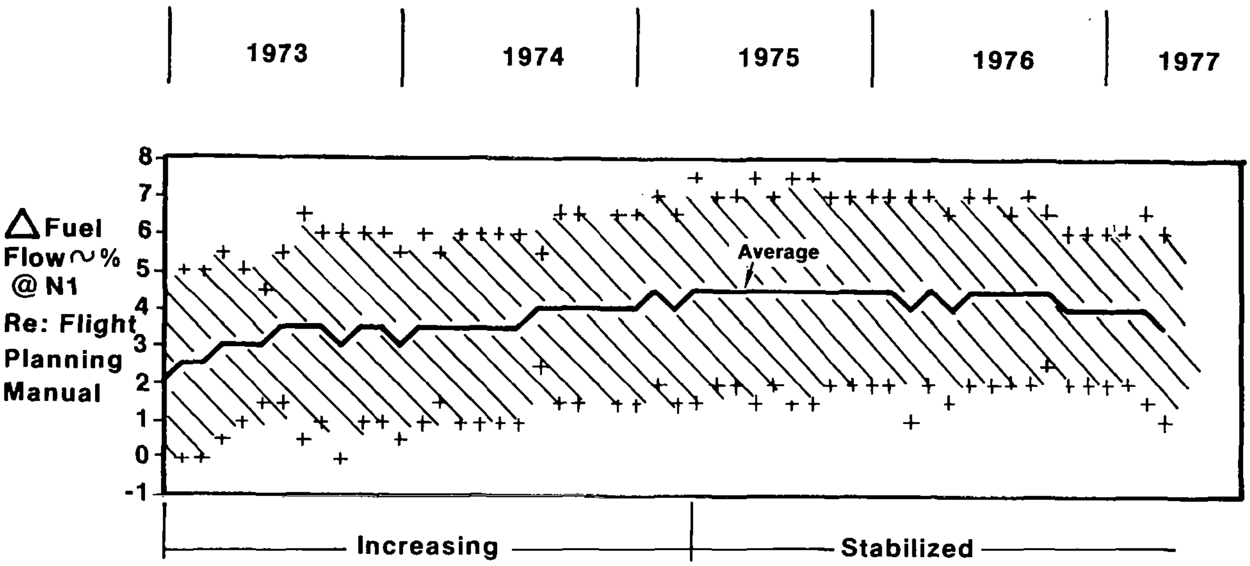


Figure 1.- Typical airline fuel flow trends.

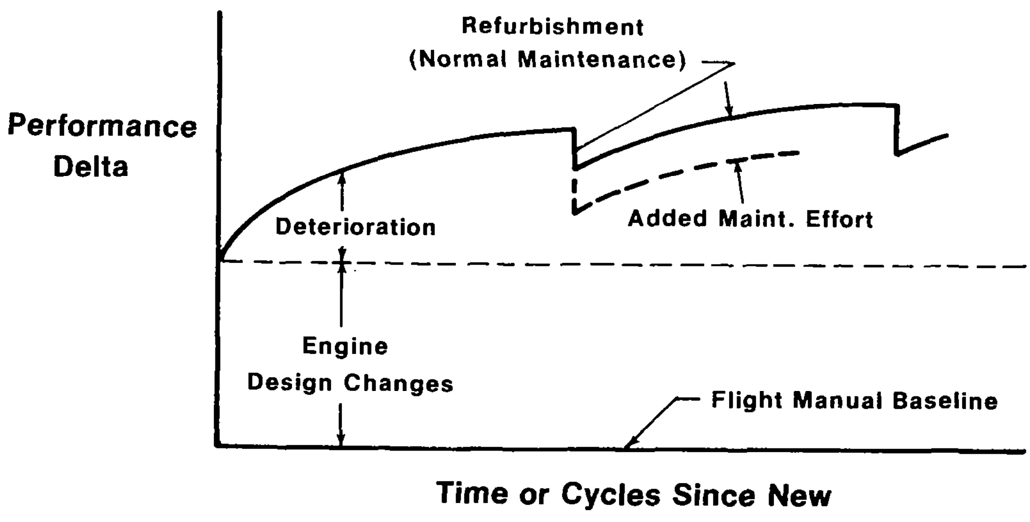


Figure 2.- Schematic of typical engine revenue service history.

| Performance Items | ΔWf%@N1 | ΔFn@N1 | ΔEGT°C@N1 | ΔSFC%@Fn |
|---|---|---|---|---|
| • Fan Blades LE Recontour (P16) | +2.02 | +2.17 | +7.2 | -0.31 |
| • Increase LP Nozzle Flow Function | +0.29 | +0.43 | -8.9 | +0.06 |
| Durability Items | | | | |
| • Frame Revent | +0.22 | -0.13 | +2.0 | +0.35 |
| Fan Clearance Increase | +0.44 | -0.02 | +1.3 | +0.49 |
| • Miscellaneous | | | | |
| — Solid Fan Blades (P04) | | | | |
| — Honeycomb Shrouds | | | | |
| — G44 Combustor | | | | |
| — HPT Improvements | +0.21 | +0.01 | +5.4 | +0.20 |
| Total | +3.18% | +2.46% | +7.0°C | +.79% |

Figure 3.- Effect of CF6-6D design changes on cruise performance.

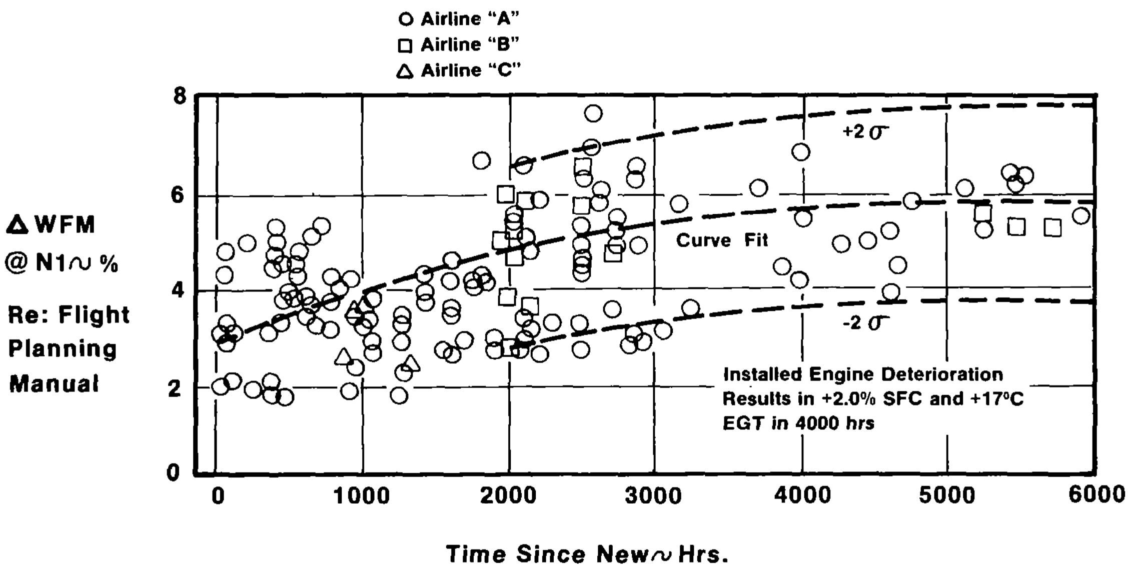


Figure 4.- CF6-6D installed cruise deterioration trends - first DC10-10 installation.

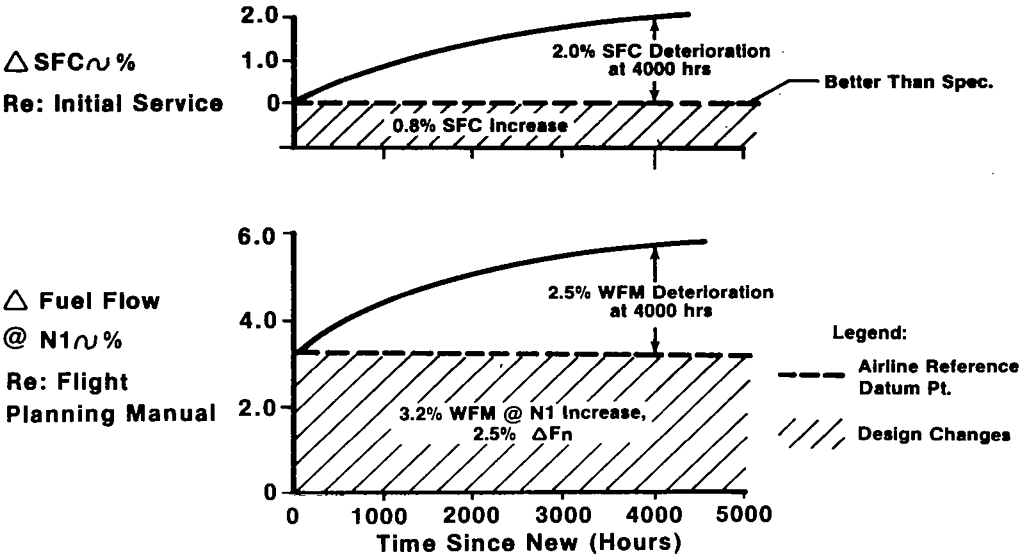


Figure 5.- First installation cruise characteristics - design changes plus deterioration effects.

## Comparison of CF6-6D and CF6-50A Prior to Refurbishment

- **Cruise Deterioration Rates**

| | ΔFuel Flow @ N1 | | ΔSFC @ Fn | | ΔEGT @ N1 | |
|---|---|---|---|---|---|---|
| | -6D | -50A | -6D | -50A | -6D | -50A |
| First 1000 Hours | 1.0% | 0.6% | 0.8% | 0.6% | 8°C | 5°C |
| @ 2000 Hours | 1.7% | 1.2% | 1.4% | 1.1% | 13°C | 10°C |
| @ 3000 Hours | 2.2% | 1.7% | 1.7% | 1.5% | 15°C | 14°C |
| @ 4000 Hours | 2.5% | 2.1% | 2.0% | 1.9% | 17°C | 17°C |

Figure 6.- Effects of engine model design changes on deterioration rates.

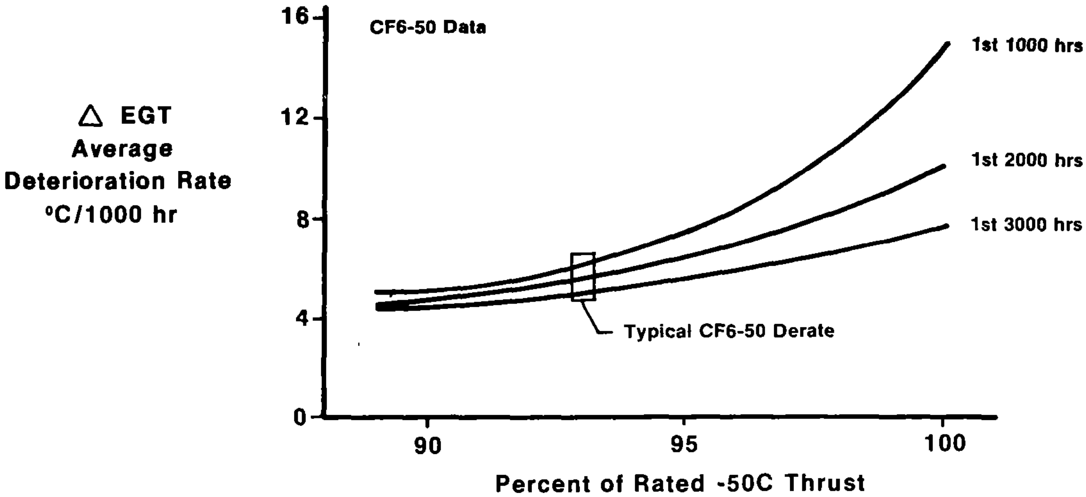


Figure 7.- Operational procedure which reduces deterioration rates - effect of derate.

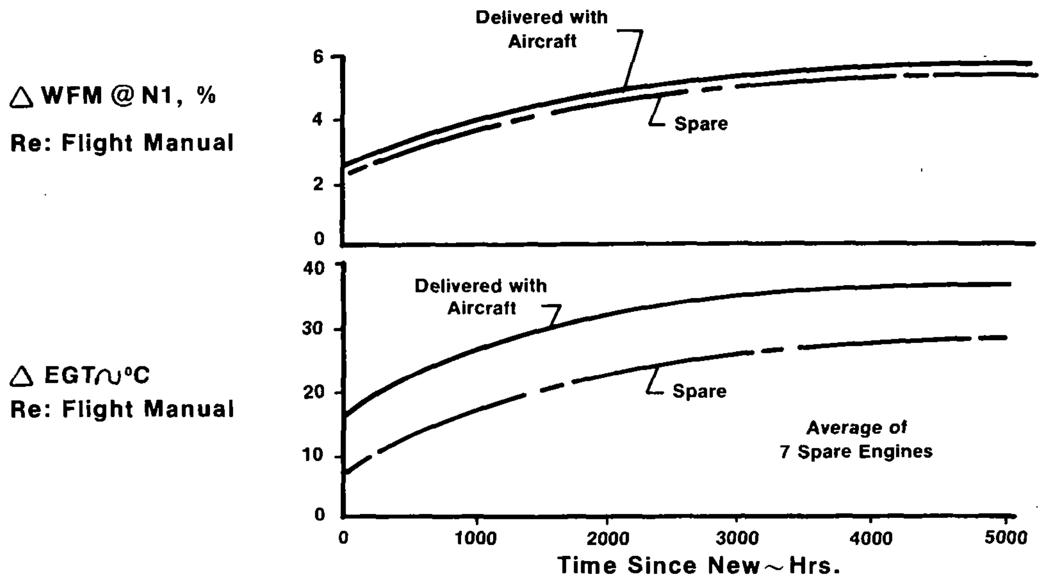


Figure 8.- Deterioration of CF6-6D's delivered as airline spares.

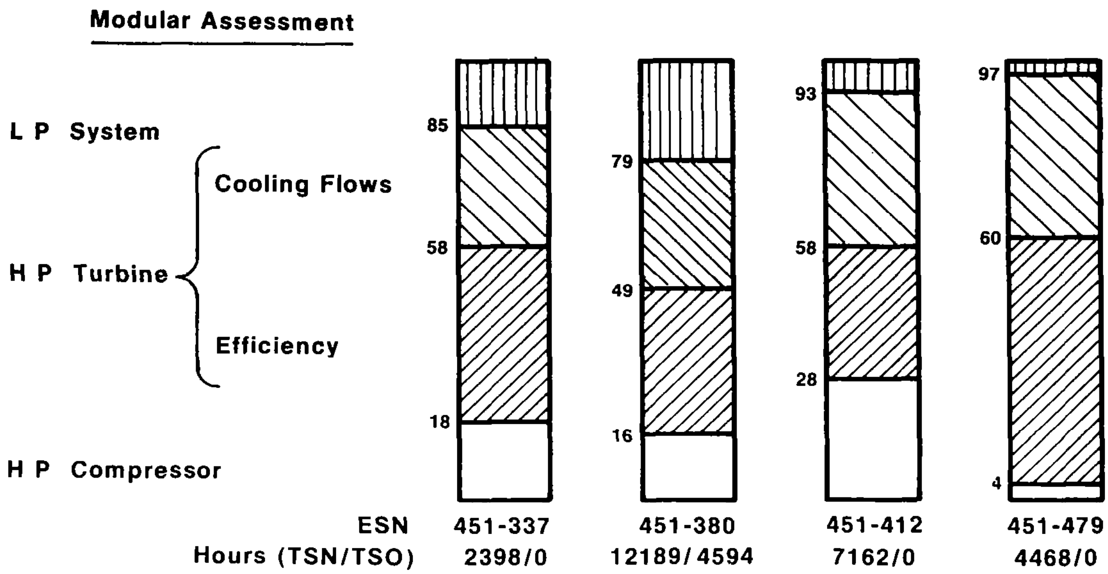


Figure 9.- Examples of CF6-6D modular contribution to SFC deterioration.

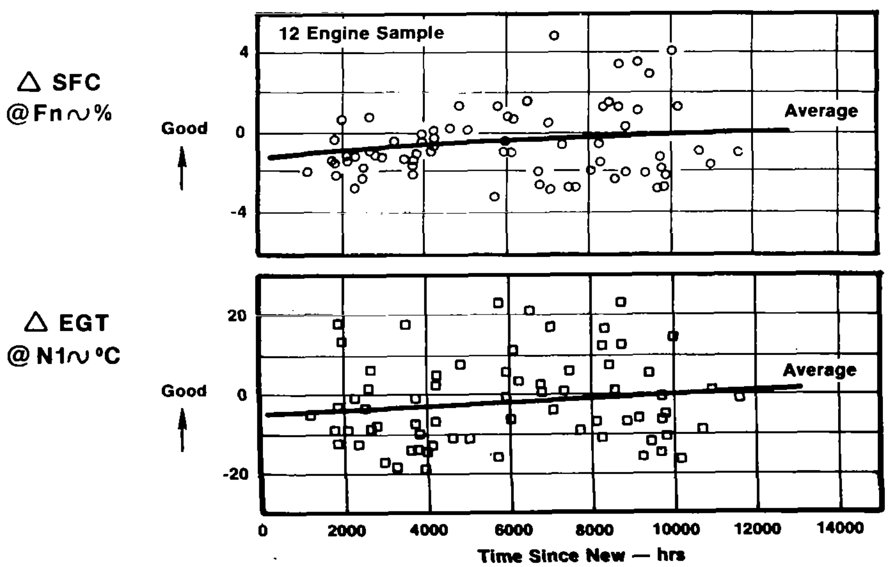


Figure 10.- CF6-6D outbound performance history.

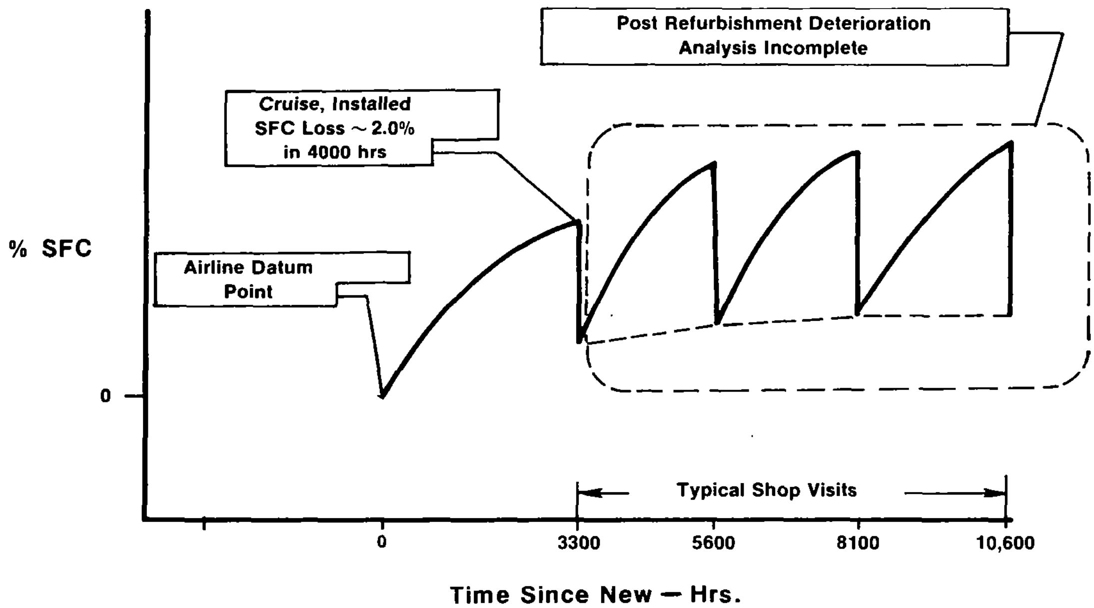


Figure 11.- Summary of CF6-6D SFC performance trend.