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CF6-6D ENGINE PERFORMANCE DETERIORATION

by

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16. Abstract

Cruise cockpit recordings and test cell performance data in conjunction with hardware inspection data from airline overhaul shops were analyzed to define the extent and magnitude of performance deterioration of the General Electric CF6-6D model engine. These studies successfully isolated short-term deterioration from the longer term, and defined areas where a significant reduction in aircraft energy requirements for the 1980's can be realized. It was determined that unrestored losses which remain after engine refurbishment represent over 70% of the loss at engine shop visit. Sixty-three percent of the unrestored losses are cost-effective to restore which could reduce fuel consumed by CF6-6D engines in 1980 by 10.9 million gallons.

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PREFACE

The work was performed by the General Electric Engine Business Group located in Evendale Ohio during the 1977 through early 1980 time period. The factors utilized for cost effectiveness and other economic studies were based on the estimated levels for the mid-1979 time period, and these results can be extrapolated to obtain "then year" dollars.

The program was conducted for the National Aeronautics & Space Administration Lewis Research Center, Cleveland, Ohio under Contract NAS3-20631, "CF6 Jet Engine Diagnostics Program". The NASA Project Engineers for this program were Robert P. Dengler and Charles M. Mehalic.

The General Electric Company extends its thanks and appreciation for the efforts expended by the airlines in support of this program; and in particular to United Airlines, which provided the majority of the hardware and performance data.

The requirements of NASA Policy Directive NPD22204 (September 14, 1970) regarding the use of SI units have been waived in accordance with the provisions of paragraph 5d of that Directive by the Director of Lewis Research Center.

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1.0 SUMMARY

A program was initiated with the General Electric Company to conduct performance deterioration studies for the CF6-6D engine. The basic objectives were to determine the specific causes of engine deterioration that increase fuel consumption, and to identify potential ways to minimize these effects. Cruise cockpit recordings and test cell performance data were analyzed along with hardware inspection data from airline overhaul shops, to define the extent and magnitude of engine deterioration. These studies successfully isolated short-term deterioration from the longer-term, and defined areas where a significant reduction in aircraft fuel consumption can be realized for the 1980's.

The short-term studies indicated that a 0.9 percent cruise fuel burn (cruise sfc) loss occurs during aircraft checkout flights prior to aircraft delivery to the airlines for revenue service. While this loss may be minimized by a change in the flight checkout procedure, high pressure turbine blade tip rubs must be controlled to eliminate this source of engine deterioration.

The magnitude of long-term deterioration for the initial installation of a production new engine at 4000 hours is 1.7 percent cruise fuel burn, which is in addition to the short-term loss of 0.9 percent. The long-term loss for a typical airline-refurbished engine is 0.9 percent in cruise fuel burn after 3000 hours. Short-term losses were not isolated for the airline-refurbished engine since sufficient data were not available.

It was shown that the average refurbished engine when re-installed for revenue service has an increased cruise fuel burn of 2.1 percent. This increase over the production new baseline represents 70 percent of the total performance deterioration at next removal. Based on 1979 estimated labor and fuel costs, it is potentially cost effective to restore 63 percent of this 2.1 percent in cruise fuel burn. This represents a potential savings of 10.9 million gallons of fuel that would be consumed by CF6-6D engines in 1980.

The fan section is the most promising area to regain performance by additional restoration during each shop visit. This results from the on-condition maintenance concept that requires repair during a shop visit of mechanical distress which exceeds published limits. Performance deterioration of the fan section generally consists of superficial damage which does not exceed mechanical limitations. In contrast, the unrestored losses in the high pressure turbine are very small since that area is repaired during each shop visit to restore durability properties.

The potential to make a notable impact toward energy conservation in the 1980's has been demonstrated.

2.0 INTRODUCTION

A program has been initiated for the CF6 family of turbofan engines to identify and quantify the causes of performance deterioration which increase fuel consumption. The recent energy demand has outpaced domestic fuel supplies, creating an increased United States dependence on foreign oil. This increased dependence was accentuated by the OPEC embargo in the winter of 1973/74 which triggered a rapid rise in the price of fuel. This rise, along with the potential for further increases, brought about a set of changing economic circumstances with regard to the use of energy. These events were felt in all sectors of the transportation industry, including the air transport industry. As a result, the Government, with the support of the aviation industry, has initiated programs aimed at both the supply and the demand aspects of the problem. The supply problem is being investigated by determining the fuel availability from new sources such as coal and oil shale, with concurrent programs in progress to develop engine combustor and fuel systems to accept these broader base fuels.

Reducing fuel consumption is the approach being used to lessen its demand. The long-range effort to reduce fuel consumption is expected to evolve new technology which would permit the development of a more energy efficient turbofan, or the use of improved propulsion cycles such as that used for turboprops. Studies have indicated that these approaches could yield large reductions in fuel usage - as great as 15 to 40 percent but a significant impact in fuel usage is considered to be fifteen or more years away. In the near term, the only practical approach is to improve the fuel efficiency of current engines since these engines will continue to be the significant fuel users for the next fifteen or twenty years.

Accordingly, NASA is sponsoring the Aircraft Energy Efficient (ACEE) program which is directed toward reducing fuel consumption for commercial air transports. Within the ACEE program, the Engine Component Improvement (ECI) program is the element directed toward improving the fuel efficiency of current engines. The ECI program consists of two parts: (1) Performance Improvement, and (2) Engine Diagnostics. The Performance Improvement program is directed toward developing component performance improvements and improved performance retention for new production and retrofit engines. The Engine Diagnostics effort is to provide information to identify the sources and causes of engine deterioration.

OBJECTIVES AND APPROACH

As part of the Engine Diagnostic effort, NASA Lewis initiated a program with the General Electric Company to conduct performance deterioration studies for the CF6-6D and CF6-50 engines. The major objectives of the program were 1) to determine the specific causes of engine deterioration that increase fuel burn, 2) to isolate short-term losses from the longer term losses, and 3) to identify potential ways to minimize the performance deterioration effects. This report covers the investigation of the CF6-6D engine model. The results for the CF6-50 engine will be presented in a NASA contractor report to be issued at a later date.

The basic approach employed for the CF6-6D diagnostics efforts was to gather sufficient performance and hardware inspection data to establish magnitude and trends of performance deterioration for the entire life cycle of the engine. Performance data were obtained from test cell recordings at the General Electric and airline facilities, from aircraft manufacturer's aircraft acceptance flights, and from cruise cockpit readings obtained during revenue service. Hardware inspection data were obtained from both General Electric and airline records, and supplemented by a special program between General Electric and United Airlines where current hardware conditions were documented. To provide a representative sample of deterioration, analytical teardown analyses were conducted on engines and modules that had accrued various operating times. In addition, special engine tests were conducted involving selective refurbishment activities to aid in isolating specific deterioration mechanisms.

The performance data were used to establish the magnitude and characteristic trend of performance/deterioration. The hardware inspection data in conjunction with previously derived influence coefficients were used to isolate the deterioration mechanism, and to assign a magnitude or loss to each mechanism. Comparison of the overall loss assessed independently from hardware and performance data were used to determine the validity of the results.

REPORT FORMAT

Figure 2-1 is a schematic of a typical engine life cycle which defines the major divisions of performance deterioration which occur during the useful life of the engine. The data in this report are presented in the same order that performance deterioration occurs during the engine life cycle. First, Section 3.0 documents short-term deterioration which occurs during testing at the aircraft manufacturer's facility prior to revenue service. Then, Section 4.0 addresses the long-term results which cover airline revenue service operation. The long-term results for the initial installation engine (production new) are treated separately from those for the multiple build (also referred to as multiple installation) engine since the latter includes the effects of airline repairs and practices.

The presentations for short- and long-term deterioration are self-supporting and use similar formats. First, engine performance results describing rate and magnitude of increased fuel usage are discussed. Then, hardware inspections results used to document deterioration sources are presented, including analytical analyses to assign fuel burn effects to the individual hardware conditions. Performance and hardware inspection results are compared to produce an analytical teardown model which documents the magnitude and rate for each of the observed deterioration sources.

The hardware data presentations also include an understanding of current airline refurbishment practices which permit documentation of after-repair part condition. These data were used to produce recommendations for more effective maintenance during each shop visit which can reduce fuel consumption. The recommendation section also includes the results of studies conducted to determine which of these items are potentially cost effective.

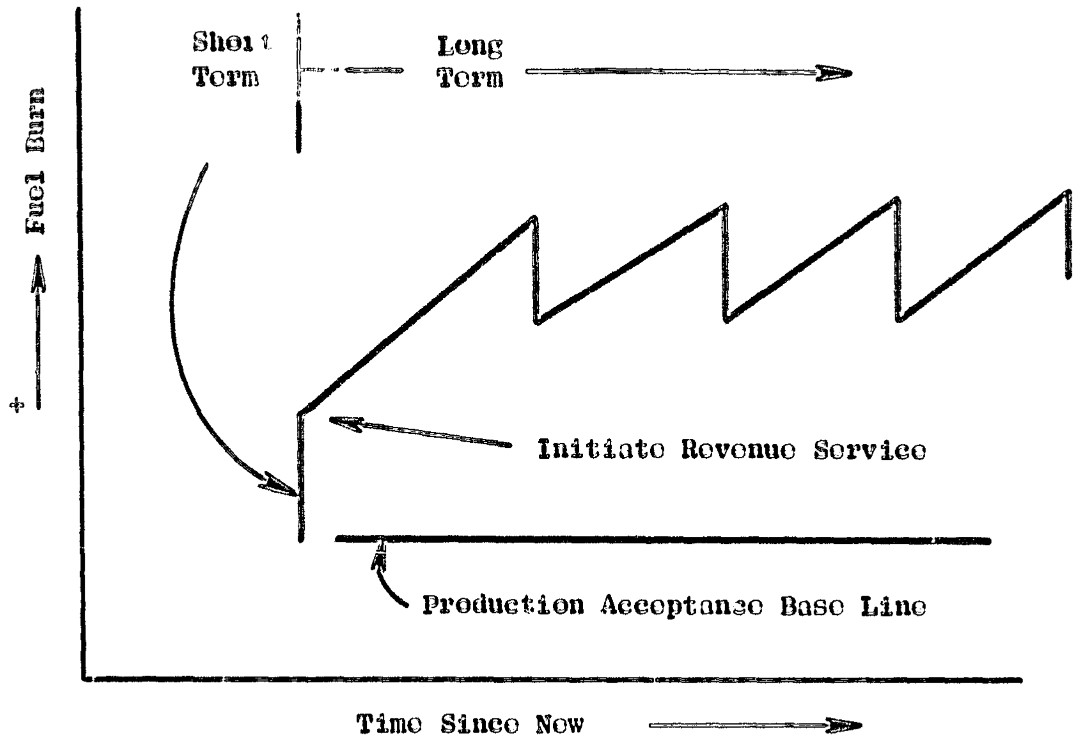


Figure 2-1. Engine Life Cycle.

3.0 SHORT TERM DETERIORATION

The phenomenon of short-term deterioration is the first topic discussed, as this is the first instance of performance deterioration following production engine acceptance testing. This significant loss of performance occurs at the very beginning of the engine life cycle for a high bypass-ratio turbofan. Short-term deterioration is rep: sented schematically for the CF6-6D in Figure 3-1 as an abrupt increase of fuel consumption prior to airline revenue service, and is defined in detail in the following paragraphs.

DEFINITION OF SHORT-TERM DETERIORATION

Although short-term losses could conceivably include the losses during the first few hundred hours of revenue service operation, it was decided to define short-term deterioration for the CF6-6D engine as those performance losses which occur at the aircraft manufacturer during airplane acceptance flights, prior to initiation of revenue service. This decision was based on several important considerations. Historical records had indicated that significant losses do occur during this phase of the life cycle, and a sufficient sample of acceptance flight performance data was available for analysis. Hardware inspection data for engines with low numbers of revenue service hours were not available. An analytical teardown inspection of a low time engine was required to provide representative hardware information which was used to isolate short-term effects. Obtaining an engine for this teardown inspection after relatively few hours of revenue service operation was not feasible due to scheduling and other concerns. However, it was possible to arrange an engine removal, for the purpose of a hardware inspection, after completion of the aircraft checkout yet prior to aircraft delivery. Hence, a dominant factor in structuring/defining this investigation of short-term deterioration was the availability of required performance and hardware inspection data for engines prior to revenue service operation. (It will be shown later that the emphasis on deterioration during aircraft acceptance testing was a most appropriate decision).

Short-term deterioration is evident when actual cruise performance levels obtained during aircraft acceptance testing are compared with cruise values predicted from production acceptance test calibrations. The predicted cruise values include adjustments for installation factors, such as bleed and power extractions for airplane systems. Short-term deterioration consists of those changes in performance that are in addition to the installation effects. These short-term losses are real and nonreversible when the engine is recalibrated in the test cell, while installation effects are completely reversible.

BASIS OF DETERIORATION ASSESSMENT

The general approach used by DACo (Douglas Aircraft Company) for acceptance testing of the DC-10-10 aircraft (the only aircraft powered by the CF6-6D engine), is similar to that employed by other manufacturers of wide body commercial aircraft. After extensive ground tests, aircraft/engine overall performance and system operation are checked during the initial flight.

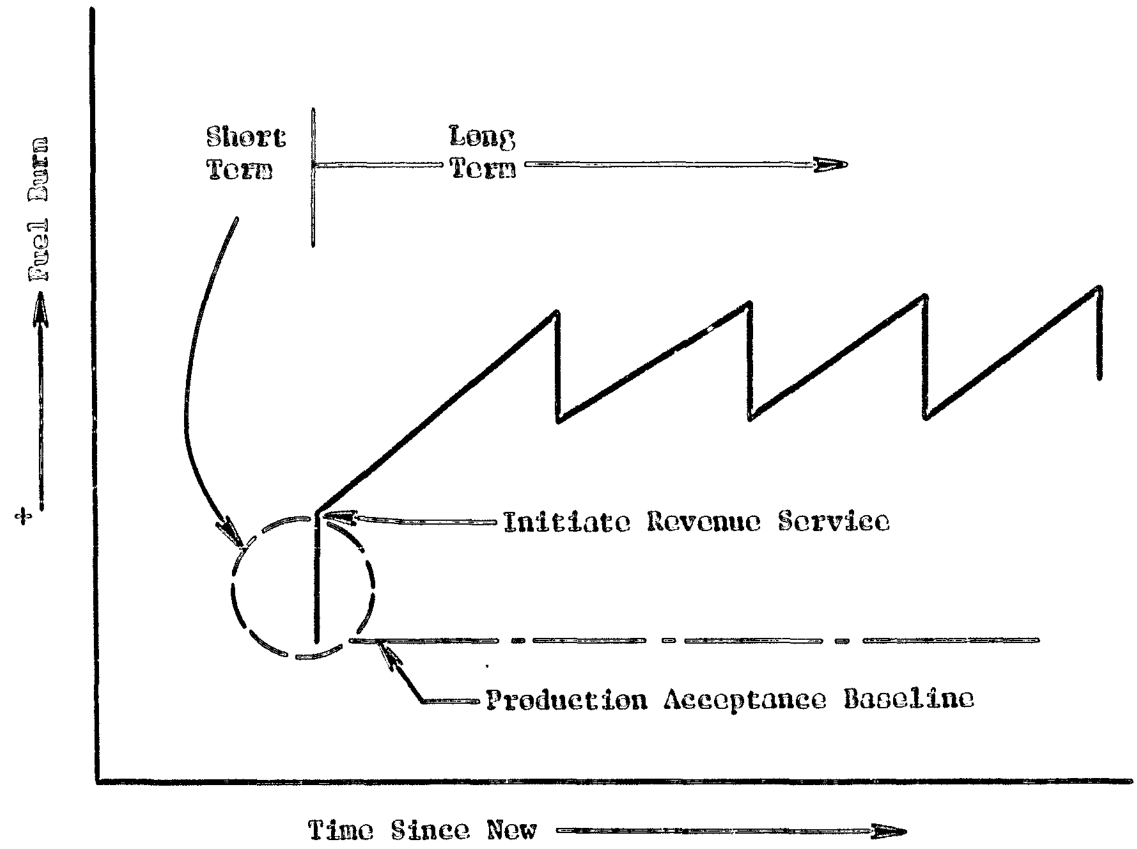


Figure 3-1. Short-Term Deterioration Schematric.

Additional flights are conducted, as required, to test corrective actions and for formal customer acceptance. Short-term deterioration is assessed from steady-state cruise performance measurements which are obtained during the initial flight.

A representative DC-10-10 airplane checkout sequence for a typical initial acceptance flight is presented schematically in Figure 3-2. After normal takeoff and climb to medium altitude, a number of system checks are conducted including one approximating airplane stall conditions which can result in large excursions of engine power. These checks are followed by a climb to high altitude, during which, acceleration checks from flight idle to maximum climb power are conducted on each engine, one at a time. (These acceleration checks could potentially result in "hot rotor rebursts"; the significance of which will be discussed later.) Stabilized cockpit readings of airplane/engine parameters are obtained upon reaching a cruise altitude - typically 35,000 to 39,000 feet. (These cruise performance measurements were used to evaluate short-term deterioration.) Additional acceleration and system checks are then performed at cruise. These checks are followed during descent, by a shutdown, and air start for each engine. The approach landing operation during the initial flight generally includes several go-arounds, and finally the flight is terminated with a landing utilizing full reverse power.

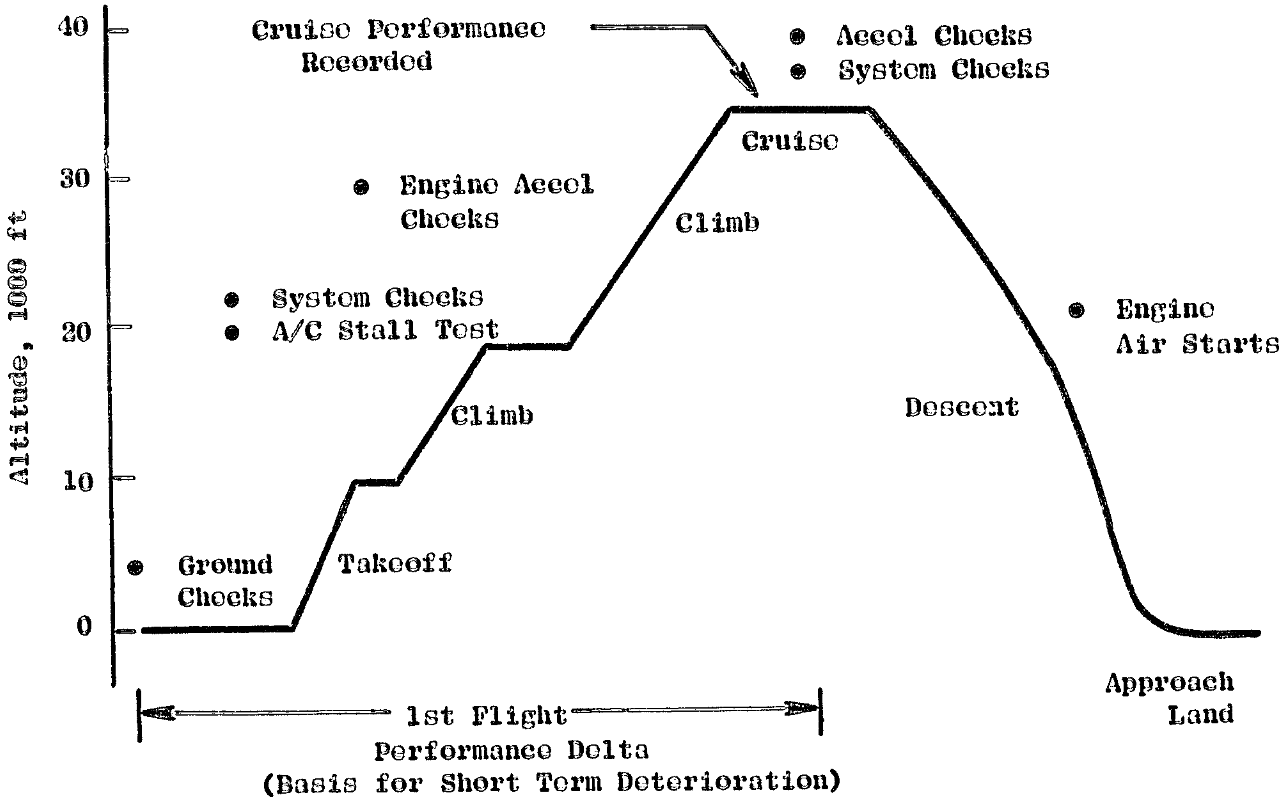


Figure 3-2. Typical Initial Acceptance Flight for DC-10-10.

OBJECTIVE AND APPROACH

The objectives of the CF6-6D short-term deterioration studies were to define the magnitude of the loss; and to isolate the individual deterioration mechanisms for the respective components including apportioning the loss to these sources. These studies included the analysis of existing DC-10-10 acceptance flight data to establish average engine performance losses from production acceptance levels. A production engine (ESN 451507) was removed following aircraft acceptance flights specifically to undergo a test cell recalibration and an analytical teardown inspection to provide the necessary hardware inspection data. A second and supplementary source of short-term hardware inspection data was obtained from the High Pressure Turbine (HPT) Tip Notch program. This independent program was designed to use notches in the blade tips to evaluate HPT blade-tip-to-shroud rubs and their resultant effect on blade lengths. While this specific program addresses only one source of deterioration, it is of special interest since the preliminary results indicated that blade tip rubs are a significant contributor to short-term losses.

The detailed results from efforts expressly designed to understand short-term deterioration are presented in the report, "CF6-6D Engine Short-Term Performance Deterioration" (Reference 1). The report includes cruise and test cell performance results for over eighty production CF6-6D engines, including ESN 451507. Assessment of short-term deterioration mechanisms utilizing hardware inspections results from ESN 451507 are also presented including details concerning the locations of inspection checks, inspection methodology, and supplementary inspection results. Finally, that report includes a summary of the results quantifying short-term deterioration. The salient results from that Short-Term Deterioration report, with sufficient detail for continuity will be presented herein.

3.1 PERFORMANCE DETERIORATION RESULTS

Two sources of performance data were available for the study of CF6-6D short-term deterioration. First, there were cruise performance cockpit-measurements which are routinely recorded by DACo during each initial DC-10-10 checkout/acceptance flight. These records were available for all engines delivered to the airlines on new DC-10-10 airplanes, and data were analyzed for all engines beginning with ESN 451406. (Major product improvements for engine durability considerations have been introduced into production engines starting with ESN 451406. These items have been retrofitted into all CF6-6D engines and this vintage production engine is also representative of the current revenue service configuration.) The second source consisted of inbound tests of two CF6-6D engines after undergoing airplane/engine checkout flights, but prior to their entry into revenue service. One of these engines (ESN 451507) was removed from wing and tested specifically as part of this short-term investigation.

The large sample of cruise performance measurements from the initial airplane checkout flight was used to establish the average short-term loss. The inbound test results were used to demonstrate that the losses were the result of real, nonreversible deterioration; and, further, to substantiate the assessment of the cruise checkout data. In both instances, assessments were based on analysis of individual engines.

CRUISE PERFORMANCE TRENDS

Cruise cockpit data recorded at stabilized conditions during the first checkout flight of each DC-10-10 aircraft included both engine and airplane flight parameters. Significant engine performance parameters recorded during the cruise setting consisted of fuel flow (WFM), exhaust gas temperature (EGT), fan speed (N1), and core speed (N2), while airplane conditions included altitude, Mach number and ambient temperature. In order to assess performance deterioration, it was necessary to compare these cruise measurements at altitude with measurements of uninstalled, sea level static performance data obtained during the engine production acceptance testing.

Prior efforts had indicated that a reasonable correlation of EGT measurements was possible between production acceptance test-cell levels and initial cruise readings. This correlation was derived by separately establishing the relationship of each (test cell and cruise EGT measurements) to a common reference temperature, namely the maximum EGT certified for the CF6-6D. Margins with respect to the maximum certified EGT could be determined, and the change in performance could be assessed by direct comparisons of test cell and cruise EGT margins. This correlation between test-cell and cruise temperatures were developed primarily because of the historic interest in EGT as an indication of engine health; experience indicates it produces acceptable results.

However, a correlation of fuel flow between test-cell and cruise measurements has been very difficult to develop, and presently no reasonable correlation is available. Experience has shown that cruise fuel flow levels have been useful primarily to trend changes in usage with time, but absolute levels of fuel flow have been less consistent than EGT measurements. Several conditions are known to contribute to the greater inconsistencies of fuel flow compared with those of EGT measurements. First, small differences in core exhaust nozzle area that exist between the individual core thrust reversers or the fixed nozzles can produce large changes in fuel flow but small changes in EGT. Similarly, changes in thrust as the engine deteriorates produce relatively large changes in fuel flow with smaller changes in EGT.

Based on these considerations, the procedure used to establish short-term fuel burn deterioration was to determine the change in EGT margin between test-cell and initial cruise measurements. The corresponding change in fuel flow was then calculated from the delta temperature, using the computer cycle deck, engine derivatives and component models. This fuel flow calculation procedure was substantiated with inbound test cell performance runs, where deterioration in both fuel flow and EGT can be more properly assessed.

Analysis of Initial Flight EGT Measurements

Cruise performance data recorded during initial DC-10-10 acceptance checkout flights were analyzed for ninety engines. These include all CF6-6D engines flown on initial DACo checkout flights between January, 1974 and February, 1978 (engine serial numbers 451406 to 451512). Apparent measurement errors were noted for eight engines; their data were not considered. Analysis of the cockpit data for the remaining eighty-two engines have been summarized in terms of equivalent margins relative to the CF6-6D certified maximum EGT, as follows:

Table 3-I. Summary of EGT Margins & Deterioration.

	Average (° C)	Std. Deviation (° C)
Production EGT Margin	45.3	8.8
Checkout Flight EGT Margin	31.2	8.9
Short-Term EGT Deterioration	14.1	7.4

Thus, the deterioration became evident as a loss in EGT margin. As will be shown from comparisons of shipped-to-inbound test cell performance, this loss in EGT margin was real and not the result of an installation effect.

The initial checkout EGT performance data for the eighty-two engines were also examined to identify any apparent trends. While the confidence level in the first-flight average deterioration was high, large engine-to-engine variations were observed. Statistical analysis indicated a tendency for the short-term deterioration of individual engines to vary from the average 14° C loss according to their production test cell EGT margin (EGTM). Although not a strong trend, engines with better as-shipped production margin tended to deteriorate more during the airplane checkout, as suggested in Figure 3-3. However, the significance of this observation was considered to be questionable based on the degree to which it reduced the data scatter. The standard error of estimate (SEE) associated with the data-fit was only slightly lower than the standard deviation (σ) associated with the mean of the data (6.8° C versus 7.4° C). Further analysis, as additional data becomes available, will be required to determine whether such a general trend does exist.

Analysis of Multiple DACo Flight Data

The DC-10 checkout procedure typically consists of three or four different flights, including an airline acceptance flight. The question arises whether additional short-term EGT margin losses are typically incurred during these later flights or, for that matter, during the remainder of the first flight after the cruise performance measurements have been obtained. To answer this

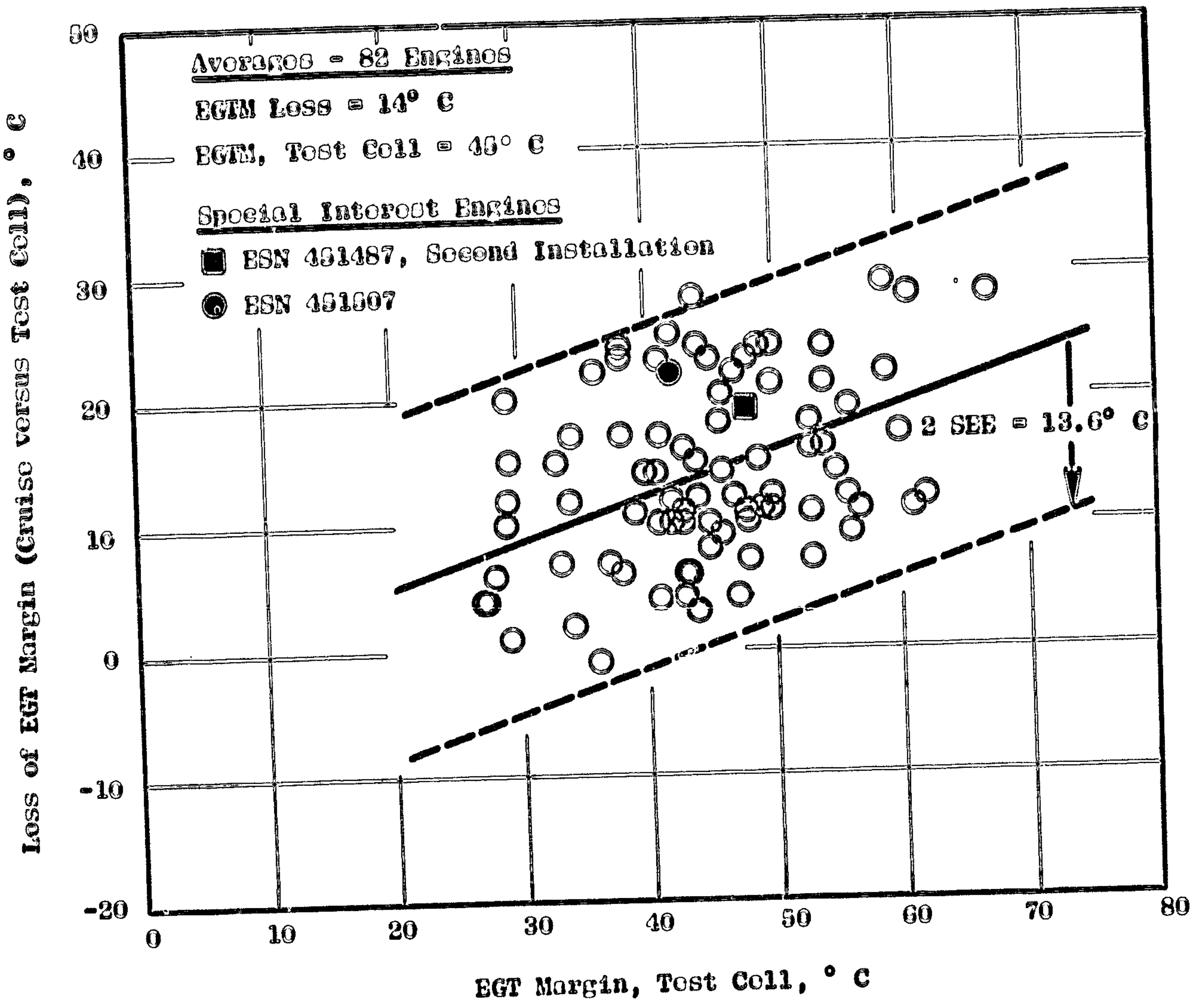


Figure 3-3. EGT Cruise Losses - First Checkout Flight.

question, the first flight cruise performance was compared with successive DACo flight data and with early revenue service cruise trends for a limited number of engines.

Multiple check-flight cruise data were available for ten of the eighty-two engines. The EGT losses for these engines during DACo flight tests and early revenue service are presented in Figure 3-4. The average loss of EGT margin for the seven engines for which cruise data from three flights were obtained at DACo were 15.7° C, 15.6° C, and 15.9° C, respectively - indicating that there was no additional loss during the remainder of the aircraft checkout flights. Likewise, no general trends of increasing EGT losses were evident from early revenue service cruise data for these ten engines.

Initial Revenue Service Data

In addition, airline trend data were available for forty-eight engines within about the first 300 hours of revenue service operation, and these EGT levels were compared with the performance levels during the initial DACo aircraft checkout flight. The average EGT increase was about 2° C which confirms the results presented in Figure 3-4. While there were the expected engine-to-engine variations about the average additional 2° C loss, engines from one airline recorded average additional early losses of 6° C which compared with less than a degree average change experienced by two other airlines. (These differences were not considered to be of major importance, and did not warrant additional investigations with the available information.) In general, there appears to be little additional short-term deterioration after the initial DACo checkout flight.

Initial Loss for Spare Engines

Cruise performance data were also analyzed for new spare engines delivered directly to the airlines, in order to assess whether differences exist in their short-term deterioration characteristics. Early cruise trend data were available for eleven new spare engines which entered revenue service having bypassed the DACo checkout. EGT deterioration for these spare engines was determined to be 9° C (σ = 6° C) after an average of 351 hours of operation. This deterioration was about one half of that recorded at approximately the same number of revenue service hours for the forty-eight engines which had undergone airplane checkout procedures. While these spare engines comprised a small size sample, their performance trends indicated that a significant amount of short-term losses observed at DACo might have resulted from non-standard, revenue service operation during the airplane checkout sequence. (This will be further discussed after the test cell results are presented.)

Assessment of Fuel Burn From Cruise Data

As previously noted, the measured loss in cruise EGT margin was used to predict the short-term fuel burn increase. Based on previous experience (confirmed by hardware inspection data presented in Section 3.2), the overall

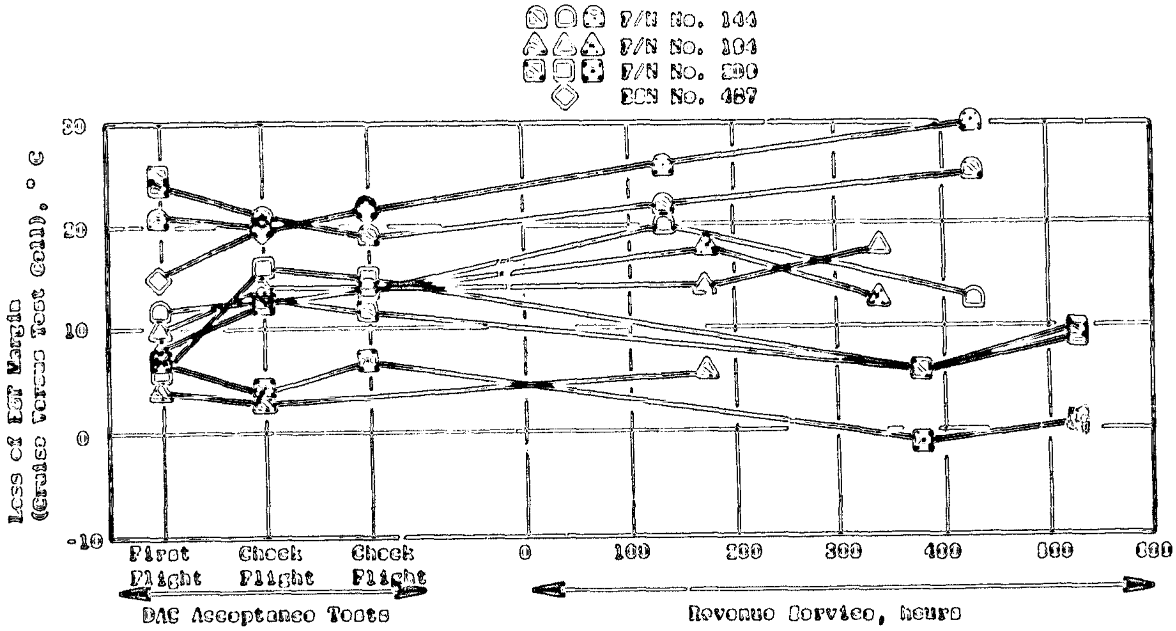


Figure 3-4. EGT Margin During DACo Flights/Early Revenue Service.

short-term loss in EGT margin can be assigned to the high pressure system (core module). Engine derivatives were available to equate given changes in EGT for the individual modules to unique fuel burn effects. The relationships between EGT and fuel burn changes are approximately the same for each of the core modules. Thus, using this derivative, a short-term fuel burn increase was calculated which was equivalent to the measured EGT increase (whether due to deterioration of any individual module or combination). Using this method, the average loss of 14° C in cruise EGT margin for the eighty-two engines sample was equivalent to a cruise fuel burn increase of 0.9 percent.

Thus, a representation of overall short-term performance deterioration was derived based on the average measured loss of cruise EGT margin which was attributed to core deterioration. Utilizing a mathematical model of the thermodynamic cycle for such a deteriorated engine, the equivalent sea level static deterioration was estimated in terms of overall performance. This assessment of short-term deterioration is summarized in Table 3-II.

Table 3-II. Assessment of Average Overall Short-Term Deterioration Based on Cruise EGT Measurements.

Overall Performance (Delta From New)	Sea Level Static	Installed Cruise
Δ SFC at FN (%)	1.3	0.9
Δ EGT at N1 (° C)	18	14
Δ WFM at N1 (%)	1.5	1.3

This assessment remained to be verified by test cell measurements of short-term deterioration as will be discussed next.

INBOUND TEST CELL RESULTS

Inbound test-cell performance calibrations to substantiate short-term deterioration were available for two engines. The first, ESN 451487, had been removed to be investigated for a vibration complaint and was tested at Ontario, California (ASO/O) during 1975. The second, ESN 451507, was removed specifically for this investigation and was also tested at the General Electric facilities at Ontario, California (ASO/O).

ESN 451487 Inbound Test

Prior to its inbound test-cell calibration, ESN 451487 was installed on two different DC-10-10 airplanes during their respective initial checkout flights.

This engine was initially flown on the first flight of fuselage number (F/N) 209 during which it lost 14° C in EGT margin, matching the average cruise loss for the eighty-two CF6-6D engines as presented in Figure 3-3. The engine was removed after this first flight and installed on F/N 210 for the first checkout flight of that aircraft. During this flight (the second flight of the engine), an additional loss of 5° C cruise EGT margin was noted, making the total 19° C since the production acceptance test. The EGT deterioration derived from this second flight is shown in Figure 3-3.

While the engine was removed after the second flight to investigate a vibration complaint, a performance calibration test was conducted. The short-term deterioration assessment based on a comparison between the inbound test cell results and factory performance levels indicated a sea level static sfc increase of 2.2 percent at constant thrust as well as 21° C EGT and 1.8 percent fuel flow increases at constant fan speed. These data thus verified that the short-term losses incurred prior to introduction to revenue service were both real and non-reversible.

These test results for ESN 451487 were compared with assessments of short-term sea level deterioration estimated from the average cruise levels obtained from the eighty-two engine sample (previously presented in Table 3-II). Further, the test cell deterioration for ESN 451587 was projected to cruise conditions and then compared with the cruise deterioration assessments for the eighty-two engine sample. As shown in Table 3-III, both the test cell and projected cruise performance levels for ESN 451487 were higher than the assessments for the average engine.

Table 3-III. Short-Term Performance Deterioration Assessment Inbound Test of ESN 451487

Overall Performance (Delta From New)	SLS Test Cell		Installed Cruise		
	ESN 451487 Measured	Fleet Average Estimated	ESN 451487 Measured	ESN 451487 Projected	Fleet Average Measured*
Δ SFC @ Fn (%)	2.2	1.3	---	1.5	0.9
Δ EGT @ N1 (° C)	21	18	19	17	14
Δ WFM @ N1 (%)	1.8	1.5	---	1.6	1.3

*Estimated based on measured EGT level

However, the measured cruise EGT loss determined from the checkout flight for this engine substantiated that this engine deteriorated more than the average at the time of its second flight. The cruise EGT loss analytically derived for ESN 451487 from the measured test cell data was within 2° C of the EGT deterioration measured during the cruise checkout. This comparison, also shown in Table 3-III, indicated that the calculation and comparison procedure used to equate cruise and test cell EGT levels were reasonable.

ESN 451507 Inbound Test

As noted previously, the activities to quantify short-term performance deterioration included special testing of ESN 451507. This engine had completed the entire DC-10-10 aircraft/engine checkout at DACo before being removed for the test-cell performance calibration. Performance testing of this engine included the standard factory production acceptance test calibration as well as the special inbound test at the Ontario, California (ASO/O) facilities. The inbound performance calibration test at ASO/O following the DACo flight testing consisted of three separate runs: two calibrations with the engine in the as-received condition, and the third following cleaning of the Stage 1 fan blades. (No measurable difference was observed.) The instrumentation was identical to that used at Evendale.

Unfortunately, an undetected thrust measurement error during the inbound calibration made changes in thrust levels and, thus, the resultant sfc values, unreliable. However, test-cell measured changes in fuel flow along with EGT at constant fan speed were available to assess deterioration. The measured sea level deterioration based on the comparison of the inbound test cell data with the production acceptance performance was 15° C EGT and 1.6 percent fuel flow at constant fan speed. Analytically projected to cruise conditions, the losses were 12° C EGT and 1.4 percent fuel flow. As shown in Table 3-IV, the sea level test cell data as well as the projected cruise losses for this engine matched the average deterioration derived for the fleet.

Table 3-IV. Short-Term Performance Deterioration Assessment Inbound Test of ESN 451507.

Overall Performance (Delta From New)	SLS Test Cell		Installed Cruise			
	ESN 451507 Measured	Fleet Average Estimated	ESN 451507 Airplane Checkout	ESN 451507 Initial Rev. Serv	ESN 451507 Projected	Fleet Average Measured*
Δ SFC @ Fn (%)	---	1.3	---	---	---	0.9
Δ EGT @ N1 (° C)	15	18	22	17	12	14
Δ WFM @ N1 (%)	1.6	1.5	---	---	1.4	1.3

*Estimated based on measured EGT level

These projected cruise EGT and WFM increases thus support the sfc deterioration estimated from the airplane acceptance cruise performance. While the cruise EGT loss measured for ESN 451507 during the initial airplane checkout flight (22° C) appeared high (Table 3-IV), measurements made during initial revenue service only indicated a loss of 17° C - magnitude which was more in line with the expected loss.

These inbound test results again demonstrated that short-term performance deterioration was both real and nonreversible. Further, the similarity between the measured performance loss for ESN 451507 and the estimated fleet average deterioration indicated that the observed short-term deterioration of this particular engine should be representative of typical CF6-6D engines after airplane/engine checkout procedures; that is, prior to entry into revenue service. As such, the observed hardware conditions of ESN 451507 should likewise be representative and can be used to quantify short-term parts deterioration of the CF6-6D engine model.

OBSERVATIONS FROM PERFORMANCE ANALYSIS

Analysis of cruise performance data indicated that significant losses do occur for the CF6-6D model engine during the first checkout flight at DACo, but the performance generally remains relatively stable through at least the first 300 hours of revenue service operation. Further, test cell performance results demonstrated that this short-term deterioration is both real and nonreversible, not just an installation effect.

No firm evidence was available to determine the specific engine operation which results in this short-term deterioration by the time cruise performance measurements are taken during the first flight. These measurements are taken under stabilized cruise conditions after the airplane attains high altitude flight for the first time. Prior to recording the first flight cruise performance, the engines have undergone an extensive series of ground checks, their first takeoff rotation, operation at altitude and in-flight system tests. It would normally be expected that some deterioration of engine performance would occur during the initial on-wing operation of the engine; however, neither factory tests nor airline experience (with the initial operation of rebuilt and new spare engines) would suggest as much short-term deterioration as experienced during airplane acceptance testing.

It was inferred during the discussion of the checkout flight that the short-term deterioration experienced during the airplane checkout resulted from some engine operation which was not typical of revenue service. One such checkout sequence was identified which is not typically encountered during revenue service operation and which could contribute significantly to the short-term deterioration. This sequence was the acceleration checks from flight idle to maximum climb power, during which the potential exists for a "hot rotor reburst" to occur. This was considered very significant since it is known that a "hot rotor reburst" - that is, rapid acceleration of the engine from low power with the engine still hot from previous operation at high power - can result in abnormal thermal closure of engine clearances, notably between the high pressure turbine blade tip and shroud. Another possibility is that a "hot rotor reburst" could inadvertently occur during the ground system checks prior to the first flight, for example, while the engine throttle linkages are being trimmed. In either instance, turbine clearances would be increased if a blade tip rub would occur, resulting in a loss of performance. Neither potential occurrence would be typical of revenue service, which is in agreement with the spare engine data that indicated that short-term deterioration resulted from nonstandard operation of the engines.

If HP (High Pressure) turbine blade tip rubs have occurred, inspection of the turbine hardware would show that clearances were increased. As will be shown, in Section 3.2, the hardware from ESN 451507 did indicate significant tip rubs had occurred, suggesting the possibility of a "hot rotor reburst" occurrence.

No matter what specific causes contribute to the total deterioration, the magnitude of the short-term losses has been determined. The average increase in cruise fuel burn prior to an engine's delivery for revenue service operation was established as 0.9 percent, based on the analysis of the eighty-two engine sample. Also, the cruise and inbound test-cell results were found to be consistent. Further, it was determined that the short-term deterioration for ESN 451507 was representative of that established for the CF6-6D model engine, therefore, the hardware inspection results for that engine will be considered to be rpresentative of the CF6-6D fleet.

3.2 HARDWARE INSPECTION RESULTS

The second major part of the short-term performance deterioration studies was to obtain and analyze hardware inspection data. While cruise performance data were used to establish the magnitude of the loss, hardware inspection data were required to isolate the sources or causes of the performance deterioration.

After its inbound performance test, ESN 451507 was subjected to an analytical disassembly to obtain hardware inspection data required to isolate the causes or sources of short-term performance deterioration. It was previously shown that cruise performance deterioration for ESN 451507 was typical of the fleet; therefore, these hardware data used to assign short-term losses to the various deteroration mechanisms should likewise be a representative sample of the CF6-6D engine model. A limited quantity of hardware inspection data, available from another source, was used to substantiate the major deterioration mechanism isolated from the ESN 451507 results.

The testing and inspection of ESN 451507 was conducted at the General Electric facility located in Ontario, California. All engine modules were inspected, and attention was directed toward the three major sources of deterioration: clearances, airfoil quality and leakages. These inspection results, in conjunction with Influence Coefficients, were used to isolate the deterioration mechanisms and assign a fuel burn deterioration to each source. Influence

Coefficients are empirically or analytically derived factors which equate a change in a hardware condition to a change in performance. For example, a 30 mil increase in Stage 1 HPT blade-tip-to-shroud clearance is equivalent to a 0.8 percent increase in cruise fuel consumption. The detailed inspection results, including methodology, location and analyses are contained in the "CF6-6D Engine Short-Term Performance Deterioration" Report (Reference 1). These details will not be repeated in this report; only a short discussion to define the extent of inspections with salient results for report continuity will be presented.

The CF6-6D engine is of modular construction, such that the major components of the engine can be independently repaired and modified with complete interchangeability with other modules. Hardware inspection data are generally summarized in the same manner, i.e., by individual sections of the engine. Since the CF6-6D is a dual-spool, turbofan model engine, it is logical to isolate the compressor and turbine section for each spool - that is, the low and high pressure (core) systems. Accordingly, the hardware data have been summarized into four major categories: fan, high pressure compressor, high pressure turbine, and low pressure turbine. Figure 3-5 is a cross section of the engine showing these major divisions.

FAN SECTION

The fan section consists of two stages: one full fan stage and a second booster or quarter stage to supercharge the gas flow to the high pressure compressor. Fixed stator vanes are incorporated aft of each stage, but inlet guide vanes were excluded because of noise considerations.

Hardware inspections included a visual inspection of the entire module as well as measurement of Stage 1 fan blade-to-shroud clearance. The Stage 1 fan blade airfoils were inspected for leading edge shape (profile) and for airfoil surface finish changes.

There was no measured short-term loss associated with the fan section. A back-to-back test cell run was completed which indicated no change in performance after cleaning the fan blades. Six fan blades were removed, and leading edge inspection by comparison to blueprint specifications indicated no change in contour.

HIGH PRESSURE COMPRESSOR SECTION

The high pressure compressor is a 16-stage, high-pressure-ratio (approximately 16 to 1), axial flow design. Variable inlet guide vanes are included, and the first six stages of stator vanes are variable. The compressor section provides bleed air at various commpression stages for hot section cooling and purge, along with airframe pressurizing and antiicing air.

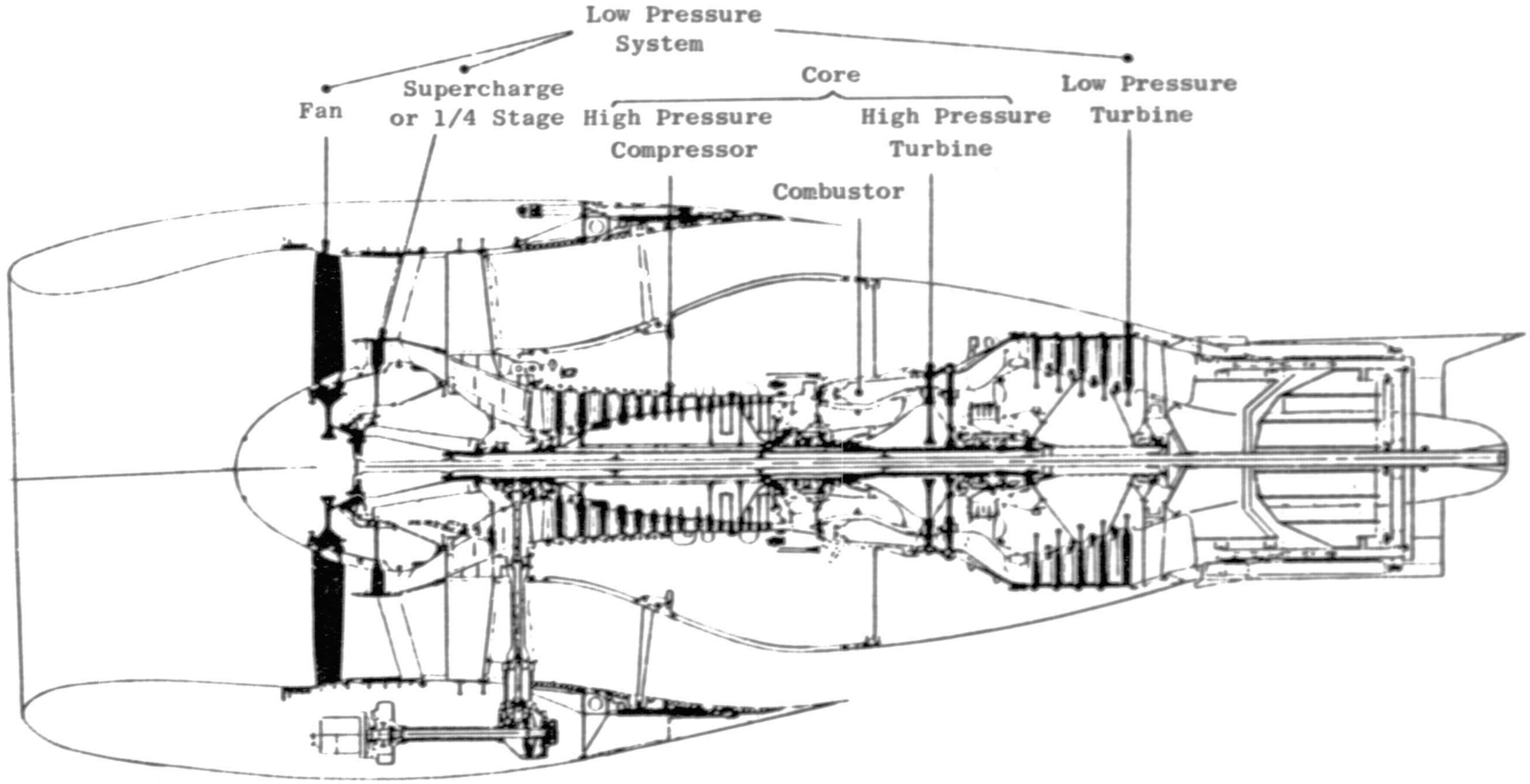


Figure 3-5. General Electric CF6-6D Engine Cross Section.

The high pressure compressor rotor and stator subassemblies were removed from the engine for inspection. Ten blades per stage (Stages 3 through 16) and ten vanes per stage (Stage 7 through OGV) were removed to obtain representative surface finish data. The flowpath coating was inspected for spalling and evidence of rubs to ascertain potential clearance changes. The radial CDP rotating-to-stationary seal clearance was determined to isolate any potential parasities (internal leakages).

Rubs were noted on the stator casing rub coat from compressor blade tips, particularly in the upper half near the 12 o'clock position. These rubs were noted in most stages, ranging from a "kiss" (no depth) up to 0.008 inch. Minor spalling of the casing rub coat was also noted. The performance associated with the estimated clearance change was 0.05 percent in compressor efficiency - equivalent to 0.03 percent in cruise fuel consumption. All other measured conditions were within new engine tolerances.

HIGH PRESSURE TURBINE SECTION

The high pressure turbine consists of two stages of rotor and stator airfoils. The two rotor stages incorporate air-cooled, non-shrouded blades and passive cooling and purge features for tip clearance control. Fixed stator vanes are provided upstream of each rotor stage; both vane rows are cooled by convection, and the Stage 1 vanes also incorporate film cooling.

Detailed measurments were made to determine the change in blade tip-to-shroud clearance from their original condition. Selected Stage 1 and 2 blades and vanes were subjected to surface finish measurements, and the static parts (shrouds, supports, and vanes) were inspected for distortion that could result in an internal leakage (parasitic).

Degradation of the high pressure turbine is the dominant factor in short-term deterioration. Over 90 percent of the assessed cruise sfc loss for ESN 451507 was attributed to this section of the engine. Turbine blade rubs had occurred on both stages, resulting in a Stage 1 and 2 blade tip clearance increase of 0.021 inch and 0.011 inch, respectively. This was almost all of the turbine degradation and is equivalent to 0.72 percent in increased cruise fuel consumption. To further understand short-term performance deterioration, notches were incorporated into the tips of seven production engines to assess blade length change with time. Borescope inspection (which does not require engine disassembly), conducted on these engines after completion of aircraft acceptance testing, verified the results noted for ESN 451507 and substantiated that blade tip rubs are the dominant mode of short-term deterioration. The details of this tip notch program are presented in Reference 1.

Surface finish measurements of all airfoils indicated a slight roughening of the Stage 1 nozzle vanes resulting in a 0.02 percent increase in cruise sfc. Measurement of turbine seals and Stage 1 vanes for distortion indicated no parasitic loss, and the measured Stage 1 nozzle vane throat area (A4) was within nominal tolerances.

LOW PRESSURE TURBINE SECTION

The low pressure turbine consists of five stages of rotor and stator airfoils. All rotor stages have low tip speed, high-aspect-ratio, shrouded blades. Each rotor stage is preceded with a fixed stator vane. The blade and vane airfoils are not cooled, but cooling is provided to the stator casing for clearance control purposes.

Inspections to assess deterioration mechanisms included determination of blade tip-to-shroud and interstage seal clearances. In addition, representative surface finish data were obtained for each airfoil stage by measurement of six randomly selected parts.

Two areas of minor deterioration were assessed in the low pressure turbine section; surface finish change for the Stage 1 vane and interstage seal radial clearance. The Stage 1 vane surface finish was 80μ in. (AA) compared with new engine requirement of 63μ in. The rotating interstage seal teeth were found to be from 3 to 10 mils smaller than new engine minimum, which calculates to be a 0.04 percent increase in cruise sfc. The effect of vane surface finish change was negligible.

SUMMARY OF HARDWARE INSPECTION DATA

The short-term losses assessed from hardware inspection data for the various engine sections are summarized in Table 3-V.

Table 3-V. Short Term Hardware Inspection Results.

Section	Δ Efficiency (%)		Δ Cruise sfc (%)
Fan		0.00	0.00
HP Compressor		0.05	0.03
Airfoil Surface Finish	0.00		
Stator Land Rubs	0.05		
HP Turbine		0.95	0.74
Stage 1 Nozzle Surface Finish	0.03		
Blade Surface Finish	0.00		
Stage 1 Blade Tip Clearance (+ 21 mils)	0.70		
Stage 2 Blade Tip Clearance (+ 11 mils)	0.22		
Parasitics		0.00	0.00
All Seals Nominal	0.00		
LP Turbine		0.07	0.04
I/S Seal Clearance	0.07		
Total			0.81

As shown, losses in the high pressure turbine are the major source of short-term performance deterioration and blade tip-to-shroud rubs are the dominant factor. The calculation of fuel consumption effects to the second decimal point is not intended to convey that this is the level of accuracy. Rather, the loss mechanisms which were isolated for the HP compressor and LP turbine sections have a small influence on fuel consumption and the measured deltas were also very small. Realistically, the only condition isolated, which is a significant contributor to short-term deterioration, is Stage 1 and 2 high pressure turbine blade tip rubs.

3.3 DISCUSSION OF SHORT-TERM RESULTS

It can be concluded from these data that ESN 451507 is typical of the average short-term deterioration for the CF6-6D model engine, since measured cruise performance loss and the dominant deterioration source agree well with similar data from other CF6-6D engines. However, a comparison of the short-term loss assessed from hardware inspection data from ESN 451507 with the total measured loss based on performance data is also required before it can be substantiated that the hardware results are reasonable.

Data presented in the Short Term Deterioration Report (Reference 1) indicated the total fuel consumption increase derived from the two independent methods for ESN 451507 was as follows:

	Δ Cruise Fuel Consumption (%)
Hardware Inspection	+0.8
Cruise Performance	+0.9

As noted, these independent studies produced results within 0.1 percent of each other, and the hardware data isolated over 88 percent of the loss expected from cruise performance data. This comparison is considered excellent, and substantiates that the hardware assessments are a realistic representation of short-term deterioration.

Therefore, based on (1) these test results which indicated that ESN 451507 performance and hardware results were typical of those expected for other CF6-6D model engines, and (2) the excellent agreement between cruise performance data for ESN 451507 and the short-term deterioration independently assessed from hardware inspection, it is concluded that the short-term deterioration for the CF6-6D model engine is 0.9 percent in cruise fuel burn and that the major source of this loss is high pressure turbine Stage 1 and 2 blade tip-to-shroud rubs.

3.4 RECOMMENDED ACTION

Three separate courses of action have been initiated to eliminate or alleviate these short-term losses. It was noted that each engine is decelerated from high power to flight idle and then subjected to a rapid accelertation during aircraft climb prior to recording stabilized performance data during the aircraft acceptance flights (see Section 3.1). It is known that this type of thermal transient (termed "hot rotor reburst") can cause HP turbine blade tip rubs due to different thermal growth rates for the rotating and stationary structures. The aircraft acceptance flight test procedure is being reviewed by DACo/GE in an effort to modify this procedure which is not considered representative of revenue service operation.

The companion Performance Improvement program sponsored by NASA Lewis is developing two generic items for HP turbines. Both of these - the Roundness Control program, which is developing improved and more efficiently cooled static structures, and the HPT Active Clearance Control, which will meter cooling air based on thermal and operational considerations rather than by fixed orifices - can help reduce or eliminate these short-term losses.

A third approach being developed by General Electric is to utilize an abrasive coating on the high pressure turbine blade tips. This coating is to provide the mechanism to "machine" the shroud during adverse thermal conditions, thus producing local removal of shroud material rather than shortening of all the blades. This approach eliminates the performance effect from the rubs since studies have indicated that the rubs are very local, and the total shroud material removal and resultant clearance increase will be minimal.

In summary, these studies have effectively isolated the short-term loss of 0.9 percent in cruise fuel burn to increased high pressure turbine blade-to-shroud clearances due to rubs, and have identified the probable cause for the rubs. As a result of the findings, work has begun toward the development of modifications that would eliminate or reduce these losses.

4.0 LONG-TERM DETERIORATION

Following aircraft acceptance testing by the aircraft manufacturer (DAC only for the CF6-6D model engine), the aircraft is delivered to the airlines for revenue service utilization. Losses which occur during revenue service operation are broadly classified as long-term deterioration.

DEFINITION OF LONG-TERM DETERIORATION

The long-term deterioration studies were aimed at dividing losses under this broad category into three separate but related classifications. These classifications are termed initial-installation, multiple-build, and unrestored performance. Figure 4-1 shows a typical life cycle in terms of fuel consumption delta versus time.

An explanation of this schematic follows:

1. Testing of production new engines in the manufacturer's facility establishes the average production new baseline.

2. Losses experienced during revenue service (beyond short-term losses incurred during aircraft acceptance), and prior to removal for first repair are called initial-installation losses.

3. The first removal of an engine for repairs occurs after completing an unspecified number of hours based on exceeding an on-condition limit (as opposed to fixed time). After serviceable modules are reassembled, the engine is performance calibrated; the delta between this level and the production new baseline establishes the unrestored performance. The word "serviceable" is used by the airlines to denote a repaired engine ready for service.

4. The on-wing deterioration that occurs during additional revenue service, after reinstallation, is termed multiple-build loss.

5. The cycle of engine removal, repair, and reinstallation continues until the engine is retired from service. The multiple-build and unrestored performance designations are representative for the remainder of the engine's life cycle.

OBJECTIVES AND APPROACH

The major objectives of the long-term studies were to define the extent and magnitude of deterioration, establish statistical trends, isolate and quantify the sources and causes of deterioration, as well as recommend areas where performance improvement/retention items can be applied for current and future engines.

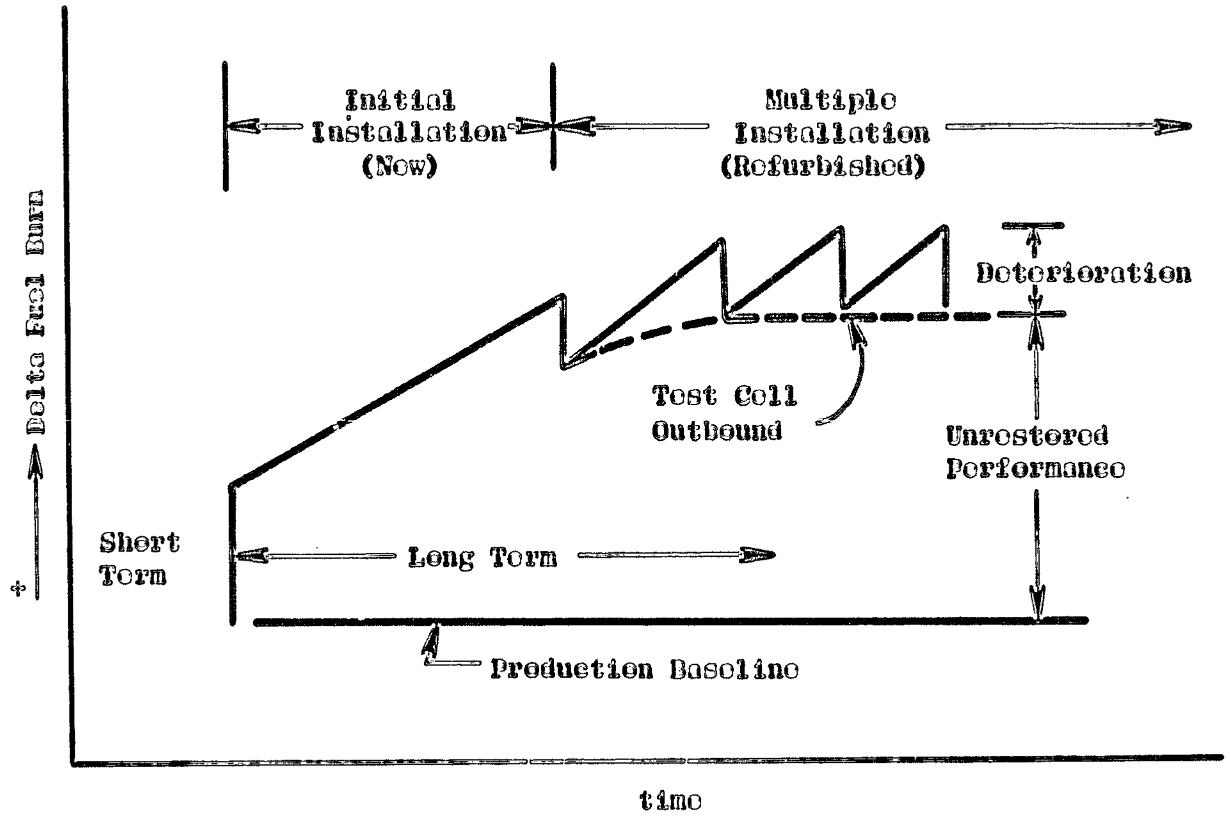


Figure 4-1. Long-Term Deterioration Schematic.

The basic approach used for long-term studies was to gather sufficient performance and hardware data to establish the magnitude and trends of performance deterioration for each major portion of the life cycle. Performance data used to analyze long-term deterioration were obtained from test cell recordings at the General Electric and airline facilities and from cruise cockpit recordings obtained during revenue service. Hardware inspection data were obtained from historical General Electric and airline records and were supplemented by a special program with United Airlines whereby current hardware conditions were documented. Analytical teardown analyses were conducted on engines and modules that had accrued various operating times to provide a representative sample. In addition, special back-to-back engine tests were conducted involving selective refurbishment activities to isolate specific deterioration mechanisms.

The performance data were used to establish the magnitude of the overall deterioration. The hardware inspection data, in conjunction with previously derived influence coefficients, were used to isolate the deterioration mechanisms and to assign a magnitude of loss to each mechanism. Comparisons of the overall loss assessed independently from hardware and performance data were used to determine the validity of the results and to establish deterioration models which would assign and quantify long-term deterioration losses.

REPORT FORMAT

The presentation of the long-term deterioration is in a format similar to that used to present the short-term results. First, cruise and test cell performance results are discussed to describe the characteristic rate and magnitude of long-term deterioration. These data presentations have been arranged to separately discuss each major portion of the life cycle: initial-installation, multiple-build and unrestored performance. Hardware inspection results used to document the sources and causes of deterioration are then presented. The hardware data are presented for each of the four major sections of the engine (fan, high pressure compressor, high pressure turbine, and low pressure turbine). Each section includes a deterioration model documenting the magnitude and rate for each observed source.

A discussion of the salient performance and hardware inspection results are then presented. The results from these two independent assessment techniques are compared and summarized. Together they are used to quantify the sources of long-term deterioration.

4.1 PERFORMANCE DETERIORATION RESULTS

Two general types of performance data were utilized for the study of CF6-6D long-term deterioration. These data types were similar to those utilized during the study of short-term deterioration. First, cockpit measurements of cruise performance were obtained from routine airline trend records for individual engines in revenue service. These cruise data were available, in various formats, for four of the five domestic airlines that operate CF6-6D powered DC-10 airplanes. Secondly, test cell performance calibration data were obtained from a limited number of inbound tests of deteriorated engines prior to refurbishment and from a large number of routine outbound tests of serviceable engines returning from the airline repair shops to revenue service. The performance data (both types) were recorded between 1976 and 1978, during a period when it is known that the CF6-6D engines incorporated current production hardware (either factory-installed or upgraded in the field). As expected, more performance data were available for investigations of long-term deterioration than for short-term since almost all of an engine's lifespan is spent in the long-term realm.

The large quantity of revenue service cockpit recordings was used to statistically derive the magnitude and trends of cruise performance deterioration. The airlines currently use such cruise data to derive monthly trends for the average performance of all engines in their fleets - fleets whose engines range from the recently installed to units that have logged thousands of hours. While this procedure produces a statistical fuel burn trend for the fleet (information of major economic concern), it provides very little insight into the deterioration characteristics of the individual engine. Therefore, for this study, the revenue service cruise data were analyzed by tracking the performance level from installation to removal for specific individual engines on a regular basis (monthly, or as regularly as feasible). This method not only permitted assessment of engine performance deterioration characteristics but also produced the necessary comparative data required to identify potential effects from operational variables. Each engine's performance was trended as a delta since installation where the base point for each installation was the earliest cruise data available. This eliminated engine-to-engine variations of initial performance levels. Having normalized the starting performance levels, it was thus possible to group similar individual trends to derive a statistical average to evaluate operational variables such as airline-to-airline, tail-to-wing, and 4000-hour engines, to name a few.

Test cell performance data and, in particular, calibration runs of incoming deteriorated engines were used to correlate the observed cruise losses at the time of removal with sea level deterioration. Since thrust cannot be measured during cruise, this correlation permitted assessment of expected cruise sfc loss (actual fuel burn) based on cruise fuel flow trends. The cell calibration data from inbound deteriorated engines were also used during the hardware studies to verify performance assessments based on hardware inspection data.

Test results for outbound serviceable engines were used to establish an average performance level of multiple-build engines as they return to revenue service. This produced a new base from which multiple-build deterioration occurred. Equally as important, the recalibrated outbound performance levels of individual serviceable engines were compared to an average production new baseline to establish the average unrestored performance loss of outgoing serviceable engines.

A summary of the performance results from this study of long-term deterioration follows. Separate discussions are provided for each of the major long-term deterioration classifications: initial-installation, multiple-build, and unrestored performance (outbound-serviceable engines). Cruise performance trends developed for the initial-installation engine are presented, as are test cell calibration results which are used to correlate e' .se results with expected sea level static levels. The multiple-build engine section includes representative statistical performance trends for similar time-since-installation engines as well as comparisons of several operational variables, such as airline-to-airline and tail-to-wing. The unrestored performance subsection contains the results from the analysis of test cell performance calibrations for outbound-serviceable engines obtained after shop repair and prior to return for revenue service.

INITIAL REVENUE SERVICE INSTALLATION

The performance of CF6-6D engines during their initial revenue service installation was investigated as an important part of the study of long-term deterioration. This first installation was the only installation in which the modules and hardware in the engine were all new. As such, performance results for initial-installation engines provided a reference against which results could be compared for multiple-build engines (currently over 90 percent of CF6-6D engines).

The investigation of initial installation deterioration was limited to a specific group of engines, including only those produced since ESN 451406. As noted in Section 3.1 of this report, these engines incorporated a production hardware configuration which is typical for the current airline fleets. The engine selection was further restricted to those having undergone the aircraft manufacturer's flight checkout procedures. Thus, the entry into revenue service was similar for each of the engines considered; i.e., each had experienced short-term deterioration.

By the end of 1978, 75 of these engines had completed their first installation. The initial installations of these engines (ESN 451406 to 451496, excluding 15 spare engines delivered directly to the airlines) spanned periods of time between early 1974 to 1977. Airline cruise trend data were available for about 85 percent of these installations, although it was difficult to obtain trend samples at the desired frequency for all engines. Also, inbound performance calibrations were conducted for ten initial-installation engines from 1976 to 1977. (These consisted of almost all of the inbound performance tests prior to refurbishment that were available for CF6-6D engines.)

The length of installed time for these first installation engines varied considerably - from 400 hours to 5800 hours, with an average installed time of 3640 hours for the 75 engines. However, those few engines which were removed early from the airplane (for instance, before 1500 hours) were not considered to have undergone "typical" deterioration; they were removed early for mechanical problems with some specific part or for FOD problems. Accordingly, eight such short-time engine installations were excluded from consideration. (Negligible amounts of cruise data were available to establish trends for these particular engines anyway since they were installed for such short periods.) Without these "nontypical" installations, the average installation period increased to 3970 hours and 1674 cycles; thus, 4000 hours was used as a representative age for initial-installation engine, and similarly 2.4 hours was used as a typical flight length. The majority (90 percent) of these initial installation engines were removed between 2600 hours and 5800 hours. Analyses of the cruise performance for this selection of engines revealed a curve shape for the individual engine different from that currently obtained for the fleet trend; that is, different from the average of all engines trended monthly. This is discussed later in this report.

Initial-Installation Cruise Performance Trends

Cruise performance trend data were obtained and examined for 60 first-installation engines operated by three domestic airlines. Airline performance trends were analyzed to quantify the additional deterioration (subsequent to short-term losses at DACo) experienced during the initial revenue service installation. These long-term cruise losses were derived from routine cockpit readings of engine performance relative to the earliest available measured cruise performance on an individual engine basis.

Over 500 initial-installation, airline cruise data points were collected for this study (largely from in-house files). These were fuel flow (WFM) and exhaust gas temperature (EGT) cockpit measurements recorded during stabilized cruise operation. The measurements are bookkept both by the airlines and in-house as delta's from a cruise performance baseline at constant fan speed (N1). (The baseline consisted of reference performance levels for various fan speeds and airplane conditions. These reference levels are contained in the DC-10-10 "Flight Planning and Cruise Control Manual.") Trending the cockpit measurements in this fashion eliminated the variations in performance that were caused by airplane conditions (altitude, Mach number, etc.). A sample of WFM data trended at N1 is shown in Figure 4-2. These individual data points were obtained by tracking (or sampling) 60 individual engine trends at regular intervals through the course of their first installation. Each point shown represents the average WFM level from between 4 and 20 airplane flights, depending on the type of airline records available, in order to reduce the data scatter associated with cruise measurement. To evaluate deterioration characteristics, the data points from the individual trends were normalized to show changes in performance relative to each initial data point.

Analysis of the 60 available engine trends led to further refinement of the data base prior to establishing a statistical fit representative of initial installations performance. As noted earlier, the initial removal times were concentrated between 2600 hours and 5800 hours. Five available installation/removals were outside of this range and were excluded since very few cruise data points had been obtained for these particular installations. Further, examination of these cruise performance trends indicated that engine data for

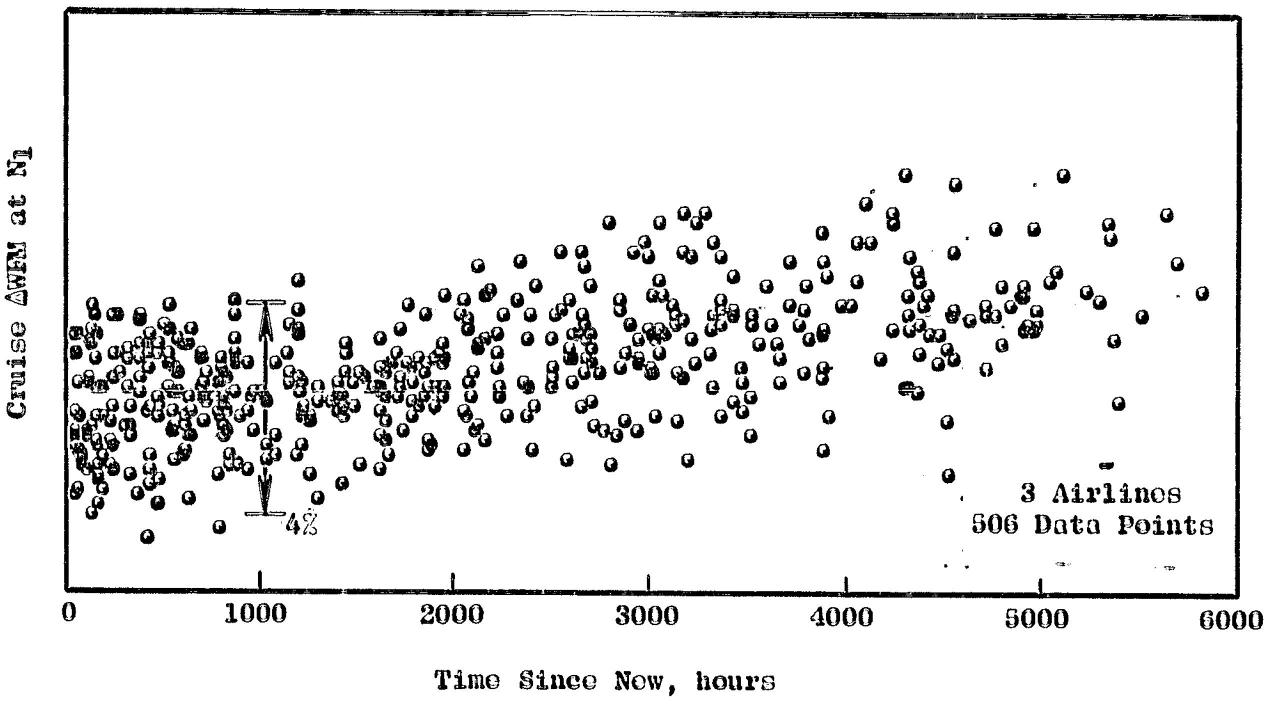


Figure 4-2. CF6-6D Cruise Performance Data.

15 engines were only available for the beginning period of their installation, falling 1000 or more hours short of the removal time. Trends for these installations were also disregarded. The remaining 40 cruise performance individual installation trends were considered to be both adequate and representative of long-term initial installations.

Statistical cruise performance trends for these 2600-to-5800-hour installations are presented in Figures 4-3 and 4-4. Average changes of WFM and EGT (both at N1) for this specific group of engines are shown as functions of time since new (TSN) and cycles since new (CSN), respectively. The 410 data points used to derive these curves were from the remaining 40 revenue service trends of initial installation engines at three domestic airlines (average removal time of 4000 hours).

Statistical fits of the data points were derived using least-square polynomial curve fit techniques for a third degree polynominal of the form:

$$Y = B_0 + B_1X + B_2X^2 + B_3X^3$$

The cruise data had been obtained for individual engine installations and had been normalized relative to the first data point for each installation. Stepwise regression techniques were used to identify "best fit" curves for the normalized data from initial installations. The curves were derived as functions of TSN as:

$$\Delta WFM = 0.05 + 9.658 \times 10^{-8} (TSN)^2$$

$$\Delta EGT = -0.3 + 1.998 \times 10^{-6} (TSN)^2 - 2.135 \times 10^{-10} (TSN)^3$$

The curve fits derived as functions of CSN for these performance data were polynomials with a constant and second-order term. It should be noted that several different polynomial fits of the initial installation data could have been used to describe the average performance trends with little difference in curve shape or accuracy within the 0-5000 hour or 0-2000 cycle ranges. Cruise data from the initial installation engines are presented in Appendix B.

There are several measures of the quality for the resulting statistical fit. The standard errors of estimate (SEE), which indicate the deviation about a fitted curve, are shown. (This parameter is a measure of the data spread and is similar to a standard deviation but is the root-mean-square deviation about the curve fit instead of about the mean of the data). While there is a wide spread of the data, the confidence levels associated with the average or composite trends are over 99 percent. Further, a numerical measure of the proportion of variation accounted for by the regression is provided by the coefficient of determination (R^2). (In other words, this is a measure of how well the statistical fit matches the data, where a coefficient of "1" indicates a perfect fit and a coefficient of "0" indicates a lack of fit.) R^2 equaled 0.34 and 0.27 for the ΔWFM fits and 0.38 and 0.45 for the ΔEGT curves for the TSN and CSN functions respectively.

- Number of Installations - 40
- Range of Removal Times - 2600 to 5800 hours
- Average Removal Time - 4000 hours

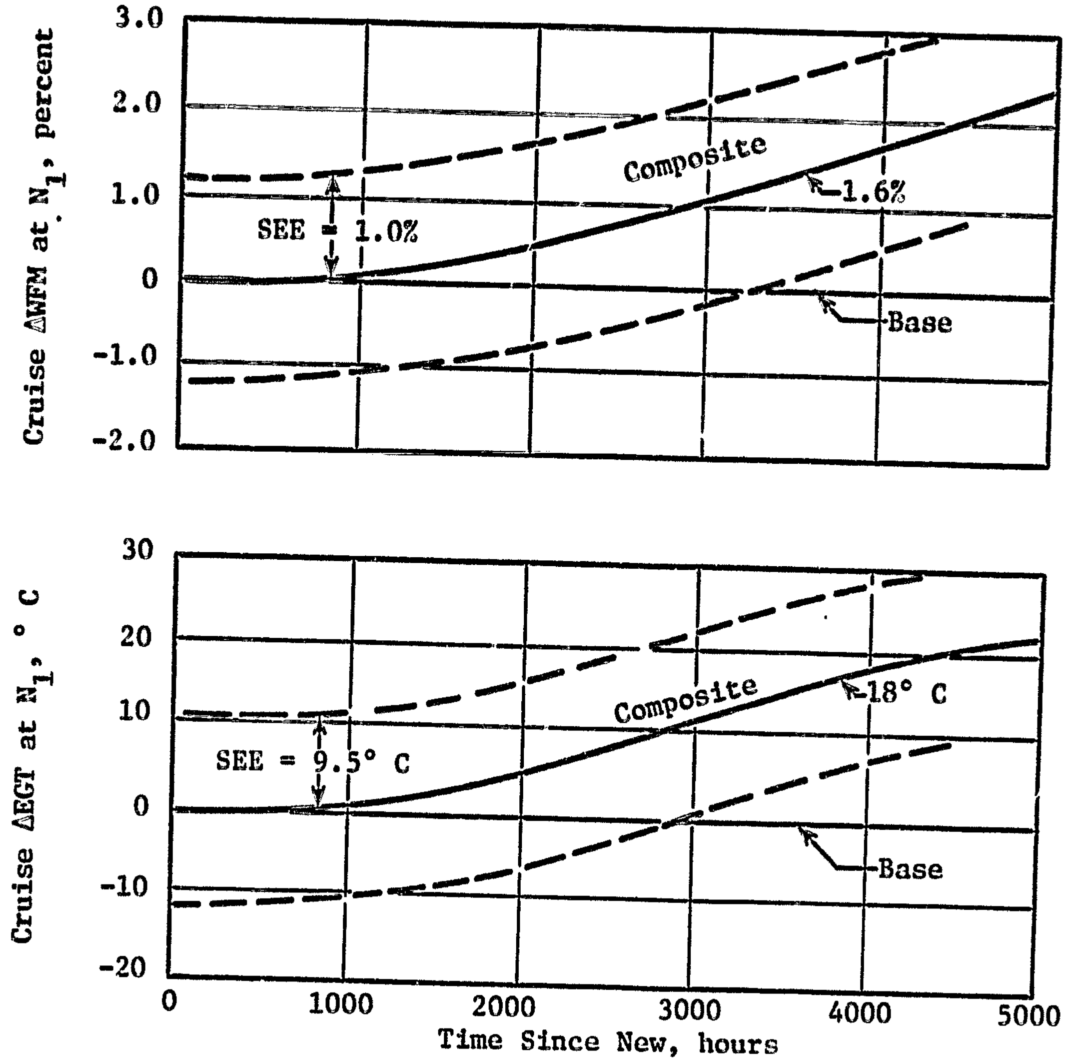


Figure 4-3. Average of Initial-Build Engine Data Versus TSN.

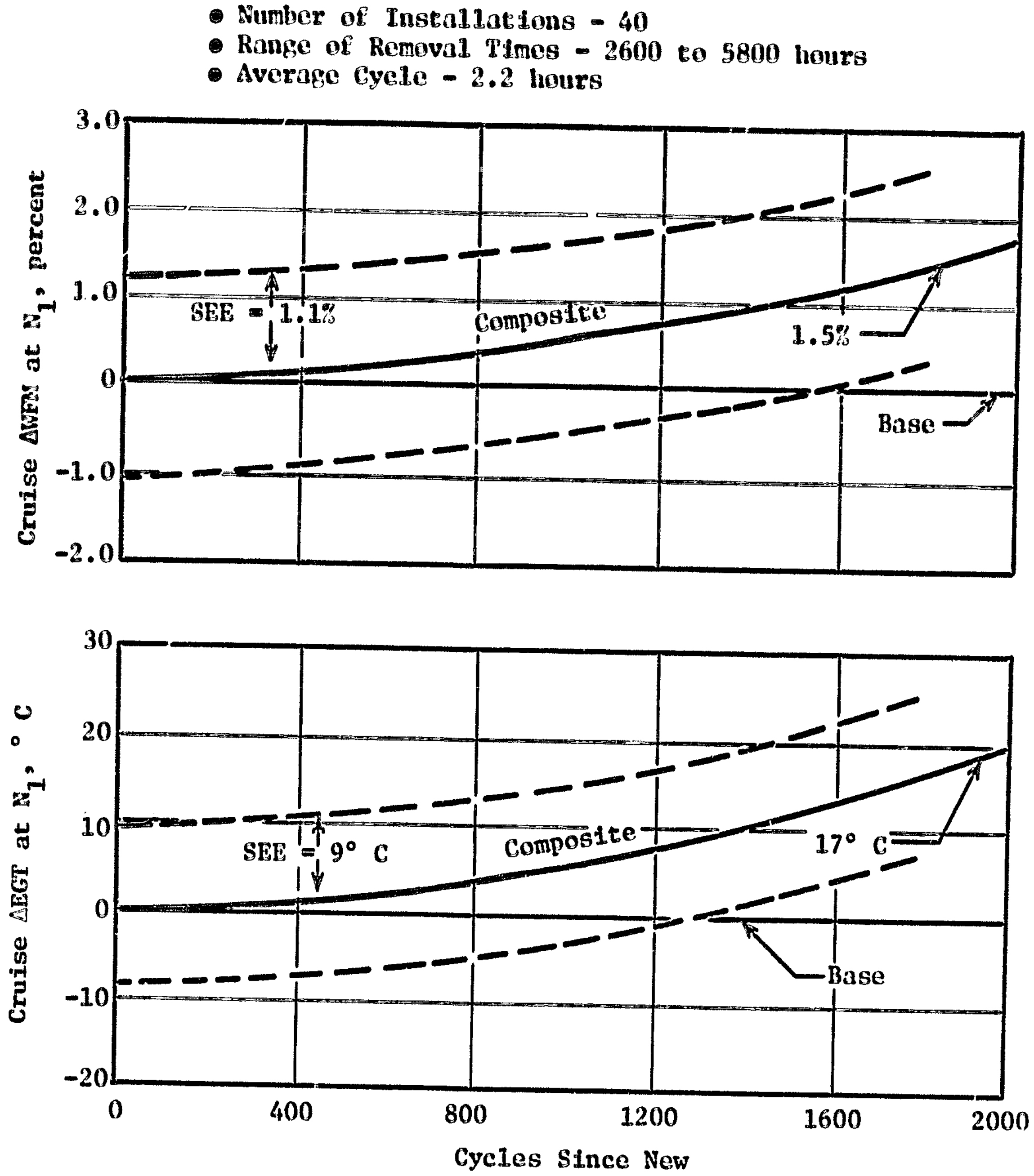


Figure 4-4. Average Initial-Build Engine Data Versus CSN.

These composite trends presented in Figures 4-3 and 4-4 are analogous to fleet trends. These trends represent average changes associated with a specific group of initial-installation engines: 2600 to 5800-hour installations. With a large data sample, the average loss for all these engines can be determined with a high degree of confidence although any one engine trend can be significantly different from the average, as evidenced by rather large standard deviation.

Analysis of airline revenue service trends has revealed deterioration characteristics for the individual engines under investigation to be different from traditional concepts. The shape of the individual engine curve is inverted from that generally published for the fleet average in that the individual engine deterioration rate was small during early revenue service but then increased significantly during the latter part of the installation prior to removal. Elimination of the infant-mortality and early-removal engines (less than 2000 hours) substantially influenced the shape of the deterioration curve during the early portion of the installation. The curve shape isolated for this study was based on selected individual engines and is considered a correct representation of the long-term deterioration characteristics. It does not, however, represent the typical airline fleet trend, nor is it intended to alter the traditional curve shape concept.

To better understand how individual engines deteriorate, the analysis approach was refined. First, it was important to obtain sufficient cruise data in order to trace individual engines from installation to removal and, further, to analyze these performance data as individual installation trends rather than as a collection of individual data points. Second, it proved very useful to divide these individual engine trends by removal time-since-installation into similar age groups analysis (for instance, a group of deteriorated engines all of which were removed for refurbishment approximately 4000 hours after installation).

Available initial trends for 4000 ±450 hour installations from three airlines were examined to further understand engine deterioration. Statistical trends were derived for these initial installations using data from ten engines which remained on-wing from between 3550 hours and 4450 hours. (Recall that each of the ten trends consisted of cruise performance samples at regular intervals, usually every 300 to 500 hours, from the start of revenue service until removal.) This group of engines was selected for analysis since the average installed time of initial installation engines was nominally 4000 hours.

The WFM and EGT deterioration of this representative group of initial-installation engines is tabulated in Table 4-I and shown as trends of these parameters at constant N1 versus TSN in Figure 4-5. The performance deterioration curves were again least-square stepwise-regression fits, yielding the average deterioration trend for the ten individual installations (each of which were described by at least six and as many as twenty data points).

The statistical fit of the ten "4000-hour" installations was compared to the composite trend for the forty "2600-to-5800-hour initial-build installations"

Table 4-I. Representative CF6-6D Initial-Build Cruise Performance, 4000-Hour Installation.

Hours Since New	Cruise ΔWFM at N1 (%)	Cruise ΔEGT at N1 (° C)
0	Base	Base
1000	0.2	1
2000	0.6	6
3000	1.3	13
4000	2.3	23
SEE	0.9	8
R^2	0.57	0.76

$\Delta WFM = B_2 (TSN)^2$ $\qquad$ $\Delta EGT = B_2 (TSN)^2$

$B_2 = 1.45 \times 10^{-7}$ $\qquad$ $B_2 = 1.44 \times 10^{-6}$

2.3% ΔWFM ≈ 1.7% ΔFuel Burn

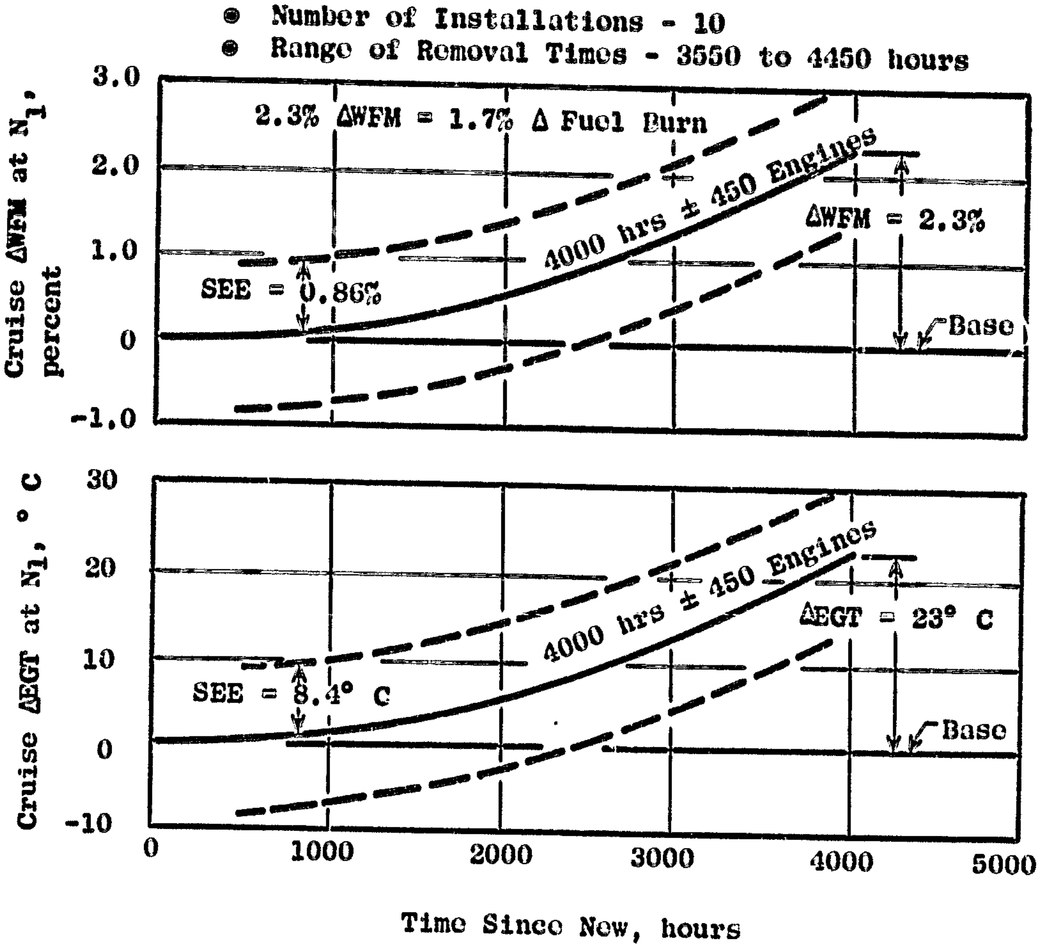


Figure 4-5. Representative Initial-Build Engine Deterioration.

presented in Figure 4-3. Restricting the analysis to the "4000-hour" engine data resulted in slightly lower standard errors of estimate than determined for the entire group of "2600-5800-hour" engines. However, the "4000 hour" assessments nearly doubled the R^2 level associated with the curve fits for the composite trends - from 0.34 to 0.57 for ΔWFM and from 0.39 to 0.76 ΔEGT. (Recall that the larger the "R^2" coefficient, from 0 to 1.0, the better the statistical fit matches the data.)

Several observations can be made based on these comparison results. First, restricting the analysis group to similar-age engines reduced the amount of engine-to-engine variability in deterioration rates occurring in the larger sample of first-installation engines, as evidenced by the significant increase in the R^2 level. Second, the data scatter for an individual engine trend is inherently large for the airline trending data and the reduction of the SEE assocaited with the statistical fits was only about 10%. (Had the performance data for the "2600 to 5800 hour" engines not been normalized on an individual basis, the SEE associated with the fits of these points would have been larger and thus the reduction of the SEE resulting from the analysis of "4000 hour" individual trends would have been greater.)

Other groups of similar initial-installation engines have been likewise examined (including a group of engines, to be discussed later, which underwent inbound tests). These other groups showed different, yet similar, deterioration characteristics. For instance, one statistical trend was more linear; another had smaller SEE and larger R^2 values; while a third group deteriorated more slowly and remained on-wing longer.

The question arises as to which approach to modeling deterioration trends is better. The answer must depend on what is being sought. Composite trends as shown in Figures 4-3 and 4-4 are useful in determining average performance levels for large groups or fleets of engines. For instance, such assessments are important for airline operational planning or for fleet cost projections. On the other hand, averaging trends of numerous engine installations with significant engine-to-engine variation tends to mask differences. Analysis of performance trends selected from similar installations offers better opportunities to assess deterioration characteristics. (Nevertheless, cruise cockpit readings produce large variations in performance measurements for any given installation; hence, cruise readings from several consecutive flights were averaged to produce each data point.)

For the purpose of this investigation of engine performance deterioration, it is believed that the statistical trends for the "4000-hour" initial-installation engines are representative of long-term deterioration for this class of engines. This trend will thus be used as the average deterioration characteristics for the new CF6-6D engines which entered revenue service between 1974 and 1976.

Further, it is important to note that the airlines trend fuel flow at fan speed, not at thrust. This provides a convenient and effective method for trending performance changes. However, the actual fuel-burn increase caused by deterioration is less than the increased WFM at N1 for the CF6-6D, based on projections of sea level static deterioration to airline cruise conditions. It is necessary to analytically calculate these changes in cruise fuel burn since installed thrust, which is required to determine sfc, cannot be measured in flight. Based on previous experience using a mathematical model of a thermodynamic cycle for a deteriorated CF6-6D, the change in cruise fuel burn is taken to be approximately equivalent to 75 percent of the cruise ΔWFM. The increased fuel burn for the "4000 hour" initial-build engines was thus 1.7 percent.

Initial-Installation Inbound Tests

Test cell performance calibration results for initial-installation engines prior to repair/refurbishment were available for ten separate engines. These included five specifically tested in conjunction with this program, and ESN 451479. The test cell performance results for ESN 451479 are presented in the report "Long-Term CF6 Engine Performance Deterioration - Evaluation of Engine S/N 451479" (Reference 3).

The ten inbound engines are listed in Table 4-II. All engines but one were operated by the same airline, and eight of the ten were grouped in a tight ESN band (-467 to -493) which were the last engines shipped in late 1975 prior to resuming production deliveries in late 1977. One engine, ESN 451412, was shipped directly to the airline as a new spare, thus not sustaining the short-term losses associated with checkout of the DC-10-10 aircraft at DACo.

The average time-on-wing for these ten engines was significantly longer (over 5000 hours) than the representative "4000-hour" initial build engine, with installed time ranging from 3070 to 7100 hours. These engines were among the few production engines remaining on wing when this program was initiated; that is the reason the average time was significantly longer than the representative engine.

The inbound tests of these deteriorated engines were conducted at three different facilities, while the as-shipped performance levels were all established at the General Electric facility in Evendale. Engine S/N 451412, the 7000-hour-plus engine, was inbound tested at the Evendale facility. ESN 451479 was tested at the General Electric facility located at Ontario, California (ASO/O). The remainder were all inbound-tested in the facilities of a particular airline.

The deterioration experienced by these engines is tabulated in Table 4-II. The performance losses were derived by comparisons of the inbound results with as-shipped data, using appropriate data adjustments for the subject test cells. Recall that those as-shipped-to-inbound deterioration assessments determined for those initial-installation engines include both short-

Table 4-II. Initial-Installation Inbound Engine Test Results.

ESN	Symbols	Test Date	Location	TSN at Removal	CSN at Removal	SLS Performance Deterioration	
						Δsfc @ FN (%)	ΔEGT @ N1 (° C)
451479	□	3/22/77	ASO/O	4470	1910	4.5	58
451412	⬡	1/18/77	Factory	7100	3330	4.7	54
451420	▲	6/10/76	Airline	5780	2575	7.6	67
451467	◇	2/5/76	Airline	3123	1488	2.0	35
451476	△	8/2/77	Airline	5765	2543	3.2	54
451477	○	6/1/77	Airline	5143	2296	3.5	64
451480	⬭	7/5/77	Airline	5353	2279	4.1	46
451481	✖	8/18/77	Airline	5801	2459	3.4	58
451486	⌂	9/30/76	Airline	3070	1340	9.8	43
451493	◺	6/8/77	Airline	4587	2097	2.6	15

term and long-term losses except for the spare engine (S/N 451412). The inbound test cell data measurements generally include multiple readings for each point, and the comparisons were made for both the takeoff and maximum continuous power settings.

These inbound deterioration results, presented in Table 4-II, are also shown graphically in Figure 4-6, plotted as a function of time since new (TSN). The dotted line is an imaginary plot starting at zero reference and passing through the average Δsfc or ΔEGT level for the average TSN of 5200 hours. Despite the small sample size, all the points (except those for one or two engines) are within a reasonably tight band around the lines. (The losses for ESN 451486 were not included in the average since the Δsfc, which was based on a single inbound test point, was unreasonably high and inconsistent with the measured ΔEGT.)

A very important aspect of the analysis of the inbound test cell results was the development of a correlation between sea level static deterioration at takeoff power and observed cruise deterioration levels. Since thrust cannot be measured during cruise, this correlation was used to establish the relationship of cruise fuel flow trends with expected cruise sfc loss. The relation of cruise to sea-level assessed deterioration data is presented in Figure 4-7 (Symbols from Table 4-II). The relation between measured EGT losses matched the analytically produced correlation line quite well. The cruise fuel flow correlations produced more data scatter for the individual engines, but, as shown, the average substantiated the previously derived correlation curve. These data again illustrate the large variation in data for individual engines, requiring the average of substantial amounts of data in order to be effective.

MULTIPLE-BUILD REVENUE SERVICE INSTALLATION

The second classification examined in the study of long-term deterioration was the multiple-build engine installations. These include any installations of an engine after it had undergone an initial shop visit. Emphasis was placed on assessing the long-term performance deterioration of these engines since they comprise more than 90 percent of the CF6-6D fleet today. As such, any reduction of the deterioration of these multiple-build engines would have a major impact on fuel conservation.

Before proceeding, it should be noted that CF6 engines are maintained utilizing an "on condition" concept, such that the engines are repaired as required based on engine inspection data rather than at a fixed time between overhaul (TBO). This concept requires a modular construction so that the engine is easily disassembled into basic subassemblies or modules which are completely interchangeable. This permits maintenance to be conducted on individual modules rather than on engines and moreover permits repair of only those parts within a specific module that are defective. As a result, a rebuilt

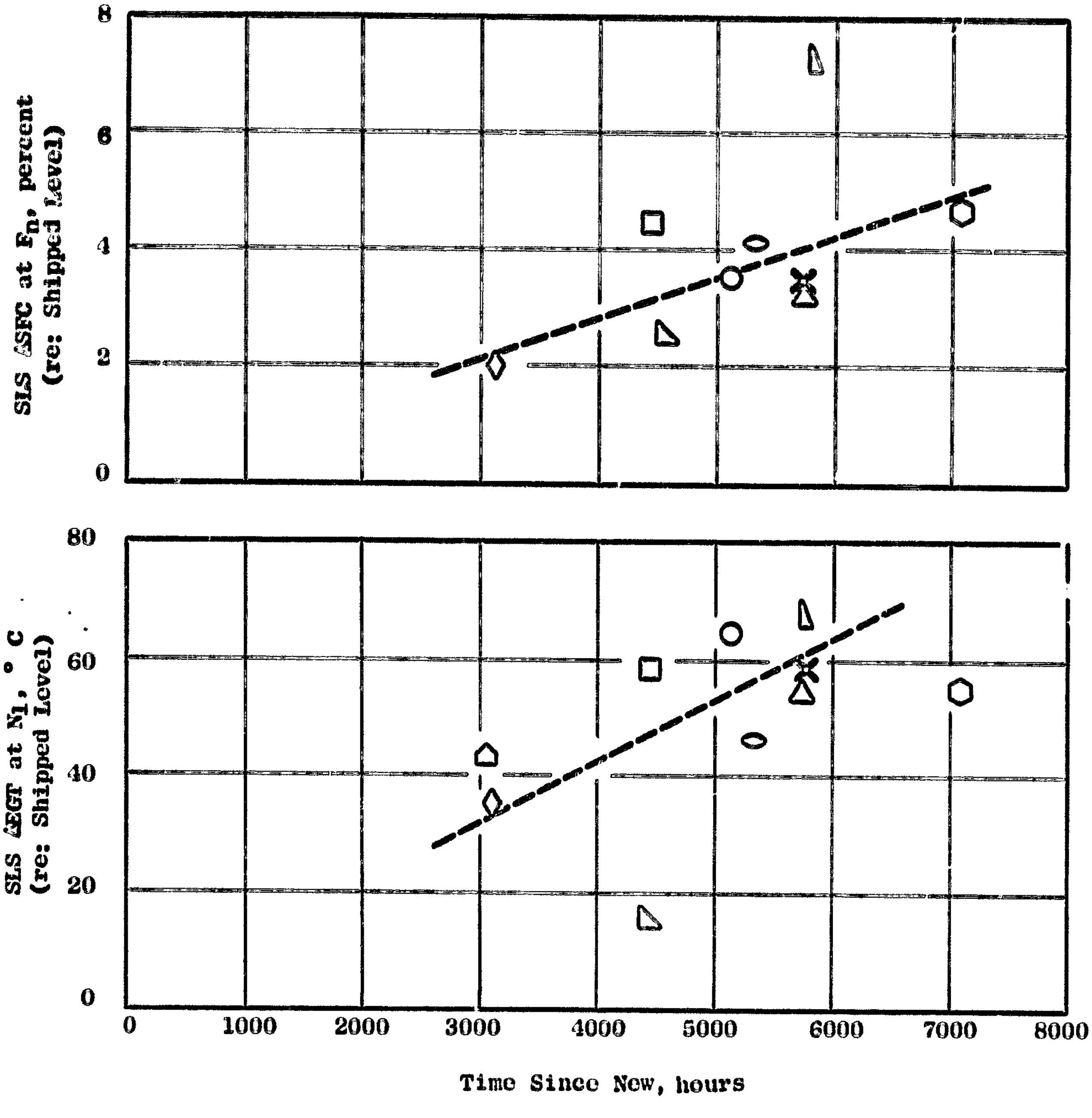


Figure 4-6. Initial-Build Engine Deterioration - Inbound Test Results.

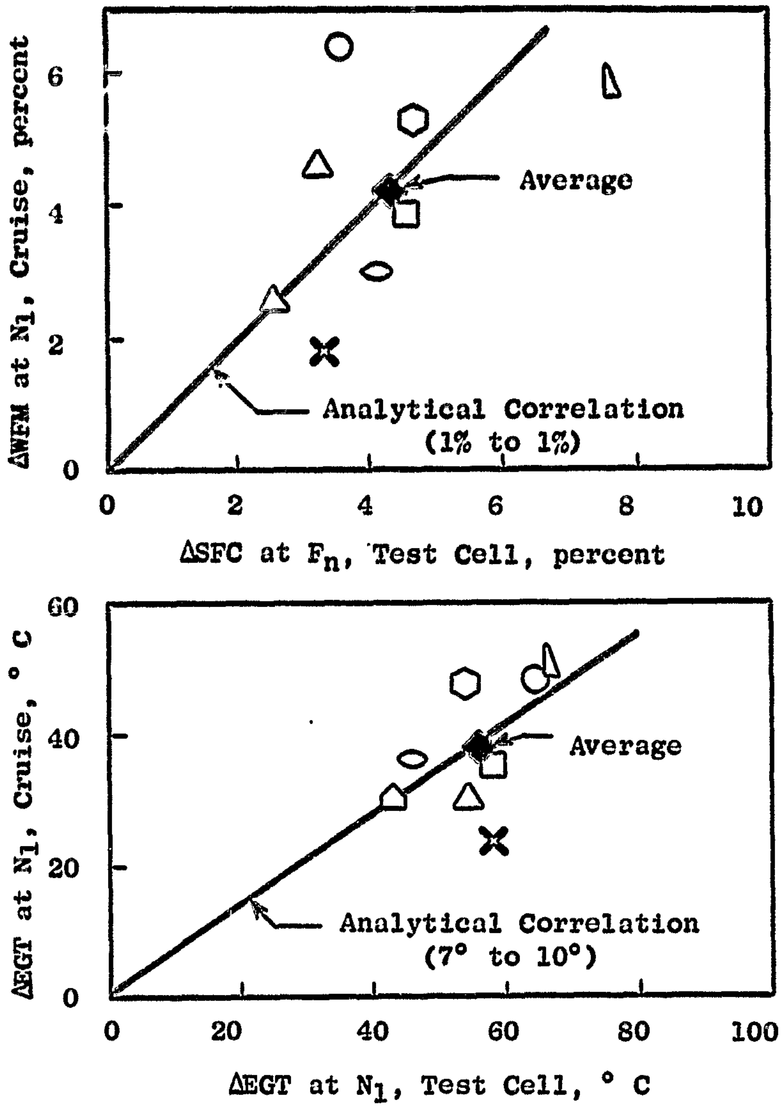


Figure 4-7. CF6-6D Test-Cell-To-Cruise Deterioration Correlation.

(multiple-build) engine is typically reassembled with any serviceable modules. This produces an engine which has a wide variation in part times, resulting in extremely large engine-to-engine variations.

Airline revenue-service cruise performance data were obtainable for a large number of installations. As in the other studies, only engines which incorporated current production hardware were considered. Based on analysis of engine maintenance performance by the individual airlines, engines installed in 1976 or later were rebuilt with modules containing current hardware.

Four groups of recent (1976-1978) multiple-build installations were examined. The average installation length for unscheduled, engine-caused removals for these engines is shown in Table 4-III.

Table 4-III. Multiple-Build Installations (1976-1978).

Airline	Number of Installations	Average Removal	
		Hours	Cycles
A	204	2652	1084
B1	52	2605	804
B2	94	2226	1032
C	92	2359	1171

The average multiple-build installation increased to a nominal 3000 hours and 1250 cycles if those engines removed prior to 1000 hours were excluded (18 percent of installations). Many engine removals prior to 1000 hours were due to durability failures of unrefurbished modules or due to maintenance errors; neither situation was considered typical of long-term deterioration.

Multiple-Build Cruise Performance Trends

Cruise performance trend data were examined for 179 multiple-build engine installations. These airline cruise trends were analyzed to quantify long-term deterioration of engines after they had returned to revenue service following a shop visit. As with the study of initial-installation engines, cruise losses were derived using airline cockpit readings of engine performance. These losses were calculated relative to the earliest available measured cruise performance on an individual engine basis.

The trends for multiple-build installations were obtained from three of the five domestic airlines that operate CF6-6D engines. Cruise trends from 179 multiple-build installations were examined; these were for 125 different engine serial numbers. These cruise performance trends included data for over 90 percent of the engine serial numbers between ESN 451406 and ESN 451496 and for 30 percent of all CF6-6D engines produces prior to ESN 451496. A total of 1586 data points were used for this multiple-build engine study; each data point represented the average level for four to twenty airplane flights.

Examination of the assimilated cruise trends indicated that, although the time-since-installation at removal for the installations varied considerably, removal times were concentrated between 2000 and 5000 hours. The distribution of removal times for the multiple-build installations used for these long-term deterioration studies is presented in Figure 4-8. The distribution of these installations peaked at 3000 hours - a time which coincides with the average engine-caused, unscheduled removal time for recent multiple-build CF6-6D engines. As previously noted, engine installations outside the 2000-to-5000-hour age band were considered to have untypical long-term deterioration characteristics and were eliminated from the study.

Statistical cruise performance trends for the average of all 2000-to-5000-hour installations for a representative CF6-6D operator are presented in Figures 4-9 and 4-10. (The specific cruise data are presented in Appendix B.) Average changes of cruise WFM and EGT at N1 are shown as functions of time and cycles since installation (TSI and CSI respectively). These statistical fits were derived from 273 data points from 45 installations, using the previously discussed least-square polynomial curve-fit techniques. The fit of the data points represents an average of a specific portion of the CF6-6D fleet. The standard error of estimate indicated a wide spread in the data. The confidence level associated with these average or composite trends, however, was over 99 percent. The R^2 terms associated with these fits were relatively low, on the order of 0.2, indicating the statistical fits only explain 20% of the data variation.

A question remains concerning the very early portion of the deterioration characteristic curve. This portion of the curve was of special concern based on the short-term results which indicated that a substantial loss does occur during initial on-wing engine operations (airplane flight checkout). A rapid deterioration could not be isolated during the first hours of revenue service since the available cruise data were rarely obtained earlier than 50 hours after installation. Comparisons of outbound performance calibrations to early revenue service levels proved inconclusive. Assessments of 17 engines for one airline indicated a 4° C early deterioration; however, the average TSI was 175 hours, and more significant, the standard deviation was 11° C for these data. Assessments of engines from a second airline indicated 6° C to 10° C early deterioration, but again there was large scatter (σ = 14° C) which leaves the question of short-term losses for rebuilt engines unresolved. Since WFM correlation from sea level static to cruise conditions has not yet been accurately developed, it was not possible to assess the potential of a

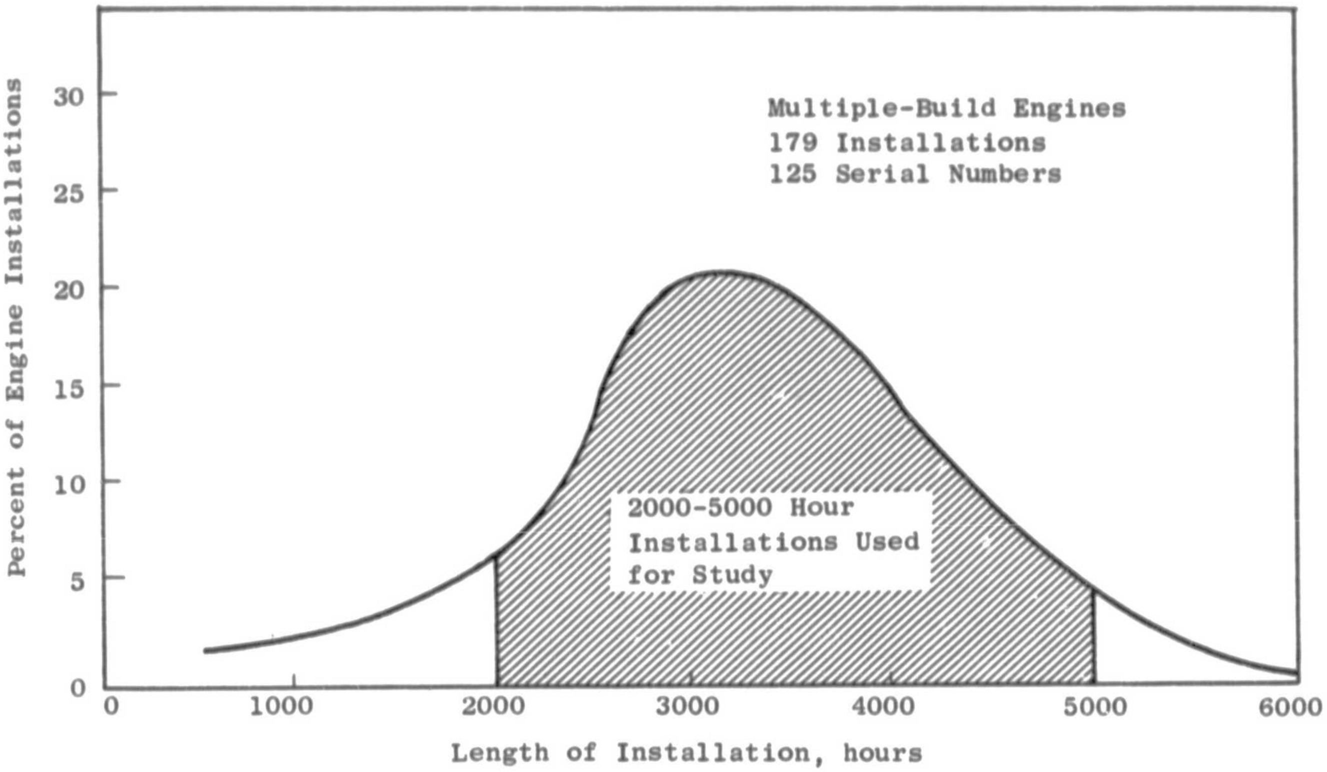


Figure 4-8. Duration of CF6-6D Multiple-Build Installations.

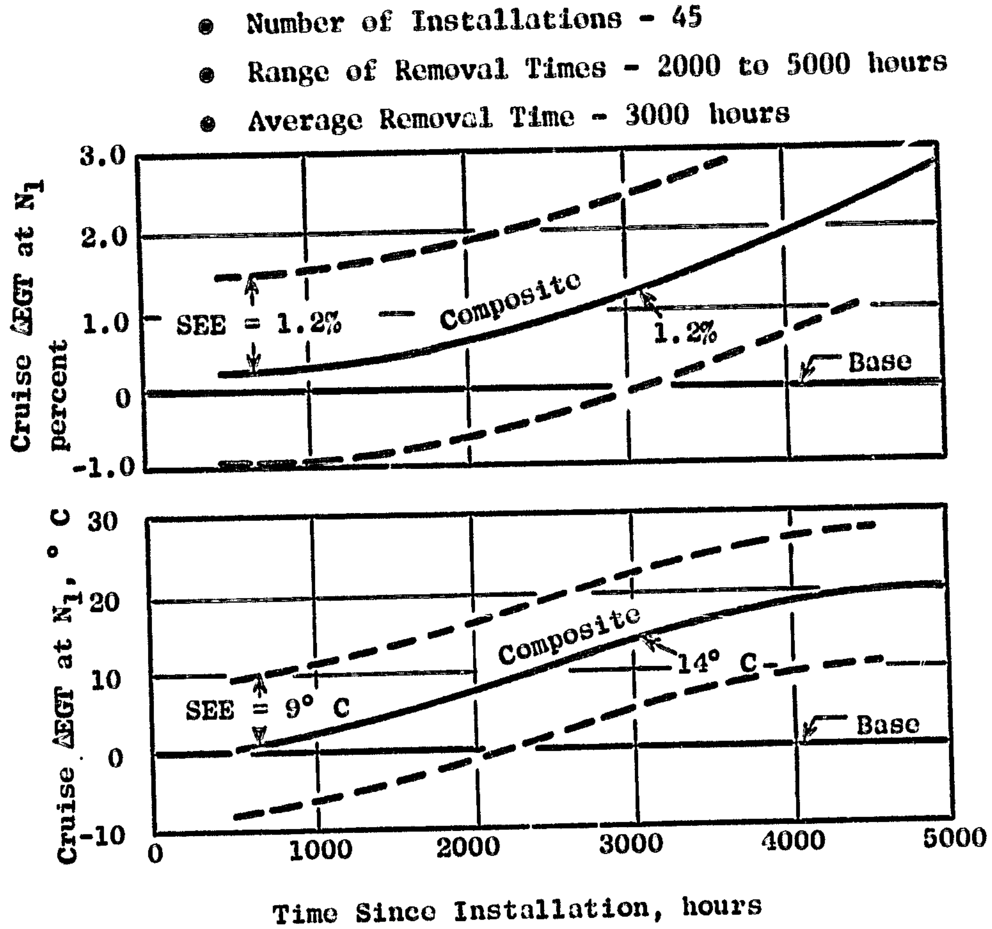


Figure 4-9. Average of Multiple-Build Engine Data Vs TSI.

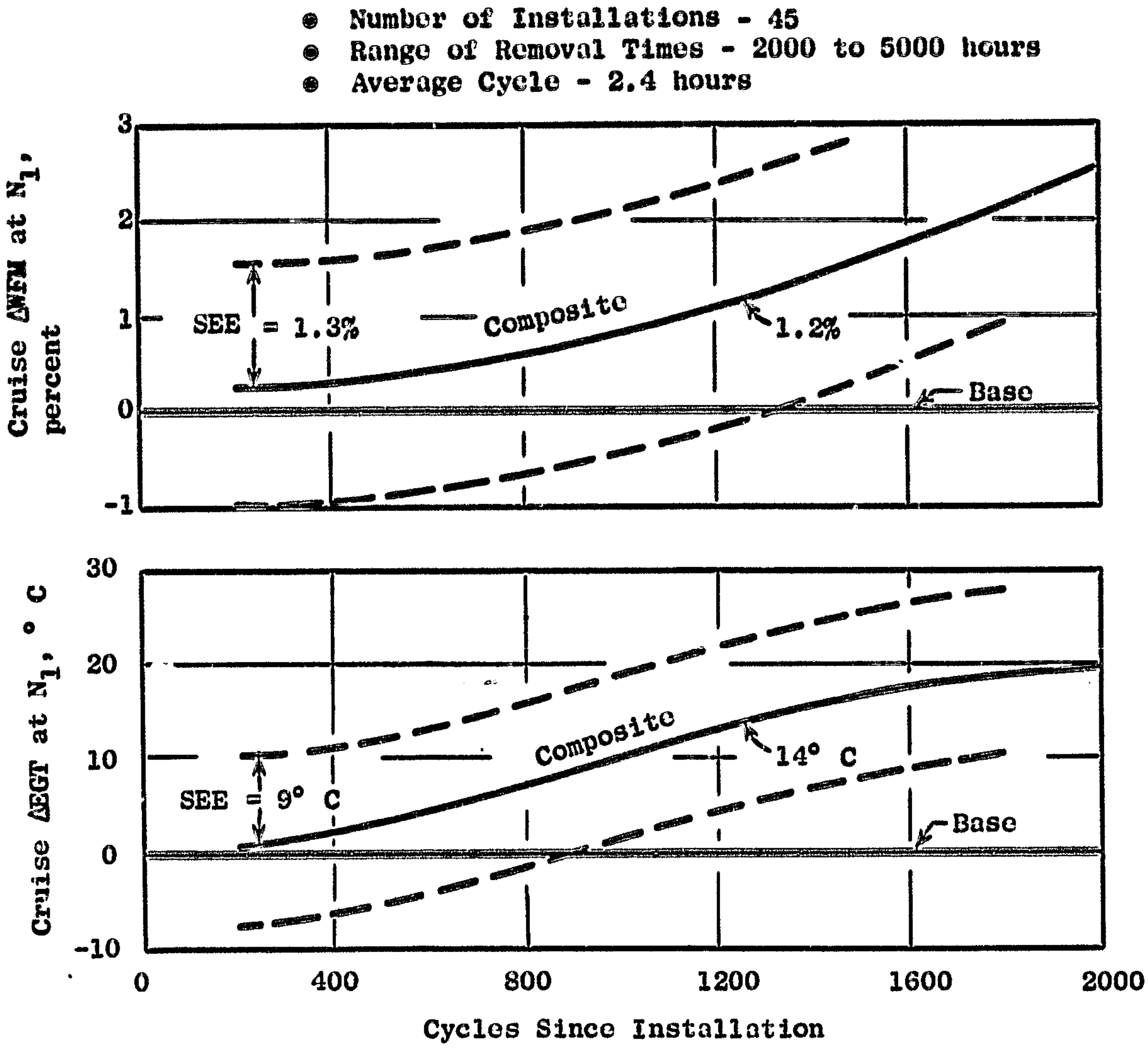


Figure 4-10. Average of Multiple-Build Engine Data Vs CSI.

rapid WFM deterioration during early revenue service. Accordingly, deterioration characteristics for the first 500 hours of the 2000-to-5000-hour composite trend for multiple-build installations are not delineated. It is reasonable to expect that some instant loss does occur, but certainly not anywhere near the extent identified for the short term.

Continuing the deterioration assessment of multiple-build CF6-6 engines, it also proved advantageous to separate these engine installations into groups with similar ages (removal times) in order to better understand individual engine deterioration trends. It was possible to separate the forty-five installations from Airline "A" into five families where the installations were divided into 500 hour blocks according to their TSI at removal. These families have been designated by the nominal removal times of the engines within each family - "2500 hours," "3000 hours," etc. Performance changes in terms of fuel flow and EGT at N1 with each TSI and CSI are presented in Figures 4-11 and 4-12 for the five families of engines. Each family trend is a least-square fit of the 8 to 10 individual engine trends comprising that family. These individual installation trends are the same as those averaged together to derive the multiple-build composite trend. It can be seen from the results for this airline that a relation exists between deterioration rate and length of installation. The same comments concerning the curve shape as discussed earlier in Section 4.1 apply to these data.

The fits of these family trends showed significantly better statistical characteristics than those for the composite fits of all the 2000-to-5000-hour engines. Summarized in Table 4-IV are the details of the fuel flow and EGT fits as functions of TSI. The SEE of the WFM trends ranges from 0.9 to 1.2 percent, accounting for from 54 to 77 percent of the variability of the data by the fit. The EGT trends have SEE's ranging from 3° C to 8° C, accounting for from 69 to 97 percent of the data variability. Although the confidence level for these deterioration trends of the various families was again greater than 99 percent, other polynominal fits could have been utilized. However, these would have a negligible effect on the accuracy of the fit. The particular polynomial fits employed were considered to best describe the WFM or EGT deterioration characteristics of all five families.

As with initial-build engines, one family was selected to represent multiple-build engine deterioration. The trends for the family of "3000-hour" engines were chosen as being representative since these engines remained on-wing for approximately the average length of time for multiple engines. The deterioration trend for this family of installations is shown separately in Figure 4-13. As noted, the increase in cruise fuel flow at fan speed was estimated to be equivalent to an increase of 0.9 percent cruise fuel burn at 3000 hours.

Effect of Operational Variables of Deterioration

A number of studies were conducted to determine what operational factors influence overall performance deterioration characteristics. Statistical cruise trends of multiple-build engines were utilized for these studies since these

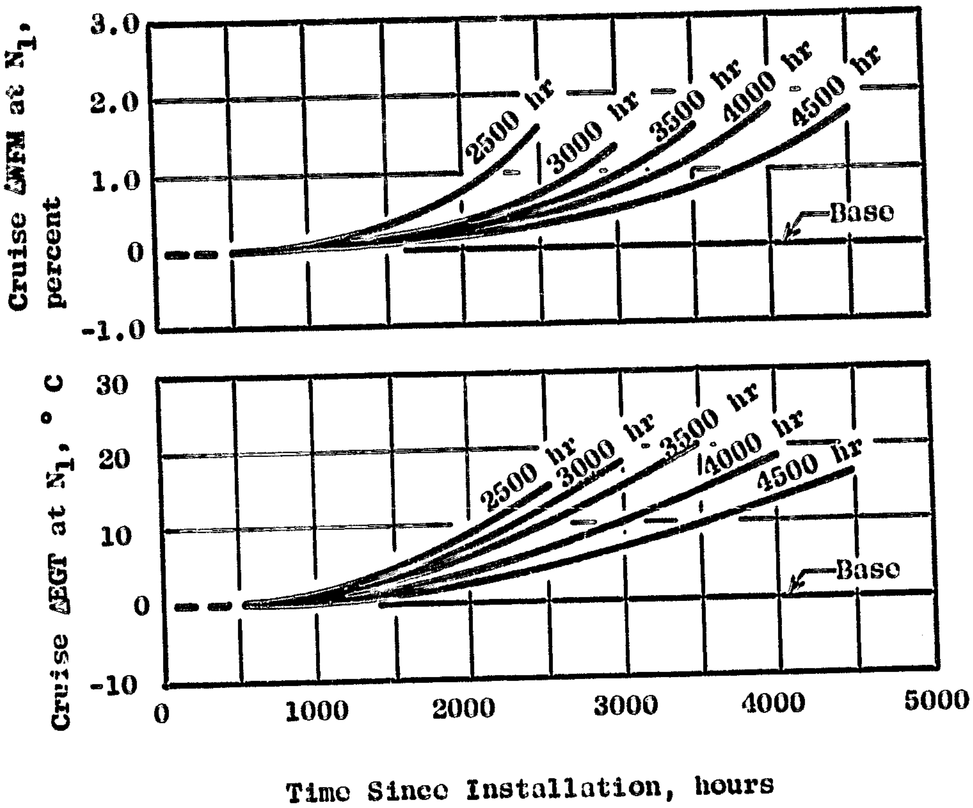


Figure 4-11. Similar-Age Multiple-Build Engine Trends Vs. TSI.

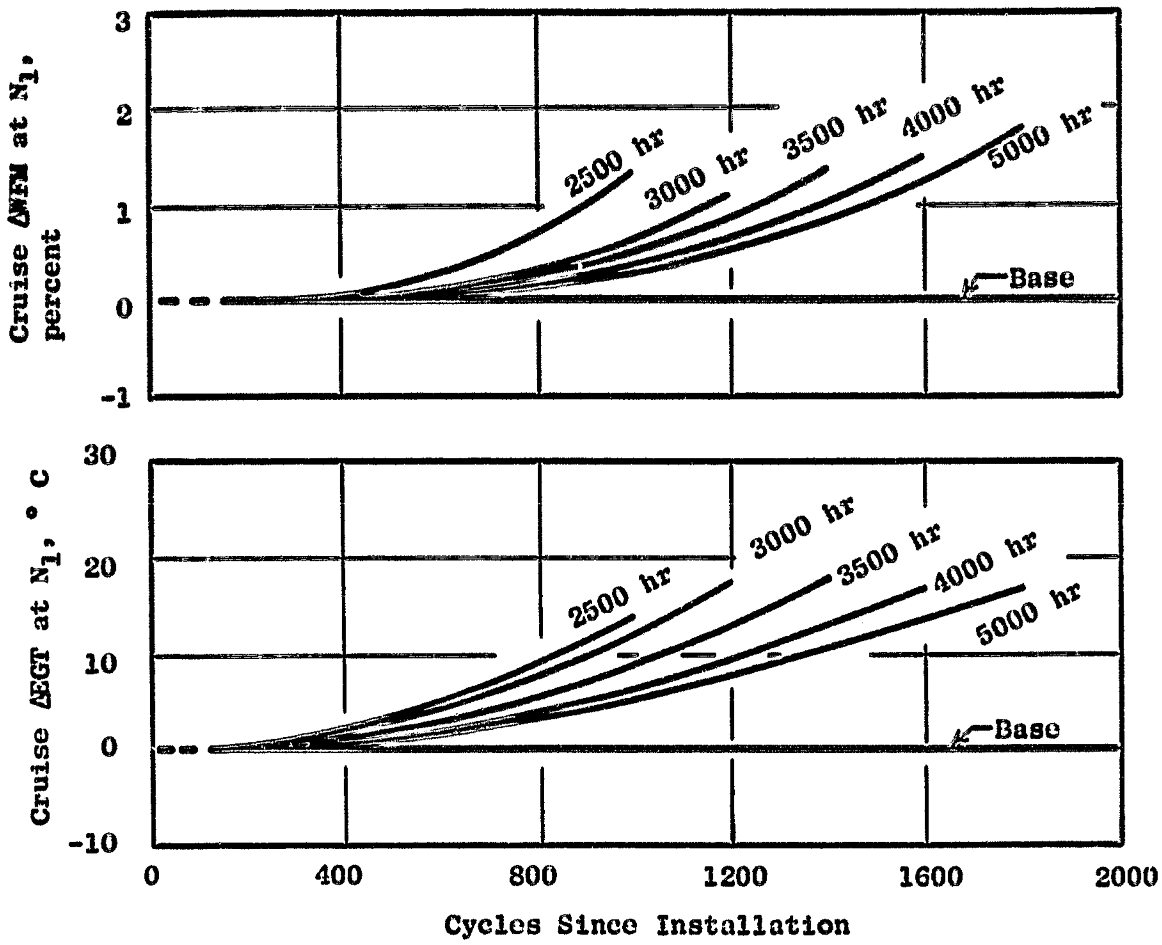


Figure 4-12. Similar-Age Multiple-Build Engine Trends Vs. CSI.

Table 4-IV. Families of Similar-Age Multiple-Build Engines.

- Statistical Deterioration Trends -

Least Square, Polynomial Curve Fits:

$$\Delta WFM = A_1(TSI) + A_2(TSI)^2 + A_3(TSI)^3$$

$$\Delta EGT = B_1(TSI) + B_2(TSI)^2 + B_3(TSI)^3$$

Family	Fuel Flow Trends					EGT Trends				
	Coefficients			SEE(%)	R^2	Coefficients			SEE (°C)	R^2
(±250 Hrs)	A_1	A_2	A_3			B_1	B_2	B_3		
2500 Hrs	0	0	$9.9X10^{-11}$	1.1	0.66	0	$2.4X10^{-6}$	0	7	0.70
3000 Hrs	0	0	$4.7X10^{-11}$	0.9	0.77	0	$2.1X10^{-6}$	0	6	0.78
3500 Hrs	0	0	$3.7X10^{-11}$	1.2	0.67	0	$1.7X10^{-6}$	0	8	0.80
4000 Hrs	0	0	$2.8X10^{-11}$	1.0	0.74	0	$1.2X10^{-6}$	0	3	0.97
4500 Hrs	0	0	$1.9X10^{-11}$	1.1	0.54	0	$0.9X10^{-6}$	0	6	0.77

SEE - Standard Error of Estimate (The Root-Mean-Square of Deviations about a Fitted Curve.)

R^2 - Coefficient of Deterioration (A Measure, of From 0 to 1, of the Proportion of Variation Accounted for by the Multiple Linear Regression Fit where a Value of 1 Indicates a Perfect Fit).

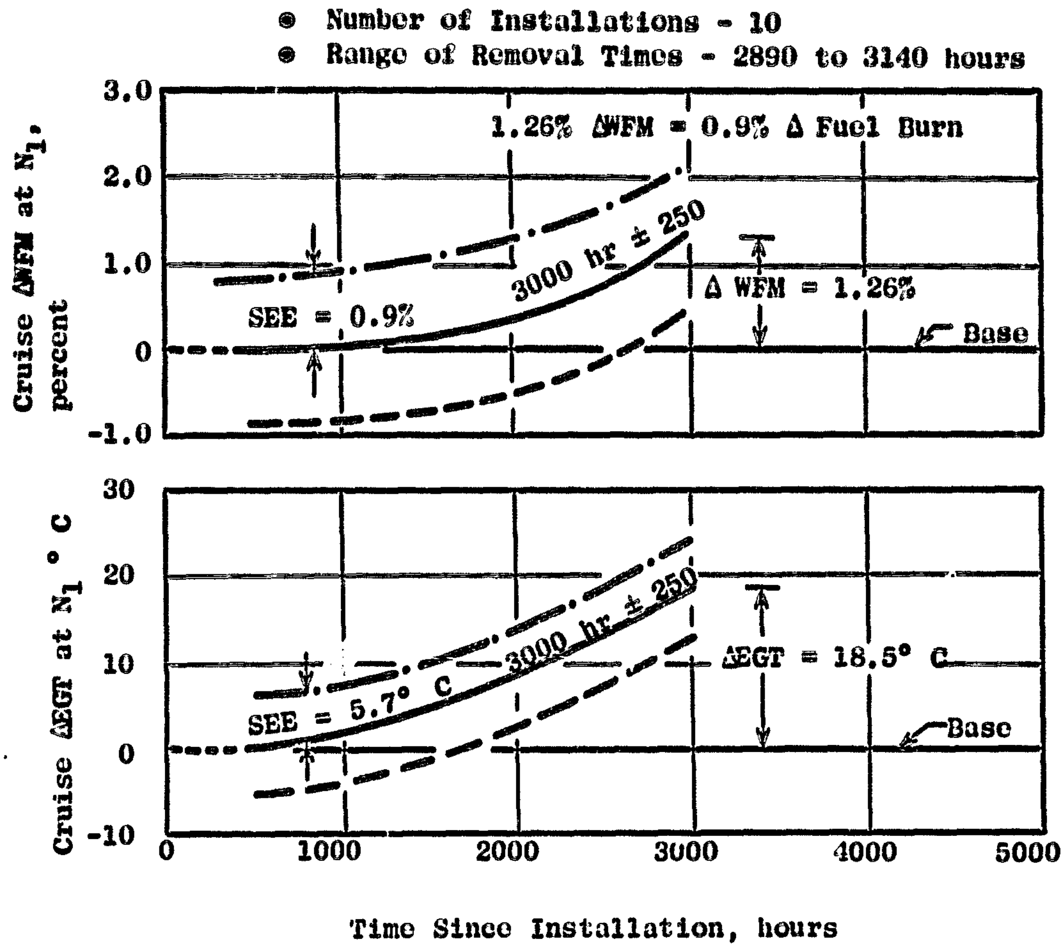


Figure 4-13. Representative Multiple-Build Engine Deterioration.

cruise data comprise the largest source of performance data. The studies consisted of comparisons of deterioration rates between various groupings of engines to determine whether significant differences could be identified. The variables examined included: airline vs. airline, wing vs. tail-mounted engines, second vs. third installtion, and pre vs. post ESN 451406 engines.

Originally these comparisons were made using composite trends (average of all individual engine trends between 2000 and 5000 hours). Average statistical trends were derived from all the available engine installations incorporating the desired feature; for example, Airline "A" engines, tail-mounted engines, etc. As noted in the discussion of initial-installation engines, such composite trends indeed provide an average with a high degree of confidence but also tend to mask subtle differences. Comparisons of such composite trends yielded no significant differences for the variables examined. However, comparison of engines by similar-age groups did reveal some differences. While not necessarily major differences, only the deterioration comparisons between airlines and installed position did produce some notable observations.

Airline-to-Airline Variation - Multiple-build installation trends were available for three airlines, one of which had two distinct route structures. Although only the installed cruise trends of Airline "A" (most available data) were used to represent multiple-build engine trends, similar statistical deterioration trends were derived for families of engines in each of the three remaining airlines/route structures. Again, approximately ten installations were used to derive the statistical fit for each family; and again, ΔWFM and ΔEGT trends were calculated as functions of both TSI and CSI.

The average installation information is presented again in Table 4-V for all unscheduled, engine-caused removals since 1976. For this analysis, engines having less than 1000 flight hours since installation were excluded from consideration.

Table 4-V. Multiple-Build Installations - (1000 Hr Plus Removals)

Airline	Flight Length (Hours)	Removal (1000 Hours Plus)	
		Hours	Cycles
A	2.5	3120	1266
B_1	3.2	3036	938
B_2	2.1	2605	1215
C	2.0	2695	1337

B_1 and B_2 are the same airline; B_1 aircraft are used on a longer route structure.

Comparisons of these four groups are presented in Figures 4-14 and 4-15, where each deterioration curve represents a statistical fit for a "3000-hour" family of engines. While comparisons were made of the various ages of family groups, these 3000-hour engines best illustrated the observed differences. Generally, the engine families had similarly shaped deterioration curves, but not every airline/route group demonstrated the relation between deterioration rate and length of installation to the same degree as was observed for Airline "A."

The performance trends for the four airline/route groups of engines are presented in Figure 4-14 as a function of time since installation. Some small differences in deterioration rate can be seen. Trends from "B1" and "B2" installations generally indicate higher deterioration rates, possibly related to gross weight differences for the two routes. The lower EGT deterioration of the "B1" installations relative to "B2" might trace to the fact that at the same number of hours of operation, these engines had experienced fewer cycles. However, when comparisons of the "2500-hour" and "3500-hour" families (not shown) were also taken into account, no overall trend with time was observed. Thus, the observed differences at constant hours in Figure 4-14 were concluded to be insignificant.

On the other hand, the comparison of the same engine installations as a function of cycles, in Figure 4-15, yields quite a different picture. The deterioration rate for the "B1" engines as a function of cycles was much greater than the rates of the other groups. At the same number of cycles, the engines in group "B1" have operated significantly more hours than engines in the other groups. Furthermore, it was understood that the operation of these "B1" engines was generally without the benefit of derate due to gross weight considerations, resulting in a more severe cycle. As for the engines from group "B2", although they generally had less hours of operation at the same number of cycles as those from "A," it was understood that these engines were usually operated with a smaller amount of derate; possibly the effects of these two factors balanced each other. The lower deterioration rate for the group "C" engines was not understood but could have been influenced by the greater amount of observed data scatter for this family of engines than for the others. (See Appendix B.)

While only inconclusive differences between airline deterioration characteristics were observed based on time of operation, significant differences were evident based on a cycle of operation. These differences appeared to be related to route structure and operational procedures. Nevertheless, the three factors - time, cycles, and derate - are very much interrelated, and it is very difficult to isolate subtle effects unless the derate factor is accurately known.

Effect of Installated Position - The effect of installated position - i.e., whether the engine was tail- or wing-mounted - was also investigated. Both multiple-build cruise performance trends and engine removal records were used. Comparisons were made within particular airline/route structures between engines of similar age. With these restrictions, very few families of engines were available for statistical trending.

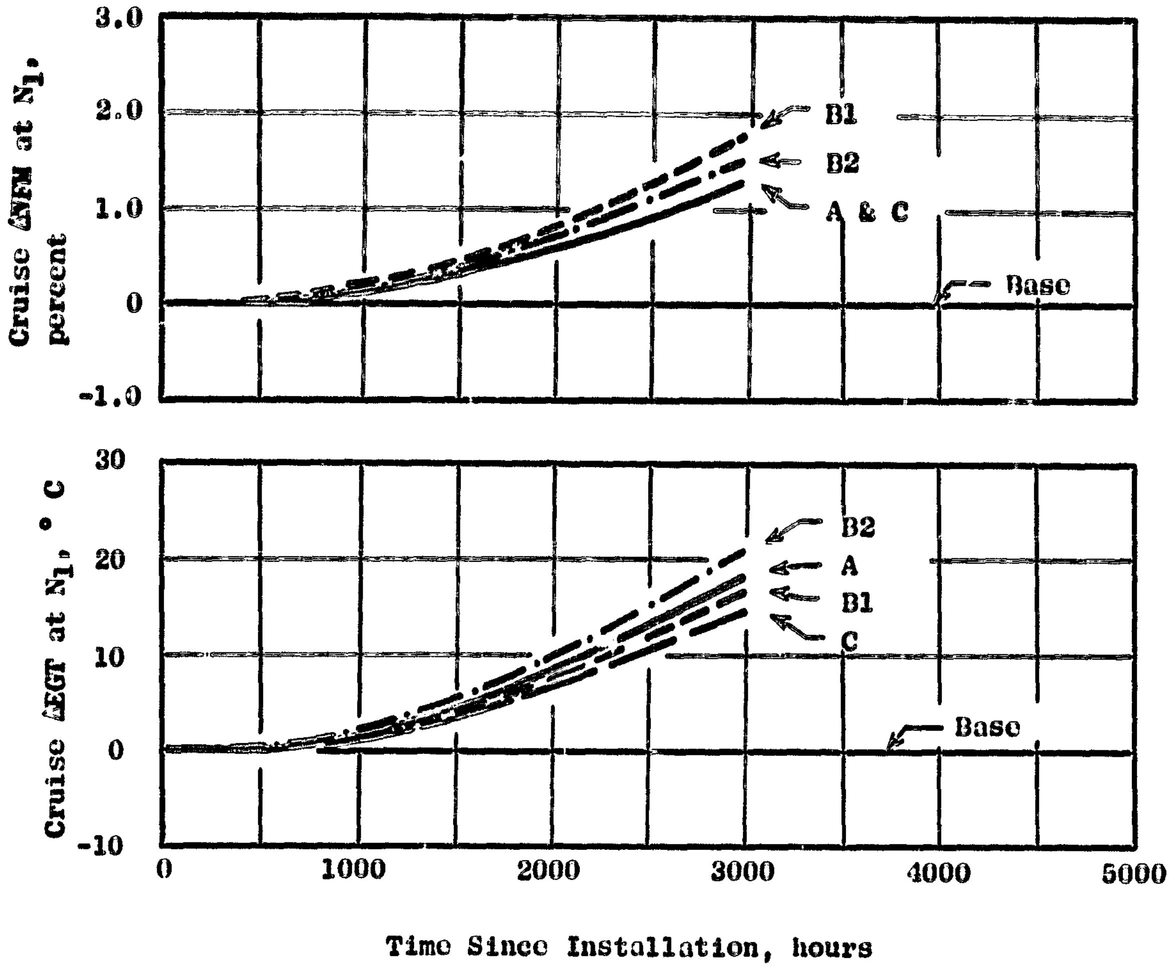


Figure 4-14. Comparison of Airline/Route Cruise Trends Vs. TSI.

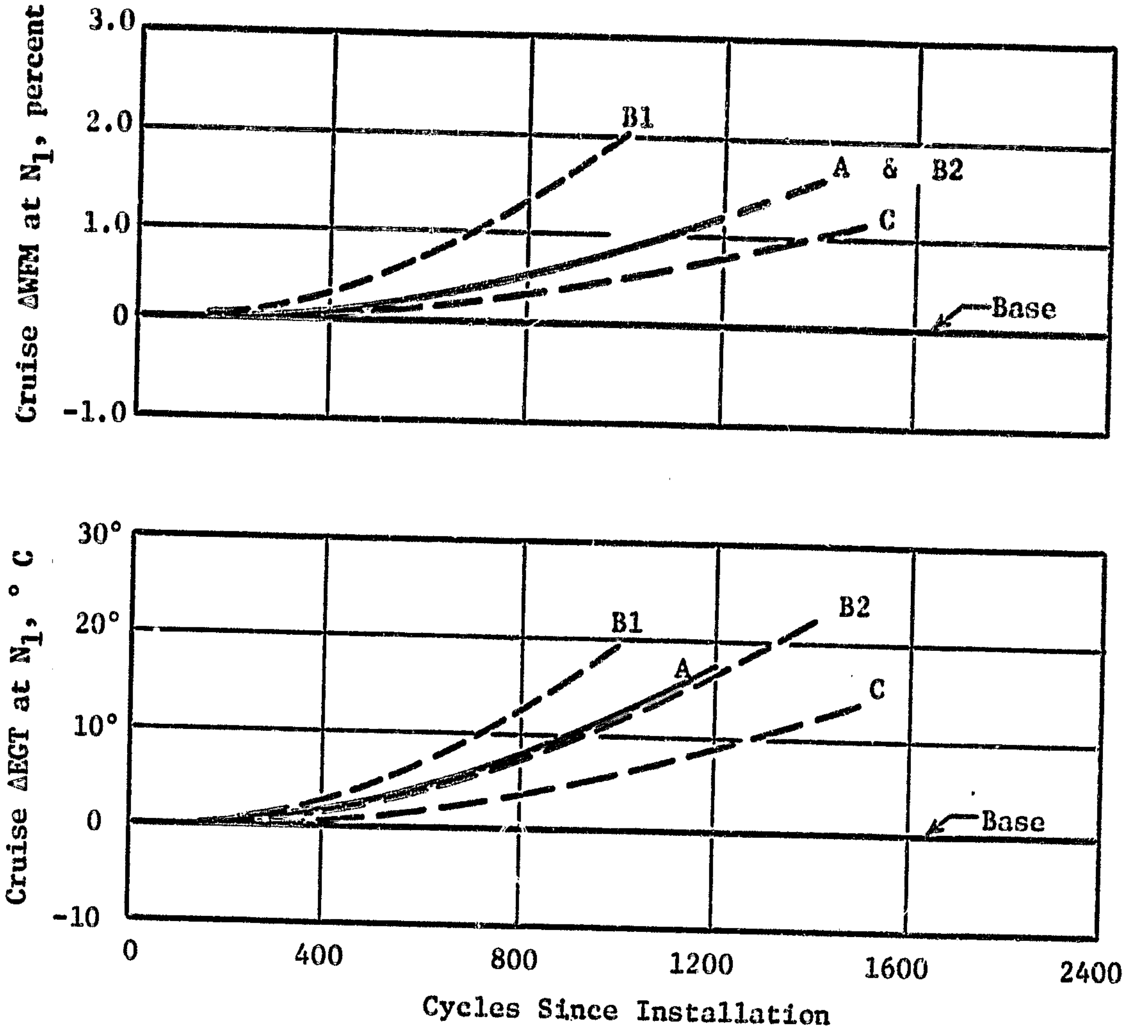


Figure 4-15. Comparison of Airline/Route Cruise Trends Vs. CSI.

The results were mixed. No difference in deterioration characteristics was observed among Airline "A" tail- and wing-mounted engines. However, a tendency for the wing engines to deteriorate more rapidly was observed for the other airlines. Statistical-trend comparisons were possible only between "B" installations, shown in Figure 4-16, in which wing engines seemed to deteriorate more rapidly. Table 4-VI shows the comparison of average unscheduled, engine-caused removals by position; this also indicates tail-mounted engines remained in revenue service longer than wing-mounted engines at Airlines "B" and "C."

Table 4-VI. Unscheduled Removal Times.

Airline	Average Removal Time (Hours)			Number of Engines
	Wing-1	Tail-2	Wing-3	
A	2636	2643	2682	204
B1	2643	2902	2352	52
B2	2189	2395	2099	94
C	2194	2938	2062	92

Exactly why the tail-mounted engine tends to remain installed longer for three of these groups, but not for the largest group, is unknown. Obviously, such conditions as erosion, FOD, maintenance practices (wing engines are easier to inspect and remove), and the like have an impact on these data. That the differences observed were small and applied to only some of the airlines indicates that the trend appears not to be significant.

Multiple-Build Inbound Test

Only one inbound performance calibration of a multiple-build engine was available for this program. In fact, this engine, ESN 451380, was tested as a part of the program. The details of this inbound test and subsequent hardware inspection are contained in the report "Long-Term CF6 Engine Performance Deterioration - Evaluation of Engine S/N 451380" (Reference 4). The details will not be represented herein, but the results were in general agreement with those previously discussed for initial installation engines.

UNRESTORED PERFORMANCE - OUTBOUND SERVICEABLE ENGINES

The third and final classification of long-term performance deterioration was that of unrestored performance of outbound serviceable engines. After an engine is rebuilt from serviceable modules, its performance is recalibrated in a test cell at the repair facility to ensure that the refurbished

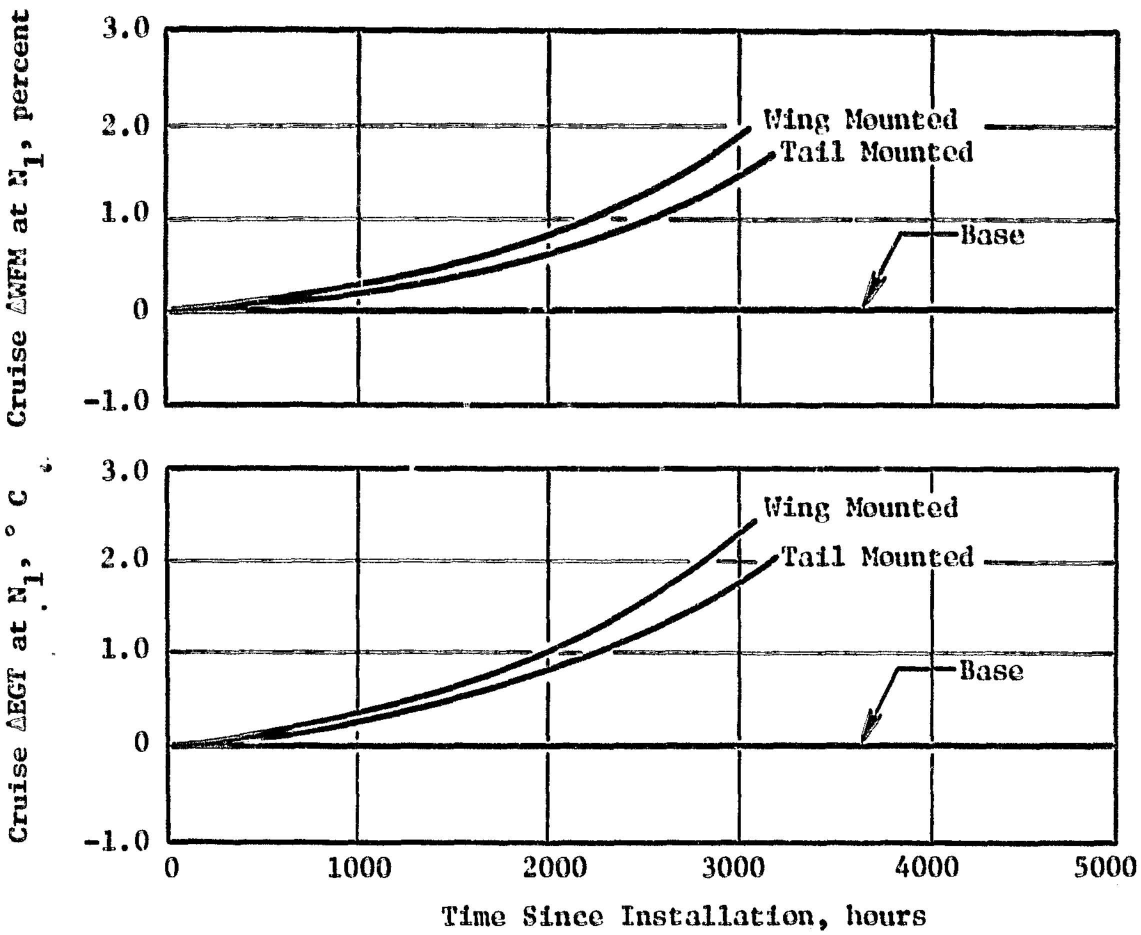


Figure 4-16. Effect of Engine Position on Cruise Performance.

engine meets thrust and EGT requirements. Not only does an outbound performance calibration establish the engine condition at the onset of the next revenue service installation, but also the delta between the outbound level and a production new baseline quantifies the unrestored performance.

Outbound performance calibrations at a major repair facility were analyzed to derived trends of serviceable refurbished engines prior to reentry to revenue service. Results of CF6-6D outbound performance tests were examined for a 32-month period from May 1976 to December 1978, for engines utilizing current-configuration hardware. The examination covered 270 test results from 165 different serial numbers. Results were obtained from one to three tests per engine serial number, including anywhere from the first to the tenth shop visit. Outbound performance calibrations from at least one test were obtained for over 70 percent of ESN 451406 series engines and 45 percent of all CF6-6D serial numbers through ESN 451496.

These outbound results were compared to average performance levels of new production engines. Average production performance levels were based on the seventeen CF6-6D engines shipped during 1975. This baseline was appropriate for the analysis of outbound engines since significant product improvements incorporated into these 1975 production engines had also been incorporated into field engines since that time.

Several adjustments to the repair-facility-measured performance were required to obtain data on a comparable basis with the referenced as-shipped performance of new production engines. These adjustments were to account for test cell differences (fuel flow measuring system, fan nozzle area, and thrust calibration error over an early portion of the data) as well as the engine hardware configuration (fan booster shroud configuration). The effects of these adjustments were largely to lower the fuel flow measurements by 1 percent to 2 percent as well as to increase the thrust measurements up to 1 percent. The combined effect was to lower outbound sfc assessments by from 1 percent to 4 percent depending on the time period of test and test cell utilized. Although these adjustments were significant, they produced average outbound performance levels similar to those observed at other repair facilities.

Unrestored sfc and EGT performance levels for serviceable outbound engines, relative to the new production engine baseline, are presented in Figure 4-17 as a function of shop visit number. Each symbol represents the average performance from 19 to 37 outbound tests of serviceable engines during a particular shop visit - for example, 29 engines were tested during their third vists to the repair shop. The average performance level with shop visit was observed to be steady, although considerable variance among individual engines was seen. Likewise, when these performance parameters were plotted against time or cycles since new, the individual test points scattered about the average unrestored levels of 2.8 percent sfc and 14° C EGT as shown in Figure 4-18 and 4-19.

The CF6-6D outbound performance trends indicated that after the second installation/removal cycle the average unrestored performance levels remained

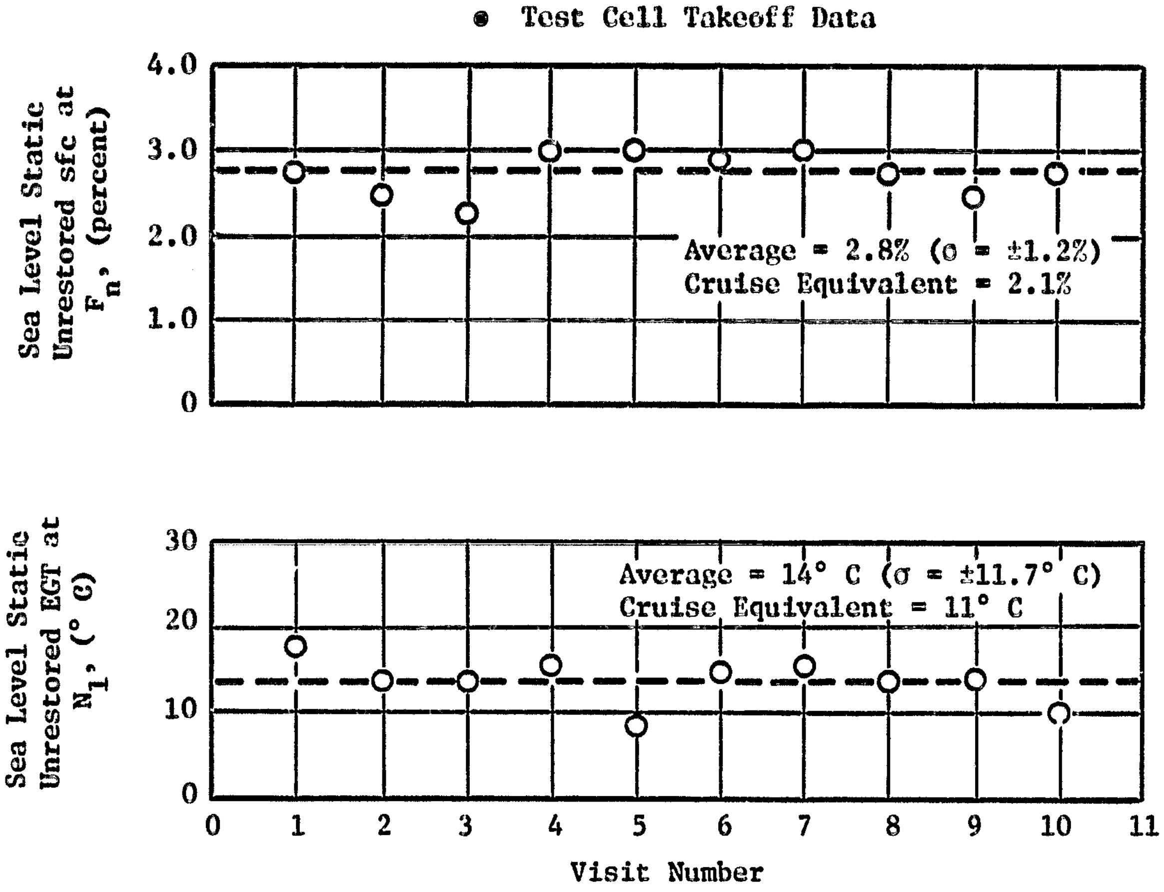


Figure 4-17. Outbound Performance Trends of Serviceable Engines.

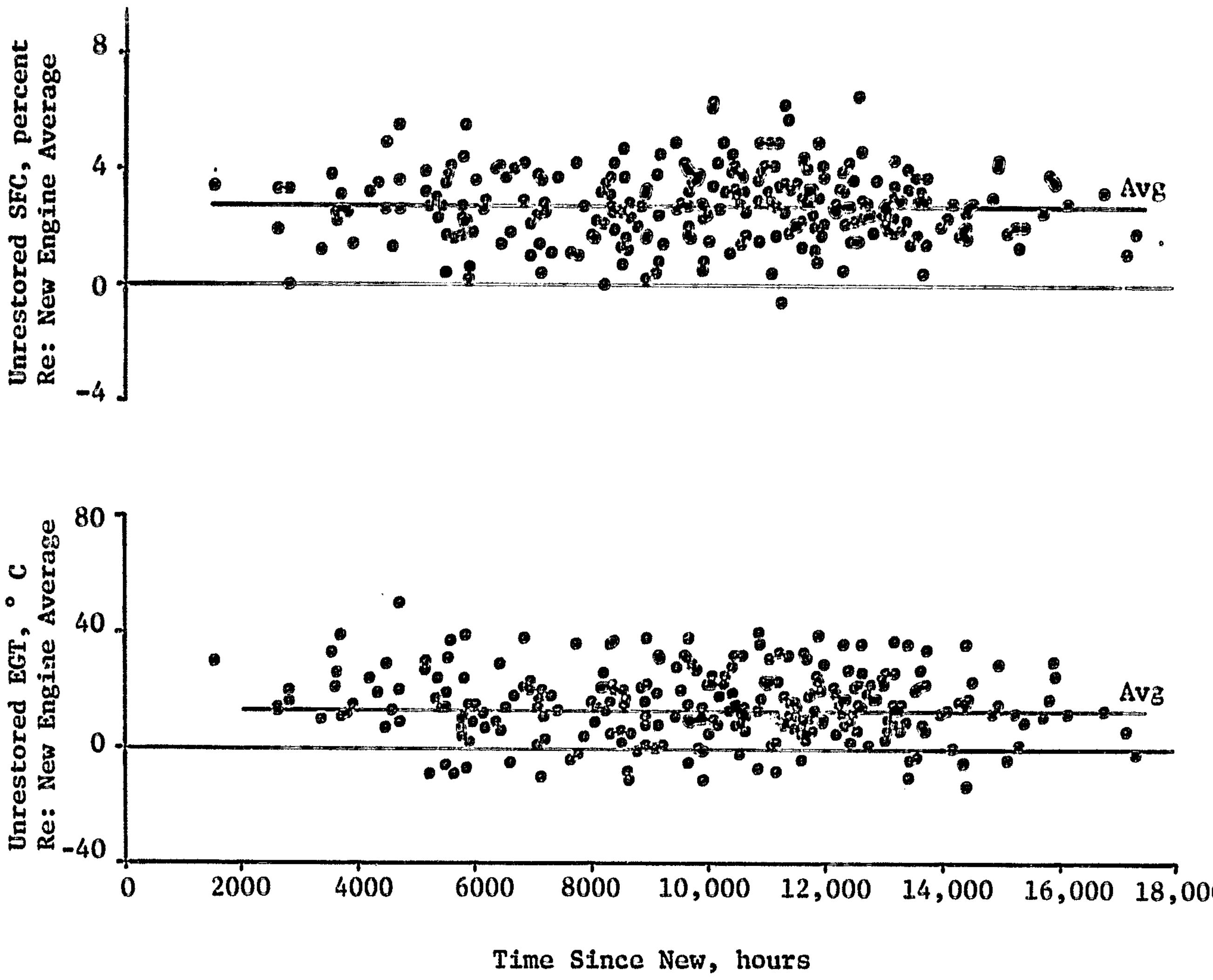


Figure 4-18. Unrestored Outbound Performance Vs TSN.

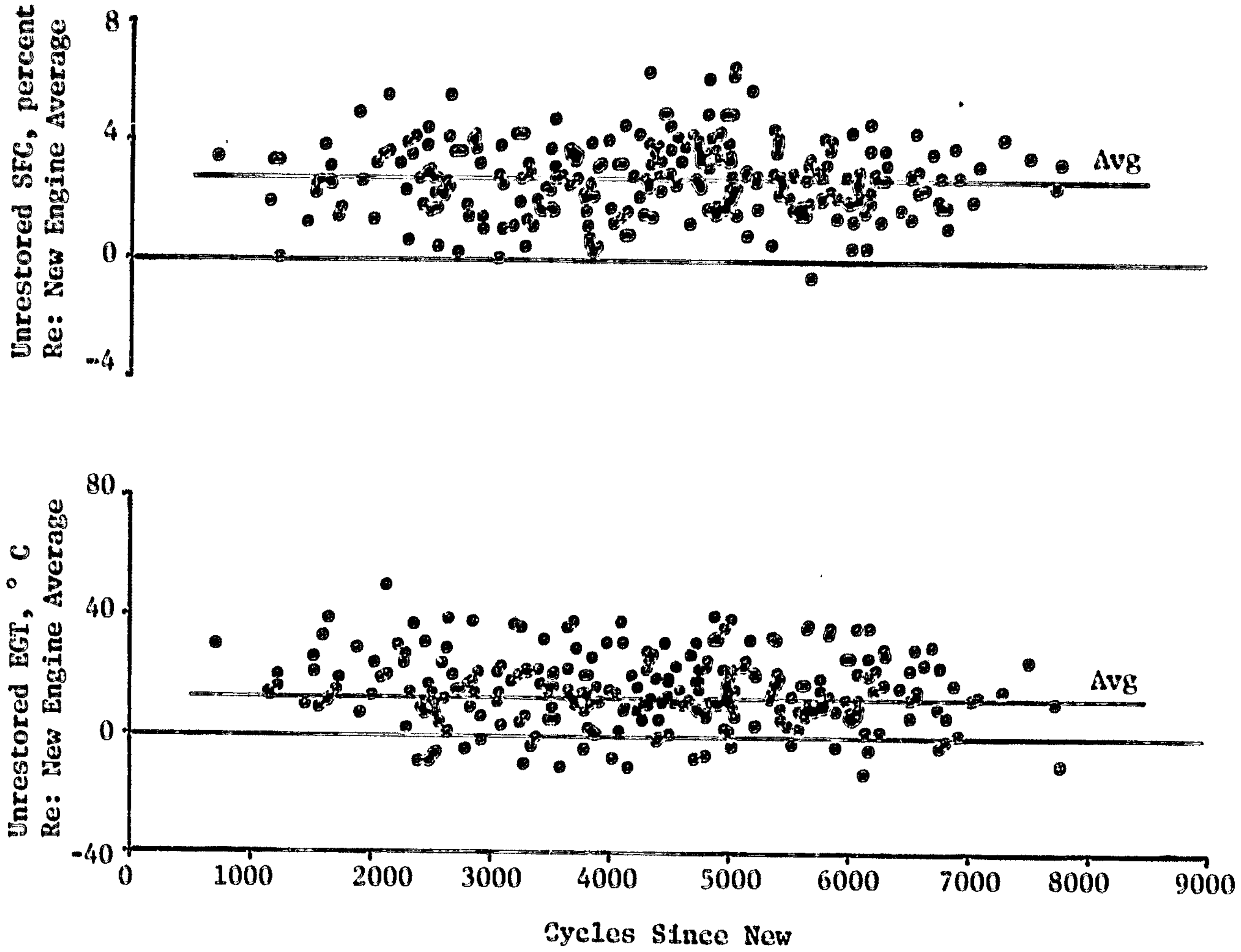


Figure 4-19. Unrestored Outbound Performance Vs CSN.

essentially constant. (There were not sufficient data available to be confident about the amount of performance restoration during the first shop visit.) This means that the average amount of performance restored during refurbishment was coincidentally equivalent to the average loss during the previous installation. It must be recognized, however, that these were based on averaging a large number of engines in the fleet and were not representative of individual engines which, when compared with each other, showed considerable variance in the amount refurbished and the amount lost during the prior installation.

This steady outbound performance trend differs from that which was anticipated at the onset of this program. Originally, it was expected that the data would exhibit an increasing deterioration trend, showing progressively higher levels of unrestored performance for each successive installation. The observed trend of relatively constant levels, however, can be attributed to the modular maintenance concept employed to repair engines. Since engines were built up using both serviceable and repaired modules as available, the assembled engine contained a collection of modules/parts of various ages. For example, some serviceable 10,000 hour parts could have been mixed with new spare parts during the rebuild of an engine. This maintenance concept thus contributed to the variation in rebuilt quality for the individual engines. However, since the use of parts for any given engine was random, the average quality and performance remained similar.

Since no changing trend was identified, unrestored overall performance of these airline refurbished CF6-6D engines can best be represented by determining the mean level from the available data. These average unrestored levels, relative to the 1975 engine reference levels, and their associated standard deviations are presented in Table 4-VII.

Table 4-VII. Average Unrestored Peformance of Outbound Engines.

Overall Performance	Sea Level	Cruise Equivalent	Standard Deviation
Δsfc at FN (%)	2.8	2.1	1.2
ΔH.D. EGT at N1 (° C)	14	11	11.7
ΔWFMK at N1 (%)	0.8		1.2

The estimates of cruise equivalent performance levels were based on previous experience using a thermodynamic cycle for a refurbished CF6-6D engine.

A consideration regarding this unrestored performance should be noted. The basic objective of the refurbishment efforts at the repair facilities during the time period in which the outbound data were available, was to replace damaged or nonserviceable parts and to restore EGT temperature margin so that the engine could be expected to return to revenue service for an acceptable period of time. The refurbishment emphasis was directed at the core hot section to provide mechanical durability and restore core performance; maintenance of the other modules was generally not required at the same frequency in order to achieve the primary refurbishment objectives. Since fuel conservation was not the primary concern during the time, the unrestored sfc could become significant.

LONG-TERM PERFORMANCE SUMMARY

Each of the elements of long-term performance deterioration are presented in Figure 4-20 for the CF6-6D, showing equivalent cruise fuel burn increases relative to a production new baseline.

The initial installation is shown on the left. Engines incurred an average short-term loss of 0.9 percent prior to revenue service. During their initial installation, fuel burn increased an average of 1.7 percent (based on the 4000-hour family of engines.) The total increased fuel burn of this deteriorated engine was thus 2.6 percent from production new. Insufficient data were available to determine the amount of performance restoration during the first shop vist.

During the "nth" installation, the serviceable engine returned to revenue service after a shop visit with an average unrestored cruise fuel burn performance of 2.1 percent. During revenue service, the cruise fuel burn of this multiple-build engine increased 0.9 percent and the total increased fuel burn of this deteriorated engine at 3000 hours was 3.0 percent from new. On the average, the 0.9 percent cruise fuel burn lost during 3000 hours on wing is restored during the next shop vist. Thus, the 2.1 percent deterioration at installation and 3.0 percent deterioration in fuel burn at removal is representative for the life cycle of the engine.

It is noted that while these data are based on the average of large sample sizes, considerable variation was noted for the individual engines.

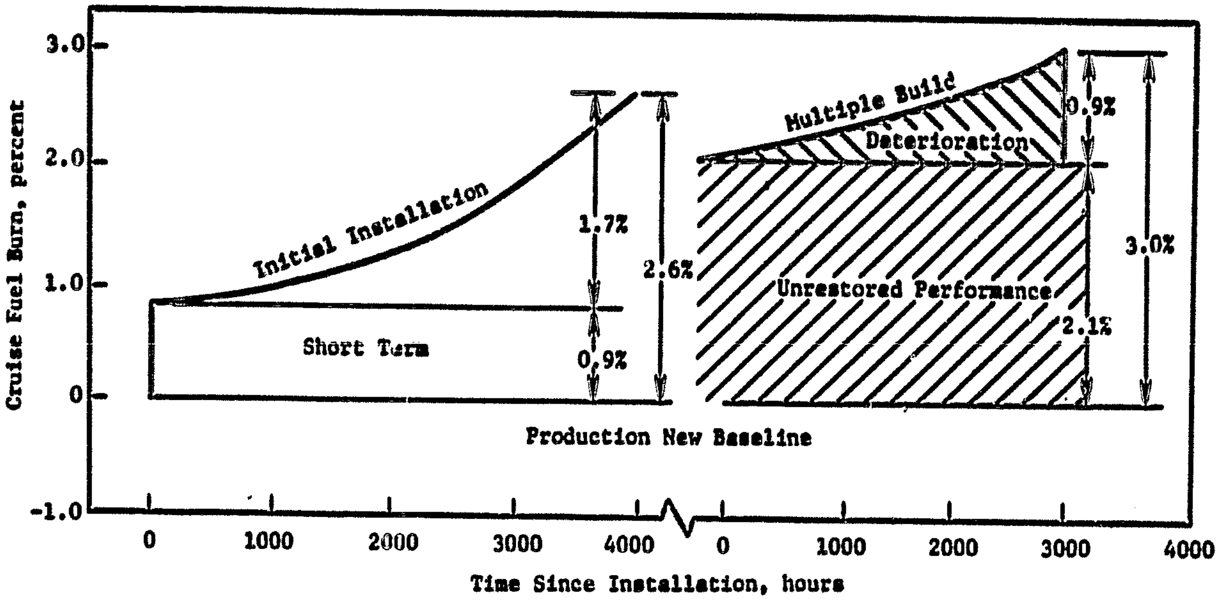


Figure 4-20. CF6-6D Cruise Performance Summary.

4.2 HARDWARE DATA

In order to obtain a representative sample of deteriorated hardware data, a multifaceted program was established to collect, document and analyze used-parts data from a number of different airline and General Electric facilities. Historical data were obtained, as available, from airline and General Electric files and independent overhaul sources. It was readily apparent, based on initial reviews, that available historical data were generally neither the correct type nor sufficiently detailed to satisfy the objectives of this program.

Accordingly, programs were established to obtain the required data with the necessary details. Current hardware inspection data were obtained from United Airlines (UA) where analytical teadown inspections were performed on 24 sets of deteriorated and repaired engine modules. Back-to-back tests with selected refurbishment of the low pressure turbine module were also conducted in conjunction with the UA efforts. The details for the low pressure program are presented in Reference 2, and the pertinent results are included in these analyses.

In addition to the UA program, additional used-parts data were collected from two special revenue service engines. These engines had accumulated representative on-wing time and performance deterioration at removal. Not only were these engines completely disassembled to provide hardware inspection data for all modules, some selected refurbishment and back-to-back testing were conducted to evaluate specific low pressure turbine and fan deterioration items. References 3 and 4 document the details and results from this program.

The special UA program and analyses of hardware data were conducted by teams of General Electric personnel with on-site airlines support from United Airlines. A team for each of the four major engine sections (fan, high pressure compressor, high pressure turbine, and low pressure turbine) was established; and each team consisted of a mechanical designer, an aerodynamic design expert, and airline service hardware engineer (normal customer interface), a performance restoration specialist and a performance analysis engineer. These teams were totally responsible for their assigned hardware, and in addition to hardware conditions, they evaluated shop procedures, quality of repairs, current restoration workscopes, and adequacy of field instructions.

The design teams conducted detailed analyses of the salient inspection measurements and the deterioration modes were categorized as either a clearance change, an airfoil quality degradation, or an internal/external gas flow leakage. Influence coefficients were used by the aero designers to convert the delta hardware conditions to calculted losses in component efficiencies and flows. These in turn were stated in terms of cruise sfc deterioration by the use of engine computer cycle model derivatives. These module assessments were refined using the back-to-back engine test data to finalize the deterioration characteristics for each module. In addition, the teams conducted analyses to determine potential causes for the deterioration, and participated in cost-effective restoration studies which are discussed later in this report.

As noted previously, the long-term studies were conducted to determine performance deterioration characteristics for the initial-installation (new) and multiple-build (repaired) engines, and to isolate the sources of the unrestored losses for the multiple-build engines. The deterioration characteristics for the initial-installation engines are the "truest" form of CF6-6D engine deterioration since all parts are brand new and have the same time or cycles since repair/overhaul. The multiple-build engines include a mixture of used, new, and repaired parts and are typical of the current airline fleet since few new CF6-6D engines have been manufactured since 1976.

Very little hardware data were available from initial-installation engines to empirically determine the deterioration characteristics for the engine model. However, engine modules inspected from multiple-build engines did include replacement or retrofit with new parts, and those data in conjunction with the other data were used to describe the deterioration characteristics. The majority of the hardware data samples were in the excess of 2000 hours; therefore, while the magnitude of deterioration could be established for a fixed time above 2000 hours, the deterioration curve shape could not be empirically derived for each module. The procedure used to "average" the results and to estimate the deterioration curve shape was as follows:

1. A representative time-to-repair was selected for each module based on hardware data analysis and engine removal statistics.
2. The hardware team used the empirical hardware data to determine the expected loss for each module for the time-to-repair selected as representative.
3. The teams then estimated the shape of the deterioration curve for each module using engineering judgment in conjunction with the available hardware data.

The shape of the deterioration curve is considered reasonable but not necessarily reliable, having been generated using a small amount of empirical data and large application of engineering judgment. However, the curve shape is best described by cruise performance data since a sufficient data sample size is available for all areas of the curve. The curve shape based on hardware inspection data is considered of minor importance and is used only for cost-effectiveness studies.

Hardware inspection data will be presented in the next two sections of this report. First, deterioration data describing part conditions prior to repair are presented in the next subsection. The actual findings are presented along with a general discussion as to potential causes, severities and significance. These data are then summarized and the expected deterioration at the selected number of revenue service hours is then presented, followed by the estimated curve shape based on the aforementioned criteria.

The following section then, contains all data concerning serviceable modules - i.e., modules after repairs. A general discussion of the findings and work-scope philosophy is presented, and these data are then summarized to present the best esitmate of average unrestored losses for each module.

A tabulation of the actual hardware data, including sample size, and a detailed description of how and where the data were obtained, is presented in Appendix A.

HARDWARE DATA - DETERIORATED ENGINE

Hardware inspection data describing the deterioration modes and inspection findings are presented for fan, high pressure compressor, high pressure turbine and low pressure turbine sections in the following paragraphs.

Fan Section

Deterioration of the fan section is generally time dependent (i.e., erosion rather than FOD) and can be categorized into two broad classifications: (1) flowpath deterioration, and (2) airfoil quality degradation. Each of these two classifications will be discussed separately. The results presented are based on inspecting airline modules that have accumulated 15,000 to 20,000 hours since new, and which have logged 3000 to 4000 hours since the last shop visit. A cross section of the basic fan module is presented in Figure 4-21, which notes the pertinent area of performance deterioration.

The sources of flowpath deterioration (Figures 4-21) include shroud erosion, outlet guide vane (OGV) spacer cracking, splitter erosion and protrusion of inlet guide vane (IGV) inner bushings.

Fan Shroud Erosion - A shroud is provided as part of the fan casing to control the clearance between the tip of the fan blade and the static structure. Two types of shroud material are used for CF6-6D engines: epoxy microballoon and open cell honeycomb. Most of the engines in the fleet utilize the epoxy microballoon material which is rugged and easy to replace. A particular advantage of this type of shroud is that additional microballoon material can be added to obtain desired tip clearances. The open cell honeycomb material can only be replaced at the manufacturer's facility and there is no way of adding material to reduce (or control) tip clearance. The initial blade-to-shroud cold clearances are set such that blade tip rubs are not experienced during normal engine operation, but instead occur only in the event of a large rotor unbalance. Discussions will be limited to the epoxy microballoon material since fewer than 20 percent of the CF6-6D engines incorporate the open cell honeycomb shrouds.

Clearances between the fan blade tip and shroud are set to achieve a minimum of 0.145 inch and a maximum average of 0.171 inch. The minimum clearance is designed to prevent blade tip rubs while the average clearance, which considers blade tip and shroud runouts, is designated for performance reasons.

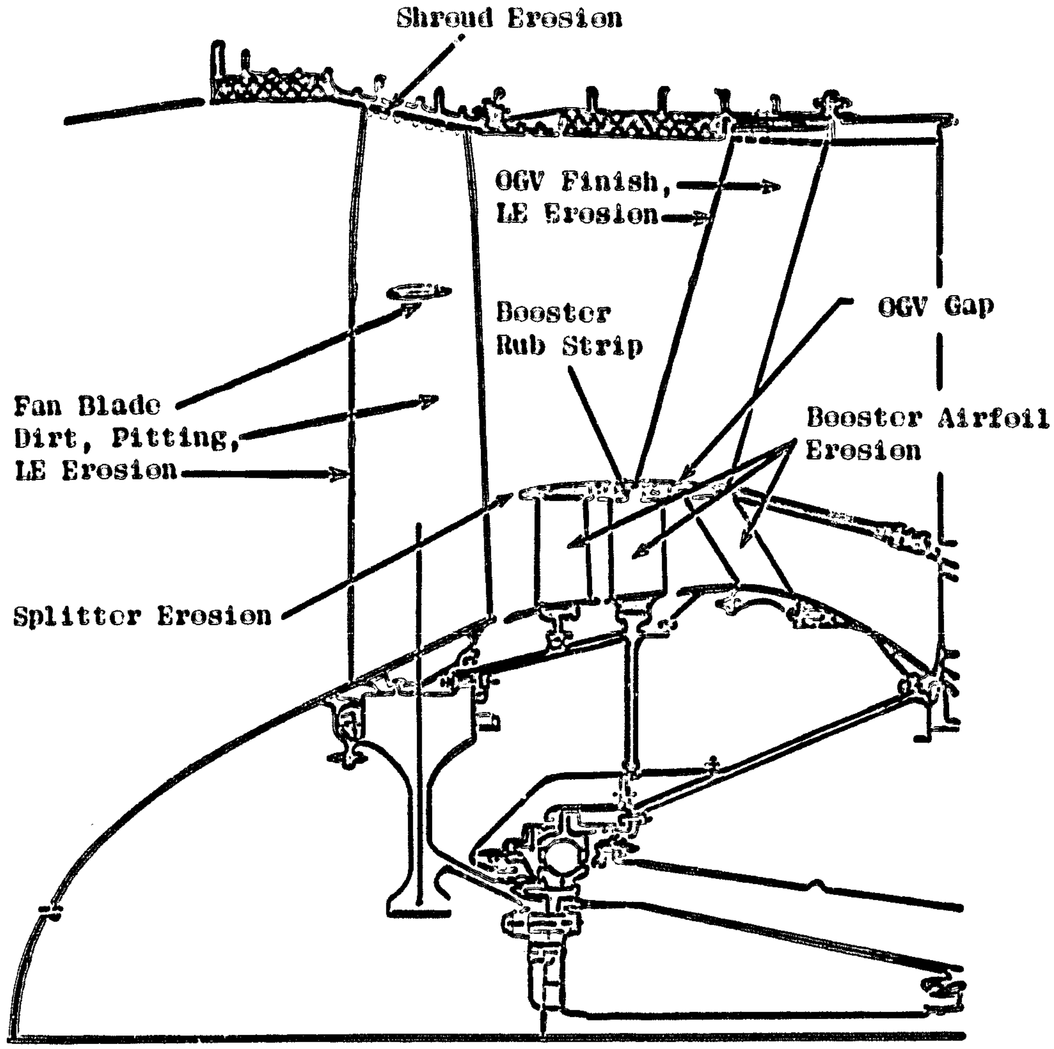


Figure 4-21. Fan and Booster Areas of Deterioration.

Measurements from eleven engines removed from revenue service indicated that the average clearance was 0.187 inch as compared with the production new engine average of 0.167 inch. Part of this clearance increase is attributed to the airline practice of controlling only the minimum clearance since clearance measurements are required only when exchanging the fan rotor or fan casing. Any under-the-minimum clearances recorded during engine buildup are opened by grinding the entire shroud diameter, which results in an increased average clearance.

Blade tip rubs were not observed on any shroud, but it was noted that shroud material experiences erosion with increasing time. An example of an eroded shroud is shown in Figure 4-22. The amount of erosion is a function of the operational environment (sandy runways, etc.), and the position of the aircraft (the wing engines showing more erosion tha tail-mounted engines). Because of maintenance procedures practices by the airlines, it is difficult to determine the amount of performance deterioration attributed to erosion from clearance measurements. Through measurements and inspections it has been estimated that shroud loss due to erosion was approximately 0.002 inch per 1000 hours of engine operation. It can be expected that considerable difference in erosion would be noted from engine to engine according to differences in route structure, etc.

Another condition that contributed to shroud deterioration was the poor quality of microballoon material replacement efforts as shown in Figure 4-23. It appears that when the microballoon material was installed in a metal mesh structure in the casing, the material was not completely filled in the lower portion of the mesh structure. These gaps or holes are exposed during subsequent machining operations carried out to obtain required tip clearances and to incorporate circumferential grooves.

The combined effect of the shop maintenance practices and erosion for an engine after 6000 hours operation is a fan tip running clearance increase of 0.020 inch. This is equivalent to a 0.4 percent loss in fan efficiency and a 0.21 percent loss in cruise fuel burn efficiency.

Booster Shroud Erosion - The rub strip material in the booster casing over the booster blade (quarter stage) was originally epoxy microballoon. The material was determined by General Eelctric to be a hazard if severe rubs were to occur, and the rub strip was removed throughout the fleet. An open cell honeycomb replacement design was developed and recommended for field use, but operation was permitted without any rub strip material in place. For all engines inspected the rub strip had been removed and not replaced. This same condition exists throughout the fleet. Even though this condition is not the result of engine deterioration, it is categorized as deterioration for these studies.

Removal of the rub strip material over the rotor resulted in a 0.185 inch clearance increase. This clearance increase results in a loss of 1.33 percent in booster efficiency or a 0.19 percent loss in cruise fuel burn efficiency.

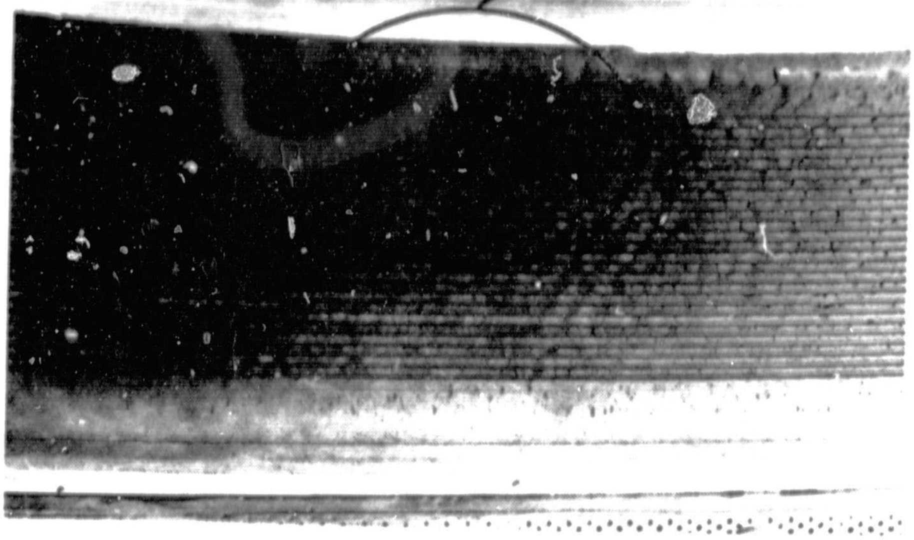


Figure 4-22. Epoxy Microballoon Fan Shroud Showing Typical Erosion Effects After Revenue Service.

Figure 4-23. Epoxy Microballoon Fan Shroud with Open Cells After Repair.

OGV Spacer Cracking - Nylon spacers are used between the outlet guide vanes to form the outer flowpath. These plastic spacers fit snugly against the concave side of one vane and the convex side of the adjacent vane. With time, the edge of the spacer adjacent to the vane airfoil may crack, causing a piece to eventually break away from the spacer. This results in a leakage path as well as allowing flow recirculation. The accepted repair for this condition is to replace the spacer or to fill in the gap with a material such as a room-temperature vulcanizing (RTV) compound, which provides an excellent flowpath filler. Most of the repairs observed, however, had very poor filler radii and poor smoothing of the RTV, so that a blockage was formed. Since the quality of this repair is variable and the performance impact small, it is difficult to estimate an efficiency loss. An improvement in performance, however, can be realized by replacing the poor-quality RTV repair with a new nylon spacer or replacing the RTV.

Splitter Leading Edge Erosion - The flow splitter, located behind the fan rotor, forms the OD flowpath for the quarter-stage rotor. This splitter showed heavy erosion and bluntness on all engines inspected. This erosion probably occurs in the first 6000 hours with little additional bluntness occurring beyond the 6000 hours mark. The increased drag coefficient due to the splitter bluntness results in a loss of 0.15 percent in fan efficienty or 0.08 percent in cruise fuel burn.

Inner IGV Bushings - Most engines use the inner IGV design that utilizes a nylon bushing that forms the inner flowpath of the quarter-stage flow and stabilizes the inner section of the vane. This nylon bushing tends to work itself out into the flowpath by as much as 0.10 inch, causing a blockage. This condition can be remedied by using an adhesive. With the installation of the nylon bushing, the adhesive can be RTV which has proven successful at keeping the nylon bushing flush with flowpath surface. Since this condition varies from engine to engine and within an engine, a loss in performance will not be presented for the average engine, but properly seating or attaching this bushing with adhesive will results in some performance improvement.

Airfoil Quality

This is the second of two general classifications of fan section deterioration and includes fan blade leading edge quality, airfoil quality of fan and booster blades, and condition of the fan OGV surfaces.

Fan Blade Leading Edge - The physical condition and shape of the fan blade leading edge is extremely important for optimum performance. Erosion of the leading edge in 6000 to 8000 hours of engine operation has been observed to be a significant deterioration mode. This erosion tends to blunt the edge as shown in Figure 4-24. While it is difficult to analytically assess the performance effects of changes to the fan blade leading edge shape, factory and field experience have permitted a reasonable assessment. Based on visual observation, the performance degradation due to fan blade leading edge bluntness was assessed at 0.71 percent fan efficiency or 0.38 percent cruise fuel burn.

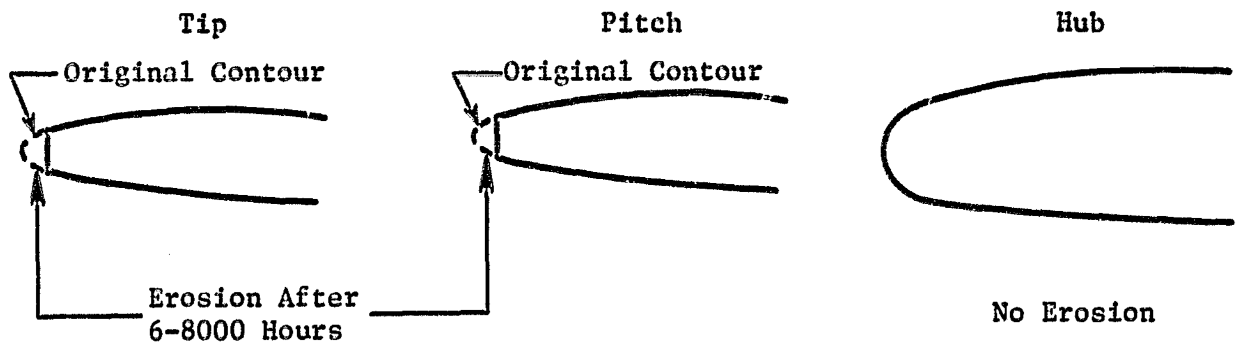


Figure 4-24. Results of Erosion on Fan Blade Leading Edge.

Since the erosion/impact condition is dependent on geographical area, ground time, and low altitude flight time, the leading edge condition can vary significantly.

As part of this program, back-to-back engine tests were conducted before and after fan blade refurbishment. The refurbishment consisted of reworking the leading edge to an acceptable contour and cleaning the airfoil surface with a non-oil-base cleaning agent. The results of two tests indicated that the total delta effect was 0.8 percent in fan efficiency (0.43 percent cruise sfc), a loss which agrees favorably with the hardware inspection assessment.

Fan Blade Airfoil Quality - Small pock marks approximately 0.004 inch to 0.006 inch deep were observed in the concave surface of the fan blade airfoil in the first two to three inches above the hub. There was a large difference in the number of indentations observed in blades from different engines, suggesting they may be a function of engine position and environment as well as time. During a shop visit the indentations are not removed since complete removal would result in excessive removal of blade material, resulting in thinning of the airfoil. Dirt buildup on both the concave and convex side of the fan blade was present, and analyses of data indicate that the dirt accumulates during the first few hundred hours of operation and seems to remain constant after that. The dirt accumulation is of a "cosmetic" nature and is easily removed by washing the blades with a commercial solvent. The expected losses in efficiency and flow due to surface finish and dirt accumulation are within experimental test accuracies and must be estimated by analytical means.

The pitting observed on the fan blade pressure side of the airfoil degrades the new blade surface finish from a required 55 μ in. AA to an estimated 120 μ in. AA in about 6000 hours. This increase in surface roughness occurs primarily over the first three inches of the airfoil chord for the entire airfoil span. This results in a loss of 0.06 percent fan efficiency, or 0.03 percent cruise fuel burn.

Dirt deposited on airfoils is considered a surface roughness condition. Attempts to make surface roughness measurements, however, were unsuccessful since the dirt deposits are relatively soft and the instrument stylus acutally penetrates the deposits. Reference can be made, however, to test cell experience where dirt deposition occurs at a more rapid rate due to the industrial environment. Washing fan blades with a non-oil-base cleaning agent has resulted in fan efficiency improvements of over 0.3 percent. Based on the engines inspected, however, it is estimated that the loss due to dirt accumulation for a 6000-hour engine is 0.24 percent in fan efficiency or 0.13 percent in cruise fuel burn.

Fan Outlet Guide Vane Degradation - The fan OGV airfoils of engines presently in service are protected with a polyurethane coating over the entire outer surface. With time, it has been observed that portions or all of this coating is missing as a result of significant erosion. Repair or replacement of this coating is not normally made during an engine shop visit. In addition to the coating loss, the OGV leading edge become blunt due to the erosive action. Measurements have shown that the surface roughness has increased from 20 μ in. AA to approximately 160 μ in. AA on the suction side and to 180 μ in. AA on the pressure side due to the coating loss.

The increased surface finish drag results in a fan efficiency loss of 0.35 percent and the blunt leading edge is estimated to sustain an additional 0.12 percent loss in fan efficiency. This is equivalent to a 0.25 percent loss in cruise fuel burn. It is estimated that this level of deterioration occurs by 6000 hours and remains relatively constant after that.

Booster Stage Blade and Vane - Minor erosion was noted on the concave surface of the first-stage vanes (IGV) and booster (quarter-stage) rotor blades, with some blunting of the leading edge. The inner OGV's had experienced cracking, and the cracks were repaired by hand rework (grinding) of the crack and adjacent metal. This leaves the reworked vane blunt and with an incorrect contour in the area of rework, as shown in Figure 4-25.

Surface finish measurements on the booster airfoils indicates a roughness of 45 μ in. AA whereas new parts are nominally 24 μ in. AA. This increased roughness results in an inner flowpath efficiency loss of 0.18 percent for all three airfoil rows. The increased leading edge bluntness of all three rows is estimated to account for an additional 0.18 percent loss in efficiency resulting in a total cruise sfc deterioration of 0.05 percent. Here also, the degradation occurs by 6000 hours and then remains relatively constant with increasing time.

SUMMARY OF FAN SECTION RESULTS

The fan section performance deterioration is presented in Table 4-VIII. The data have been summarized as "typical" at 6000 hours since new, although portions of the module have accumulated 15,000 hours with little or no repair/refurbishment. As shown in Table 4-VIII, the total inbound deterioration is assessed at 1.32 percent cruise sfc (fuel burn) at constant thrust. This loss can be categorized as flowpath deterioration (0.48 percent sfc) and airfoil quality degradation (0.85 percent sfc).

Figure 4-26 shows the estimated fan section deterioration characteristics with time. It can be seen that the 0.19 percent sfc loss due to the removed booster shroud material is shown as a constant loss since it is due to shop maintenance practices rather than true revenue service deterioration.

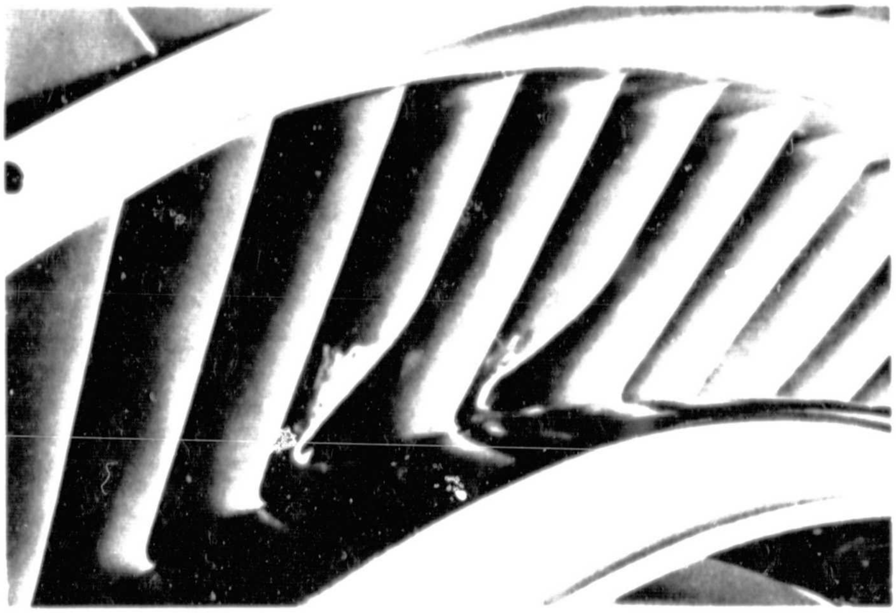


Figure 4-25. Reworked Inner OGV with Incorrect Contour and Blunt Leading Edge.

Table 4-VIII. Fan Section Deterioration After 6000 Hours.

	ΔSFC at Cruise (%)
Fan Blade	
• Tip Clearance	0.21
• Leading Edge Contour	0.38
• Surface Roughness	0.03
• Dirt Accumulation	0.13
Splitter Leading Edge	0.08
Bypass OGV Leading Edge	0.06
Bypass OGV Roughness	0.19
Quarter Stage	
• Rotor Tip Clearance	0.19
• Airfoils Leading Edge	0.025
• Airfoils Roughness	0.025
Net	1.32

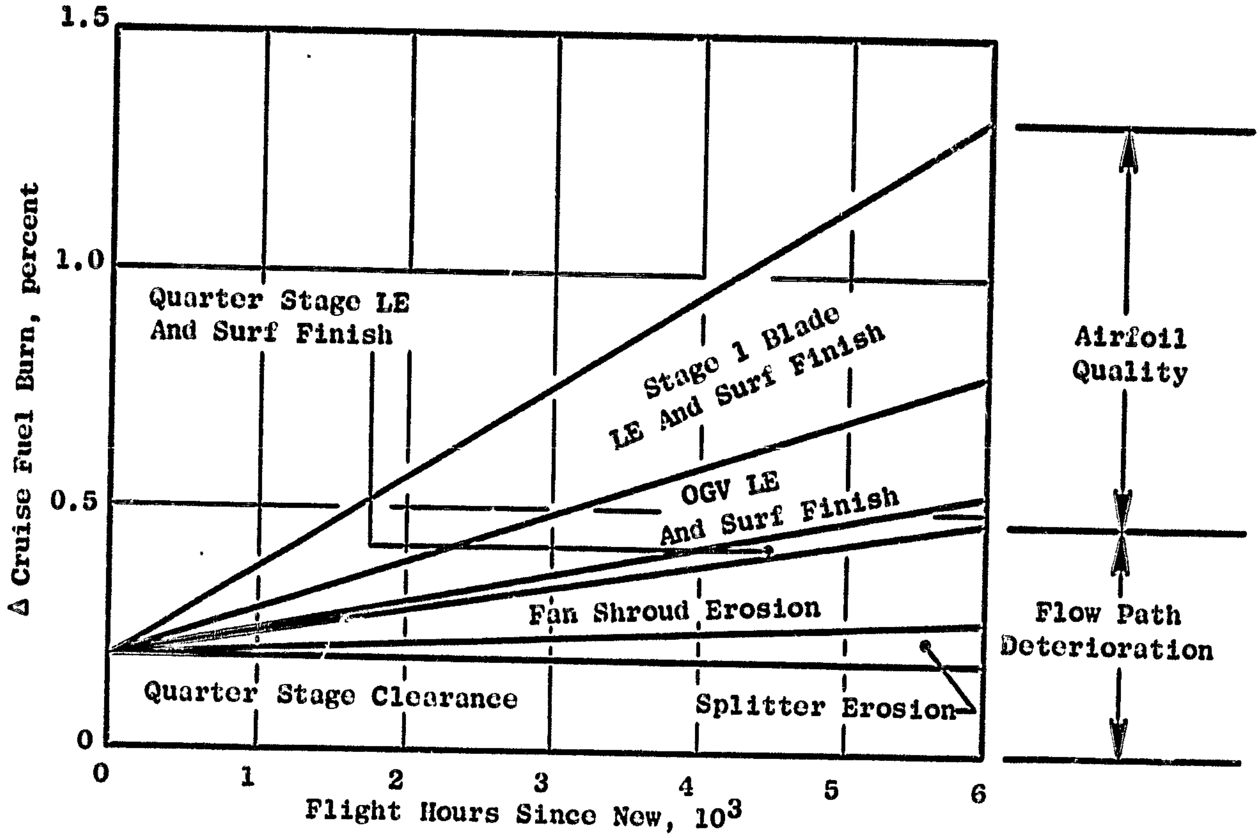


Figure 4-26. Fan Section - Estimated Deterioration Characteristics.

High Pressure Compressor (HPC) Section

Performance deterioration of the high pressure compressor (HPC) can result from a number of factors. These factors can be generally classified as either airfoil tip clearance changes, airfoil quality degradation or leakage. A cross section of the HPC module showing the deterioration modes is presented in Figure 4-27.

Changes in blade-to-casing or vane-to-rotor spool clearance can result from coating loss or rubs and from shorter blades/vanes caused by rubs or airline assembly/maintenance practices.

Flowpath Coatings used in the HPC are intended to provide protection from abrasion of the casing and rotor structure surfaces; to provide an abradable material which tolerates small local rubs without causing a major change in blade or vane length; and to minimize or prevent HPC mechanical damage. A coating, Metco 450 plasma spray, is used to provide abrasive protection for the casing and rotor structural members. This material also provides a bonding surface for an abradable aluminum spray coating used in the forward stages as shown in Figure 4-28. Initially, all stages of casing and rotor lands included the abrabable aluminum spray coating. Revenue service experience indicated, however, that the aft stages of aluminum coating suffered degradation due to spalling. This condition occurs as a result of thermal cycling which causes the aluminum/Metco 450 bond coat interface to fail due to the differences in thermal expansion between the aluminum and structural surface. Since the loss of the aluminum coating produces clearance increases on the order of 0.015 inch and additional performance losses due to surface finish degradation, the aluminum coating was replaced with the Metco 450 coating for the aft stages as shown in Figure 4-28. No Metco coating has been lost in service by spalling. Since most field engines incorporate the Metco 450 coating for the aft stages, this configuration will be used for the long-term deterioration study.

Analysis of 15 engines indicates that spalling of the aluminum coating still occurs in some latter stages just forward of the stages which incorporate Metco 450. The estimated average amount of spalling for a 6000-hour HP compressor is shown in Figure 4-29. Note that on the casing forward of Stage 11 and on the rotor forward of Stage 7, spalling does not occur.

Blade Tip Rubs were observed on the forward-to-mid stages generally at or near the twelve o'clock position. These rubs are localized and shallow, producing only a small effect on performance. Rubs are occasionally observed in other locations, but all significant rubs were associated with abnormal events like compressor stalls or mechanical failures. An estimate for clearance effect due to rubs is included in Figure 4-30.

Blade and Vane Tip Clearance. Part of the blade and vane clearance changes that were detected have been attributed to causes that were not a direct result of revenue service deterioration. It has been determined that the aft rabbet on the forward casing flanges (located at Stage 12) expands approximately 0.014 inch (diametrically) during 6000 hours of engine operation. This

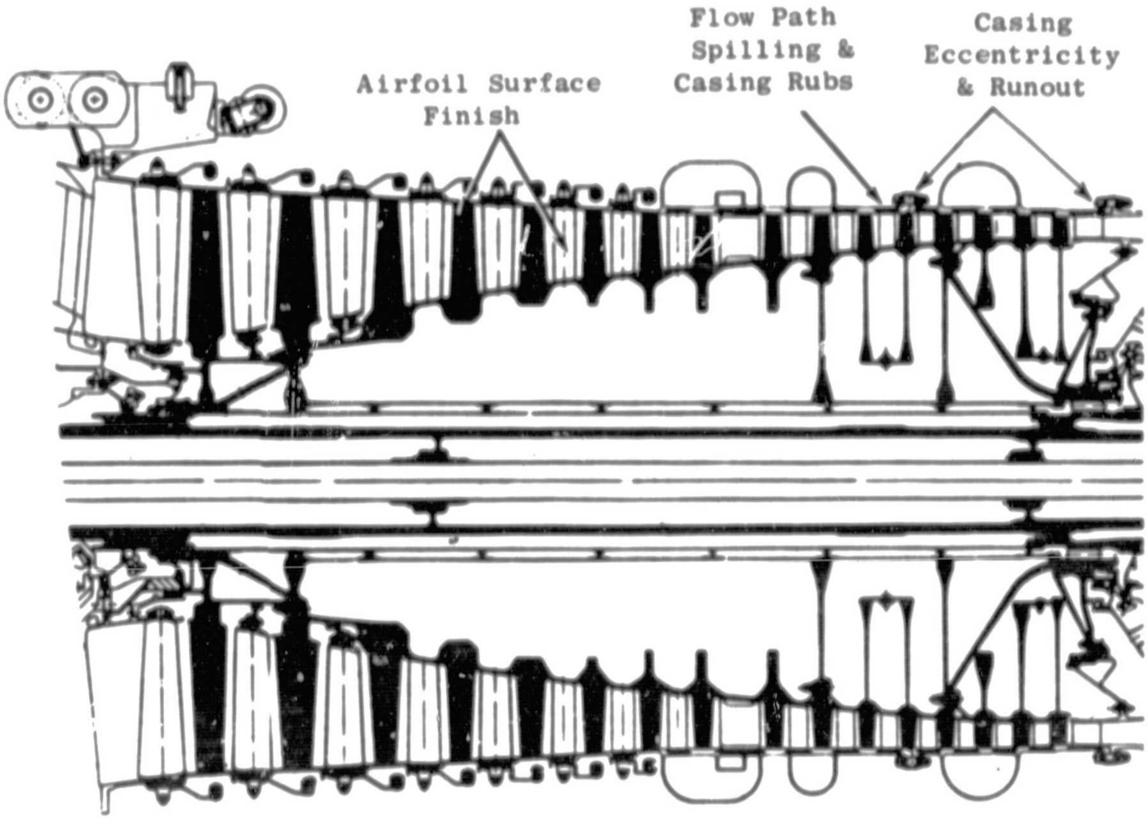


Figure 4-27. CF6-6 Deterioration Modes - HP Compressor Section.

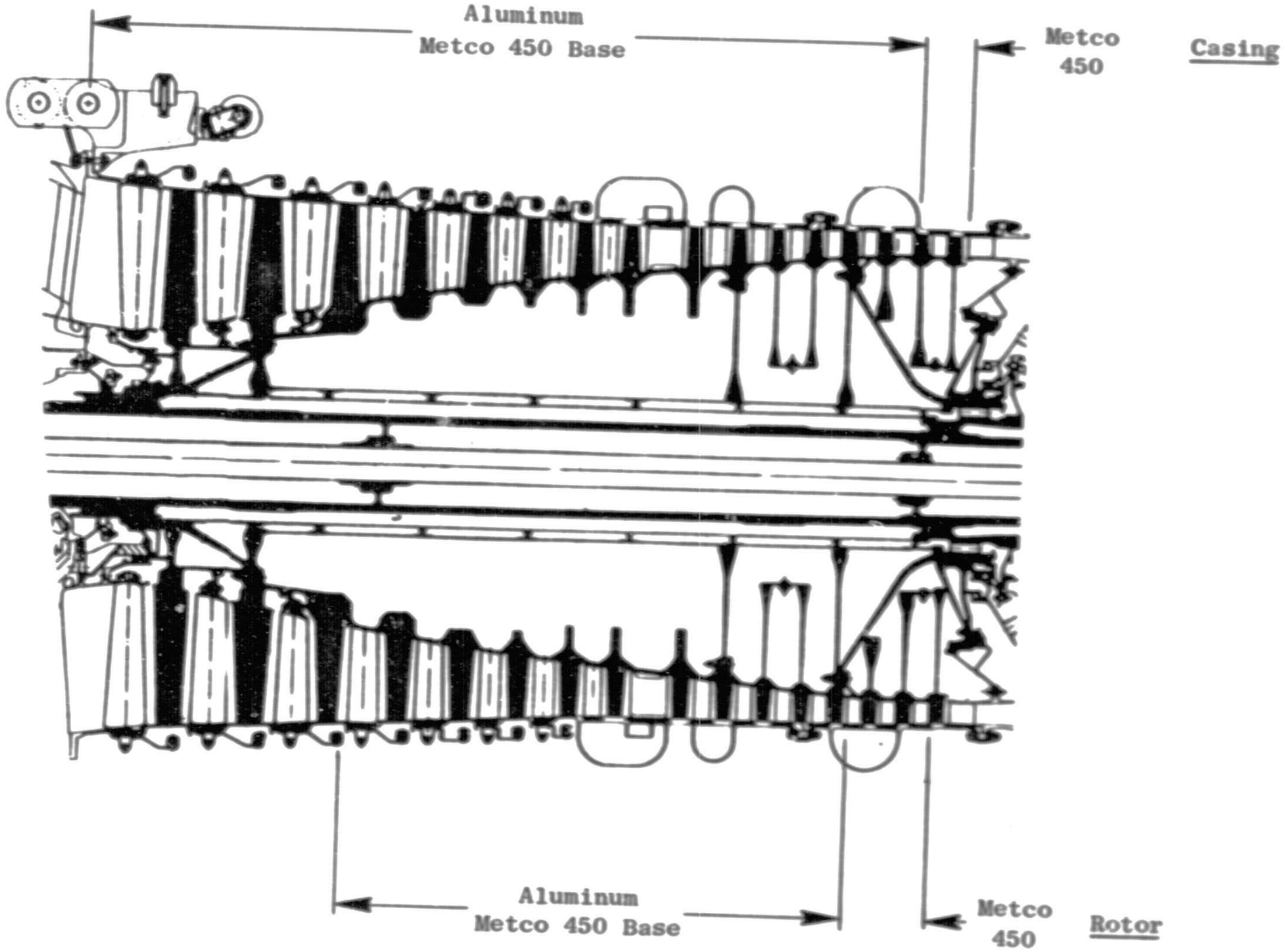
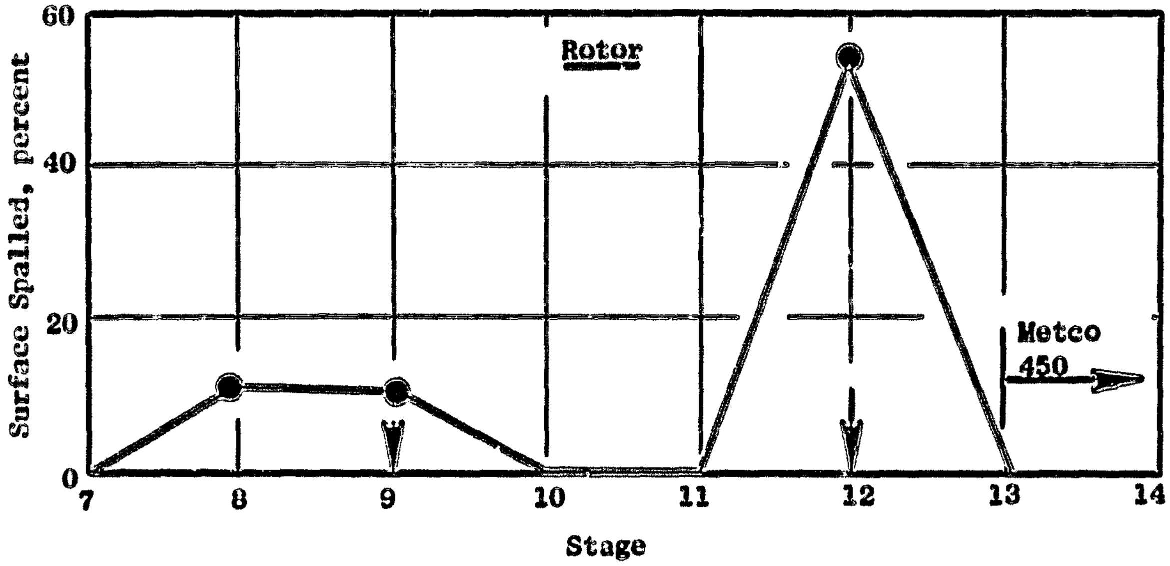


Figure 4-28. CF6-6 Flowpath Coatings - HP Compressor Section.



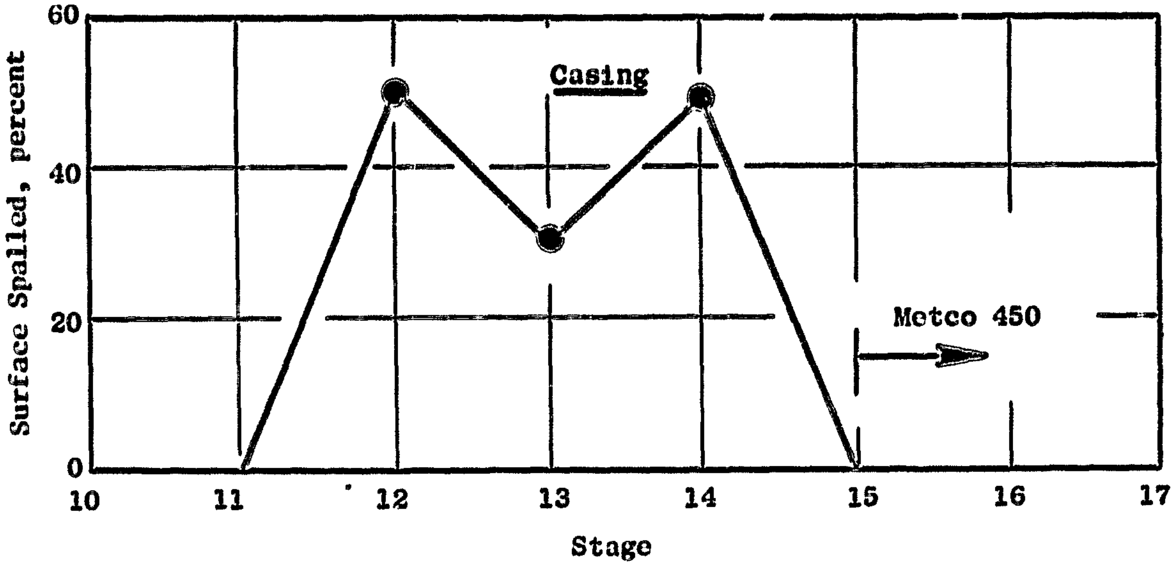


Figure 4-29. CF6-6 High Pressure Compressor - Abradable Aluminum Rub Coating Spalling Deterioration at 6000 Hours.

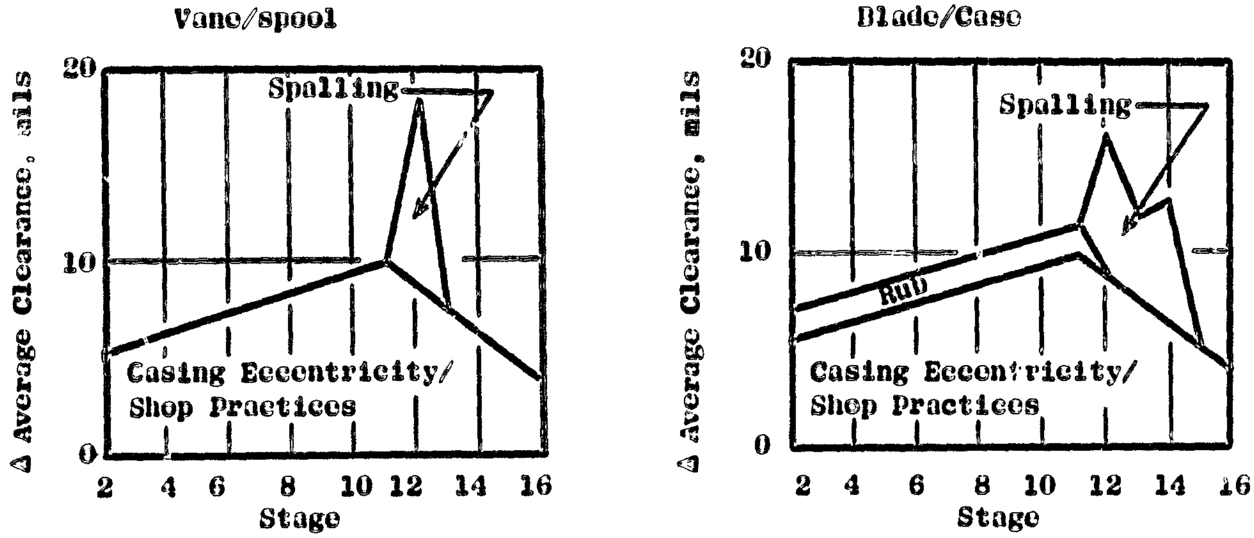


Figure 4-30. CF6-6 High Pressure Compressor - Tip Clearance at 6000 Hours.

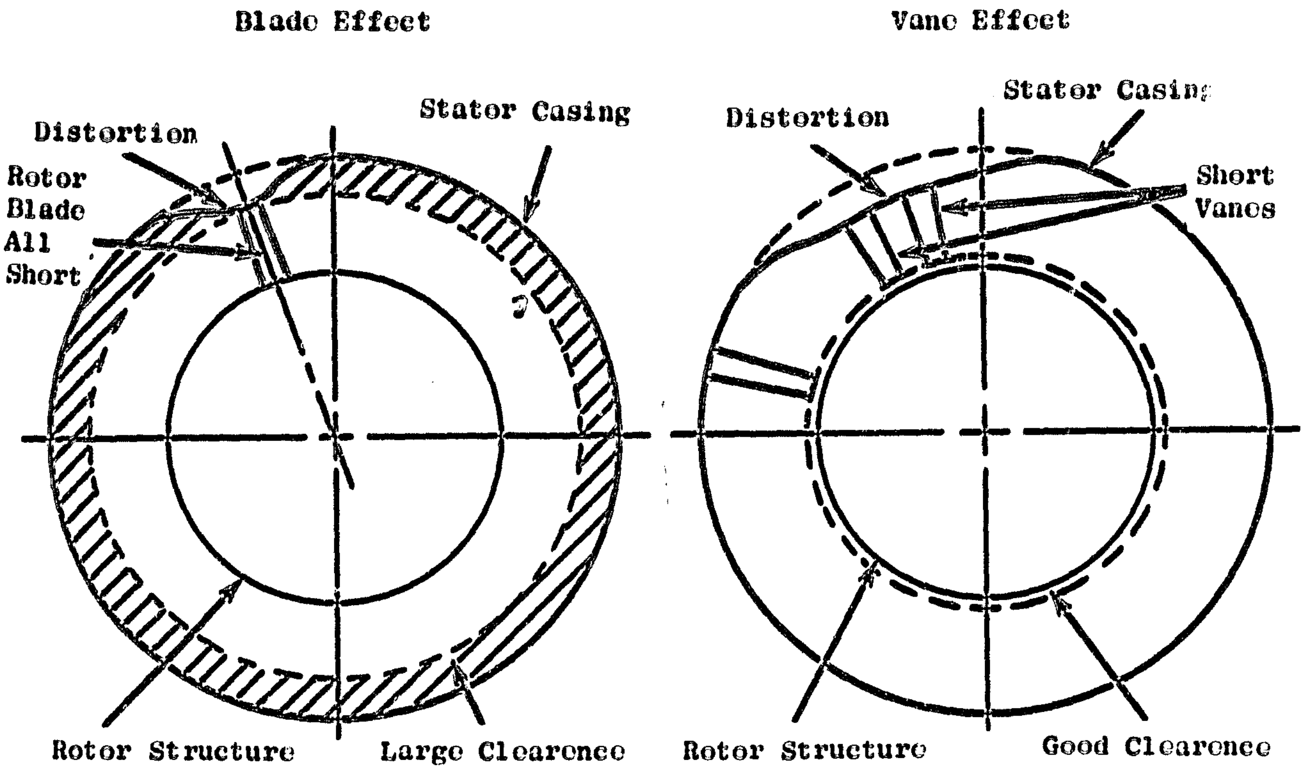


Figure 4-31. Effect of Casing Distortion on Blades and Vanes.

change in diameter can result in an eccentricity between the forward and rear casing during assembly/disassembly due to rabbet looseness. Measurements of local radial casing distortions as large as 0.025 inch have been measured. This out-of-roundness will produce local areas of inward distortion, resulting in less than the minimum required cold clearances Therefore, all the blades (or vanes) are ground to maintain this required minimum clearance. This rework produces an increase in the average clearances and a resultant performance loss. A schematic of the clearance increase due to casing distortion is shown in Figure 4-31.

The magnitude of the casing eccentricity was estimated by comparing blade and vane radii in used HP compressors with new production measurements. The average differences ranged from 0.004 inch to 0.012 inch, depending on the stage. Clearances tend to be the largest near Stage 12 (the rabbet location), where the casing eccentricity effect will be largest. The average clearance increase per stage is represented in Figure 4-30. This figure shows the total increase including the effects of spalling and rubs.

The increase in clearance presented in Figure 4-30 results in a loss of 1.31 percent in HP compressor efficiency or 0.73 percent in cruise fuel burn efficiency. This loss can be further broken down into 0.10 percent sfc flowpath spalling, 0.04 percent sfc rubs, 0.17 percent sfc casing distortion (eccentricity), and 0.42 percent sfc short airfoils.

Airfoil surface roughness increase and contour change due to erosion have been evaluated as causes of degraded performance. Audits of typical new production blades indicate that titanium blades have an average surface finish of 16μ in. AA while vanes average 25 μ in. AA. Inspection of twelve engines that had each logged approximately 6000 hours of operation indicate little change in the steel blades and vanes while titanium blade surface roughness increase to approximately 20-30 μ in. AA. This condition is prevalent for all the titanium-bladed stages and results in a loss of 0.17 percent in HP compressor efficiency or 0.10 percent in cruise fuel burn efficiency.

Visual inspection of contour changes, including leading edge bluntness and tip thinning, indicates an insignificant performance effect for the average airfoil. Used parts had been inspected prior to this program for contour changes using "eyelash" charts. These charts are 10X representations of specific airfoil sections obtained by scribing the actual parts. Comparison of these charts with a master chart indicated that performance degradation of airfoils could be discerned visually. Visual inspection of engine parts with times up to 8000 hours indicated no change in airfoil contour and, therefore, "eyelash" charts were not produced.

Another potential factor related to performance deterioration within the high pressure compressor is internal and external leakage of the gas flow. Recirculation leakage through loose blade platform gaps and flowpath steps that might cause flow separation was judged negligible based on visual observations made. External leakage can occur as a result of worn and/or missing variable stator bushings and washers located between vane OD and casings for Stages IGV

C-2

through 6. Visual inspection of these parts indicated minor deterioration did occur for Stage 5 and 6 parts after approximately 5000 to 6000 hours. This leakage can result in an overboard loss of 0.04 percent core airflow or 0.02 percent cruise fuel burn.

Summary of HPC Results

A summary of the HPC section performance deterioration is presented in Table IX. The data are given for a typical 6000-hour compressor. The total inbound deterioration is assessed at 0.85 percent cruise sfc (fuel burn) at constant thrust.

Figure 4-32 is a best estimate of the HP compressor section deterioration characteristics with time. It can be seen that the 0.42 percent sfc loss due to the short airfoils is shown as a constant loss since it is due to shop maintenance practices and not true revenue service deterioration.

Table 4-IX. High Pressure Compressor Section - Estimated Deterioration at 6000 Hours.

Blade Tip	ΔSFC at Cruise (%)
Blade and Vane Tip Clearance Increases	
• Flowpath Coating Degradation	0.10
• Flowpath Coating Rubs	0.04
• Casing Distortion	0.17
• Short Air Foils	0.42
Airfoil Quality Degradation	
• Blades	0.07
• Vanes	0.03
Leakage	
• External	0.02
Net	0.85

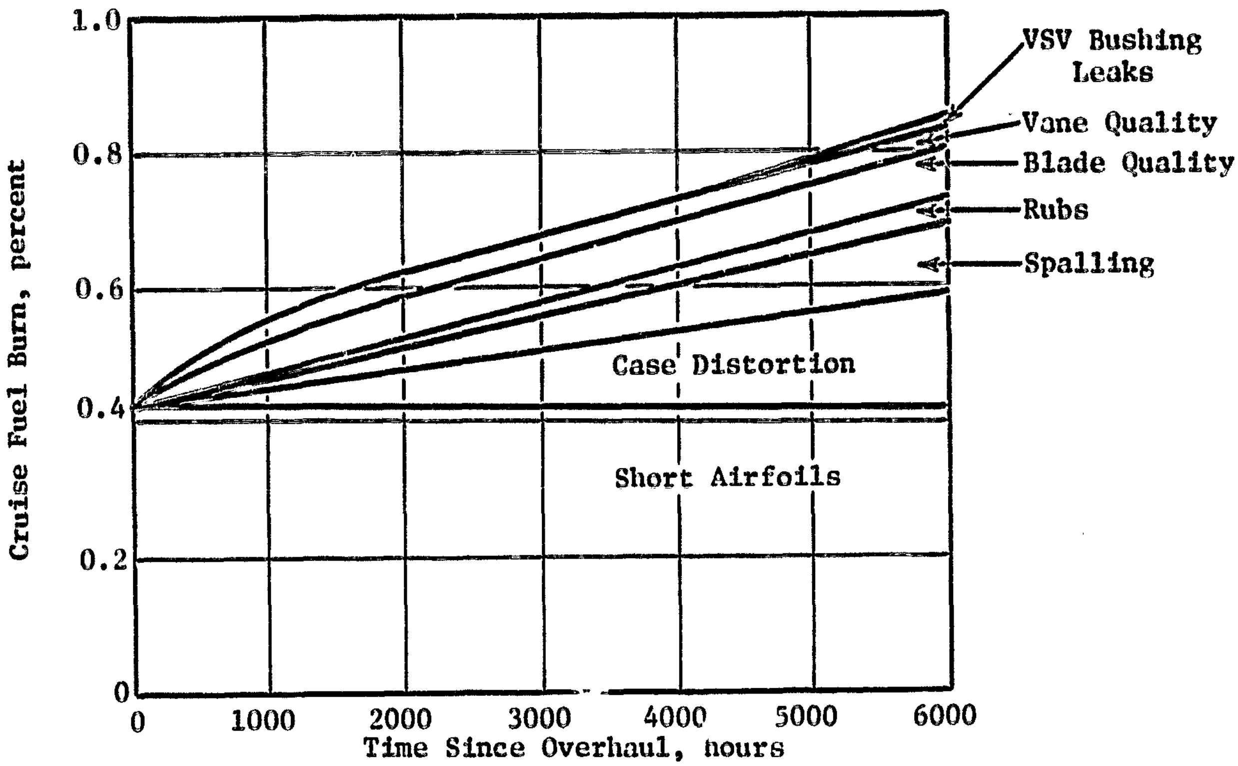


Figure 4-32. HP Compressor Section Estimated Deterioration Characteristics.

High Pressure Turbine (HPT) Section

The primary sources of high pressure turbine (HPT) deterioration are changes in blade tip-to-shroud clearance, airfoil surface finish, and internal leakage (parasitics). Figure 4-33 presents a schematic showing the areas of interest.

Blade Tip Clearance - Measurement of blade tip radii on seven deeriorated HPT modules indicated an average in-service loss of 0.019 inch and 0.013 inch respectively for Stages 1 and 2 from the as-built dimensions. The average in-service hours was 3266, and there was no correlation of blade tip wear with accumulated hours. (Reference Appendix A.)

The primary cause for blade tip clearance changes is shroud rubs. These rubs are very local, but because of the nonabradable shroud material; the blade tips are shortened. These rubs are caused by several factors, the primary ones being shroud support distortion, shroud swelling and bowing, shrinkage of the shroud supports, and hot rotor reburst (an operational condition which produces a full throttle movement from idle power with a hot engine). Secondary causes include erosion and oxidation of both blade tips and shrouds.

Analytical predictions of Stages 1 and 2 shroud distortion at takeoff power are shown in the bottom of Figure 4-34. This is an out-of-roundness type of distortion, and the arrows indicate the locations where rubs would be expected. On the top of this same figure is a histogram of the field experience showing the number of occurrences for the various rub loctaions. Comparison of the predictions and field experience show good agreement.

Engine testing has been conducted by General Electric to obtain shroud distortion data. Utilizing rub pins in the shrouds at various circumferential locations, circumferential bowing (radially inward) and chording (radially outward) of the shrouds were measured while the engine was both hot (running) and cold (shut down). Inspection of the Stage 1 shrouds when they were cold revealed about 0.001 inch to 0.002 inch of bowing at the ends. Calculations indicate, however, that when hot we would expect approximtely 0.0065 inch of chording at the ends. The Stage 2 shrouds show about 0.003 inch of bowing when cold, with no chording or bowing expected during engine operation.

Another variable that influences shroud rubs in the change ("shrink") in radial dimension of the Stage 1 shroud support. "Shrink" data were available only at 1760 hours and 7100 hours, as shown in Figure 4-35. These data show that the aft end of the shroud support comes further inward radially than the forward end does, but that the difference in deflections becomes less with increasing time. At the 4000-hour mark, the average shrink of the Stage 1 shroud support (forward and aft) is about 0.009 inch.

Hot rotor rebursts can also result in tip rubs and increased blade tip-to-shroud clearances. Figures 4-36 depicts the thermal response of the Stage 1 blade tip clearance when the engine is rapidly accelerated from idle to takeoff, stabilized at takeoff, rapidly decelerated to idle, and then, after a certain period of time, once more rapidly accelerated to takeoff (hot rotor

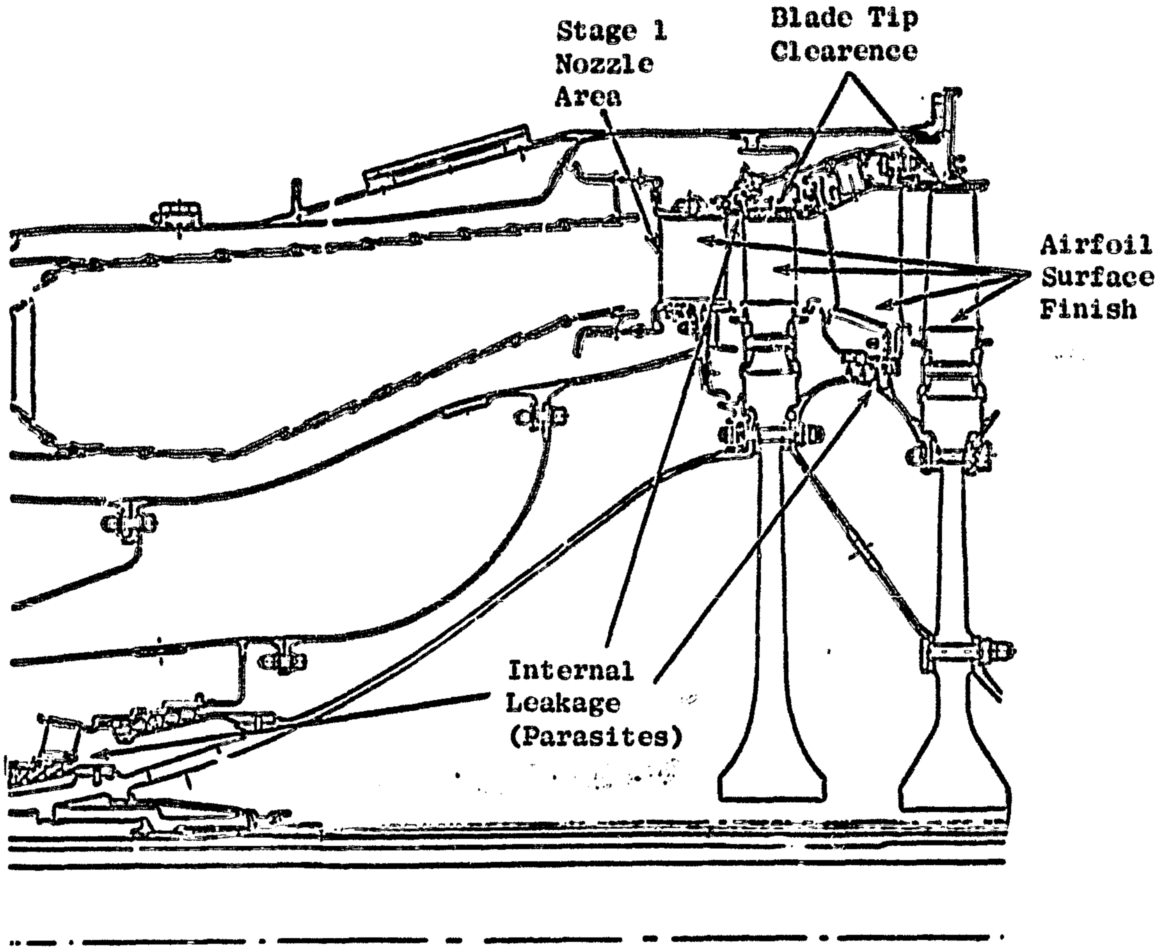


Figure 4-33. CF6-6 Deterioration Modes - HP Turbine Section.

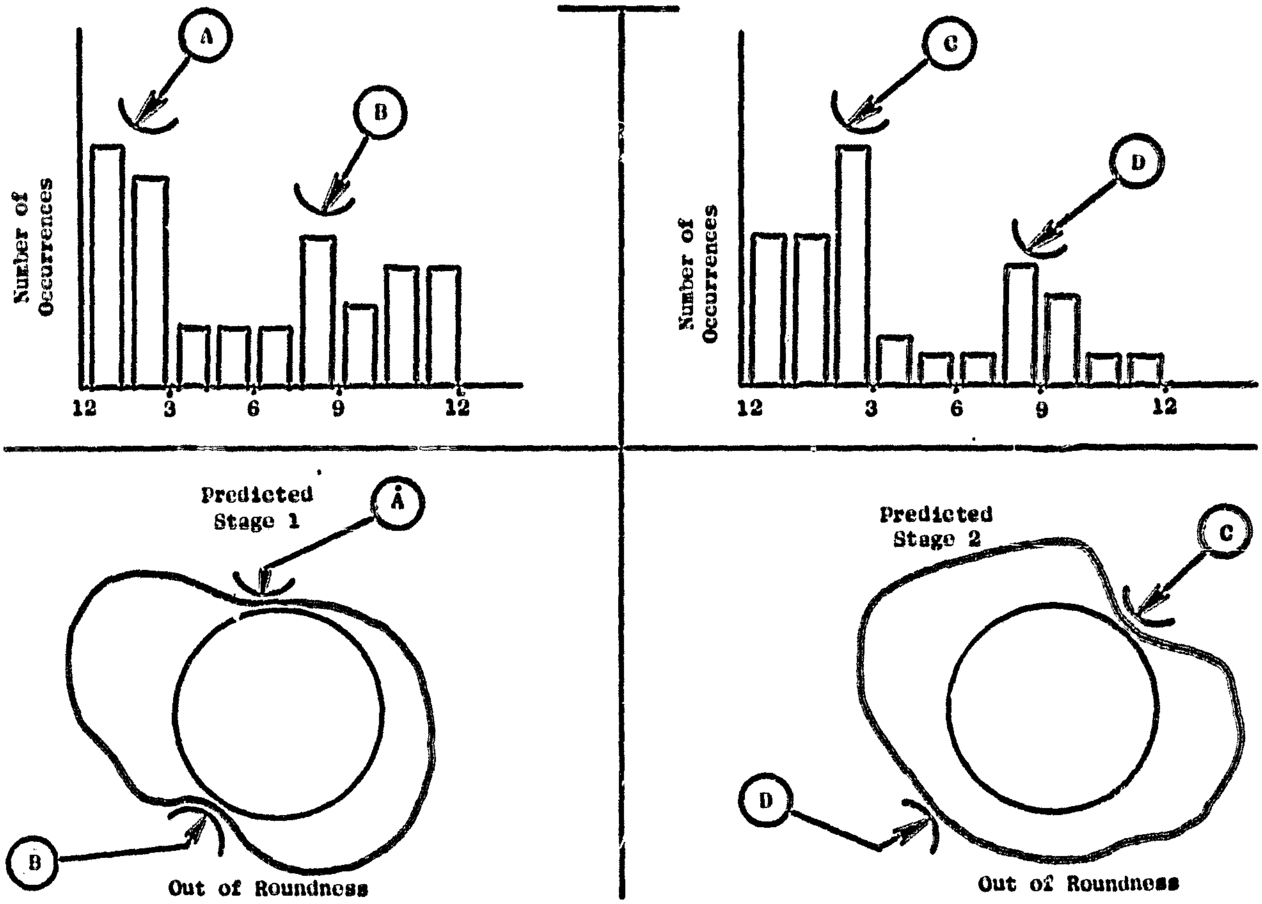


Figure 4-34. Field History - HP Turbine Shroud Rubs.

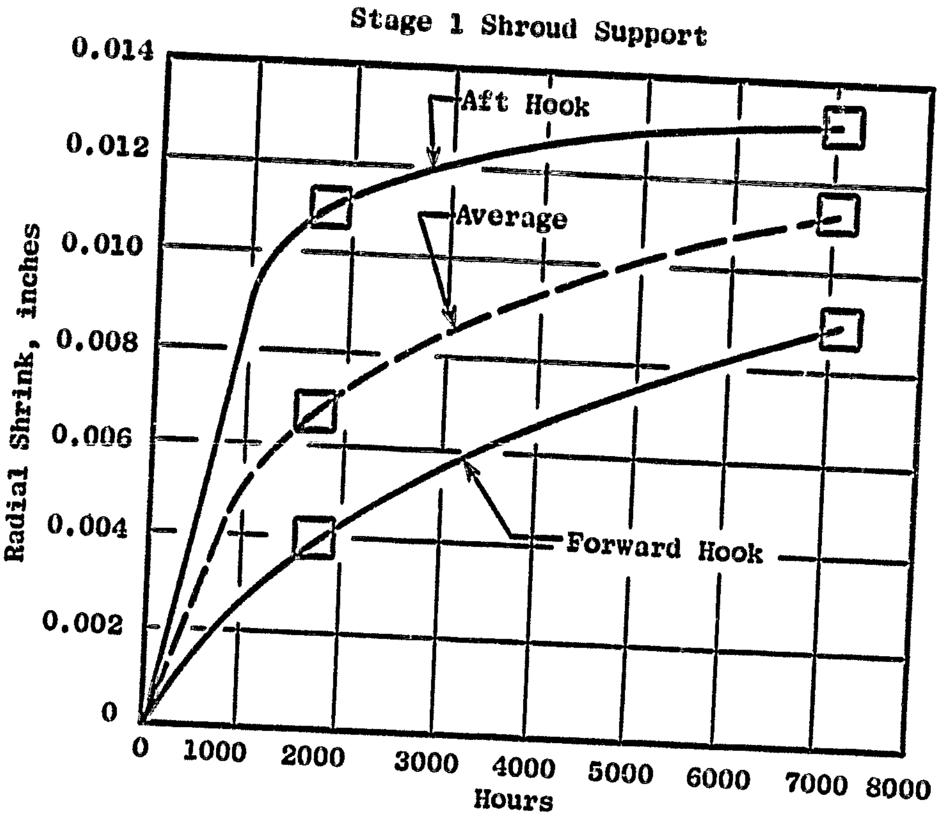


Figure 4-35. Factors Which Affect Blade Tip Rubs.

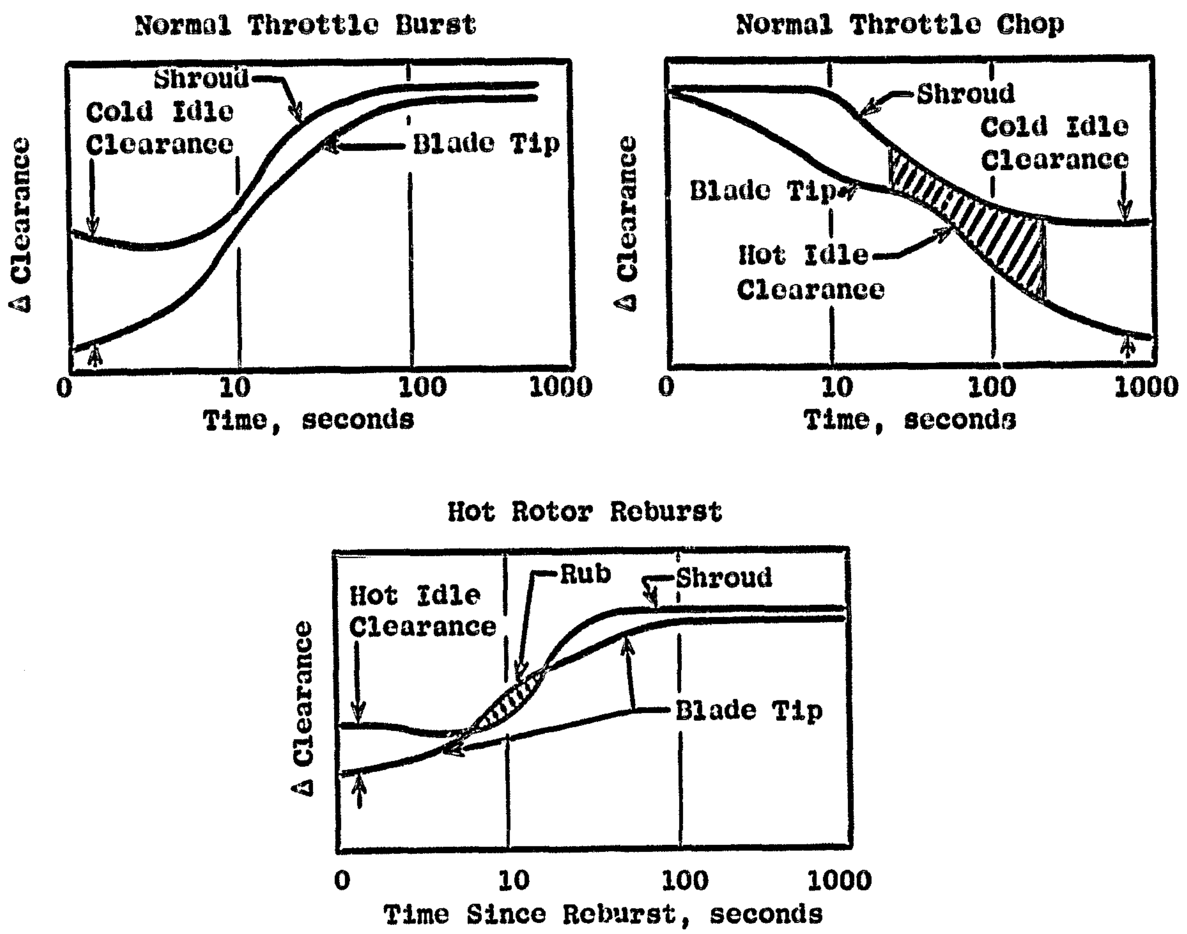


Figure 4-36. Hot Rotor Reburst Typical for Stage 1 HP Turbine.

reburst). These data indicated that while rubs would not be encountered during normal transients, the hot rotor reburst could result in rubs of 0.015 inch depth for Stage 1. It is believed that this, or a similar operational maneuver that produces thermal mismatch between the HPT rotor blade tips and shrouds, is the most likely cause of HPT blade tip rubs in revenue service operation. Revenue service data indicate that blade tip rubs occur randomly and infrequently during a given engine installation. This strongly suggests that HPT tip clearances are event-oriented.

The performance loss resulting from 19 mils increase in Stage 1 clearance and 13 mils in Stage 2 is 0.67 percent and 0.26 percent in HP turbine efficiency respectively. This corresponds to a 0.72 percent increase in cruise fuel burn (sfc).

Airfoil Surface Finish has been evaluated as a possible source of engine degradation. Figure 4-37 shows the range of surface finishes on the convex side of high pressure turbine vanes and blades for a ten-engine sample having a range of operating times from 600 to 4600 hours. The data shown are for averages of three measurements made on each vane and blade. As can be seen, the change in surface finish does not seem to correlate with time since installation; instead, it seems to be rather random. Using the average surface finish obtained from Figure 4-37 and the maximum average surface finish allowed in the respective blade or vane drawing specifications, the following changes in convex surface roughness (from new) are obtained:

Stage 1 Convex		Stage 2 Convex	
Vane	Blade	Vane	Blade
+11μ in. AA	+11μ in. AA	+18μ in. AA	+9μ in. AA

Although the concave surfaces of blades and vanes are consistently rougher than the convex surfaces, they have considerably less effect on turbine efficiency and are considered a negligible performance loss.

The turbine efficiency loss associated with increased airfoil surface finish is calculated to be 0.07 percent for the blades and 0.07 percent for the vanes. This corresponds to a 0.10 percent increase in cruise sfc.

Internal Leakage (Parasitics) - Areas for leakage within the high pressure turbine which may affect performance are the distortion of the Stage 1 nozzle and clearance increases for the pressure balance, inter-stage turbine and forward and aft CDP seals. The location of these areas is illustrated in Figure 4-38.

Distortion of the Stage 1 turbine nozzle outer band allows leakage into the flowpath and a resulting mixing loss over the Stage 1 blade. The average change in the "x" dimension (see Figure 4-39) for a 15-engine sample was

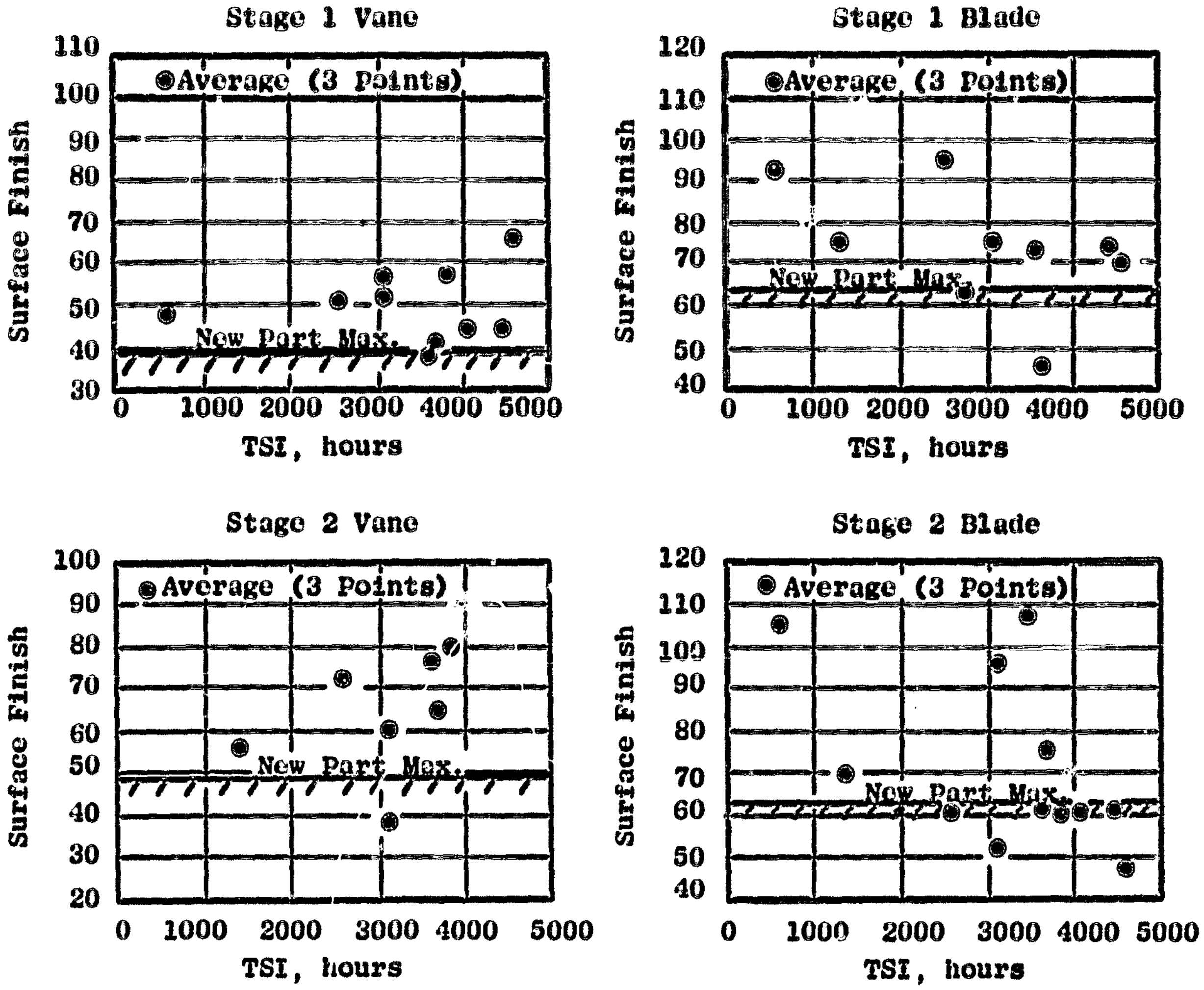


Figure 4-37. HP Turbine Vane and Blade Convex Side.- Surface Finish Versus Service Time.

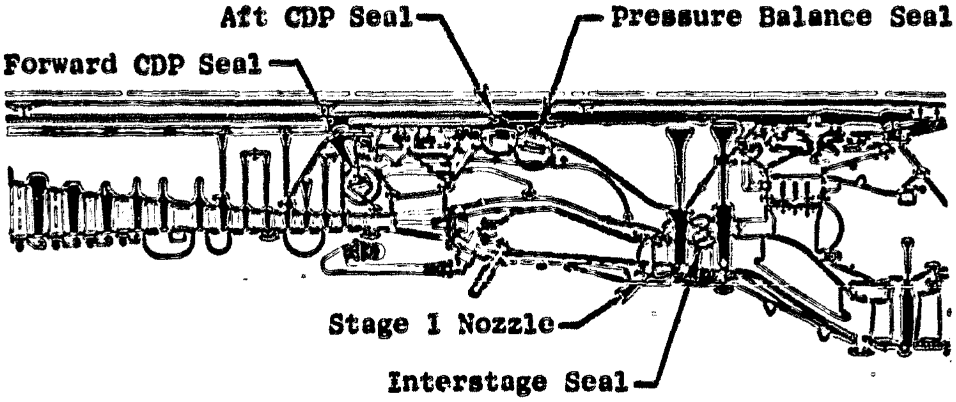


Figure 4-38. Areas of Internal Leakage (Parasitics).

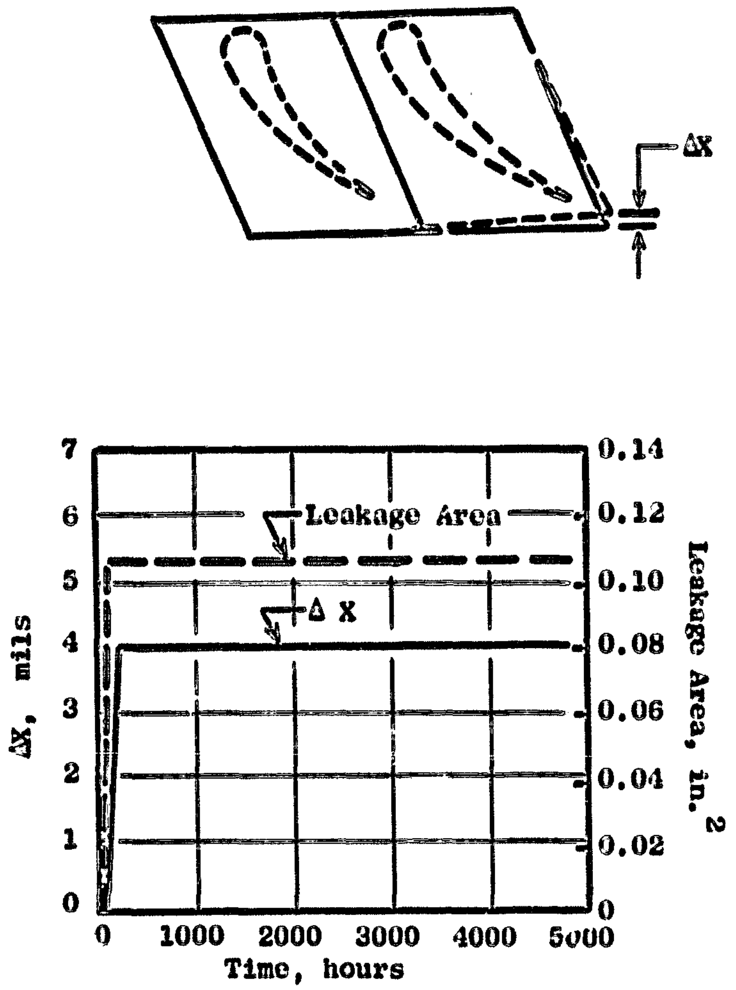


Figure 4-39. Stage 1 HPT Nozzle Vane Outer Band Distortion.

0.004 inch which produces a leakage area of 0.104 in.^{2}. This in turn results in a loss of 0.06 percent in turbine efficiency which corresponds to a 0.05 percent in cruise fuel burn. The distortion occurs during the first few hours of engine operation and remains constant thereafter.

Examination of pressure balance seal clearances for 15 engines indicated no change in clearance with increased operating time. For this study, therefore, no HPT performance deterioration was attributed to pressure balance seal clearances.

Measurements made for the forward CDP seal on 13 engines also indicated no change in clearance had occurred with running time. This seal, while part of the HP compressor module, is bookkept as a parasitic loss and is included in the summary of HPT losses. For this study, however, no loss was indicated.

Data from 15 engines show that the average clearance for the aft CDP seal is 0.010 inch for a new engine and 0.011 inch for a used engine. This 0.001 inch clearance increase results in an additional CDP leakage of 0.02 percent and an increase of 0.01 percent cruise fuel burn.

The average inbound interstage seal radial clearnce for 15 engines was found to increase from a nominal 0.035 inch to 0.045 inch. This 0.010 inch clearance increase results in a loss in turbine efficiency of 0.06 percent and a fuel burn increase of 0.05 percent.

The blueprint specifications require that the total nozzle area (A4) for the Stage 1 nozzle assembly to be between 52.313 in.^{2} and 53.373 in.^{2}.

Examination of Figure 4-40 shows that A_4 tends to increase as a function of time. After 4000 hours of engine operation, the nozzle throat area increases by an average of 2 percent. This area change has little effect on the overall engine performance level, but it is a very important measurement since it has a significant effect on the assignment of performance losses to the specific engine modules.

Summary of HPT Results

The deterioration assessment for a 4000-hour CF6-6D HPT is presented in Table 4-X. The total HPT performance loss is 0.9% sfc at cruise. Note that about 78 percent of the assessed loss can be attributed to the increase in Stage 1 and Stage 2 blade tip clearances.

Figure 4-41 presents an estimate of the HP turbine section deterioration with respect to operating time. Note that since the HPT blade tip clearance is event-oriented, instantaneous increases in sfc can result from blade tip rubs. Although an event such as this does not occur every flight, it is not unexpected and typically occurs at least once during a given engine installation. Therefore, the performance deterioration due to increased blade tip clearance will be shown as a dashed line since no definite time or number of cycles can be associated with the event.

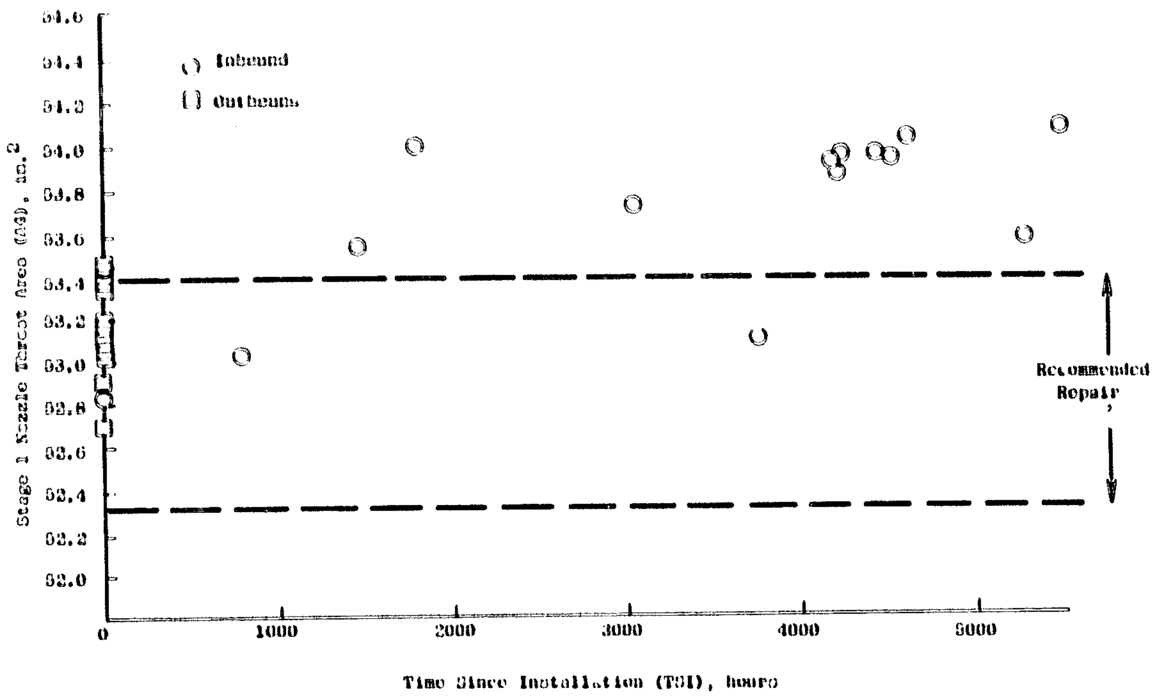


Figure 4-40. HP Turbine Stage 1 Nozzle Throat Area Versus Time.

Table 4-X. HP Turbine Section - Estimated Deterioration at 4000 Hours.

	ΔSFC at Cruise (%)
Blade Tip Clearance Increase	
• Stage 1	0.52
• Stage 2	0.20
Airfoil Surface Finish	
• Blades	0.05
• Vanes	0.05
Internal Leakage (Parasities)	
• Stage 1 HPTN Distortion of Outer Band	0.05
• Interstage Turbine Seal	0.05
Net	0.92

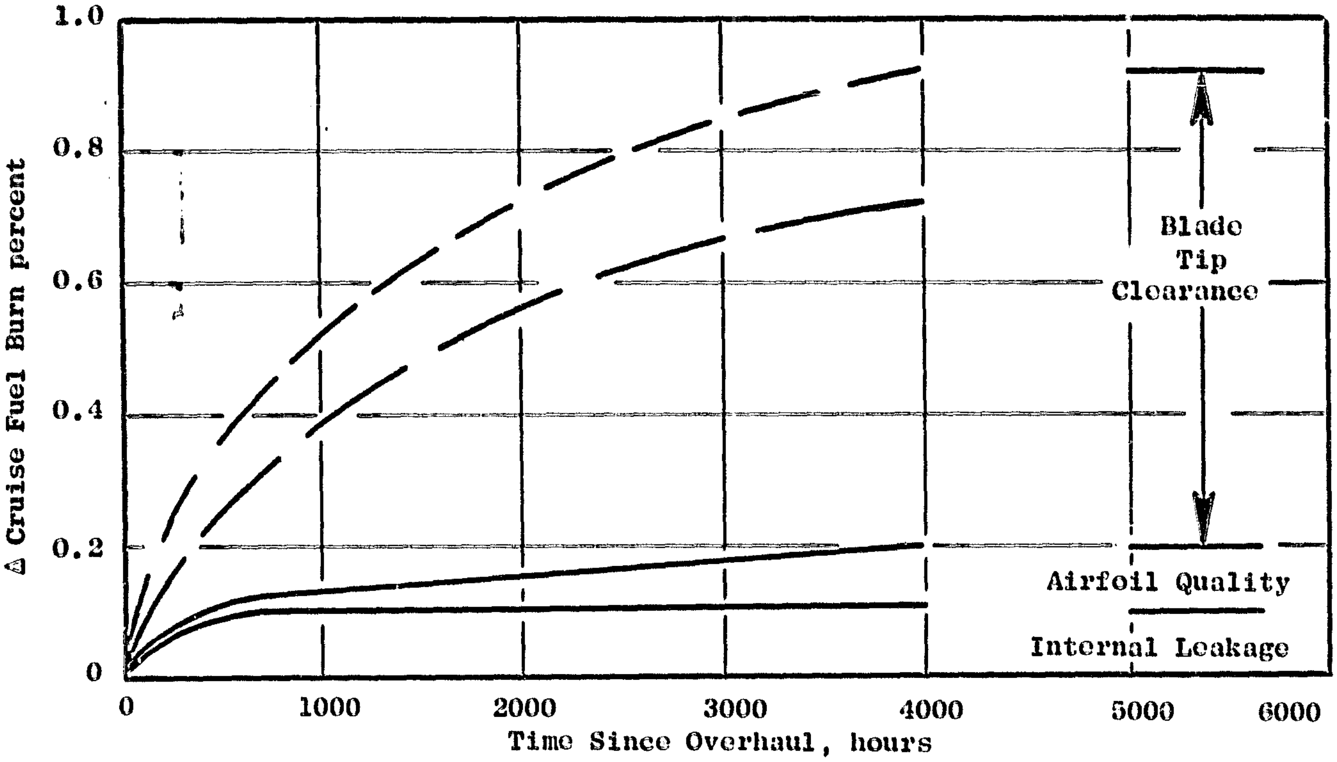


Figure 4-41. HP Turbine Section - Estimated Deterioration Characteristics.

Low Pressure Turbine (LPT) Section

Deterioration of low pressure turbine (LPT) components occurs primarily as a result of increased blade tip/shroud and interstage seal clearances, cracking of the LPT case rail cooling manifold, and increased airfoil surface roughness. These modes of deterioration are illustrated in Figure 4-42.

Clearances - Increases in running clearance can occur as repeated rubs lead to wearing away of blade seal teeth and honeycomb seal material. Transient operations such as hot rotor rebursts and windmilling air starts result in decreased clearances, which, over an extended period of time, will have the effect of increasing steady-state running clearances.

Efforts to determine the clearance increases attributed to the rotor have met with mixed results. Some measurements, particularly those reported in Reference 2 which deals with a limited number of back-to-back LPT module tests, had indicated that significant seal tip wear was occurring during revenue service. However, no such indicator was observed when a greater number of inbound LP turbine rotors were inspected. This latter finding is more consistent with examinations of individual blades in the repair/refurbishment cycle. Most blades do not require repair in order to restore seal teeth radial dimensions. Based on the larger sample of data, it is concluded that within the accuracy of the measurement techniques employed, no significant amount of blade seal teeth or rotating interstage seal wear is occurring on the average engine.

Observation of rub depths in the honeycomb material of shrouds and interstage seals shows wear tracks that averaged 0.060 inch in depth. This represents an average of 0.020 inch increase in clearance over that of new engines. Both these data and the LPT rotor data are presented in Section A.4 of Appendix A.

Figures 4-43 and 4-44 show calculated performance loss curves by stage for blade tip and interstage seal clearances. The estimated change of 0.020 inch in each stage from a 0.040 inch clearance baseline is equivalent to a total of 0.61 percent loss in LP turbine efficiency or a 0.37 percent increase in cruise sfc.

Another clearance-related deterioration mode is cracking of the LPT case hook cooling tubes. This condition can lead to additional cooling airflow in the cracked area and can also lead to circumferential starving of the flow downstream. These cooling air variations could result in increased operating clearance through hot flowpath gas inflow, loss of hook cooling, and increased thermal distortion. These deterioration modes also result in increased casing temperatures; therefore, it will not be apparent from an examination of honeycomb rub depths. No quantification of this deterioration mechanism will be attempted since it appears to be a random phenomenon and not typical of average CF6-6D LP turbine deterioration. This condition, however, may contribute to differences in deterioration rates for individual modules.

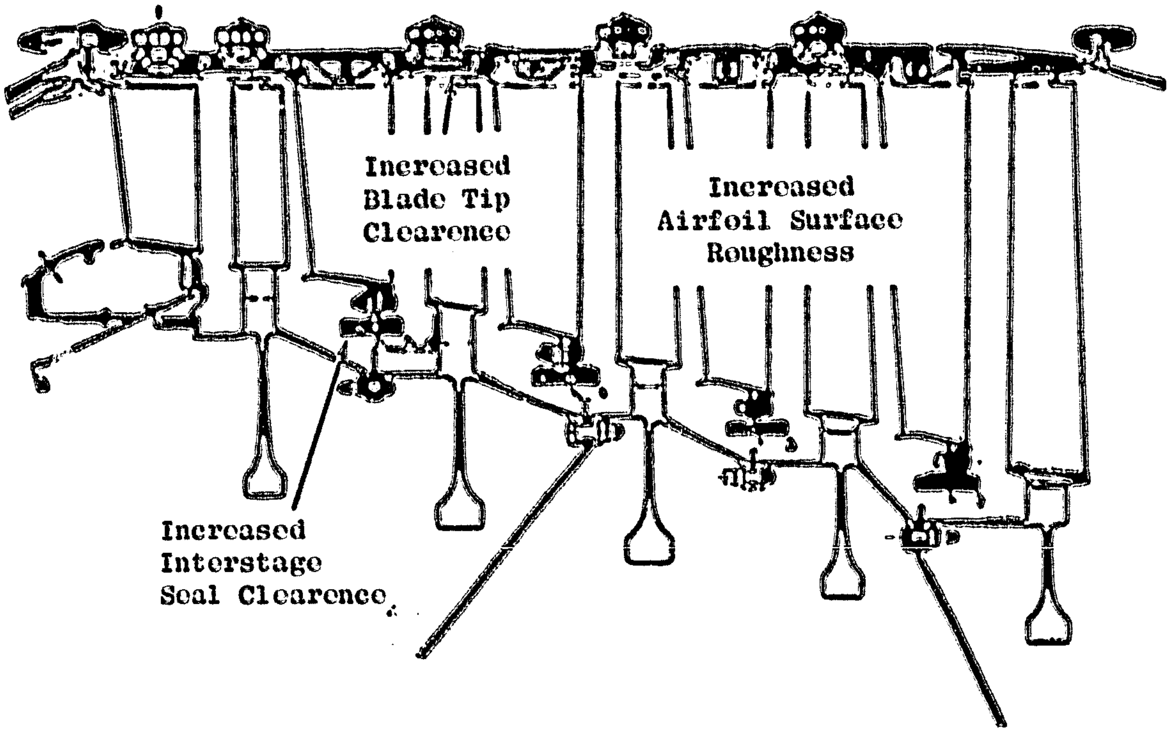


Figure 4-42. CF6-6 LP Turbine Section - Deterioration Modes.

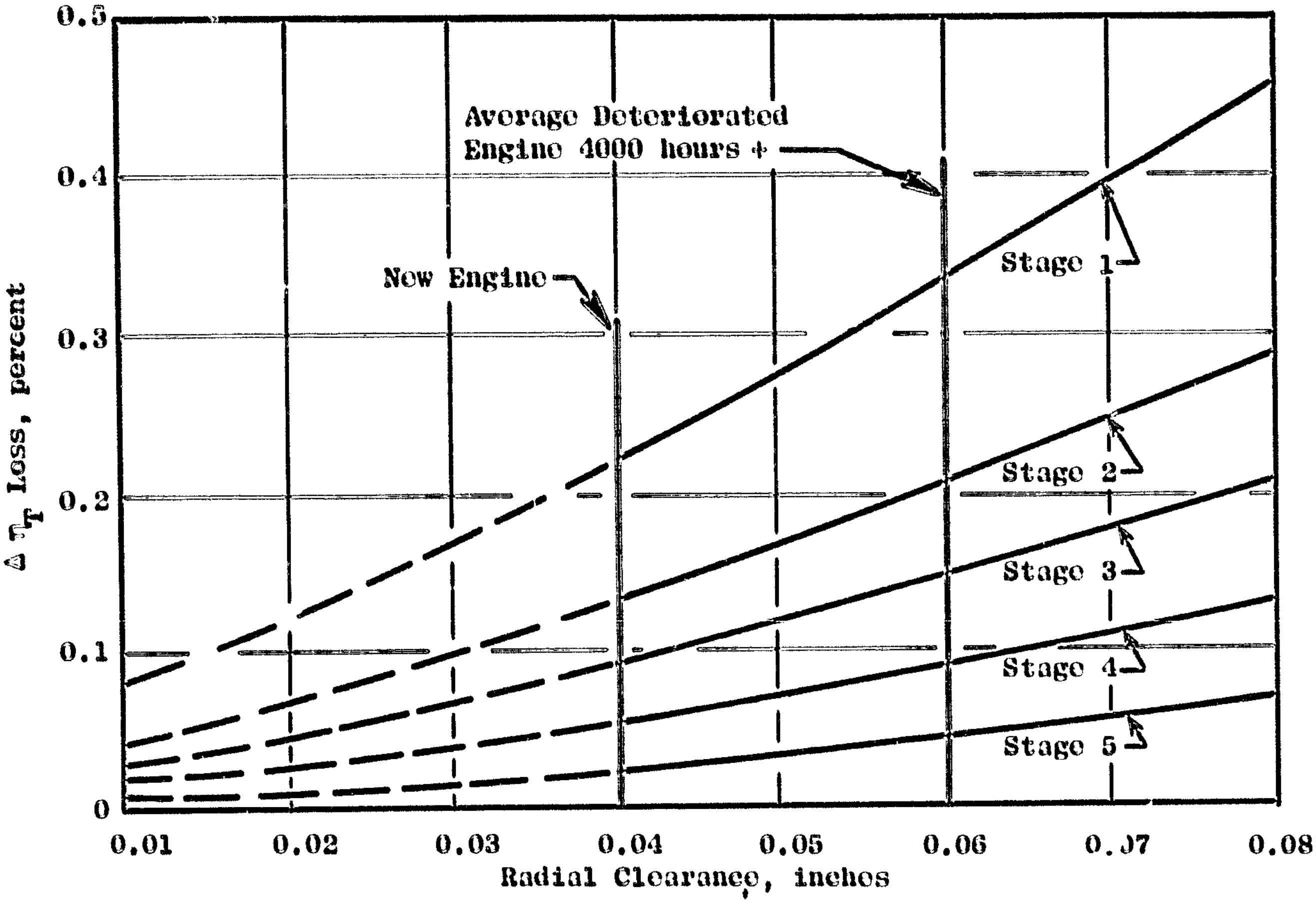


Figure 4-43. Cruise Performance Effect - LP Turbine Efficiency Versus Tip Clearance.

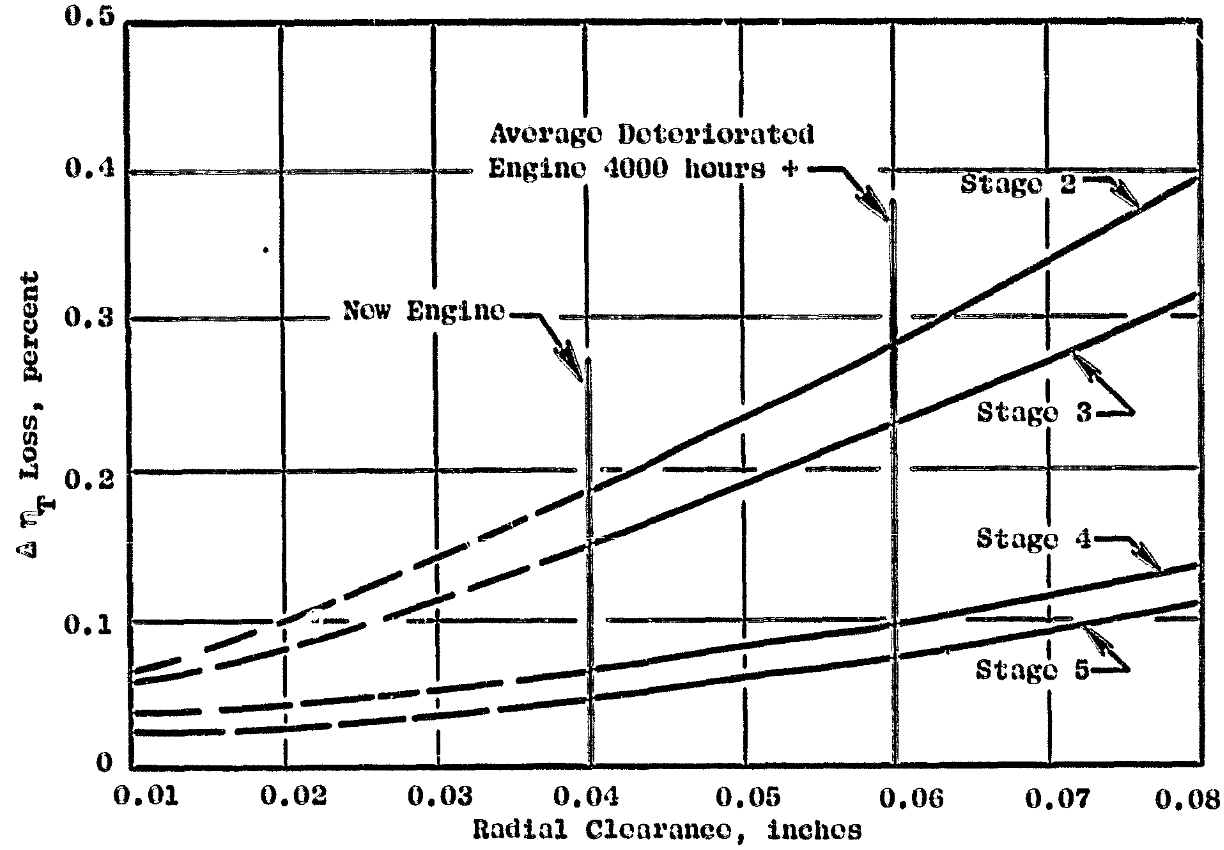


Figure 4-44. Cruise Performance Effect - LP Turbine Efficiency Versus Interstage Seal Clearance.

Airfoil Surface Finish - The other significant deterioration mode identified was increased airfoil surface roughness. Figures 4-45 and 4-46 show summaries of blade and vane measured surface finish versus time for a sample of airfoils. Increased surface roughness results from airborne and engine-induced particulates which can result in surface buildup, oxidation and hot corrosion. There are various corrosion activities which can be accelerated in the temperature ranges in which LPT airfoils operate.

Surface finish data have been collected for other CF6 engine models (CF6-50). These data consist of two populations: one in which no significant levels of corrosion attack were observed, and one in which significant corrosion was observed. As similar data for the CF6-6D has become available, this distinction is less obvious because the data scatter in each area tends to overlap. Visual inspection has shown that most airfoils exhibited the lower rate of surface roughness increase. Many of these have experienced corrosion in the sense of metallurgical attack, but this condition has not yet resulted in significant increases in surface roughness. In general, the dashed lines in Figures 4-45 and 4-46 represent the average trends of increased surface roughness for LPT airfoils. Note that the data scatter is such that only one line represents all five stages. It appears from these data that surface roughness continues to increase until 6000 or 7000 hours of operation and then remains relatively constant.

The correlations of increased surface roughness in relation to loss in LP turbine efficiency are shown in Figures 4-47 and 4-48. Relative to new engine specifications, approximately 0.07 percent decrease in LPT efficiency and 0.04 percent increase in cruise fuel burn could be attributed to the 37 μ in. AA and 31 μ in. AA increases in surface roughness for vane and blade airfoils, respectively. The correlation of increased surface roughness to losses in turbine efficiency is also shown in Figures 4-47 and 4-48. Based on these figures, only the Stage 1 blades and the Stage 1 and 2 vanes have a measurable impact on sfc for an average engine.

Summary of LPT Results

The performance deterioration for a 6000-hour LPT is summarized in Table 4-XI. This level agrees extremely well with the LPT back-to-back testing results (Reference 2), which yielded a 0.6 percent sfc (takeoff) average deterioration level for the seven LPT modules tested. This takeoff value equates to 0.4 percent sfc at cruise conditions. Approximately 90 percent of the loss results from clearance increases, while the remainder is due to airfoil surface finish degradation.

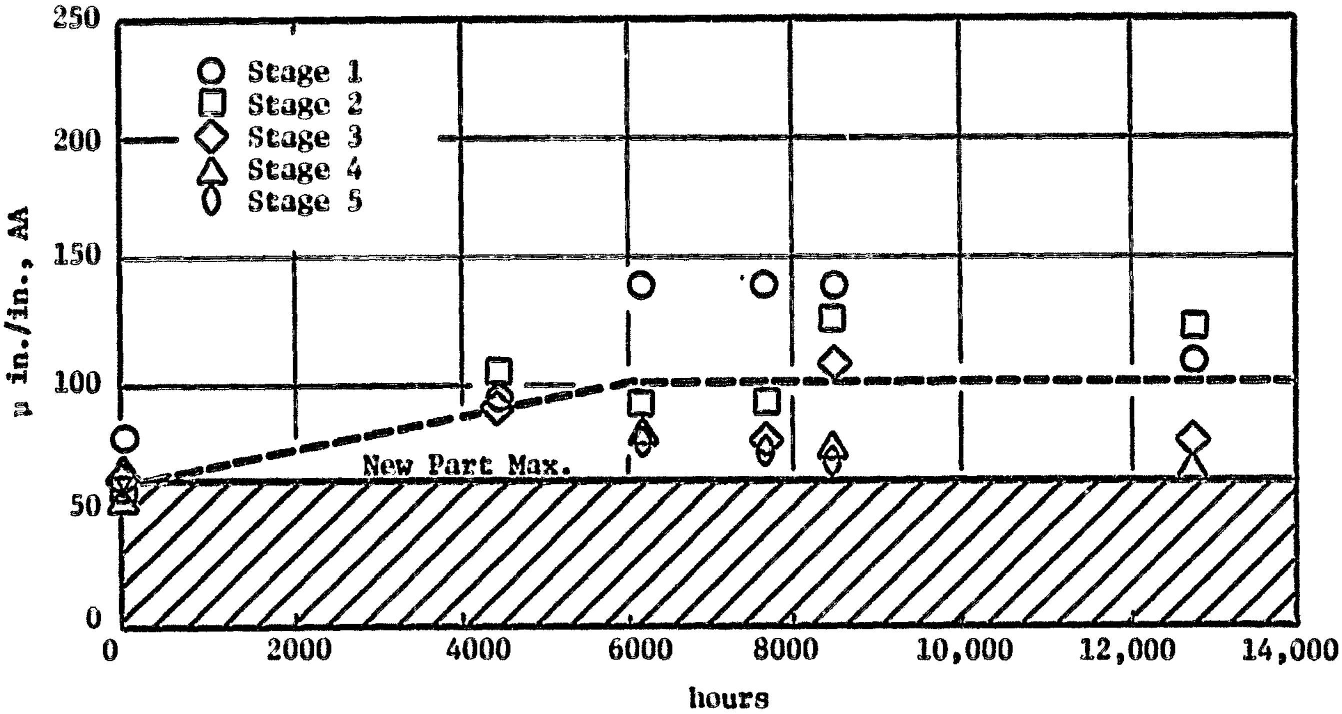


Figure 4-45. LP Turbine Vane Surface Finish - Convex Side.

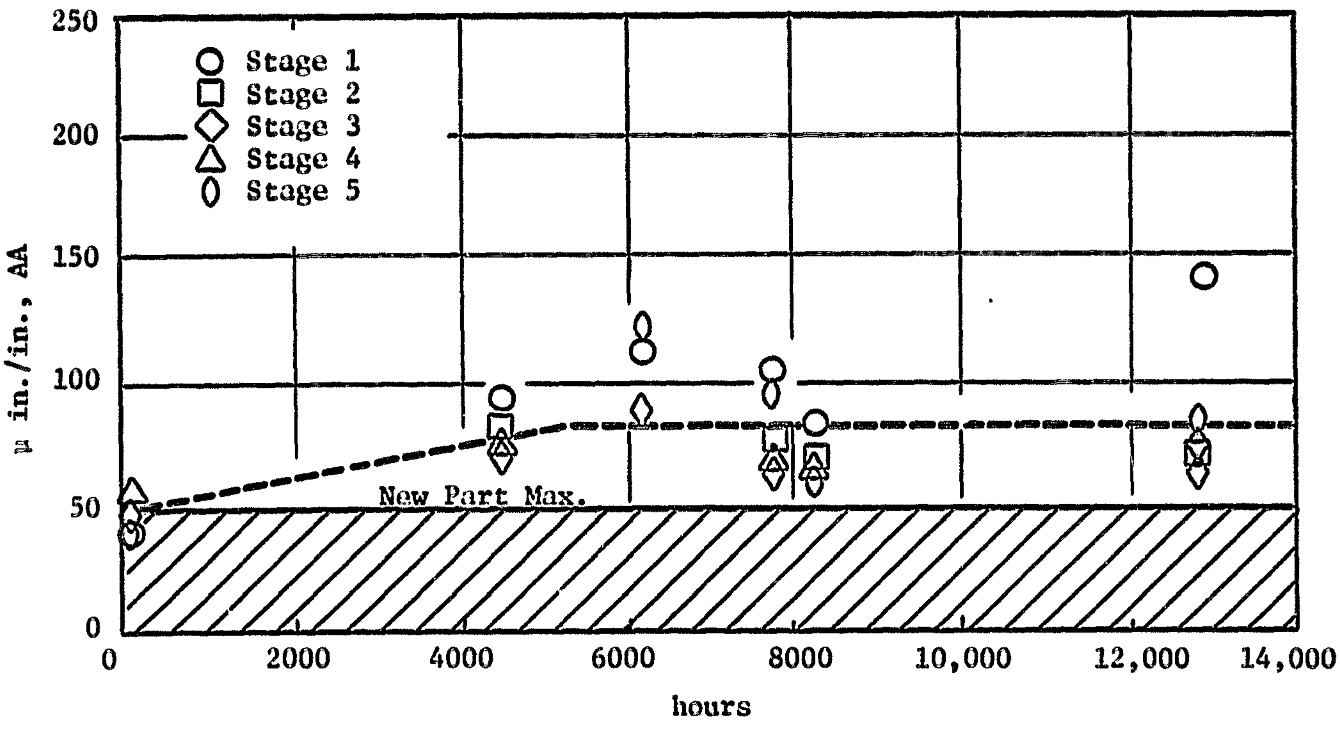


Figure 4-46. LP Turbine Blade Surface Finish - Convex Side.

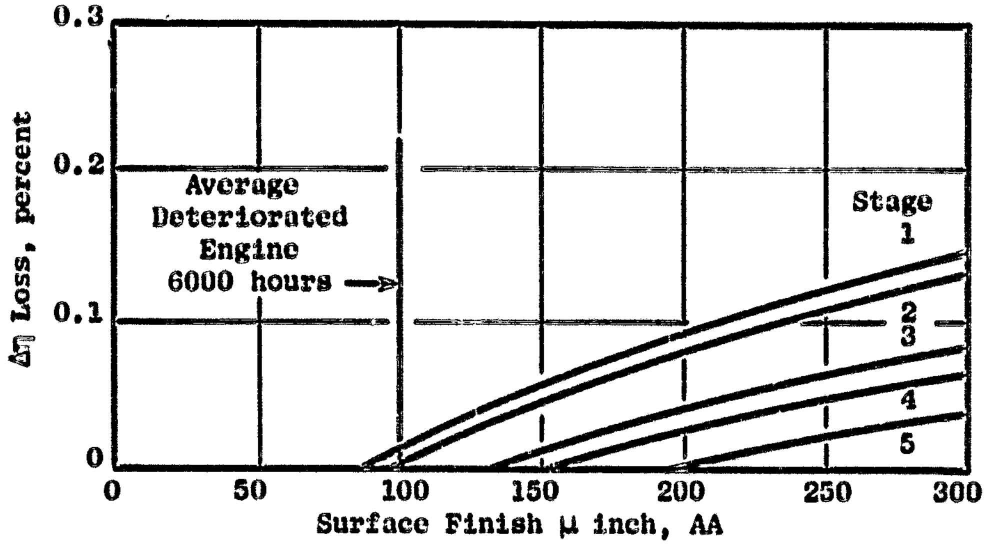


Figure 4-47. CF6-6 Low Pressure Turbine Efficiency Versus Vane Surface Finish.

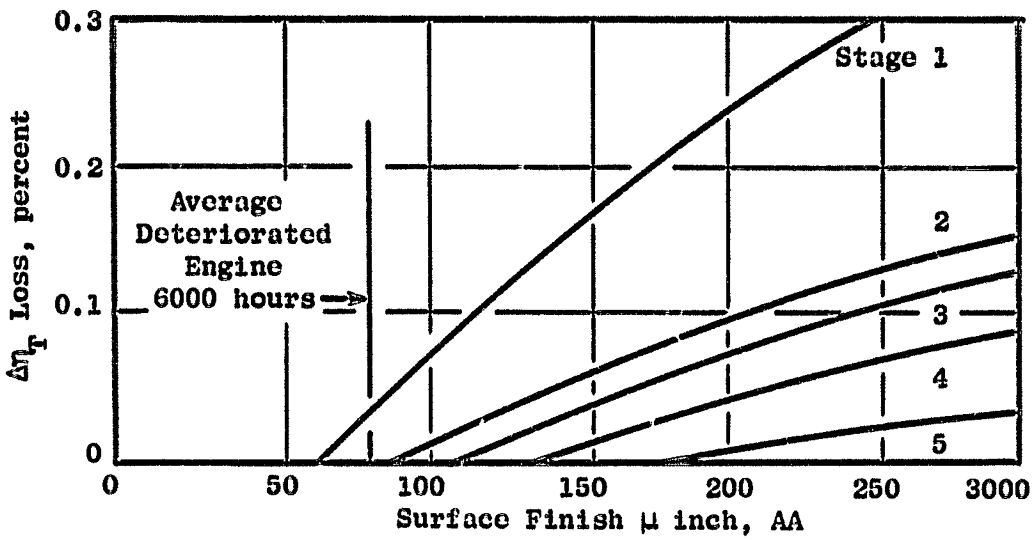


Figure 4-48. CF6-6 Low Pressure Turbine Efficiency Versus Blade Surface Finish.

Table 4-XI. LP Turbine Section - Estimated Deterioration at 6000 Hours.

	Δsfc @ Cruise (%)
Increase in Blade Tip Clearance	0.20
Increase in Interstage Seal Clearances	0.17
Surface Finish Degradation	0.04
Net	0.41

Figure 4-49 is an estimate of the LP turbine deterioration characteristics with time. The curves show that clearance increases continue until about 4000 hours while the airfoil surface finish continues to deteriorate until 6000 hours since overhaul.

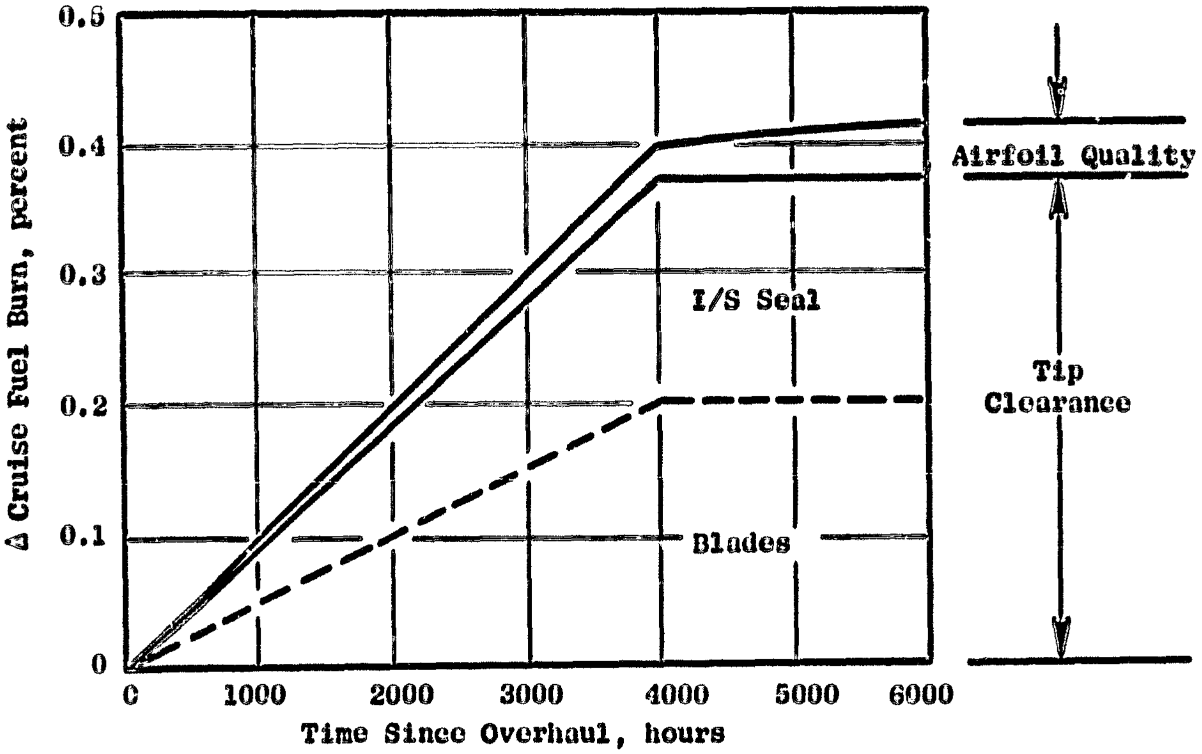


Figure 4-49. LP Turbine Section - Estimated Deterioration Characteristics.

SUMMARY ALL MODULES - AVERAGE DETERIORATED ENGINES

The results from the hardware analyses are summarized for each of the engine modules in the following listing. The cruise fuel burn (sfc) increase associated with the representative time selected for each module is presented in Table 4-XII.

Table 4-XII. Modular Hardware Performance Deterioration.

Module	Hours	Cruise Δ Fuel Burn, %
Fan/Booster	6000	1.32
HP Compressor	6000	0.85
HP Turbine	4000	0.92
LP Turbine	6000	0.41

Note that 4000 hours was selected for the HPT module while the other modules are shown for 6000 hours. This is because the HPT is typically refurbished every shop visit while the other modules, with the exception of the fan (Stage 1 blades), are refurbished only if mechanical distress causes the modules to be exposed.

HARDWARE DATA - SERVICEABLE ENGINE

Hardware inspection data and a general discussion of the observations and findings concerning average serviceable engine modules prior to entering revenue service are presented in the following paragraphs. The data are presented for the four major sections of the engine: fan, high pressure compressor, high pressure turbine, and low pressure turbine.

Fan Section

During a shop visit, repair procedures are available to restore deteriorated fan section parts to nearly new engine quality levels. Typically, however, more of the parts which cause performance deterioration in the fan are not refurbished. For several reasons, most notably those of cost effectiveness and excellent durability of the fan module, only minimal performance restoration is performed during a typical shop visit.

Fan Blade Clearance - This clearance is checked by the airlines only to ensure that the minimum clearance is controlled. This leads to local rework of the shrouds and, in conjunction with shroud erosion, results in greater average clearances. Shop Manual procedures are currently available to restore the average clearance, but little or no attention is given by the airlines to correct this condition.

With respect to blade-to-shroud clearances, the deterioration level for the average refurbished engine is therefore estimated to be the same as that determined for the deteriorated engine. This value is approximately 0.020 inch in increased clearance, which is equivalent to a fan efficiency of 0.4 percent and a 0.21 percent increase in cruise fuel burn.

Booster Shroud Material - As noted for the deteriorated engines, all engines inspected were observed to have the epoxy microballoon rub strip removed, and none had the open cell honeycomb replacement rub strip. Therefore, the performance loss for the average refurbished engine remains at 1.33 percent in booster efficiency or 0.19 percent in cruise fuel burn.

Splitter Leading Edge Erosion - The flow splitter behind the fan rotor which forms the OD flow path for the quarter-stage rotor is not being refurbished by re-forming or polishing the leading edge surface. The performance loss, therefore, remains at 0.14 percent in fan efficiency or 0.08 percent in cruise fuel burn.

Fan Bypass OGV Hub - When the CF6-6D engines were being manufactured, there was a gap of 1 to 30 mils between the bottom of the OGV and the inner flow path. There is a flow of air from the pressure side of the vane to the suction side of the vane through this gap. RTV can be added in this area, and when properly smoothed with a good fillet between the flow path and the airfoil, the leakages can be stopped. The 30 mil clearance results in a 0.21 percent loss in fan efficiency for the average refurbished engine. This leakage does exist on production engines, so it is not included as a deterioration source from new. Repair of this leakage path, however can improve performance.

Fan Blade Leading Edge Quality can be corrected with techniques made available by General Electric. Some airline service facilities have this equipment and do an excellent job of refurbishment. Attempts to recontour fan leading edges by service shops without these tools have not been as effective. It is estimated that for a fleet average, a deteriorated fan leading edge can cause a loss in fan efficiency of 0.24 percent or 0.13 percent in cruise fuel burn. Specific airline service shops are eliminating essentially all of the loss, but unrefurbished fan modules were also observed.

Fan blades are thoroughly cleaned as part of the inspection and restoration process. Restoration in this case is straightforward. A common solvent wash will remove the dirt. A non-oil-based solvent is recommended in order to leave a dry surface. It is assumed that the fan blades are cleaned for the average refurbished engine.

As in the case of the leading edge refurbishment, there is variability with airlines regarding surface finish restoration. General Electric recommends procedures which can restore the surface finish to essentially new airfoil quality. Airline service shops differ in their aggressiveness toward this restoration activity. It is estimated that half of the serviceable engines include fan blade surface finish restoration, therefore, the average outbound engine is assumed deficient in fan efficiency by 0.03 percent or 0.02 percent cruise fuel burn.

<u>OGV Airfoils</u> are not being restored for surface finish or for leading edge erosion The loose polyurethane film is left in the unrestored condition. Therefore, the deterioration level of outbound engines remains at 0.47 percent loss in fan efficiency or 0.25 percent in cruise fuel burn.

Booster Airfoils are not being cleaned or polished to improve surface finish or restore erosion damage on the leading edges. In addition, the blunt leading edges on the inner OGV's remain in the same condition in which they were found on the deteriorated engine. Therefore, the loss remains at 0.36 percent in booster efficiency or 0.05 percent in cruise fuel burn.

SUMMARY OF FAN SECTION RESULTS

A summary of the fan and booster section performance loss for the average refurbished engine is presented in Table 4-XIII. This table summarizes an average inbound fan module (no refurbishment), a refurbished module (using current refurbishment practices), and an average serviceable module (partially refurbished). The data are given for an average serviceable engine although considerable differences can exist with regard to the actual level of deterioration between individual modules. The total outbound deterioration is assessed at 0.93 percent cruise sfc at constant thrust. This loss can be categorized as flowpath degradation (0.48 percent sfc) and airfoil quality degradation (0.45 percent sfc). As with the deteriorated engine, 20 percent of the total loss is due to the removal (without replacement) of the quarter-stage rub strip material which results in increased clearances. This loss (0.19 percent sfc) is categorized as deterioration although it is not true revenue service deterioration.

High Pressure Compressor (HPC) Section

The HP compressor modules are not refurbished for performance restoration during each shop visit. Typically, only airfoils with leading edge or tip damage are replaced and any apparent mechanical distress is repaired. Based on shop audits and repair records, it is estimated that the HPC blades and vanes are removed for cleaning purposes about one-third to one-half of the times that the engine are brought in for repair.

Clearances - Average blade and vane tip clearances may be inadvertently increased during a shop visit as a result of airfoil tip rework required to correct eccentricity and out-of-roundness of the casing. As stated in the previous section (which provides results for a deteriorated engine), the performance loss associated with this and other clearance effects is 0.59 percent in cruise sfc. Based on shop audits, it is assumed that 40 percent of the HP compressor modules are refurbished (replace short blades and vanes) during a typical shop visit. The performance loss for clearance changes due to rubs and spalling for the average outbound engine is 0.14 percent in HPC efficiency or 0.08 percent in cruise fuel burn (sfc).

Airfoil Quality - A vibratory milling process commonly termed SWECO is available in the airline repair shops to clean and restore airfoil surface finish. This tumbling process also helps maintain a reasonable airfoil leading edge radius. The current procedure used by the airlines can restore both blade and vane airfoil surface finish to new-part standards. Since it is assumed that approximately 40 percent of the compressor modules are assumed to be refurbished during a typical shop visit, the performance loss due to surface finish degradation of the average refurbished engine is 0.10 percent in HPC efficiency or 0.06 percent in cruise fuel burn (sfc).

SUMMARY OF HPC RESULTS

The unrestored performance losses for the average serviceable HP compressor module is presented in Table 4-XIV. As with the fan module, values are also presented for the average inbound module and the average refurbished module. Over 90 percent of the unrestored performance loss is due to clearance increases.

High Pressure Turbine Section

Normally the high pressure turbine is restored every shop visit because of durability limitations. In the restoration process, various modes of mechanical distress - the primary cause of performance deterioration - are also corrected. The correction procedures include setting the correct blade tip-to-shroud clearances, partially restoring the airfoil surface finish, and repairing nozzle vane distortion/distress.

Measurements were obtained for typical refurbished engines to assure that additional losses were not being incurred as the result of shop procedures or any other unknown conditions. Measurements were obtained for (1) the seals that contribute to parasitic losses (pressure balance and forward and aft CDP), (2) Stage 1 and 2 blade tip and shroud dimensions to check cold clearances, and (3) the thermal shield teeth to calculate interstage seal losses. These data, presented in Appendix A - Section 3, indicate that all parts were within shop manual limits.

Table 4-XIII. Estimated Serviceable Airline Fan Module.

	Δ Cruise Fuel Burn (%) No Refurbishment	With Refurbishment	Average Serviceable
Fan Blade			
Tip Clearance	0.21	0.21	0.21
Leading Edge Contour	0.38	0	0.13
Surface Roughness	0.03	0.015	0.02
Dirt Accumulation	0.13	0	0
Splitter Leading Edge	0.08	0.08	0.08
Bypass OGV Leading Edge	0.06	0.06	0.06
Bypass OGV Roughness	0.19	0.19	0.19
Quarter Stage			
Rotor Tip Clearance	0.19	0.19	0.19
Airfoils Leading Edge	0.025	0.025	0.025
Airfoils Roughness	0.025	0.025	0.025
Average Serviceable Module			0.93

Table 4-XIV. Estimated Serviceable Airline HP Compressor Module.

	Δ Cruise Fuel Burn (%) No Refurbishment	With Refurbishment	Average Serviceable
Blade and Vane Tip Clearance Increases			
Flowpath Coating Degradation	0.10	0	0.06
Flowpath Coating Rubs	0.04	0	0.02
Casing Distortion	0.17	0.05	0.17
Short Airfoils	0.42	0.42	0.42
Airfoil Quality Degradation			
Blades	0.07	0.02	0.04
Vanes	0.03	0.02	0.02
Leakage			
External	0.02	0	0
Average Serviceable Module			0.73

The only area of unrestored performance in the HP turbine module is airfoil surface roughness. Repaired HPT airfoils are not restored to new-part specifications, resulting in a loss of 0.04 percent in HPT efficiency for the blades as well as the vanes. The total loss of 0.08 percent is equivalent to a 0.06 percent increase in cruise fuel burn. The performance loss for the average inbound module, refurbished module, and serviceable module is presented in Table 4-XV. Note that all the unrefurbished loss is due to airfoil surface finish.

Low Pressure Turbine Section

The low pressure turbine module typically lasts over 10,000 hours with little or no repair/restoration. For this reason, the performance level for the average refurbished engine is comparable to the deteriorated engine with deterioration modes of increased clearance (blade and interstage seal) and airfoil roughness.

Clearance - Restoring tip clearance to new-engine condition consists of replacing the shrouds and interstage seals. It would be expected that all of the performance degradation resulting from increased honeycomb rubs (0.37 percent cruise sfc) would be recovered. This performance restoration was demonstrated in the back-to-back testing program described in Reference 2. Since only 10 to 15 percent of the LPT modules are restored during a typical shop visit, it is estimated that the average serviceable engine is 0.32 percent deficient in cruise sfc due to the increased running clearances.

Airfoil Surface Finish - Little effort is directed toward cleaning and restoring the surface finish for LPT blades and vanes. Therefore, as for the inbound module, the performance loss for airfoil surface roughness for an average serviceable LPT module is assessed to be 0.04 percent in cruise sfc.

SUMMARY OF LPT RESULTS

The performance deterioration for an average inbound module, refurbished module, and serviceable LPT module is presented in Table 4-XVI.

As shown, almost 90 percent of the serviceable LPT module unrestored performance loss is due to blade tip and interstage seal clearance increases.

Table 4-XV. Estimated Serviceable Airline HP Turbine Module.

	Δ Cruise Fuel Burn (%) No Refurbishment	With Refurbishment	Average Serviceable
Blade Tip Clearance Increase			
Stage 1	0.52	0	0
Stage 2	0.20	0	0
Airfoil Surface Finish			
Blades	0.05	0.03	0.03
Vanes	0.05	0.03	0.03
Internal Leakage (Parasitics)			
Stage 1 HPTN Distortion of Outer Band	0.05	0	0
Interstage Turbine Seal	0.05	0	0
Average Serviceable Module			0.06

Table 4-XVI. Estimated Serviceable Airline LP Turbine Module.

	Δ Cruise Fuel Burn (%) No Refurbishment	With Refurbishment	Average Serviceable
Increase in Blade Tip Clearances	0.20	0	0.17
Increase in Interstage Seal Clearances	0.17	0	0.15
Surface Finish Degradation	0.04	0.04	0.04
Average Serviceable Module			0.36

SUMMARY ALL MODULES - AVERAGE SERVICEABLE ENGINE

The cruise fuel burn increase for the individual modules based on hardware inspection data is presented in Table 4-XVII.

Table 4-XVII. Hardware Performance Deterioration Data Summary.

	Δ Cruise Fuel Burn (%)		
	No Refurbishment	With Refurbishment	Average Serviceable
Fan Section @ 6000 Hours	1.32	0.80	0.93
HP Compressor @ 6000 Hours	0.85	0.51	0.73
HP Turbine @ 4000 Hours	0.92	0.06	0.06
LP Turbine @ 6000 Hours	0.41	0.04	0.36
			2.08

The average serviceable engine is shown in the third column, and it is noted that the data in the "no refurbishment" column cannot be totaled due to the disportionate number of hours noted for the HPT module.

4.3 DISCUSSION OF LONG-TERM RESULTS

The CF6-6D engine is maintained using the on-condition concept. Repair of the engine during each shop visit is based on results noted during routine on-wing inspections supplemented by maintenance plans designed to incorporate product improvement items. Each engine, when assigned for maintenance repairs, is disassembled into the component modules which are dispersed to separate repair lines. These modules are repaired to eliminate those mechanical conditions that exceed published inspection limits, as well as to incorporate any product improvement items. Very rarely - and then only a quick-turn engine to alleviate low spare conditions - are the individual modules from a specific engine assembled after repair into the same engine. The singularity of the individual modules disallows the establishment of an average engine. However, the establishment of an average engine which summarizes the hardware data for each section of the engine to produce a "total engine value" is required for comparison with the results from the independent assessment based on performance data. The comparison of the expected deterioration based on the two independent assessments produces confidence that the fuel usage assessments based on hardware inspection data are reasonable.

Comparisons between the fuel usage assigned based on hardware inspection and performance data for each of the three major parts of the engine life cycle - initial-installation, multiple-build, and unrestored loss - are discussed in the following paragraphs.

INITIAL-INSTALLATION ENGINE

A direct comparison of the performance and hardware results for the initial installation engine is presented in Figure 4-50.

The comparison was made at 4000 hours and, as noted, produced good agreement. The hardware plot was constructed using the individual deterioration levels presented for each module in the hardware data sections. Note that the constant loss of 0.19 percent in cruise fuel burn for the fan quarter-stage material is not involved in this comparison since all production new engines included the shroud material but the airlines have not replaced the material which had been previously removed for durability considerations. In addition, the loss of 0.57 percent in cruise fuel burn for short airfoils and casing distortion for the high pressure compressor is also not included since that loss occurs during shop maintenance and not during engine operation. Technically, part of the casing distortion and a potential erosion loss should be included for the quarter-stage during engine operation. However, these losses are small, and the net effect would be to raise the hardware figure to even closer agreement with the performance assessment.

The data plotted for the fan, HPC and LPT to 6000 hours in Figure 4-50 is intended to show only the delta deterioration for each of these modules beyond 4000 hours. The absolute delta cruise fuel burn levels shown for 6000 hours in this figure does not represent "total engine" deterioration since data for the HPT module is not available beyond 4000 hours.

Note that the high pressure turbine section represents a 0.92 percent cruise burn loss after 4000 hours, and the short-term loss was established as 0.75 percent in Δsfc and represents 80 percent of the total initial installation loss. It will be shown later in this report that the multiple-build engines generally indicate a similar loss in the high pressure turbine after 3000 hours. A product improvement to eliminate blade tip rubs, which are the major source of high pressure turbine deterioration, is required. In summary, the fuel burn assessments based on hardware inspection results are considered reasonable based on the good correlation with the results obtained from performance data.

AVERAGE SERVICEABLE ENGINE

The comparison of the fuel burn assessments based on performance and hardware inspection data is presented in Figure 4-51. The performance data are based on test cell results for the refurbished engines prior to reentering revenue service. The hardware averages were assessed by the individual teams based on their independent reviews of hardware and studies of airline refurbishment

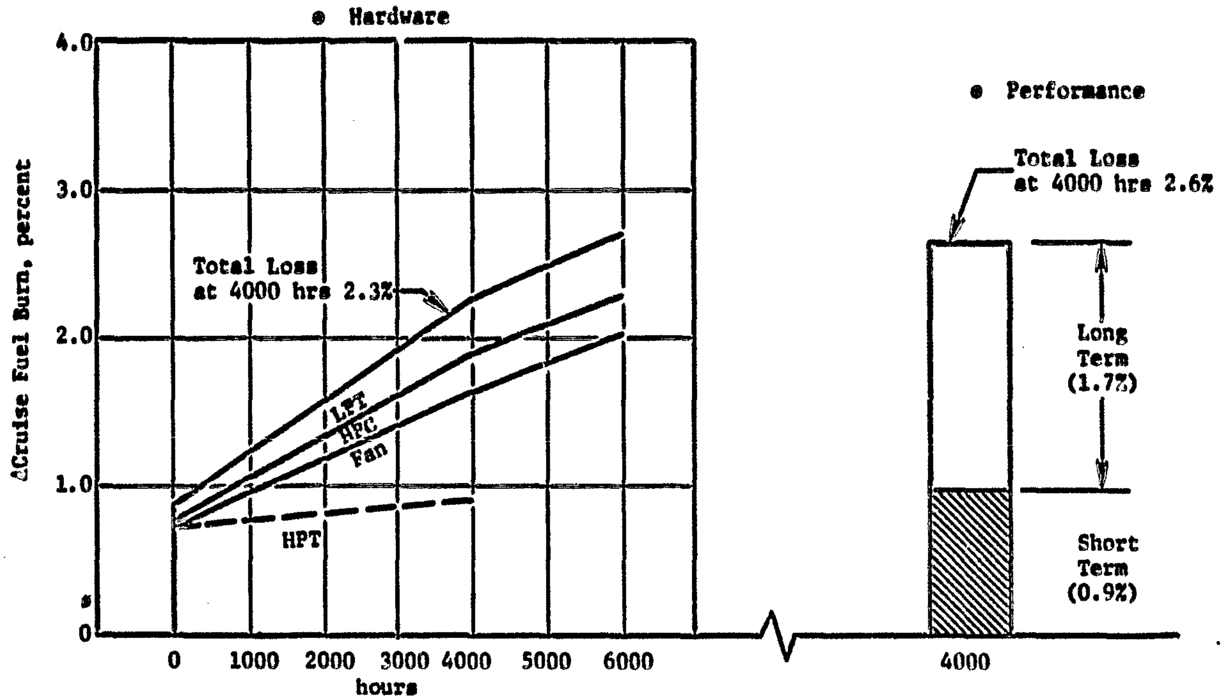


Figure 4-50. Initial Installation Engine.

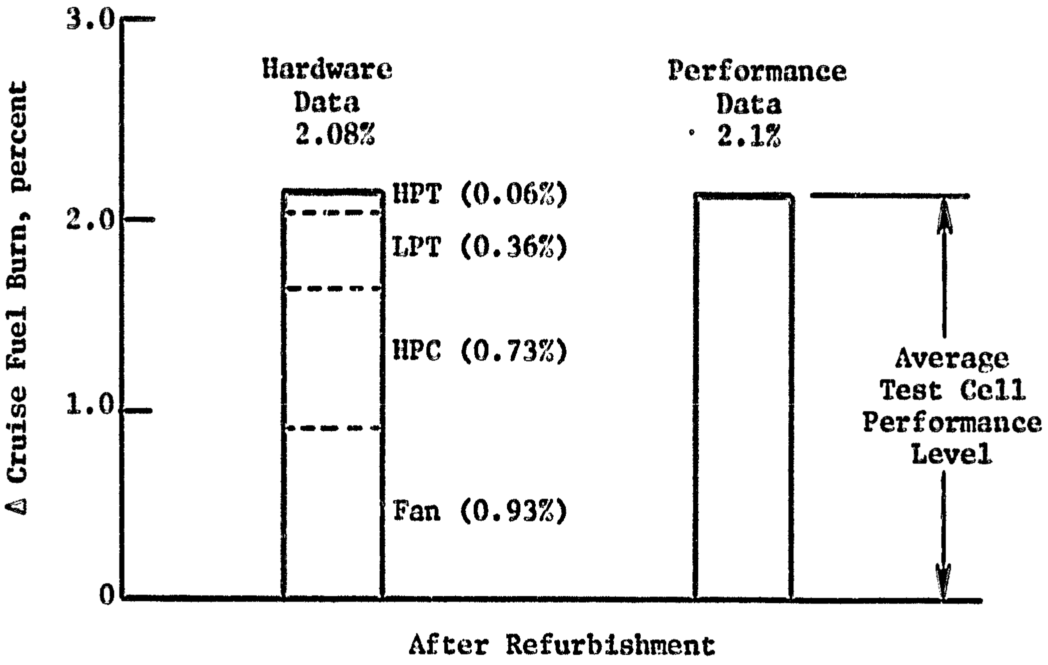


Figure 4-51. Average Refurbished Engine (Unrestored Loss).

practices. It is interesting to note that while the high pressure turbine is the largest contributor to on-wing deterioration, almost all of those losses are restored during a shop visit. This was expected, since this section of the engine has the highest deterioration rate and generally is repaired for durability reasons at each shop visit regardless of engine removal cases. In addition, refurbishment activity is required during each shop visit to restore EGT margin to avoid early removal (red line limit). Experience has shown that high pressure turbine deterioration is a major contributor to the lack of the EGT margin, and restoration of EGT margin also restores the majority of the performance losses since the major elements for both conditions are the same.

MULTIPLE BUILD ENGINE

As shown in Figure 4-52, the loss in cruise fuel burn assessed from hardware inspection data (3.3 percent), compared with that measured using performance data (3.0 percent) agrees within 0.3 percent in cruise burn. This good agreement verifies that the independently assessed results are valid and realistic. Note that a differnt baseline was used for the two data sources which were developed during the studies concerning unrestored losses. As shown, the losses for the multiple build engines are predominately in the high pressure turbine which were shown to be the result of increased blade to shroud clearances from rubs. It is important to remember that these hardware inspection and performance data represent the average for the individual modules, and that a large variation exists between individual assemblies and engines.

ADDITIONAL REMARKS

The comparison of the cruise fuel burn deterioration based on independent assessments from hardware inspection and performance data produced good agreements as follows:

	Hardware	Performance	Delta
Initial Installation, (%)	2.3	2.6	0.3
Unrestored Losses, (%)	2.08	2.1	---
Mutiple Build, (%)	3.3	3.0	0.3

Therefore, it is concluded that these data are an accurate representation of long-term deterioration characteristics for the CF6-6D model engine, and have reasonably isolated the losses for the initial-installation, multiple-build and serviceable engines.

4.4 DETERIORATION MODELS

The hardware inspection and performance results, having been verified as reasonable and realistic, were used to establish two deterioration models. These models, used to describe the rate and sources of performance deterioration which increase fuel consumption have been termed "Performance

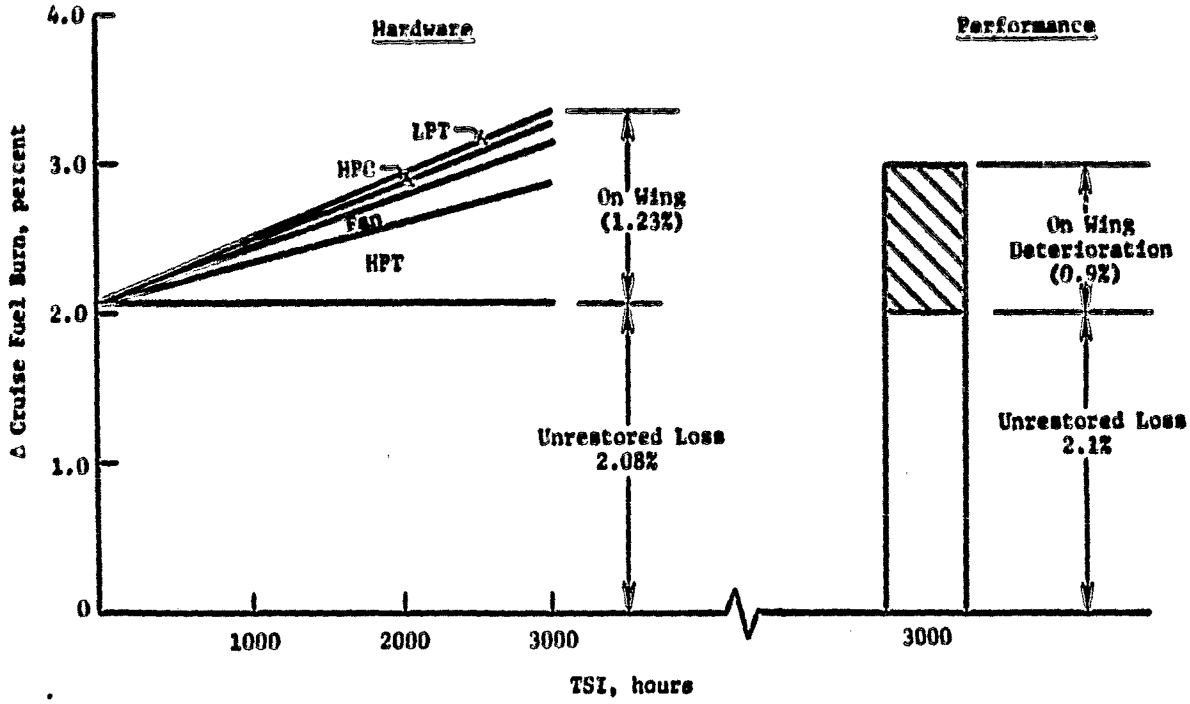


Figure 4-52. Multiple Build Engine Performance Deterioration.

Deterioration Model" and "Hardware Deterioration Model." These models are required for different reasons and constructed using different data sources. The primary reason and data used to develop each model is included in the following discussions.

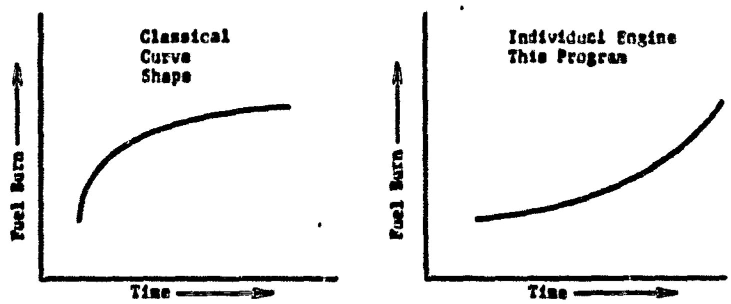
PERFORMANCE DETERIORATION MODEL

Figure 4-53 presents the "Performance Deterioration Model" which describes the magnitude of fuel burn and the rate at which these losses occur with accumulated time. Only performance data is used to construct this model since the necessary hardware data required to describe the curve shape from installation to removal was not available. Sufficient performance data was not available to specifically determine the amount of performance gained for initial installation engines following refurbishment, and is therefore, represented by a dotted line in the schematic.

While hardware inspection data was not used to develop this model, the initial and final data points for each segment (short-term, initial-installation, multiple installation and unrestored loss) were verified with hardware inspection data. (These comparisons are discussed in Section 4.3 of this report.)

The primary use of this model by the airlines is to establish overall fuel burn delta with increasing time for a given engine, and to competitively judge the performance deterioration characteristics for the different engine models. It was previously noted that the multiple build engine and unrestored loss data indicated no measurable trend from the 2nd through the 10th shop visit. Therefore, this model is considered representative for the current CF6-6D fleet.

The deterioration curve shape shown in this model differs from that generally presented to represent airline fleets. The inverted shape of the curve is the result of selectively averaging only a part of the fleet data, to produce a curve that averages individual engines for a very narrow band of engine hours; i.e., 4000 ± 450 hours for the initial-installation engine and 3000 ± 250 hours for the multiple-build engine. While the individual engines in the time families from 2000 to 5000 hours all show the same characteristics, the airline fleet average - which includes infant mortality failures as well as long-time removals - produces the classical curve shape where the rate of deterioration decreases with accumulated time. This is shown in the sketch as follows:



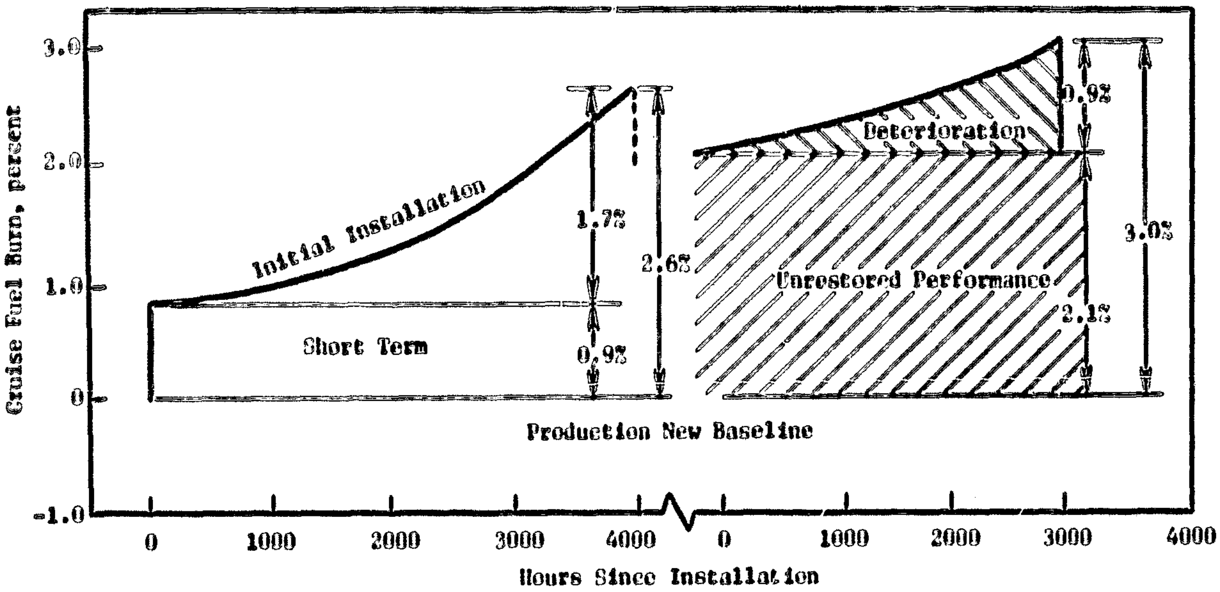


Figure 4-53. Performance Deterioration Model.

The curve shape generated for this program is considered correct for achieving the specific program objectives, but it does not represent the airline fleet average and is not intended to imply that the "classical" deterioration curve shape is incorrect.

HARDWARE DETERIORATION MODEL

Table 4-XVIII documents the "Hardware Deterioration Model" which assigns the fuel burn losses to the individual parts and respective damage mechanisms. This model is based exclusively on the hardware studies which include inspection data describing hardware conditions, and back-to-back engine tests conducted exclusively to measure the the performance effects of specific damage mechanisms. The model represents the deterioration losses that were estimated for new hardware with the accumulated hours as shown for each module. In addition, the fuel burn increases that have occurred during a shop visit for engine refurbishment are also included. These items are those which do not occur during revenue service, but as a result of maintenance practices or policy. As shown by the asterisks on Table 4-XVIII and discussed in detail in Section 4.2 of this report, they include such items as quarter-stage tip clearance (material not installed) short or average airfoil HP compressor (results from rework to produce minimum clearance) and fan blade tip clearance increase (partially due to rework of shrouds to meet minimum clearance requirements).

The "Hardware Deterioration Model" is used primarily by the airlines to determine items to be included in the individual workscopes and by General Electric to determine areas where produce improvements are required in order to reduce or eliminate sources of fuel burn deterioration. Care must be exercised in using this model, as not all of the itemized deterioration modes and especially the magnitude are observed for each module. Indeed, a wide variance in the condition of the various modules (and serviceable engines) does exist since the engine is being maintained using the on-condition concept which permits selective repair rather than the fixed time between overhaul method which would require the same repairs for each module.

While the construction of deterioration models are a necessary product of the overall program studies, the question arises regarding what to do with the results? Since this program is part of an "umbrella" Energy Conservation Program, the answer must be that the results should be used to reduce fuel consumption for the CF6-6D model engines. Based on a review of the deterioration models, the answer becomes evident. As shown in Figure 4-53, the fuel burn losses that are not restored represent a constant 70 percent fuel burn deterioration (2.1 percent of 3.0 percent cruise sfc) when the average refurbished engine has accumulated 3000 hours. The remaining 30 percent (0.9 percent cruise fuel burn) is attributed to on-wing deterioration occurring during the 3000 hours typically accumulated between shop visits. The 0.9 percent cruise fuel burn loss is restored during each shop visit, and is primarily the result of high pressure turbine blade tip rubs. Two alternatives can be considered to eliminate or at least reduce these unrestored losses.

Table 4-XVIII. Hardware Deterioration Model.

Fan Section (at 6000 hours)	Δ Cruise Fuel Burn (%)
Stage 1 Blade Leading Edge Contour	0.38
Stage 1 Blade Tip Clearance Increase*	0.21
Bypass OGV Airfoils Roughness	0.19
Quarter Stage Tip Clearance Increase*	0.19
Stage 1 Blade Dirt Accumulation	0.13
Splitter Leading Edge Degradation	0.08
Bypass OGV Leading Edge Degradation	0.06
Stage 1 Blade Airfoils Roughness	0.03
Quarter Stage Airfoils Leading Edge	0.025
Quarter Stage Airfoils Roughness	0.025
Total	1.32

High Pressure Compressor Section (at 6000 hours)	Δ Cruise Fuel Burn (%)
Tip Clearance Increases	
• Short Blades and Vanes*	0.42
• Casing Distortion	0.17
• Flowpath Coating Degradation	0.10
• Flowpath Coating Rubs	0.04
Blade Airfoil Quality Degradation	0.07
Vane Airfoil Quality Degradation	0.03
External Leakage	0.02
Total	0.85

Low Pressure Turbine Section (at 6000 hours)	Δ Cruise Fuel Burn (%)
Increase in Blade Tip Clearances	0.20
Increase in Interstage Seal Clearances	0.17
Airfoils Surface Finish Degradation	0.04
Total	0.41

High Pressure Turbine Section (at 6000 hours)	Δ Cruise Fuel Burn (%)
Blade Tip Clearance Increase, Stage 1	0.52
Blade Tip Clearance Increase, Stage 2	0.20
Blade Airfoil Quality Degradation	0.05
Vane Airfoil Quality Degradation	0.05
Internal Leakage	
• Stage 1 HPTN Outer Band Distortion	0.05
• Increase in Interstage Seal Clearances	0.05
Total	0.92

*Result During Shop Visit.

First, product improvements could be developed to prevent the deterioration from occurring in the first place, thereby eliminating both the on-wing losses and the subsequent unrestored losses. While this is the ultimate long-range goal of the General Electric Company, it is not realistic to expect that all losses will be eliminated. However, General Electric is working to develop product improvements that will have a positive effect on reducing the effect for most of the sources. In addition, the companion NASA Performance Improvement Program includes efforts to develop several generic items for high pressure turbine which was the area shown to be the largest contributor to performance deterioration which increase fuel burn. These include a Roundness Control Program which is aimed at eliminating part distortions and resultant rubs, and an Active Clearance Control Program which utilizes preferential cooling air to achieve more optimum clearances during cruise. The results from these two NASA-sponsored programs will be available in the near future.

The second alternative is to develop more effective restoration teeniques, or to incorporate additional restoration items which can reduce the unrestored losses present after each shop visit. While this does not necessarily affect the deterioration rate, it can produce an instant and short-range reduction in energy consumption. This alternative was evaluated as part of this program, and the results are discussed in the next section of this report. That section is entitled "Recommendations" since the indicated action from those studies addresses to the question, "How can these results be applied to reduce fuel consumption for the CF6-6D model engine?"

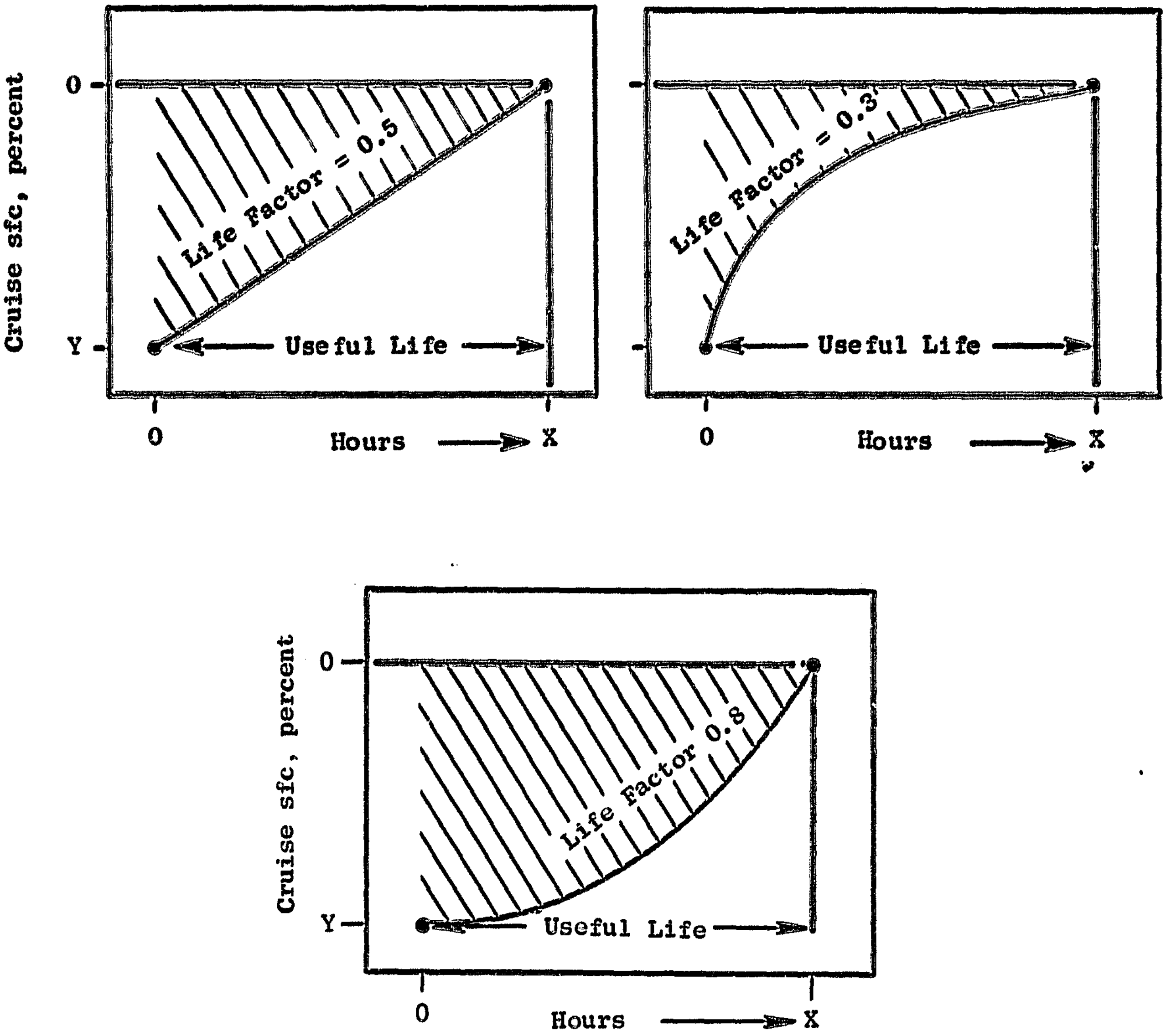
5.0 RECOMMENDATIONS

The primary objective of this program was to identify performance deterioration sources for current CF6-6D engines and ways to minimize these effects; thus having a favorable impact on the national energy shortage. Unrestored performance, that is, the in-service deterioration which is not corrected during subsequent shop visits, offers the largest potential for fuel conservation. This represents 70 percent of the total fuel burn deterioration calculated for the CF6-6D model engines and amounts to over 15 gallons of cruise fuel burn for every engine flight-hour. Immediate fuel burn deduction can be realized by more effective and/or additional restoration during each shop visit. While reducing energy consumption is of national interest, the airlines require that any maintenance action, over and above that required to restore mechanical integrity, be cost-effective. The individual airlines have their own distinct ground rules on what is to be included in cost studies and include: labor and fuel costs, burden costs (overhead), investment, and maintenance philosophy.

The hardware teams conducted cost-effectiveness feasibility studies for each of the deterioration items. These studies consisted simply of calculating the labor and material costs, with no attempt to incorporate other financial considerations. They were not evaluated for any specific airline since the required input data are considered proprietary and, therefore, not available. Reasonable assumptions were used by the teams based on normal airline relationships to determine the specific input data. It is for these reasons that these studies are termed cost-effectiveness feasibility studies, and each airline has to adjust the results to its specific criteria.

The cost-effectiveness studies were based primarily on two major considerations: additional costs for the modification, and expected reduction in operation costs. The difference between the increased costs and potential reductions represents the anticipated savings. The estimated costs to incorporate the added refurbishment were calculated using a labor rate of $23.00 per hour (which includes an estimated overhead of 100 percent) and material costs based on the 1979 parts catalog. The teams estimated the amount of labor needed to perform the modification which included the man-hours required to disassemble/reinstall the individual part into its specific module. It was assumed that the individual modules were exposed as a result of normal mechanical repair. The "cost of money" was not included in the study, nor were any investment criteria ("bricks and mortar") other than the 100 percent overhead consideration. The material costs assumed the vendor repair cost rather than new-part cost, where applicable.

The calculation of reduced operating costs required the establishment of the amount to be gained, the "useful life" or hours until the gain is completely lost, and a "life factor" which represents the rate at which the gain deteriorates. The useful life and life factor were derived for each condition by the hardware teams based on their observations, other General Electric studies or tests, analytical calculation and common sense. Figure 5-1 indicates three



X = Hours when Gain is Completely Lost

Y = Total Gain

Figure 5-1. Cost Effective Factors.

examples of the curve shape for deterioration rates that could be developed, and the area above the curve represents the time where fuel consumption is available. In general, the deterioration rate was considered linear with time and assigned a life factor of 0.5 unless otherwise determined. The amount of cruise sfc to be gained for each condition was not assumed to be equivalent to its total assessed loss, but rather was estimated in terms of what percentage of the loss could be restored using current technology and tooling.

The fuel usage was calculated for a typical DC10-10 mission and estimated to consume 746 gallons of fuel per engine flight hour at a cost of $0.63 per gallon. This combination produced a $4.70 cost saving per engine flight hour for each one percent reduction in cruise fuel burn.

An improvement in cruise fuel burn (sfc) will produce a corresponding improvement in EGT margin which will reduce hardware consumption because of lower operating temperatures, and possibly extend time on-wing between shop visits. While these are potentially significant considerations, they are very difficult to generalize and are not included in these studies. Rather, this potential for cost savings, while not estimated, can be used to justify acceptance of marginally cost-effective items.

The statistics used to determine the cost effectiveness for the individual items are presented in Table 5-I. The items are arranged by the individual modules, and the column headings are those previously mentioned. The listing includes the major performance deterioration items isolated by these studies and is not presumed to include all sources. For those items where a materials cost is noted under the Modification column without a corresponding labor cost, a fixed vendor replacement repair cost is shown which includes both material and labor. As shown in Table 5-I, the useful life for the repairs ranged from 4000 to 12,000 hours, with most of the life factors estimated to be 0.5. The items of deterioration that are normally corrected during each shop visit, such as high pressure turbine blade-to-shroud clearance, were of course, not considered in this study.

These results (as shown in the last 3 columns in Table 5-I) were used to calculate the potential cost-effectiveness for each item using the labor and fuel costs previously noted. The pertinent results form the cost-effectiveness studies excluding detailed calculations are summarized in Table 5-II. The last column in this table shows the savings as a cost per flight-hour to make all items on an "apples-to-apples" basis. These studies indicate a potential savings from $1.15 per hour to a potential loss of $1.37 per hour. As noted earlier, any saving, however marginal, is considered cost-effective based on the potential additional savings in part life expected from the corresponding reduction in EGT.

The data presented in Table 5-III indicates that 80 percent of the total 2.1 percent cruise fuel burn increase is potentially cost-effective to restore. However, these potential figures are somewhat misleading in that some of the listed items are being restored on a parttime basis rather than during each

Table 5-I. Cost Reduction Studies.

	Reduced Costs			Additional Costs		
	SFC Gain (%)	Useful Gain (hrs)	Life Factor	Removal/ Install (hrs)	Modification Labor (hrs)	Modification Materials ($)
FAN SECTION						
Recontour Fan Blade	0.38	6000	0.5	1.5	9.5	--
Repair Fan Bypass OGV	0.25	12000	0.5	7	--	1000
Correct Fan Blde Clear	0.21	12000	0.5	6	18	100
Quarter Stage Shroud	0.19	12000	0.5	16	30	300
Replace Splitter Lead Edge	0.08	9000	0.5	3	16	--
Polish Quarter Stg. Airfoils	0.05	6000	0.5	40	4	125
Fan Blade Surface Finish	0.015	6000	0.5	1.5	16	--
HP COMPRESSOR						
Replace Short Airfoils	0.42	6000	1.0	54	--	3730
Flowpath Coating	0.10	6000	0.5	--	30	100
Clean Airfoils	0.10	6000	0.3	32	6	303
Replace Vane Bushings	0.02	6000	0.8	8	--	200
HP TURBINE						
Restore Blade Finish	0.02	6000	0.5	0	8	--
Restore Vane Finish	0.02	6000	0.5	0	8	--
Vane Distortion						
Interstage Seals	Not Applicable					
Blade Tip Clear						
LP TURBINE						
Replace Tip Shrouds	0.20	4000	0.5	8	--	6400
Replace Interstage Seals	0.17	4000	0.5	8	--	6913
Airfoil Surface Finish	0.04	6000	0.5	26	6	520

Table 5-II. Summary of Cost Savings.

	Expected Gain		Costs		Savings Per Hour	
	SFC (%)	Length (hrs)	Reduced ($)	Added ($)	Fuel (Gal)	Dollars* ($)
FAN SECTION						
Recontour Fan Blade	0.38	6000	5358	253	1.42	0.85
Repair Fan Bypass OGV	0.25	12000	7050	1161	0.93	0.49
Correct Fan Blade Clear	0.21	12000	5922	652	0.78	0.44
Quarter Stage Shroud	0.19	12000	5358	1358	0.71	0.34
Replace Splitter Lead Edge	0.08	9000	1692	437	0.30	0.14
Polish Quarter Stg Airfoils	0.05	6000	705	1137	0.19	-0.07
Fan Blade Surface Finish	0.015	6000	212	403	0.06	-0.03
HP COMPRESSOR						
Replace Short Airfoils	0.42	6000	11844	4972	3.13	1.15
Flowpath Coatings	0.10	6000	1410	790	0.37	0.10
Clearn Airfoils	0.10	6000	846	1177	0.22	-0.06
Replace Vane Bushings	0.02	6000	451	3[illegible]4	0.12	0.01
HP TURBINE						
Restore Blade Finish	0.02	6000	282	184	0.07	0.02
Restore Vane Finish	0.02	6000	282	184	0.07	0.02
LP TURBINE						
Replace Tip Shrouds	0.20	4000	1598	7097	0.75	-1.37
Replace Interstage Seals	0.17	4000	1880	6584	0.63	-1.18
Airfoild Surface Finish	0.04	6000	564	1256	0.15	-0.12

*Includes Fuel Savings

Table 5-III. Cost-Effectiveness Feasibility Results.

	Total Cost Effective (Cruise SFC)	Currently Being Restored	Total Available (Cruise SFC)	Potential Savings Fuel (Gal/Hr)	Potential Savings Cost $/Hr
Fan	1.11%	0.25%	0.86%	6.4	1.69
HP Compressor	0.54%	0.08%	0.46%	3.4	1.18
HP Turbine	0.04%	0.03%	0.01%	0.1	0.01
LP Turbine	0.00%	0.00%	0.00%	0.0	0.00
	1.69%	0.36%	1.33%	9.9	2.88

shop visit. The hardware teams estimated how often each specific item was restored and the effectiveness of the restoration in order to calculate the real potential. Those analyses, presented in Table 5-III, show that of the total 1.69 percent cruise fuel burn deterioration that is cost-effective to restore, 21 percent (0.36 percent cruise fuel burn) is effectively being restored today on a part time basis. This leaves a potential of 1.33 percent in cruise fuel burn, equivalent to 9.9 gallons fuel usage and an estimated $2.88 engine flight hour. This is equivalent to 10.9 million gallons of fuel and 3.2 million dollars in savings based on 1.1 million flight hours estimated for CF6-6D model engines for 1980.

In summary, the majority of the unrestored losses for the CF6-6D model engine are cost-effective to restore. It is recommended that the airlines conduct their own cost-effectiveness studies and initiate action to more effectively restore fuel burn losses during each shop visit. This restoration in conjunction with action to minimize deterioration through design modifications can make a notable impact on energy consumption in the 1980's.

6.0 CONCLUDING REMARKS

The studies to determine the performance deterioration characteristics for the CF6-6D model engine specifically related to increased fuel burn revealed wide variances in the rates for individual engines. The current on-condition maintentance concept, as opposed to fixed time-between-overhaul (TBO), together with the modular concept of the engine, which permits selective refurbishement, contribute to this condition. In addition, cockpit recordings of performance parameters - in particular, fuel flow - were not consistent as would be desired, which also contributed to the wide variance for individual engines.

While the nature of this program was not such that explicit results could be formulated and verified to the "Nth" degree by experiments, the salient results presented in this report are a reasonable and accurate representation of the deterioration characteristics for the CF6-6D model engines. This is based on the following key observations:

- Teams of General Electric technical personnel, experienced in all phases of engine/airline operation (mechanical design, aero design, performance restoration, performance analysis, and airline service engineering), conducted the detailed data reviews, produced the results and completed analytical analysis to assure that their results agreed with the facts and/or engineering logic.

- Specific data obtained as part of this program or from special General Electric programs, including special hardware inspections, back-to-back testing to isolate specific deterioration modes, etc., in conjunction with the routine airline data, produced sufficiently large samples of data to adequately document deterioration characteristics at selected points in the engine life cycle These points were for a deteriorated engine when removed for a normal shop visit, and for the refurbished engine after repairs had been completed but prior to reentry into revenue service. This permitted the most important program objectives to be determined using empirical performance and hardware inspection data.

- When engine deterioration levels produced by summarizing the losses assessed from hardware inspection data for the individual deterioration sources were compared with independently determined levels based exclusively on engine performance data, good agreement resulted for each major part of the engine life cycle.

Therefore, based on these key observations, it is reasonable and prudent to believe the results obtained during these studies are a reasonable assessment of performance deterioration characteristics for the CF6-6D model engine. The more important results are presented in the following paragraphs:

- Short-term losses equivalent to 0.9 percent in cruise fuel burn occur during the initial checkout flight conducted at the aircraft manufacturer (DACo) prior to delivery for revenue service. These losses are almost exclusively the result of rubs between the blade tips and the stationary shrouds in Stage 1 and 2 of the high pressure turbine. These rubs were most likely the result of an operational condition which, while not prohibited, is nontypical of revenue service operation. Product improvements are required to eliminate or reduce these losses, and are being purused independently in other NASA (Performance Improvement) and General Electric programs.

- The magnitude of deterioration for the average new engine during the initial installation for revenue service was determined to be 1.7 percent in cruise fuel burn after 4000 hours, which is in addition to the 0.9 percent short-term loss.

- The on wing long-term loss for the typical refurbished airline engine was 0.9 percent in cruise fuel burn following 3000 hours of revenue service. Short-term losses could not be isolated for typical airline overhaul engines entering revenue service.

- The unrestored loss for the typical airline refurbished engine was equivalent to 2.1 percent in cruise fuel burn. This level was noted to be constant following the second shop visit, with no trend evident through the tenth shop visit.

- While product improvements are being developed in an effort to eliminate the major sources of performance deterioration, additional and/or more effective restoration during each shop visit is the most promising area for expeditious reduction in energy consumption.

- Cost effectiveness feasibility studies conducted as part of this effort indicated that more than 80 percent of the unrestored loss was cost-effective to restore. Based on 1.1 million flight hours expected for CF6-6D engines during 1980, cost-effective items not currently being restored represent the potential to reduce fuel consumption by 10.9 million gallons with a net cost savings (fuel savings minus additional cost to incorporate) of $3.2 million dollars.

- The potential to make a notable impact on energy consumption in the 1980's has been demonstrated.

APPENDICES

Data are included in these appendices for the following items:

Appendix A	Hardware Inspection Data
Appendix B	Cruise Performance Data
Appendix C	Symbols and Acronyms
Appendix D	Terminology
Appendix E	Special Analysis - 6000-Hour Deterioration Models
Appendix F	Quality Assurance Report
Appendix G	List of References

APPENDIX A

HARDWARE INSPECTION DATA

The following pages contain the hardware inspection procedures and measurement data used for the short-term (Section 3.0) and long-term (Section 4.0) deterioration studies. The "Task III" engine referenced in many of the tables is the short-term deterioration engine described in Reference 1. The two "Task IV" engines are described in References 3 and 4, respectively.

A.1 FAN SECTION

Stage 1 fan blade-to-shroud tip clearances are established at the E12 and E13 locations of the Stage 1 fan shroud. E12 is located 7.8 inches aft of the forward flange of the fan stator case, while E13 is located 10.6 inches from the forward flange, as shown in Figure A-1. The average blade-to-shroud tip clearance at each of the two locations is calculated by adding the average rotor runout to the average case clearance of the longest blade.

Average rotor runout at each location is determined by measuring the clearance between each of the 38 blade tips and the shroud at the six o'clock position. The tightest clearance (belonging, of course, to the longest blade) is then subtracted from the average of the measured clearances at each location yielding the average rotor runout. Using the established long blade, clearances to the shroud are measured at twelve equally spaced circumferential locations to obtain the average case clearance.

Table A-I is a summary of the fan clearance measurement inspections.

Fan blade tip clearance changes and their effect on performance are discussed in the portion of Section 4.2.1 entitled "Fan Section".

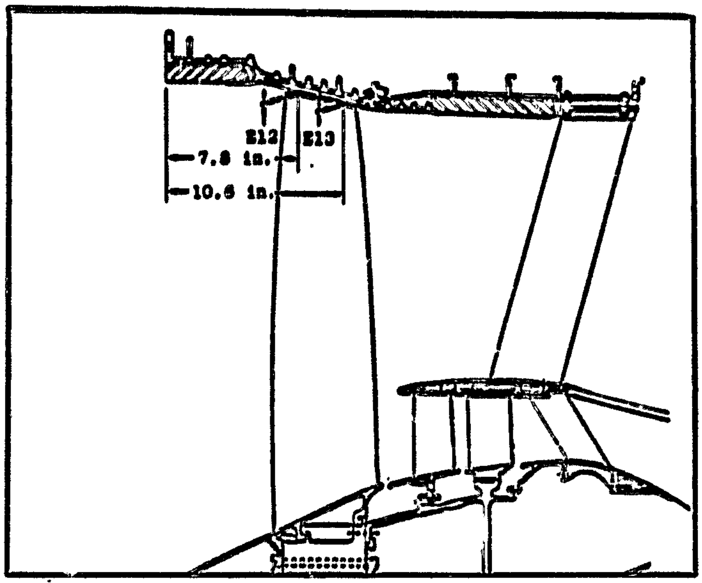


Figure A-1. Locations of Stage 1 Fan Blade Tip Clearance Tip Clearance Measurements.

Table A-I. Stage 1 Fan Blade Tip Clearance Measurements (Inches) (Tasks III and IV - Inbound; All Others - Outbound).

Engine Serial Number	E12				E13				Overall Avg. Clearance
	Minimum Clearance	Avg. Case Clearance	Avg. Rotor Runout	Average Clearance	Minimum Clearance	Avg. Case Clearance	Avg. Rotor Runout	Average Clearance	
451-359	.172	.190	.010	.200	.152	.167	.021	.188	.194
451-360	.161	.165	.038	.203	.176	.184	.028	.212	.208
451-426	.168	.180	.010	.190	.150	.165	.015	.180	.185
451-221	.151	.161	.014	.175	.152	.168	.018	.186	.181
451-424	.160	.166	.016	.182	.151	.161	.018	.179	.181
451-234	.174	.188	.012	.200	.147	.182	.018	.200	.200
451-484	.148	.153	.025	.178	.150	.155	.035	.190	.184
451-250	.164	.169	.021	.190	.159	.169	.013	.182	.186
451-238	.155	.180	.014	.194	.155	.184	.013	.197	.196
451-440(1)	.125	.144	.015	.159	.125	.141	.029	.170	.165
451-380(2)	.142	.166	.018	.184	.145	.169	.013	.182	.183
451-479(2)	.130	.145	.018	.163	.120	.146	.012	.158	.160
451-507(3)	.149	.162	.012	.174	.142	.158	.015	.173	.174
AVERAGE				.187				.187	.187

(1) ESN 451-440 shroud ground to open clearances to minimum prior to return to service, not included in average.

(2) Task IV engine

(3) Task III engine (short-term) not included in average.

A.2 HIGH PRESSURE COMPRESSOR SECTION

A.2.1 HPCR Blade Tip Radii

Table A-II summarizes the accumulated HPCR blade tip radii data. Tables A-IIa through A-IIf present the data taken manually on a "runout" fixture utilizing a calibrated bar assembly set up on the forward and aft shaft straddling the rotor blades as shown in Figure A-2. A calibrated gauge is used to measure the distance from the bar to the blade tip. A laser beam Electronic Read Out Machine (EROM) was used to acquire the data presented in Tables A-IIg through A-IIk. Table A-III is a tabulation of the average measurements for each stage for all HPC's inspected. Blade tip clearance and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Compressor Section".

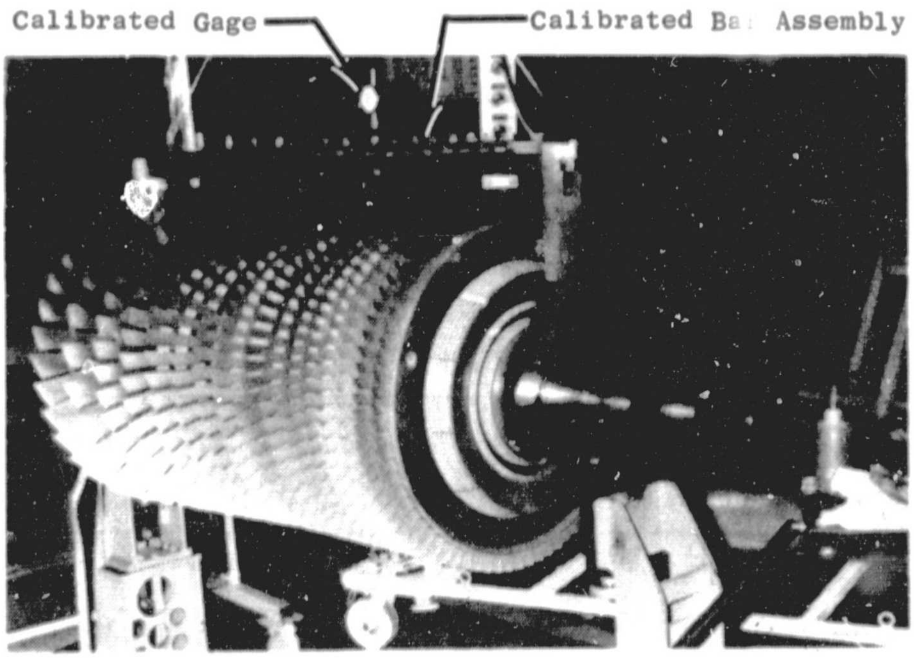


Figure A-2. HP Compressor Rotor in Measuring Fixture.

Table A-IIa. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-144
TSO/CSO 6051/2460

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.368	14.334	14.363	0.010
2	14.143	14.137	14.124	14.132	0.011
3	13.925	13.918	13.910	13.914	0.011
4	13.733	13.731	13.709	13.724	0.009
5	13.553	13.555	13.535	13.548	0.005
6	13.396	13.396	13.382	13.392	0.004
7	13.251	13.243	13.227	13.239	0.012
8	13.222	13.220	13.210	13.214	0.008
9	13.223	13.223	13.214	13.220	0.003
10	13.226	13.222	13.215	13.219	0.007
11	13.220	13.216	13.205	13.211	0.009
12	13.224	13.225	13.192	13.211	0.013
13	13.224	13.217	13.205	13.213	0.011
14	13.212	13.197	13.185	13.191	0.021
15	13.151	13.145	13.140	13.143	0.008
16	13.066	13.055	13.048	13.052	0.014

Table A-IIb. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-245
TSO/CSO 1766/602

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.370	14.340	14.360	0.013
2	14.143	14.146	14.133	14.138	0.005
3	13.925	13.928	13.911	13.919	0.006
4	13.733	13.734	13.709	13.725	0.008
5	13.553	13.556	13.539	13.548	0.005
6	13.396	13.396	13.381	13.389	0.007
7	13.251	13.243	13.228	13.238	0.013
8	13.222	13.220	13.204	13.215	0.007
9	13.223	13.225	13.205	13.218	0.005
10	13.226	13.229	13.210	13.223	0.003
11	13.220	13.222	13.210	13.216	0.004
12	13.224	13.222	13.208	13.216	0.008
13	13.224	13.218	13.202	13.210	0.014
14	13.212	13.195	13.186	13.192	0.020
15	13.151	13.140	13.125	13.134	0.017
16	13.066	13.059	13.041	13.049	0.017

Table A-IIc. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-116

TSO/CSO 7648/3288

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.368	14.360	14.365	0.008
2	14.143	14.136	14.130	14.132	0.011
3	13.925	13.920	13.902	13.914	0.011
4	13.733	13.728	13.718	13.722	0.011
5	13.553	13.552	13.544	13.549	0.004
6	13.396	13.390	13.380	13.385	0.011
7	13.251	13.249	13.239	13.243	0.008
8	13.222	13.222	13.214	13.218	0.004
9	13.223	13.224	13.211	13.217	0.006
10	13.226	13.224	13.212	13.220	0.006
11	13.220	13.217	13.183	13.211	0.009
12	13.224	13.215	13.196	13.206	0.018
13	13.224	13.211	13.198	13.207	0.017
14	13.212	13.205	13.188	13.196	0.016
15	13.151	13.140	13.124	13.132	0.019
16	13.066	13.055	13.041	13.049	0.017

Table A-IId. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-250
TSO/CSO 6752/2348

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.363	14.356	14.360	0.013
2	14.143	14.133	14.122	14.128	0.015
3	13.925	13.916	13.909	13.912	0.013
4	13.733	13.726	13.697	13.719	0.014
5	13.553	13.550	13.524	13.544	0.009
6	13.396	13.391	13.380	13.388	0.008
7	13.251	13.248	13.234	13.242	0.009
8	13.222	13.215	13.200	13.209	0.013
9	13.223	13.219	13.208	13.214	0.009
10	13.226	13.225	13.216	13.220	0.006
11	13.220	13.215	13.205	13.211	0.009
12	13.224	13.220	13.198	13.210	0.014
13	13.224	13.212	13.189	13.204	0.020
14	13.212	13.198	13.174	13.193	0.019
15	13.151	13.137	13.121	13.131	0.020
16	13.066	13.050	13.043	13.044	0.022

Table A-IIe. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-259
TSO/CSO 6506/2809

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.364	14.351	14.359	0.014
2	14.143	14.131	14.120	14.127	0.016
3	13.925	13.915	13.893	13.908	0.017
4	13.733	13.726	13.700	13.718	0.015
5	13.553	13.549	13.530	13.543	0.010
6	13.396	13.394	13.384	13.389	0.007
7	13.251	13.247	13.234	13.242	0.009
8	13.222	13.218	13.205	13.214	0.008
9	13.223	13.219	13.212	13.215	0.008
10	13.226	13.228	13.214	13.223	0.003
11	13.220	13.213	13.199	13.207	0.013
12	13.224	13.215	13.206	13.211	0.013
13	13.224	13.215	13.201	13.209	0.015
14	13.212	13.192	13.172	13.187	0.025
15	13.151	13.139	13.126	13.134	0.017
16	13.066	13.051	13.038	13.046	0.020

Table A-IIf. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-390
TSO/CSO 6085/2605

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.370	14.359	14.365	0.008
2	14.143	14.142	14.129	14.135	0.008
3	13.925	13.916	13.910	13.914	0.011
4	13.733	13.726	13.715	13.721	0.012
5	13.553	13.544	13.514	13.541	0.012
6	13.396	13.381	13.370	13.375	0.021
7	13.251	13.232	13.224	13.227	0.024
8	13.222	13.203	13.198	13.200	0.022
9	13.223	13.219	13.210	13.215	0.008
10	13.226	13.226	13.215	13.218	0.008
11	13.220	13.209	13.201	13.205	0.015
12	13.224	13.215	13.206	13.211	0.013
13	13.224	13.213	13.202	12.208	0.016
14	13.212	13.194	13.183	13.190	0.022
15	13.151	13.137	13.128	13.134	0.017
16	13.066	13.050	13.039	13.045	0.021

Table A-11g. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-443
TSO/CSO 9000/2770

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.379	14.371	14.376	+0.003
2	14.143	14.152	14.132	14.143	0.000
3	13.925	13.929	13.921	13.926	+0.001
4	13.733	13.737	13.732	13.734	+0.001
5	13.553	13.558	13.548	13.555	+0.002
6	13.396	13.399	13.380	13.394	-0.002
7	13.251	13.257	13.251	13.255	+0.004
8	13.222	13.226	13.218	13.223	+0.001
9	13.223	13.227	13.216	13.223	0.000
10	13.226	13.230	13.219	13.226	0.000
11	13.220	13.224	13.203	13.217	-0.003
12	13.224	13.226	13.216	13.222	-0.002
13	13.224	13.225	13.208	13.220	-0.004
14	13.212	13.207	13.187	13.204	-0.008
15	13.151	13.144	13.134	13.141	-0.010
16	13.066	13.054	13.046	13.050	-0.016

Table A-11h. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-155
TSO-CSO 6641/2960

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.371	14.359	14.364	0.009
2	14.143	14.147	14.134	14.142	0.001
3	13.925	13.926	13.917	13.922	0.003
4	13.733	13.733	13.722	13.729	0.004
5	13.553	13.555	13.542	13.550	0.003
6	13.396	13.394	13.385	13.390	0.006
7	13.251	13.250	13.241	13.246	0.005
8	13.222	13.216	13.209	13.213	0.009
9	13.223	13.220	13.203	13.214	0.009
10	13.226	13.232	13.215	13.226	0.000
11	13.220	13.219	13.201	13.213	0.007
12	13.224	13.218	13.203	13.213	0.011
13	13.224	13.215	13.206	13.212	0.012
14	13.212	13.201	13.178	13.193	0.019
15	13.151	13.140	13.129	13.135	0.016
16	13.066	13.052	13.045	13.049	0.017

Table A-III. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-424

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.368	14.345	14.356	0.017
2	14.143	14.147	14.127	14.135	0.008
3	13.925	13.928	13.913	13.920	0.005
4	13.733	13.730	13.714	13.722	0.011
5	13.553	13.553	13.526	13.541	0.012
6	13.396	13.396	13.380	13.389	0.007
7	13.251	13.250	13.239	13.244	0.007
8	13.222	13.220	13.212	13.216	0.006
9	13.223	13.223	13.210	13.221	0.002
10	13.226	13.226	13.214	13.221	0.005
11	13.220	13.221	13.208	13.216	0.004
12	13.224	13.223	13.207	13.217	0.007
13	13.224	13.223	13.205	13.213	0.011
14	13.212	13.197	13.190	13.193	0.019
15	13.151	13.136	13.127	13.132	0.019
16	13.066	13.051	13.036	13.045	0.021

Table A-IIj. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-452

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.367	14.347	14.357	0.016
2	14.143	14.143	14.127	14.137	0.006
3	13.925	13.917	13.900	13.912	0.013
4	13.733	13.732	13.718	13.725	0.008
5	13.553	13.554	13.539	13.548	0.005
6	13.396	13.395	13.382	13.390	0.006
7	13.251	13.246	13.237	13.241	0.010
8	13.222	13.218	13.209	13.214	0.008
9	13.223	13.215	13.187	13.206	0.017
10	13.226	13.226	13.217	13.223	0.003
11	13.220	13.220	13.196	13.216	0.004
12	13.224	13.222	13.210	13.219	0.005
13	13.224	13.218	13.209	13.214	0.010
14	13.212	13.198	13.186	13.192	0.020
15	13.151	13.138	13.110	13.132	0.019
16	13.066	13.054	13.042	13.048	0.018

Table A-IIk. HPCR Blade Tip Radii, Inbound (Inches).

ESN 451-212

Stage	Nominal	Maximum	Minimum	Average	Δ Nom
1	14.373	14.370	14.345	14.362	0.011
2	14.143	14.152	14.134	14.145	+0.002
3	13.925	13.928	13.913	13.925	0.000
4	13.733	13.738	13.722	13.734	+0.001
5	13.553	13.560	13.546	13.555	+0.002
6	13.396	13.399	13.390	13.395	0.001
7	13.251	13.254	13.239	13.250	0.001
8	13.222	13.224	13.215	13.220	0.002
9	13.223	13.225	13.206	13.220	0.003
10	13.226	13.228	13.223	13.225	0.001
11	13.220	13.219	13.205	13.214	0.006
12	13.224	13.228	13.210	13.223	0.001
13	13.224	13.227	13.210	13.224	0.000
14	13.212	13.216	13.186	13.198	0.014
15	13.151	13.146	13.128	13.143	0.008
16	13.066	13.063	13.040	13.058	0.008

Table A-III. HPCR Blade Tip Radii; Average, Inbound.

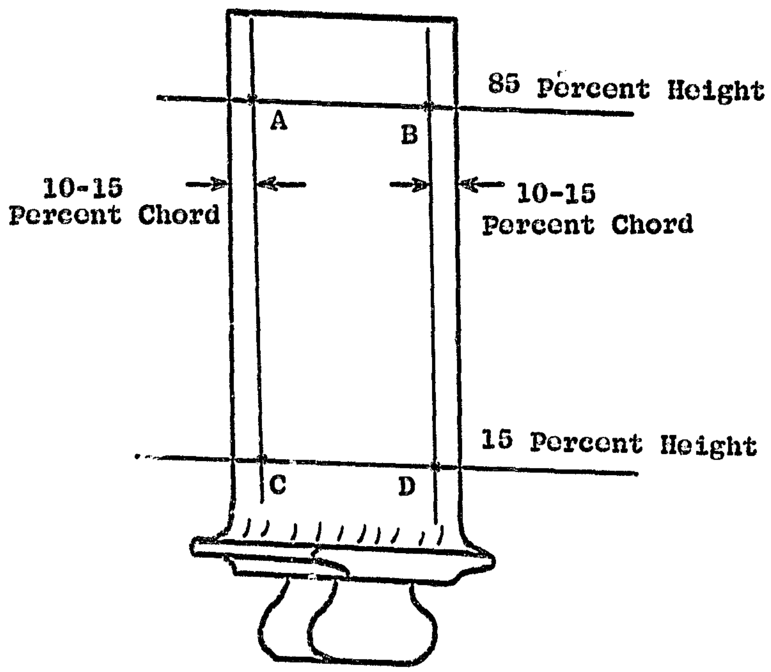
ESN	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
451-144	14.363	14.132	13.914	13.724	13.549	13.332	13.239	13.214	13.220	13.209	13.200	13.201	13.213	13.191	13.149	13.032
451-145	14.360	14.138	13.919	13.725	13.548	[illegible]	13.238	13.215	13.218	13.229	13.216	13.216	13.210	13.192	13.159	13.049
451-116	14.355	14.132	13.914	13.722	13.549	13.335	13.243	13.219	13.207	13.220	13.200	13.205	13.227	13.196	13.152	13.043
451-250	14.360	14.128	13.912	13.719	13.544	13.339	13.242	13.229	13.214	13.220	13.200	13.210	13.224	13.193	13.150	13.048
451-259	14.359	14.127	13.928	13.718	13.543	13.359	13.242	13.214	13.215	13.229	13.227	13.200	13.229	13.187	13.138	13.045
451-330	14.365	14.135	13.914	13.721	13.541	13.375	13.227	13.230	13.215	13.218	13.225	13.200	13.228	13.190	13.138	13.045
451-443	14.376	14.143	13.926	13.734	13.555	13.334	13.255	13.223	13.223	13.226	13.207	13.222	13.220	13.224	13.140	13.050
451-155	14.354	14.142	13.922	13.729	13.550	13.330	13.245	13.213	13.218	13.225	13.213	13.209	13.212	13.193	13.135	13.049
451-424	14.355	14.135	13.920	13.722	13.541	13.329	13.244	13.216	13.221	13.221	13.216	13.207	13.209	13.193	13.132	13.045
451-452	14.357	14.137	13.912	13.725	13.548	13.330	13.241	13.214	13.225	13.223	13.216	13.219	13.218	13.192	13.132	13.048
451-212	14.352	14.145	13.925	13.724	13.555	13.335	[illegible]	13.220	13.220	13.225	13.218	13.222	13.224	13.198	13.140	13.059
AVERAGE	14.352	14.136	13.917	13.725	13.547	13.339	13.242	13.216	13.217	13.222	13.212	13.214	13.212	13.194	13.135	13.039
NOMINAL	14.373	14.143	13.925	13.733	13.559	13.336	13.250	13.222	13.223	13.225	13.220	13.224	13.224	13.212	13.150	13.055

A.2.2 HPCR Airfoil Surface Finish

A profilometer was used to obtain airfoil surface finish measurements of blades from each stage of several high pressure compressors from engines just removed from revenue service. The averages of all measurements taken for each rotor are presented in Table IV. Figure A-3 depicts a typical setup of the equipment that was used.

Measurements were taken at 10/15 percent chord distance from the leading and trailing edges at both 15 and 85 percent span position for both the convex and concave surfaces, for a total of eight measurements per blade. (See Figure A-4.) Any usual change in surface condition for the concave (pressure) side is known to have minimal effect on performance; therefore, only changes in the surface quality of the convex (suction) side were considered in assessing performance deterioration.

Airfoil quality degradation and resultant performance loss are discussed in the portion of Section 4.2.1 entitled "High Pressure Compressor (HPC) Section".



Typical Concave/Convex

Figure A-4. Location of Surface Finish Measurements - HP Compressor Rotor Blade.

Table A-IV. HPCR Airfoil Surface Finish, Inbound.

(μ inch/inch AA)

ESN	TSO	CSO	CONVEX	CONCAVE
451-507(1)	15	28	14	18
451-492	801	259	17	23
451-245	1766	1602	23	22
451-479(2)	4468	1910	26	40
451-380(2)	4595	1270	40	49
451-365	5200	1928	27	28
451-623	6051	2460	25	31
451-390	6085	2605	22	36
451-155	6641	2960	21	30
451-250	6752	2348	22	34
451-116	7648	3288	23	33
451-156	7658	2978	27	34
451-443	9000	2770	28	33

The specification for new blade airfoils is 14-16 μinch per inch AA.

(1) Task III Engine (2) Task IV Engine

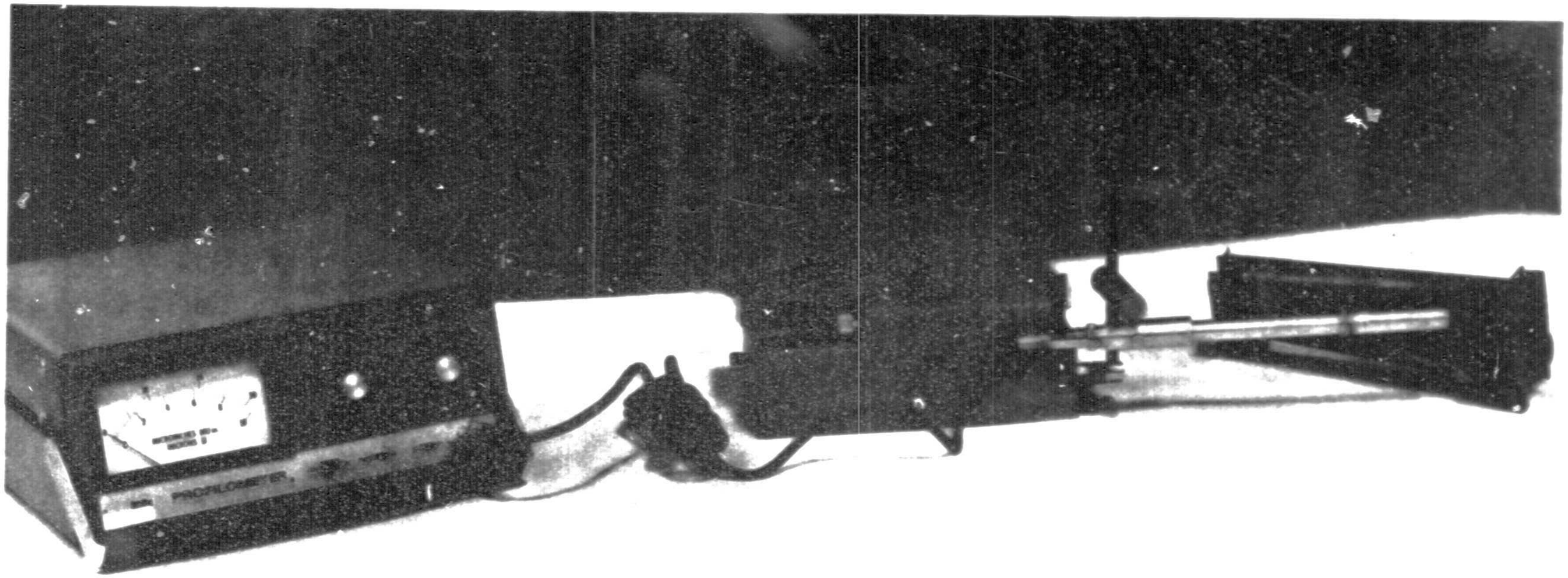
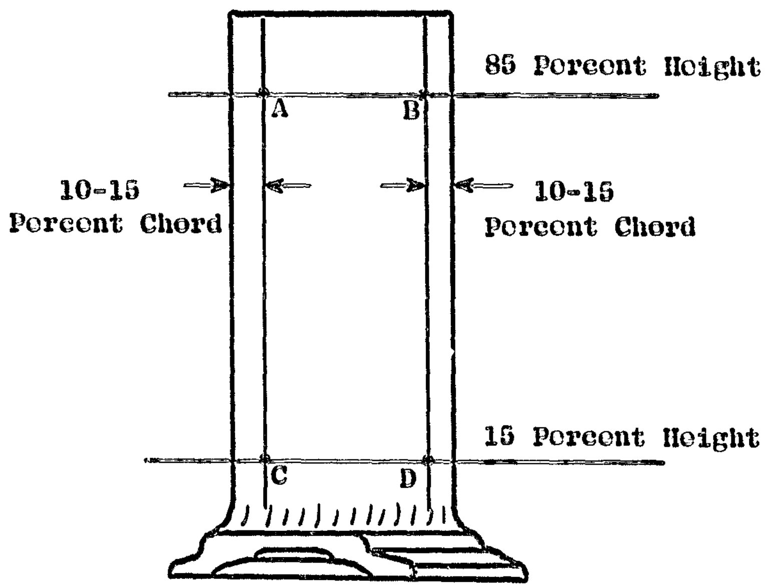


Figure A-3. Typical Profilometer Setup.

A.2.3 HPCS Airfoil Surface Finish

High pressure compressor stator vanes were selected, inspected, and assessed in a similar manner to that for the rotor blades. (See Figure A-5.) The averages of all measurements taken for each stator assembly are presented in Table A-V.

Airfoil quality degradation and the resultant performance loss are discussed in the portion of Section 4.2.1 entitled "High Pressure Compressor Section".



Typical Concave/Convex

Figure A-5. Location for Surface Finish Measurements - HP Compressor Stator Vane.

Table A-V. HPCS Airfoil Surface Finish, Inbound.

(μ inch/inch AA)

ESN	TSO	CSO	CONVEX	CONCAVE
451-507(1)	15	28	23	26
451-492	801	259	31	34
451-245	1766	1602	26	33
451-479(2)	4468	1910	39	55
451-380(2)	4595	1270	63	68
451-232	4799	1779	25	33
451-398	4814	1522	38	42
451-390	6085	2605	31	34
451-155	6641	2960	33	35
451-259	8275	3588	31	35

The specification for new blade airfoils is 2[illegible]-28 μinch per inch AA.

(1) Task III engine (2) Task IV engine

A.2.4 HPCS Variable Stator Bushings

Inbound high pressure compressor stator assemblies were inspected to determine whether washers and bushings were missing from the variable stator assemblies, which can result in increased gas flow leakage. While all washers and bushings were intact for Stages IGV through 4, there were a number missing in Stage 5 (S5) and Stage 6(S6). Table A-VI lists the engines inspected and indicates those engines which revealed "lost" washers or bushings.

Generally, all missing washers and bushings are replaced during each shop visit; therefore, the leakage characteristics for outgoing stators are as good as new. A discussion of compressor leakage is found in the portion of Section 4.2.1 entitled "High Pressure Compressor (HPC) Section".

Table A-VI. HPCS Variable Stators, Inbound.

(Metal-to-Metal)
(Lost Bushings)

ESN	TSO	CSO	S5	S6
451-507	15	28	0	0
451-245	1766	602	0	0
451-129	1867	856	0	0
451-365	2326	806	0	0
451-479	4468	1910	0	1
451-380	4595	1270	0	0
451-398	4814	1522	0	0
451-469	5288	1631	0	0
451-430	5569	2727	0	0
451-280	5606	2351	0	2
451-390	6085	2605	4(1)	28(1)
451-426	6517	1978	4	8
451-155	6641	2960	6(1)	2(1)
451-443	6686	2050	0	4
451-116	8897	3844	6	16
451-250	14374	5484	21(1)	6(1)

(1) Bushings in these stator cases were a combination of the old style (Armalon) and the newer design (Vespel) material.
All others were made of Vespel material.

A.2.5 HPC Stator Case Rabbet Diameters

Measurements were made for both the forward and the aft flange rabbets of each of ten forward and three aft high pressure compressor stator (HPCS) cases. Measurements were obtained at eight equally spaced circumferential locations. A summary of the data is presented in Table A-VII.

Blade and vane tip clearance changes that result from flange distortion are discussed in the portion of Section 4.2.1 entitled "High Pressure Compressor (HPC) Section" (see Figure A-6).

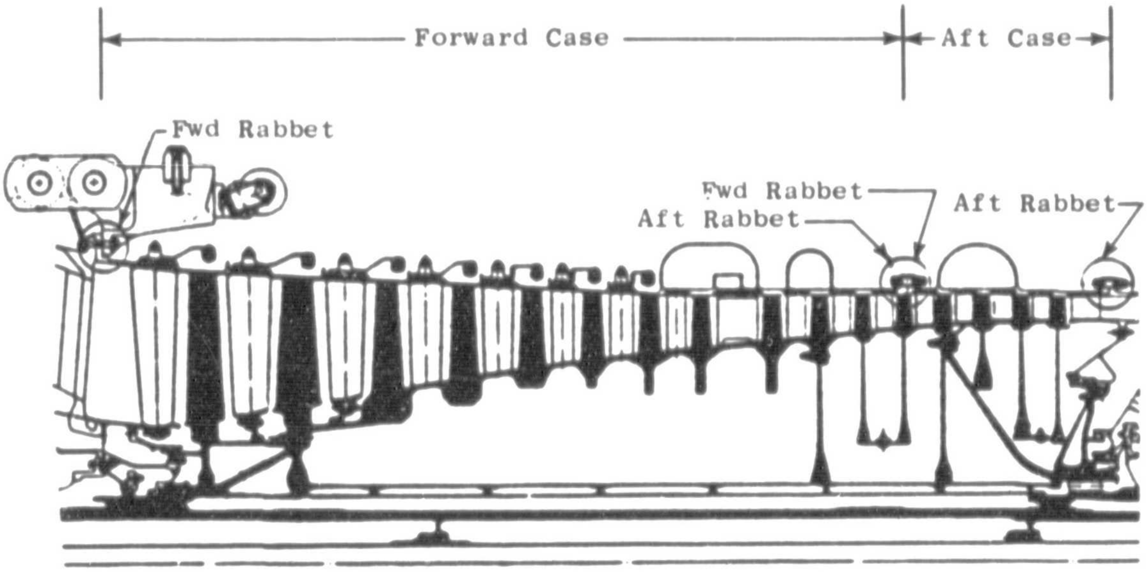


Figure A-6. High Pressure Compressor Cross Section.

Table A-VII. HPC Stator Case Rabbet Diameters, Inbound (Inches).

FORWARD CASE						
	Forward Rabbet			Aft Rabbet		
Case S/N	Max.	Min.	Avg.	Max.	Min.	Avg.
01871	32.722	32.707	32.715	26.770	26.740	26.753
01931	32.735	32.697	32.715	26.810	26.707	26.752
01724	32.729	32.718	32.723	26.780	26.743	26.762
01755	32.728	32.706	32.716	26.811	26.714	26.761
01871	32.725	32.717	32.721	26.782	26.749	26.766
01978	32.728	32.721	32.724	26.784	26.720	26.755
02142	32.725	32.720	32.722	26.787	26.742	26.761
01654	32.732	32.702	32.719	26.790	26.728	26.757
02111	32.732	32.712	32.722	26.816	26.716	26.769
01426	32.744	32.703	32.723	26.797	26.714	26.760
Serviceable Limits	32.717 - 32.725			26.743 - 26.753		

AFT CASE						
	Forward Rabbet			Aft Rabbet		
Case S/N	Max.	Min.	Avg.	Max.	Min.	Avg.
00917	26.748	26.735	26.742	26.462	26.445	26.454
00690	26.775	26.734	26.751	26.478	26.436	26.452
01145	26.758	26.735	26.745	26.461	26.446	26.453
Serviceable Limits	26.742 - 26.749			26.452 - 26.459		

A.3 HIGH PRESSURE TURBINE SECTION

A.3.1 Stage 1 HPTN Area (A_4) Measurements

Stage 1 high pressure turbine nozzle (HPTN) exit area (see Figure A-7) was measured on both inbound and outbound engines. Results are shown in Table A-VIII. Measurements were made using tool 2C6505 shown in Figure A-8 which integrates the Stage 1 HPTN vane throat area using mechanical finger to give an average throat height and width.

The importance of these measurements is presented in the portion of Section 4.2.1 entitled "high Pressure Turbine (HPT) Section".

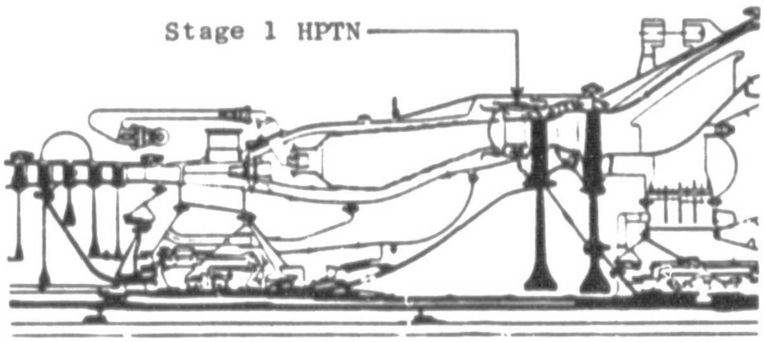


Figure A-7. High Pressure Turbine Nozzle.

Table A-VIII. Stage 1 HPTN Area (A4) (Inches).

OUTBOUND		INBOUND			
Module	A4	ESN	A4	TSO	CSO
51278	53.218	451-507(2)	52.813	15	28
51250	53.156	451-492	53.024	801	259
51472	53.418	451-420	53.530	1448	594
51259	53.024	451-245	53.994	1766	602
51279	53.037	451-244	53.307	2904	1217
51360	53.330	451-390	53.717	3035	1277
51480	52.691	451-234	53.102	3735	1405
51156	52.890	451-250	53.930	4178	1165
51430	53.371	451-116	53.888	4204	1786
51478	53.370	451-479(1)	53.960	4468	1910
51439	53.397	451-326	52.959	4535	1798
51492	53.062	451-380(1)	54.045	4595	1270
51469	53.082	451-232	53.899	4800	1779
Average	53.157	451-444	52.488	4941	2072
		451-469	53.567	5288	1631
		451-457	54.087	5468	2413
		Average	53.566		

(1) Task IV Engine

(2) Task III Engine (Short term) not included in average.

Serviceable Limits: 52.313/53.373 $in.^2$

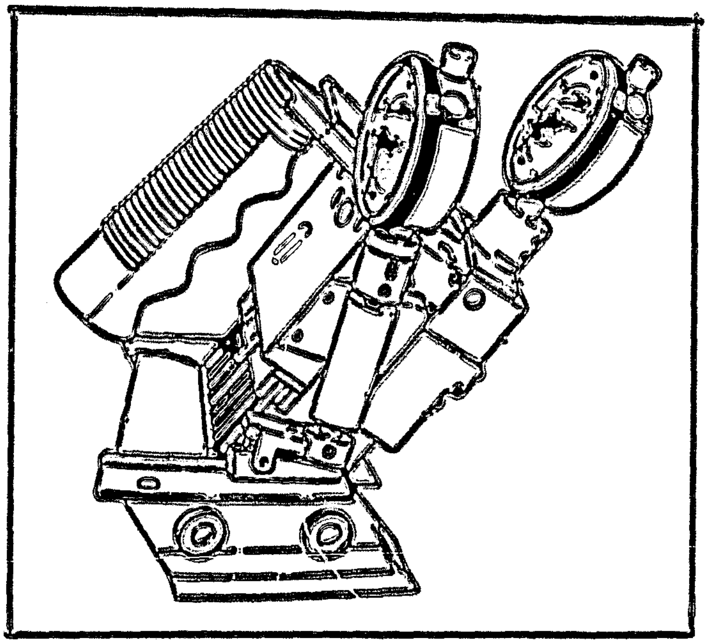


Figure A-8. Stage 1 HP Turbine Nozzle Segment Area Gage, 2C6505.

A.3.2 Stage 1 HPTN Vane Segment Gap Measurements

The spaces between the outer platforms on adjacent Stage 1 vane segments were measured at 16 places (every other segment) at the vane aft end for both inbound and outbound engines (see Figure A-9). The average gap of all assemblies inspected is presented in Table A-IX.

Because of the potential for thermal expansion problems at engine operating conditions, a minimum gap of 0.015 inch (cold measurement) is required in order to reduce the possibility of vane outer band distortion and resultant performance loss due to cooling air leakage into the flowpath. Internal leakage (parasitics) and its effect on performance are discussed in the portion of Section 4.2.1 called "High Pressure Turbine (HPT) Section".

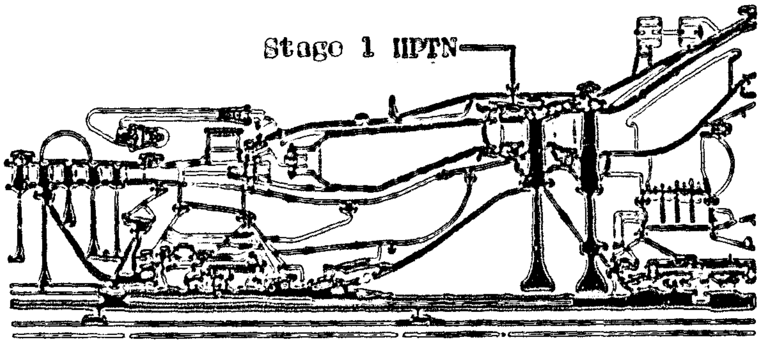


Figure A-9. High Pressure Turbine Nozzle.

Table A-IX. Stage 1 HPTN Vane Segment Gap (Inches).

OUTBOUND

Module No.	Avg. Gap
51278	0.024
51250	0.026
51472	0.024
51259	0.018
51279	0.016
51360	0.019
51480	0.011
51156	0.026
51430	0.021
51478	0.024
51439	0.021
51492	0.022
51469	0.018
Average	0.021

INBOUND

ESN	Avg. Gap
451-232	0.019
451-444	0.021
451-492	0.016
451-234	0.018
451-245	0.019
451-420	0.021
451-250	0.015
451-116	0.021
451-326	0.019
451-390	0.021
451-244	0.014
451-457	0.026
451-469	0.026
451-479(1)	0.029
451-380(1)	0.015
451-507(2)	0.026
Average	0.021

(1) Task IV Engine

(2) Task III Engine (short term) not included in average

A.3.3 Drop Dimension (Dim "D") - CRF Aft Flange to Stage 1 Vanes

Drop dimensions (Dim "D") from the compressor rear frame (CRF) aft flange to the aft face of the Stage 1 vane outer hook (see Figure A-10) were obtained at each end of eight equally spaced nozzle segments on inbound engines. The average of measurements taken are presented for each engine in Table A-X.

The dimension (Dim "D") minus Dim "K" (defined in Section A.3.4, "Stage 2 HPTN Support") plus 0.020 inch (size of shim installed between the Stage 2 HPTN support forward flange and the CRF aft flange) stacks up the clearance between the forward face of the Stage 2 HPTN support and the aft face of the Stage 1 vane outer hook. The accumulated data show an actual average gap of 0.024 inch. The maximum permitted gap is 0.042 inch, and the minimum is an interference fit of 0.012 inch.

Internal leakage (parasitics) and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

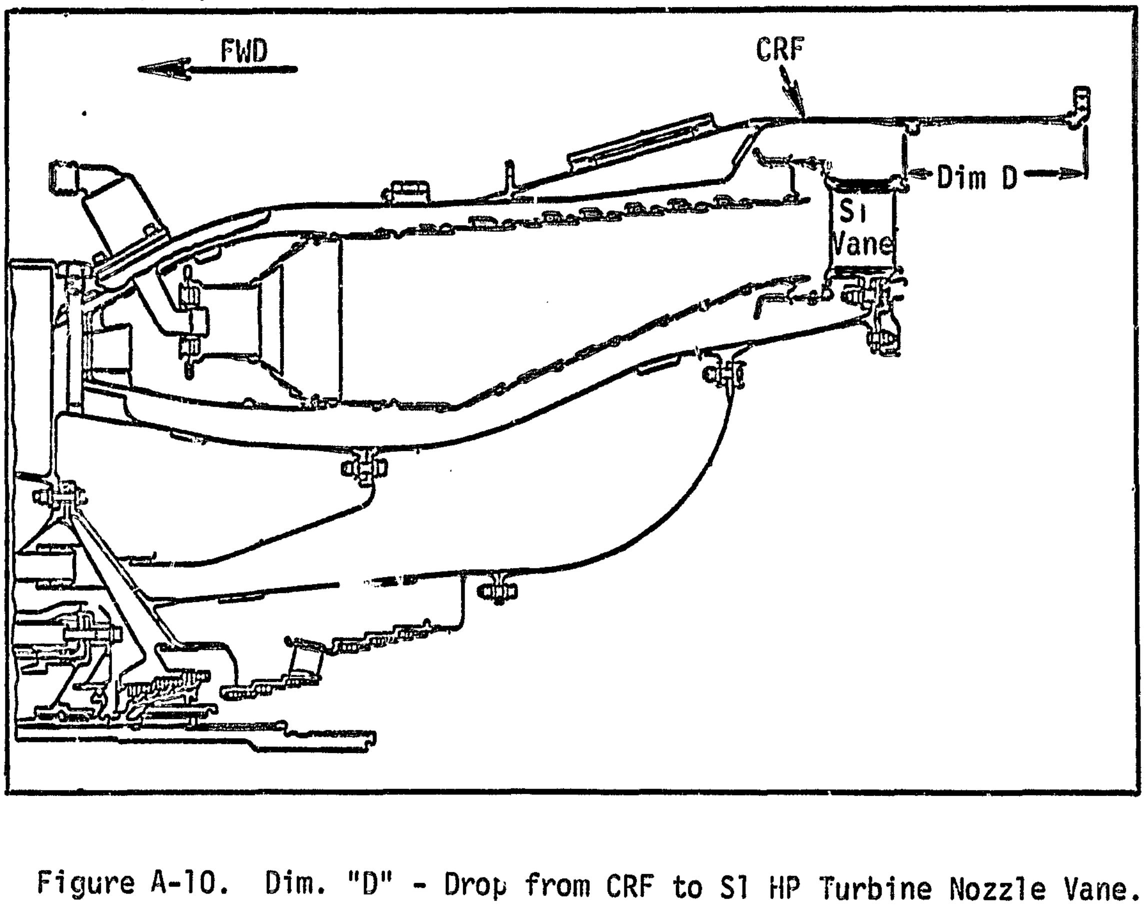


Figure A-10. Dim. "D" - Drop from CRF to S1 HP Turbine Nozzle Vane.

Table A-X Dim "D" - Drop Check CRF Aft Flange to Stage 1 HPTN, Inbound (Inches).

ESN	Counter-clockwise End	Clockwise End	Average
451-232	4.825	4.830	4.828
451-492	4.896	4.893	4.895
451-365	4.870	4.867	4.868
451-245	4.866	4.861	4.863
451-116	4.860	4.862	4.861
451-250	4.849	4.853	4.851
451-259	4.852	4.855	4.853
451-390	4.845	4.850	4.847
451-244	4.887	4.892	4.890
451-457	4.844	4.842	4.843
451-398	4.875	4.881	4.878
451-469	4.849	4.851	4.850
451-479(1)	-----	-----	4.861
451-380(1)	-----	-----	4.855
451-507(2)	4.874	4.873	4.873
Average			4.860

(1) Task IV Engine

(2) Task III Engine - Not included in average

A.3.4 Stage 2 HPTN Support (Dim "K")

The dimension (Dim "K") from the aft flange of the Stage 2 high pressure turbine nozzle (HPTN) support to the forward face of the lugs that support the Stage 1 vane outer hook (see Figure A-11) was measured at sixteen equally spaced locations on each of twelve outbound nozzle assemblies. In all instances, these were supports that had already been exposed to revenue service. The averages of all measurements taken are tabulated in Table A-XI.

The importance of these measurements is discussed in Section A.3.3.

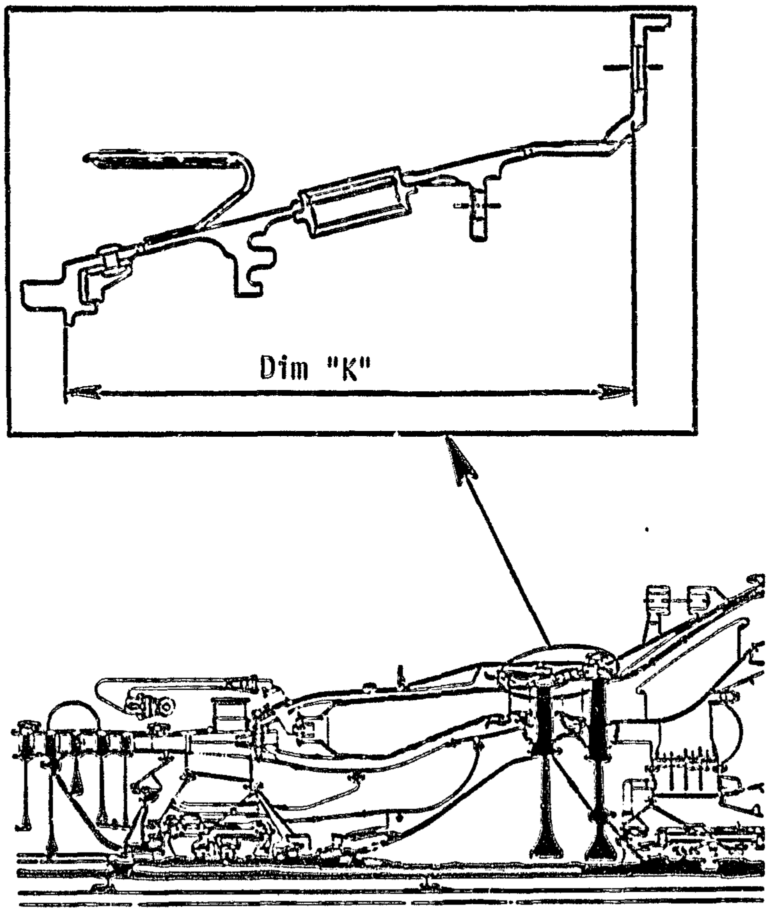


Figure A-11. Dim "K" - Stage 2 HP Turbine Nozzle Support Measurement.

Table A-XI. Dim "K", Stage 2 HPTN Support, Outbound (Inches).

ESN	Dim "K"
451-439	4.855
451-426	4.853
451-489	4.848
451-279	4.862
451-232	4.858
451-293	4.858
451-454	4.860
451-444	4.856
451-410	4.858
451-116	4.856
451-250	4.860
451-489	4.852
451-469	4.852
451-479(1)	4.861
451-380(1)	4.850
451-507(2)	4.856
Average	4.856
Serviceable Limits	4.853/4.865

(1) Task IV Engine

(2) Task III Engine

A.3.5 HPT Interstage Seal Grooves

A steel rule was used to estimate the depth and width of high pressure turbine interstage seal grooves at four equally spaced locations on each seal land for each of 12 inbound engines (see Figure A-12). A summary of the results is shown in Table A-XII.

Generally, when the high pressure turbine (HPT) is removed for refurbishment, the interstage seals are replaced. Therefore, outbound engines are the same as new in that region of the HPT.

Internal leakage (parasitics) and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

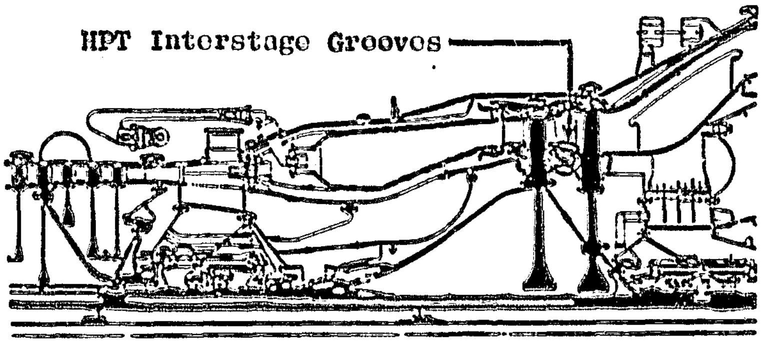


Figure A-12. HPT Interstage Grooves.

Table A-XII. HPT Interstage Seal Grooves, Inbound (Inches).

	Average Depth	Average Width	TSO	CSO
451-507(2)	0.060	0.110	15	28
451-418	0.055	0.090	327	109
451-492	0.055	0.100	682	259
451-365	0.105	0.165	2326	806
451-243	0.075	0.120	2527	1213
451-234	0.065	0.125	3735	1405
451-283	0.090	0.090	3808	1642
451-259	0.060	0.110	3936	1449
451-250	0.085	0.090	4178	1165
451-479(1)	0.070	0.120	4468	1910
451-326	0.075	0.090	4535	1798
451-380(1)	0.050	0.100	4594	1270
451-398	0.065	0.090	4819	1523
451-444	0.075	0.100	4941	2072
451-469	0.065	0.110	5288	1631
Average	0.070	0.107		
Serviceable Limit	0.060	0.120		

(1) Task IV engine

(2) Task III engine

A.3.6 Forward CDP Rotating Seal Teeth Measurements

Measurements of the rotating compressor discharge pressure (CDP) seal, Figure A-13, were made while the rotor was installed in the runout fixture. Runouts were recorded at twelve equally spaced circumferential locations while a Pi tape was used to obtain the average diameters for the inbound engine inspections. Results are shown in Table A-XIII.

Internal leakage (parasitics) is discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

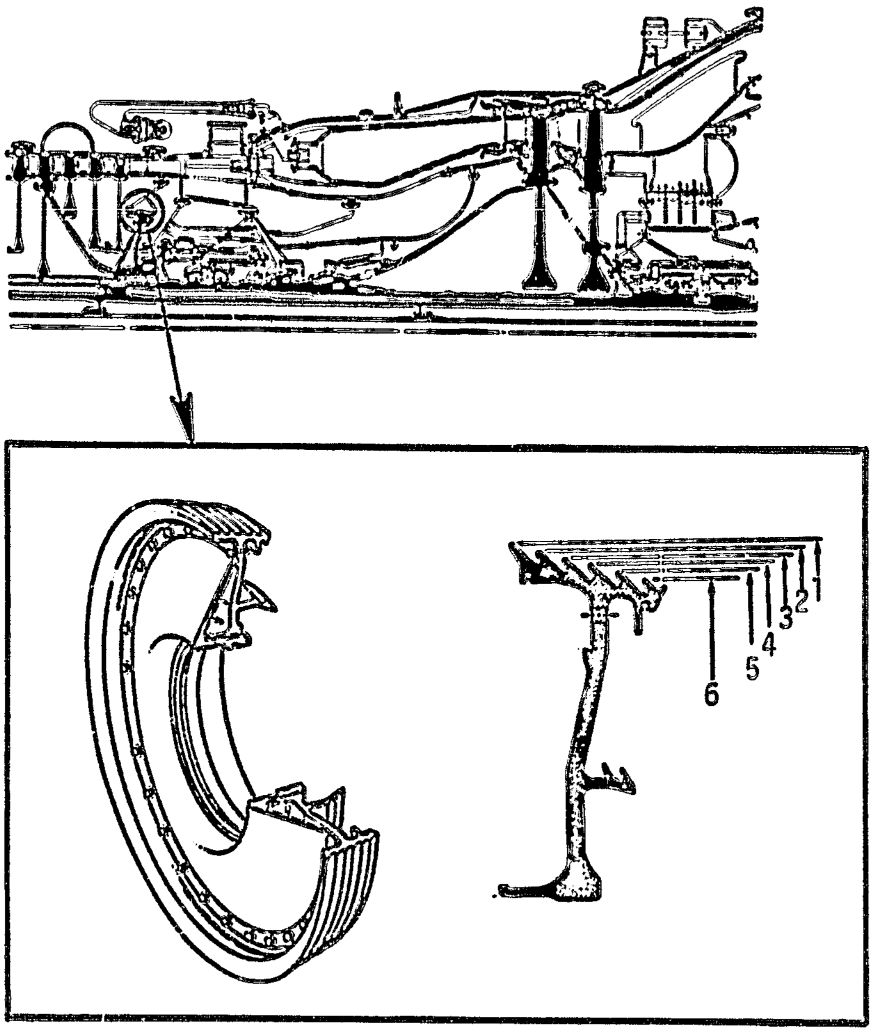


Figure A-13. Forward CDP Seal, Rotating.

Table A-XIII. HPCR CDP Seal Teeth Diameters, Inbound (Inches).

	Teeth Number 1		2		3		4		5		6	
	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR
451-452	18.134	.002	17.934	.002	17.732	.002	17.530	.002	17.334	.002	17.130	.002
451-155	18.127	.005	17.927	.003	17.7[illegible]5	.001	17.529	.002	17.331	.002	17.128	.002
451-443	18.129	.004	17.930	.002	17.730	.002	17.526	.001	17.325	.002	17.126	.003
451-390	18.132	.003	17.935	.004	17.734	.003	17.532	.002	17.333	.001	17.134	.001
451-259	18.129	.006	17.931	.004	17.731	.005	17.528	.005	17.332	.003	17.128	.004
451-116	18.128	.005	17.924	.007	17.728	.004	17.526	.002	17.327	.002	17.126	.002
451-250	18.127	.005	17.930	.005	17.731	.005	17.525	.003	17.328	.002	17.128	.003
451-245	18.130	.003	17.926	.002	17.727	.002	17.527	.002	17.327	.003	17.128	.002
451-144	18.129	.004	17.930	.002	17.732	.003	17.532	.002	17.332	.001	17.135	.002
451-469	18.125	N/R	17.932	N/R	17.732	N/R	17.532	N/R	17.332	N/R	17.132	N/R
451-479(1)	18.130	.004	17.931	.002	17.731	.002	17.531	.001	17.331	.001	17.131	.001
451-380(1)	18.122	.002	17.926	.002	17.729	.001	17.525	.002	17.329	.001	17.130	.001
451-507(2)	18.133	.004	17.933	.002	17.736	.001	17.532	.001	17.335	.001	17.135	.001
Average	18.129	.004	17.930	.003	17.730	.003	17.529	.002	17.330	.002	17.130	.002
Serviceable Limits	18.129 - 18.134		17.929 - 17.934		17.729 - 17.734		17.529 - 17.534		17.329 - 17.334		17.129 - 17.134	

(1) Task IV Engine

(2) Task III Engine (short term) - not included in average.

A.3.7 Forward CDP Stationary Seal Measurements

Forward stationary compressor discharge pressure (CDP) seals (see Figure A-14) were measured by recording the diameter at four equally spaced circumferential locations on each seal land. A runout of the seal land relative to the No. 4R bearing was also recorded. The average diameters and the runouts are presented in Table A-XIV.

Internal leakage (parasitics) is discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

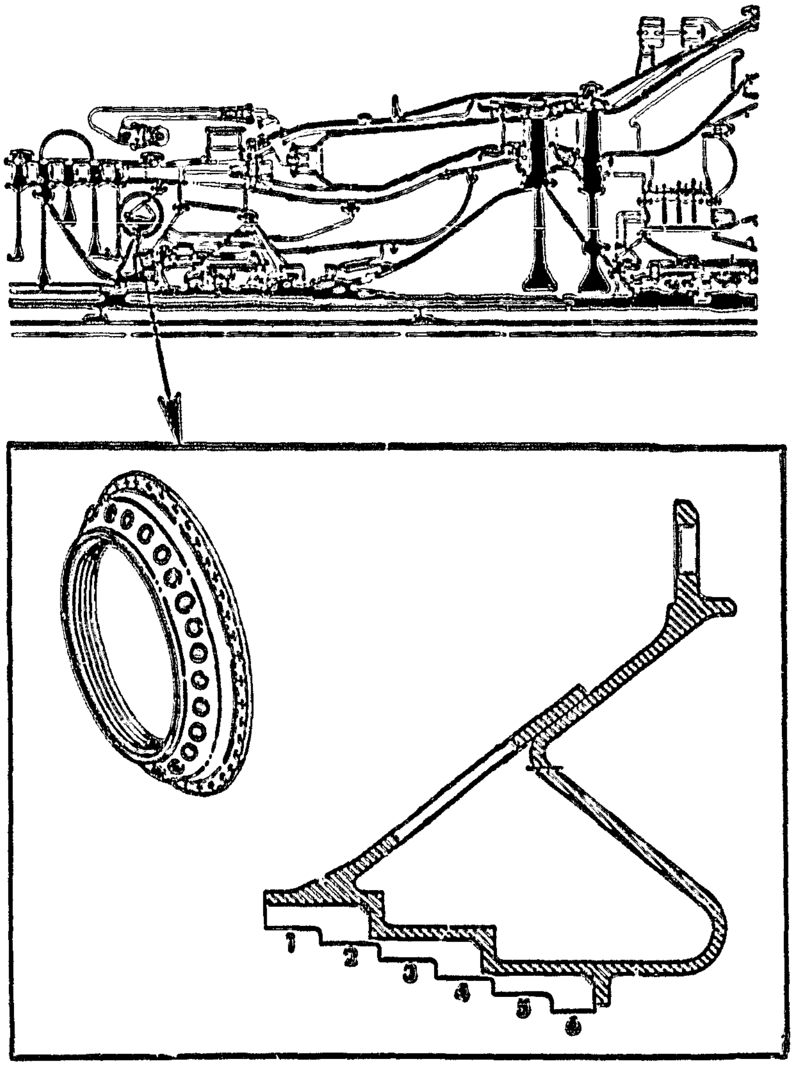


Figure A-14. Forward CDP Seal, Stationary.

Table A-XIV. Forward CDP Stationary Seal Diameters, Outboard.
(Task III and IV Engines, Inbound)
(Inches)

ESN	Land Number 1	2	3	4	5	6	Installed Runout
451-293	18.147	17.947	17.746	17.546	17.348	17.147	.007
451-439	18.150	17.950	17.750	17.550	17.351	17.151	.005
451-423	18.150	17.953	17.753	17.554	17.354	17.154	.005
451-144	18.148	17.948	17.748	17.548	17.348	17.148	.004
451-359	18.154	17.952	17.753	17.555	17.356	17.155	N/R
451-390	18.147	17.949	17.748	17.550	17.350	17.148	.009
451-229	18.150	17.948	17.749	17.547	17.348	17.147	.008
451-259	18.144	17.942	17.741	17.542	17.341	17.142	.009
451-454	18.148	17.948	17.749	17.548	17.347	17.149	N/R
451-204	18.149	17.947	17.747	17.553	17.346	17.146	N/R
451-398	18.148	17.947	17.749	17.547	17.347	17.145	N/R
451-232	18.148	17.948	17.749	17.548	17.348	17.147	.007
451-479(1)	18.148	17.949	17.749	17.549	17.352	17.152	N/R
451-507(2)	18.149	17.948	17.749	17.550	17.351	17.150	N/R
Average	18.149	17.948	17.749	17.549	17.349	17.148	.007
Maximum Serviceable Limit	18.156	17.956	17.756	17.556	17.356	17.156	.008

(1) Task IV Engine

(2) Task III Engine - Not included in average.

A.3.8 No. 4B Pressure Balance Seal (Mini-Nozzle)

Diameters were measured and recorded at four equally spaced circumferential locations for each land of each of the aft seals contained in the mini-nozzle (see Figure A-15). Also recorded were the runouts of the seal lands relative to the No. 4B bearing. These seals mate with the high pressure turbine rotor's forward shaft seals to form the aft CDP seal (shaft forward seal) and the HPT balance piston seal (shaft aft seal). The average diameters and runouts are tabulated in Tables A-XV and A-XVI.

Internal leakage (parasitics) is discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

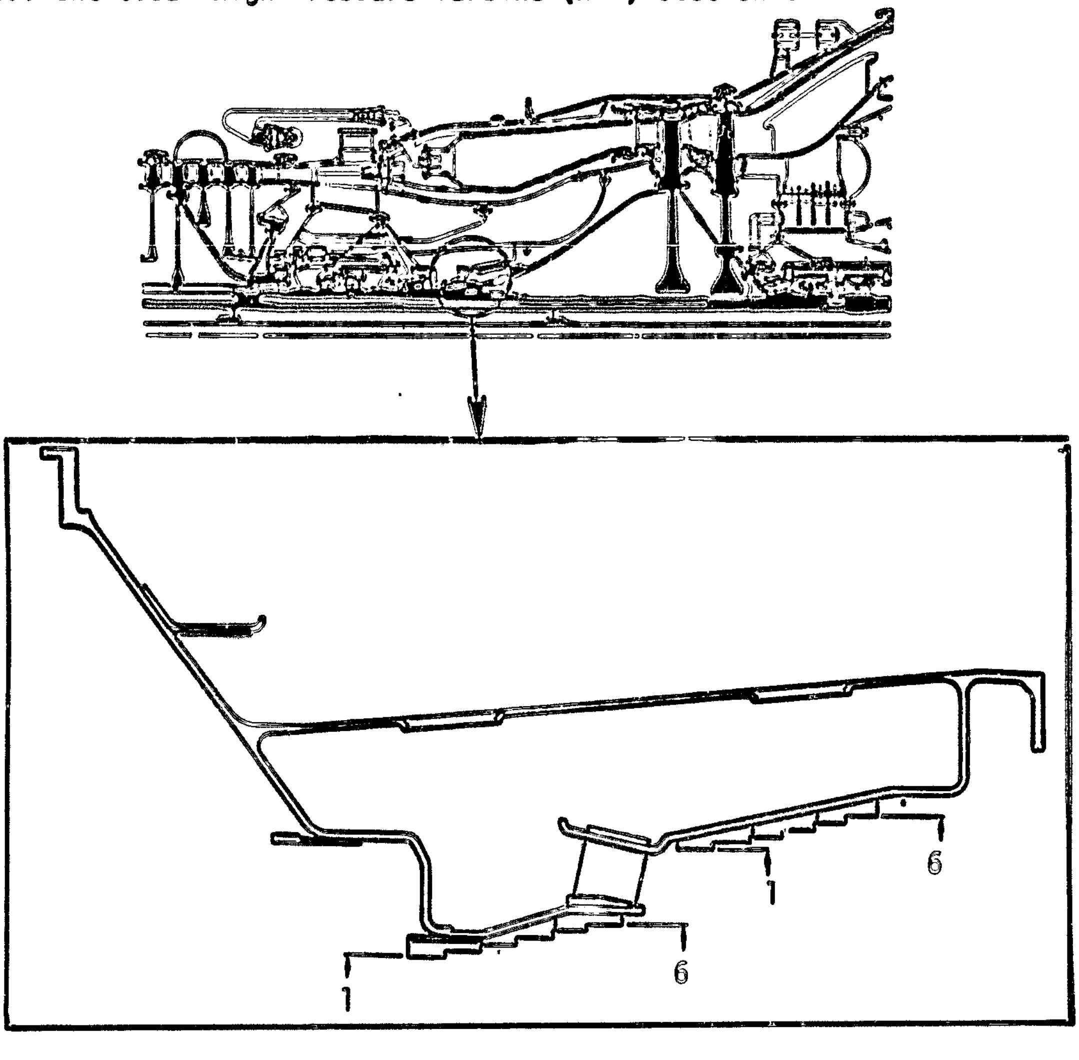


Figure A-15. No. 4B Pressure Balance Seal (Mini-Nozzle).

Table A-XV. Aft CDP Seal (Stationary) Diameters (Inches).

OUTBOUND

ESN	Land Number 1	2	3	4	5	6	Installed Runout
451-293	7.943	8.101	8.261	8.422	8.583	8.746	.006
451-439	7.943	8.102	8.265	8.424	8.584	8.744	.007
451-423	7.940	8.100	8.260	8.422	8.583	8.746	.002
451-144	7.937	8.098	8.258	8.419	8.581	8.744	.004
451-359	N/R	N/R	8.264	8.424	8.583	8.744	N/R
451-390	7.940	8.102	8.264	8.423	8.582	8.742	.005
451-229	7.941	8.099	8.259	8.419	8.577	8.744	.002
451-209	7.939	8.100	8.254	8.414	8.575	8.736	.006
451-454	7.940	8.101	8.260	8.421	8.580	8.750	N/R
451-244	7.940	8.101	8.260	8.421	8.581	8.743	N/R
451-398	7.939	8.101	8.262	8.423	8.582	8.742	N/R
451-232	7.941	8.101	8.262	8.423	8.581	8.742	.003
Average	7.940	8.101	8.261	8.421	8.581	8.744	.004
INBOUND (TASK III & IV ENGINES)							
451-479	7.943	8.103	8.264	8.423	8.583	8.743	N/R
451-380	7.946	8.113	8.275	-----	8.597	8.754	N/R
451-507	7.943	8.102	8.261	8.422	8.582	8.742	N/R
Maximum Shop Limit	7.945	8.105	8.265	8.425	8.585	8.745	.008
Maximum Serviceable Limit	7.947	8.107	8.267	8.427	8.587	8.747	.008

Table A-XVI. HPT Pressure Balance Seal (Stationary) Diameters (Inches).

OUTBOUND

ESN	Land Number 1	2	3	4	5	6	Installed Runout
451-293	10.442	10.601	10.760	10.919	11.076	11.237	.005
451-439	10.443	10.603	10.764	10.924	11.083	11.243	.008
451-423	10.440	10.600	10.759	10.918	11.078	11.239	.004
451-144	10.441	10.600	10.757	10.915	11.074	11.235	.004
451-359	N/R	N/R	10.762	10.923	11.082	11.243	N/R
451-390	10.443	10.603	10.763	10.925	11.082	11.243	.005
451-229	10.439	10.596	10.753	10.914	11.073	11.235	.003
451-259	10.439	10.595	10.756	10.915	11.074	11.230	.007
451-454	10.440	10.598	10.759	10.920	11.080	11.239	N/R
451-244	10.438	10.598	10.761	10.919	11.079	11.239	N/R
451-398	10.439	10.599	10.759	10.921	11.082	11.240	N/R
451-232	10.440	10.597	10.759	10.921	11.080	11.239	.004
Average	10.440	10.599	10.759	10.920	11.079	11.239	.005

INBOUND (TASK III & IV ENGINES)

451-479	10.443	10.619	10.773	10.941	11.101	11.256	N/R
451-380	10.474	10.609	10.799	10.963	11.123	11.272	N/R
451-507	10.440	10.600	10.760	10.921	11.080	11.240	N/R
Maximum Shop Limit	10.446	10.606	10.766	10.926	11.086	11.246	.008
Maximum Serviceable Limit	10.448	10.608	10.768	10.928	11.088	11.248	.008

A.3.9 HPTR Forward Shaft and Thermal Shield Seals

The high pressure turbine rotor (HPTR) forward shaft seal teeth and the thermal shield teeth (see Figure A-16) were measured on both inbound and outbound rotor assemblies. Measurements generally consisted of a diameter and of runouts at twelve equally spaced locations for each tooth; however, some of the thermal shield teeth were measured with a Pi tape because a gauge large enough to measure the diameter was not available. The average diameter and FIR for each seal tooth is presented in Tables A-XVII through A-XXII.

Internal leakage (parasitics) is discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

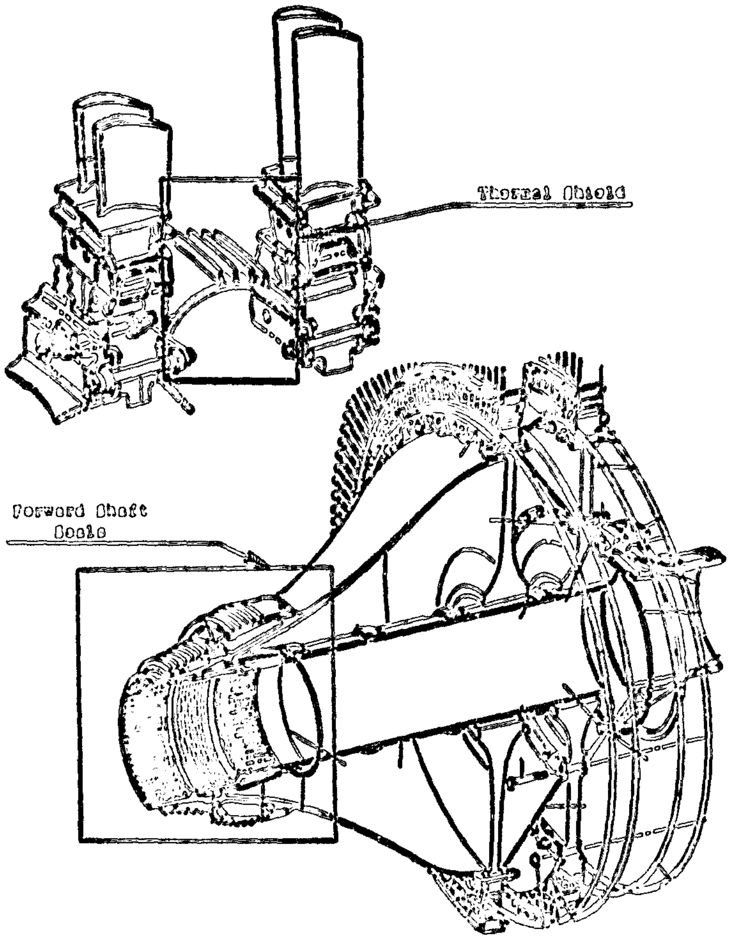


Figure A-16. HP Turbine Rotor Forward Shaft Seals and Thermal Shield.

Table A-XVII. HPTR Forward Shaft, Forward Seal Teeth (Aft CDP Seal) Dimensions, Inbound (Inches).

ESN	Tooth Number 1 Diameter	1 FIR	2 Diameter	2 FIR	3 Diameter	3 FIR	4 Diameter	4 FIR	5 Diameter	5 FIR	6 Diameter	6 FIR	Total Diameters
451-243	7.902	.003	8.081	.002	8.245	.003	8.406	.004	8.565	.003	6.725	.002	49.925
451-492	7.906	.003	8.083	.003	8.247	.003	8.408	.003	8.568	.003	8.710	.039	49.922
451-444	7.906	.004	8.085	.003	8.247	.004	8.406	.002	8.562	.005	8.713	.012	49.918
451-468	7.900	.002	8.074	.004	8.240	.004	8.401	.003	8.561	.004	8.720	.002	49.856
451-234	7.906	.006	8.082	.005	8.245	.005	8.406	.005	8.566	.003	8.724	.003	49.929
451-365	7.905	.003	8.082	.003	8.248	.003	8.406	.004	8.567	.005	8.725	.003	49.934
451-469	7.901	.004	8.081	.005	8.240	.003	8.399	.002	8.562	.002	8.721	.003	49.904
451-479(1)	7.902	.002	8.081	.003	8.242	.002	8.397	.003	8.564	.002	8.720	.002	49.906
451-380(1)	7.904	.004	8.080	.005	8.242	.005	8.404	.003	8.563	.002	8.720	.002	49.913
451-507(2)	7.904	.003	8.083	.003	8.245	.002	8.406	.003	8.567	.003	8.725	.003	49.931
Average	7.904	.004	8.081	.004	8.244	.004	8.404	.003	8.564	.004	8.720	.005	49.916
Shop Manual Dimensions	7.899/7.909		8.083/8.087		8.246/8.250		8.406/8.410		8.566/8.570		8.726/8.730		49.926
Minimum Serviceable Limit =													49.896

(1) Task IV Engine

(2) Task III Engine (short term) - Not included in average.

Table A-XVIII. HPTR Forward Shaft, Forward Seal Teeth (Balance Piston) Dimensions, Inbound (Inches).

ESN	Tooth Number 1 Diameter	1 FIR	2 Diameter	2 FIR	3 Diameter	3 FIR	4 Diameter	4 FIR	5 Diameter	5 FIR	6 Diameter	6 FIR	Total Diameters
451-243	10.411	.025	10.583	.020	10.742	.019	10.899	.016	11.061	.013	11.219	.009	64.915
451-492	10.417	.010	10.586	.011	10.745	.010	10.906	.007	11.064	.006	11.224	.005	64.942
451-444	10.415	.014	10.585	.013	10.746	.010	10.898	.007	11.055	.008	11.226	[illegible]	64.926
451-468	10.408	.012	10.580	.012	10.739	.009	10.898	.007	11.056	.007	11.218	.005	64.899
451-234	10.413	.016	10.577	.015	10.739	.014	10.904	.014	11.060	.015	11.216	.010	64.909
451-365	10.405	.015	10.585	.015	10.745	.024	10.906	.011	11.066	.010	11.226	.008	64.933
451-469	10.405	.010	10.580	.009	10.740	.009	10.899	.008	11.059	.006	11.220	.006	64.903
451-479(1)	10.420	.008	10.567	.008	10.749	.007	10.906	.009	11.064	.007	11.224	.006	64.950
451-380(1)	10.407	.029	10.577	.028	10.736	.023	10.896	.020	11.057	.016	11.217	.010	64.890
451-507(2)	10.414	.005	10.584	.003	10.743	.002	10.904	.004	11.061	.004	11.227	.003	64.933
Average	10.414	.015	10.582	.014	10.742	.013	10.901	.011	11.060	.010	11.221	.007	64.918
Shop Manual Dimensions	10.413/10.417		10.583/10.587		10.743/10.747		10.903/10.907		11.063/11.067		11.223/11.227		64.928
Minimum Serviceable Limit =													64.898

(1) Task IV Engine

(2) Task III Engine

Table A-XIX. HPTR Thermal Shield Seal Teeth Dimensions, Inbound (Inches).

ESN	Tooth Number 1 Diameter	1 FIR	2 Diameter	2 FIR	3 Diameter	3 FIR	4 Diameter	4 FIR
451-243	26.050	.002	26.305	.003	26.458	.003	26.610	.005
451-492	26.054	.005	26.303	.006	26.464	.006	26.620	.005
451-444	26.055	.006	26.308	.005	26.470	.004	26.620	.003
451-468	26.050	.003	26.306	.004	26.462	.003	26.616	.003
451-234	26.055	.004	26.310	.002	26.475	.003	26.627	.003
451-365	26.060	.005	26.308	.005	26.471	.006	26.628	.005
451-469	26.039	.003	26.298	.005	26.456	.003	26.612	.004
451-479(1)	26.055	.004	26.311	.003	26.473	.003	26.630	.002
451-380(1)	26.049	.004	26.300	.003	26.445	.003	26.618	.002
451-507(2)	26.045	.006	26.298	.005	26.462	.006	26.621	.005
Average	26.052	.004	26.305	.004	26.464	.004	26.620	.004
Shop Manual Dimensions	26.050/26.058		26.300/26.308		26.462/26.470		26.622/26.630	
Minimum Serviceable Limit	26.04[illegible]		26.293		26.455		26.615	

(1) Task IV Engine

(2) Task III Engine (short term) - Not included in average

Table A-XX. HPTR Forward Shaft Forward Seal Teeth (Aft CDP Seal) Dimensions, Outbound (Inches).

ESN	Tooth Number												Total Diameters
	*1		2		3		4		5		6		
	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR	Diameter	FIR	
451-489	7.906	.000	8.086	.000	8.251	.000	8.409	.000	8.570	.000	8.723	.000	49.945
451-359	7.904	.003	8.084	.003	8.244	.002	8.408	.002	8.571	.001	8.730	.003	49.941
451-238	7.902	.001	8.081	.003	8.242	.003	8.403	.004	8.562	.004	8.724	.002	49.914
451-282	7.900	.005	8.079	.006	8.242	.004	8.402	.004	8.563	.003	8 725	.002	49.911
451-279	7.905	.005	8.075	.006	8.237	.007	8.400	.007	8.559	.008	8.723	.006	49.899
451-221	7.902	.004	8.074	.005	8.243	.004	8.407	.006	8.567	.004	8.721	.004	49.914
Average	7.903	.003	8.080	.004	8.243	.003	8.405	.004	8.565	.003	8.724	.003	49.921
Shop Manual Dimensions	7.899/7.909		8.083/8.087		8.246/8.250		8.406/8.410		8.566/8.570		8.726/8.730		49.926
Minimum Serviceable Limits =													49.896

Table A-XXI. HPTR Forward Shaft Aft Seal Teeth (Balance Piston) Dimensions, Outbound (Inches).

ESN	Tooth Number 1 Diameter	1 FIR	2 Diameter	2 FIR	3 Diameter	3 FIR	4 Diameter	4 FIR	5 Diameter	5 FIR	6 Diameter	6 FIR	Total Diameters
451-489	10.417	.000	10.585	.000	10.748	.000	10.905	.000	11.068	.000	11.226	.000	64.950
451-359	10.416	.003	10.585	.003	10.745	.003	10.906	.002	11.067	.002	11.227	.002	64.946
451-233	10.411	.003	10.583	.003	11.741	.003	10.905	.003	11.063	.005	11.222	.002	64.915
451-282	10.411	.020	10.582	.018	10.743	.017	10.902	.013	11.062	.009	11.223	.009	64.923
451-279	10.415	.015	10.585	.012	10.747	.012	10.907	.011	11.067	.011	11.223	.003	64.950
451-221	10.414	.005	10.585	.005	10.745	.005	10.905	.005	11.066	.005	11.224	.004	64.941
Average	10.414	.008	10.585	.007	10.745	.007	10.905	.007	11.064	.005	11.225	.004	64.933
Shop Manual Dimensions	10.413/10.417		10.583/10.587		10.743/10.747		10.903/10.907		11.063/11.067		11.223/11.227		64.928
Minimum Serviceable Limit =													64.883

Table A-XXII. HPTR Thermal Shield Seal Teeth Dimensions, Outbound (Inches).

ESN	Tooth Number 1 Diameter	1 FIR	2 Diameter	2 FIR	3 Diameter	3 FIR	4 Diameter	4 FIR
451-489	26.050	0.000	26.304	0.000	26.465	0.003	26.610	0.000
451-359	26.053	0.002	26.304	0.002	26.470	0.001	26.625	0.001
451-238	26.053	0.004	26.309	0.004	26.475	0.004	26.616	0.001
451-282	26.050	0.006	26.305	0.006	26.470	0.004	26.621	0.006
451-279	26.044	0.002	26.296	0.003	26.456	0.003	26.616	0.003
451-221	26.054	0.002	26.308	0.002	26.468	0.002	26.615	0.002
Average	26.051	0.003	26.304	0.003	26.467	0.002	26.617	0.002
Shop Manual Dimensions	26.050/26.058		26.300/26.308		26.462/26.470		26.622/26.630	
Minimum Serviceable Limit	26.043		26.293		26.455		26.615	

A.3.10 HPTR Blade Tip Radii

Blade tip radii data were obtained for both outbound and inbound HPT rotors. Blades were shimmed in each rotor in accordance with the procedure outlined in the shop manual, and the rotor was installed on a fixture that permitted rotation. A measuring fixture containing a calibrated bar with a known dimension to the rotor centerline was mounted off the forward and the aft shafts as shown in Figure A-17. Radii measurements were made at two axial locations (0.100 inch from both the leading edge and the trailing edge) of each blade. Summaries of the results are shown in Tables A-XXIII through A-XXIV.

HPTR blade tip clearance and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

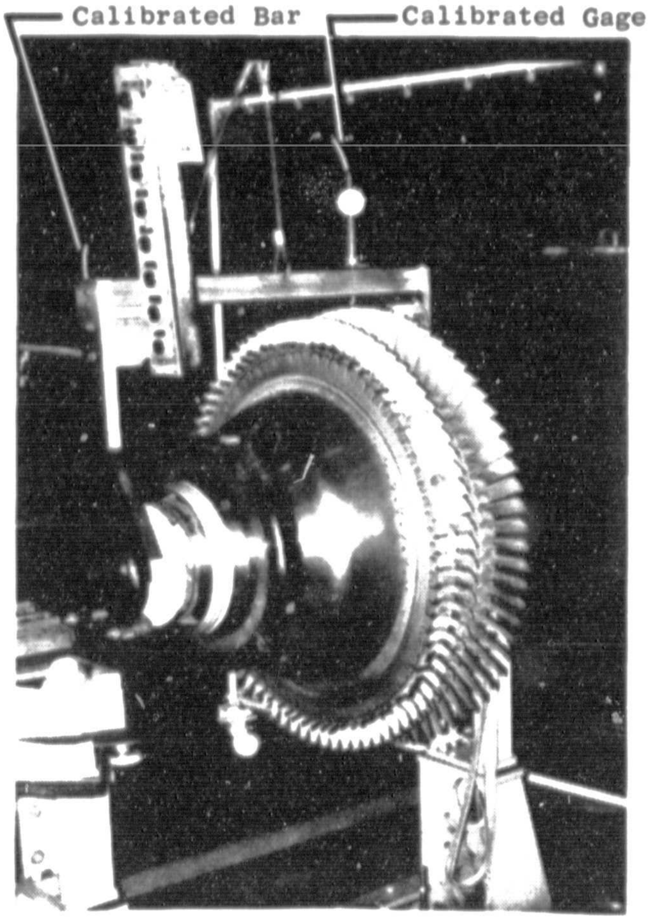


Figure A-17. Setup for HP Turbine Rotor Blade Radii Measurements.

Table A-XXIII. HPTR Stage 1 Blade Radii, Inbound-UAL (Inches).

ESN	FORWARD			AFT			Overall Average	Original Grind	Δ	TSO	CSO
	Max.	Min.	Avg.	Max.	Min.	Avg.					
451-507(2)	16.563	16.552	16.559	16.576	16.562	16.570	16.565	16.589	-.024	15	28
451-492	16.579	16.565	16.573	16.577	16.565	16.570	16.571	16.587	-.016	801	259
451-365	16.583	16.563	16.572	16.586	16.569	16.578	16.575	16.587	-.012	2326	806
451-243	16.569	16.545	16.555	16.558	16.544	16.551	16.553	16.587	-.034	2527	1213
451-468	16.545	16.528	16.539	16.545	16.528	16.539	16.539	15.552	-.013	2961	1231
451-234	16.569	16.551	16.560	16.570	16.553	16.561	16.560	16.587	-.027	3735	1405
451-479(1)	16.564	16.550	16.558	16.569	16.553	16.562	16.560	unknown	-----	4468	1910
451-380(1)	16.543	16.528	16.539	16.543	16.521	16.535	16.537	unknown	-----	4595	1270
451-444	16.545	16.535	16.541	16.548	16.536	16.542	16.541	16.552	-.011	4941	2072
451-469	16.573	16.551	16.561	16.574	16.553	16.569	16.565	16.587	-.022	5288	1631

(1) Task IV Engine

(2) Task III Egnine

Table A-XXIV. HPTR Stage 2 Blade Radii, Inbound-UAL (Inches).

ESN	FORWARD			AFT			Overall Average	Original Grind	Δ	TSO	CSO
	Max.	Min.	Avg.	Max.	Min.	Avg.					
451-507(2)	17.225	17.211	17.220	17.231	17.217	17.225	17.222	17.242	-.020	15	28
451-492	17.236	17.220	17.230	17.232	17.216	17.224	17.227	17.237	-.010	801	259
451-365	17.197	17.186	17.191	17.197	17.187	17.193	17.192	17.202	-.010	2326	806
451-243	17.220	17.200	17.212	17.222	17.204	17.214	17.213	17.237	-.024	2527	1213
451-468	17.234	17.217	17.227	17.237	17.220	17.229	17.228	17.237	-.009	2961	1231
451-234	17.236	17.210	17.226	17.237	17.214	17.228	17.227	17.237	-.010	3735	1405
451-479(1)	17.217	17.207	17.213	17.223	17.215	17.220	17.217	unknown	-----	4468	1910
451-380(1)	17.189	17.176	17.183	17.199	17.187	17.194	17.189	unknown	-----	4595	1270
451-444	17.226	17.211	17.220	17.227	17.214	17.222	17.221	17.237	-.016	4941	2072
451-469	17.194	17.180	17.189	17.193	17.181	17.187	17.188	17.202	-.014	5288	1631

(1) Task IV Engine

(2) Task III Engine

Table A-XXV. HPTR Stage 1 Blade Radii, Outbound-UAL (Inches).

ESN	FORWARD			AFT			Overall Average	Grind Dimension
	Max.	Min.	Avg.	Max.	Min.	Avg.		
451-489	16.552	16.552	16.552	16.552	16.552	16.552	16.552	16.552 ± .002
451-359	16.597	16.585	16.590	16.597	16.585	16.590	16.590	16.587 ± .002
451-238	16.588	16.583	16.587	16.590	16.586	16.587	16.587	16.587 ± .002
451-282	16.588	16.580	16.586	16.591	16.584	16.587	16.587	16.587 ± .002
451-279	16.553	16.546	16.552	16.553	16.550	16.552	16.552	16.552 ± .002
451-221	16.586	16.579	16.584	16.585	16.573	16.584	16.584	16.587 ± .002

Table A-XXVI. HPTR Stage 2 Blade Radii, Outbound-UAL (Inches).

ESN	FORWARD			AFT			Overall Average	Grind Dimension
	Max.	Min.	Avg.	Max.	Min.	Avg.		
451-489	17.240	17.240	17.240	17.240	17.240	17.240	17.240	17.237 ± .002
451-359	17.244	17.234	17.239	17.246	17.234	17.239	17.239	17.237 ± .002
451-238	17.240	17.238	17.239	17.239	17.238	17.239	17.239	17.237 ± .002
451-282	17.241	17.237	17.240	17.245	17.234	17.240	17.240	17.237 ± .002
451-279	17.241	17.237	17.239	17.241	17.238	17.239	17.239	17.237 ± .002
451-221	17.241	17.234	17.237	17.239	17.233	17.237	17.237	17.237 ± .002

A.3.11 HPT Shroud Radii

Prior to the grinding of the HP turbine shrouds, the Stage 2 high pressure turbine nozzle assembly (which contains both stages of shrouds; see Figure A-18) is mounted on its aft flange to a restraining fixture and installed on a VTL. Readings were taken at the ends and center of each shroud segment at each of two axial locations (0.5 inch from the leading edge and 0.25 inch from the trailing edge) for each stage. Diameter measurements were obtained at the twelve/six o'clock position and runouts relative to the twelve o'clock position were recorded for each axial location. The results for 12 serviceable and 3 inbound modules are summarized in Tables A-XXVII and A-XXVIII.

HPT blade tip clearance and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

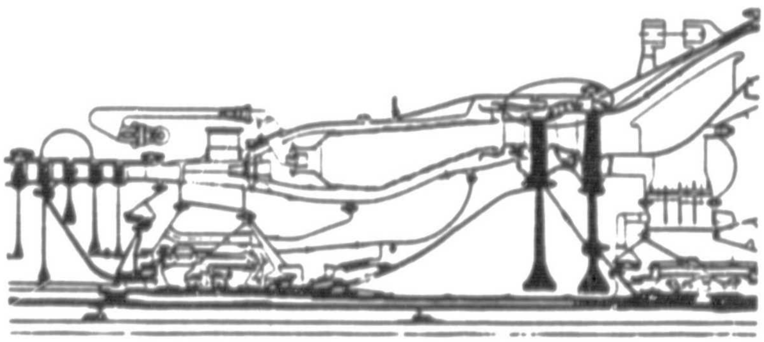


Figure A-18. Stage 2 HP Turbine Nozzle Assembly.

Table A-XXVII. HPT Stage 1 Shroud Radii (Inches).

MODULE NO.	OUTBOUND FORWARD MIN	OUTBOUND FORWARD MAX	OUTBOUND FORWARD AVG	OUTBOUND AFT MIN	OUTBOUND AFT MAX	OUTBOUND AFT AVG	OVERALL AVG	TARGET GRIND DIMENSION
51300	16.656	16.673	16.665	16.656	16.671	16.664	16.664	16.665 ± .002
51457	16.642	16.674	16.660	16.642	16.674	16.661	16.660	
51293	16.657	16.672	16.665	16.657	16.672	16.665	16.655	
51397	16.654	16.676	16.666	16.654	16.677	16.666	16.666	
51232	16.657	16.675	16.667	16.657	16.676	16.667	16.667	
51418	16.654	16.676	16.665	16.655	16.675	16.665	16.665	
51410	16.657	16.674	16.665	16.657	16.674	16.665	16.665	
51147	16.655	16.673	16.665	16.655	16.674	16.666	16.665	
51283	16.653	16.670	16.662	16.653	16.671	16.663	16.663	
51456	16.646	16.674	16.664	16.649	16.673	16.665	16.665	16.665 ± .002
51444	16.621	16.638	16.630	16.622	16.638	16.630	16.630	16.630 ± .002
89103	16.621	16.638	16.631	16.621	16.639	16.631	16.631	16.630 ± .002
INBOUND								
451-479 (1)	16.641	16.568	16.653	16.632	16.662	16.649	16.651	Unknown
451-380 (1)	16.613	16.635	16.626	16.610	16.630	16.623	16.629	Unknown
451-507 (2)	16.650	16.667	16.658	16.647	16.665	16.656	16.657	16.662

(1) Task IV Engine

(2) Task III Engine

Table A-XXVIII. HPT Stage 2 Shroud Radii (Inches).

OUTBOUND

MODULE NO.	FORWARD MIN	FORWARD MAX	FORWARD AVG	AFT MIN	AFT MAX	AFT AVG	OVERALL AVG	TARGET GRIND DIMENSION
51300	17.312	17.323	17.317	17.313	17.324	17.319	17.318	17.317 ± .002
89103	17.311	17.324	17.317	17.310	17.325	17.317	17.317	│
51293	17.310	17.321	17.315	17.310	17.320	17.315	17.315	│
51397	17.308	17.331	17.320	17.311	17.326	17.317	17.318	│
51232	17.311	17.322	17.316	17.310	17.321	17.315	17.315	│
51418	17.312	17.323	17.318	17.312	17.322	17.317	17.318	│
51444	17.309	17.326	17.316	17.307	17.325	17.314	17.315	│
51410	17.311	17.324	17.317	17.311	17.327	17.317	17.317	│
51147	17.312	17.323	17.317	17.310	17.324	17.317	17.317	│
51283	17.310	17.326	17.319	17.310	17.326	17.319	17.319	17.317 ± .002
51456	17.274	17.289	17.282	17.275	17.292	17.285	17.284	17.282 ± .002
51457	17.264	17.286	17.278	17.261	17.289	17.274	17.276	17.282 ± .002

INBOUND

MODULE NO.	FORWARD MIN	FORWARD MAX	FORWARD AVG	AFT MIN	AFT MAX	AFT AVG	OVERALL AVG	TARGET GRIND DIMENSION
451-479 (1)	17.291	17.308	17.299	17.293	17.308	17.301	17.300	Unknown
451-380 (1)	17.263	17.290	17.278	17.262	17.288	17.275	17.276	Unknown
451-507 (2)	17.300	17.318	17.309	17.299	17.317	17.308	17.308	17/318

(1) Task IV Engines

(2) Task III Engine

A.3.12 HPT Airfoil Surface Finish

A Bendix profilometer was used to measure the airfoil surface finish on incoming high pressure turbine blades and vanes at the airfoil locations shown in Figures A-19 through A-22. All surface finish measurements were recorded for the convex (suction) side. Changes in performance due to airfoil quality degradation on the concave (pressure) side are known to have minimal effect on performance (approximately ten percent of the suction side influence). A summary of the data is shown in Tables A-XXIX through A-XXXII.

Airfoil suface finish change and its effect on performance are discussed in the portion of Section 4.2.1 entitled "High Pressure Turbine (HPT) Section".

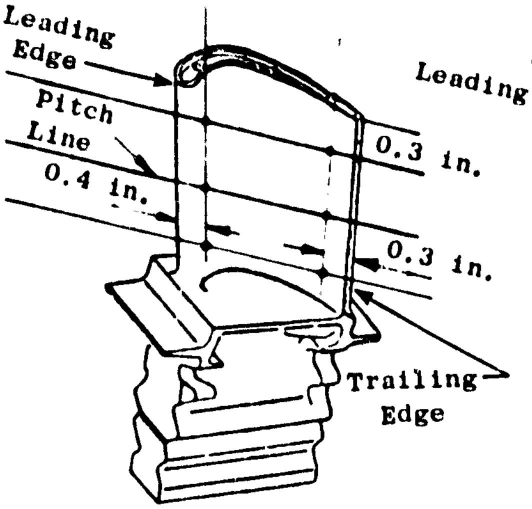


Figure A-19. HPT Turbine Rotor Stage 1 Blade.

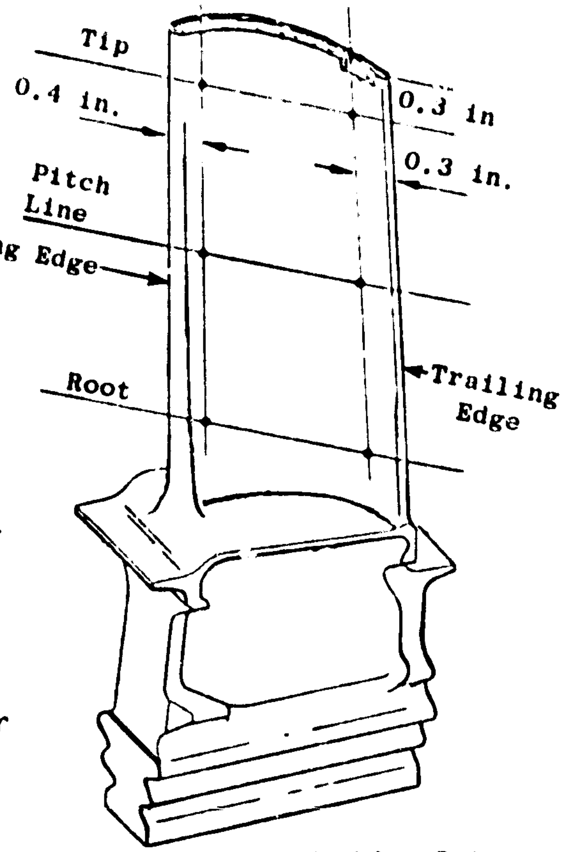


Figure A-20. HP Turbine Rotor Stage 2 Blade.

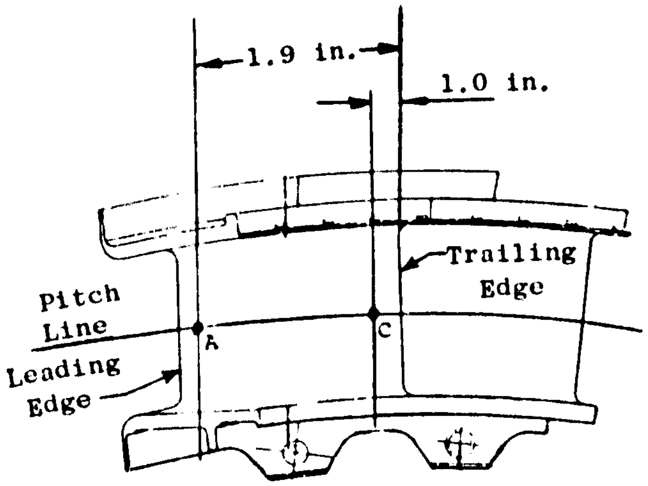


Figure A-21. HP Turbine Stage 1 Vane.

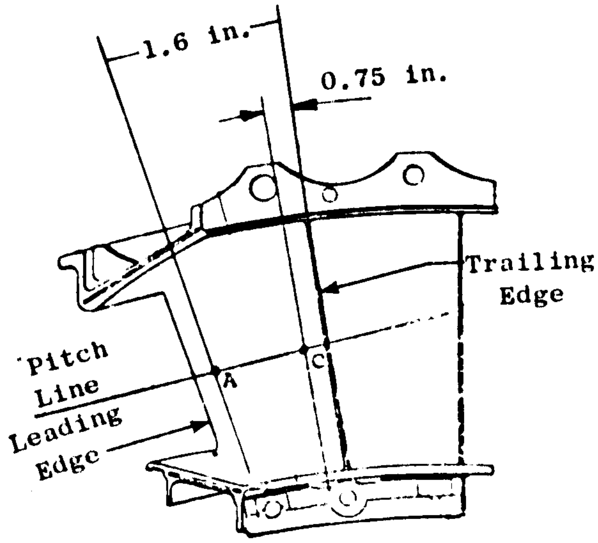


Figure A-22. HP Turbine Stage 2 Vane.

Table A-XXIX. Surface Finish - Stage 1 HPTR Blade.

ESN	SURF. FIN. (µ in/in AA)	TSO (Hrs)	CSO (Cycles)
451-507	43	15	28
451-212	92	598	228
451-493	75	[illegible]	420
451-259	95	[illegible]0	1360
451-467	63	2790	1282
451-217	75	3113	1275
451-132	73	3621	1594
451-133	45	3678	1723
451-479	74	4468	1910
451-380	70	4594	1270
Average	74 (451-507 not included)		

New Blade Specification - 63 µinch per inch AA maximum

Table A-XXX. Surface Finish - Stage 2 HPTR Blade.

ESN	SURF. FIN. (µ in/in AA)	TSO (Hrs)	CSO (Cycles)
451-507	41	15	28
451-212	106	598	228
451-493	70	1350	420
451-259	61	2570	1360
451-234	97	3111	1239
451-217	52	3113	1275
451-469	108	3455	1662
451-132	62	3621	1594
451-133	76	3678	1723
451-293	61	3856	1860
451-404	61	4078	1757
451-479	62	4468	1910
451-380	48	4594	1270
Average	72 (451-507 not included)		

New Blade Specification - 63 µinch per inch AA maximum

Table A-XXXI. Surface Finish - Stage 1 HPTN Vane.

ESN	SURF. FIN. (μ in./in. AA)	TSO (Hrs)	CSO (Cycles)
451-507	46	15	28
451-212	48	598	228
451-259	51	2570	1360
451-234	57	3111	1239
451-217	47	3113	1275
451-132	38	3621	1594
451-133	41	3678	1723
451-293	58	3856	1860
451-479	44	4468	1910
451-380	66	4594	1270
Average	50 (451-507 not included)		
New Vane Specification - 39 μ inch per inch AA maximum			

Table A-XXXII. Surface Finish - Stage 2 HPTN Vane.

ESN	SURF. FIN. (μ in./in. AA)	TSO (Hrs)	CSO (Cycles)
451-493	67	1350	420
451-259	73	2570	1360
451-234	46	3111	1239
451-217	60	3113	1275
451-132	77	3621	1594
451-133	65	3678	1723
451-293	80	3856	1860
Average	67		
New Vane Specification - 49 μ inch per inch AA maximum			

A.4 LOW PRESSURE TURBINE (LPT) SECTION

A.4.1 LPTR Blade and Air Seal Radii

Radii measurements of blades and air seals were obtained for 12 inbound and 12 outbound low pressure turbine rotors (LPTR). The rotors were mounted in a runout fixture and measurements were taken from a calibrated bar (with a known distance to the centerline of the rotor) to the blade tip shroud seal serrations and to the air seal teeth (see Figure A-23). A summary of the data is presented in Tables A-XXXIII and A-XXXIV.

Additional data accumulated are summarized in Table A-XXXV. Measurements of the these rotors were obtained using both a Pi tape and a runout fixture similar to the fixture described above.

Low pressure turbine clearances and their effect on efficiency are discussed in the portion of Section 4.2.1 entitled "Low Pressure Turbine (LPT) Section".

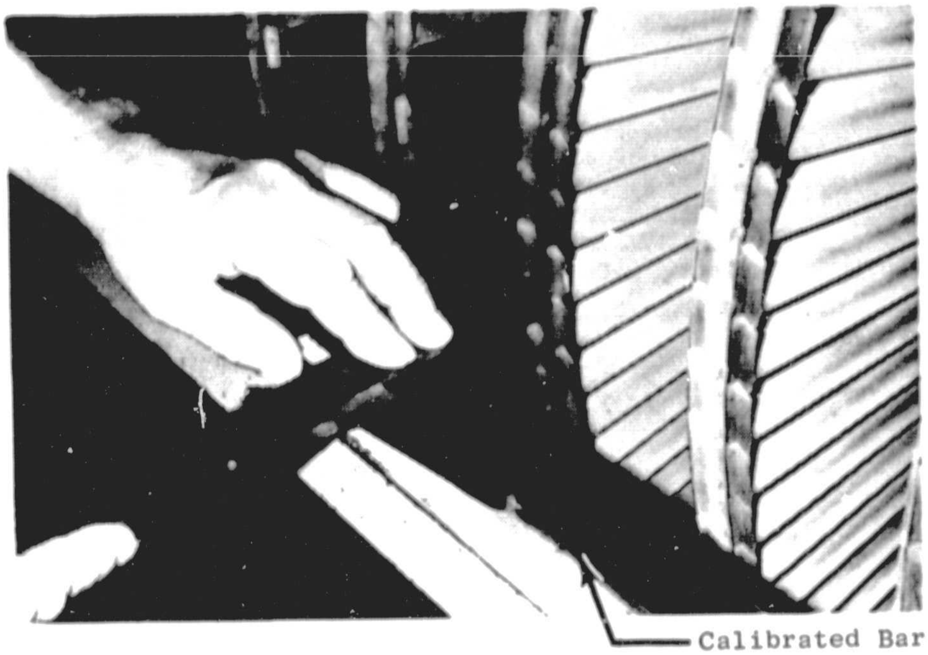


Figure A-23. Setup for LP Turbine Rotor Radii Measurements.

Table A-XXXIII. LPTR Blade and Air Seal Radii, Inbound-UAL (Inches).

ESN 451XXX	-424	-321	-144	-360	-419	-308	-250	-116	-457	-155	-469	-467	AVG.	S/M LIMITS
TSO	12287	8737	15909	2582	9275	3146	7732	12187	5468	7459	5286	11525	8466	
BLADES														
Stg 1	24.129	24.129	24.129	24.119	24.130	24.131	24.121	24.130	24.129	24.131	24.124	24.130	24.128	24.132 ± .011
2	24.128	24.123	24.129	24.126	24.128	24.127	24.130	24.127	24.126	24.122	24.129	24.119	24.126	24.125
3	24.117	24.116	24.111	24.111	24.116	24.117	24.112	24.115	24.114	24.113	24.113	24.114	24.114	24.113
4	24.124	24.125	24.120	24.117	24.129	24.125	24.128	24.124	24.127	24.127	24.131	24.126	24.125	24.123
5	24.123	24.120	24.120	24.124	24.132	24.125	24.125	24.128	24.120	24.116	24.125	24.128	24.124	24.123 ± .011
Avg.													24.123	
SEALS														
Stg 1	18.206	18.200	18.204	18.202	18.194	18.199	18.217	18.203	18.207	18.203	18.202	18.199	18.203	18.203 ± .004
2	17.996	18.013	18.010	18.016	18.015	18.002	17.997	18.013	18.012	18.015	18.016	18.013	18.010	18.011
3	16.852	16.856	16.858	16.856	16.852	16.860	16.858	16.857	16.857	16.860	16.859	16.857	16.857	16.854
4	15.590	15.583	15.587	15.592	15.582	15.588	15.589	15.583	15.588	15.584	15.586	15.584	15.586	15.584
5	14.233	14.234	14.236	14.239	14.231	14.235	14.231	14.230	14.229	14.234	14.231	14.228	14.233	14.229 ± .004
AVG.													16.578	

Table A-XXXIV. LPTR Blade and Air Seal Radii, Outbound-UAL (Inches).

MODULE #	1	2	3	4	5	6	7	8	9	10	11	12	AVG	S/M LIMITS
BLADES														
STG 1	24.126	24.134	24.108	24.131	24.134	24.133	24.139	24.123	24.133	24.131	24.125	24.137	24.129	24.132 ± .011
2	24.130	24.128	24.129	24.125	24.130	24.130	24.130	24.129	24.123	24.126	24.112	24.132	24.127	24.125
3	24.119	24.112	24.116	24.117	24.118	24.113	24.113	24.113	24.108	24.116	24.115	24.112	24.114	24.113
4	24.120	24.128	24.127	24.128	24.122	24.125	24.134	24.119	24.123	24.126	24.128	24.130	24.126	24.123
5	24.123	24.131	24.136	24.125	24.125	24.125	24.130	24.128	24.119	24.126	24.129	24.128	24.127	24.123 ± .011
AVG													24.125	

MODULE #	1	2	3	4	5	6	7	8	9	10	11	12	AVG	S/M LIMITS
SEALS														
STG 1	18.203	18.209	18.205	18.205	18.207	18.184	18.205	18.209	18.208	18.199	18.182	18.204	18.202	18.203 ± .004
2	18.007	18.016	18.014	18.012	18.012	18.009	17.992	18.015	17.996	18.003	18.012	18.014	18.009	18.011
3	16.852	16.857	16.862	16.857	16.859	16.859	16.857	16.857	16.854	16.854	16.858	16.863	16.857	16.854
4	15.579	15.592	15.591	15.589	15.587	15.586	15.589	15.591	15.589	15.588	15.587	15.590	15.588	15.584
5	14.239	14.239	14.232	14.231	14.231	14.228	14.235	14.237	14.233	14.231	14.236	14.222	14.233	14.229 ± .004
AVG													16.578	

Table A-XXXV. LPTR Blade and Air Seal Radii (Inches).

ESN 451XXX	-509	-515	-507	-479	-380	-410	-129	-440	S/M LIMITS
	AFTER INITIAL BUILD	AFTER GREEN RUN	TASK II	TASK IV #1	TASK IV #2	UAL #1	UAL #3	UAL #5	
BLADE									
STG 1	24.127	24.124	24.131	24.125	24.122	24.101	24.090	24.128	24.132 ± .011
2	24.120	24.120	24.126	24.100	24.113	24.096	24.115	24.119	24.125 ± .011
3	24.113	24.099	24.106	24.095	24.101	24.106	24.093	24.100	24.113 ± .011
4	24.117	24.118	24.110	24.112	24.115	24.117	24.118	24.111	24.123 ± .011
5	24.120	24.116	24.112	24.109	24.113	24.111	24.113	24.109	24.123 ± .011
SEALS									
STG 1	N/R	18.202	18.198	18.190	18.185	18.199	18.188	18.201	18.203 ± .004
2	N/R	17.993	18.004	18.003	18.002	18.005	18.000	18.005	18.011 ± .004
3	N/R	16.847	16.847	16.846	16.854	16.850	16.848	16.852	16.854 ± .004
4	N/R	15.573	15.572	15.579	15.560	15.577	15.572	15.582	15.584 ± .004
5	N/R	14.214	14.215	14.217	14.198	14.229	14.217	14.228	14.229 ± .004

A.4.2 LPT Airfoil Surface Finish

A Bendix profilometer was used to measure the airfoil surface finish of several blades and vanes per stage for each of several low pressure turbine (LPT) modules. Measurements were made at approximately 0.5 inch from both the leading and trailing edges at the pitch line and 0.5 inch radially inward from the outer platform on both the convex and concave surfaces of the airfoils (see Figure A-24). However, an assessment of deterioration is made using the suction-side data only, since surface finish roughness on the pressure side is known to have minimal effect on performance. A summary of the data is presented in Table A-XXXV.

LPT airfoil surface finish and its significance are discussed in the portion of Section 4.2.1 entitled "Low Pressure Turbine (LPT) Section".

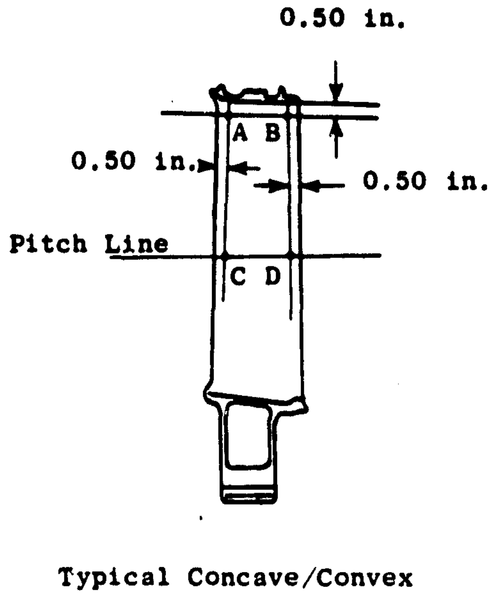


Figure A-24. Location of Surface Finish Measurements on LPT Blades (and Vanes).

Table A-XXXVI. LPT Airfoil Surface Finish Measurements.

LPTR BLADES (μ in./in. AA)

ESN	451-507		451-479		451-410		451-380		451-129		451-440	
TSO	15		4468		6150		7717		8246		12823	
CSO	28		1910		2715		2179		3713		5206	
	CV	CC	CV	CC	CV	CC	CV	CC	CV	CC	CV	CC
STAGE 1	39	41	92	73	114	117	103	132	80	98	138	140
2	--	--	82	60	---	---	77	93	67	72	68	80
3	48	45	76	63	90	95	63	59	61	60	63	82
4	57	38	74	69	89	100	66	66	55	54	71	81
5	41	41	60	60	121	127	91	91	63	69	79	101
AVG.	46	41	76	65	104	110	80	88	65	73	84	97
New Blade Specification - 45 maximum												

LPTS VANES (μ in./in. AA)

STAGE 1	80	67	95	100	140	133	141	142	138	138	110	154
2	57	60	110	94	91	86	89	93	126	105	126	110
3	62	58	89	85	89	83	79	73	108	91	81	73
4	54	58	90	79	79	73	78	77	82	58	67	54
5	59	51	89	75	72	67	74	66	78	75	80	81
AVG.	62	57	95	87	94	88	92	90	107	93	93	94
New Vane Specification - 63 Maximum												

APPENDIX B

CRUISE PERFORMANCE DATA

Cruise performance data were obtained from airline revenue service cruise trends. Engine installed performance is recorded regularly for individual engines as a normal airline operational procedure. These cruise data consist of cockpit measurements for significant engine parameters, notably WFM (fuel flow), EGT (exhaust gas temperature), N1 (fan rotational speed), and N2 (core rotational speed), recorded during stabilized operation at altitude. This information is used by the CF6 operators to monitor the relative health of each engine, to anticipate normal maintenance requirements of the engines, and to assess the performance trends of their fleets.

For the CF6 family of engines, fuel flow and EGT measurements are compared to values from the "Flight Planning and Cruise Control Manual" (FP & CCM) for the same flight condition and N1. This manual 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.

The cruise performance data points were stored in computer files and utilized to develop statistical trends. Each data point represented an average level obtained from between four and twenty airplane flights. Airline trends in the Contractor's files had generally been normalized to the "FP & CCM" by the operator, and in the one case, smoothed for each engine by a running average of four out of the last six readings. In cases where only as-measured cockpit readings were available, these data were normalized by the Contractor. In all cases, sufficient readings were averaged to yield performance data points which were representative of the individual engines at that period of time.

A summary of the cruise performance data assimilated and used to establish statistical trends of overall performance is presented in Table B-I. These data span the life cycle of CF6-6D engines. Emphasis was placed on obtaining data for engines incorporating the latest hardware, represented by ESN 451-406+ series engines, and recent builds/installations of earlier serial numbers.

Performance data utilized in this report are present in Figures B-1 to B-25 in terms of cruise ΔWFM and ΔEGT performance at N1, relative to the

Table B-I. Summary of CF6-6D Cruise Performance Data.

	DIAGNOSTIC FILES			FLEET
	ESN	INST.	DATA PTS.	ESN
DAC CHECKOUT (S/N -406 to -496)	75	78	100	75
FIRST INSTALLATION (S/N -406 to -496)				
AIRLINE "A"	33	33	270	34
AIRLINE "B"	23	23	133	24
AIRLINE "C"	5	5	103	7
AIRLINE "D"	5	5	10	10
SPARES	7	7	69	8
OTHER	1	1	11	7
TOTAL	74	74	596	90
REFURBISHED ENGINES (S/N -406 to -496)				
AIRLINE "A"	50 } 64	67	338	64
AIRLINE "B"	38 }	46	459	
AIRLINE "C"	7	10	139	7
AIRLINE "D"	11	13	22	11
OTHER	--	--	--	8
SUB-TOTAL	82	136	958	90
(Pre S/N -406)				
AIRLINE "B"	15	15	205	29
AIRLINE "C"	28	28	423	32
OTHER	--	--	--	221
SUB-TOTAL	43	43	628	282
TOTAL	125	179	1586	372

"FP & CCM." Cruise data points used to derive composite statistical fits are shown in Figures B-1 and B-2 for initial-installation engines and in Figures B-4 and B-5 for multiple-build engines. The remaining figures (Figure B-3 and B-6 to B-25) present individual trends for similar-age engines used to derive statistical trends of the various families of engines. These include: the 4000-hour initial-installation family, the families of multiple-build engines from 2500 hours to 4500 hours, the 3000-hour families for four airline/route structure groups, and wing/tail families for one 3000-hour group.

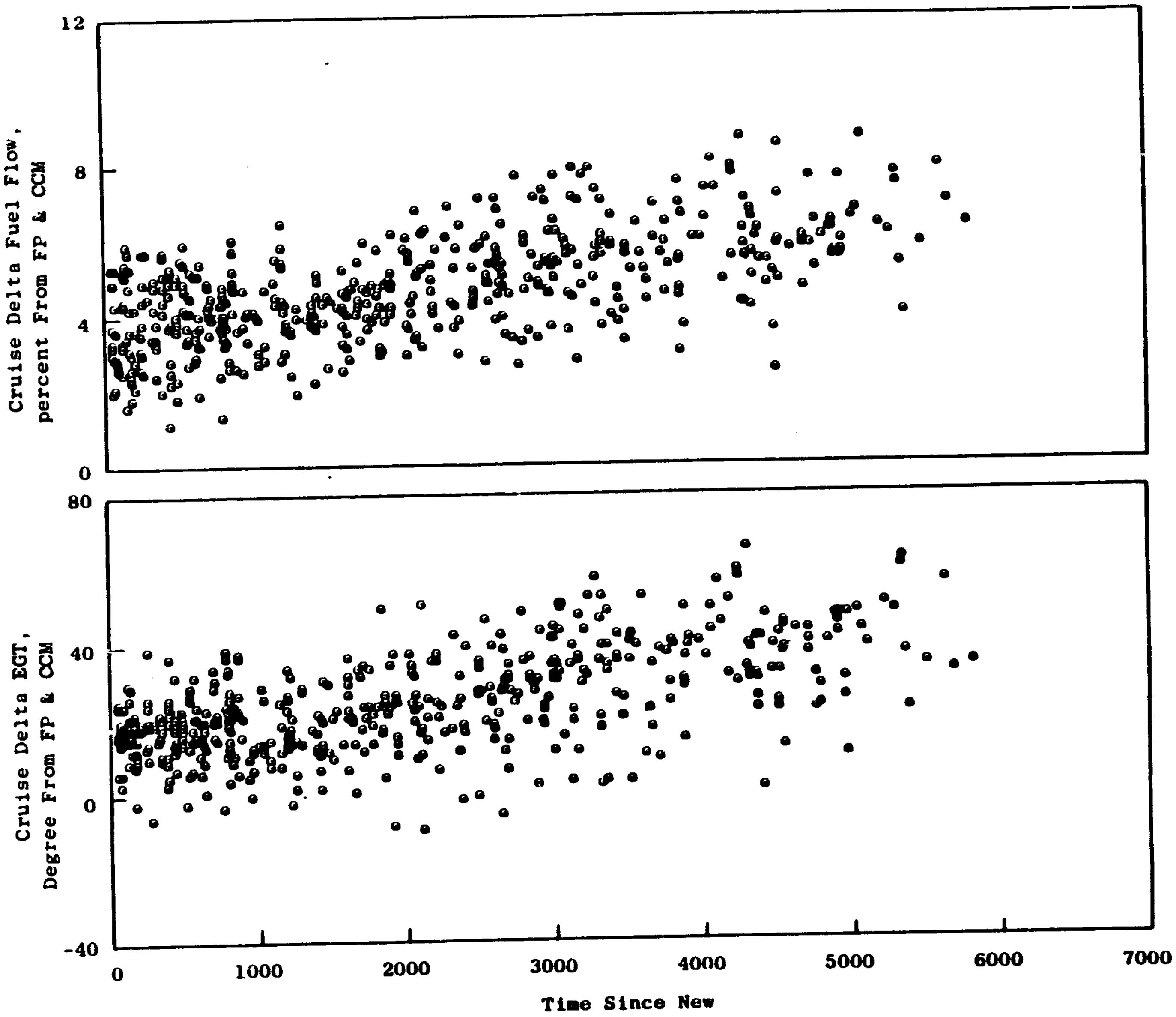


Figure B-1. CF6-6 Cruise Performance of Initial-Installation Engines, Three Airlines.

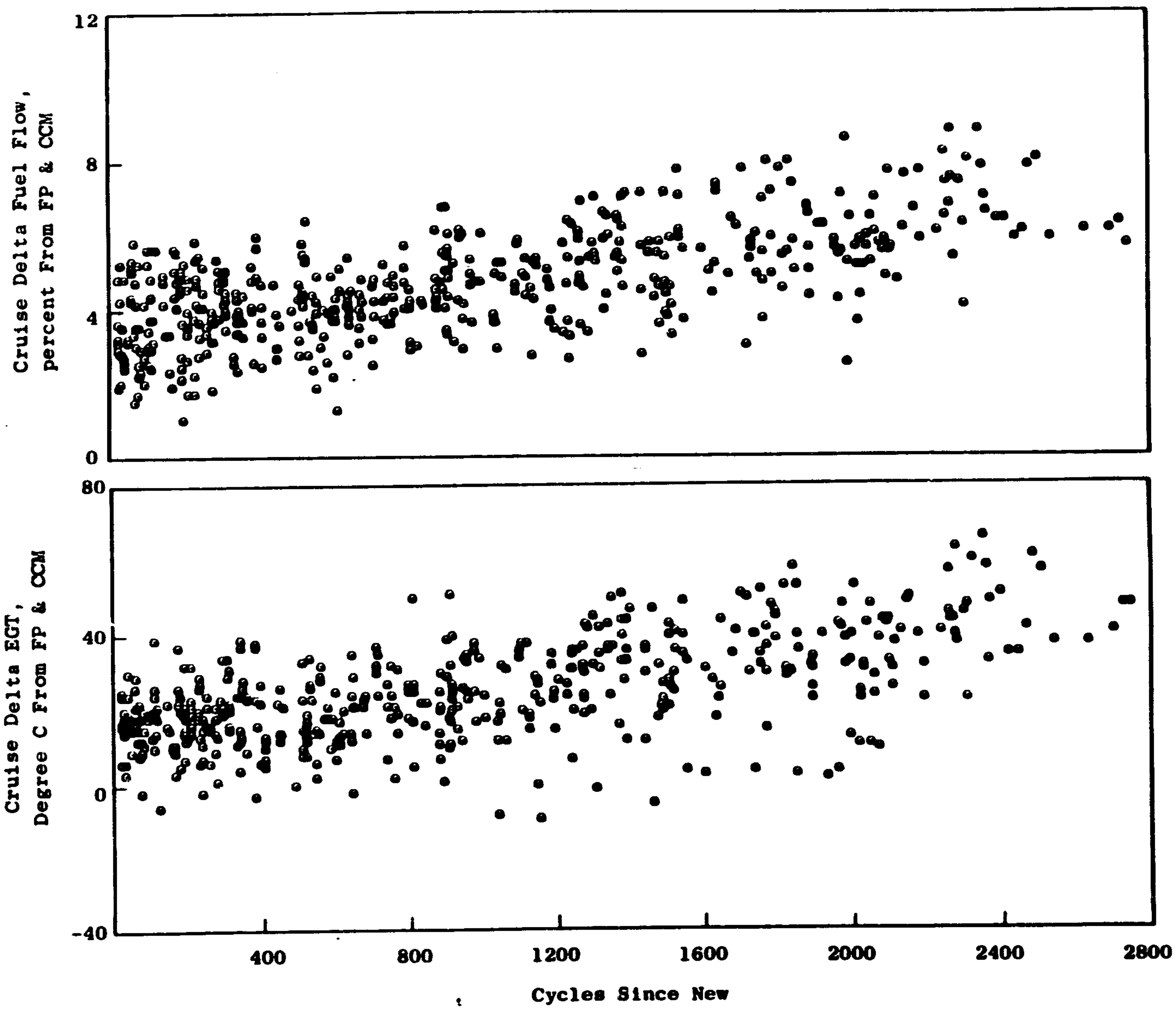


Figure B-2. CF6-6 Cruise Performance of Initial-Installation Engines, Three Airlines.

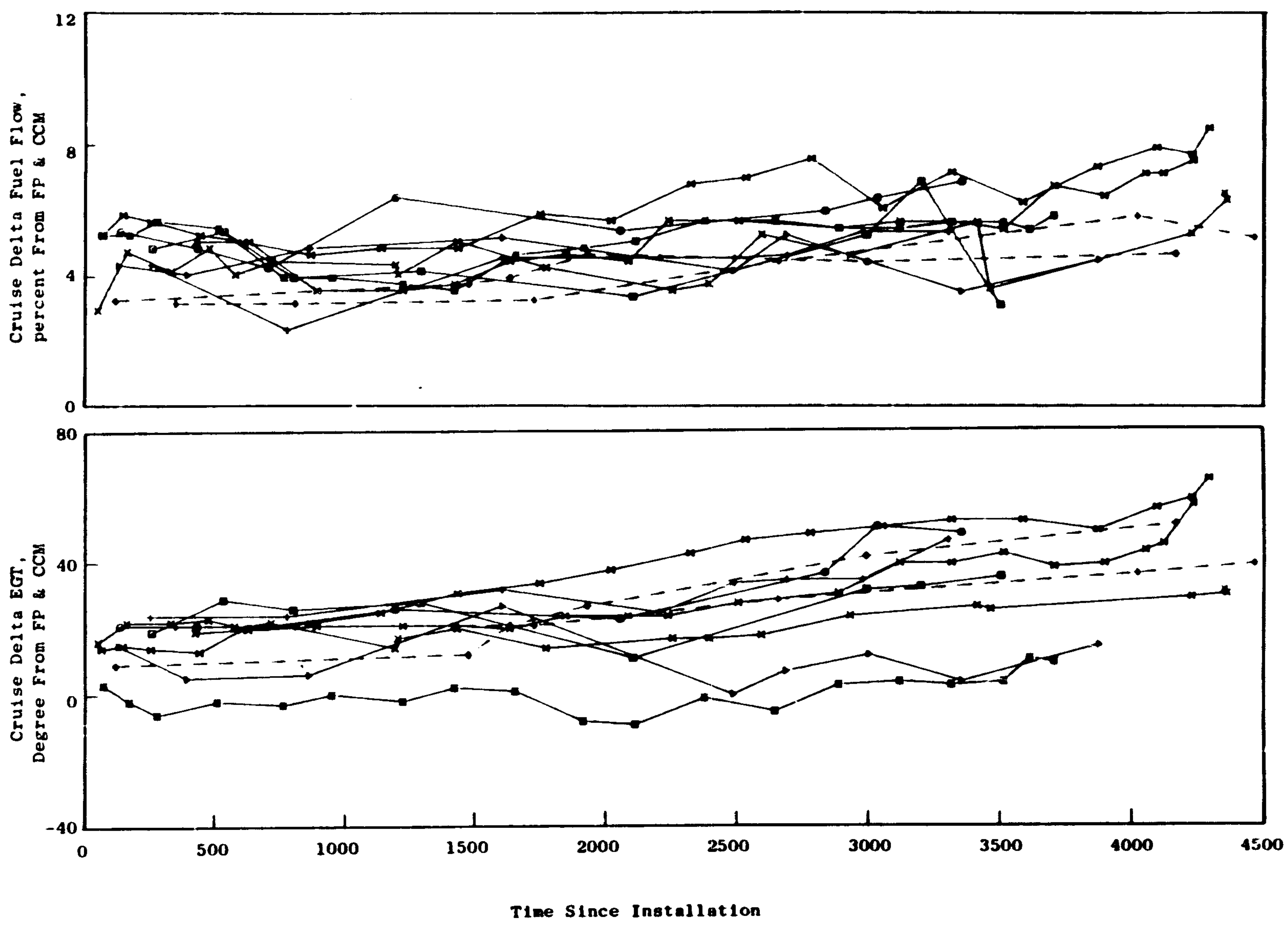


Figure B-3. CF6-6 Cruise Performance of Initial-Revenue-Service Installations, 4000 Hours.

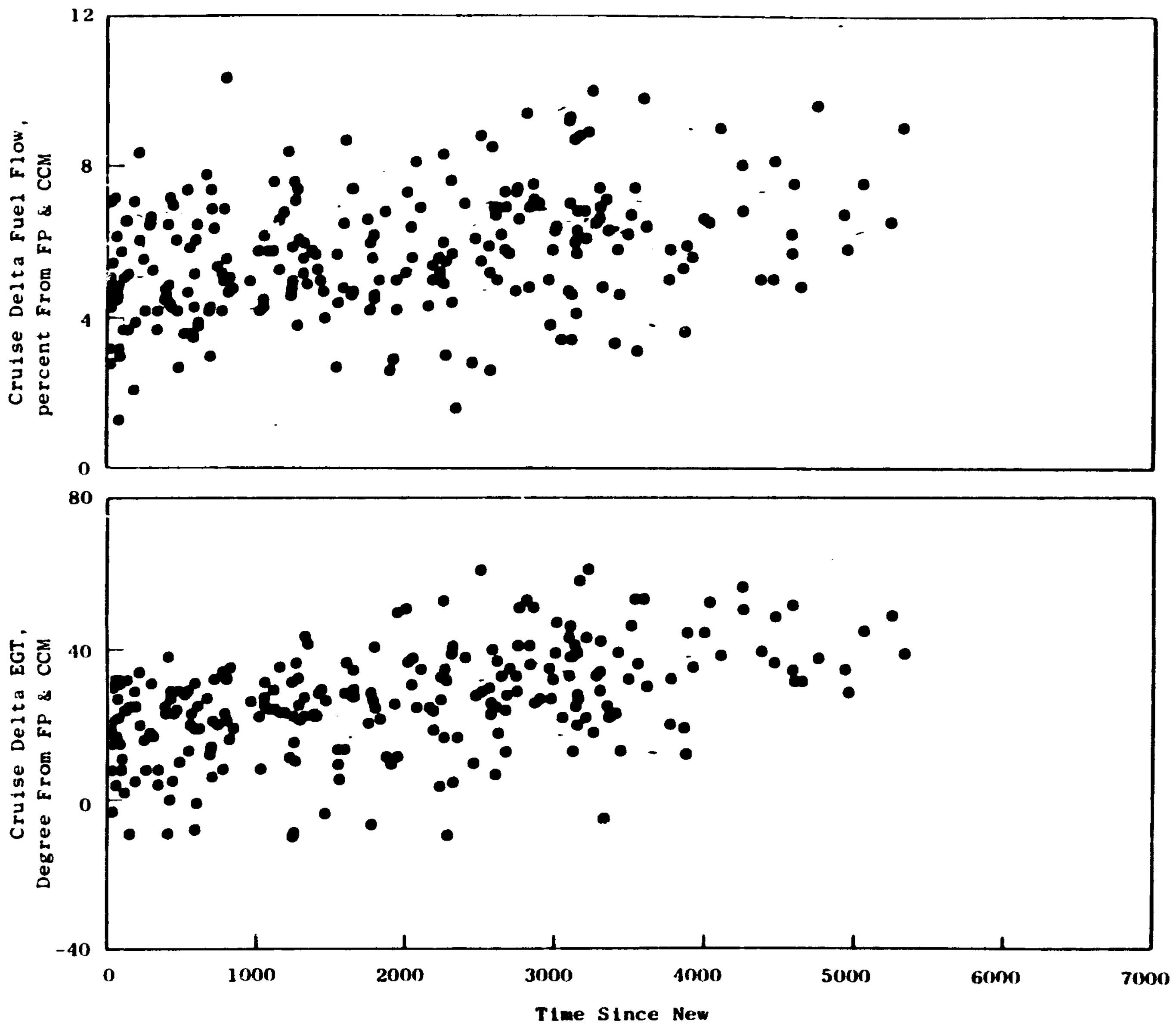


Figure B-4. CF6-6 Cruise Performance of Multiple-Build Installations, Three Airlines.

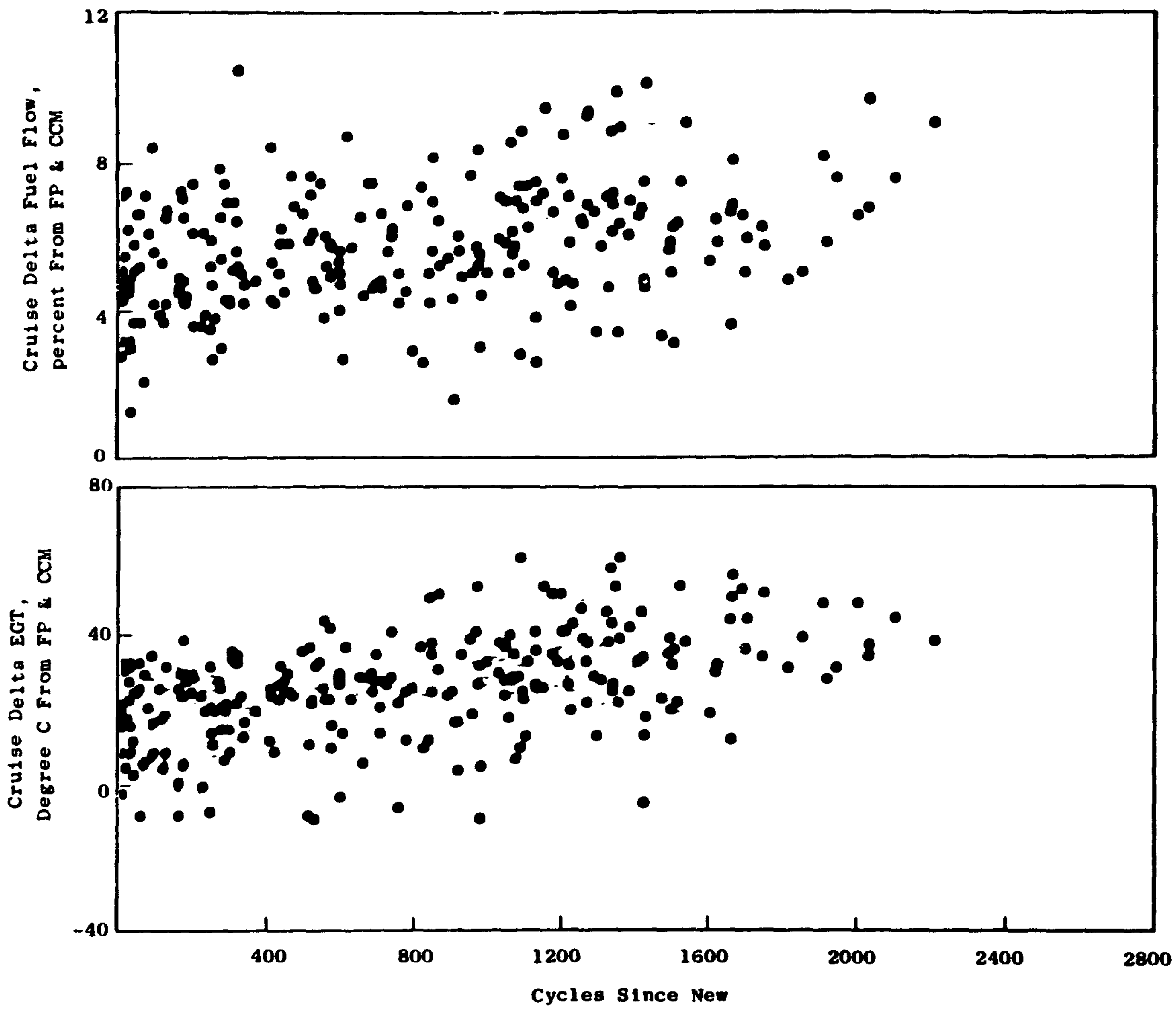


Figure B-5. CF6-6 Cruise Performance of Multiple-Build Installations, Three Airlines.

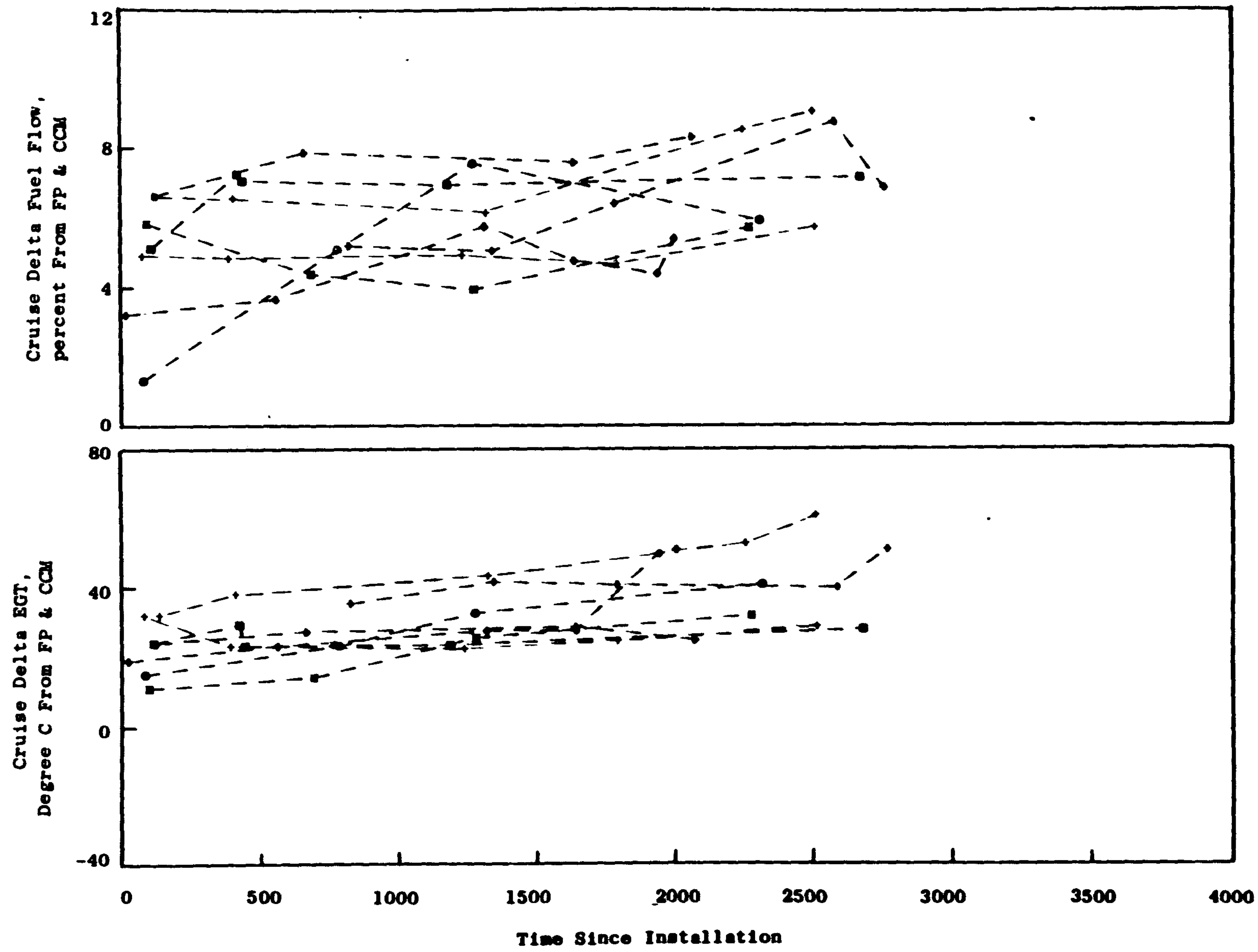


Figure B-6. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (2500 Hours).

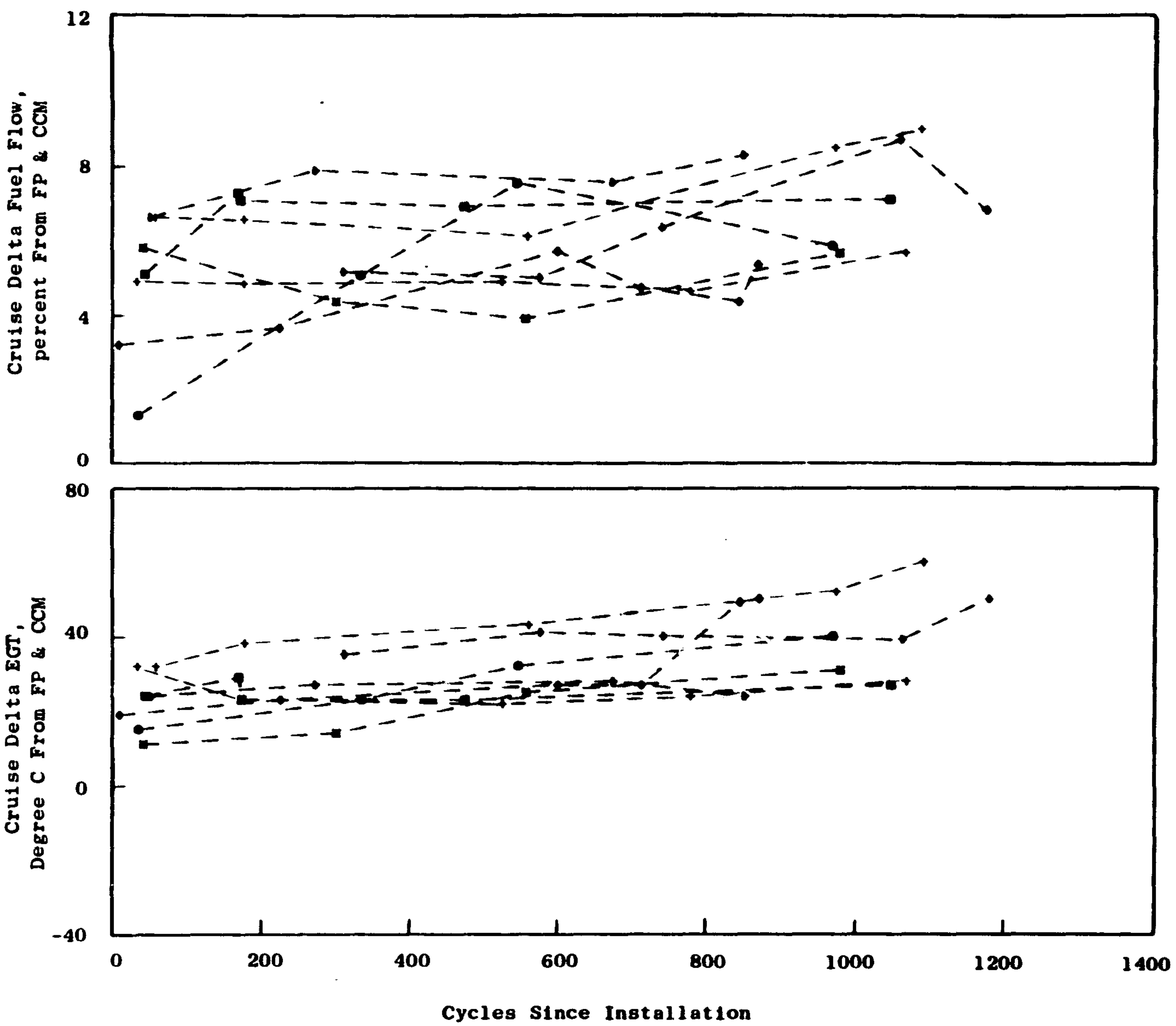


Figure B-7. CF6-6 Cruise Performance of Multiple-Build Engines, Airline "A" (2500 Hours).

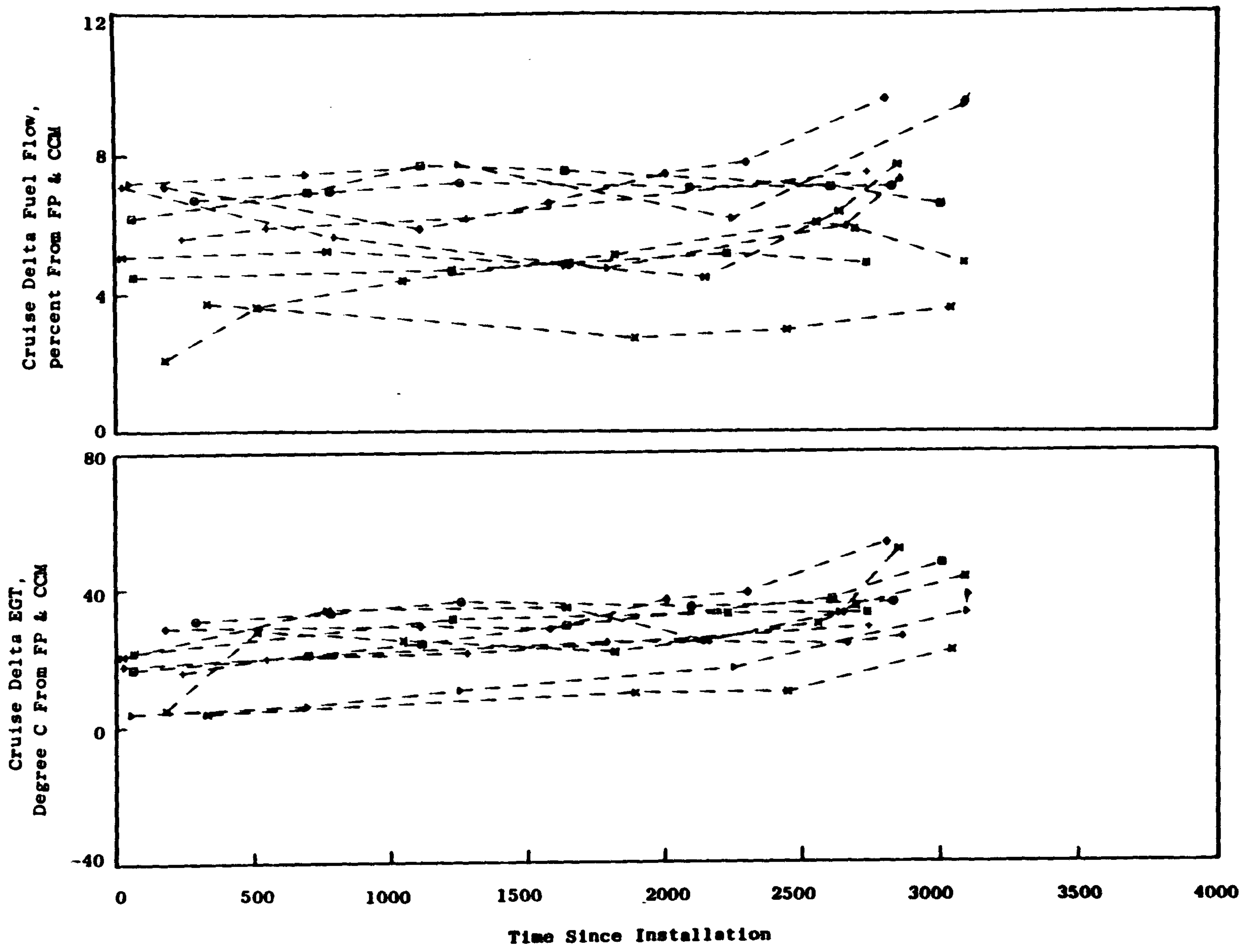


Figure B-8. CF6-6 Cruise Performance of Multiple-Band Installations, Airline "A" (3000 Hours).

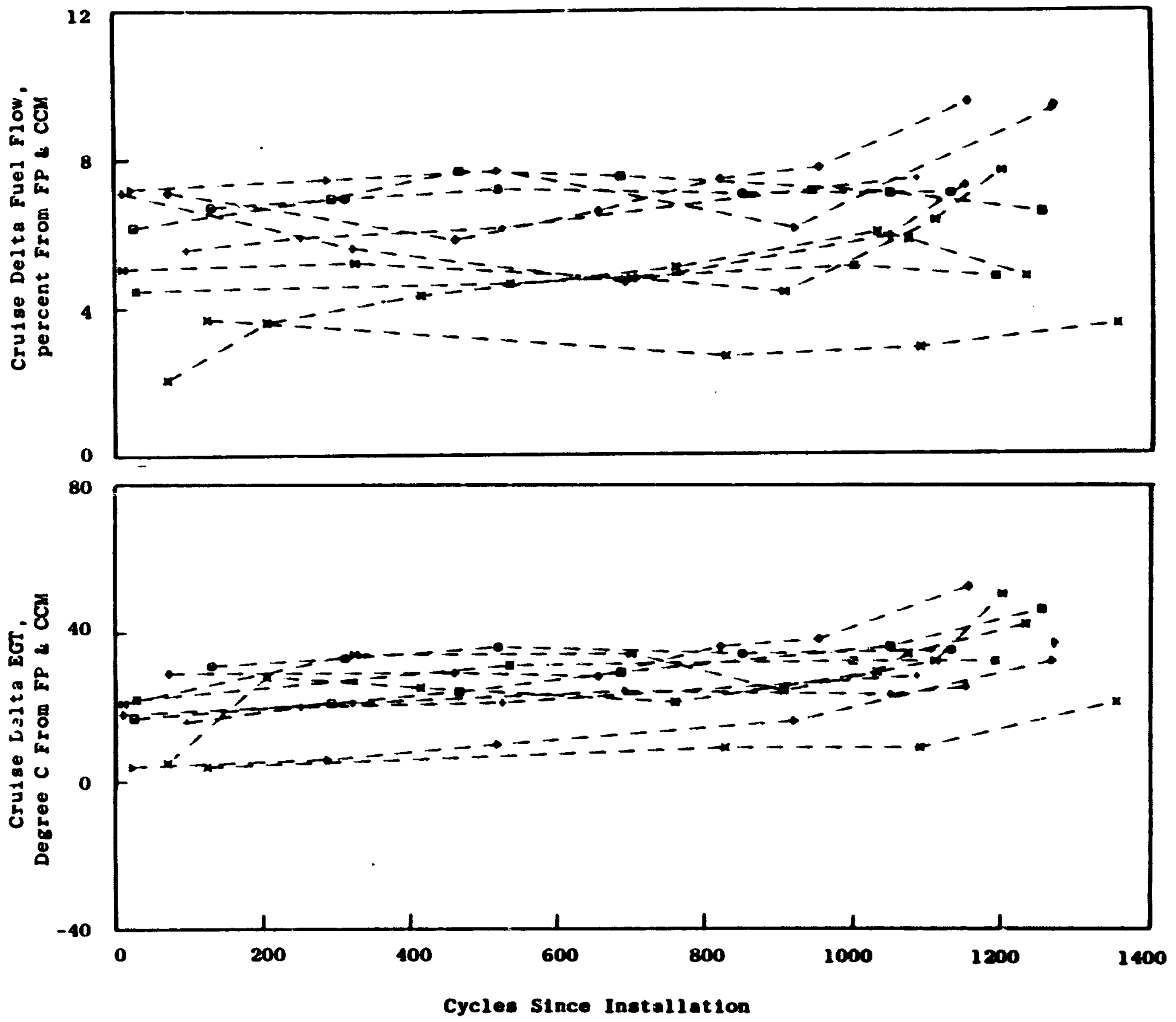


Figure B-9. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (3000 Hours).

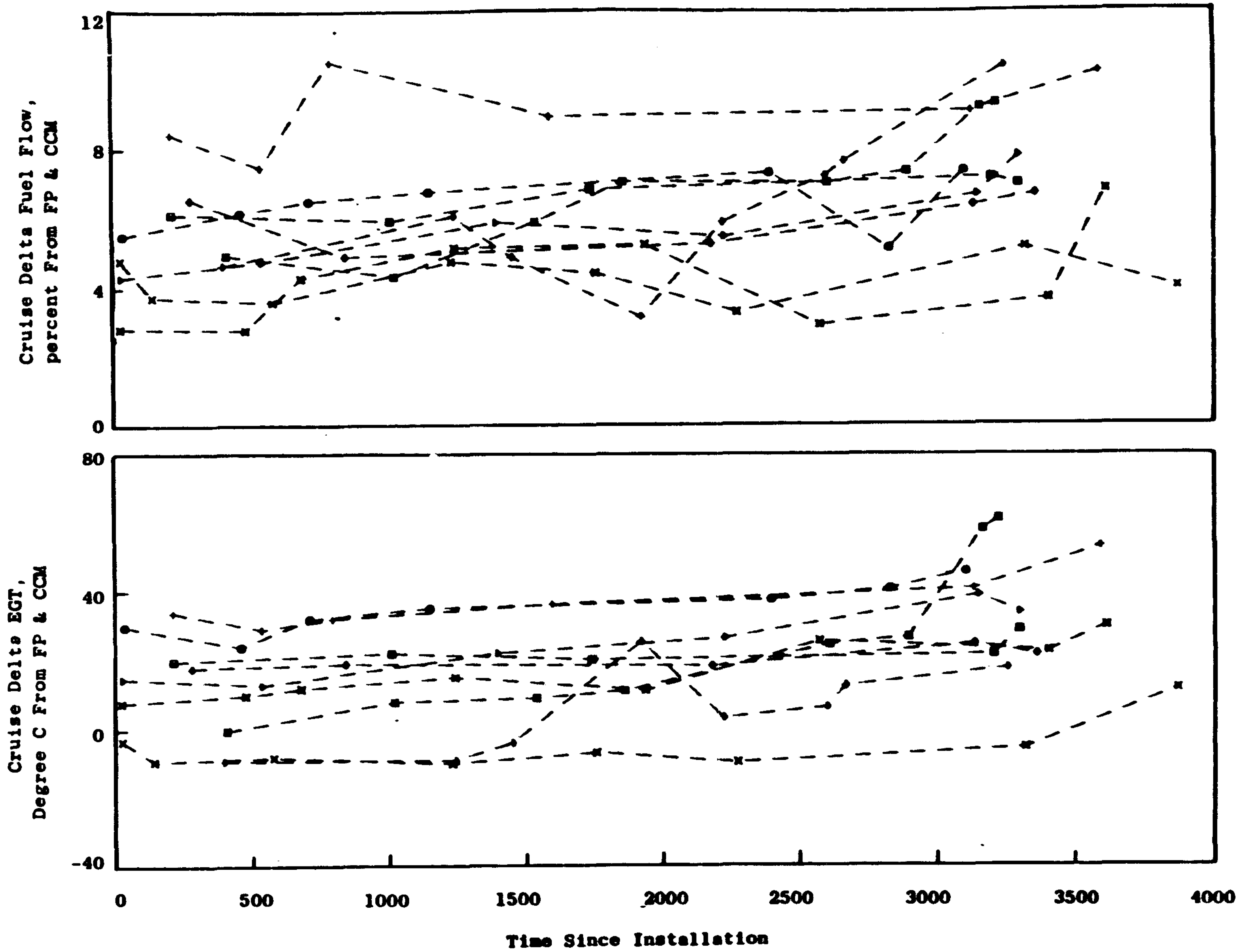


Figure B-10. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (3500 Hours).

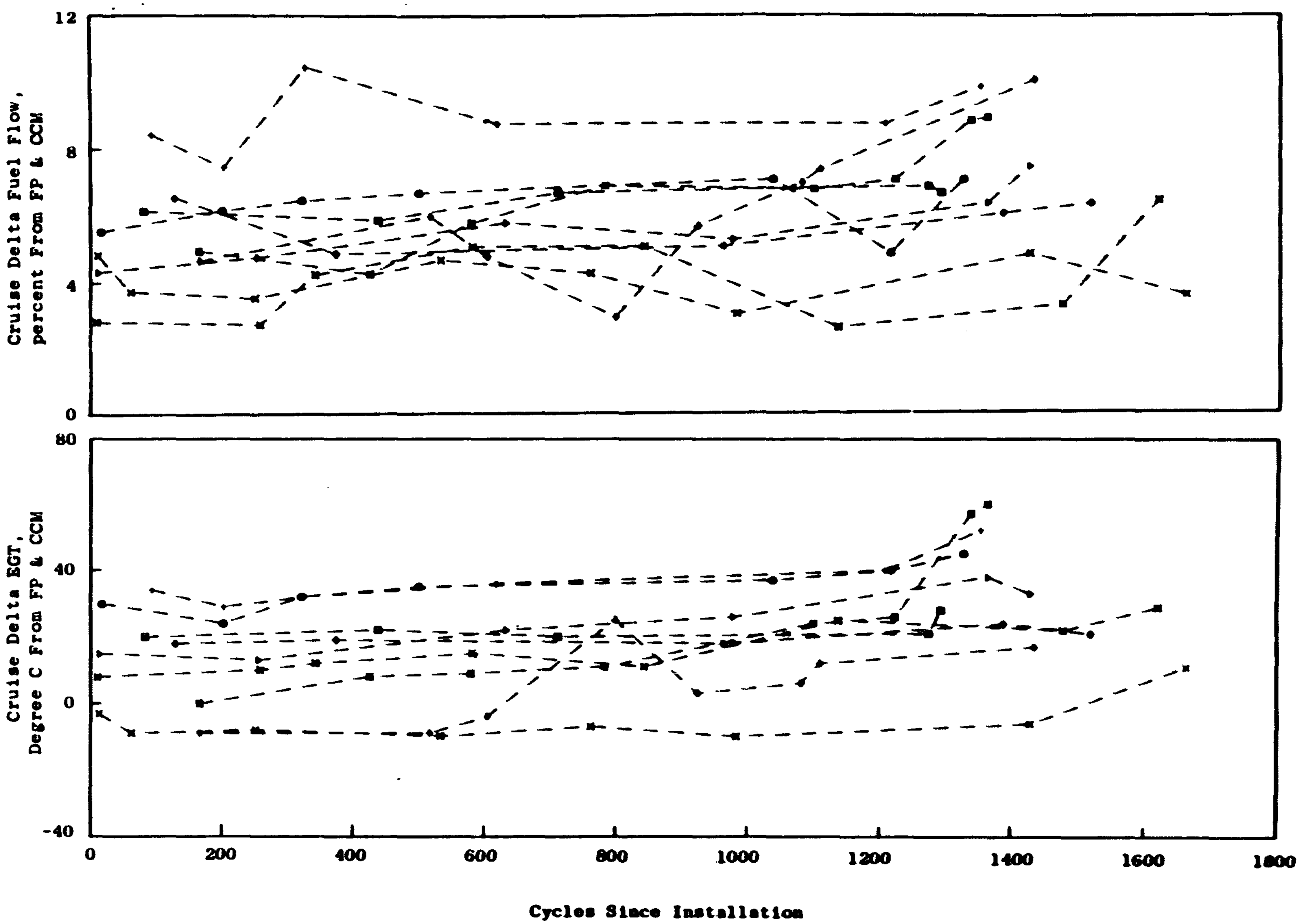


Figure B-11. CF6-6 Cruise Performance Plotted Against Cycles - Multiple-Build Installations, Airline "A" (3500 Hours).

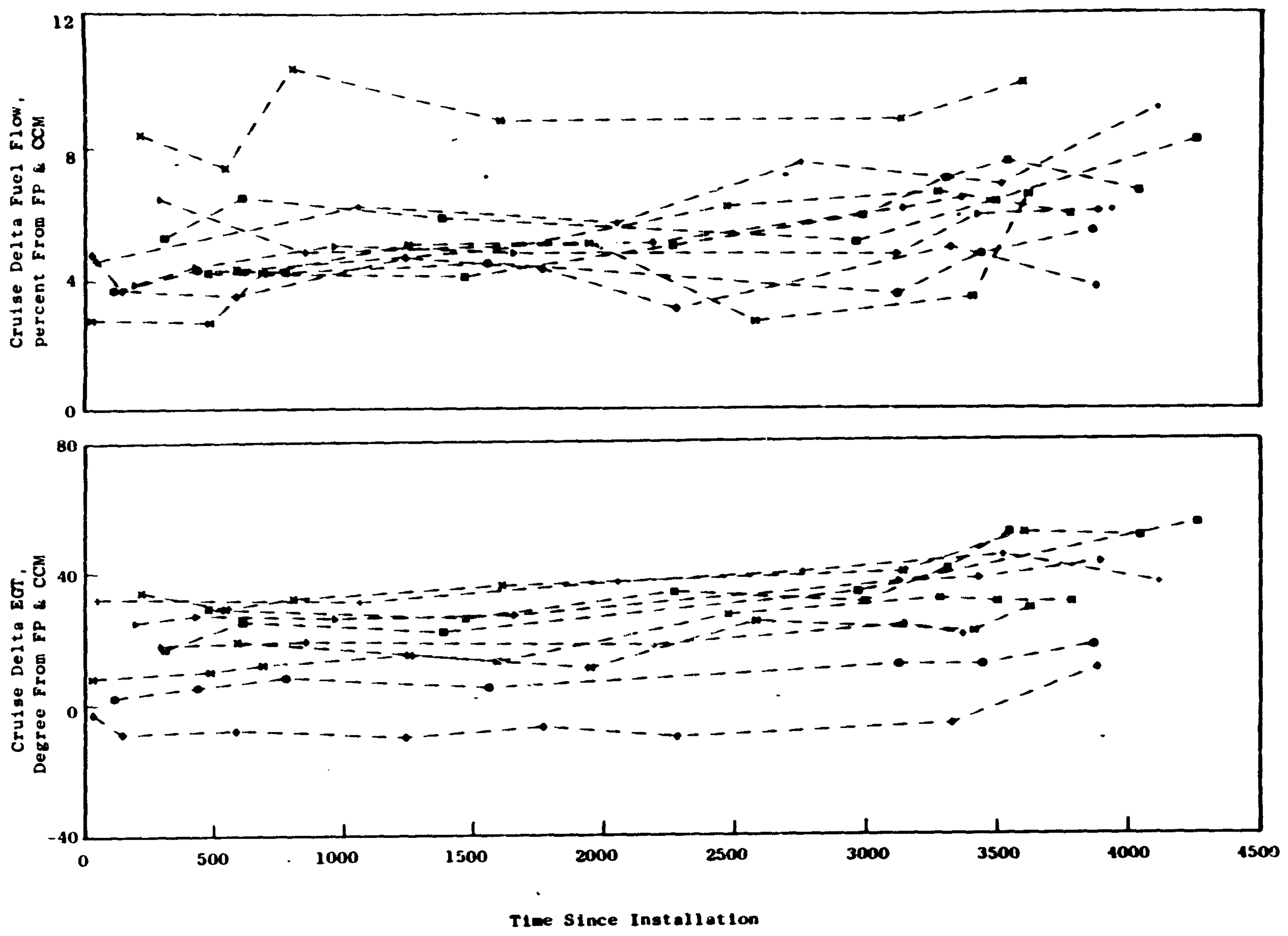


Figure B-12. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (4000 Hours).

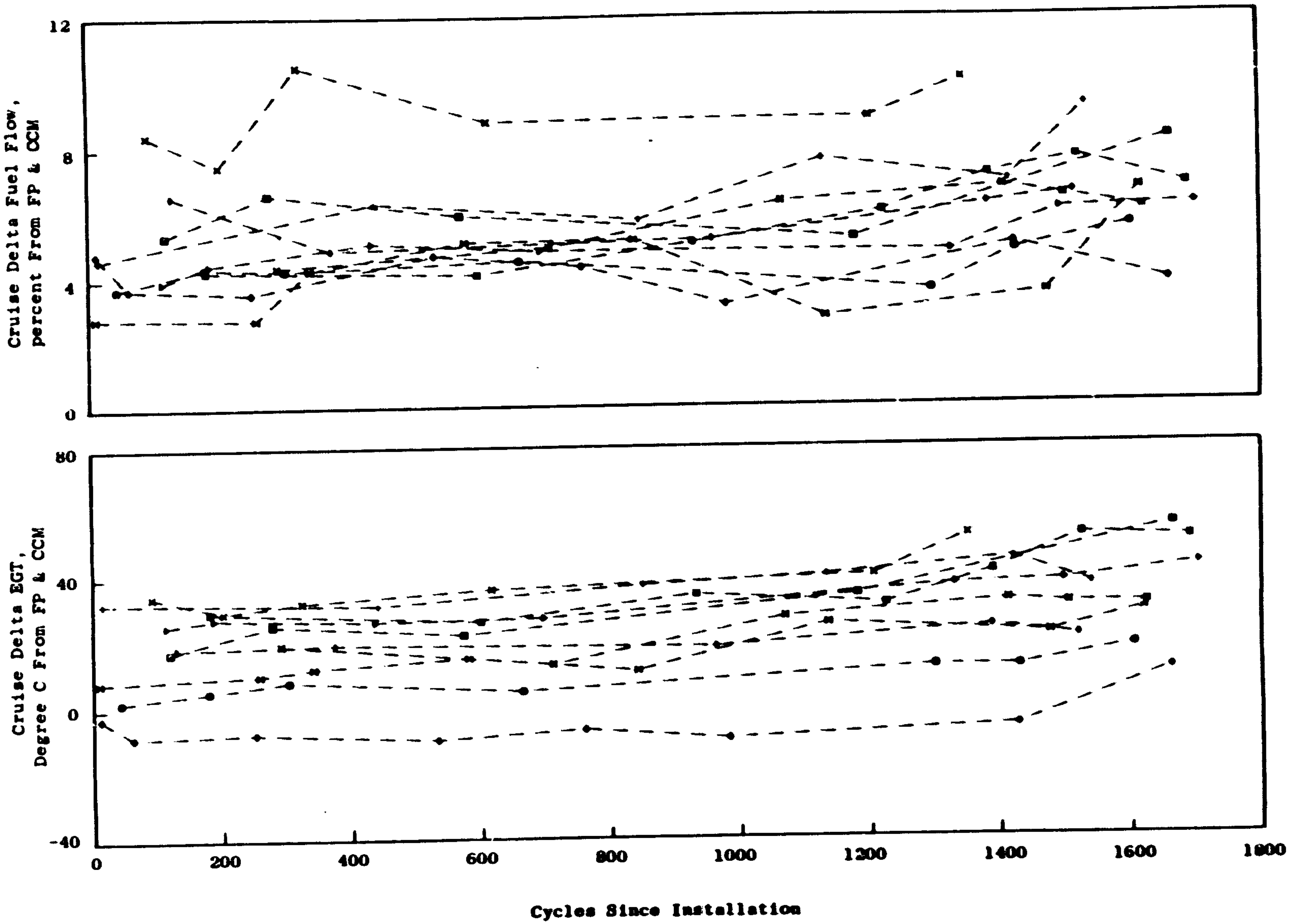


Figure B-13. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (4000 Hours).

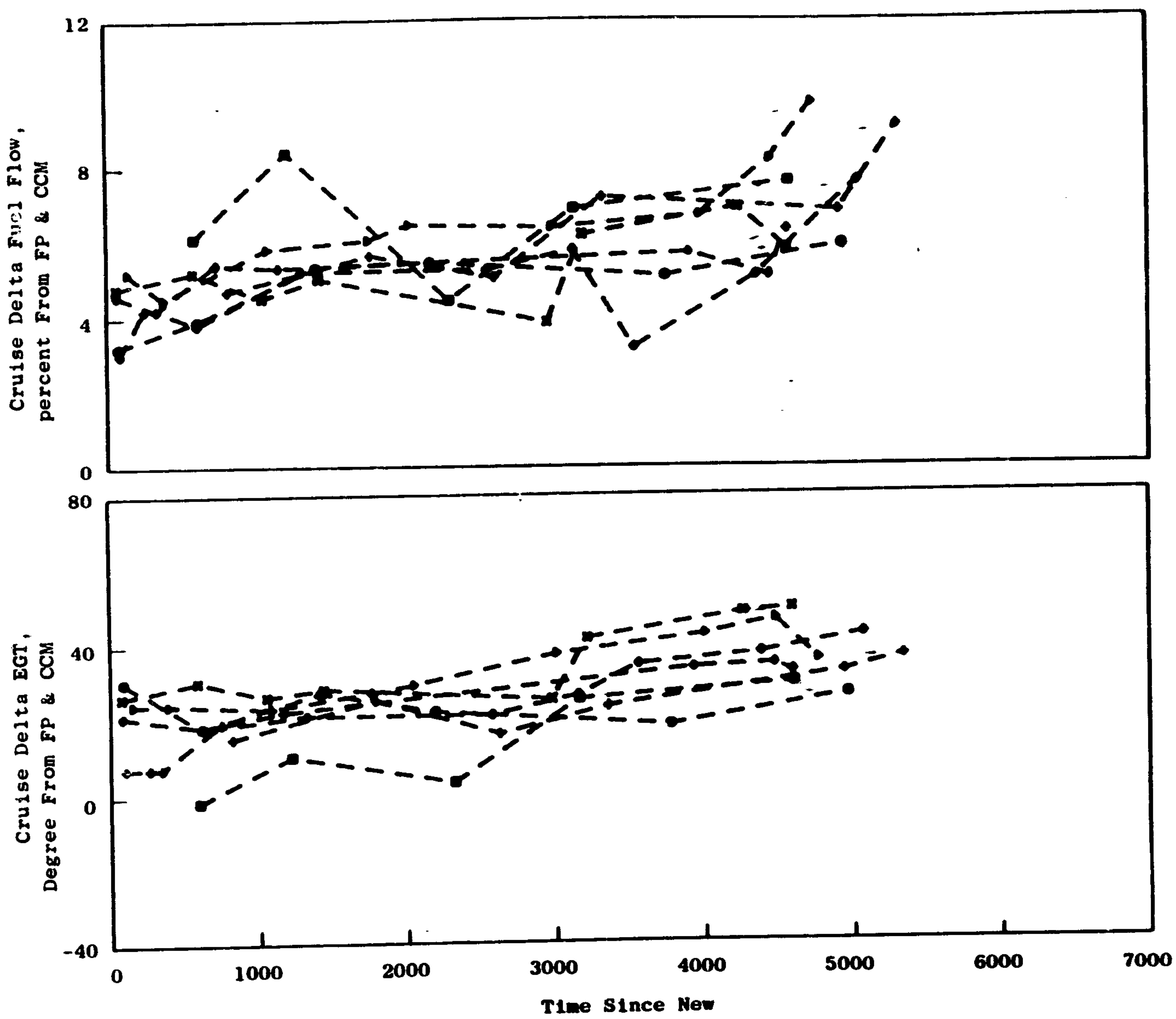


Figure B-14. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (4500 Hours).

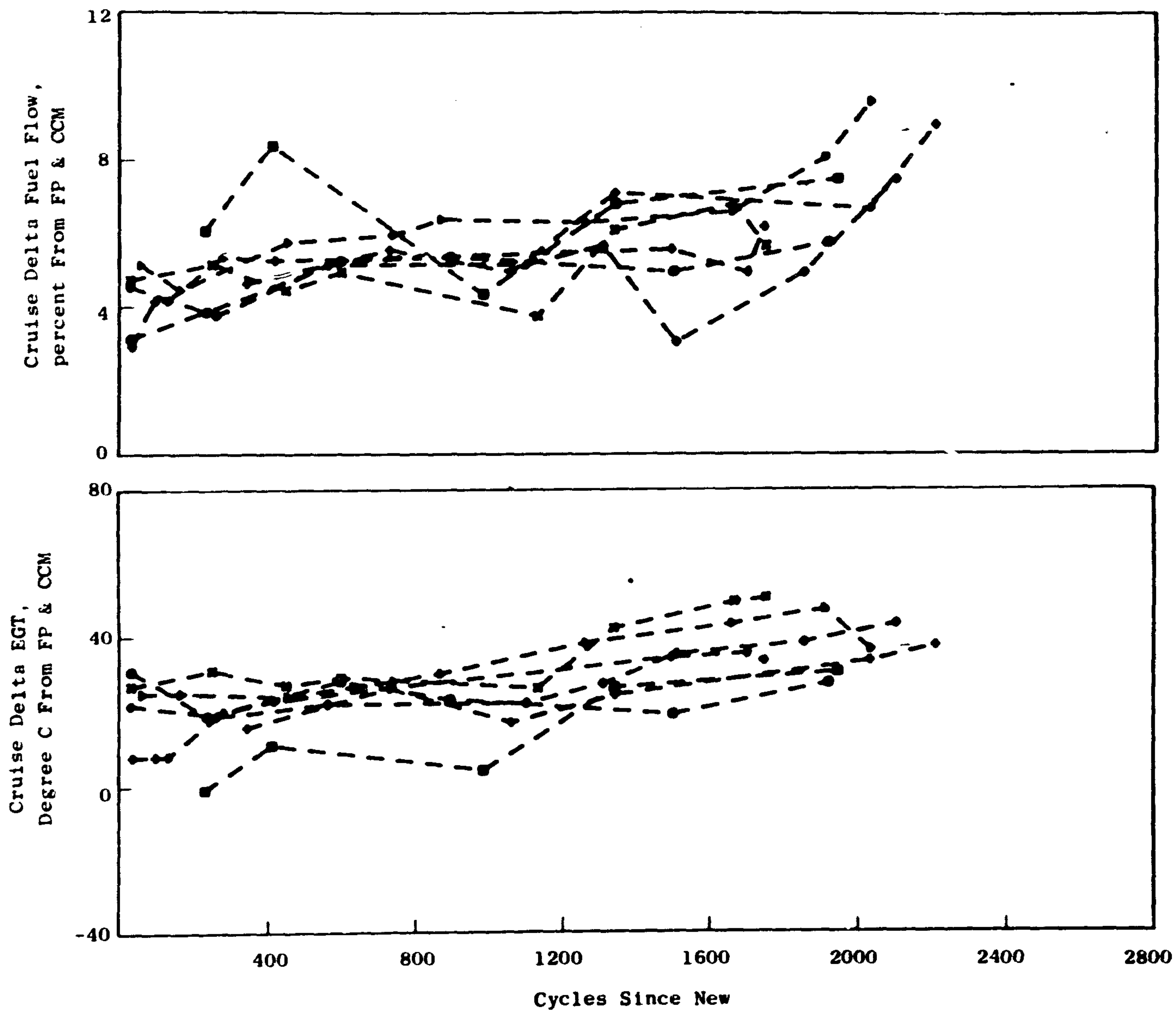


Figure B-15. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "A" (4500 Hours).

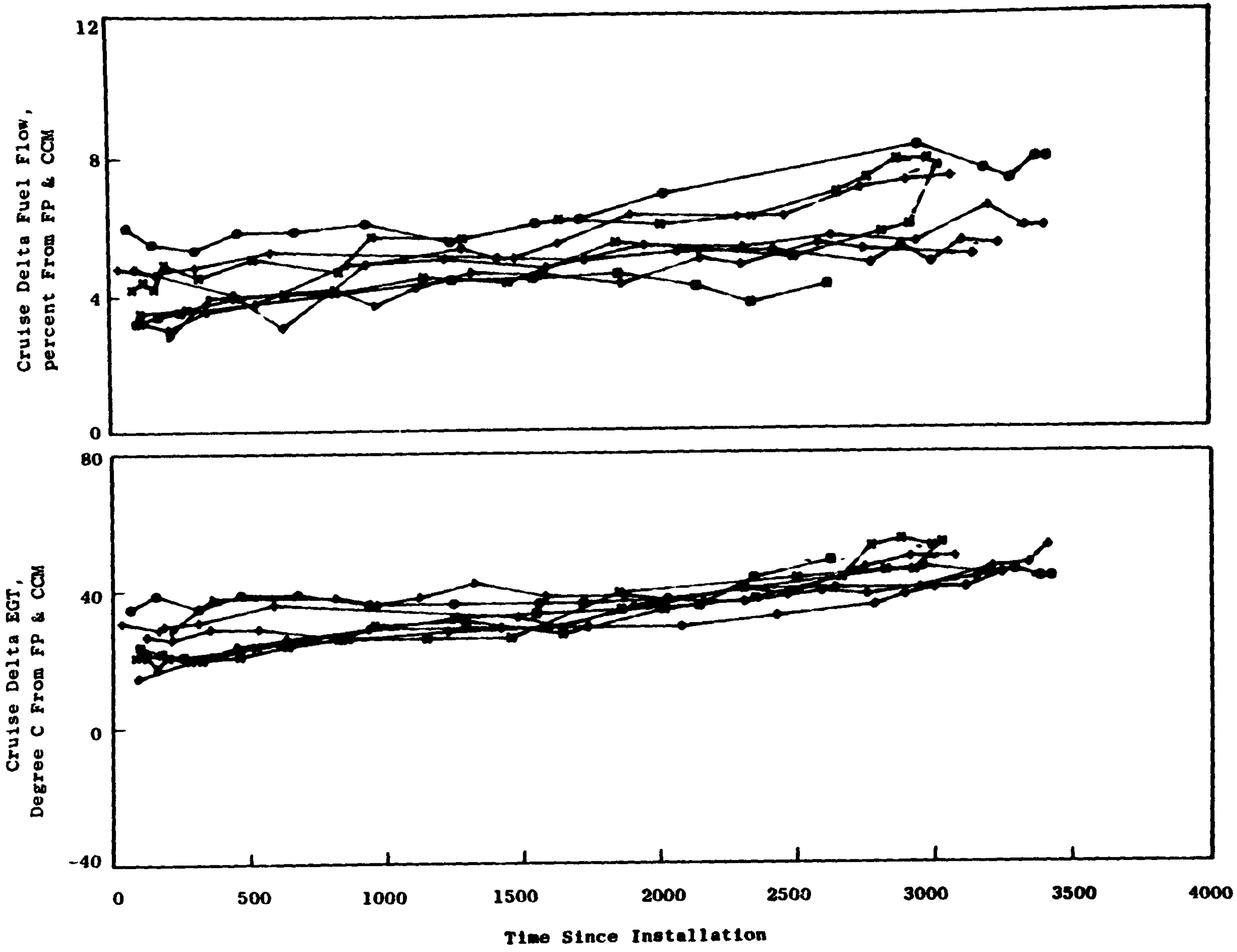


Figure B-16 CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B1" (3000 Hours).

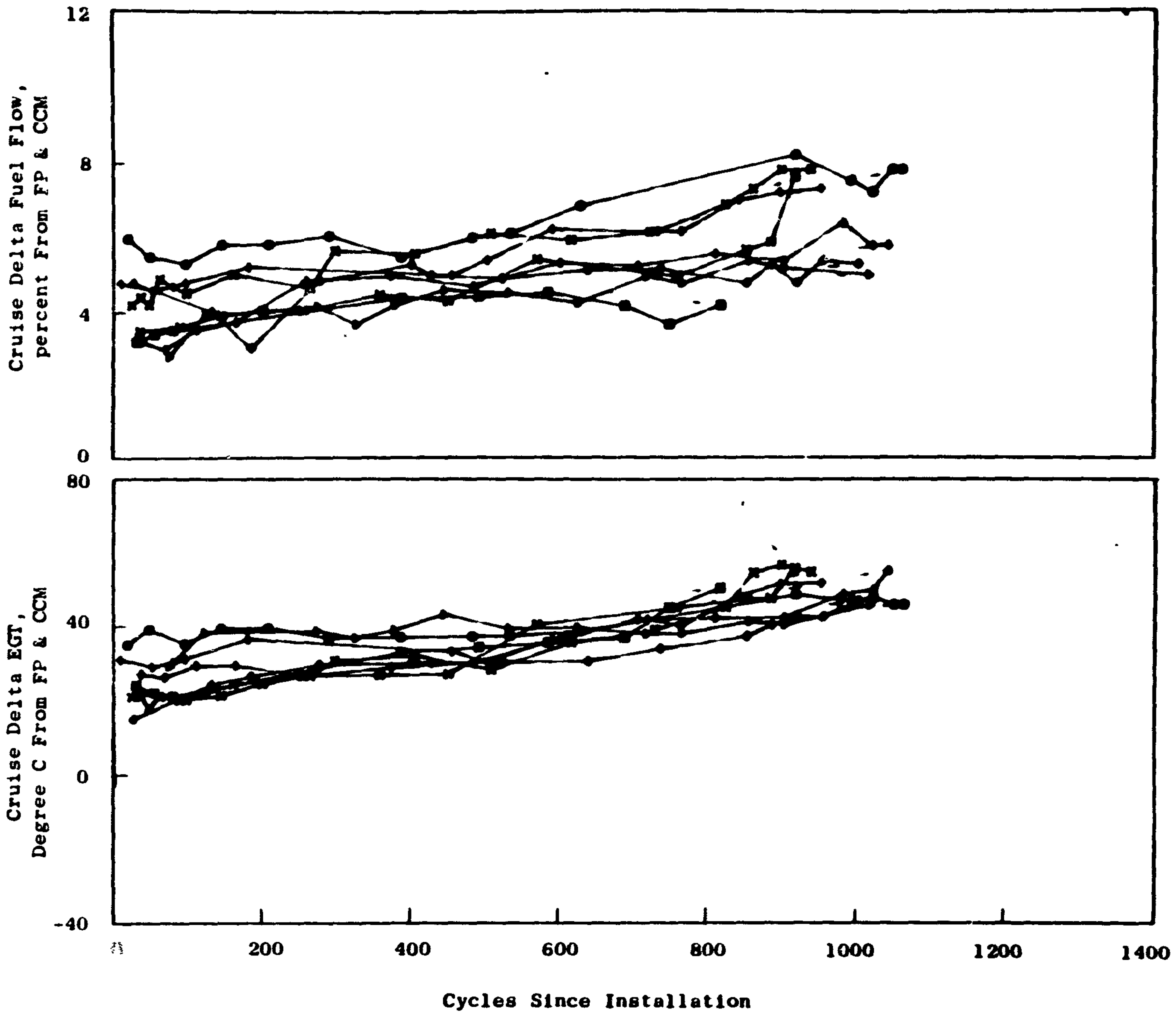


Figure B-17. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B1" (3000 Hours).

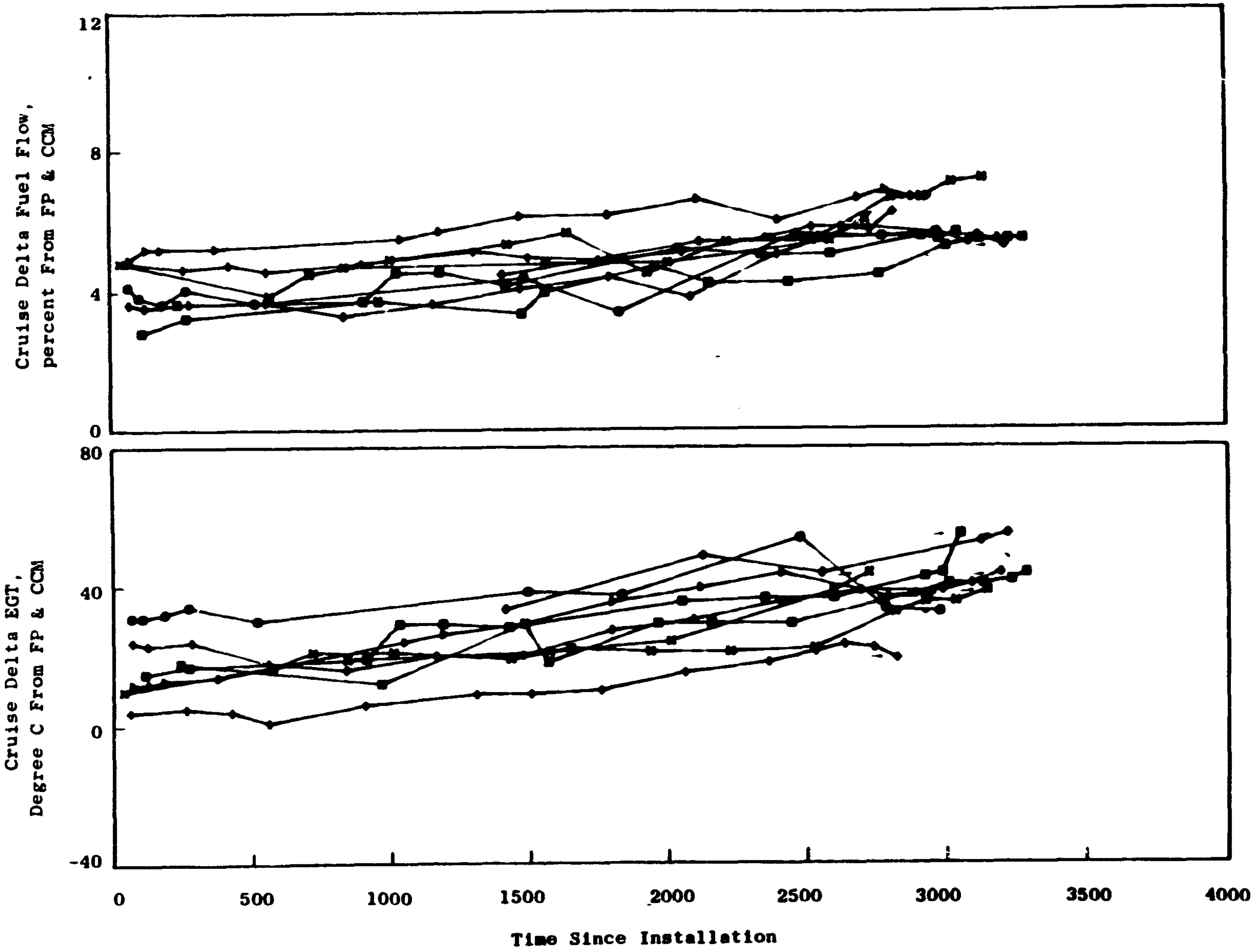


Figure B-18. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" (3000 Hours).

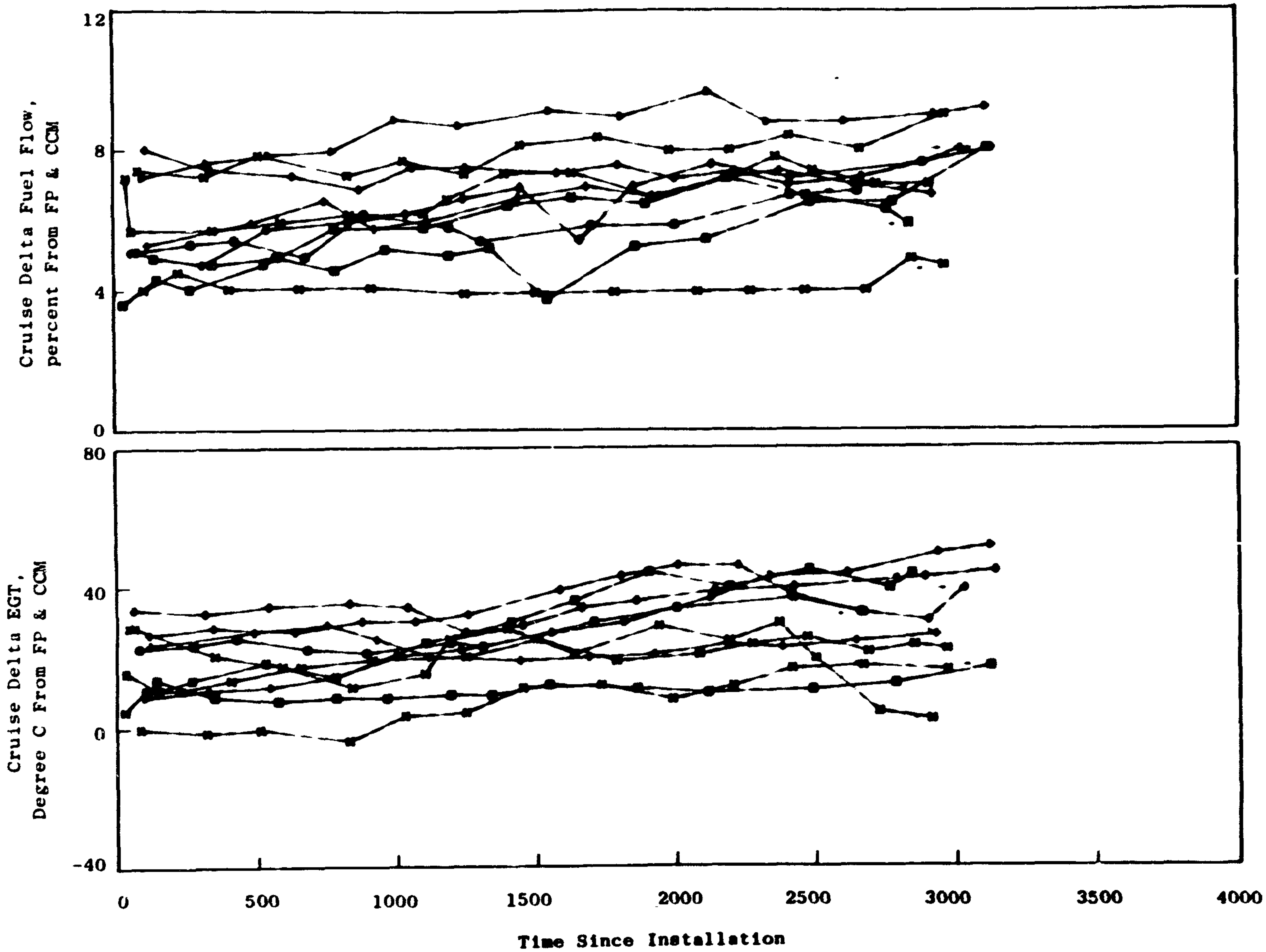


Figure B-19. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" (3000 Hours).

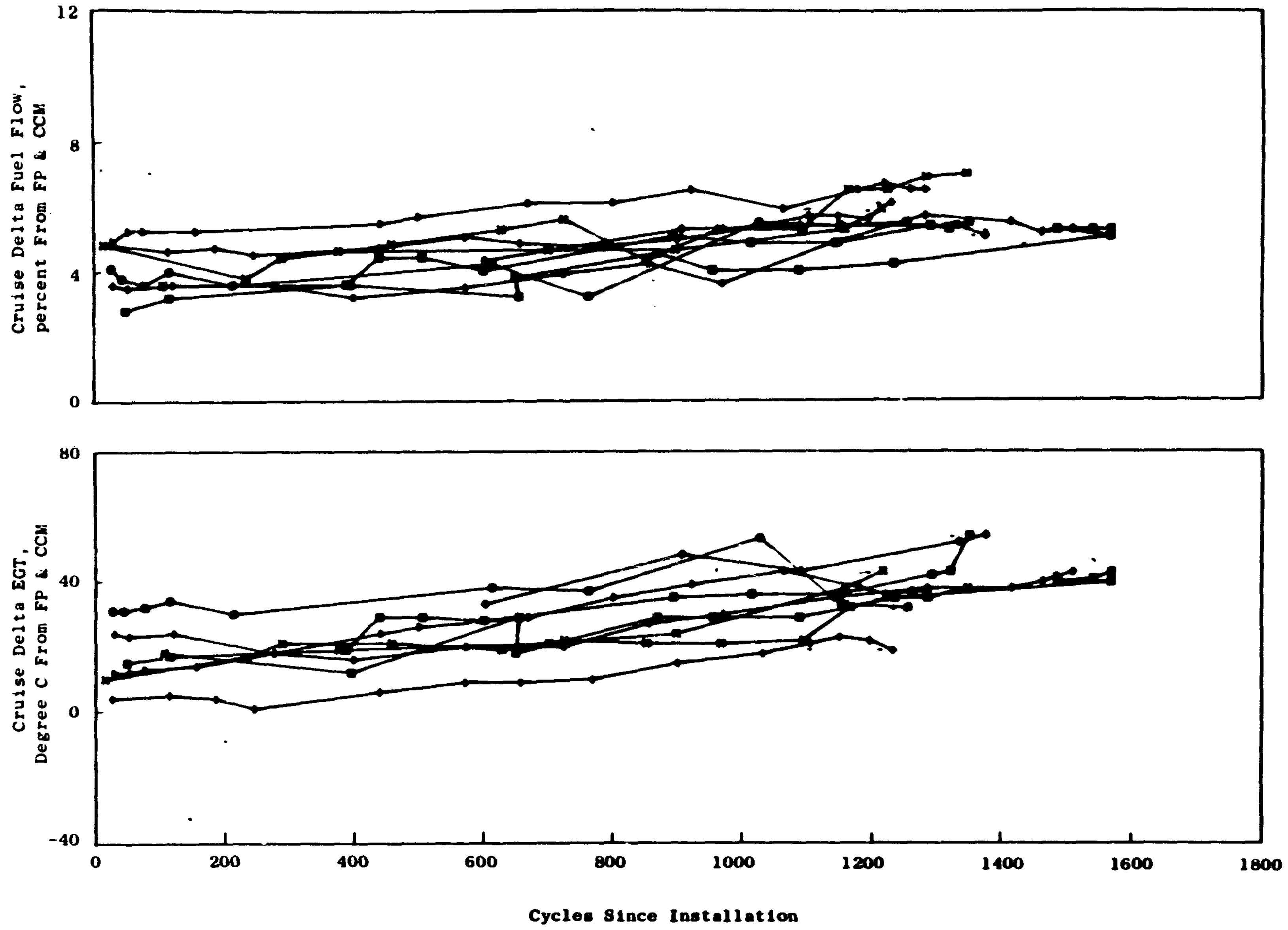


Figure B-20. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "C" (3000 Hours).

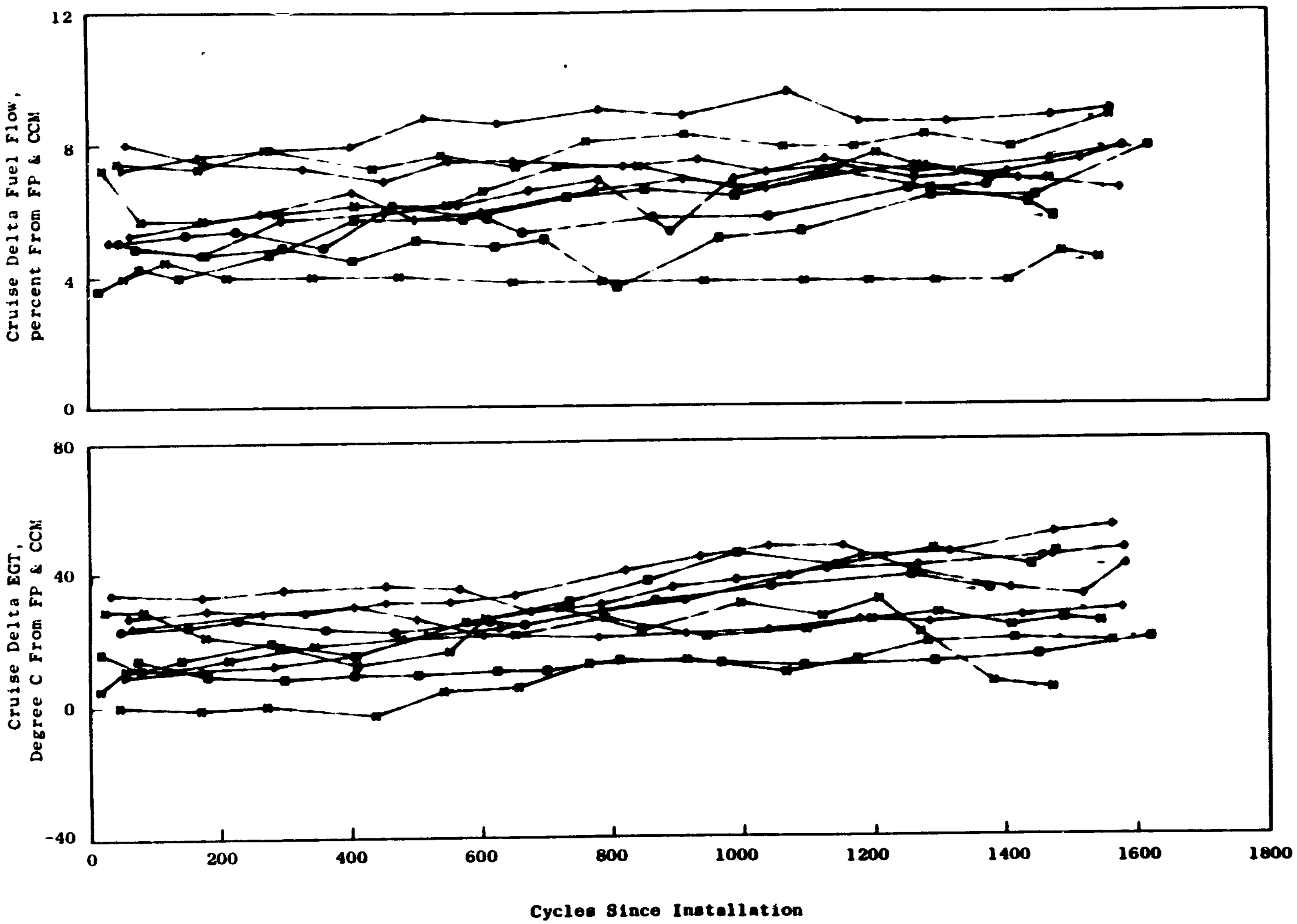


Figure B-21. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "C" (3000 Hours).

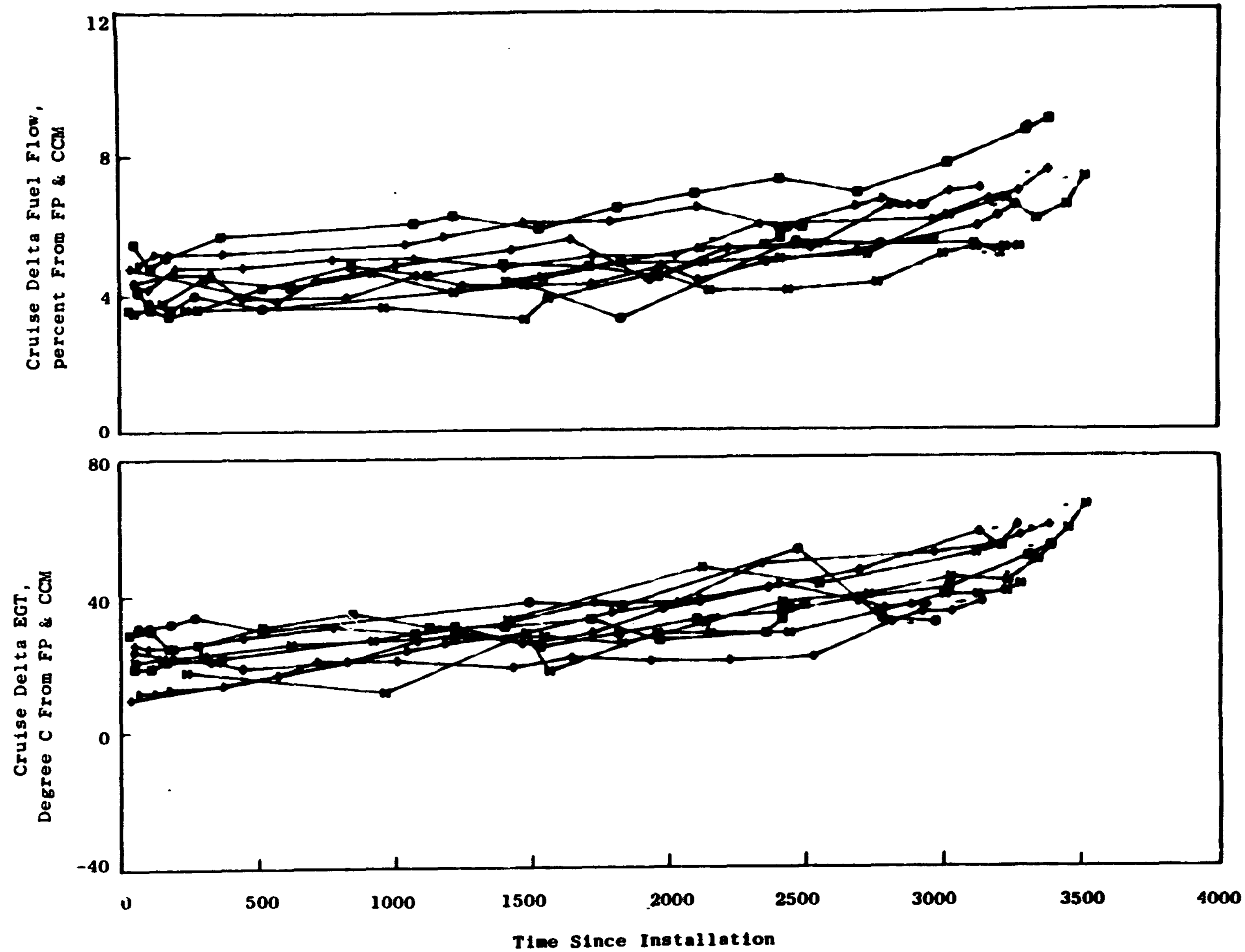


Figure B-22. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" Wing-Mounted Engines.

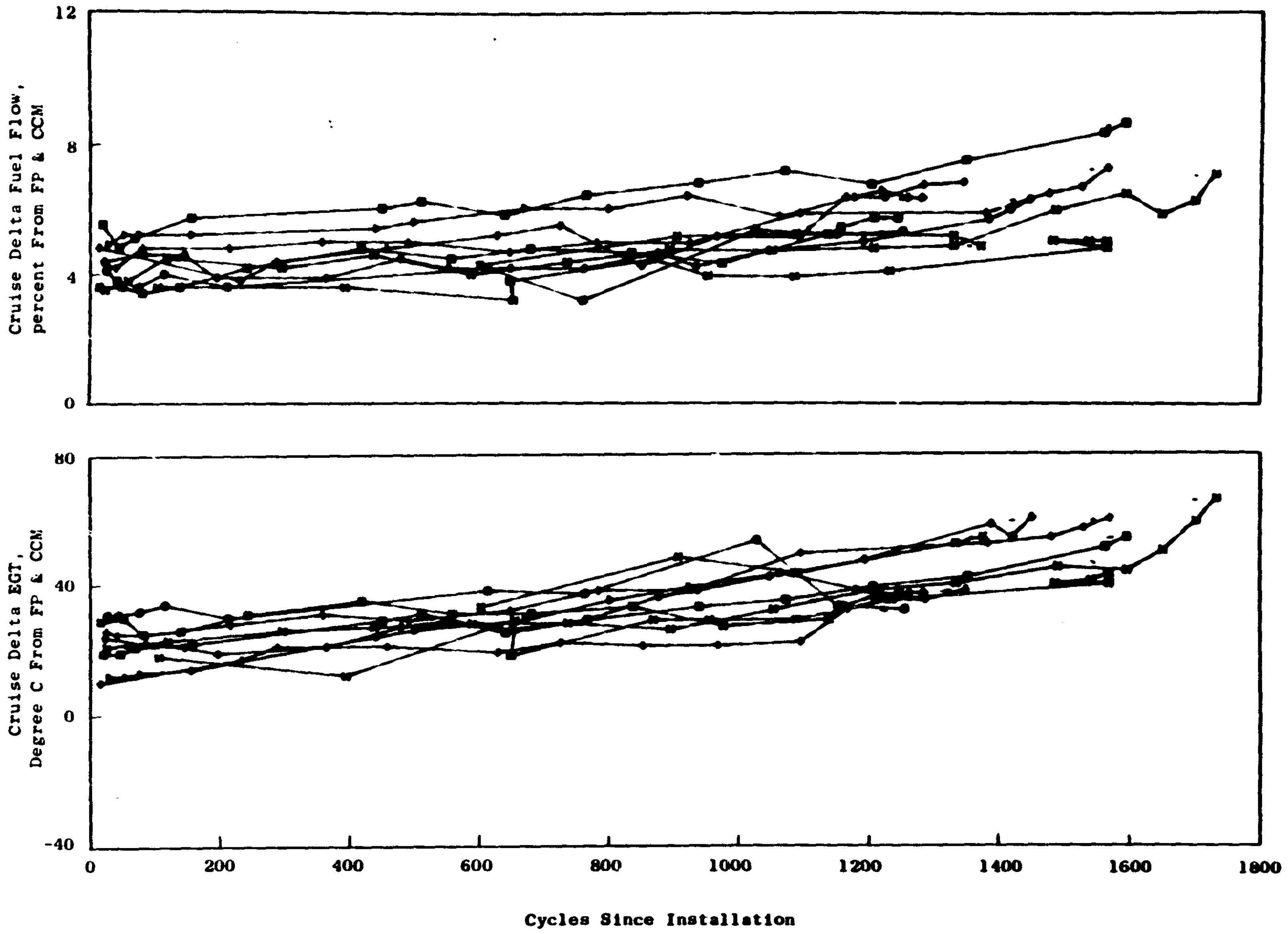


Figure B-23. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" Wing-Mounted Engines.

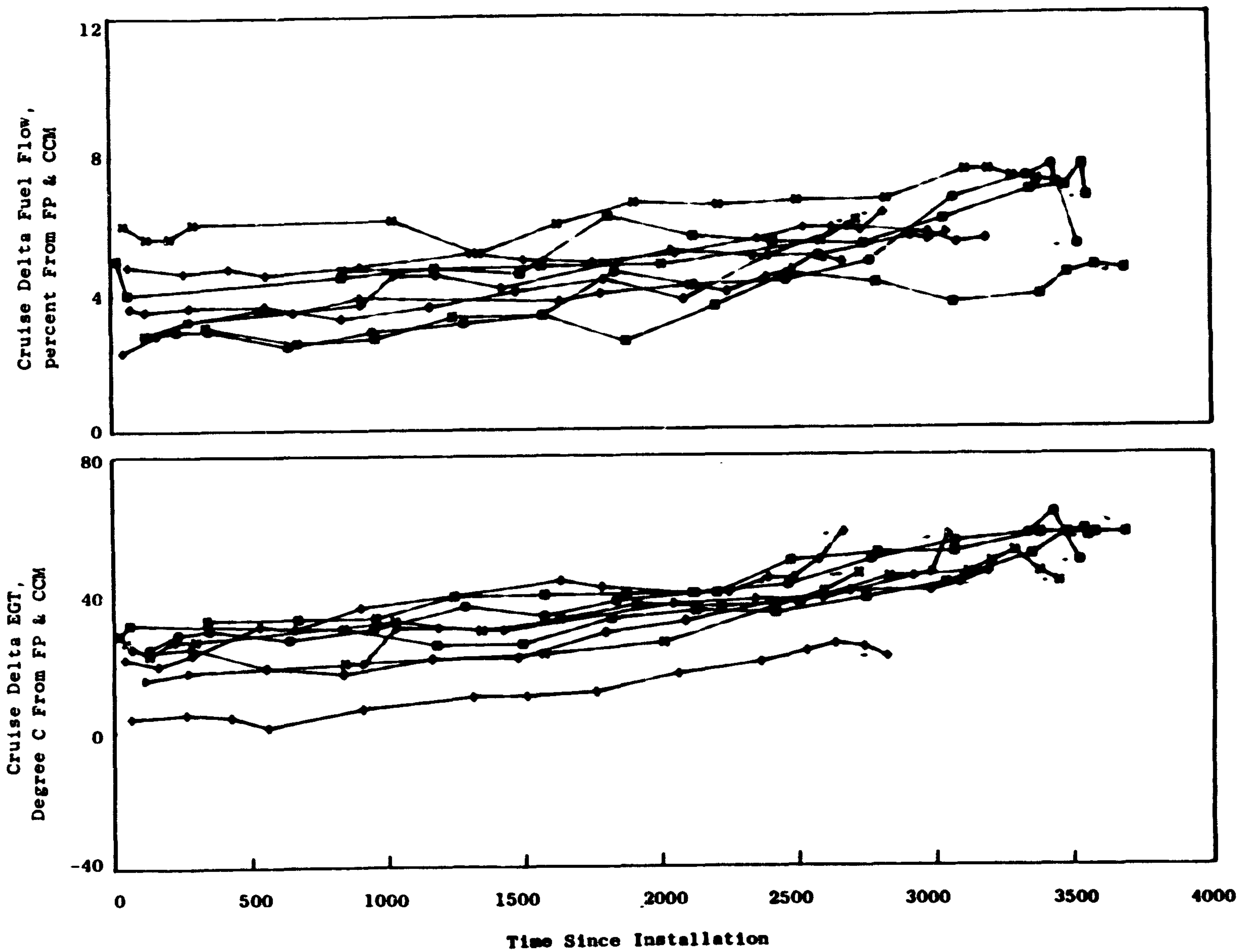


Figure B-24. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" Tail-Mounted Engines.

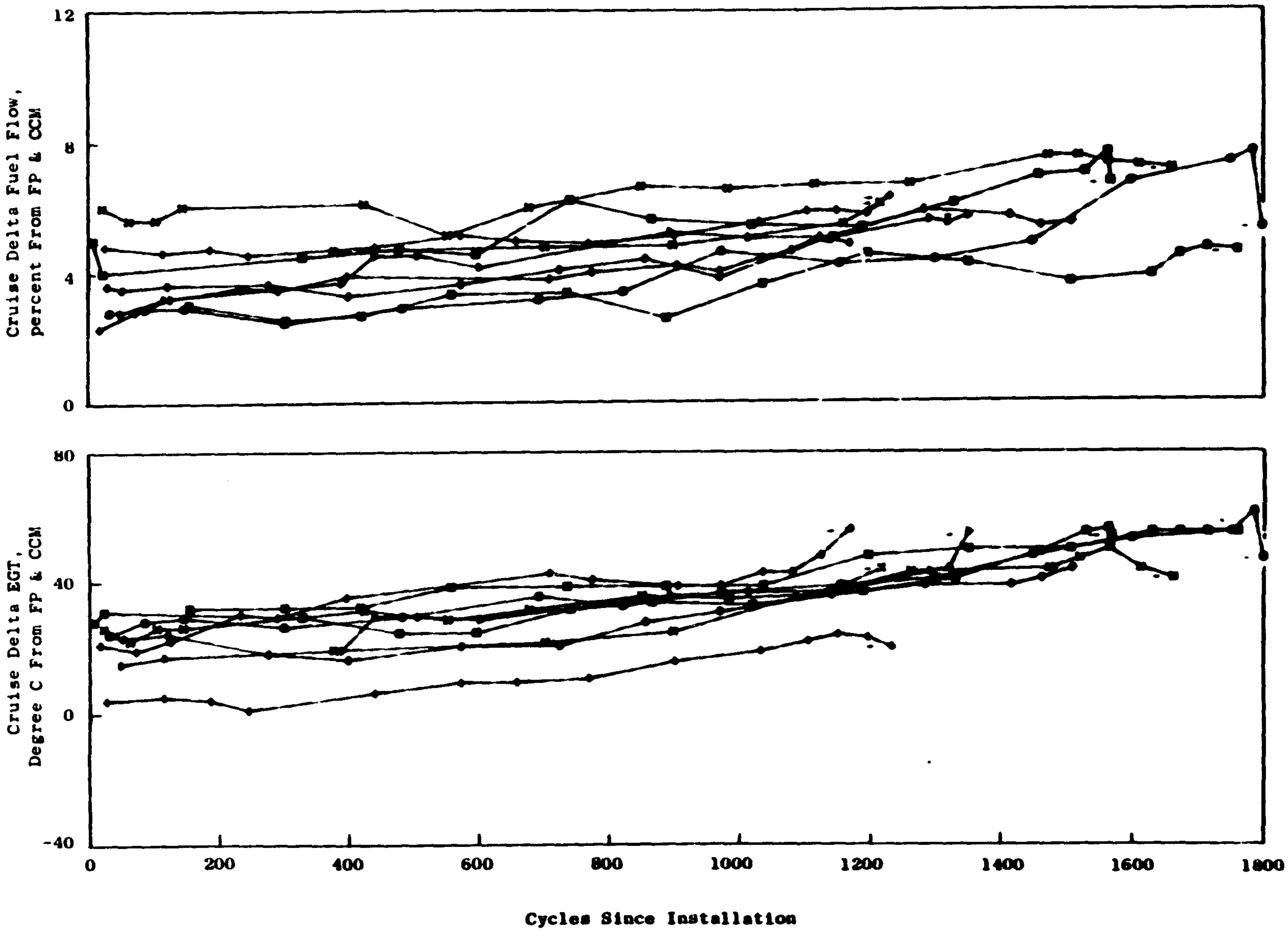


Figure B-25. CF6-6 Cruise Performance of Multiple-Build Installations, Airline "B2" Tail-Mounted Engines.

APPENDIX C

SYMBOLS AND ACRONYMS

A4	Stage One High Pressure Turbine Nozzle Area
A/C	Aircraft
ACEE	Aircraft Energy Efficiency Program
ALF	Aft Looking Forward
ASE	Airline Support Engineering
ASO	Aviation Service Operation
ASO/O	Aviation Service Operation/Ontario, California
Avg.	Average
B/P	Blueprint
BW	Blade Width
CCM	Cruise Control Manual
CDP	Compressor Discharge Pressure
CR	Cruise
CRF	Compressor Rear Frame
CSI	Cycles Since Installed
CSN	Cycles Since New
CSO	Cycles Since Overhaul
CW	Clockwise
DACo	Douglas Aircraft Company

SYMBOLS AND ACRONYMS (Continued)

DELT	Delta
DETAC	Delta High Pressure Compressor Efficiency
DETALP	Delta Low Pressure System Efficiency
DETALPS	Delta Low Pressure System Efficiency
DFN1	Delta Net Thrust at Constant Fan Speed
Dia.	Diameter
DPARA	Delta Parasitic
DPARAS	Delta Parasitics
E12, E13	Fan Blade Tip Clearance Locations
ECI	Engine Component Improvement Program
EGT	Exhaust Gas Temperature
EGTM	Exhaust Gas Temperature Margin
Eff.	Efficiency
EMU	Engine Maintenance Unit
EPR	Engine Pressure Ratio
EROM	Electronic Readout Machine
ESN	Engine Serial Number
ETAC	High Pressure Compressor Efficiency
ETALPS	Low Pressure System Efficiency
ETAT	High Pressure Turbine Efficiency
FBW	Full Blade Width

FIR	Full Indicated Runout
FLA	Forward Look Aft
Fn	Net Thrust
Fn @ N1	Net Thrust at Constant Fan Speed
F/N	Fuselage Number
FOD	Foreign Object Damage
FP & CCM	Flight Planning and Cruise Control Manual
FPI	Fluorescent Penetrant Inspection
FWD	Forward
GE	General Electric Company
HD EGT	Hot Day EGT
HP	High Pressure
HPC	High Pressure Compressor
HPCR	High Pressure Compressor Rotor
HPCS	High Pressure Compressor Stator
HPS	High Pressure System (Core Engine)
HPT	High Pressure Turbine
HPTN	High Pressure Turbine Nozzle
HPTR	High Pressure Turbine Rotor
Hrs.	Hours

<u>SYMBOLS AND ACRONYMS</u> (Continued)

ID	Inside Diameter
IGB	Inlet Gearbox
IGV	Inlet Guide Vane
In.	Inch
I/S	Interstage
Dim "K"	Dimension "K", High Pressure Turbine Nozzle Support - Reference Shop Manual, 72-52-00
LE	Leading Edge
LP	Low Pressure
LPS	Low Pressure System (Fan and LPT)
LPT	Low Pressure Turbine
LPTN	Low Pressure Turbine Nozzle
LPTR	Low Pressure Turbine Rotor
Max.	Maximum
M/C	Maximum Continuous
Min.	Minimum
MM	Maintenance Manual
MRL	Maximum Repairable Limit
MXCR	Maximum Cruise
N1	Fan Speed
N2	Core Speed
N/A	Not Applicable

NASA-Lewis	National Aeronautics and Space Administration Lewis Research Center
No.	Number
No. 4B	Number Four Ball Bearing
Noz.	Nozzle
OD	Outer Diameter
OGV	Outlet Guide Vane
P3	Compressor Discharge Pressure
P49	Low Pressure Turbine Inlet Pressure
QEC	Quick Engine Connect
R2	Coefficient of Determination
Rad.	Radius
Ref.	Reference
RMS	Root Mean Square
RPM	Revolutions Per Minute
RTV	A Room Temperature Vulcanizing Compound
SB	Service Bulletin
SEE	Standard Error or Estimate
Serve Limit	Serviceable Limit
sfc	Specific Fuel Consumption
SI	International System of Units
SLS	Sea Level Static
S/M	Shop Manual

S/N	Serial Number
Stg.	Stage
SWECO	Vibratory Mill Cleaning Process
T3	Compressor Discharge Total Temperature
T5X	Calculated Exhaust Gas Temperature
T/C	Thermocouple
TE	Trailing Edge
TMF	Turbine Midframe
T/O	Takeoff
TSI	Time Since Installed
TSN	Time Since New
TSO	Time Since Overhaul
UAL	United Air Lines
VTL	Vertical Turret Lathe
WAL	Western Airlines
WC16	Sixteenth Stage Cooling Airflow
WFM	Fuel Flow
WK	Corrected Airflow
Δ	Delta
η	Efficiency (Eta)
η_c	High Pressure Compressor Efficiency
η_f	Fan Efficiency
η_t	High Pressure Turbine Efficiency

SYMBOLS AND ACRONYMS (Concluded)

$\eta 2t$	Low Pressure Turbine Efficiency
σ	Standard Deviation
μin./in. AA	Microinch Per Inch - Arithmetical Average

APPENDIX D

TERMINOLOGY

Analytical Teardown

The disassembly of an engine specifically to provide hardware inspection data to determine the sources and mechanisms for performance deterioration.

Coefficient of Determination (R^2)

A statistical term for the numerical measure of the proportion of variation accounted for by the multiple linear regression fit where a value of "1" indicates a perfect fit while a value of "0" indicates lack of fit.

Deteriorated Engine (or Module)

An engine (or module) as removed from wing for induction into the shop, prior to any repairs.

Deterioration Model

Two models are utilized in this report. The "Performance Deterioration Model" is based on performance data and describes the magnitude and rate at which deterioration occurs with time. The "Hardware Deterioration Model" assigns the performance deterioration to the individual parts and damage mechanisms, and is based on hardware inspection data and influence coefficients.

Engine Derivatives

Computer cycle model factors which equate changes in component efficiencies, flows, and areas to changes in engine cycle parameters.

Fuel Burn

Fuel consumed (sfc at constant thrust) during the cruise portion of a revenue flight.

Influence Coefficients

Empirically or analytically derived factors which equate a change in hardware condition to a change in performance.

Initial Installation

The portion of long-term deterioration which occurs during the revenue service operation of a production new engine prior to the first shop visit.

Long-Term Deterioration

This broad category defines all performance losses which occur during revenue service operation for the life of the engine.

Modular Maintenance

The maintenance concept that concentrates on repairing modules as opposed to the engine as a whole. This concept is utilized as part of the on-condition maintenance concept to achieve optimum repair costs.

Multiple Build Installation

The revenue service operation of an engine following the first shop visit. This category includes all long-term deterioration except that which occurs during the initial installation.

Parasitics

The internal leakage of gas flow that bypasses a stage or stages of airfoils. An example of a parasitic leakage is any excess (beyond design) turbine mid frame liner purge air which bypasses the high pressure turbine.

Refurbished Engine (or Module)

This designation as used in this report implies that performance losses were restored in addition to the minimum mechanical repair required to satisfy the serviceable classification. In airline service, the term "refurbished engine" applies to any engine subjected to maintenance repair after removal from the aircraft. In actual practice, very little performance restoration, beyond tha accomplished for mechanical reasons, is performed.

Serviceable Engine (or Module)

An engine that meets the minimum inspection requirements for the particular maintenance concept being utilized so that it is eligible for additional revenue service. The engine (or module) may or may not be completely refurbished.

Shop Visit

When the engine is inducted into the maintenance shop for repair after removal from the aircraft.

Short-Term Deterioration

Performance losses which occur at the aircraft manufacturer during airplane acceptance test flights prior to initiation of revenue service.

Standard Deviation (σ)

The root-mean-square of deviations from a mean, used as the measure of the spread of a sample or population.

Standard Error of Estimate (SEE)

The root-mean-square of deviations about a fitted curve, used as the measure of the spread of a sample or population about that fitted curve.

Unrestored Performance

The difference between the production new performance levels and those for a revenue service engine after a shop visit.

APPENDIX E

SPECIAL ANALYSIS - 6000-HOUR DETERIORATION MODELS

The data presented in the main text of this report is considered to be representative of performance deterioration for an average fleet of CF6-6D engines. In actuality, the data encompasses a myriad of conditions, operational procedures, maintenance practices and other differences which makes it difficult to project a "typical" engine's deterioration.

As pointed out earlier, the design for the CF6 engine is based on a modular concept, and the airlines employ an "on condition" inspection/modular maintenance procedure. After about 4000 hours of service, the average new engine is typically removed for hot section repair. Generally, the modules are separated, repaired if required, and then dispersed to inventory for a subsequent engine build-up. This same procedure is duplicated in subsequent engine removals, and as a result, each serviceable engine becomes a mixture of modules with various stages of deterioration, all within established inspection criteria. Models depicting engine deterioration have been presented for the initial installation (typically 4000 hours) and for multiple builds which could be up to 12,000 hours. The "multiple-build" model is representative of all engines coming in for repair - regardless of how many previous repairs and assemblies have occurred. These "multiple-build" engines result in a mixture of modules having various degrees of deterioration.

From a designer's viewpoint, it becomes important to be able to estimate the deterioration characteristics beyond the normal 4000 hours nominal time to removal for both an engine without repair and one with minimum repair. Accordingly, two performance deterioration models have been established and are designated "6000 Hours Without Repair" and "6000 Hours With Hot Section Repair". To further assist the designer, these models include deterioration by damage mechanisms as well as a modular breakdown for performance deterioration. These models are disucssed in the following paragraphs.

6000 HOURS - WITHOUT-REPAIR MODEL

The hypothetical models to be discussed will consider only performance deterioration that can be related to operational aspects - either from flight acceptance testing or actual revenue service. This differs from the Hardware Inspection Model presented in Section 4.3 which also includes causes of performance deterioration that result from maintenance-related actions. Specifically, some of these maintenance actions are (1) HPC blade and vane tip clearance changes due to rework to achieve minimum clearance, (2) removal of fan quarter-stage material (without replacement of honeycomb), and (3) fan blade-to-shroud clearance increases due to localized rework. (These are discussed in detail in Section 4.2.)

When assuming HPT losses beyond 4000 hours, it was estimated that additional blade tip-to-shroud rubs would not occur and that deterioration would be limited to erosion of the shroud and degradation of the airfoil surface finish. While this is a reasonable extrapolation of the data, the actual deterioration would most likely be higher due to mechanical deterioration of the components. It is impractical to estimate the durability effect, since experience has shown a wide variance in mechanical life for each specific part. Deterioration beyond 4000 hours for the other engine modules was developed in accordance with the deterioration curves presented in Section 4.2.

Figure E-1 presents the performance deterioration model that was generated for the CF6-6D engine after 6000 hours of operation assuming that no repairs would have been required. For comparative purposes, the deterioration models for the first flight (short-term) and after 4000 hours (initial installation) are also presented. These latter two models were constructed according to data already presented in Sections 3.2 and 4.2. The figure presents composite models, and includes the modular distribution of fuel burn deterioration as well as the damage mechanisms. These two items are presented separately in Figures E-2 and E-3 for clarity.

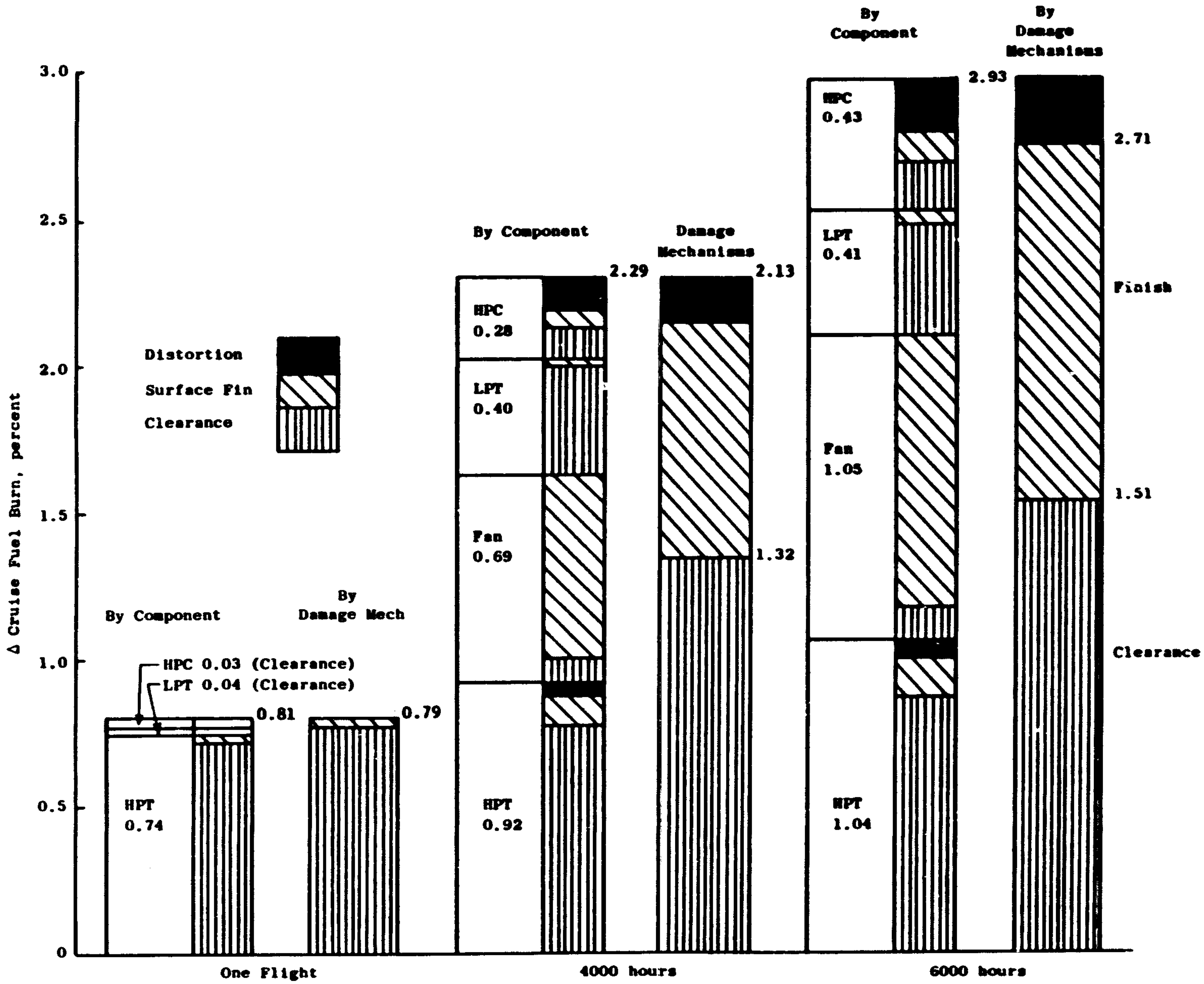


Figure E-1. No-Repair Models (Composite).

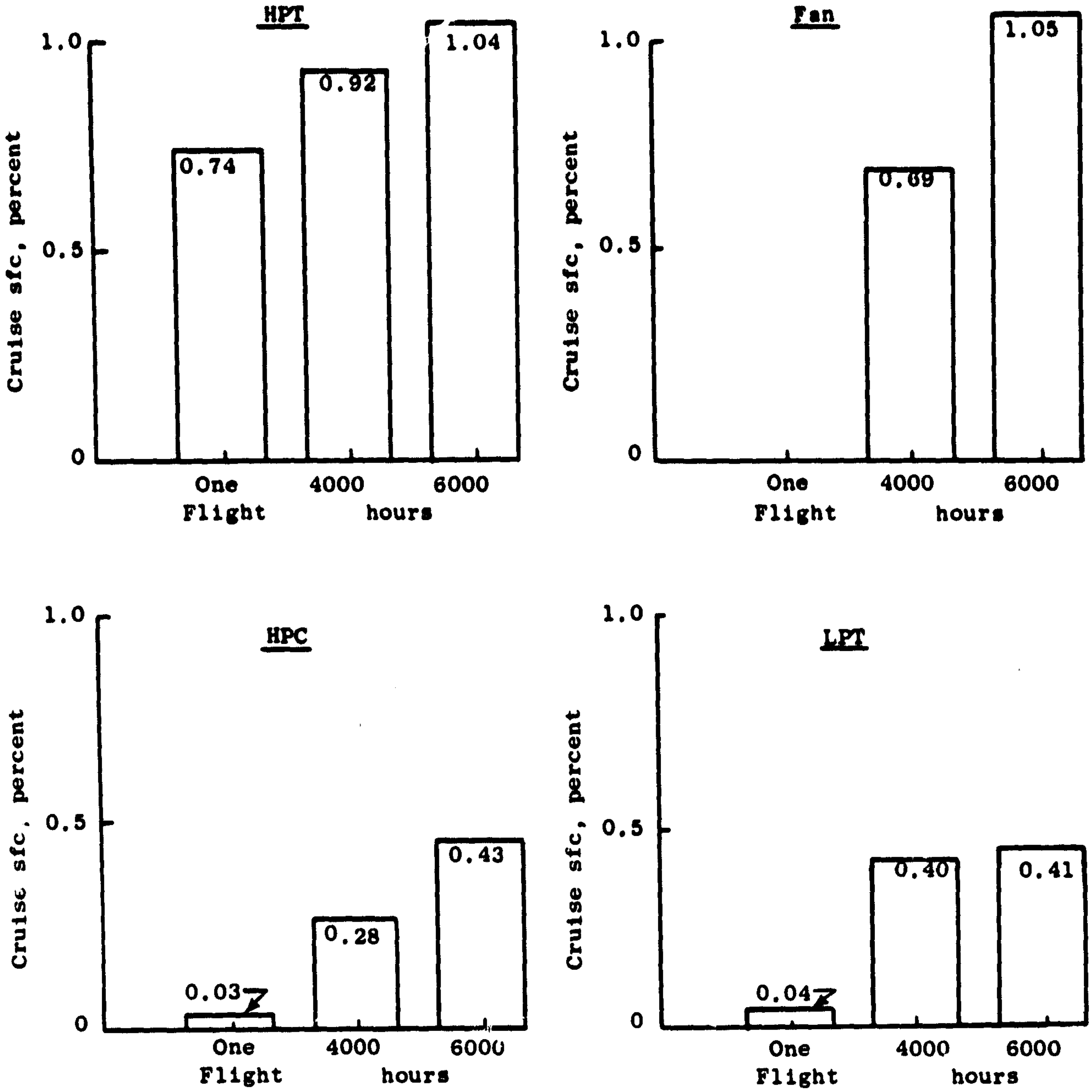


Figure E-2. No-Repair Models - By Component.

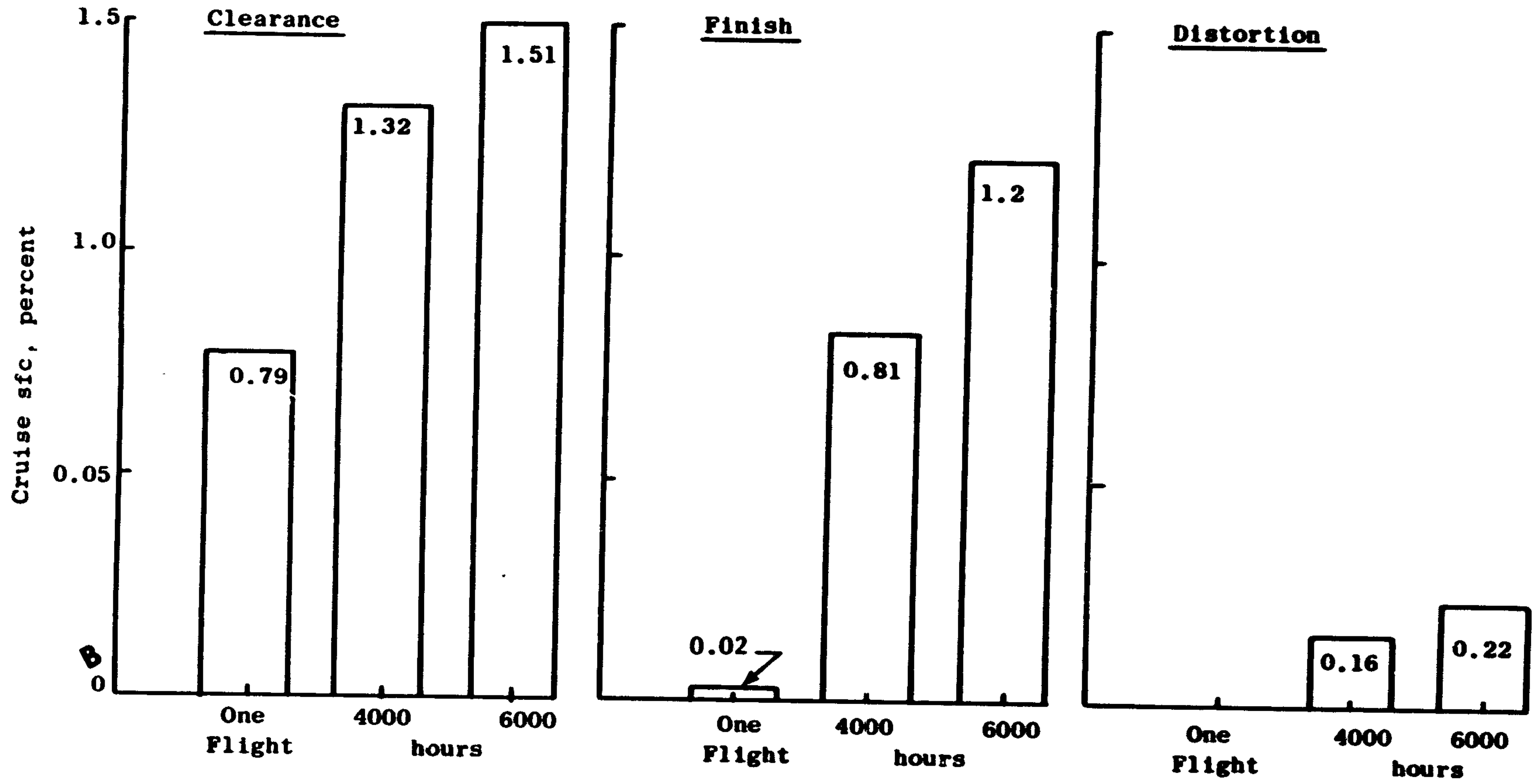


Figure E-3. No-Repair Models - By Damage Mechanisms.

As presented, the additional performance deterioration estimated for the period between 4000 and 6000 hours is 0.64 percent cruise fuel burn. This does not include the probable effects from losses associated with loss of mechanical integrity. The data presented in Figures E-2 and E-3 do confirm previous assessments as follows. The clearance effects (Figure E-3) generally occur during the initial 4000 hours, but the surface finish effects continue at about the same rate through 6000 hours. The data presented in Figure E-2 show the additional losses in both turbines to be small beyond 4000 hours, while the fan and HP compressor losses continue at the same rate through 6000 hours. This is as expected since clearance changes dominate the turbine distress, while erosion and loss of airfoil surface finish are the major deterioration modes for the fan and HP compressor modules.

Performance records were available for one specific engine which received an inbound test cell calibration as part of another General Electric program. This was ESN 451412 (listed in Table 4-II of this report) which had deteriorated 3.5 percent in cruise fuel burn during 7100 hours of revenue service operation. This compares favorably with the 2.93 percent in cruise fuel burn estimated for the 6000 hour engine. The slightly higher deterioration for ESN 451412 can be attributed to the additional flight hours or to losses in mechanical capability. While one engine cannot be considered an adequate data sample, it does add confidence that the estimates and assumption used to create the 6000 hour model are reasonable.

6000 HOURS - WITH-REPAIR MODEL

Hardware inspection results indicated that the primary reason for engine removals prior to 6000 hours was due to high pressure turbine distress. The major assumptions for this model were that the production new engine would be removed after 4000 hours, and after repair of only the HP turbine, all modules would be reassembled into the same engine. This model also requires estimations or interpolation of the available data. The data presented in Section 4.2 were used to document the deterioration characteristics for the fan, HP compressor and LP turbine modules through 6000 hours. The deterioration level of the HP turbine after 4000 hours of operation, and its after-refurbishment condition are also presented in Section 4.2. The refurbished HP turbine module was used to establish the new on-wing baseline for the engine after 4000 hours, i.e., deteriorated fan, HP compressor and LP turbine modules with refurbished HP turbine module. The on-wing deterioration for the HP turbine module from 4000 to 6000 hours was estimated using the performance data presented in Section 4.1 for a multiple-build engine.

The "6000 Hours With-Repair Model" is shown in Figure E-4 and the assessment by module and damage mechanism is shown separately in Figures E-5 and E-6. These figures also include the deterioration levels without repair after one flight and after 4000 hours for comparison. Note that the total loss at 6000 hours (with repairs after 4000 hours) is very nearly the same as the total loss after 4000 hours prior to repairs. This agrees with an observation noted for the multiple build engines (reference Section 4.1) in that the on-wing loss after shop repairs is the same as that refurbished during the previous shop visit. Since the HPT module is the major source for the on-wing deterioration of a multiple-build engine, and the HPT module was the only modules repaired in this theoretical 6000 hour model, this agreement is not surprising.

The data presented in Figures E-5 and E-6 show similar results to that presented in Figure E-2 and E-3 for the "6000 Hour-Without-Repair Model". The losses attributed to the turbine modules agree with its dominant damage mechanism, i.e., increase clearances. Similarly, the surface finish changes correlate with the deterioration trends for the fan and high pressure compressor.

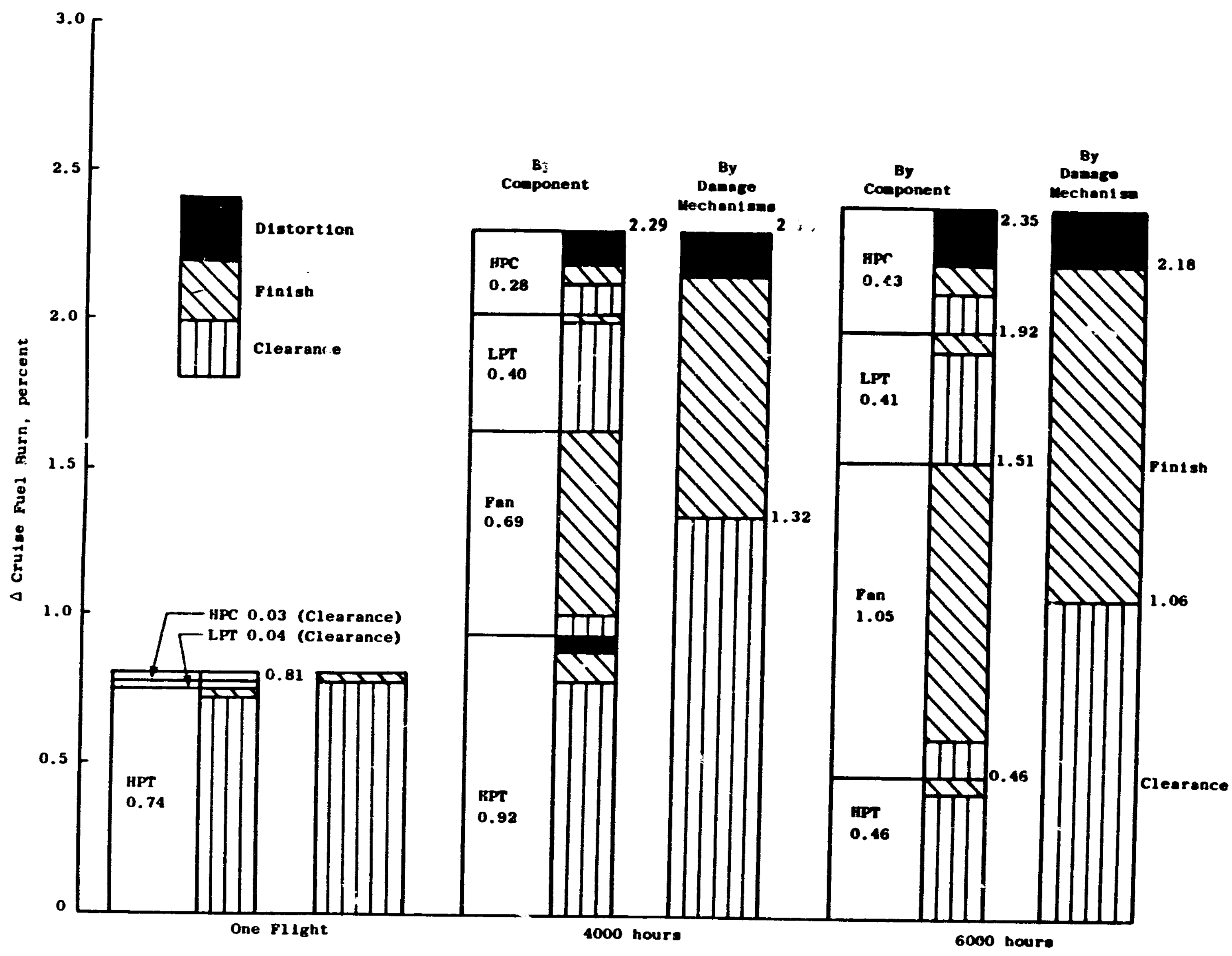


Figure E-4. 6000 Hours With-Repair Model (Composite).

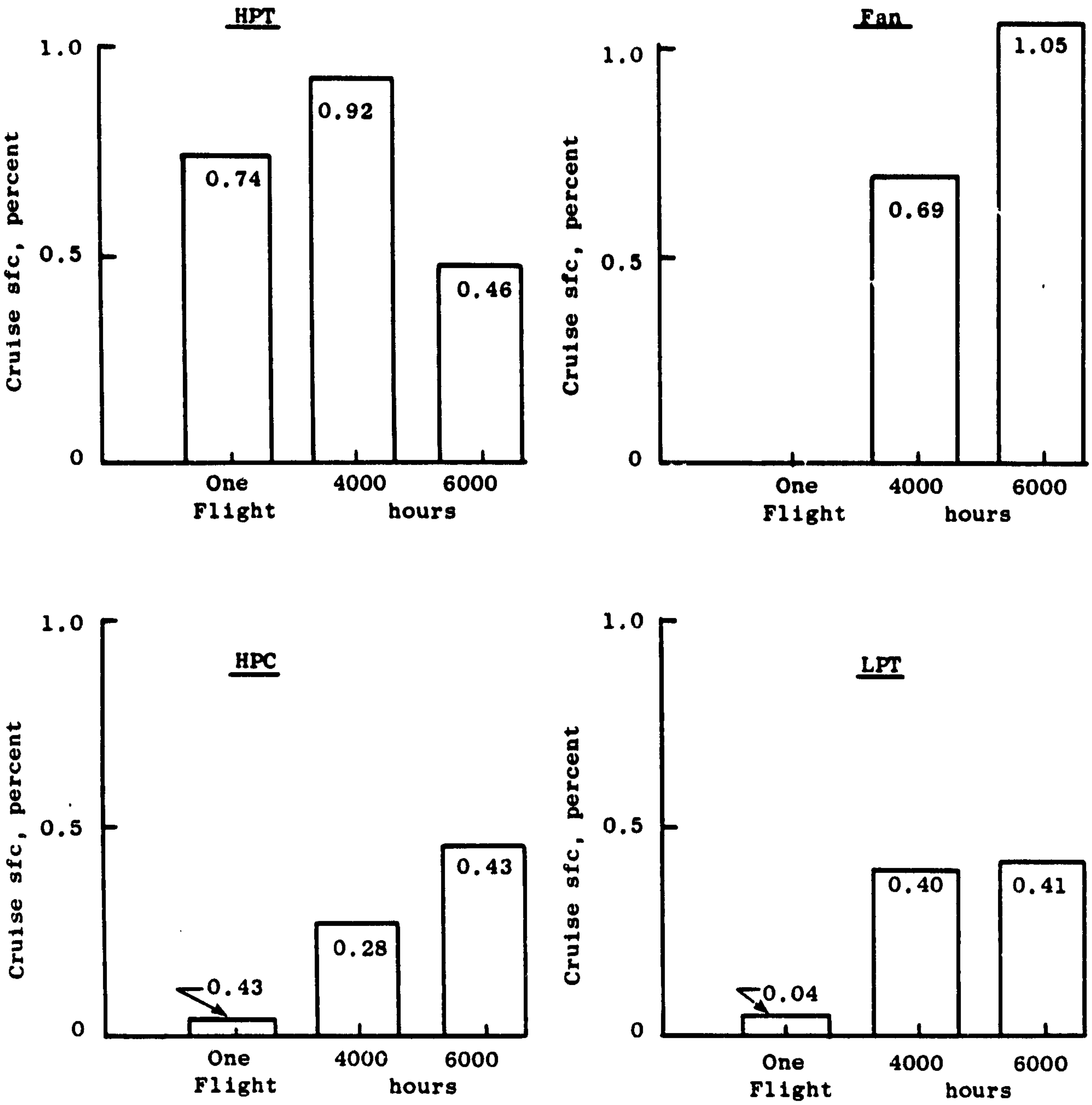


Figure E-5. 6000 Hours With-Repair Model - By Component.

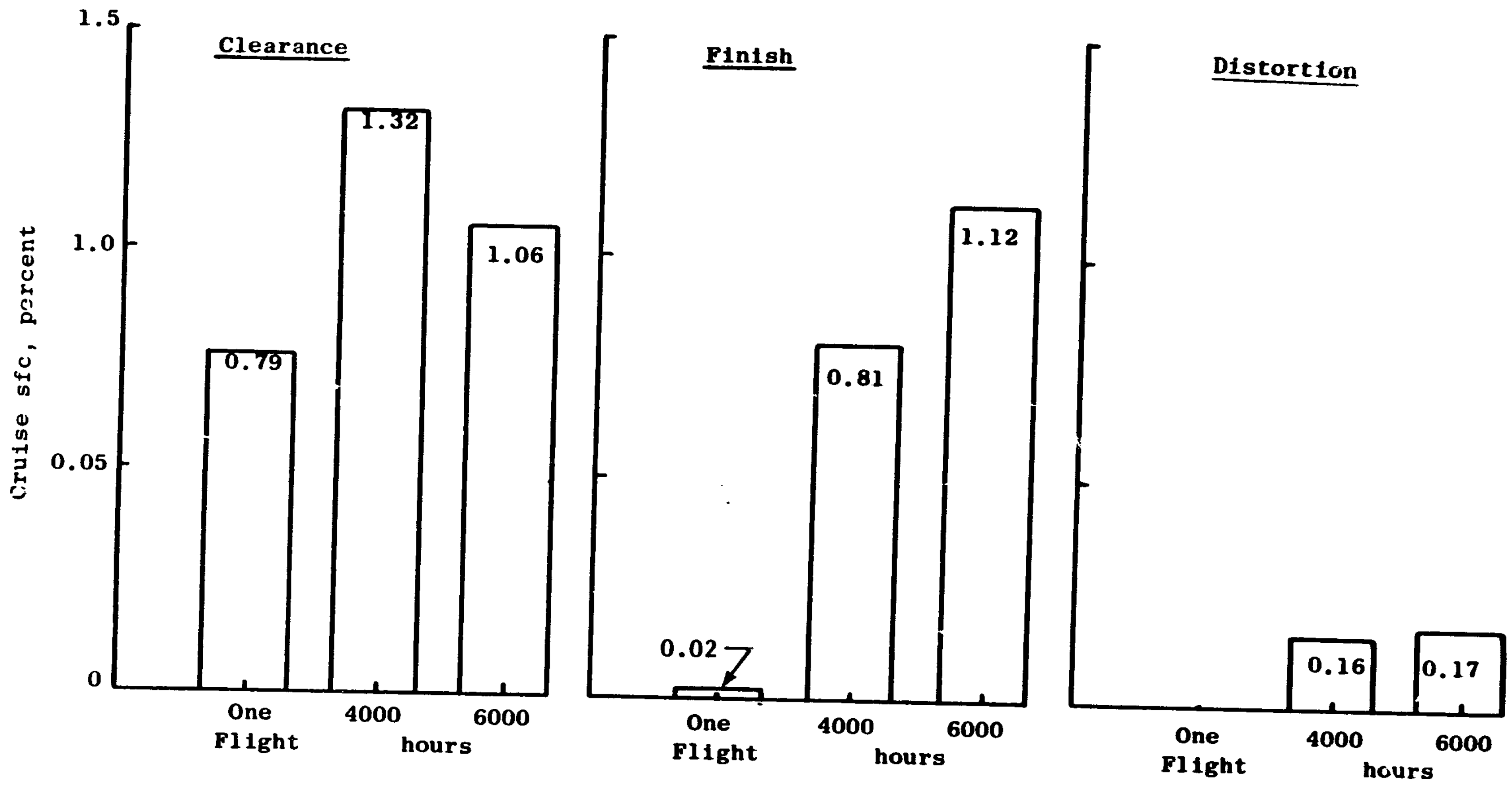


Figure E-6. 6000 Hours With-Repair Model - By Damage Mechanisms.

APPENDIX F

QUALITY ASSURANCE REPORT

INTRODUCTION

It is the fundamental precept of the Aircraft Engine Group to provide products and services that fulfill the Product Quality expectations of customers and maintain leadership in product quality reputation, in conformance to the policy established by the Executive Office.

The Quality System as documented in Aircraft Engine Group Operating Procedures provides for the establishment of Quality assurance requirements through the design, development, manufacture, test, delivery, application and post-delivery servicing of the product. These instructions and Operating Procedures clearly delineate the cross-functional responsibilities and procedures for implementing the system, which includes coordination with cognizant FAA/AFPRO functions prior to issue and implementation.

The Quality Organization implements the Quality System requirements in each of their assigned areas of responsibility, providing design review participation, quality planning, quality input to Manufacturing planning, quality assurance and inspection, material review control, production testing and instrument calibration.

The Aircraft Engine Group has additional Manufacturing facilities, and Overhaul/Service Shops such as the one at Ontario, California. These various facilities are termed "satellite" plants or locations. They are not considered vendors or suppliers for quality control purposes and have the same status and requirements they would have if located in the Evendale Manufacturing Facility.

The specific requirements for this contract were accomplished at the following locations:

- Production Assembly and Engine Test - Evendale
- Ontario Service Shop - Ontario

A summary of activities for each location is included in this report.

QUALITY SYSTEMS

Quality Systems for Evendale and Ontario are constructed to comply with Military Specifications MIL-Q-9858A, MIL-I-45208A, and MIL-C-45662A, and with Federal Aviation Regulations FAR-145 and (where applicable) FAR-21. The total AEG Quality System has been accepted by NASA-LeRC for fabrication of engines under prior contracts.

Inherent in the system is the assurance of conformance to the quality requirements. This includes the performance of required inspections and tests. In addition, the system provides change control requirements which assure that design changes are incorporated into manufacturing, procurement, and quality documentation, and into the products.

Engine parts are inspected to documented quality plans that define the characteristics to be inspected, the gages and tools to be used, the conditions under which the inspection is to be performed, the sampling plan, laboratory and special process testing, and the identification and record requirements.

Work instructions are issued for compliance by operators, inspectors, testers, and mechanics. Component part manufacture provides for laboratory overview of all special and critical processes, including qualification and certification of personnel, equipment, and processes.

When work is performed in accordance with work instructions, the operator/inspector records that the work has been performed. This is accomplished by the operator/inspector stamping or signing the operation sequence sheet to signify that the operation has been performed.

Control of part handling, storage, and delivery is maintained through the entire cycle. Engines and assemblies are stored in special dollies and transportation carts. Finished assembled parts are stored so as to preclude damage and contamination, openings are covered, lines are capped, and protective covers are applied as required.

A buildup record and test log is maintained for the assembly, inspection, and test of each major component or engine. Component and engine testing is performed according to documented test instructions, test plans, and instrumentation plans. Test and instrumentation plans were submitted to NASA for approval prior to the testing.

Records essential to the economical and effective operation of the Quality Program are maintained, reviewed, and used as a basis for action. These records include inspection and test results, nonconforming material findings, laboratory analysis, and receiving inspection.

Nonconforming hardware is controlled by a system of material review at the component source. Both a Quality representative and an Engineering representative provide the accept (use-as-is or repair) decision. Nonconformances are documented, including the disposition and corrective action if applicable to prevent recurrence.

CALIBRATION

The need for product measurement is identified and the design, procurement and application of measuring equipment specified at the start of the product cycle. Measuring devices used for product acceptance and instruments used to control, record, monitor, or indicate results of, or readings during, inspection and test are initially inspected, calibrated, and periodically reverified or recalibrated.

Documented procedures are used to define methods of calibration and verification of characteristics which govern the accuracy of the gage or instrument. Provisions are made for procurment of instrument calibration capability as a part of instrument system acquisition.

Frequency of recalibration is specified and measuring gages and instruments are labeled to indicate the period of use before recalibration is necessary. Records are maintained for each gage or instrument which lists the identification, serial number, calibration frequency, procedure, and results of each calibration.

Recalibration periods (frequency of calibration) are prescribed on the basis that the gages and instruments are within calibration tolerance limits at the end of the recalibration period. The results of recalibration are analyzed to determine the effectiveness of the recalibration period, and adjustments are made to shorten or lengthen the cycle when justified.

Standards used to verify the gages and instruments are traceable to the National Bureau of Standards.

QUALITY ASSURANCE FOR INSTRUMENTATION

Items defined as Standard Instrumentation (items appearing on the engine parts lists) will have Quality Assurance Control to the same degree as other engine components. Instrumentation on engines for Revenue Service will be subject to the test and inspection criteria identified in the applicable Shop Manual.

Items defined as "Test Instrumentation" (standard test instrumentation as identified in the applicable engine manual GEK 9266 for CF6 test section 72-00) will be subject to the same controls required for measuring and test equipment. This instrumentation is periodically reverified by the technician and recalibrated, at a prescribed frequency, against standards traceable to the National Bureau of Standards.

Items identified as "Special Instrumentation" (non-parts list or non-Tech Manual instrumentation supplied for this program) will have Quality Assurance Control consistent with the stated objectives of this program.

The instrumentation used for obtaining data for this contract fulfillment has not affected the engine operations or performance.

ACTIVITY SUMMARY BY LOCATION

PRODUCTION ASSEMBLY

In Production Assembly, the standard engine build procedures were used to insure compliance to Quality Systems. These procedures and practices are approved under FAA Production Certificate 108. The operating procedures utilize an Engine Assembly Build Record (EABR) and an Engine Assembly Configuration Record (EACR). These documents, incorporated into an Engine Record Book, serve as a historical record of the compliance to the Assembly Procedure, a record of critical assembly dimensions, and a record of the engine configuration. Work performed is claimed by the applicable inspector or assembler. (Samples of the EABR and EACR cards are provided in Figures F-1 and F-2 respectively.)

Production Assembly releases the engine to Test and upon successful completion of the required test, performs the necessary work and inspection in preparation for shipment to the customer.

PRODUCTION ENGINE TEST

In Production Engine Test, the engine is inspected and prepared for test per Engine Test Instruction (ETI) Number F15.

Limits and restrictions of Production Test Specifications were applied during the testing of engines under this contract. The safety of the test crew and engine is ensured by conducting ETI F-18 CF6 cell check sheets prior to the performance of the test.

The engine performance data and safety parameters are recorded by automatic data recording (ADR). The data systems, test cell, thrust frame, fuel measuring systems, are calibrated on a periodic basis by specialized technicians. During testing, the ADR system is continually monitored by test engineers to ensure the quality of the data being recorded.

GT 6331 (6/73)

ENGINE ASSEMBLY BUILD-UP RECORD

DATE ISSUED ________ ENGINE SERIAL NO. 451-507 ASSEMBLY SERIAL NO. ________ PAGE 02 OF 04

WORK STAT.	ENGINE MODEL	ASSEMBLY DWG. NO.	ASSEMBLY NAME	PROCEDURE TITLE	PROCEDURE DATE	REV. NO.
NSG56	CF6-60			FAN FRAME SUB-ASSY		
07-14-77						

DATA IDENTIFICATION	OPER NO.	OPERATION INSTRUCTIONS	GREEN	FINAL	EPR	C/I
	036	TORQUE INLET GEARBOX MOUNTING BOLTS	A 4245	A		0
	037	DROP C / / REF DIM 1.200 — 1.193 1.193 1.193	I J-30			0
		DIFF / / REF LIMIT 8- .002 — .002 .002 .001	I J-30			0
		DROP C / / REF DIM 1.200		I		0
		DIFF / / REF LIMIT 8- .002		I		0
NO2BHBF	038	FIR OF NO 2 BRG HOUSING BORE LIMIT MAX .010 — .008	I J-30	I		0
NO3BHBF	041	FIR OF NO 3 BRG HOUSING BORE LIMIT MAX .008 — .006	I J-30	I		0
	043	ASSURE PROPER NO 3 BRG AND RECORD BRG S/N — SCA C1833	A 4245			0
	047	TORQUE NO 3 BRG BOLTS	A 4245			0
	056	TORQUE 2 SCREWS TO 25 IN LB AND ASSURE SCREW HEADS ARE				0
		.001-.020 BELOW FLANGE	A 4245			0
	059	CHECK NO 2 BRG HOUSING SEATING	A N/D			0
	061	PLUG GAGE INTO ID OF SEAL NUT	A N/D			0
	064	TORQUE NO 1 BRG HOUSING BOLTS	A N/D			0
NO2FIR	065	RECORD MAX FIR LIMIT .010 FIR MAX	A N/D			1
	071	CHECK FOR .060 CLEARANCE BETWEEN TUBES AND FRAME	A N/D			0
	075	CHECK NO 2 BRG SEATING	A N/D	A		0
	076	TORQUE NO 2 BRG BOLTS	A N/D	A		0

Figure F-1. EABR Card.

DRAWING NUMBER	NOMENCLATURE	VENDOR CODE	SERIAL NO	PART TRANSFERS INSP STAMP	DATE	TOTAL TIME	PENALTY	FUNCT FAULT	TRANSFERRED FROM	REASON

QCI & SPECIAL CHECKS
REEN RELEASE
D RELEASE
INAL RELEASE
S RELEASE

SPECIAL NOTES TO BE CLEARED							
NOTE	ENTERED BY	DATE	CORRECTION MADE	ENTERED BY	DATE	CLEARED INSP	CLEARED DAT

Figure F-1. EABR Card (Concluded).

1556

ENGINE ASSEMBLY CONFIGURATION RECORD

BOOK/ENG NUMBER	WORK STATION	DATE ISSUED	WORK STATION DESCRIPTION	MODEL	SUB ASSY	DRAWING NO	S/A SERIAL NO	PAGE
451-507	MSG56	09-02-77	FAN FRAME S/A	CF6-6				1

BOD DATA	G.E. DRAWING NUMBER	A I I	R W	NOMENCLATURE	PART POSITION NUMBER	QTY	V S E	VENDOR CODE	R O D	PART SERIAL/HEAT LOT NO	R O D	CURE DATE
BR	MIL-L-25681C			SO-SO MOLY	00000025 B	A/R		XXXXX		XXXXXXXX		
NEW MAJ	9155M67P01			NO 3 BEARING	01100	1	•	52676 SGA	S	SGA 01833		
BR	MS9217-06			BOLT-STA S	01121	17		XXXXX		XXXXXXXX		
BR	R584P05SL			BOLT BRG 3+4	01122	12		XXXXX		XXXXXXXX		
BR	MS9208-10			BOLT STA S	01123	20		XXXXX		XXXXXXXX		
BR	MS9321-09			WASHER	01130	20		XXXXX		XXXXXXXX		
BR	9607M05P08			PKG PREFOR	01152	1		XXXXX		XXXXXXXX		
•••	9654M23P04			NO 3 BRG SEAL	01153	1	•	11512 LAM	S	LAM 01269		
MAJ							•	YA736 BES	S			
BR	R149P09A			PKG PREFOR	01155	1		XXXXX		XXXXXXXX		
•••	9654M03G05			SEAL COMP INLE	01156	1	•	07492 PMR	S	PMB 40502		
NEW	9009M78G27			G/B ASSY INLET	03000	1		XXXXX	S	FIA 00203		
BR	R1324P015			BOLT	03020	12		XXXXX		XXXXXXXX		
BR	AN960C416L			WASHER	03030	12		XXXXX		XXXXXXXX		
	9065M44G01			TUBE LUBE	44900	1		XXXXX		XXXXXXXX		
	9064M10G01			MANFD LUBE	44901	1	•	96593 TUPR		XXXXXXXX		
	9065M45G02			MANIFOLD	44902	1		XXXXX		XXXXXXXX		
BR	9064M12P01			BRACKET	44910	1		XXXXX		XXXXXXXX		
BR	MS9208-C7			BOLT	44921	3		XXXXX		XXXXXXXX		
99	CONTINUED ON NEXT PAGE WORKSTATION MSG56											

GE A336

Figure F-2. EACR Card.

ORIGINAL PAGE IS
OF POOR QUALITY

OPERATION RECORD

START	FINISH	ASSY BADGE	ASSEMBLER NAME	DATE	REMARKS
1	29	4245	J.E. Jones	23 Sept 77	Various operations
30	100	4245	J.E. Jones	26 Sept 77	not Detailed
					See orig. Bk. Sheet
					J.E.J. 9-26-77
101	120	4245	J.E. Jones	26 Sept 77	

SIGN OUT LAST OPERATION IN HEAVY BLACK LINES

INSPECTION OPERATION RECORD

START	FINISH	INSP BADGE	INSPECTION NAME	DATE	REMARKS

SIGN OUT LAST OPERATION IN HEAVY BLACK LINES

Figure F-2. EACR Card (Concluded).

ONTARIO SERVICE SHOP

At the Ontario facility, a Quality Control Work Instruction (QCWI DF015) was written and coordinated with NASA LeRC. The QCWI provided instructions on these specific items as applicable to the CF6 Diagnostic Program.

Assembly/Disassembly Control
Rework Control
Workscope Definition
Nonconformance
Quality Planning
Auditing
Instrumentation Control (Safety)
Measuring and Test Equipment
Engine Test
Witnessing
Records
Failure Recording

To document the condition of the engine hardware, photographs were taken of the LPT shrouds and seals, representative HPT blades, LPT blades, compressor rotor, stator case, fan inlet guide vanes, CDP seal, HPT seals and shroud, HPT rotor, HP nozzles. These photographs were of high quality and are available for review.

Work orders were written to provide work direction for Engine Test, Prep-to-Test inspections and for assembly and disassembly instructions. Inspections as requested were witnessed by the designated DCAS representative.

Examples of the work documents as issued to the Test and Assembly personnel are presented in figures:

- Figure F-3 - Test Operating Requirements Document
- Figure F-4 - Prep-to-Test & Test Check-Off Sheet
- Figure F-5 - Instrumentation Check Sheet
- Figure F-6 - Inspection Check List
- Figure F-7 - Work Order Sample
- Figure F-8 - HPTR Blade Inspection Sheet

GENERAL ELECTRIC COMPANY
AVIATION SERVICE OPERATION/ONTARIO
WORK ORDER

RZA 5/8/74

AMENDMENT NO

PERFORMANCE TESTS

5.1 INBOUND TEST

THE FOLLOWING SEQUENCE OF TESTING IS REQUIRED FOR THE CF6-6 TASK III ENGINE. THE TESTING WILL BE CONDUCTED IN THE ASO-ONTARIO CF6 TEST CELL WITH A LIGHTWEIGHT BELLMOUTH AND THE STANDARD CF6-6 ACCEPTANCE TEST COWLING CONFIGURATION.

1. INSTALL ENGINE IN THE CF6 TEST CELL AND SET UP PER CF6 SHOP MANUAL, 72-00-00 TESTING.

2. CHECK VARIABLE STATOR VANES COLD RIG, BUT DO NOT ADJUST UNLESS VSV TRACKS OUTSIDE OF THE OPEN LIMIT BY MORE THAN ONE DEGREE DURING ENGINE OPERATION. NO ADJUSTMENT IS TO BE MADE WITHOUT THE CONCURRENCE OF ASE ENGINEERING.

3. INSTALL INSTRUMENTATION AS DEFINED BY THE INSTRUMENTATION PLAN FOR THE TASK III ENGINES.

4. CONDUCT THE FOLLOWING PERFORMANCE TEST:

   a. PERFORM NORMAL PREFIRE CHECKS INCLUDING A LEAK CHECK.

   b. START ENGINE AND STABILIZE FOR FIVE MINUTES AT GROUND IDLE.

   c. SET THE FOLLOWING TWO STEADY-STATE DATA POINTS AND TAKE FULL DATA READINGS AFTER FOUR MINUTES STABILIZATION:

POWER SETTING	CORRECTED FAN SPEED
50%	76.42% (2623 rpm)
75%	90.11% (3093 rpm)

NOTE: PERFORM FULL FUNCTIONAL TEST

   d. SLOW DECEL TO GROUND IDLE, AND ANALYZE THE TWO POINTS TO DETERMINE IF THE ENGINE CAN BE SAFETY OPERATED TO TAKEOFF POWER WITHOUT EXCEEDING ANY LIMITS (N2, EGT, VSV). ALSO ASCERTAIN THAT ALL INSTRUMENTATION, INCLUDING THE RECORDER, IS FUNCTIONING PROPERLY.

   e. SET THE FOLLOWING STEADY-STATE DATA POINTS AND TAKE TWO BACK-TO-BACK DATA READINGS AFTER FOUR MINUTES STABILIZATION. THE ENGINE SHOULD BE OPERATED AT MAXIMUM CONTINUOUS POWER FOR A MINIMUM OF SIX MINUTES PRIOR TO SETTING THE FOLLOWING POINTS. TAKE ONE DATA READING AFTER SIX MINUTES.

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ASO/O-77770 REV 8-74

PRODUCTION

Figure F-3. Test Operating Requirements Document

GENERAL ELECTRIC COMPANY
AVIATION SERVICE OPERATION/ONTAR.
WORK ORDER

KLA. 5/8/78

Page 3 of 3 Pages | AMENDMENT NO

POWER SETTING	CORRECTED FAN SPEED
TAKEOFF	100.30% (3443 rpm)
MAXIMUM CONTINUOUS	98.70% (3388 rpm)
MAXIMUM CRUISE	95.85% (3290 rpm)
75%	90.11% (3093 rpm)

f. SHUT DOWN FOR A MINIMUM OF 30 MINUTES AND THEN REPEAT STEPS b AND e.

5.2 SPECIAL INSTRUCTIONS:

THE FOLLOWING SPECIAL INSTRUCTIONS APPLY FOR TESTING THE CF6-6D TASK III ENGINE:

1. GENERAL ELECTRIC-EVENDALE PERSONNEL WILL BE ON SITE AND WILL ASSURE DATA QUALITY BEFORE THE ENGINE CAN BE RELEASED FROM THE TEST CELL.

2. OBTAIN A FUEL LHV SAMPLE BETWEEN THE DUAL-PERFORMANCE POWER CALIBRATIONS. A BOMB CALORIMETER WILL BE USED TO OBTAIN THE LHV.

3. NO PERFORMANCE DATA IS TO BE TAKEN WHEN VISIBLE PRECIPITATION EXISTS OR THE RELATIVE HUMIDITY EXCEEDS XXXX 85%.

4. PRESSURE TRANSDUCERS, FUEL METERS, AND THE THRUST LOAD CELL MUST BE WITHIN FAA CALIBRATION LIMITS AND THE CALIBRATIONS REXTRACEABLE TO THE NATIONAL BUREAU OF STANDARDS.

5. AFTER FIRST INBOUND PERFORMANCE RUN, CLEAN FAN BLADES USING MCX. PERFORM ANOTHER SINGLE PERFORMANCE TEST.

RLA:mjs

PRODUCTION

Figure F-3. Test Operating Requirements Document - Concluded

W/O ______________________

ENGINE S/N ____________ ________

CF6
PREP TO TEST
&
TEST CHECKOFF SHEET

FORM NO. CF6-TEST-1
2/3/78
Page 4 Of 8
Revision 21

STEP	OPERATION	MECH. SIGNATURE DATE		DATE
	TEST CELL			
	Engine mount bolts placed correctly, secured and lockwired. Front mount bolts stretch .006"/.008". Left bolt stretch .006" 6-22-78 Right bolt stretch .008"			6-22-78
2.	Check accessory gearbox customer pads for proper installation of gear shaft plugs.			6-22
3.	Check all engine mounts for proper installation and lockwired.			6-22
4.	Check all required vibration pickups for installation, leads connected to their respective amplifier, lockwire. Check cooling air to T.R.F. pickup. Hookup.			6-22
5	Check throttle operation and for positive fuel shutoff in zero position of fuel shutoff lever.			6-22
6.	Check both ignition systems for operation of plug.			6-22
7.	Check air starter piping, secure clamp and lockwire.			6-22
8.	All electrical connections secure and lockwired.			6-22
9.	Check to see that specific gravity setting on M.F.C. is ~~.76~~ .77 per book JP4 fuel is used.			6-22
10	Visually check inlet instrumentation shoes/probes for condition and security. Check sensing holes for obstructions.			6-22
	See engineer rework instruction for steps __________ recorded on back of this page. Void sign-off for steps __________ and modify per instruction on back of this page.			

Figure F-4. CF6 Prep-to-Test and Test Checkoff Sheet.

ENGINE S/N 451-507

W/O 182960

CF6-6D-50

INSTRUMENTATION CHECKLIST

FORM NO. CF6- TEST-3
12/12/73
Page 1 of 4
Revision 1

ITEM	OPERATION	MECH	INSP	DATE
1.	Check air starter for proper servicing.	✓	(stamp)	6-22-78
2.	Vibration: 3 Pick-ups (Lockwire)			
	A. ~~Compressor~~ Turb rear frame horizontal Location: Aft 2 bolt holes of #8 strut (1st strut below 9/o/c split line)	✓	(stamp)	6-22
	B. Turbine ~~rear~~ mid frame horz. Location: 9 o/c, second & third bolt holes fwd. of T.R.F. flange "V"	✓	(stamp)	6-22
	C. Fan rear stator case horizontal Location: 3 o/c fourth bolt above the upper ignition exciter.	✓ N/A	(stamp)	6-22
	D. No. one bearing - horizontal Location: 4 o/c no. 4 fan exit strut below stator actuator.	✓	(stamp)	6-22
	Variable stator vane position ind. Location: Transducer bracket at approx. 3 o/c on comp. front casing. Check rig marks: Ref. IAASS T.R. #CF6-50/082 Synchronize indicator to read zero ± 0.005 volts full open - record full closed 9.74 volts. Lockwire.	✓	(stamp)	6-22
4.	Variable bleed valve position ind. Location: Transducer bracket at V.B.V. - Bellcrank at 9 o/c position. Check rig plate alignment bar is centered in shaft cover "V" notch - synchronize indicator to read 5.0 ± 0.02 volts. Record full open ______ Lockwire.	✓ N/A	(stamp)	6-22

Figure F-5. CF6-6D,-50 Instrumentation Checklist.

CF6-6D,-50
INSPECTION CHECKLIST

FORM NO. Q.C.-232
3/10/76
Page 2 Of 3
Revision 3

ITEM	AREAS INSPECTED	CLEAN	NORMAL	CONTAMINATED	INCOMING INSP/DATE	PREP TO TEST INSP/DATE	PREP TO SHIP INSP/DATE
2.	Starter magnetic plug					[illegible]	
	Starter valve filter					NA	
	Explain on squawk sheet, the condition of any filter that is contaminated. All filters are to be clean prior to re-installation. Report any abnormal contamination to Q.C. Engineering.						
3.	Inlet area for "FOD" & loose or missing hardware, overall condition.					[illegible]	
4.	Incoming check blocker doors: open ☐ closed ☐ (Check one). If received with blocker doors open, close them.					X	X
5.	Fan stator case & frame not including accessory gearbox area.					[illegible]	
6.	High pressure compressor stator & related plumbing - right hand side.					[illegible]	
7.	High pressure compressor stator & related plumbing - left hand side.					[illegible]	
8	Compressor rear frame - right half to forward side of fire-seal.					[illegible]	
9.	Compressor rear frame - left half to forward side of fireseal.					[illegible]	
10.	Compressor rear frame - right half aft of fireseal.						
11.	Compressor rear frame - left half aft of fireseal.						
12.	Low pressure turbine module - right half.					[illegible]	
13.	Low pressure turbine module - left half.					[illegible]	
14.	Low pressure exhaust including turbine reverser or conical nozzle.					[illegible]	
15.	Prep to ship; if received with blocker doors open, close them.				X	X	

Figure F-6. CF6-6D,-50 Inspection Checklist.

GENERAL ELECTRIC COMPANY
AVIATION SERVICE OPERATION/ONTARIO
WORK ORDER
132960

Page 4 of 8 Pages

RCA. 5/17/78

AMENDMENT NO.

REASSEMBLY

After all inspection checks are completed, rebuild the LPT module per the SM.

3. CORE ENGINE INSPECTIONS

Disassemble the engine as necessary to obtain the required data on the noted EMU's. Disassembly will be performed per the following sequence of events; visually inspect- EMU's to H.M.M.

NOTE 1: Photographs (detailed and overall) will be taken of each sub-assembly prior to its disassembly, with particular emphasis on deteriorated parts, or any unique condition. Module photographs not required RCA 5/17/78

NOTE 2: Prior to removal of the Stage 1 HPTN assembly, obtain drop checks from the aft face of the CRF outer flange to the aft face of Stage 1 HPTN vane outer platforms in 8 equally spaced locations. At each location, obtain drops to both ends of each segment (16 individual readings).

DCAS Insp. →

NOTE 3: Record inspection requirements on sheets supplied by Evendale engineer.

B. Split core engine away from fan module and route core to S/N Remove HPT module.

C. Position-mark and remove Stage 2 HPTR blades. Remove second stage nozzle.

D. Remove second stage nozzle, preserve the stage 2 blade retainer seal wire for engineering inspection.

E. Comply with Note 2 above (drop checks). Then remove the Stage 1 HPTN assembly.

F. Position-mark, then remove the 4B pressure balance seal (mini-nozzle).

G. Remove the CRF.

H. Remove the HPCS cases.

I. Send the HPC rotor to the rotor area.

4. HIGH PRESSURE TURBINE ROTOR (REFERENCE 72-53-00)

A. Install the rotor in the Runout Fixture. Shim the blades per the SM, and measure each Stage 1 and 2 blade tip at 0.1 inch from the leading and trailing edges as follows:

DCAS Insp →

1. Measure and record the radius of blade No. 1 0.1 inch from the LE of each stage.

PRODUCTION

Figure F-7. Example of Work Order.

ESN 451507

DATE ________

STAGE 1 HPTR BLADE RUNOUT DATA

RUNOUTS TAKEN AT .100" FROM LE AND TE OF EACH BLADE

No	FWD.	AFT	No.	FWD	AFT	No.	FWD	AFT	No.	FWD	AFT
1	.000	000	28	-.003	+.005	55	-.001	.001	82	+.002	+.007
2	+.002	+.003	29	-.003	+.001	56	-.002	+.001	83	-.001	+.005
3	-.003	+.001	30	000	+.005	57	000	+.003	84	000	+[illegible]
4	+.001	+.006	31	-.004	+.003	58	-.001	+.006	85	-.001	+.005
5	-.002	-.001	32	000	+.008	59	-.001	+.002	86	+.001	+.007
6	+.003	+.005	33	-.004	-.001	60	-.002	+.004	87	+.001	+.007
7	-.002	-.001	34	000	+.004	61	-.002	+.002	88	-.001	+.008
8	+.002	+.005	35	-.002	+.001	62	000	+.005	89	-.002	+.008
9	-.003	-.001	36	000	+.005	63	000	+.003	90	-.003	+.006
10	-.001	+.005	37	-.008	-.003	64	+.001	+.005	91	+.001	+[illegible]
11	-.004	-.002	38	-.002	+.004	65	.000	+.001	92	+.002	+[illegible]
12	000	+.005	39	-.004	006	66	-.001	+.005	93	+.003	+.003
13	-.002	-.003	40	-.002	+.006	67	000	-.001	94	000	+.002
14	+.001	+.004	41	-.006	+.003	68	-.001	+.004	95	000	+.006
15	-.002	000	42	-.001	+.007	69	000	-.001	96	-.002	+.007
16	+.001	+.004	43	-.002	+.002	70	+.002	+.004	97	-.001	+.006
17	-.004	-.002	44	-.001	+.005	71	-.001	000	98	-.006	+.007
18	+.002	+.003	45	-.006	+.002	72	+.002	+.005	99	-.001	+.006
19	-.001	-.001	46	-.004	+.004	73	000	+.001	100	-.004	-.006
20	+.002	+.005	47	+.001	+.003	74	+.003	+.008	101	000	+.010
21	-.002	-.004	48	+.002	+.005	75	+.001	-.001	102	-.003	+.009
22	+.001	+.002	49	-.003	+.002	76	+.003	+.005	103	-.002	+.006
23	-.002	-.001	50	+.002	+.006	77	000	000	104	-.004	+[illegible]
24	+.002	+.004	51	-.002	000	78	+.002	+.007	105	-.005	+[illegible]
25	-.002	+.001	52	+.002	+.006	79	+.002	+.001	106	-.008	+.006
26	000	+.005	53	+.001	+.001	80	+.002	+.006	107	-.006	000
27	-.004	+.001	54	000	+.005	81	+.001	+.001	108	-.008	+[illegible]

READINGS ARE IN MILS FWD

RADIUS AT #1 = 16.560 " AFT = 16.566

FWD. MAX = 16.563 MIN = 16.552 AVE. = 16.559

AFT MAX = 16.576 MIN = 16.562 AVE = 16.570

Figure F-8. HPTR Blade Inspection Sheet

APPENDIX G

LIST OF REFERENCES

1) NASA CR-159830, "CF6-6D Engine Short-Term Performance Deterioration", W. H. Kramer, J. E. Paas, J. J. Smith, and R. H. Wulf, April, 1980.

2) NASA CR-159618, "Long-Term CF6-6D Low-Pressure Turbine Deterioration", J. J. Smith, August, 1979.

3) NASA CR-135381, "Long-Term CF6 Engine Performance Deterioration - Evaluation of Engine S/N 451-479", W. H. Kramer and J. J. Smith, February, 1978.

4) NASA CR-159390, "Long-Term CF6 Engine Performance Deterioration - Evaluation of Engine S/N 451-380", W. H. Kramer and J. J. Smith, August, 1978.