NASA Technical Memorandum 81459

JT9D-7A (SP) JET ENGINE PERFORMANCE DETERIORATION TRENDS

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Prepared for the
International Aircraft Maintenance Engineering
Exhibition and Conference
sponsored by Hamilton Burr Publishing Company
Dallas, Texas, April 8-10, 1980

(NASA-TM-81459) JT9D-7A (SP) JET ENGINE PERFORMANCE DETERIORATION TRENDS (NASA) 24 p HC A02/MF A01 CSCL 21E
N80-20274
Unclas
G3/07 47617

JT9D-7A (SP) Jet Engine Performance Deterioration Trends

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ABSTRACT

The continuing escalation of fuel costs and the decreasing availability of fuel supplies have lead to an increase in the importance of maintaining good specific fuel consumption over the life cycle of jet engines. A better understanding of the trends of engine deterioration which lead to higher fuel consumption can be used to develop technology and apparatus to minimize such losses. The Pratt & Whitney JT9D Engine Diagnostics Program being sponsored by the National Aeronautics and Space Administration (NASA) Lewis Research Center has the objectives of identifying and quantifying the levels, trends, and causes of engine performance deterioration.

As part of this program, a series of installed engine calibrations (both on-the- ground and in-flight) were performed on two new Pan American World Airways 747 SP aircraft. The performance data gathered covered from before the first flight through approximately 1000 flight cycles and 6900 flight hours. To accomplish the calibrations a special-instrumentation system for ground testing of installed engines over a broad power range was used; along with performing concurrent in-flight engine calibrations under revenue service conditions.

This paper presents a discussion of this specific test program and the results of the analysis of the data, which provide a better understanding of short and long term performance deterioration of both engines and modules.

INTRODUCTION

The rapid rise in the cost of oil since the OPEC oil embargo in 1973 and the desire to decrease the United States' dependency on foreign suppliers for fuel supplies has resulted in a national effort to increase the availability of domestic oil, develop alternate sources of energy, and develop near- and long-term means to reduce fuel consumption. To counteract the adverse impact of the world-wide fuel crisis on the aviation industry, NASA is conducting the Aircraft Energy Efficiency (ACEE) program. Included in this program are major propulsion projects which are addressing both near-term and long-term goals. The near-term activities include the Engine Component Improvement (ECI) Project, which is directed toward improving the fuel consumption of current high bypass ratio turbofan engines and their derivatives by 5 percent over the life of these engines. Inasmuch as commercial aircraft in the free world are using fuel at a rate in excess of 80 billion liters of fuel per year, this five percent represents significant fuel savings. The ECI Project has two main parts, Performance Improvement and Engine Diagnostics. The Performance Improvement program, which is not covered herein, is intended to identify and evaluate improved component concepts which are technically and economically viable for the 1980-1982 time period, and then develop and demonstrate these concepts through ground and flight tests. The Engine Diagnostics program is directed toward identifying and quantifying engine performance losses that occur during service use and to develop criteria for minimizing these losses.

The first phase of the engine diagnostic project was the collection, documentation, and analysis of historical engine performance and parts usage data. That effort was completed in 1978 and the results reported in NASA CR-135448 (Reference 1). That study established average JT9D engine performance deterioration causes, and produced preliminary analytical models of both engine and module performance deterioration with service usage.

The effort reported in this paper was part of the second phase of the engine diagnostic project and was directed at expanding the understanding of engine deterioration by the collection of performance data from a selected sample of new in-service JT9D engines, under closely monitored conditions.

This paper presents the results of these studies concerning a group of new production engines, conducted during the period April 1977 to January 1979. The source of data for these studies has been Pan American World Airways JT9D-7A SP engines which were installed on two of their 747 SP aircraft. These aircraft entered service in May 1977 and June 1978, respectively.

DATA ACQUISITION SYSTEMS

Plug-In-Console (PIC) System Test Data

The PIC System was developed and operationally checked out by Pratt & Whitney Aircraft as a quick and accurate system for measuring installed static engine performance. The PIC System provided high quality data on 15 engine performance parameters. With the exception of thrust, the PIC system recorded all test data that are normally obtained in an engine test stand. The engine performance parameters obtained are shown in Figure 1. The system is shown schematically in Figure 2, and consists of:

1) an engine interface harness, including the necessary electrical cables and tubing to the pressure transducers

2) a modified "trim mast" to guide the cables and tubing through the fan stream

3) a temperature-controlled pressure transducer box

4) a data recording system

5) a portable minicomputer for reducing the data to engineering units, applying standard day corrections, and calculating preliminary module performance.

In preparation for these PIC tests, the aircraft systems and the outboard and inboard engines on the left side (positions 1 and 2 respectively) for two Pan American 747(SP) aircraft (N536PA and N537PA), were equipped with expanded instrumentation.

The first PIC tests were performed at the Boeing Commercial Airplane Company, Everett, Washington, prior to the first flight of each aircraft, and were conducted in a Quick Engine Change (QEC) configuration which included the normal flight inlet, nacelle and nozzles. Ten sets of PIC calibrations were performed on aircraft N536PA during its first 6900 hours and

1000 cycles of operation. Figure 3 shows the dates, engine age, and locations for this series of tests. Engine S/N P-695745 was removed for cause prior to the last PIC test. This engine was repaired and re-installed on a different aircraft. Six sets of PIC calibrations were performed on aircraft N537PA. Figure 4 shows the comparable data for this series of tests. As can be seen from Figure 3 and 4, these calibrations were spaced in a manner to establish engine initial flight performance, short-, and medium-term flight performance deterioration trends.

During the PIC testing, all corrected parameters were calculated by the minicomputer, plotted for data validation, and compared with data from the previous test. The initial PIC test data was compared to the production acceptance test performance data for each engine, as a baseline. Typical data gathered during two consecutive calibrations of engine P-695743 are presented in Figure 5, showing corrected fuel flow as a function of engine pressure ratio (EPR). Extensive tabular results of data were also an output of the PIC system.

In-Flight Performance Calibration Data

In an effort to establish a relationship between installed ground and in-flight engine performance, a series of in-flight calibrations were conducted on each of the four engines on aircraft N536PA and N537PA. These calibrations were performed by PA Engineering personnel concurrently with the PIC test program, on regular revenue 747 SP flights, using normal flight deck instrumentation.

Calibration conditions were standardized to the extent possible by conducting them at steady state cruise conditions. Figure 6 shows the engine and airplane parameters that were recorded at each in-flight calibration point. A calibration consisted of at least four complete data point sets where engine pressure ratio (EPR) on each engine was varied between 1.2

and 1.5. Constant Mach number (M) and altitude were maintained throughout each calibration procedure; and with one or two exceptions, altitude and M were duplicated for all flight calibrations. In addition, a fuel sample was taken at the end of each flight to establish the fuel heating value.

ANALYSIS OF DATA & DISCUSSION OF RESULTS

PIC Data

The PIC data taken at sea-level static conditions were immediately corrected to standard day conditions utilizing the portable minicomputer. Additional corrections were subsequently applied to account for variations in fuel lower heating value and water content of the ambient air. An additional correction was made to the data taken during the initial calibration at Boeing to account for the apparent presence of a vortex being ingested into the engine. This corrected was based on the analysis of the data for all four engines in this program which indicated unlikely improvements in fan and low-pressure compressor performance bettween tests at boeing and subsequent tests. Boeing requires all engine ground runs to be conducted with protective screens placed in front and partially to the sides of the engines to reduce the possibility of foreign object damage to the engine. Experience at P&WA indicated that the presence of such a device in relatively close proximity to the engine produced a weak vortex that was ingested by the engine, resulting in losses in fan and low-pressure compressor performance.

The performance deterioration for each of the four engines, as determined from the PIC tests, was referenced to the initial Production Acceptance Test (PAT) data.

Corrections (based on other engine testing) were applied to the PAT data to synthesize this data to a flight nacelle test configuration, thereby establishing each engine's baseline performance.

The measured engine performance parameters from the first PIC test at Boeing were then compared to the baseline to determine the differences in engine performance. To complete the analysis of each set of data, a performance analysis was performed to assess the modular performance losses corresponding to the measured changes in engine performance.

Each subsequent PIC engine test was compared to the previous test for each specific engine, and a further analysis of the modular performance losses was again made. Finally, the cumulative modular performance losses were plotted versus engine flight cycles to establish the overall performance deterioration trends relative to the reference baseline.

Plots of all engine parameters were made for each test (figure 5 is a typical example). Changes (deltas) in all parameters were read at an EPR of 1.43. Figure 7 presents the deltas in all the parameters occuring between two consecutive calibrations, and the results of the analysis of this particular data set. Calculated parameters have been adjusted to correct any discrepancies in the data caused by EGT profile shifts, etc.

The performance analysis of the PIC data yields estimated efficiency and flow capacity losses for individual engine modules. Figures 8 through 12 show the estimated module performance losses for engines P-695745 and P-695743 (aircraft N536PA, positions 1 and 2, respectively) and engines P-695760 and P-695763 (aircraft N537PA, positions 1 and 2, respectively).

Fan modules (Figure 8) of both aircraft deteriorate very rapidly at first. The engines on aircraft N536PA show a higher initial fan module loss. No marked difference between inboard and outboard engines is noted.

Low-pressure compressor modules (Figure 9) exhibit a similar characteristic deterioration trend as that for the fan, but the early performance loss is slightly less than in the fan module. Here again, the engines on aircraft N536PA show a higher initial loss, and there is no apparent inboard/outboard effect.

The high-pressure compressor modules (Figure 10) of engines on aircraft N537PA exhibit the characteristic deterioration trend, but the engines airplane N536PA exhibit very little short-term high-pressure compressor performance loss. As can be seen, no well-defined engine position effect is apparent.

The engines of both aircraft show some initial loss of high-pressure turbine efficiency and flow capacity (Figure 11). No significant differences between aircraft or engine position are apparent.

The deterioration of the low-pressure turbine modules (Figure 12) is almost negligible for both aircraft.

To varying degrees, all modules except the low-pressure turbine show the same deterioration trend; performance deteriorates rapidly for the first 50 cycles or so then levels off and deteriorates gradually over the longer term. The rapid early loss is most likely the result of blade tip interference and wearing-in of seals; the gradual long-term loss is due to blade and vane erosion.

As can be seen from the figures, deterioration trends appear to be different for the two aircraft. The scope of this test program did not permit a satisfactory understanding of these differences. Also, the current data does not suggest any differences in deterioration trends between inboard and outboard engines.

Overall Engine Deterioration

The influence of these individual module performance losses on engine TSFC loss at sea level static conditions versus flight cycles can be assessed by the use of engine influence coefficients. The results of this assessment are presented in Figure 13. The data show a rapid loss in TSFC of about 1 percent during the initial 50 cycles, and a more gradual long-term loss to about 2.2 percent at 1000 cycles. A usage-oriented breakdown of each module's contribution to the TSFC loss shown on Figure 13 is presented on Figure 14 for 50, 150, and 500 cycles. At 50 cycles, the TSFC loss is dominated by the high-pressure turbine deterioration with lesser impacts by the low-pressure compressor, fan, and high-pressure compressor. At 500 cycles, the high-pressure turbine and low-pressure compressor deterioration effects are dominant and are equal in their contribution to the total loss; the fan and high-pressure compressor impact continues to increase; and the impact of the low-pressure turbine is practically negligible.

Over the short term, the TSFC losses are nearly equally split between the cold section (fan, LPC, HPC) and hot section (HPT & LPT) as well as between the high-pressure spool and the low-pressure spool. At 500 cycles, the cold section dominates the TSFC losses, and the low-pressure spool exhibits more deterioration than does the high-pressure-spool.

Similar to the influence on engine TSFC loss, the individual module performance losses can be translated into engine EGT deterioration at sea level static conditions, as shown in Figure 15.

In-Flight Data

Using the data taken during the in-flight calibrations, Figure 16 presents engine fuel flow and EGT versus EPR for a typical calibration made on engine P-695738 on airplane N536PA. It can be seen that the data are consistent in that very little scatter exists across the range of power at which data were recorded.

Using the type of data shown in figure 16, the change in EGT and Fuel Flow for an EPR of 1.40 are shown in figure 17 for all four engines on airplane N536PA. The irregularities in the data are believed to be a result of instrumentation drift and non-uniformity in the amount of bleed air from each engine. An example of the latter characteristic appears to have occurred between 130 and 370 flight cycles when engines 3 and 4 showed a substantial rise in fuel flow in EGT while engines 1 and 2 were showing a corresponding decrease.

Using the average values from all four engines yields the trends shown in figure 18 where changes in EGT and Fuel Flow are shown as a function of flight cycles for two airplanes, N536PA and N537PA. These figures show a 5 to 7^{o}C rise in EGT and about 0.3 percent rise in Fuel Flow over the range of flight cycles from 0 to 700. These type of data are useful for indicating relatively long term trends in performance, but because of the data quality, short term variations are not well defined.

CONCLUSIONS

The in-service engine performance deterioration study was the second phase of the NASA JT9D Diagnostics Program to be completed. Two performance data acquisition systems, in-flight calibrations and PIC testing, were used. Analysis of these data resulted in a refinement of preliminary performance deterioration models and has provided a more comprehensive understanding of performance deterioration levels and trends in these engines.

In general, the flight data was useful in defining airplane average engine performance trends but was the least reliable of the two data sources in identifying individual engine deterioration trends and levels. The PIC testing provided better measurement of installed ground data on engine and module performance and performance changes, and in the same time frame as the in-flight calibrations. These PIC data were limited to approximately 1000 flight cycles, and were therefore valuable in establishing the short-term performance deterioration trends for the JT9D-7A SP engine, but did not provide (nor was intended to provide) a base for defining longer term performance deterioration trends.

Thus, to obtain the desired understanding of engine performance deterioration required in-depth analyses of the data systems, knowledge of their limitations, and finally, a comparison of the results with the historical data study results, with the proper judgemental weighting of each. From these analyses, it can be concluded that there are a number of contributing causes of performance deterioration in the JT9D-7A SP engine.

Estimation of engine performance loss based on sea level PIC data indicates that significant losses occur very early, followed by a more gradual loss over the longer term. A TSFC loss of about 1.0 percent occurs within the first 50 cycles, increasing to about 2.2 percent by 1000 cycles.

The TSFC loss in the first 50 cycles is dominated by low-pressure compressor and high-pressure turbine deterioration with smaller, but significant contributions from the fan and high-pressure compressor. Over this short term, TSFC losses are nearly equally split between the hot and cold sections and between the high- and low-pressure spools. No significant difference in engine deterioration trends due to wing position is apparent from the data obtained.

In-flight calibration data proved to be of limited value in evaluating individual engine deterioration. These data were obtained from aircraft starting at about 20 cycles, and therefore do not provide any information about very short-term engine deterioration. Nor can any conclusions be drawn concerning individual engine deterioration trends over the long term because of appreciable scatter in these data.

Deterioration averaging for the four engines on an airplane eliminates a considerable amount of scatter, suggesting that airplane systems may be influencing individual engine trends. Thus, the usefulness of in-flight calibration data is limited to indicating gross average deterioration trends.

REFERENCE

1. Sallee, G.P.: Report on Performance Deterioration Based on Existing (historical) data. NASA CR-135448, 1980.

ACRONYMS AND SYMBOLS

ACRONYMS (Organizations)

NASA	National Aeronautics and Space Administration
PA	Pan American World Airways
P&WA	Pratt & Whitney Aircraft

SYMBOLS & ACRONYMS

AGW	Aircraft gross weight
EGT	Exhaust Gas Temperature (^{o}C) - measured at HPT discharge
EPR	Engine Pressure Ratio
FOD	Foreign Object Damage
HPC	High-pressure Compressor
HPT	High-pressure Turbine
LPC	Low-pressure Compressor
LPT	Low-pressure Turbine
M	Mach Number
N	Rotor Speed
p	Gage Pressure (lb/in^2) (psig)
P	Absolute Pressure (lb/in^2) (psia)
PIC	Plug-In-Console
QEC	Quick Engine Change
SLS	Sea Level Static
(SP)	Special Performance
t	Temperature (^{o}F)(^{o}C)
T	Absolute Temperature (^{o}R)(^{o}K)
TSFC	Thrust Specific Fuel Consumption (lb/hr-lb)
w	Mass Flow (lb_m/sec)(lb_m/hr.)
β	Vane Angle (degrees)
Δ	Change

SUBSCRIPTS

1	Undisturbed inlet (pressures and temperatures)
1	Low-pressure rotor (rotor speeds)
2	Fan inlet (pressures and temperatures)
2	High-pressure rotor (rotor speeds)
2.4	Fan blade discharge
2.6	Fan exit guide vane discharge
3	LPC discharge
4	HPC discharge
5	HPT inlet
6	HPT discharge
7	LPT discharge
am	Ambient
avg	Average
f	Fuel
ind	Individual
s	Static
t	Stagnation (total)

TEMPERATURES	PRESSURES	OTHER
t_{AM}	P_{AM}	N_1
t_{t3}	P_{S3}	N_2
t_{t4}	P_{T3}	FUEL FLOW
t_{t6} - avg	P_{S4}	VANE ANGLE
t_{t6} - ind(6)	P_{S5i}	
t_{t7} - avg	P_{T7}	
t_{t7} - ind(6)		
TOTALS 5	6	4

15 DATA PARAMETERS

Figure 1. - Engine performance parameters obtained during PIC testing.

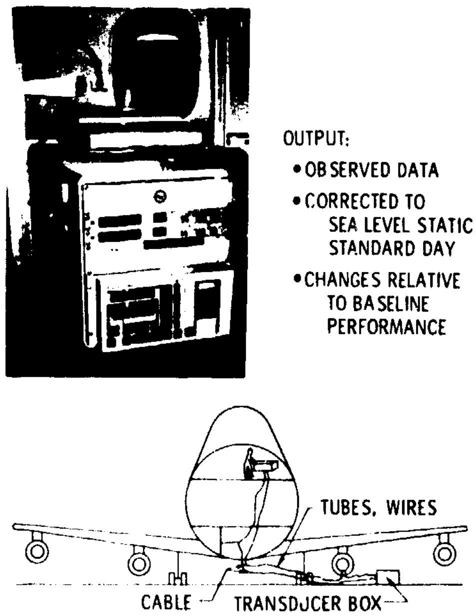

Figure 2. - Schematic of PIC system.

DATE	ENGINE	HOURS	CYCLES	TEST LOCATION
4-21-77	743, 745	0	0	BOEING, SEATTLE
5-09-77	743, 745	18	11	JFK, N.Y.
5-16-77	743, 745	110	19	JFK, N.Y.
5-19-77	743, 745	155	23	JFK, N.Y.
6-20-77	743, 745	614	91	JFK, N.Y.
7-18-77	743, 745	1021	133	JFK, N.Y.
11-02-77	743	1081	141	SFO
11-02-77	745	2486	365	SFO
2-11-78	743	2473	360	JFK, N.Y.
2-11-78	745	3878	584	JFK, N.Y.
4-18-78	743	3415	475	SFO
4-18-78	745	4820	700	SFO
12-04-78	743	6903	1078	LAX

Figure 3. - Chronology of PIC testing on aircraft N536PA, engines P-695743 and P-695745.

DATE	HOURS	CYCLES	TEST LOCATION
5-04-78	0	0	TBC
6-07-78	52	15	TBC
6-27-78	297	54	SFO
7-20-78	609	110	LAX
11-05-78	2224	331	JFK, N.Y.
1-04-79	3165	510	SFO

Figure 4. - Chronology of PIC testing on aircraft N537PA, engines P-695760 and P-695763.

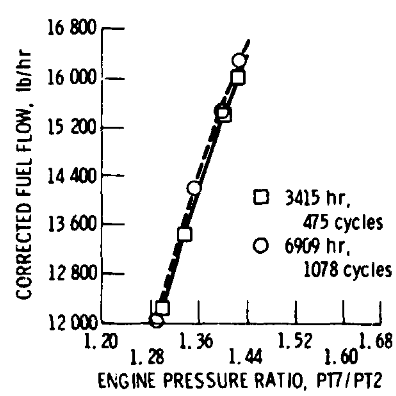

Figure 5. - Typical data acquired on two consecutive PIC performance checks, corrected fuel flow as a function of engine pressure ratio.

PARAMETER	
PRESSURE ALTITUDE	P_{am}
INLET AIR TOTAL TEMPERATURE	T_{t2}
INLET AIR STATIC TEMPERATURE	T_{s2}
MACH NUMBER	M
LOW-PRESSURE ROTOR SPEED	N_1
HIGH-PRESSURE ROTOR SPEED	N_2
HIGH-PRESSURE TURBINE EXHAUST GAS TEMPERATURE	EGT
FUEL FLOW	w_f
ENGINE PRESSURE RATIO	EPR
NUMBER OF AIR-CONDITIONING PACKS IN USE	----
AIRCRAFT GROSS WEIGHT	AGW

Figure 6. - Performance parameters obtained during in-flight calibrations.

MEASURED PARAMETER	CHANGE IN MEASURED PARAMETER	ADJUSTED CHANGE IN PARAMETER
LOW-PRESSURE ROTOR SPEED	+0.21%	+0.23%
HIGH-PRESSURE ROTOR SPEED	+0.29%	+0.29%
HPC DISCHARGE TOTAL TEMPERATURE	+1.0 °R	+2.0 °R
HPT DISCHARGE TOTAL TEMPERATURE	+28 °R	+21 °R
LPT DISCHARGE TOTAL TEMPERATURE	+11 °R	+17 °R
P_{t3}/P_{t2}	+1.41%	+1.44%
P_{s4}/P_{t7}	-0.65%	-0.67%
ENGINE AIR FLOW	-0.41%	-0.63%
FUEL FLOW	+1.07%	+0.99%
ANALYZED MODULE PARAMETER CHANGES:		
FAN EFFICIENCY		-0.80 pts.
FAN FLOW CAPACITY		-0.50%
LOW-PRESSURE COMPRESSOR EFFICIENCY		-0.65 pts.
LOW-PRESSURE COMPRESSOR FLOW CAPACITY		-0.40%
HIGH-PRESSURE COMPRESSOR EFFICIENCY		-0.60 pts.
HIGH-PRESSURE COMPRESSOR FLOW CAPACITY		-0.45%
HIGH-PRESSURE TURBINE EFFICIENCY		-0.40 pts.
HIGH-PRESSURE TURBINE FLOW CAPACITY		+0.40%
LOW-PRESSURE TURBINE EFFICIENCY		0. pts.
LOW-PRESSURE TURBINE FLOW CAPACITY		0. %

Figure 7. - Gas generator analysis of PIC calibration data for engine P-695743.

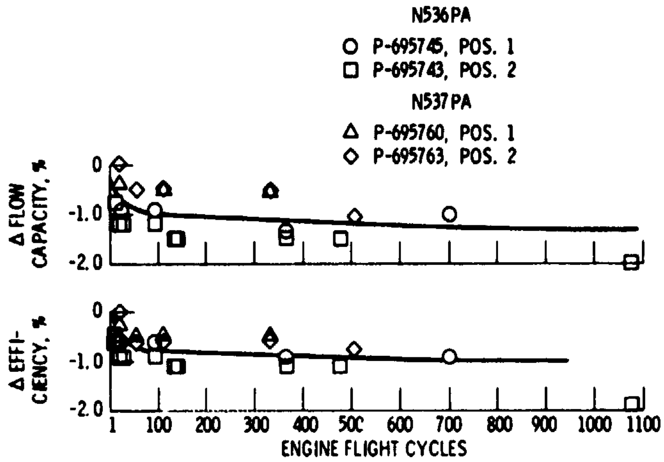

Figure 8. - Fan module performance deterioration.

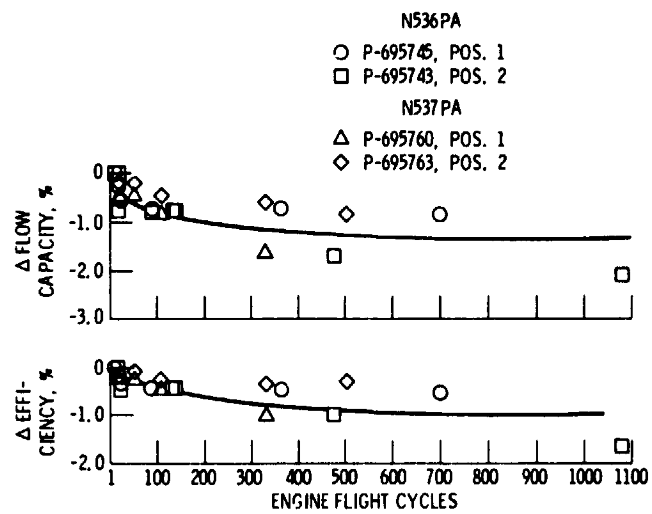

Figure 9. - Low-pressure compressor performance deterioration.

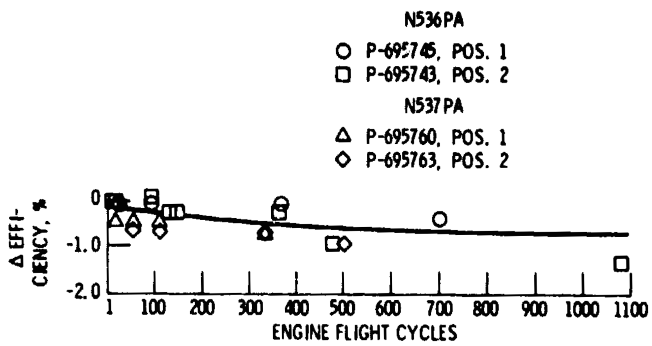

Figure 10. - High-pressure compressor performance deterioration.

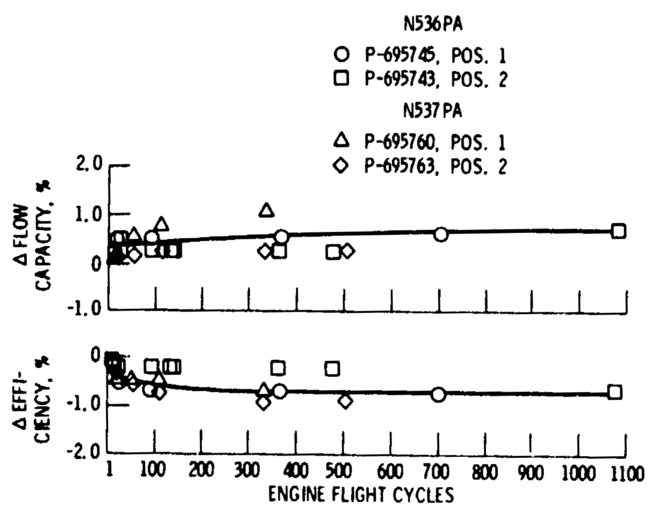

Figure 11. - High-pressure turbine performance deterioration.

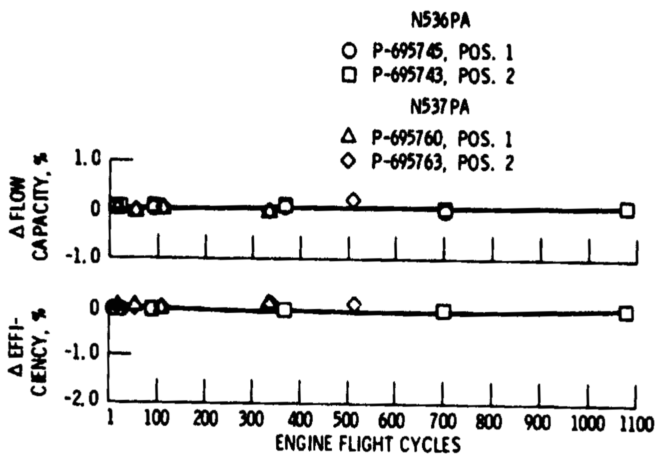

Figure 12. - Low-pressure turbine performance deterioration.

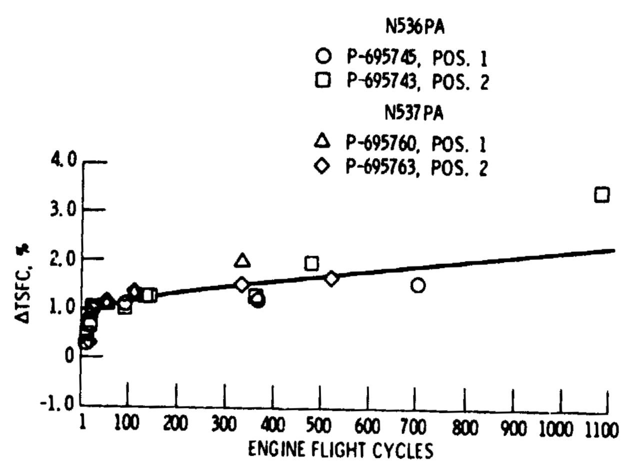

Figure 13. - Estimated sea level static TSFC deterioration.

MODULE/COMPONENT	CHANGE IN TSFC, %		
	50 CYCLES	150 CYCLES	500 CYCLES
FAN	0.20	0.25	0.30
LOW-PRESSURE COMPRESSOR	.25	.40	.60
HIGH-PRESSURE COMPRESSOR	.10	.20	.30
HIGH-PRESSURE TURBINE	.40	.50	.60
LOW-PRESSURE TURBINE	0	.05	.15
TOTAL	0.95	1.40	1.95
HIGH-PRESSURE SPOOL	0.50	0.70	0.90
LOW-PRESSURE SPOOL	.45	.70	1.05
COLD SECTION	0.55	0.85	1.20
HOT SECTION	.40	.55	.75

Figure 14. - Average module contribution to sea level static long-term TSFC deterioration.

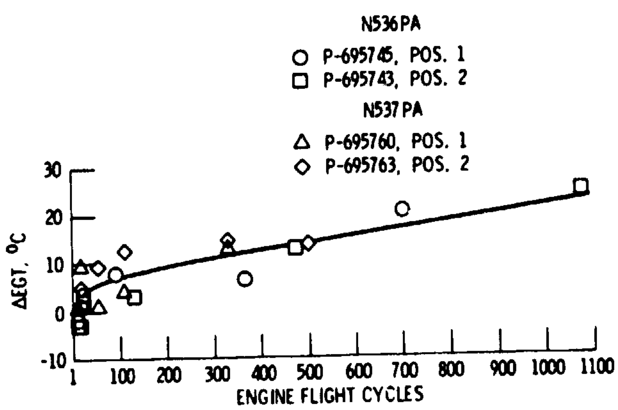

Figure 15. - Estimated sea level static EGT deterioration.

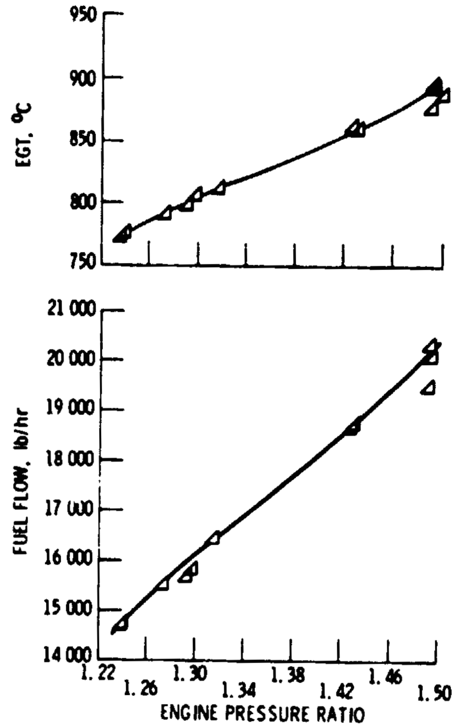

Figure 16. - In-flight calibration of JT9D-7A(SP) engine P-695738 on airplane N536PA; fuel flow and EGT.

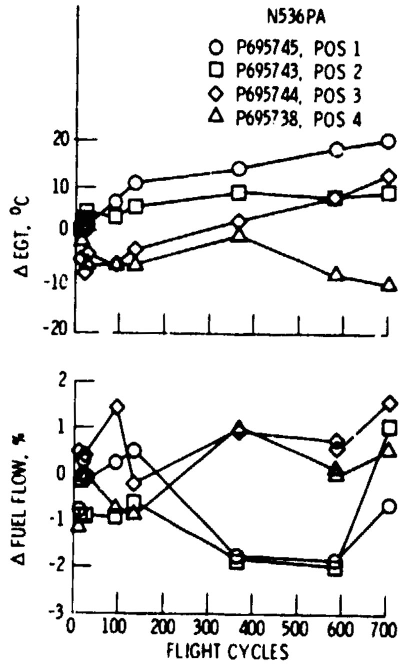

Figure 17. - Change in fuel flow and EGT versus usage for airplane N536PA.

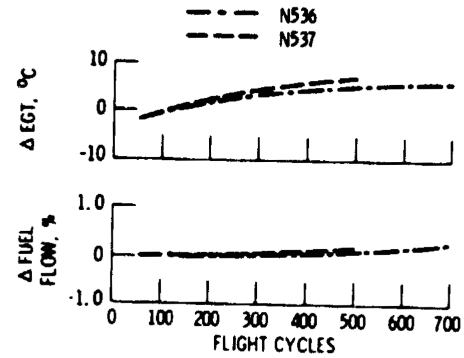

Figure 18. - Comparison of airplane four-engine averages of Δ fuel flow and Δ EGT determined by in-flight calibrations.