ENGINE HEALTH MONITORING SYSTEMS

TOOLS FOR IMPROVED MAINTENANCE MANAGEMENT IN THE 1980's

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ABSTRACT

The increased cost of fuel has placed an added importance on the "performance health" of commerical aircraft engines and greater emphasis on the performance-monitoring aspect of maintenance. This paper presents an overview of Engine Health Monitoring activities at Pratt & Whitney Aircraft. The development of Engine Health Monitoring, a description of systems currently used, and a summary of programs for improved monitoring in the 1980's are discussed.

INTRODUCTION

The first generation of commercial gas turbine engines (early JT3D and JT8D models) was largely maintained on a "hard time" or "as required" basis. Engine maintenance was performed when certain parts achieved a predetermined life limit (hard time) or when specific symptoms indicated maintenance was needed (as required).

Hard-time maintenance employs the same maintenance schedule for all similar engines. Since no two engines perform exactly alike, the schedule is based on an "average engine." Differences in engine performance may be the result of manufacturing variations and variations in engine mission and service experiences. Some engines may become fuel inefficient although safe and capable of continued operation.

There is, therefore, a need for scheduling maintenance on an on-condition, individual basis. Engine Health Monitoring satisfies this need by continually monitoring engine performance and providing the diagnostic tool for interpreting changes in performance in terms of maintenance requirements.

ENGINE HEALTH MONITORING AND FUEL COSTS

The repairing and refurbishing of engines at fixed intervals or when required has long been a standard practice in the airline industry and will probably persist at many airlines. These procedures have two advantages: 1) they are easily managed and 2) as-required maintenance tends to result in engines remaining on the wing for longer periods. However, these practices do not emphasize minimizing fuel costs.

Engine Health Monitoring can provide visibility into the performance levels of each engine, allowing better maintenance planning, as illustrated in figures 1, 2. Figure 1 shows a typical cycle of engine operation and repair, and figure 2 shows a repair schedule customized to the performance level of each engine. Fuel savings is the primary benefit. Since all engines do not deteriorate at equal rates, hard-time maintenance results in engines with high fuel consumption remaining in service too long and engines with low fuel consumption being repaired or refurbished too soon.

Using a system of Engine Health Monitoring to provide a customized maintenance schedule for each engine has benefits in addition to fuel savings. Lower overall maintenance costs are possible because engines with the highest deterioration levels will be repaired rather than left in service where they would be exposed to increasingly high turbine temperatures. Similarly, lower repair costs on engines with the lower deterioration levels can result by deferring the repair. An additional benefit of engine monitoring is greater reliability. Many developing engine problems can be foreseen with an engine monitoring system.

High fuel costs increase the need for determining repair requirements on an engine-by-engine basis with visibility from an Engine Health Monitoring system. The effect of fuel cost on repair interval is illustrated in figures 3, 4, 5. The total engine operating cost per flight cycle is the sum of the repair cost and fuel cost (fig. 3). As the time between repair increases within a reasonable range, repair costs per flight hour decrease and fuel costs increase, resulting in an interval of engine repair time over which total operating costs are minimized. Higher fuel costs shorten the optimum repair time and narrow the optimum band (fig. 4). Since the performance of each engine varies, the optimum repair intervals for individual engines are not the same (fig. 5).

Engine Health Monitoring can determine which engines require early or deferred maintenance to provide the lowest total operating cost.

DATA ACQUISITION SYSTEMS FOR AIRBORNE ENGINE HEALTH MONITORING

Systems used in flight to acquire data for Engine Health Monitoring vary considerably in both complexity and capability. The four systems most widely used by airlines today are illustrated in figure 6.

The most basic system (System 1) is also the system most commonly used today. The flight crew manually records the data, which can then be processed either manually or by computer.

Automated data acquisition systems expand on the capabilities of the mandatory flight data acquisition unit and digital flight data recorder. In System 2 (fig. 6) a flight data entry panel allows the crew to input documentary data (date, engine time, etc.) to the system. Data is recorded on cassettes (by means of the quick access recorder), which are easily removed for processing at a ground station and analyzed by computer.

An important addition to the data acquisition system is the on board computer, data management unit, which allows the system to perform many additional functions. With this unit the system can record data selectively, looking for appropriate parameter range and stability criteria. It can also make calculations and provide results to the crew by means of an on-board printer. If desired, the computer can scan the data and notify the crew of limits that have been exceeded. In system 3 (fig. 6), data acquisition is controlled by the data management unit, and the data is recorded with the on-board printer.

System 4 (fig. 6) is the most complex and capable of the in-flight data acquisition systems. Data recording is controlled by the data management unit. There is also an auxiliary data acquisition unit for more extensive analyses. Data can be stored on the quick access recorder (cassette) or on printouts from the on-board printer. The data is normally processed by computer, but can be analyzed manually if desired.

Automated data acquisition systems have, however, experienced a variety of problems. Problems have been experienced with unreliable instrumentation and inaccurate data, burdensome calibration and maintenance requirements, and difficulty with data management.

In order to improve the reliability and accuracy of the data acquired during flight, Pratt & Whitney Aircraft and Hamilton Standard jointly developed the Propulsion Multiplexer, an integral engine data acquisition system for acquiring the high quality data required for module performance analysis. The Propulsion Multiplexer (fig. 7) is a compact, durable system, housing pressure transducers, a microprocessor, and all required electronics for acquiring and sending multiplexed engine data to a recording device, such as the Airborne Integrated Data System.

INTERPRETATION OF ENGINE DATA ANALYSIS APPROACHES

Techniques for analyzing engine data obtained in flight or in test cells can be catagorized as follows:

- Limit Exceedance Checking
- Parameter Trend Monitoring
- Module Performance Analysis
- Turbine Life Accounting

Checks of specific engine parameters for operation in excess of limits is a fundamental requirement of post repair engine testing. In the test cell, compliance with engine limits indicates that an engine is suitable for service. Limits exceeded in flight can be monitored with an Airborne Integrated Data system. The information can provide cautionary warnings to the flight crew (similar to such warnings as low oil pressure) or help to define maintenance actions (as with Exhaust Gas Temperature exceedances).

Graphic display of key engine parameters is the most common method of monitoring the health trends of an engine in service (airborne data) or the performance trends of post-repair engines (test cell data). These plots provide indications of engine performance trends or instrumentation malfunctions.

The Engine Condition Monitoring Computer Program developed by Pratt & Whitney Aircraft has long been widely used to provide graphical parameter trends to improve visibility of the health of engines during service. The program can be used with all Pratt & Whitney Aircraft commercial engines and can operate with flight data acquired either manually or automatically. Manual data is recorded by the flight crew and then processed at a later date. Automatically recorded data is provided by an Airborne Integrated Data System.

The output of the Engine Condition Monitoring Program of primary importance to the user is the "plot report," which presents chronological trends of engine parameter shifts (fig. 8). Because engine parameter shifts are highly visible on the plot report, timely detection of developing engine problems is possible. The report also provides visibility into the long term deterioration trends of an engine or fleet and allows detection of large errors in measured parameters.

The primary advantage of the program is that a large amount of information about engine condition can be obtained without additional engine or airframe hardware, providing considerable benefits with little cost. A limitation to the program is that although it can recognize that a problem has occurred, it can not diagnose the cause. The user must apply judgment to determine the nature of the problem, and if necessary, request further investigation with other troubleshooting methods. For example, an experienced analyst would be required to distinguish between a bleed valve malfunction, a damaged engine module, or an error in measured engine pressure ratio.

Module Performance Analysis is a technique for using measured engine parameter shifts to determine specific engine module performance changes. This process can be illustrated using the example in figure 9. Measured parameter changes are first determined (shift in corrected high rotor speed ($\%\Delta N_2$) at a constant engine pressure ratio, for example). The analysis is used to calculate the most likely cause of these shifts, such as deterioration in high-pressure turbine efficiency. Finally, the shift in key parameters attributable to each module can be calculated. For example, exhaust gas temperature may have increased by 20°C relative to a new engine. The analysis will tell a user how this 20°C can be accounted for (e.g., 10°C due to high-pressure turbine deterioration, 5°C to fan performance losses, and 5°C to low-pressure compressor performance losses), thus indicating areas that may need maintenance.

Module Performance Analysis is currently most often used with test cell data as a tool for evaluating the effectiveness of a repair. The analysis is also used on prerepair data specifically acquired to help define shop work scope. The JT9D Test Cell Module Analysis Program, developed for analysis of JT9D engine data acquired in the test cell, combines a sea level data reduction system with module performance analysis and data validity screening. The program is very flexible, accomodating varied data input, analysis baselines, and test cell corrections. A sample output is shown on figure 10.

Module Performance Analysis systems have also been developed for use with data acquired in flight with an Airborne Integrated Data System. Data for inflight module performance analysis, including the additional parameters required for module performance analysis, must be recorded automatically by an airborne data system. The on-board computer of this system selects what data is to be recorded based on predetermined ranges of engine and aircraft parameters (data acquisition windows) and parameter stability criteria. Data from the airborne system may be manually input to the airborne module performance analysis program using data from an on-board printer or automatically using data transferred from an on-board recorder.

A typical program output, the module analysis plot report, is shown in figure 11. This report presents graphical trends of performance changes of each module in a highly visible format even if a module has been installed on a different engine.

The program can provide many benefits to a user. Knowledge of the performance of each module can be helpful in making maintenance decisions. For example, if an engine has a history of high exit gas temperature, the plot tells whether the high temperature is caused by the high-pressure compressor or the high-pressure turbine, or both. Appropriate maintenance can be planned. The In-flight Module Performance Analysis can be a useful tool for troubleshooting engine problems on the wing and can assist in improving shop scheduling.

The JT9D Airborne Integrated Data System/Module Performance Analysis Program is currently being used and evaluated at four major airlines. The program is emerging from the developmental stage and may soon be considered a developed engine monitoring tool.

Special attention must be paid to instrumentation in order to successfully perform module performance analysis. Parameters not normally measured are needed, as shown in Table I. In addition to the parameters normally acquired, temperatures at the discharge of the low-pressure compressor, high-pressure compressor, and low-pressure turbine are measured.

Special emphasis on data accuracy is also required for reliable Module Performance Analysis results. For example, if a fuel flow measurement is used only to determine engine suitability for service, a measurement error of 2% may go unnoticed. If the data is to be used for module performance analysis, a 2% error in fuel flow may be misinterpreted as an engine performance shift. Although the analysis systems now available have provisions for detection of erroneous data, a greater emphasis on data quality is necessary.

Module performance analysis capability, therefore, is an extremely useful engine maintenance tool. The use of module performance analysis with data from either a test cell or an Airborne Integrated Data System requires a commitment to additional instrumentation, closer instrumentation accuracy monitoring, and personnel trained in module performance analysis interpretation and use.

A Life Accounting Program can be used to calculate the fraction of life consumed for any set of critical high-pressure turbine airfoils. Since all routes are not equally severe on high-pressure turbine airfoils, large variations in part lives can exist. The life accounting program calculates the amount of life consumed for each critical airfoil, using analytical models of airfoil deterioration. The program can run as a subroutine of the Airborne Integrated Data System/Module Performance Analysis Program, using the accumulated time exposure of the parts to temperature, pressure, and rotor speed. The program can also be run by itself without airborne data, using the specific route structure and engine derate experience as input. A typical output from the life accounting program is shown in figure 12.

The primary purpose of the program is to maximize airfoil service life while minimizing the possibility of turbine damage. The program can also assist in efficiently scheduling hot-section maintenance, controlling inventories of airfoils, and in better planning of the hot-section assembly (e.g., a turbine could be assembled with airfoils having similar amounts of life remaining).

FUTURE TRENDS

Increasing airline fuel and maintenance costs have resulted in greater airline interest in Engine Health Monitoring. Since many aspects of this process can be addressed most efficiently by the engine manufacturer, Pratt & Whitney Aircraft is committed to providing superior Engine Health Monitoring system support.

A special emphasis will be placed upon data quality in future engine health monitoring systems. A common shortcoming of engine monitoring systems today is that analysis algorithms, although accurate, are unacceptably sensitive to sensor errors. The approach to data validity must be three fold:

1) encourage the development and proper use of accurate data measurement systems

2) develop software routines that recognize and report probable data errors for follow-up maintenance actions

3) design algorithms to be as insensitive to data errors as possible.

Present plans are to continue to develop and refine analysis software routines and to monitor current systems, making improvements where required. We will work with customers to define ways of monitoring different aspects of engine operation. Current systems now stress gaspath performance monitoring, but efforts are underway to increase the capability of monitoring the mechanical integrity of the engine and its subsystems, such as oil and bleed systems.

Table I
INSTRUMENTATION REQUIRED FOR JT9D TESTING AND MODULE PERFORMANCE ANALYSIS

		Normally Measured On Test Cell	Required For MPA
P_{T2}	Engine Inlet Total Pressure	X	X
P_{T3}	LPC Discharge Total Pressure	X	X
P_{s3}	LPC Discharge Static Pressure	X	
P_{s4}	HPC Discharge Static Pressure	X	X
P_{s5i}	Turbine Cooling Air Static Pressure	X	
P_{T7}	LPT Discharge Total Pressure	X	X
T_{T2}	Engine Inlet Total Temperature	X	X
T_{T3}	LPC Discharge Total Temperature		X
T_{T4}	HPC Discharge Total Temperature		X
T_{T6}	HPT Discharge Total Temperature	X	X
T_{T7}	LPT Discharge Total Temperature		X
F_N	Engine Total Net Thrust	X	X
N_1	Low Rotor Spool Speed	X	X
N_2	High Rotor Spool Speed	X	X
W_F	Fuel Flow	X	X
β	HPC Variable Stator Vane Bellcrank Angle	X	X

"Hard time" maintenance works well for the "average engine" and if fuel is inexpensive

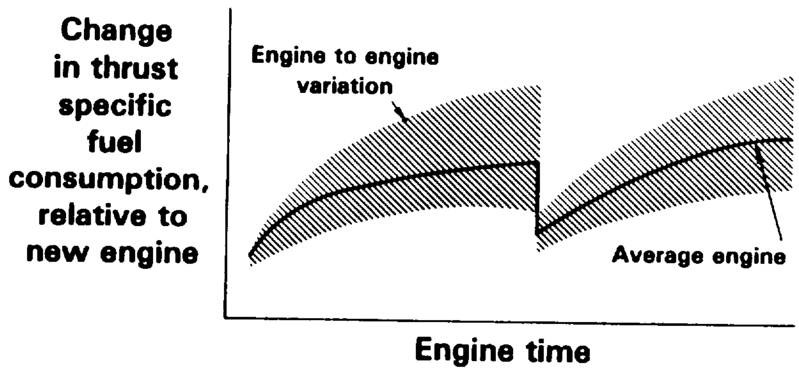

Figure 1 Typical Cycle of Engine Operation

FUEL SAVINGS RESULT IF ENGINE REPAIR IS SCHEDULED BASED ON ACTUAL ENGINE CONDITION

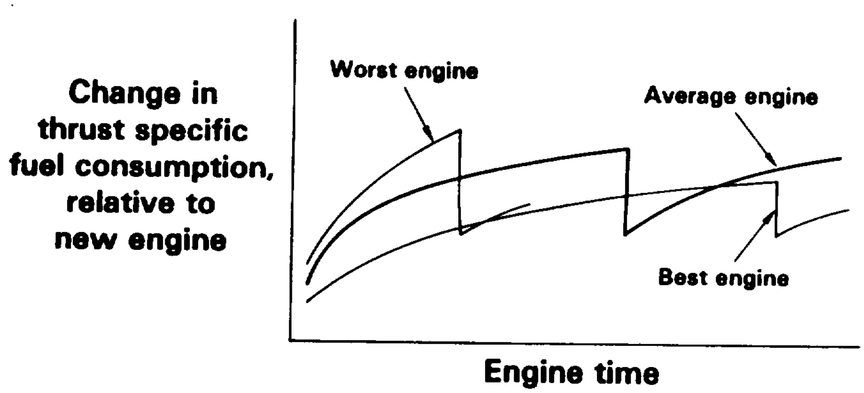

Figure 2 Repair Schedules Customized for Worst and Best Engines Compared With Schedule Based on Average Engine

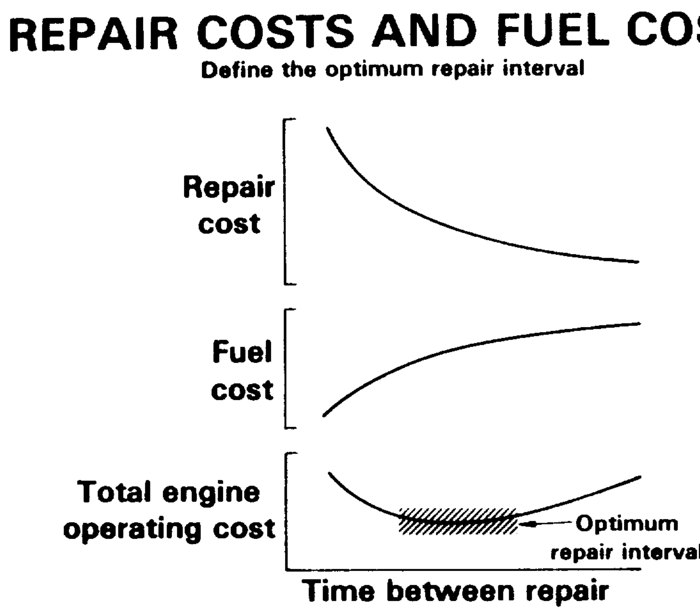

Figure 3 Effect of Time Between Repair on Repair Cost, Fuel Cost and Total Operating Cost

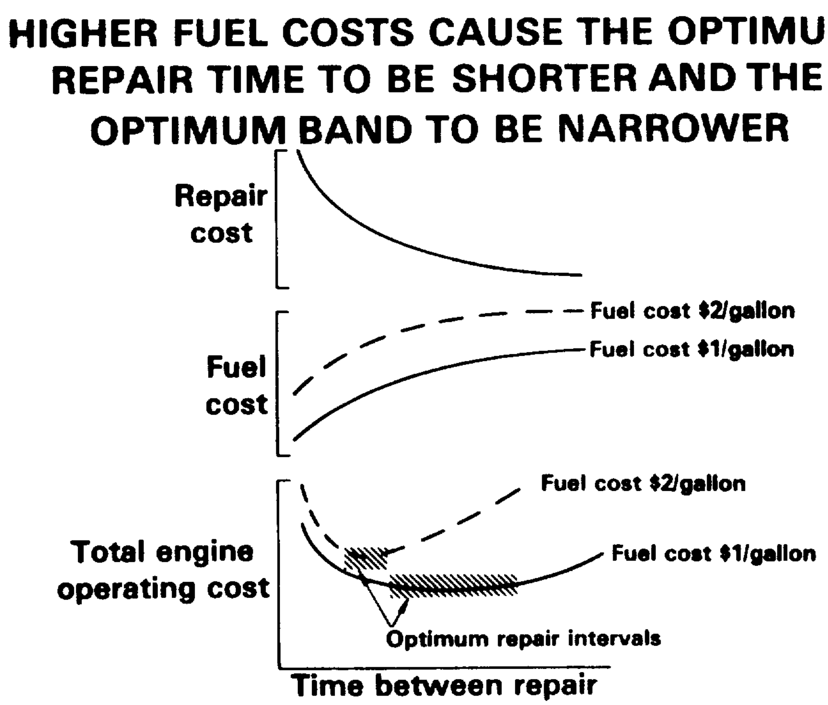

Figure 4 Effect of Fuel Cost on Optimum Repair Interval

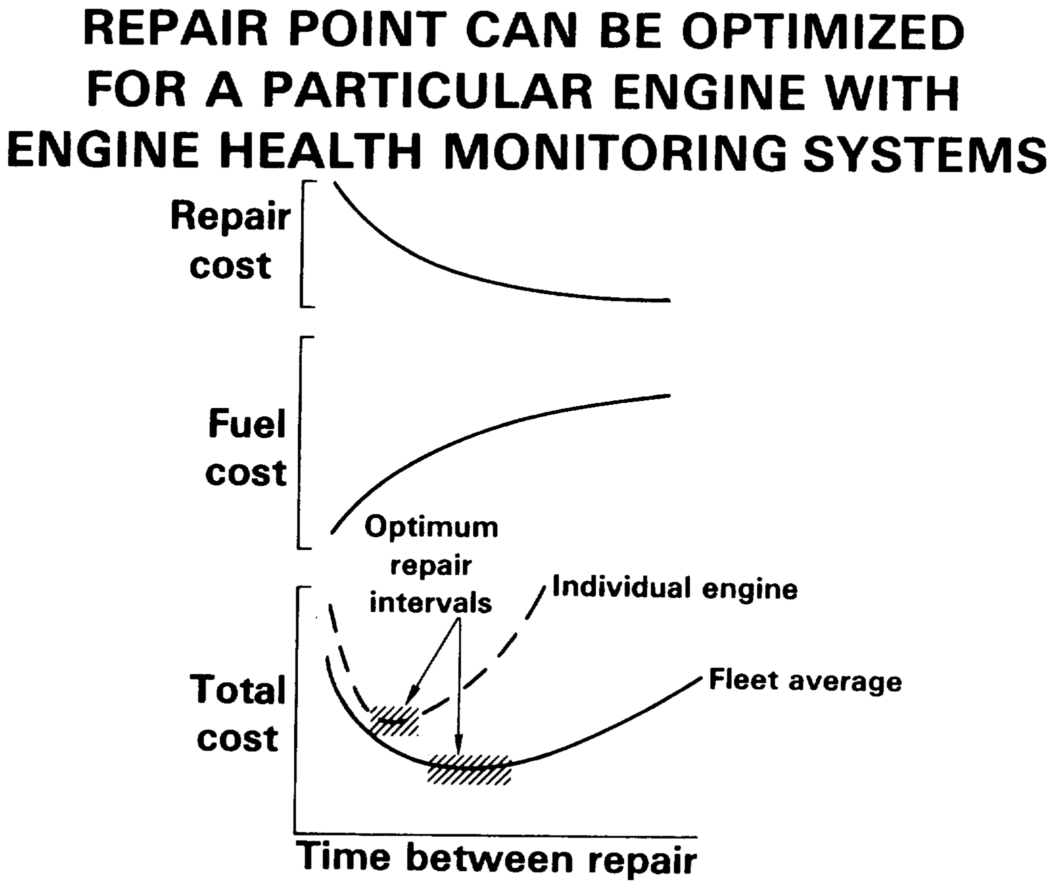

Figure 5 Comparison of Optimum Repair Intervals for Individual and Fleet Average Engine

AIRLINES USE VARIOUS DATA SYSTEMS

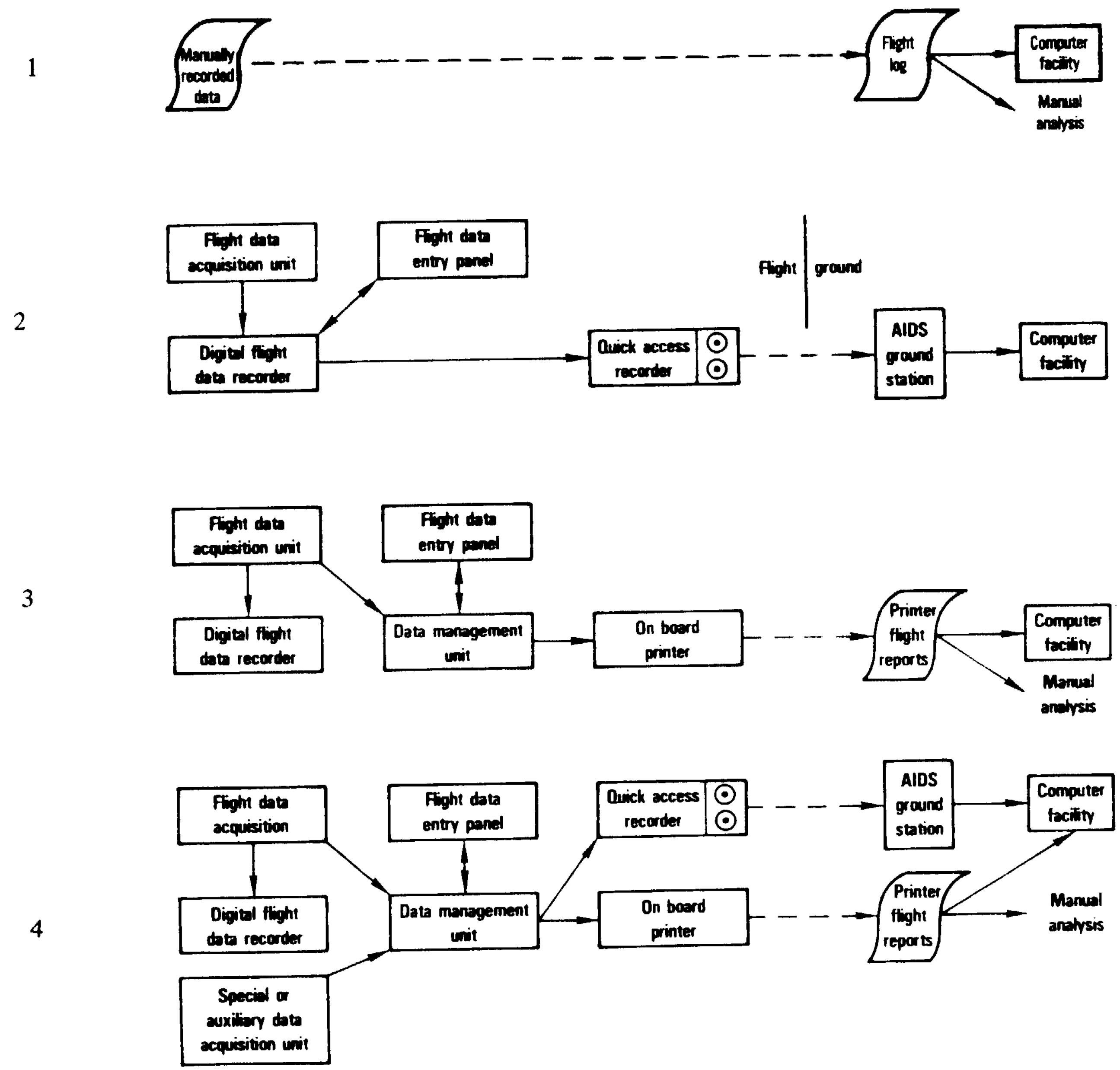

Figure 6 Various Data Acquisition Systems

THE JT9D MULTIPLEXER IS A COMPACT, DURABLE UNIT

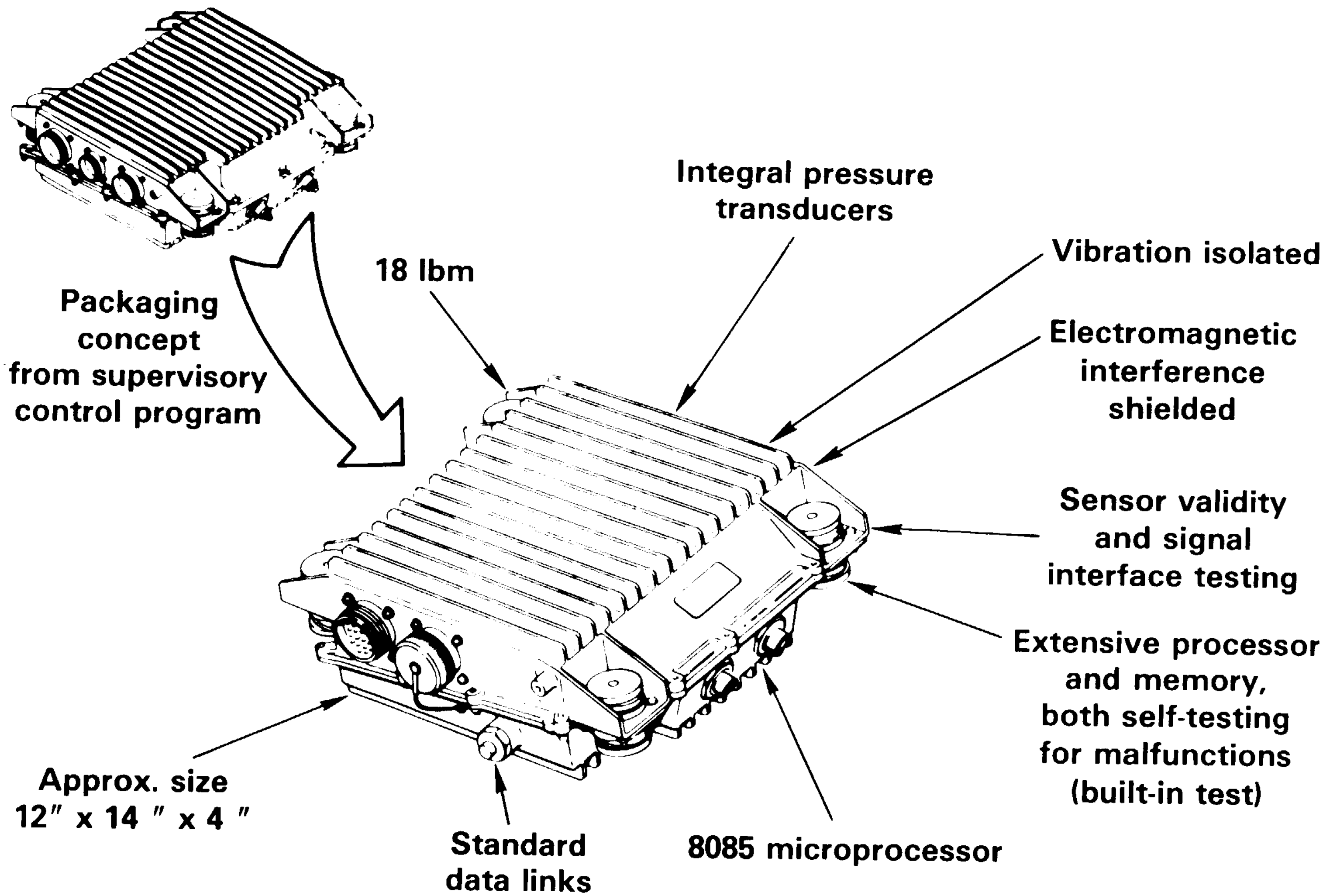

Figure 7 JT9D Compact, Durable Multiplexer

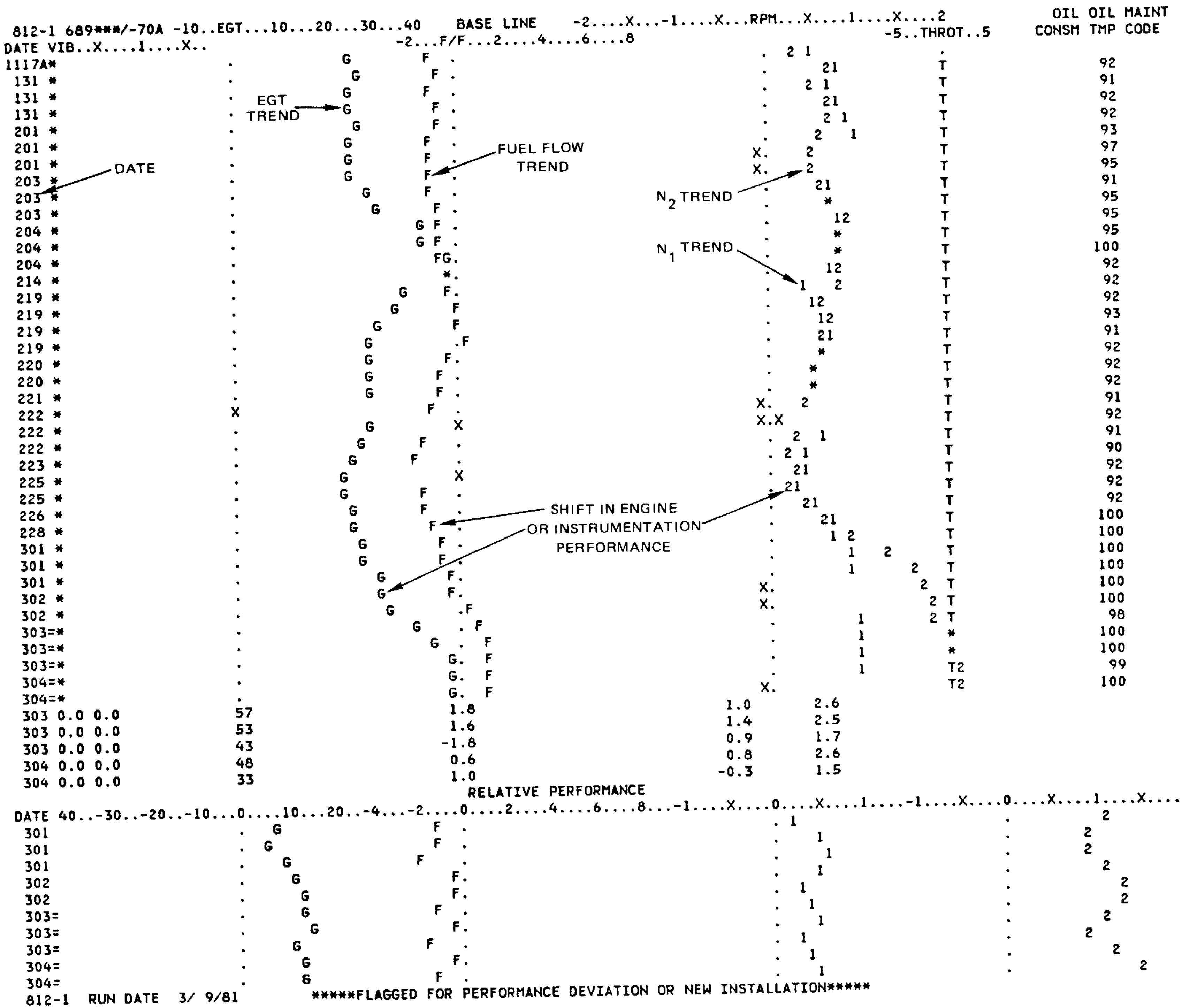

Figure 8 Sample Plot Report Showing Typical Engine Condition

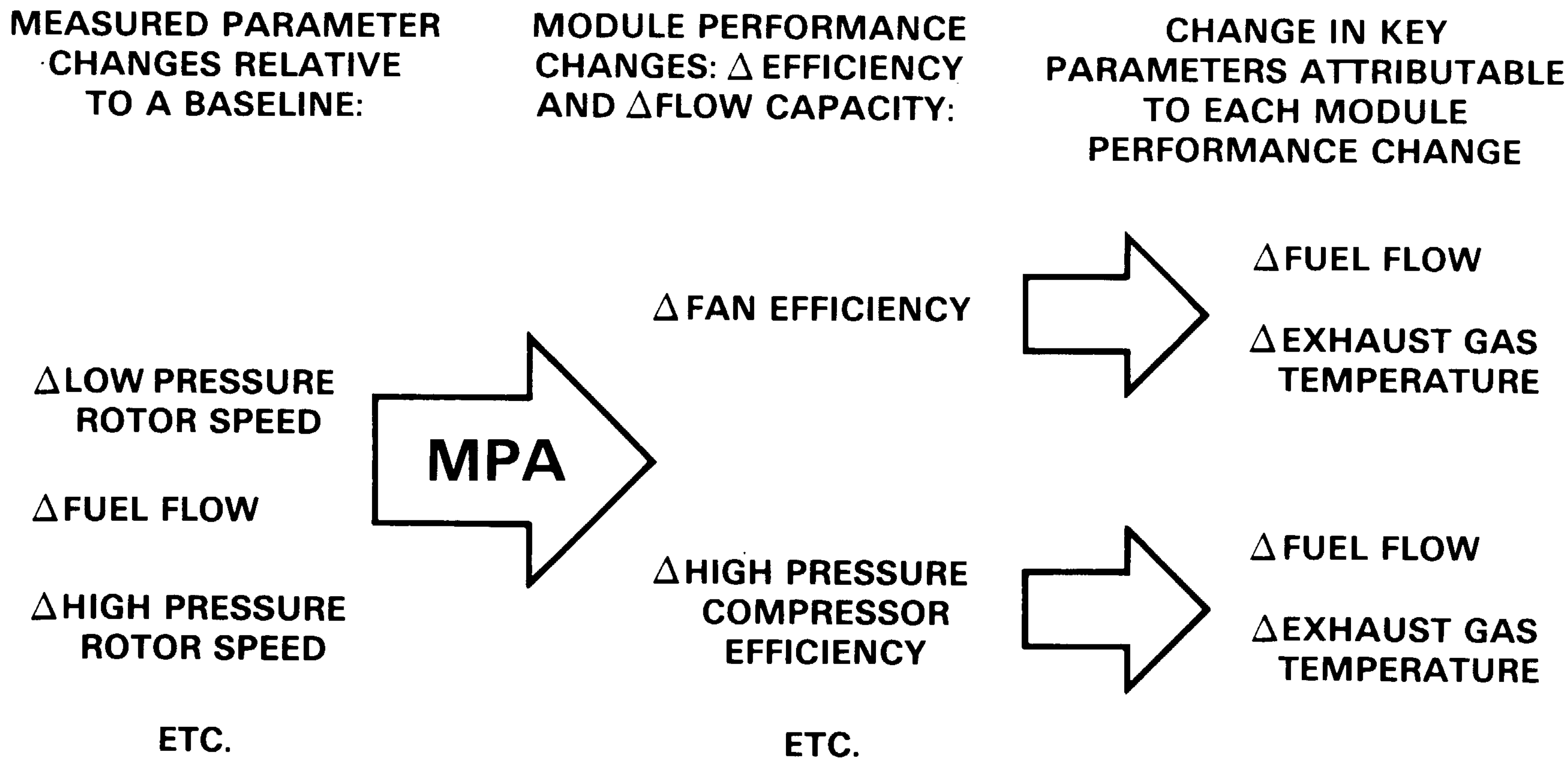

Figure 9 Module Performance Analysis Example: Analysis Determines Amount Each Engine Modules Contributes to Performance Change

POST REFURBISHMENT FOLLOWING 8 JULY 80 UER 13450 3933 A

OPERATOR: ENGINE MODEL: JT9D-3A SERIAL NUMBER: P-****** DATE: 101980

****
******* ANALYZED MODULE ASSESSMENTS *******
****

ETA FAN	FAN FCAP	ETA LPC	LPC FCAP	ETA HPC	HPC FCAP	ETA HPT	EFF A5	ETA LPT
0.1%	-0.6%	-0.5%	-0.7%	-0.1%	-0.6%	-1.1%	1.6%	-0.0%

****
******* RAW PARAMETER DIAGNOSTICS *******
****

NO RAW PARAMETER ERRORS DETECTED.

****
******* OUTLIER DIAGNOSTICS *******
****

THE VALUE OF N1/ROT2 FOR POINT NUMBER 1 HAS BEEN REJECTED AS A PROBABLE OUTLIER.

THE VALUE OF WF/KCST2KH FOR POINT NUMBER 1 IS A POSSIBLE OUTLIER.

****
******* CONFIGURATION DIAGNOSTICS *******
****

ANALYSIS ENGINE DATA CONFIGURATION ADJUSTED TO BASELINE BMOD.

ANALYSIS ENGINE DATA CONFIGURATION ADJUSTED TO BASELINE A6CL.

****
******* LARGE PARAMETER DIAGNOSTICS *******
****

NO LARGE PARAMETER ERRORS DETECTED.

****
******* PRIMARY NOZZLE AREA DIAGNOSTICS *******

Figure 10 Typical Output From JT9D Module Analysis Program

16/ 2/81

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        ACFT ID   ##*   ENG SER NO   702***   ENG POS  1   A/C TYPE  B747   ENG TYPE   -7Q
                 FAN               LOW PRES COMP          HIGH PRES COMP       HIGH PRES TURB          LOW PRES TURB
                                    S/N A  2****           S/N B  2****         S/N C  2****           S/N D  2****
             PERF  (F)               PERF  (A)              EFF  (E)             PERF  (C)              PERF  (D)
                                                            F/C  (W)
DATE                        -4..-3..-2..-1...0...1...2                 -4..-3..-2..-1...0...1...2
      -4..-3..-2..-1...0...1...2             -4..-3..-2..-1...0...1...2                 -4..-3..-2..-1...0...1...2
                   702***                    702***                   702***                   702***                   702***
 1/ 1              F                         A                        *                        C                        D
 7/ 1              F                         .A                       *                        .C                       D
14/ 1              F                        A.                        WE                       C                        . D
21/ 1              .F                        .A                       *                        C                        .D
27/ 1              F                         A                        *                       C.                        .D
 1/ 2              F                        A.                        WE                       C                        .D
 7/ 2              F                         A                        WE                      C.                        .D
15/ 2              .F                        .A                       *                       C.                        .D
22/ 2              .F                       A.                        WE                       C                        . D
 1/ 3              .F                       A.                       EW                        C                        .D
 8/ 3              .   F                     A                        *                        .C                       .  D
15/ 3              F                       A .                        WE                      C.                        .D
22/ 3              F                        A.                        WE                      C.                        .D
 1/ 4             F.                      A  .                        *                        .C                      D.
 8/ 4             F.                      A  .                        *                        .C                      D.
15/ 4              .F                       A.                        *                       C.                        .D
22/ 4             F.                       A .                        *                        .C                      D.
 1/ 5              . F                     A .                      * .                        C                        .D
 8/ 5              F                      A  .                     WE .                       C.                       D
15/ 5              .F                    A   .                     WE .                       C.                        .D
22/ 5              .F                      A .                      W E                        C                        .D
 1/ 6              F                    A    .                    WE .                         .C                      D
 8/ 6              F                     A   .                      * .                        .C                      D
15/ 6              F                     A   .                     WE .                        C                        . D
22/ 6              .F                      A .                      * .                        C                        .D
 1/ 7              F                     A   .                      * .                      C .                        .D
 8/ 7              F                    A    .                     WE .                       C.                        .D
15/ 7              F                    A    .                     WE .                      C .                        .D
22/ 7              .F                     A  .                      * .                      C .                        .D
 1/ 8              .F                 A      .                     WE .                      C .                        . D
 1/ 8              .F                   A                           EW                       C .                        .D
 8/ 8              .   F                  A  .                      * .                       C.                        .  D
15/ 8              F                   A     .                     WE .                    C   .                        .D
22/ 8              F                    A    .                     WE .                     C  .                        .D
 1/ 9             F.                   A     .                      * .                       C.                       D.
 8/ 9             F.                   A     .                      * .                      C .                       D.
15/ 9              .F                    A   .                      * .                    C   .                        .D
22/ 9             F.                      A  .                     *  .                      C .                       D.
 1/10              . F                A      .                     *  .                     C  .                        .D
 8/10              F                   A     .                    WE  .                    C   .                       D
15/10              .F                 A      .                    WE  .                    C   .                        .D
22/10              .F                 A      .                    W E .                     C  .                        .D
 1/11              F                   A     .                   WE   .                    C   .                       D
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ENG S/N 702*** HAS NO DATA ON FILE

Figure 11 Typical Output From Airborne Integrated Data System/Module Performance Analysis System

L I F E   A C C O U N T I N G   P R O G R A M   R E P O R T   O N E

AIR-CRAFT ID	P	-7A ENGINE NUMBER	FAIL MODE = 1V PART-NUMBER	AMT	PCNT USED	LOT NO	FAIL MODE = 1BCF PART-NUMBER	AMT	PCNT USED	LOT NO
8126	1	685709	[illegible]	66	30.1		773441	116	45.3	
	2	685791	76027	66	22.1		773531	116	22.2	
	3	686015	[illegible]	15	10.1		773441	100	88.2	
			75275	51	0.1		773441	16	22.2	
			[illegible]	0	0.0		0	0	0.0	
	4	685706	[illegible]	5	0.1		773441	2	40.2	J
			[illegible]	[illegible]	60.1		773441	5	90.2	I
				0	0.0		773441	5	80.2	H
			0	0	0.0		773441	10	70.2	G
				0	0.0		773441	20	60.2	F
				[illegible]	0.0		773441	3	50.2	A
				0	0.0		773441	4	30.2	K
			[illegible]	0	0.0		773441	1	20.2	C
			0	[illegible]	0.0		773441	9	10.2E	F
			0	0	0.0		773441	7	5.2E	Q

AIR-CRAFT ID	P	-7A ENGINE NUMBER	FAIL MODE = 1BOC PART-NUMBER	AMT	PCNT USED	LOT NO	FAIL MODE = 2V PART-NUMBER	AMT	PCNT USED	LOT NO	FAIL MODE = 2B PART-NUMBER	AMT	PCNT USED	LOT NO
8126	1	685709	773441	116	55.3		735882	90	15.2		770102	66	10.1	
	2	685791	773531	116	33.3		772572	90	41.1		770102	138	15.0	
	3	686015	773441	100	92.3		735882	30	10.1		770102	138	60.1	
			773441	16	30.3		735882	30	20.1		0	0	0.0	
			0	0	0.0		772572	30	30.1		0	0	0.0	
	4	685706	773441	2	5.3	J	735882	90	60.1		770102	138	0.0	
			773441	5	30.3	I	0	0	0.0		0	0	0.0	
			773441	5	25.3	H	0	0	0.0		0	0	0.0	
			773441	10	20.3	G	0	0	0.0		0	0	0.0	
			773441	20	15.3	F	0	0	0.0		0	0	0.0	
			773441	3	10.3E	A	0	0	0.0		0	0	0.0	
			773441	4	0.3	K	0	0	0.0		0	0	0.0	
			773441	1	0.3	C	0	0	0.0		0	0	0.0	
			773441	9	0.3	F	0	0	0.0		0	0	0.0	
			773441	7	0.3	Q	0	0	0.0		0	0	0.0	

ID	P	-7Q	FAIL MODE = 1V PART-NUMBER	AMT	PCNT USED	FAIL MODE = 1BOC PART-NUMBER	AMT	PCNT USED
8130	1	702043	[illegible]	[illegible]	12.2	778741	100	54.3
	2	702044	[illegible]	62	12.2	778741	100	54.3
	3	702045	774281	62	12.2	780441	100	54.3
	4	702062	[illegible]	[illegible]	12.1	780441	100	53.6

Figure 12   Typical Output From Life Accounting Program