

ENGINE HEALTH MONITORING - AN ADVANCED SYSTEM*

R.J.E. Dyson
General Electric Company

INTRODUCTION

The Advanced Propulsion Monitoring System (APMS) described in this paper fulfills a growing need for effective engine health monitoring. This need is generated by military requirements for increased performance and efficiency in more complex propulsion systems, while maintaining or improving the "cost to operate." This program represents a vital technological step in the advancement of the state-of-the-art for monitoring systems in terms of reliability, flexibility, accuracy, and provision of user-oriented results. It draws heavily on the technology and control theory developed for modern, complex, electronically controlled engines and utilizes engine information which is a by-product of such a system.

The General Electric Company has participated, and is participating, in a number of military and commercial engine health monitoring efforts which serve as a basis for this program. Most of the existing military systems would require a costly retrofit program of relatively mature vehicles with resultant cost, weight and space penalties. Therefore, this program is designed to progress concurrently with technologically advanced engines and electronic systems so that maximum advantage can be obtained from early development testing and then utilized in these engines and systems.

The intent of the APMS program is to demonstrate the usefulness of an efficient engine health monitoring system which ultimately could become part of a total aircraft data system. A concept for a future transport application is shown in Figure 1. One of the most important aspects is the development of MIL-STD-1553B data bus integration techniques which will be demonstrated in the APMS program. The system implementation will identify engine abnormalities, calculate and record engine life usage, and provide accurate and timely support information for flightline, intermediate and base maintenance personnel (see Figure 2 for a data flow schematic). With this equipment linked to a global data management network, as shown in Figure 3, an effective maintenance schedule and logistical support of an operational engine and weapons system can be realized. In short, APMS is being designed to support an On-Condition Reliability Centered Maintenance scheme.

* The work presented herein is being performed under a USAF-funded contract (No. F33615-79-C-2092) with Mr. K. R. Hamilton as the Project Engineer.

SYSTEM OVERVIEW

Several systems have adequately demonstrated the ability to acquire and record data but have suffered from shortcomings regarding the automatic analysis and presentation of useful data. Particular emphasis is being placed in the APMS program on three items:

- Improved result precision through data filtering, validation, and sensor degradation routines.
- Display simplicity and usefulness leading to increased system utilization.
- Life usage tracking information.

In the field of life usage tracking, the objective of this program is to collect and store sufficient data in the APMS processor to allow ground based determination of life consumption on specific life limited parts. This information could then ultimately be provided to the Comprehensive Engine Management System (CEMS) which would encompass the maintenance information, inventory accountability and technical information required by all levels of engine managers.

The specific purpose of the APMS program is to design, procure, and demonstrate an engine health monitoring system which utilizes, to the fullest extent, signals available from an electronic control. Other supplemental data required to provide useful information for all operational and maintenance levels will be acquired and integrated with the control information. In order to implement this, the following tasks will be performed:

- A comprehensive system operating analysis will be conducted in order to design a complete user-oriented system.
- The supplemental engine data will be handled by an on-engine signal conditioner and multiplexer (SCM) and transmitted, together with the control data, through a MIL-STD-1553B port or terminal.
- The flow of data on a MIL-STD-1553B data bus through a system of remote ports (terminals) will be demonstrated.
- An aircraft-type processor and memory will be provided for event detection, event storage, engine usage tracking, and acquisition of trend data.
- An off-engine support system will control the data bus, display flight-line data, store trend data, and obtain and process corroborating data. The plan for development and test of the APMS off-engine subsystem is shown in Figure 4.
- Software will be developed for the aircraft-type processor and the support system which will allow event, trend and engine usage data

to be acquired, stored and made available for subsequent ground processing.

- The functional capability of the total hardware/software system will be demonstrated by testing on an advanced engine and by subsequent data display and analysis.
- Software for the WPAFB ASD CYBER 175 computer to provide analysis of long-term trends, life usage, modular fault isolation, and parts tracking is being developed under a parallel contract.

DESIGN OBJECTIVES AND IMPLEMENTATION

The objectives of the Advanced Propulsion Monitoring System (APMS) are to demonstrate a system which identifies aircraft turbine engine operating abnormalities early to minimize secondary damage, optimizes scheduling of engine repairs, improves effective use of maintenance facilities, increases aircraft availability, and reduces operating cost. This will be achieved through monitoring of signals from engine-mounted sensors through an on-aircraft computer which acquires and stores data and provides engine health status to the flight crew and maintenance personnel. Due to the limited processing capability of this on-aircraft computer, further processing of the accumulated data by a ground-based central computer will be performed to establish long-term engine health trends and computed cyclic life expenditure of life-limited engine parts. See Figures 5 and 6 for operational application. Figure 5 shows a typical fighter application with engine health monitoring data on a dedicated data bus. Figure 6 shows the associated flight line and central computer equipment.

The ultimate objective of the APMS is installation in an operational aircraft to demonstrate the feasibility of the system. The current program however will address only the installation on a demonstrator engine to be run in a test cell (see Figure 7). Under this condition, the APMS off-engine system will be housed in a room adjacent to the test cell instead of the electronics bay of the aircraft.

All of the signals required for engine health monitoring will be obtained from the SCM through a MIL-STD-1553B data bus. The SCM will obtain data from the engine control and from supplemental condition monitoring sensors. It will condition and digitize all signals necessary for engine health monitoring and provide a MIL-STD-1553B interface.

The APMS can be divided into two subsystems for discussion purposes as follows:

On-Engine Data Acquisition Subsystem

This subsystem consists of the on-engine hardware, including sensors, cables, and the SCM with MIL-STD-1553B terminal. The SCM is capable of receiving digital data from a Full Authority Digital Electronic Control (FADEC) or analog data from an Augmentor/Fan Temperature (AFT) control. The following functions are performed on-engine:

- a. FADEC
 - Updates data every 10 ms.
 - Provides limited sensor screening and self test.
 - Furnishes digital output of control parameters.
- b. AFT (IF USED)
 - Provides analog output of control parameters.
- c. SCM
 - Interfaces with FADEC digital output or AFT control analog output.
 - Interfaces with additional required engine health monitoring sensors.
 - Provides signal conditioning where necessary.
 - Provides sensor range checks and channel filtering.
 - Interfaces with MIL-STD-1553B data bus, which is a military standard defining the requirements for digital, command/response time division multiplexing techniques on aircraft. It establishes uniform requirements and promotes standard digital interfaces.

Off-Engine Subsystem

This subsystem as shown in Figure 8 will acquire data through the digital data bus and will include the following:

- a. APMS Processor

This represents the aircraft-mounted computer and memory, and performs the following prime functions:

- Acquires engine data from SCM via the data bus.
- Acquires airframe-related data via the data bus.

- Provides data-sensor processing validation and filtering.
 - Recognizes conditions for taking trend and life usage data.
 - Performs exceedance checks and transmits limit exceedances to display via data bus.
 - Records event, trend and life usage data.
 - Downloads to data computer.
- b. Simulated Cockpit Display
- This will provide real time indication in the cockpit of critical limit exceedances and events. This hardware will be in demonstrator form in order to validate a concept which could be included in a future application.
- c. Air Data Signal Simulator Signals
- These signals would normally be available from the air data computer and will be obtained from the test cell or simulated by the air data signal simulator and transmitted to the data bus.
- d. Data Computer
- This data computer and its peripherals are laboratory-type equipment which in total perform the following functions:
- MIL-STD-1553B Bus Controller (see Figure 9 - Bus System)
 - Real Time Data Display
 - Flight Data Retrieval and Storage
 - Flight Line Data Display
 - Mission readiness from major cycles, minor cycles, time at temperature and total hours
 - Sensor failure
 - Manual event trigger
 - APMS loader and editor
 - Interface with the WPAFB CYBER 175

The most important task in the preliminary design is the System Requirement and Software Definition for data display, analysis and maintenance decisions. The definition of these requirements is an iterative process among General Electric, co-contractors, subcontractors and the Air Force and will

integrate needs and existing hardware into an acceptable package within the cost/schedule constraints. A critical system requirements review was held eight months after contract go-ahead so that hardware and software specifications could still be influenced yet not delay procurement and programming. A final critical detail review will be held at the conclusion of the design phase.

SYSTEM FUNCTIONAL DESCRIPTION

System requirements will define the comprehensive system concepts which will form the basis for the final design. The system functions can be broken down to the following functions for discussion purposes.

Parameter Signal Sources

It is planned that twenty-three engine parameter signals will be acquired from either the control or from CM sensors. These conditioned, digitized, and multiplexed signals will be transmitted to the APMS processor via the MIL-STD-1553B data bus. The parameters are shown in Figure 10.

In addition to the above, a number of aircraft signals will also be transmitted to the APMS processor via the MIL-STD-1553B digital data bus. These are shown in Figure 11. Other aircraft signals could be added if required for a specific application.

System Operation

The Advanced Propulsion Monitoring System (APMS) consists of data acquisition and processing hardware and associated software logic. The purpose of the APMS is to monitor installed turbine engine behavior, to detect start-up and in-flight malfunction events, to track engine life usage, and to assess long-term performance degradation.

The APMS program will demonstrate a test system configuration representative of a flight-type installation. The major components are described below.

Signal Conditioner/Multiplexer (SCM) - The SCM acquires, conditions, and processes engine sensor data for transfer to the APMS. It is an engine-mounted, fuel-cooled unit, based on a SBP 9900 microprocessor which performs the following functions:

- Interfaces with FADEC or AFT control and CM sensor set
- Obtains data every 10 milliseconds
- Performs circuit built-in test

- Performs range checks on non-FADEC data
- Performs channel filtering on 10 samples
- Performs stall detection
- Outputs conditioned, digitized, serialized data in MIL-STD-1553B format every 100 milliseconds.

APMS Processor - The APMS processor receives data via the 1553B data bus from the SCM and the air data signal simulator (ADSS). It issues event messages to the cockpit display and status panel regarding detected conditions. It selectively retains data for subsequent transfer to a ground processing unit. It performs the following functions:

- Minor Loop Processing (every 0.1 sec.)
 - Data Acquired every 0.1 sec.
 - Engineering units conversion
 - Sensor validation
- Major Loop Processing (every 1 sec.)
 - Diagnostic Functions
 - Median Calculated (9 readings)
 - Data Mode
 - Event Storage of Exceedances
 - Trend Storage of Stabilized Data
 - Mission Profile Corner Points Calculated
 - Life Usage Updated

Data Computer - The data computer provides the bus controller function to effect data transfer between APMS components every 0.1 second during normal running. It controls off-line data transfer, it provides bulk data storage, engineering access to the system, and controls data transfer (via telephone MODEM) to the central computer, a CYBER 175 at Wright Patterson Air Force Base (WPAFB). The data computer operates in one of the following modes which are descriptive of its functions:

- Load - Load APMS processor through RS232
- Run - Normal APMS operation

- Display - Current APMS 1 second data scan
- Record - SCM 100 millisecond data to disc
- Data Transfer - by file
 - Engine History
 - Trend
 - Takeoff
 - Mission Profile
 - Flight Record
 - Exceedance
- Life Usage Calculation

DATA ACQUISITION/ANALYSIS EMPHASIS

In addition to the emphasis placed on system requirements, on-engine electronics and central data bus implementation, certain areas of data acquisition and analysis have been identified for receiving special attention. Two of these areas will be discussed below.

Data Filtering

Statistical approaches are presently in use in overhaul test cells to assess the performance of engine components and to estimate measurement errors. These approaches are being developed for "on-wing" applications, some of which will be demonstrated in this APMS program.

"Filtering" works by augmenting the measurement data with additional information which is available to the analyst but has not traditionally been incorporated into analysis programs. This additional information includes:

- typical values of the measured parameters;
- a list of possible engine problems which could cause a change in performance (reduced efficiency or pumping capacity, etc.);
- a signature or pattern which tells how each of the potential problems would be reflected in the measured parameters;
- a standard deviation for each of the potential engine problems which indicates what magnitude of change might reasonably be expected;

- a standard deviation for each of the measurements which indicates what level of measurement error might reasonably be expected.

This extra information is used to interpret the actual measurements. If an engine problem has occurred, it will normally be reflected in several of the measurements, and, hence, the "filter" can look for the pattern to recognize the problem. Deviations which do not fit an expected pattern are attributed to measurement error. To express the same thought in a more rigorous way, the "filter" finds the most probable combination of engine problems and measurement errors to explain the observed measurements given the additional information identified above. Examples of unfiltered and filtered data are shown in Figures 12 and 13.

The data in both figures has been normalized to account for variations in power setting and environmental conditions (i.e., speed, Mach number, altitude, etc.). In Figure 13, in addition to filtering the data as described above, the initial data point has been defined as "zero" to facilitate identifying subsequent changes in efficiency.

Implementation of Engine Parts Usage Tracking

Background - The On-Condition Maintenance Concept (OCM) depends heavily on the ability to change or replace parts only when necessary to preclude in-service malfunction or performance deterioration. This requires that an accurate evaluation of the operating history of the engine and its components be available to the maintenance and logistics specialists.

To achieve this, engine operating parameters, which significantly affect the potential lives of engine components, must be monitored. Also, the serial numbers and installation history of parts subject to wear-out, maximum operating time, low cycle fatigue damage, or other limitations which are considered logistically important must be tracked.

Engines most recently introduced into the USAF inventory have been designed for the OCM concepts. Previous maintenance has been based on the requirement to perform teardown inspections and overhauls at prescribed engine flight-hour intervals (Hard Time). This normally requires the replacement of many items reaching predetermined time or cycle limits. This system does not provide for differentiation or discretion based on the severity of the exposure to life-consuming conditions. As an example, a simple time (hours) limit does not provide information on whether the time was accumulated at a high power setting or at a lower value which may have consumed less life. In the case of simple cycles (idle-max-idle), data is not normally available to identify the actual level of power extremes which may affect life consumption. In addition, other variations in power setting (80 percent to max, 90 percent to max, etc.) also consume life not accounted for in a gross measuring system.

To fully utilize the life potential of parts limited by low cycle fatigue, thermal fatigue, stress rupture, wear-out, operating time, etc., it is necessary to keep track of each part's operating exposure, location, and serial number. Assuming the life limiting parameters (cycles, hours, time at temper-

ature, etc.) have been established for each life limited part, and a system devised to collect the data, a system must be implemented which provides maximum utilization of this data for logistics and maintenance purposes.

Engine Usage Tracking Description - It is the objective of this program to acquire appropriate data in the APMS processor to allow future ground-based determination of:

- Mission severity impact on maintenance and logistics indices
- Parts life consumption

Engine operation will be continuously monitored and data sets will be selectively saved to allow reconstruction of the mission profile defining changes in operating conditions which affect mission severity indices and parts life consumption, although neither of these computations are included in this program.

The parameters to be monitored and to be used to detect a meaningful change in operating condition and, thus, effect the saving of a data set, are:

- Fan Speed
- Power Lever Angle
- Compressor Inlet Temperature
- Ambient Air Temperature

The data set to be saved will include the above parameters, plus:

- Core Speed
- HPT Blade Temperature
- Altitude
- Mach Number
- Engine Run Time

The acquired data could be processed by a ground-based system to provide the following functions:

- Mission severity indices could be calculated to establish the relationships with "Normal" mission severity factors used to determine maintenance and logistic indices. Time-weighted composite severity indices could be used to adjust maintenance and logistics indices which reflect the way the fleet was "in fact" being operated.
- The data would be processed to count major and minor cycles accumulated during operation for those rotating parts with established LCF

cyclic life limits.

- The data would be processed to count time at temperature (two levels) for assessment of hot section static parts life consumption.
- Total engine operating time could also be established.

CONCLUDING REMARKS

The hardware to implement these system requirements and functions is presently under development. The SCM is a flight-type SBP9900 microprocessor based, on-engine, electronic box. The APMS processor is a TI 9900 based avionics bay-type electronic box designed, using applicable provisions of MIL-E-5400R as a design guide. All other off-engine hardware is laboratory-type equipment intended to demonstrate the concepts described in this paper with a TI 990/10 mini-computer serving as the heart.

The APMS program will advance engine health monitoring concepts by offering an integrated and comprehensive approach. The purpose is to design, develop and demonstrate efficient methods of acquiring, processing and utilizing data and information obtained from an advanced engine system from engine inlet controls and from aircraft subsystems so that the monitoring system itself can be incorporated early in the design and development of aircraft weapons systems of the 1980's and 1990's.

The Advanced Propulsion Monitoring System can provide the generic technology base for monitoring the health of sophisticated propulsion systems of high performance aircraft of the 1980's and 1990's.

Advanced Propulsion Monitoring System

- Typical Future Transport Application with All Aircraft Data Flowing on a Single Data Bus

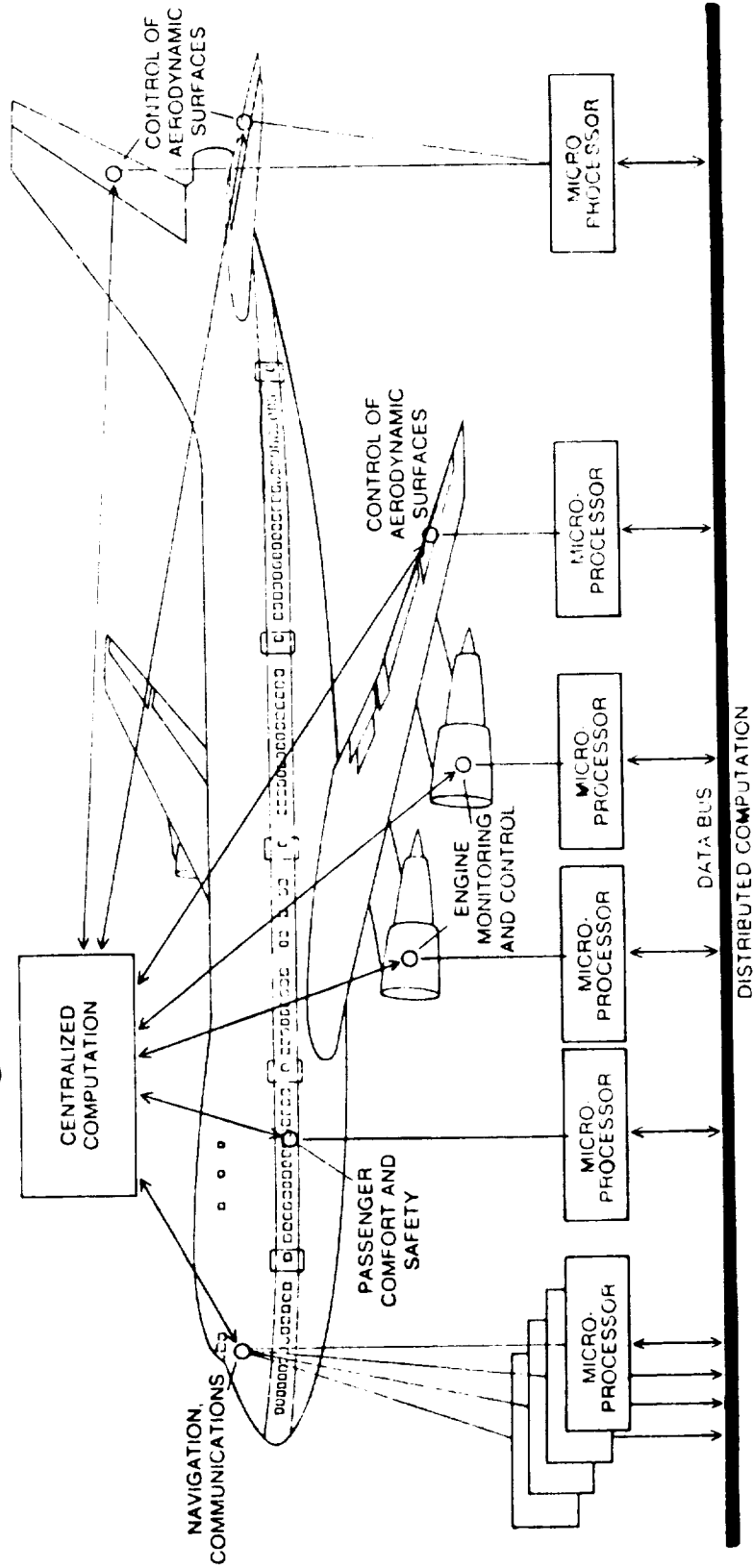


FIGURE 1

Engine Maintenance Process and Information Flow

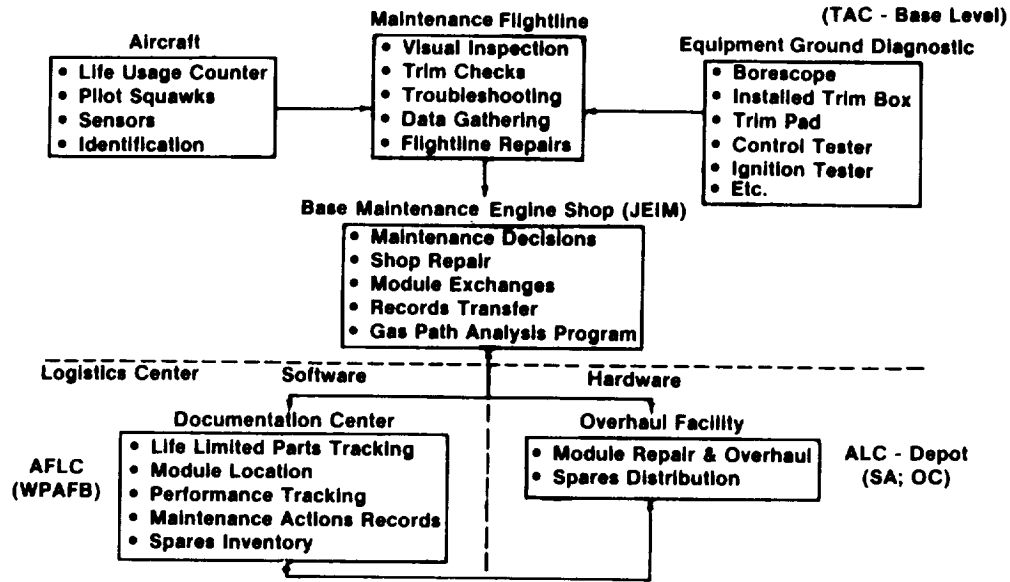


FIGURE 2

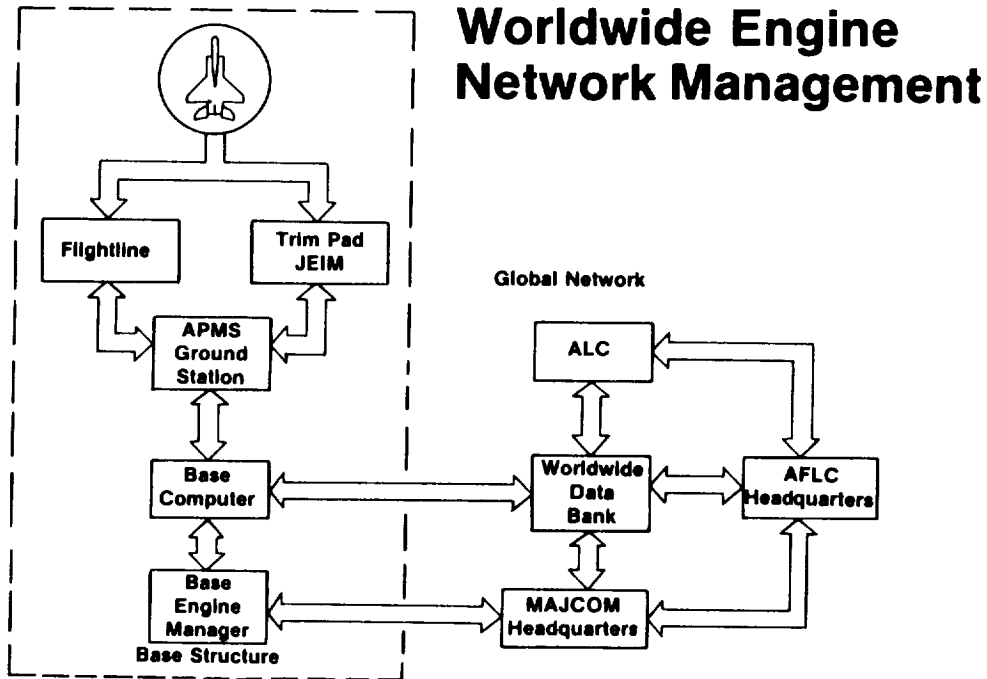


FIGURE 3

Off-Engine Subsystem Development Plan

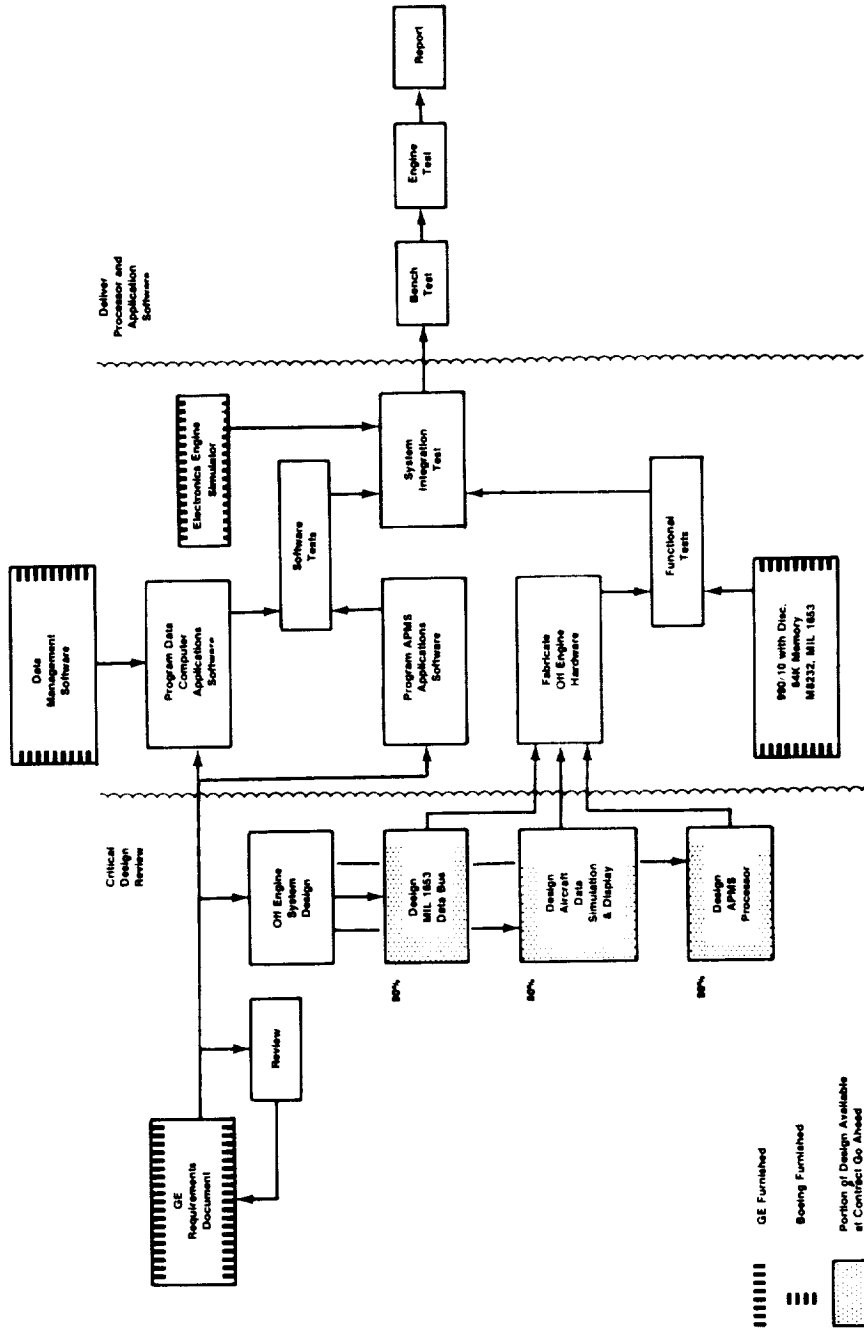
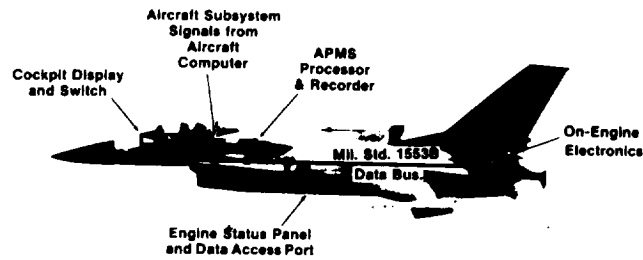


FIGURE 4

**Advanced Propulsion Monitoring System
Proposed Follow-on Flight Configuration**



Typical Future Fighter Application with Engine Hours Monitoring Data on a Dedicated Data Bus.

FIGURE 5

**Advanced Propulsion Monitoring System
Data Flow for Fighter Application**

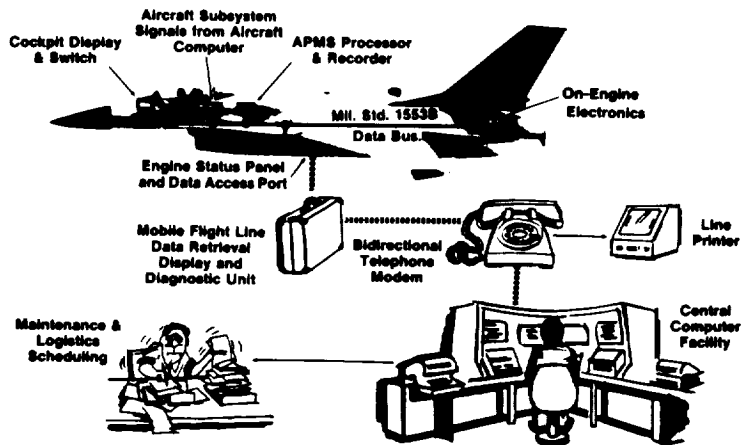


FIGURE 6

APMS Demonstration Configuration

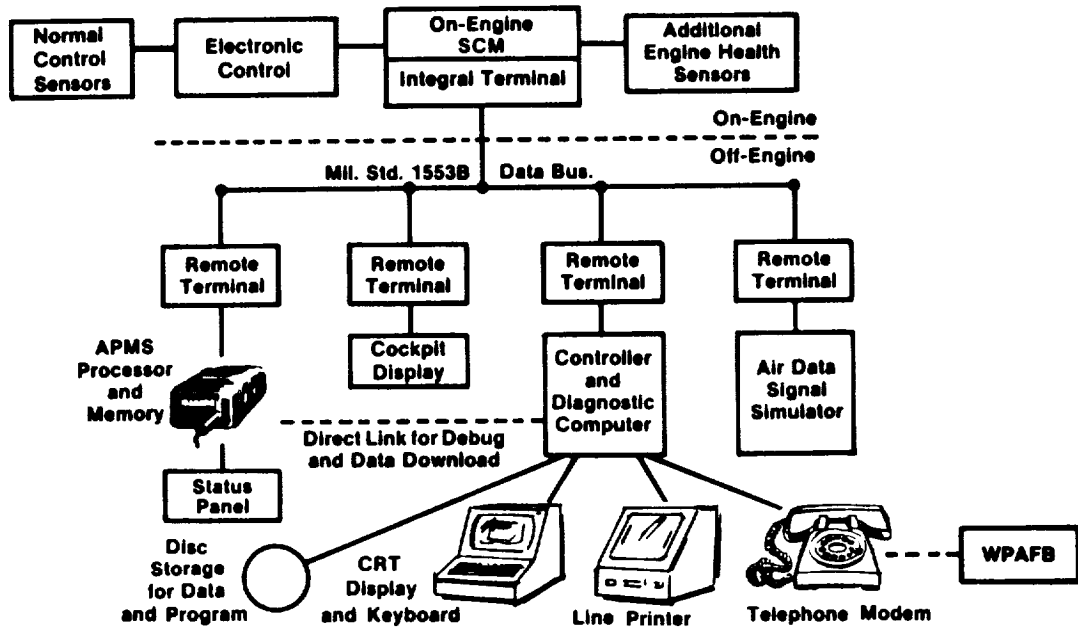


FIGURE 7

APMS Off-Engine Subsystem

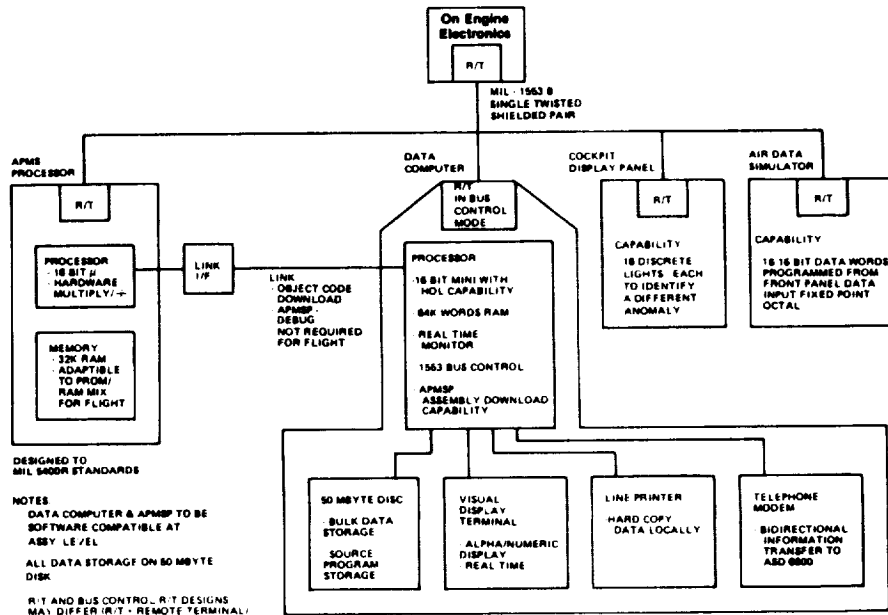
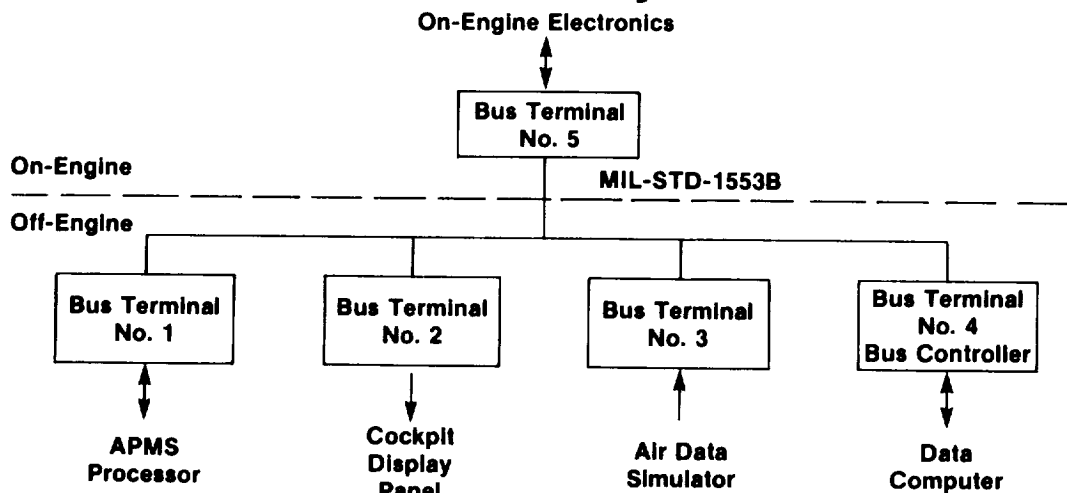


FIGURE 8

APMS Bus System



Note: Bus Terminals Functionally Identical but Packaged Integrally with Each Subsystem.

FIGURE 9

Condition Monitoring Parameters

Available from Electronic Control

A8 Exhaust Nozzle Area
 BF IGV Position
 WFM Main Fuel Flow
 WFR Augmentor Fuel Flow
 T2 Inlet Temperature
 N1 Fan Speed
 N2 Core Speed
 PS3 Compressor
 PLA Power Lever Angle
 T4B HPT Blade Temperature
 FDS Flame Detector
 PAUG Augmentor Switch
 DP14 Fan Pressure Ratio
 BC Core Stator Position
 T25 Compressor Inlet Temperature
 PS14 Fan Discharge Pressure

Additional C/M Sensors

T3 Compressor Discharge Temperature
 P49 Turbine Interstage Pressure
 QL Lube Quantity
 TL Lube Temperature
 PL Lube Pressure
 VF Fan Vibration
 VC Core Vibration

FIGURE 10

Air Data Simulator Signals

PAMB	Ambient Pressure	Real Cell Sensor
TAMB	Ambient Temperature	Real Cell Sensor
ALT	Altitude	Calculated in Signal Simulator
MN	Mach No.	Calculated in Signal Simulator
PLA	Power Lever Angle	Test Cell Sensor
WOW	Weight on Wheels	Manual Switch
POS	Pilot Option Switch	Manual Switch or Keyboard Entry

FIGURE 11

Component Efficiency vs Cycles

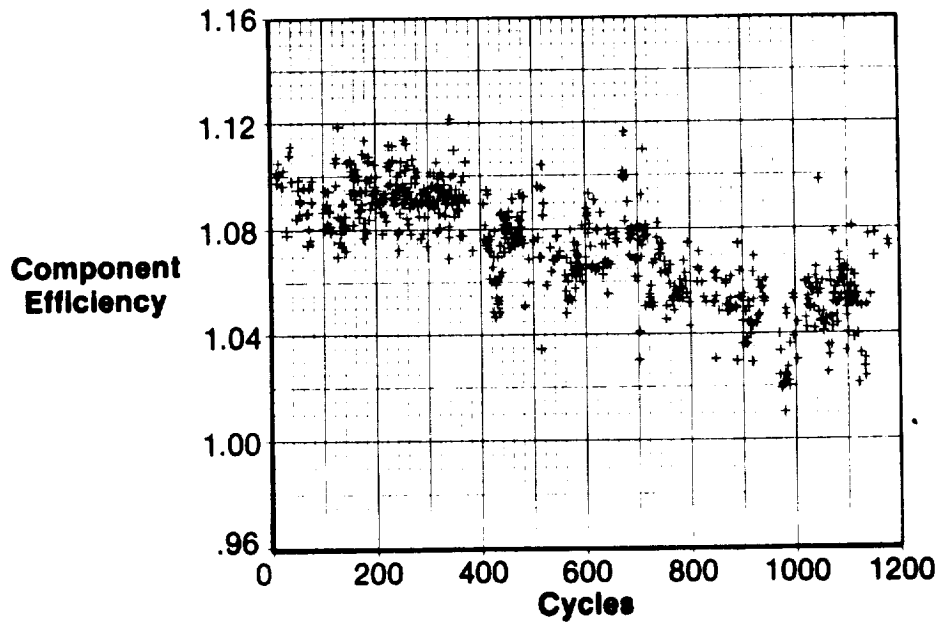


FIGURE 12

Filtered Component Efficiency vs Cycles

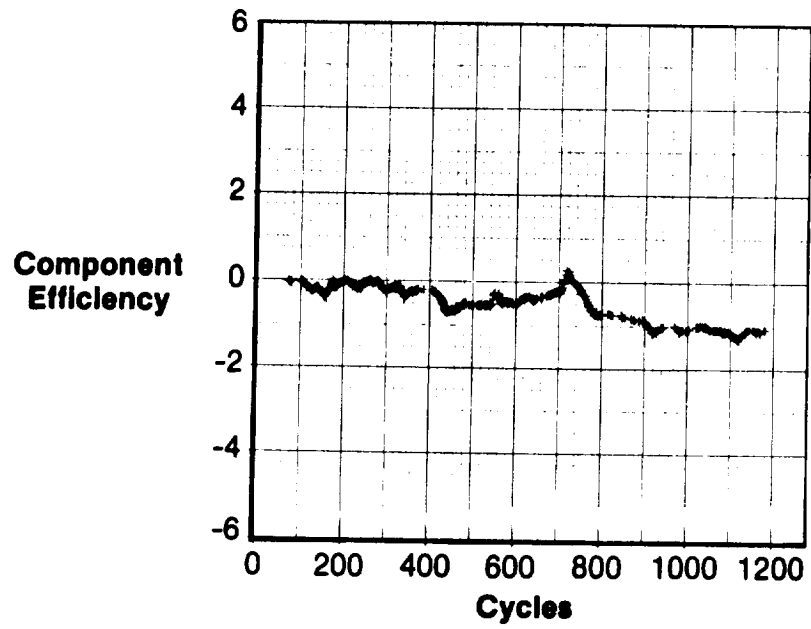


FIGURE 13

