



AEROSPACE RECOMMENDED PRACTICE

ARP5120™

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Aircraft Gas Turbine Engine Health Management System Development and Integration Guide

RATIONALE

The aviation industry uses Engine Health Management technologies to improve engine and aircraft reliability, availability and maintainability. This SAE Aerospace Recommended Practice (ARP) provides guidance on how to develop and implement an integrated end-to-end health management system for gas turbine engine applications. ARP5120 consolidates AIR1873, AIR4061B, AIR4175A, and AIR5120 into one document per the direction of the SAE E32 committee.

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1. SCOPE

ARP5120 provides recommended best practices, procedures, and technology to guide the physical and functional design, development, integration, verification, and validation of highly reliable Engine Health Management (EHM) systems for aircraft engines and Auxiliary Power Units (APUs). This SAE Aerospace Recommended Practice (ARP) also serves as a concise reference of considerations, approaches, activities, and requirements for producing the end-to-end engine health management system comprised of both on and off-board subsystems for the sensing, acquisition, analysis, detection, and data handling functions for EHM. These functions may also be used to effect continued operation or return to service decisions when demonstrated as compliant with the applicable airworthiness requirements defined by the responsible Aviation Authority. Where practical, this document delineates between military and commercial practices.

1.1 Purpose

The purpose of this ARP is to provide guidelines for the physical and functional integration of an EHM system with other aircraft systems and subsystems that can be used by the flight crew and/or maintenance staff. This includes guidelines for the development, support, and usage of ground station systems as part of EHM in an operational environment for processing engine data and supporting the customer and Original Equipment Manufacturer (OEM) in logistics management.

This ARP supplements ARP1587 by providing additional guidance on best practices for general gas turbine engine monitoring with typical commercial and military systems.

1.2 Introduction

EHM is a term that has been adopted to cover the overall system aspects associated with both the engine's health and usage. From hardware to software and from diagnostics through prognostics, the principal functions of EHM are to assess the engine condition. Assessing engine condition is accomplished by gathering: event data to perform diagnostics; data for trending and performance analysis; and data to assess life usage of life limited parts (LLPs). EHM adds value by providing real time or near real time information on the functional and physical condition of a gas turbine via an Engine monitoring system (EMS). This information is used to alert operators to conditions that could impact safe operation, schedule inspections/repairs, and targeted troubleshooting to improve functional performance, forecast spares requirements, and manage warranties.

A basic concept of EHM is that data gathering and analysis be derived as much as possible through existing systems. Actual implementation of an EHM varies across customers/operators and the OEMs where an EHM system can be either fully or partially integrated into an aircraft or be dedicated to a propulsion system itself. Initial design should make use of engine variables which are primarily sensed for other purposes (e.g., engine control or flight deck display) before consideration of any additional parameters incorporated specifically for EHM. Integrating an EHM system within a platform's existing systems is dependent on several influencing factors including communication networks, signal interferences, power requirements, etc.

The capabilities and technologies required to support EHM continue to be developed, becoming progressively more sophisticated to meet the increasing requirements for data acquisition, storage, transfer, processing, analytics and user interface both on and off-board. This ARP describes the recommended practices for EHM throughout the engine life-cycle including:

- Conception
- Design and Development (Specification, Hardware and Software Build, Verification and Validation)
- Training and Entry into Service (EIS)
- Sustaining Support (Maintenance, Error Correction, Systems Enhancements, De-Commissioning)

ARP4754 provides foundational guidance for designing and developing EHM system support hardware and software installed on the air vehicle. In addition, other available documents, such as RTCA DO-178, which provides guidance to the development of EHM software, and RTCA DO-248, which provides supporting guidance to RTCA DO-178. However, RTCA DO-178 does not specifically address the unique characteristics of ground based EHM software. As of the issuance of this document, there are activities underway within SAE to address this aspect. This ARP identifies, as applicable, additional or alternative development guidance for onboard hardware and software systems as well as off-board systems. This ARP also provides guidance for the development of the supporting infrastructure required for these ground-based functions. The guidance of this ARP applies to an EHM system implemented on a new platform or for retrofit on a legacy application.

When applying the guidelines of this ARP it should be noted that engine monitoring systems may be physically or functionally integrated with the engine control system and may also affect safety or be used to effect continued operation or return to service. For any decision to apply the guidelines of this ARP, the decisions shall be subject to the Type Investigation of the product in which they will be incorporated and must show compliance with the applicable airworthiness requirements as defined by the responsible Aviation Authority. This is not limited to but includes the application of software levels consistent with the criticality of the performed functions. For instance, Low Cycle Fatigue (LCF) cycle counters for safety critical parts would be included in the Type Investigation but most trend monitors and devices providing information for economically based maintenance decisions would not.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP1587	Aircraft Gas Turbine Engine Health Management System Guide
ARP4102	Flight Deck Panels, Controls, and Displays
ARP4176	Determination of Costs and Benefits from Implementing an Engine Health Management System
ARP4754	Certification Considerations for Highly Integrated or Complex Aircraft Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP5783	Health and Usage Monitoring Metrics, Monitoring the Monitor
ARP6275	Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System
AS8034	Minimum Performance Standard for Airborne Multipurpose Electronic Displays
R-405.SET3	Jennions, I.K., "IVHM/Integrated Vehicle Health Management 3-Book Set," (Warrendale, SAE International, 2013), ISBN 978-0-7680-8101-5

2.1.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Aerospace Technical Report.

ADS-37	Aeronautical Design Standard for Electromagnetic Environmental Effects Performance and Verification Requirements
ADS-79	Aeronautical Design Standard Handbook, Condition Based Maintenance System for US Army Aircraft
ANSI/EIA-649	American National Standard Institute, Configuration Management Standard
ANSI/EIA-836	American National Standard Institute, Configuration Management Data Exchange and Interoperability
GEIA-HB-649	Government Electronics & Information Technology Association, Implementation Guide for Configuration Management
GEIA-STD-0009	Reliability Program Standard for Systems Design, Development, and Manufacturing
IEEE 1012	Standard for Software Verification and Validation
IEEE 1362	Guide for Information Technology - System Definition - Concept of Operations (ConOps) Document
IEEE 1451	Standard for a Smart Transducer Interface for Sensors and Actuators
Dr. Abernethy and J. Thompson, "Uncertainty in Gas Turbine Measurements," USAF Report AEDC-TR-73-5 (AD755356)	
Vermeulen, H., "AIR1873—A Guide to Limited Engine Monitoring System for Aircraft Gas Turbine Engines," SAE Technical Paper 841460, 1984, doi:10.4271/841460.	
JSSG 2010-2	Department of Defense, Joint Service Specification Guide for Crew Station Automation, Information and Control/Display Management
MIL-HDBK-217	Military Handbook for Reliability Prediction of Electronic Equipment
MIL-HDBK-470	Department of Defense, Military Handbook for Designing and Developing Maintainable Products and Systems
MIL-STD-461	Department of Defense Interface Standard for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment
MIL-STD-464	Department of Defense Interface Standard for Electromagnetic Environmental Effects Requirements for Systems
MIL-STD-704	Department of Defense Interface Standard for Aircraft Electrical Power Characteristics
MIL-STD-810	Department of Defense, Test Method Standard for Environmental Considerations and Laboratory Tests
RTCA/DO-160	Environmental Conditions and Test Procedures for Airborne Equipment
RTCA/DO-178	Software Considerations in Airborne Systems and Equipment Certification
RTCA/DO-248	Supporting Information to DO-178C and DO-278A
RTCA/DO-254	Design Assurance Guidance for Airborne Electronic Hardware
RTCA/DO-278	Software Integrity Assurance Considerations for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) Systems

RTCA/DO-330	Software Tool Qualification Considerations
RTCA/DO-331	Model-Based Development and Verification Supplement to DO-178C and DO-278A
RTCA/DO-332	Object-Oriented Technology and Related Techniques Supplement to DO-178C and DO-278A
RTCA/DO-333	Formal Methods Supplement to DO-178C and DO-278A
RTO-TR-28	North Atlantic Treaty Organization Technical Report, "Recommended Practices for Monitoring Turbine Engine Life Consumption."
S2000M	International Specification for Materiel Management: Integrated Data Processing for Military Equipment
SAND 2003-3769	Verification, Validation, and Predictive Capability in Computational Engineering and Physics, Sandia National Laboratories

2.2 Definitions

CONDITION INDICATOR (CI): A measure of detectable phenomena derived from sensors that show a change in physical properties related to deterioration (normal or abnormal) or a specific failure mode or fault.

DATABASE: An organized collection of data. The data are typically organized to model relevant aspects of reality in a way that supports processes requiring this information.

DATABASE MANAGEMENT SYSTEM: Specially designed applications that interact with the user, other software applications, and the database itself to capture and analyze data.

DIAGNOSTICS: Data analysis techniques which lead to the detection and identification of a deterioration, malfunction, or failure.

EXHAUST GAS TEMPERATURE (EGT): Literally, exhaust gas temperature. As used, "EGT" refers to the temperature measurement defined by the engine manufacturer as a limiting parameter (for example, MGT, T4.5, TIT, TOT, TGT, TBT, SOT, etc.).

ENGINE HEALTH MANAGEMENT (EHM): The general discipline or techniques for detection, accommodation, diagnosis and prognosis of degradation or failure of an engine system, piece of equipment, component or subassembly and offering a maintenance action or decision support to address the degradation.

EHM SYSTEM: The complete end-to-end system including onboard and off-board subsystems involved in monitoring, indicating, and analyzing engine health and data analysis. Examples of systems are an EMS and ground station. A complete EHM system approach consists of an integrated set of onboard and off-board hardware, software, and logistical process that can be manual, computer aided or fully automated.

ENGINE MONITORING SYSTEMS (EMS): The set of features and capabilities that is allocated for detection and isolation of component failures and monitoring of engine health and usage. An EMS can refer strictly to those automatic features incorporated into embedded electronics or it may include all means used to detect and isolate failures including ground support equipment, personnel and procedures. For the purposes of this ARP, EMS will refer specifically to those onboard features that have been included in the engine (or aircraft) to aid in detection and isolation of engine component failure, performance deterioration, abnormal engine operation as well as usage. Such indications are obtained through the use of onboard sensor input, data collection, processing, analysis, and the human decision process.

EHM SYSTEM ACCURACY:
$$\frac{[\text{Total Indications} - \text{False Alarms} - \text{Missed Detections}]}{\text{Total Indications}} * 100 \%$$

FALSE ALARM: The indication by the EHM system that a problem condition exists when no problem is present.

FAULT ISOLATION RESOLUTION (FIR):
$$\frac{[\text{No. of Faults Correctly Isolated}]}{\text{No. of Faults Correctly Indicated}} * 100 \%$$

HEALTH INDICATOR (HI): An indication of needed maintenance action resulting from the combination of one or more CI values.

LIFE CYCLE COST (LCC): LCC refers to the cost of purchasing and maintaining an engine system throughout its operational life of which an EHM system is an integrated part. One of the main objectives of an EHM system is to achieve a reduction in engine system LCC. Included in the LCC is the cost of all EHM system hardware and software components. Reduction in the LCC achieved as a result of benefits derived from the EHM system should be greater than the added cost of the EHM system. From a general perspective the cost benefit analysis gives an analytical indication of the LCC Return on Investment (ROI).

LIFE USAGE: A method of determining the remaining useful life or life consumed of a life-limited part in a gas turbine engine.

LIMITED EMS: The measurement parameters are usually limited to those provided as part of the standard aircraft instrumentation.

MISSED DETECTION: The non-indication by the EHM system of a problem condition that it was designed to detect.

OPEN SYSTEMS ARCHITECTURE (OSA): A standard that describes the layered hierarchical structure, configuration, or model of a communications or distributed data processing system that: (1) Enables system description, design, development, installation, operation, improvement, and maintenance to be performed at a given layer or layers in the hierarchical structure; (2) Allows each layer to provide a set of accessible functions that can be controlled and used by the functions in the layer above it; (3) Enables each layer to be implemented without affecting the implementation of other layers; (4) Allows the alteration of system performance by the modification of one or more layers without altering the existing equipment, procedures, and protocols at the remaining layers.

POWER ASSURANCE: The measurement and interpretation of the engine data to determine whether sufficient power or thrust will be delivered by the engine within mission operating limits.

POWER SETTING (PS) PARAMETER: That parameter used by the engine manufacturer to determine engine power or thrust. Various parameters are used for this purpose (for example, EPR, Torque, N1, etc.).

PROGNOSTICS: EMS functions that address the detection and/or isolation of future component failures, degradation, etc., before that failure or deterioration causes the engine to fail to perform its intended function. The forecast can be expressed as remaining useful life (RUL), or time to reach a specific degradation level, or time to reach a point at which the risk of component failure is unacceptable.

TRENDING: Utilization of a backward looking time scale incorporating parametric data to detect deviations from historical or expected data.

2.3 Terminology

AC	Alternating Current or Advisory Circular
ACARS	Aircraft Communication Addressing and Reporting System
A/D	Analog to Digital
ADR	Accident Data Recorder
AIR	Aerospace Information Report
AIRCOM	Air to Ground Communication

ALE	Application Level Events
API	Application Programming Interface
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio Incorporated
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ASD	Aerospace and Defence Industries Association of Europe
BIT	Built-In-Test
BITE	Built-in Test Equipment
BOD	Business Object Document
B2B	Business to Business
B2MML	Business to Manufacturing Markup Language
CAD/CAM	Computer Aided Design/Computer Aided Manufacturing
CAS	Calibrated Air Speed
CBA	Cost Benefits Analysis
CDF	Common Data Format
CFR	Code of Federal Regulations
CI	Condition Indicator
CMC	Central Maintenance Computer
CNS/ATM	Communication, Navigation, Surveillance and Air Traffic Management
CONOPS	Concept of Operations
COTS	Commercial off the Shelf
CRC	Cyclic Redundancy Check or Cyclic Redundant Code
CSV	Comma Separated Values
CPU	Central Processing Unit
D/A	Digital to Analog
DAL	Design Assurance Level
DEX	Data Exchange
DFM	Design for Maintainability

DFR	Design for Reliability
DSP	Digital Signal Processor
DTD	Data Transfer Device
DVD	Digital Versatile Disc
EASA	European Aviation Safety Authority
ECU	Engine Control Unit
EEC	Electronic Engine Controller
EEPROM	Electrically Erasable Programmable Read Only Memory
EGT	Exhaust Gas Temperature
EMS	Engine Health Management System
EIS	Entry Into Service
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
EMS	Engine Monitoring System
EPR	Engine Pressure Ratio
EPROM	Electronic Program Read Only Memory
ERFE	External Radio Frequency Environment
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
FDR	Flight Data Recorder
FFT	Fast Fourier Transformation
FHA	Functional Hazard Assessment
FMEA	Failure Modes Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
FOQA	Flight Operations Quality Assurance
HDF	Hierarchical Data Format
HI	Health Indicator
HIRF	High Intensity Radiated Fields
ICD	Interface Control Document

IEC	International Electro technical Commission
IEEE	Institute of Electrical and Electronic Engineers
IETM	Integrated Electronic Technical Manual
ILS	Integrated Logistics Support
IRIG	Inter-Range Instrumentation Group
ISA	International Standard Atmosphere
ISO	International Standards Organization
IVHM	Integrated Vehicle Health Management
LCC	Life Cycle Cost
LCF	Low Cycle Fatigue
LLP	Life Limited Parts
LSAR	Logistic Support Analysis Record
LRU	Line Replaceable Unit
MD5	Message Digest version 5
MGT	Mean Gas Temperature
MIMOSA	Machinery Information Management Open Systems Alliance
MOS	Management Operating System
MRO	Maintenance Repair and Overhaul
MTBR	Mean Time Between Removal
N1, N2	Engine Spool Speeds
OAGIS	Open Applications Group Integration Specification
OCR	Optical Character Recognition
OEM	Original Equipment Manufacturer
OSA-CBM	Open System Architecture for Condition Based Maintenance
OSA-EAI	Open System Architecture for Enterprise Application Integration
OWL	Web Ontology Language
PC	Personal Computer
PCM-CIA	Personal Computer Memory Card International Association
P-F	Potential to Failure

PLCS	Product Life Cycle Support
PLM	Product Lifecycle Management
PMA	Portable Maintenance Aid
POD	Probability of Detection
PPI	Power Performance Index
PROM	Programmable Read Only Memory
PSAC	Plan for Software Aspects of Certification
QAR	Quick Access Recorder
RAM	Random Access Memory
RFID	Radio Frequency Identification
ROI	Return on Investment
ROM	Read Only Memory
RPM	Revolutions per Minute
RTCA	Radio Technical Commission for Aeronautics
RTO	Research and Technology Organization
RUL	Remaining Useful Life
SAT	Static Air Temperature
SATAA	Sense, Acquire, Transfer, Analyze, Act
SD	Secure Digital card
SHP	Shaft Horse Power
SIL	Systems Integration Laboratory
SITA	Société Internationale de Télécommunications Aéronautiques communications provider
SLOATL	Sea-Level, Outside Air Temperature Limit
STEP	Standard for the Exchange of Product
TAT	Total Air Temperature
TLA	Throttle Lever Angle
TSA	Technical Service Agreement
UER	Unscheduled Engine Removals
UMS	User Modifiable Software

USB	Universal Serial Bus
V&V	Verification and Validation
VHF	Very High Frequency
WBF	Windows Biometric Feedback
XML	Extensible Markup Language

3. CONCEPTS AND CONSIDERATIONS

3.1 Elements of Engine Health Management

The data flow through an EHM system is typically described as a five-stage process: Sense, Acquire, Transfer, Analyze and Act (SATAA). These data flow processes support the EHM functional elements described in ARP1587.

Sense

The Sense element involves determination of the value of one or more physical parameters that will be used to determine the condition of the engine being monitored. The Sense element may include a variety of physical parameters, such as pressure, temperature, speed, force, vibration, as well as time of utilization or cycles count. The Sense element includes any low level signal conditioning and amplification as well as the conversion of the sensor signal to a digital or analog representation of the measurement. The sensors may be permanently installed or may be temporarily fitted for diagnostic purposes.

Manual actions such as inspection observations (view of a physical part, reading data hand-written on paper or from a computer terminal, etc.) or audit results (verifying existence of hand-written or computer generated data records, validation of results, etc.) may also be considered Sense elements. In the case of a manual inspection or audit, a person (flight or maintenance crew, maintenance control personnel) is a “sensor.” In this case, the electronic conversion is not part of the sense element. A manual action should be considered a Sense element when the sensed data is an input to the initial EHM analysis. In the case of a flight crew recording data on paper from a cockpit display, the display is being fed by a sensor somewhere in the vehicle. That sensor is just as important as it would be if feeding the EHM directly. It is critical to know exactly what/where that sensor is measuring, how or if it is being conditioned on its way to the cockpit. The sensor or the data transfer to the cockpit could be at fault. The crew is a sensor to the extent that they correctly observe and record the cockpit indications. Assuming they do, their subsequent role is acquire and transfer. Manual actions performed as a result of the output of the EHM analysis should be considered Action elements as described below.

Engine configuration (model, current thrust rating, part numbers, serial number) and operational state (flight condition, flight path) should also be data that is sensed by or fed into an EHM. The Sense element for these data may be either electronic or manual.

Acquire

The Acquire element of the EHM will collect previously digitized parametric data at the appropriate time and/or state. The captured data might be steady state or transient data at specific conditions, events triggered by parameter exceedances, or continuous (full flight) data. Some data processing and analysis, for plausibility checks or compression, may also be applied. For most recent airplane models, the airframe manufacturer typically provides data acquisition systems as part of the aircraft avionics suite such as a central maintenance computer.

An EHM system may include an Acquire element that is to be performed after an Act element is complete. In many cases this will be a manual process. For this data or data from a manual Sense element, the Acquire element entails the conversion to and storage as digital information. As stated, some data processing and analysis may occur in the acquisition of data obtained manually.

Transfer

The Transfer element of the EHM system moves data between process stages. Typically, this element will include a transfer of digital data between computational resources. There may be multiple transfers in the EHM system. Transfer of data is a very significant part of the EHM system, as the options will influence the choice of architecture and how effective the system can be in detecting rapid failures. If adequate data can be transferred while in flight to the ground, then this capability may enable automated and near real time diagnostic and prognostic engine analysis. If enough data cannot be transferred, then onboard processing, compression, or analysis may be required (e.g., converting high bandwidth vibration signals to exceedance values).

A Transfer element may still be implemented as a manual process. A manual transfer interface includes the means to extract data from the Acquire element and deliver it to the Analyze element. For electronically acquired data, this includes the manual processes to extract and deliver the data. For manually acquired data, this includes the means by which the manually acquired data is transformed into electronic data and delivered to the destination acquisition element.

A Transfer element should be analyzed as a unidirectional process. This is not to say that data transfer cannot occur in more than one direction on a given transfer interface. Additionally, if this element supports only infrequent data transfers, the allowable time interval between detection of the condition by the EHM system and Potential to Failure (P-F) interval or prognostic horizon needs to be longer. Finally, consideration should be made for requiring Transfer elements between any of the other EHM SATAA processes.

Analyze

The Analyze element of the EHM manipulates the acquired data to enhance its use and/or create directly actionable information. An Analyze element attempts to detect some signature or anomaly in the data for diagnostic and/or prognostic purpose. To perform the detection function, the Analyze element may include other features such as data cleansing, correction, smoothing, or synthesis. In some applications, preliminary analysis may be carried out in onboard systems. Here, the Analysis element could include feature extraction, data sampling, data compression or other techniques to reduce the volume of data that needs to be transferred.

An Analyze element may also be a manual process. The same activities as described above may be performed or expanded upon by a human.

Each Analyze element should generate some kind of EHM output data. Additional Transfer elements may be required to deliver this output data. The resulting output is typically a variation of one of the following:

- Threshold Crossing – Comparison of the value of some parameter, or a change in the value of that parameter, against a historical trend or a limit.
- Annunciation – Some trigger condition (e.g., threshold crossing) generates a well-defined, unambiguous action to be performed. For example, an action driven by another Analyze element or a supervisory end-user as part of an Act element.

Act

The Act element comprises the final EHM process. The primary Act element of EHM is that of providing operators with an annunciation output of an Analyze element. The operator uses this information to make maintenance, logistics, or operational decision.

The key objective of this process is to ensure that specific trouble-shooting and maintenance support advice is given to the operator in time to manage or avoid potential events (this likely requires a Transfer element).

The operational decision is essentially the output of an Analyze element in the end-to-end EHM system. The Act element then is to carry out the task as described by that operational decision whether this is maintenance in the form of removal and replacement of the engine or engine components, performance of an inspection (e.g., boroscope), or performing a variation of an audit to confirm, for example, that take-off margins of the engines are sufficient for the next mission.

Because flight crew action is not normally required by EHM systems, EHM system information typically is not provided to the flight crew during flight operations. If a flight crew action is required, existing FAA standardized definitions and regulations for cockpit warning, caution, and advisory alerting systems can be found in CFR §25.1322. All elements of a system that generate this type of annunciation are to be developed using the guidance of ARP4754A.

Figure 1 illustrates the five EHM elements and provides a general portrayal of the interfaces, represented by the diagrams arrows, between the aircraft and engine/APU functions. Other SAE documents found in Section 2 contain further details of EHM as it applies to specific equipment.

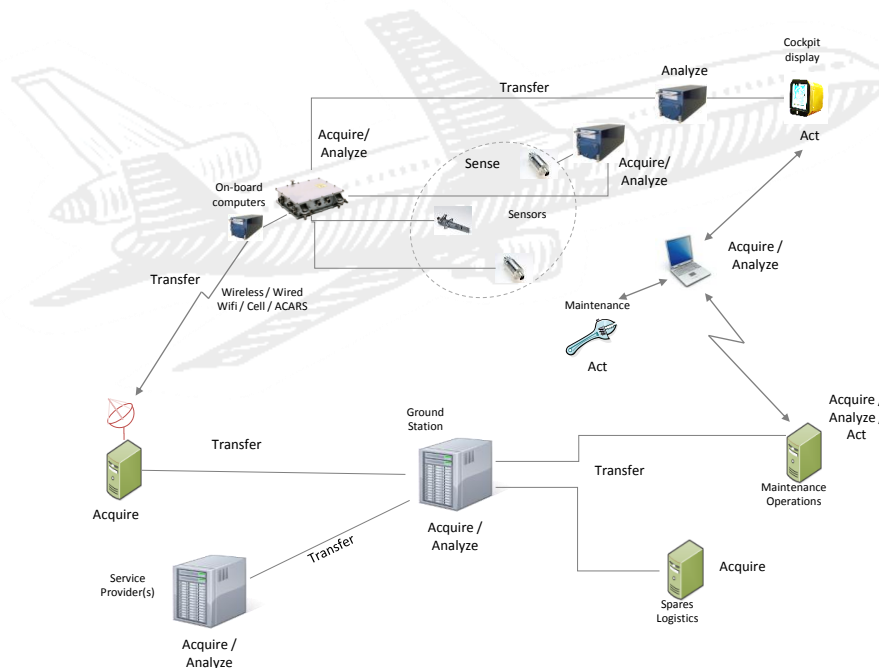


Figure 1 - EHM elements and typical integration candidates

The five EHM elements are needed to support any EHM system. Additionally, every EHM system will be dependent on core EHM tools: detection, diagnostics, and prognostics tools which represent EHM elements. These tools provide the means to derive efficiency in operations and maintenance processes. The extent to which these tools are implemented to execute the five elements should be determined via cost benefit analysis supporting a return on investment.

3.2 System Integration Considerations

Originally health management capabilities were essentially Built In Test (BIT) capabilities and implemented on aircraft using a federated architecture, where specialized electronics performed very specific functions for a specific component. As aircraft data acquisition systems evolved, federated architectures were replaced with integrated modular architectures, which enabled common processing and interface capabilities.

The architectural design of the EHM system is integral to the reliability of both the hardware and the software components of the EHM system. The correct onboard hardware architecture considerations by EHM system integrators may improve functional reliability and validity of the detection capabilities, prognostics, and diagnostics of the EHM system. The correct onboard and off-board software architecture considerations may also mitigate many of the historical problems associated with reliability of the EHM system.

The industry trend is the integration of the EHM system with other aircraft health maintenance systems, such as the Central Maintenance Computer (CMC), into a centralized web-based, network-centric integrated system. The current emphasis is to combine onboard aircraft maintenance with ground-based predictive management functions. In keeping with this trend, the EHM capabilities may be integrated with the aircraft systems to provide complete and precise fault diagnosis of the entire aircraft system which will enable timely and effective maintenance action and repair with minimum effect on aircraft availability (see 4.2.2). Figure 1 illustrates typical integration candidates as represented in a functional flow diagram. Also included are some functional growth areas for integrated EHM. With more access to high fidelity models, and the ability to run them efficiently, prognostics and predictive algorithms are being implemented via EHM. Support of prognostic concepts and predictive maintenance (as opposed to reactive maintenance) practices should be considered in the EHM system architecture design. The underlying architecture may then be structured to utilize all available data on the aircraft to provide decision support for effective maintenance of the aircraft and predictive trending for safe utilization and maintenance based on the actual condition of the operating propulsion system.

3.2.1 Electrical Power Integration Considerations

When integrating onboard aspects of an EHM system, consideration should be given to a number of characteristics of the electrical power system. Typically, an aircraft electrical power distribution system comprises multiple independently protected distribution buses. Each bus has a particular characteristic when an engine or an electrical power source (e.g., generator, battery) fails, ranging from transient disturbances to complete electrical power loss. Interruption of electrical power should not result in the loss or corruption of EHM data. Additionally, data related to a particular engine should not be corrupted by the failure of that engine or its associated subsystems.

Consideration should also be given to the possibility of low voltage or the absence of power generated by a main engine when monitoring during start or shut down. The highest integrity bus is frequently battery-direct or emergency Alternating Current (AC) bussed. These buses may be available for power during starting but often have severely restricted load capability.

3.2.2 Environmental Effects Considerations

If an onboard aspect of the EHM system is non-critical, relaxed protection standards for tolerance against environmental factors such as lightning, electromagnetic interference (EMI), external radio frequency environment (ERFE), high and low temperatures, and steady state and vibratory mechanical loads typically apply for integration. However, it is necessary to show that critical systems, e.g., flight controls and engine controls, are not compromised. Should high protection standards become necessary for shared parts of the EHM, e.g., amplification of an EHM signal within a control system box, the cost-effectiveness of sharing will need careful consideration. Aircraft EMI recommendations, guidelines, and regulations have been established by both commercial and military agencies (e.g., RTCA DO-160, MIL-STD-461/464).

3.2.3 Software Criticality Considerations

EHM system designers should consider criticality of the onboard and off-board software at the earliest opportunity. The design of both the software and the hardware need to trade benefits against the mission criticality of the function provided (e.g., maintenance, pilot operation). Partitioning may need to be considered for integrating specific onboard applications, as well. As previously iterated in 1.2, other available documents, such as RTCA DO-178, provide guidance to the development of onboard EMS software. IEEE 1012 is a reference which may be used for guidance on ground based software. There are also activities underway within SAE to further address the ground based EHM software. For software functional integration, factors to consider are:

- Impact of input and output transfers across critical partitions
- Operating systems qualification/acceptance
- Software quality and configuration management requirements
- Minimizing requalification/re-certification of other flight critical software in supporting onboard EMS software

3.2.4 Safety Considerations

Aircraft safety considerations may dictate functional independence, among the various components of integrated subsystems to protect against effects of common mode signals, coupling and crosstalk, bus interactions, and failure propagation. Several flight critical monitoring systems are typically interfaced with the design of engine controllers. An EHM system should be connected to onboard data sources in a manner such that they listen but do not influence or alter data, calculations, or processes used by other components or systems. The overarching safety consideration is that failure of any EHM functions must not reduce the overall safety of the platform.

3.2.5 Cost and Benefit Considerations

Whether an EHM system is being considered for a legacy platform or for a new, modern platform, the same integration issues with the aircraft systems and subsystems must be considered. Performing a Cost Benefit Analysis (CBA) geared towards exposing the economic feasibility of introducing and integrating the EHM system with the legacy installation or with the new design aircraft will be the determining factor for many integration issues. ARP4176 and ARP6275 as well as SAE's International book set on Integrated Vehicle Health Management (IVHM R-405.SET3) provides useful insight into how to create a CBA and facilitate the justification for implementing an EHM system. Exposing the desired use of the EHM system and identifying the propulsion subsystems whose health monitoring will provide economic and safety benefits to the operators is required to develop an accurate CBA. As such, this analysis should consider the general needs and benefits discussed in ARP1587 to include the following detailed topics:

- The use of Life Limited Parts (LLP) in the engine has an inverse impact on both safety and maintenance costs. Current practice has accepted higher maintenance costs to maximize safety. The CBA should consider means to reduce the maintenance costs associated with LLPs while maintaining equivalent or improved safety with respect to these components.
- Due consideration should be given to reductions in the operational cost as well as reduction in maintenance and repair costs. Metrics such as in-flight shut downs, air turn-backs, dispatch reliability, gate turn times, Unscheduled Engine Removals (UER) rates, asset availability, reduced secondary damage due to timely engine removal for cause, etc., would be used to quantify the benefits. In the Maintenance Repair and Overhaul (MRO) category, shop turn times, inventory levels, parts positioning, maintenance labor hours, various maintenance intervals such as mean time between removals (MTBR), shop visit rates and costs, etc., would be considered.
- Factors such as reduced cost due to enhanced work scope planning, directed engine teardown, better module matching, and inventory management should be considered.

Reducing Life Cycle Costs (LCC) of operations is a primary purpose of an EHM system. In most cases, the EHM system supplier will specify a Return on Investment (ROI) for the system. The ROI analysis has to be developed in conjunction with the engine manufacturer or design authority, who has detailed knowledge of the engine's operation, performance and failure modes. Unreliable performance of the EHM system (see ARP5783 for reliability metrics) will adversely affect the ROI and could make the EHM system a cost burden. The technology that is available for integration into an EHM system is a primary driver of both ROI and reliability. There is a direct trade-off between risk and reliability. Any technology that is not fully matured may result in additional cost and risk to the program if it fails to perform. This applies to all the items associated with the EHM system such as: data transmission, analysis techniques, sensors, hardware and software.

The CBA benefits are the driving forces that cause the consumer of the Concept of Operations, or ConOps (detailed in 4.1), to use EHM. The following examples of these beneficial effects are provided for information:

- More engine maintenance moved from costly unplanned troubleshooting events to planned events (e.g., gas path wash, controls adjustment, fan trim balance, power assurance, on-condition techniques) to reduce operational disruptions
- Trade-offs can be performed between cost of maintenance and fuel consumption
- Usable component life may be extended with approved usage-based life tracking systems
- Overhaul and repair costs are reduced by improved knowledge of deteriorated components

4. RECOMMENDED PRACTICES FOR DESIGN, DEVELOPMENT, AND TEST

The capable EHM system design team is practiced in the use of robust system design methods to assess the impact of complex interdependencies of design choices whether for a new engine design or retrofit application. An understanding of methods such as failure mode analysis, lifecycle analysis, reliability methods, risk analysis, testability methods, and optimization methods is essential. Design choices made early to address the ConOps, discussed in 4.1, will commit a particular solution and will less likely be changed as the process evolves. Therefore, the impact of the design solution, on both the overall engine system and the use of the EHM system throughout its life, needs to be assessed early in the design process. Note that the design of not only the engine system, but the air vehicle and any required ground-based support systems will be affected by the end-to-end EHM system.

Retrofit on in-service applications are more challenging in that onboard Sense and Acquire steps may have been determined long before and fleet-wide retrofit or upgrade costs may be prohibitive. In this instance, the EHM system design team must innovatively work with what is already installed to create a system that adds value to the operator while optimizing weight, power consumption, volume, costs (procurement, installation, maintenance, training, operation), and reliability.

4.1 EHM System Concept of Operations Development

For development, a clear concept of how the EHM system features and functions should integrate into engine operations and maintenance activities is necessary. The implementation of the systems, operations and maintenance processes should be aimed at managing an engine's health very early in the development cycle to most effectively influence life cycle costs, safety, and aircraft availability. Early analysis of the EHM system goals will influence design characteristics that may then improve the implementation of desired EHM functions in the design.

When considering the implementation of an EHM system, a recommended starting point is the development of a document referred to hereafter as the ConOps. The ConOps is used to communicate the quantitative and qualitative system characteristics to all stakeholders. A ConOps should evolve from a concept and describe how a set of capabilities may be employed to achieve desired objectives or end state. The ConOps should also identify the places in the operations or maintenance processes in which benefit may be derived by implementing an EHM system. IEEE 1362 provides guidance on developing the ConOps when using software.

If a modification or replacement maintenance process is being proposed, two ConOps should be documented/modelled: the current operation and the target operation. The current and target ConOps describe the operational and maintenance practices with and without an EHM system, respectively.

The development of an EHM system ConOps should be documented whether one is trying to implement EHM on a new or in-service platform. For the new platform, required support functions should be identified to allow the designer to look for opportunities to assure their implementation at the beginning of development with reduced costs whether in existing or new equipment. For the in-service platform, required support functions should be identified to define the barriers, large and small, to implementation.

All process inputs and outputs for the operations and/or maintenance practices should be identified for the ConOps, in particular, at the user integration points mentioned above. This is done by mapping out a number of use cases or scenarios for all the operational or maintenance activities envisioned for the EHM system. The use-case scenarios will include consideration of training related to operations and maintenance procedures for both the engine and the EHM system. The training and use-case analyses should also evaluate where different training programs are required for EHM system Operators or Users and the EHM system Managers or Administrators. Use of EHM at Entry-Into-Service (EIS) should be planned during the design phase and be included as a use-case scenario.

The use-cases should determine whether the EHM system under study impacts EHM system on other fielded engines from the same OEM.

4.2 Designing an EHM System

Designing propulsion systems with EHM in mind implies that one has a good understanding of the goal of the system. The design goals can vary and should typically include: life cycle cost reductions, safety enhancements, reliability and/or availability improvements over historical designs.

Active and passive monitoring of equipment health is a key element, but an EHM system actually includes much more. Ideally, an EHM system should have a robust design that fails infrequently, implements adequate data integrity, have no adverse impact on safety, and provide sufficient value incentive to minimize its time out of service, all at minimal cost.

A basic guideline is that the functional interactions of the EHM system with other aircraft systems should not adversely affect the aircraft and propulsion system operation. The health management system boundaries should be established with appropriate consideration for all the aircraft systems with which it interfaces. Special attention should be given to maintaining the criticality and reliability of those systems and their interfaces. The aircraft/propulsion system operational and mission scenario should be used to establish the desired maintenance of the system interface and data integrity. Data captured in a high integrity system could be transferred to a lower integrity system for storage. This lower integrity system could download the data under various conditions (e.g., during a powered, but benign, state of propulsion system operation) dependent on the method. Additional capability would need to be included if the original high integrity of the data is to be maintained.

4.2.1 Initial User Interface Design

As stated, a key to the successful implementation of an EHM system is the accommodation of the information consumers. A full user requirements analysis involving the personnel who will actually use the system when it begins operation is recommended. Section 4.2.1.1 provides guidance for performing this analysis. The EHM system designer should make every effort to gain access to suitably experienced personnel within the operator's organization who can provide a qualified comment on the system design proposals and offer lessons learned from other similar systems.

A concurrent engineering approach, with scheduled implementation of specific design points, generally provides the best compromise between collecting data on user preferences and maintaining development schedules. The EHM system designer is cautioned to maintain diligence in the evolution of user needs and system design.

4.2.1.1 Human Factors Analysis

Human factors are those elements of a design that are involved when humans and machines interface. These elements will differ depending on the role of the members of the user community interacting with the EHM system. As a recommended reference, ARP1587 provides a definition of the broad user community. Human Factors should be assessed for each of the functional roles in this user community. Both the physical interaction of the user, as well as user perceptions and attitudes (non-physical Human Factors) toward the system, need to be considered and analyzed in the development of the EHM system design.

4.2.1.1.1 Non Physical Human Factors

EHM system designers should be cognizant that non-physical factors affect the thinking, informational processing and rationale development capabilities of the group that will be using the integrated EHM system. The manifestations of each of these non-physical factors are the subject of numerous human factors textbooks. The reader is encouraged to consult the various textbooks in the field for a deeper understanding of the subject material.

The primary purpose of an EHM system should be to make maintenance of the aircraft engines more efficient and cost effective. However, this boundary is being blurred by newer implementations. An EHM system may include interfaces to which the Flight Crew has access or that the maintenance crew uses to determine flight-worthiness of the aircraft. In these cases, the man-machine interactions have significant consequences and therefore, the details of a human factors analysis should require more rigor.

As stated, the development of use-case scenarios for each functional role in the user community is recommended to facilitate EHM system design decisions. As a minimum, the use-cases need to answer the following questions:

- What information is needed for the functional role and when? **
- What information or data needs to be provided by the user and when? **
- What tools will be available/accessible to obtain information or input data?
- What will the environment be in which the user is working?
- What user alternatives will be available in the event of a hardware failure?
- What is the Operator workload? **
- What are the consequences of human error?
- What is the impact on maintainers of false alarms and missed detects?

** NOTE: The EHM system interface must not distract the Flight Crew from primary aviator tasks.

The use-case scenarios should be developed with input from a broad spectrum of the actual user community. This may be in the form of an interactive workshop, on-site observation by the designer, or written survey. To maintain a high level of reliability and validity, the design should be such that adjustments in the EHM system and the underlying philosophies can be easily implemented to account for changes in behavior patterns, either at EIS or as developed over time. Modularity, as discussed in 4.3.4.2, is recommended for EHM software that provides the man-machine interface. While initial development may be more expensive, flexibility/configurability for user preference should be accommodated at lower costs.

4.2.1.1.2 Physical Human Factors

EHM functional requirements can be derived from assessing the non-physical factors from the use-case scenarios. The designer will use these requirements to create physical user interfaces. This section discusses the human factors that should be analyzed in the EHM system design relative to these physical interfaces.

The physical factors include elements which can be controlled by altering some element of the physical design such as interactions through some electronic device. Interfaces to the integrated EHM system will be required at different physical locations depending on the role of the user and location of the element. In today's connected world, some level of alerts or data could be delivered anywhere wired or wireless internet access is available. Human factors for the physical interface, in any of these locations, should be evaluated for applicability and associated design, development and test requirements:

- Intellectual level of the data being presented or obtained
- Access to user guidance or help functions
- Enunciator purpose, types and locations
- Amount of data or analyses being presented or obtained at any one time
- Simplicity of output data presentation maximized or means to input data minimized
- Format of the data being presented (output) or obtained (input)
- Degree of integration into higher level systems
- Level of user customization and interaction

- Cultural preferences and considerations
- For electronic devices that are to be portable, there exists an additional set of physical Human factors. The user should be considered in the form of system design requirements when the following characteristics of a portable device are considered:
 - Viewing and operating environment (office building, hangar, cockpit, low light equipment bay, bright sun light, night-time, near fuel, outside weather, EMI, etc.)
 - Physical size of the interfacing devices
 - Weight of interfacing device
 - Retention of interfacing device (how will it be held or mounted)

If a manual transfer of large data files is required by the system, human factors considerations include those above (e.g., indication of progress) as well as:

- Type of transfer device and storage media (laptop, data cartridge, memory stick)
- Frequency of transfer
 - Process recall for infrequent transfers
 - Labor/cost burden for frequent transfers

4.2.1.1.3 Human Factors Impact Mitigation

Generally, an EHM system has a concentrated mix of physical and non-physical human factors. If there is a large mismatch of user needs to system capability, then the mismatch will create frustration and discontent among the user community. The mismatch will exhibit itself in a lack of confidence and reduced usage and an increase in the number of errors all affecting the perceived reliability of the system. Analysis of the Use-Case Scenarios in the ConOps should consider how failure of the EHM functions will be accommodated. The impacts of implementing the EHM system can be mitigated via human factors analyses, as discussed below, and providing effective user guidance documentation and training, as discussed in 4.5.

The onboard Engine Monitoring System (EMS) may have a significant Human Factors impact on Maintenance Crew interactions during turn-around time between flights. Ideally, the EMS will reduce the crew work-load in this turn-around. An EMS may be implemented as an alternative to performing some task. In this case, the EMS design should not cause the user to perform the same task twice, once in the “as is” process and then again in the EMS process. Rather, the design of the interface should allow the EMS to replace or enhance the “as is” function with a predefined path to complete the task should the EMS be non-functional.

With regard to the off-board aspects, the EHM system can also have a significant Human Factors impact in centralized operations offices that direct maintenance and scheduling for a fleet of aircraft. The interaction of these offices with the EHM system information results in the development of a maintenance action plan. The maintenance action plan may be to perform line maintenance or to schedule the removal of the asset from service to perform maintenance in a repair facility. Here, the EHM system design should output information that leads to the most efficient maintenance plan. For example, maintainers monitoring a fleet require the EHM functions to allow a prioritized presentation of the most critical alerts or condition indications. The maintenance action plan should be supported by appropriate and effective alerting methods (e.g., status watch lists) to mitigate the human factors impacts in fleet wide maintenance decision making. (See Appendix D for more detail on data alerting.)

4.2.1.2 Design Analysis for User Interpretation of System Output

The design analyses should provide recommendations for interpreting the output from the EHM system. The analyses should ensure there are two basic categories of system output that the operator will need to interpret and act upon: the engine health output and the system maintenance output. The following describes each of these outputs.

- Engine Health Output:

This output is the main function of the EHM system and comprises the information used to ascertain and convey engine health. A Health Indicator (HI) or alert may be provided in addition to the visual display of processed parameters and Condition Indicators (CI). Health Monitoring is usually applied to a fleet of assets (i.e., fleet of engines). The concept of a positive indication of function is recommended for system monitors to preclude one or more engines from being missed in the inspection process. The analyses should provide the processes to accurately interpret the variety of possible scenarios (e.g., trend shifts, alerts, flags, etc.). Where specific actions should be taken in response to the data signatures or to the HI, a link to the System Maintenance Output is to be made.

- EHM System Maintenance Output:

This output provides the information necessary to maintain the EHM system functionality. For example, this information can be in the form of fault messages, panel indications, or crew alerts that indicate the health of the EHM system. Lack of data is another form of system fault indication. However, a positive indication of EHM function is the recommended concept for maintenance interfaces. The documentation should provide the processes to clearly describe how to interpret and how to respond to any status or fault indications the system provides.

4.2.2 Design for Availability

There are two perspectives for engine availability: one for the engine and one for the EHM system. While not in the scope of this document, the availability of an engine that is supported by an EHM system may be affected by EHM system availability. Also note that an EHM system is often implemented to specifically reduce the uncertainty of engine wear out and improve engine availability.

The EHM system designer should be cognizant that opposing EHM system and operator customer requirements exist. The customer's desire is to have the EHM system be available but not add to the maintenance burden or cost of ownership. For the hardware components of the end-to-end EHM system, a dual-use concept should be implemented in the design to the greatest extent possible. That is, implement the functions required of the EHM system in hardware that exists (onboard or ground-based) to support other airplane and/or enterprise functions. The EHM system designer should analyze the following:

- Identify all functions required for the end-to-end EHM system
- Identify whether existing hardware and/or software is available to support all functions
- Where gaps exist, define requirements for new hardware and/or software (onboard or ground-based)

Frequently, EHM functions will be implemented in onboard hardware that is non-essential for flight, i.e., the airplane may be dispatched with that hardware non-functional. Conversely, ground-based aspects of an EHM system may be implemented on commercial off the shelf (COTS) hardware that may fail. There are several means by which an EHM system design could accommodate these failures:

- Redundancy
- Frequent data backups

- Accommodate failure for defined period
 - Manual reversion mode
 - Gap in service allowed for defined period
 - Recovery plan for lost/compromised data

Whether the hardware is onboard or ground-based, application of the dual-use concept provides a non-EHM incentive for maintenance. This incentive is driven by the availability requirements of the systems to support the other functions.

From the perspective of availability, if the hardware is available/functional, then any hosted software is available. A caveat is on implementation of new or modified software. Care must be taken to assure that new or modified software will not result in the failure of the hardware host. The 4.4 discussion on software validation supports availability of new or revised software.

4.2.3 Design for Reliability

As with availability, the engine and EHM system perspectives exist for reliability. Reliability of the engine is not in the scope of this document but it is noted that reliability of an engine supported by an EHM system may be affected by the reliability of that EHM system.

Reliability of the EHM system should be considered at the earliest stages of system development through the use of Design for Reliability (DFR) and related techniques (reference GEIA-STD-0009). By following DFR principles, it may be possible to completely eliminate some failure modes altogether, and significantly reduce the frequency of others. System design accommodations of failures, when they do occur, are the same as provided in 4.2.2.

The dual-use recommendation is applicable to reliability of the hardware aspects of the EHM system. There may be exceptions where the reliability of the existing hardware that could host some given EHM function is incompatible with the end-to-end system requirements.

DO-178C provides significant guidance for onboard software reliability. Much of this guidance may be used for software installed in ground-based systems as well. However, there is currently a standards gap for software reliability guidance in ground based software systems. Another area lacking guidance is on the use of COTS software (and hardware) on ground based systems. DO-178C discusses COTS, but from the perspective of onboard installations. IEEE 1012 is another reference which should be consulted for the V&V of ground based software. Yet, again, IEEE 1012 is incomplete for addressing software reliability guidance. Similar application and gaps exist for hardware and the existing guidance of DO-254.

4.2.4 Design for Maintainability

Like Availability, there are the same two perspectives for maintainability (i.e., engine and EHM system). Maintainability of the engine is not in the scope of this document but an EHM system is often implemented specifically to enhance engine maintainability. As such, maintainability of that EHM system may impact the maintainability of the engine.

Whether the hardware hosting the EHM functions are dual-use or EHM system-unique installations, the designer should assure that Design for Maintainability (DFM) practices are used. Hardware supporting the EHM system design should include the following aspects:

- Maintenance personnel should be provided with a single maintenance information source including all relevant information (onboard and ground based hardware aspects separately).
- Adequate integrated fault isolation capability for hardware components.
- Physical integration of EHM functions with other systems should be simple.
- Independent self-test capability for the EHM functions.

DO-178C provides guidance for onboard software maintainability. Of particular interest are the concepts of field-loadable, option selectable, and User Modifiable Software (UMS). Implementation of these concepts in the software and the host hardware may make maintenance (up-date) of the software less costly. However, appropriate access and configuration controls must be in place to preclude errors. As EHM software deals with moving data and information between applications, a modular or layered construction of the software is recommended.

4.2.5 Design for Safety

A system safety hazard analysis should be conducted with the initial design to ensure appropriate isolation is accorded to the interfacing safety critical items and the functional independence of the integrated systems. ARP4761 provides a number of tools to assess the safety of systems implemented onboard the airplane. There is currently no documentation for a robust means to assess how a failure of a ground based portion of an EHM system can affect the safety of the aircraft. This has not been a significant problem because the desired outcome for an EHM system has been that it has no effect on the safety of the airplane. In this case, the EHM system is intended to perform only maintenance decision aid functions (i.e., provide economic benefit only). However, the application of EHM systems is moving closer to the point where airplane safety margins are affected.

If the safety margins may be impacted, a safety case should be performed on the end-to-end EHM system software to highlight the impact of any decisions that could result from the software data analysis or interface compatibility. Ideally, the EHM software will be kept to the lowest possible DAL and segregated as recommended in 4.2.7 to best manage future changes. For any case, the level of verification and validation of the EHM software should be properly aligned to the level of system criticality. At the release of this ARP, there are activities underway within SAE to address the evolving subject of EHM software affecting safety. In the meantime, EHM system designers should make use of an aircraft-level Functional Hazard Assessment (FHA) and Failure Modes Effects Analysis and Criticality Analysis (FMECA) to determine the appropriate level of software verification and validation to ensure that the design rigor is commensurate with the consequence of failure of an EHM function. The fundamental concept that must be addressed is discussed in Advisory Circular (AC) 25.1309-1: "a function with a more severe consequence of failure must have a corresponding higher level of integrity, and thus lower probability of occurrence." Another important objective of the FHA is to identify ways to minimize the software verification and validation impact through use of mitigating actions that reduce the effect of failure of an EHM function.

4.2.6 System Failure Mode Effects and Criticality Analysis (FMECA) Considerations

One of the initial steps in the EHM system design is to clearly define how the engine and its components function and how they can potentially fail. A clear understanding and representation of the functions to be accomplished provides the framework for capturing how a system can fail, the manifestations of the failure, its consequences, and its impact on the aircraft as a whole.

Understanding and accurately representing the functions and potential failure modes of a physical engine system is critical to designing an EHM system that can be used for accurate failure detection, isolation, and restoration of the engine system to its normal operating mode. An initial FMECA is typically performed during the design stage of a physical EHM system to help organize this information. This represents the perfect link between the critical overall engine system failure modes and the EHM system to help address those failure modes. Hence, a key aspect of the EHM system design process links this traditional engine FMECA with sensor, diagnostic, and prognostic selection and optimization based on failure mode coverage and life cycle cost analysis. Based on the analyses, the engine FMECA may also drive EHM design changes for improved failure mitigation.

EHM system design should also take a system level approach to the detection and prediction of faults/failures and the mitigation of their consequences. Design tools, when available, should make use of traditional FMECA for EHM system design, but expand the capabilities to include failure mode symptoms, health management design attributes, and sensor information. In forming the design of an EHM system, a functional block diagram of the EHM system should be created to model the functional flow relationships among components of the physical EHM system. This functional block diagram will provide a clear vision of how components interact with each other. In addition, a tabular FMECA should be utilized in analyzing the EHM system which corresponds to a traditional FMECA. The tabular FMECA should also contain the EHM failure mode symptoms (see 4.5.4.1). Finally, maintenance tasks that address EHM system failure modes should also be included.

4.2.7 Architecture Design

Nominally systems architectures are either closed or open design concepts. Analysis of both design approaches will need to consider the level of function (hardware and software) criticality as well as the certification approach to be used. Many state of the art systems are moving towards an open architecture concept that supports interoperability, vehicle level integration, and data sharing with third party suppliers, such as maintenance-related applications. The benefits of an open architecture approach can be offset by the increased effort and complexity required to ensure the interface is sufficiently robust to prevent reliability and operability problems. For these reasons, use of the Open Systems Architecture for Condition Based Maintenance (OSA-CBM) construct developed by the Machinery Information Management Open Systems Alliance (MIMOSA) is recommended. Further, for data recording functions of the EHM system, an open-source, structured data file should be implemented.

An essential decision for the architecture of the off-board aspects of the EHM system is where data transferred to the ground will be stored and analyzed. The critical function of the EHM system is the display of data and/or information in these ground-based aspects. First, the EHM analyst must be able to make an intelligent decision about maintaining the propulsion system through these interfaces. Second, the maintainer must be consistently alerted to the recommended course of action. In addition, the off-board architecture may require interfacing with third party suppliers for logistics and resource planning. The ground-based aspects of the EHM system should be “outward-facing” in that data and/or information should be provided in a documented open and consistent format that any potential consumer can use.

4.2.8 Relevant Standards

The information standards relevant to the EHM domain are shown in Appendix A. The approach, scope and capability of each standard are briefly detailed, together with a maturity assessment. The standards in Appendix A were selected because of their direct support for EHM, OSA-CBM, and support for logistics, supply chain, Business to Business (B2B) exchange and product/life cycle information. In addition, a view of recent interoperability initiatives that link EHM relevant standards across the aircraft and Enterprise domains is provided. These standards are recommended for designing, developing, and testing an EHM system.

Standards Maturity is measured as an aggregate of how long the standard has been ratified and published, combined with how widely it has been adopted and implemented and how useable the standard is in terms of building compliant system interfaces.

Relevance to the EHM domain is measured by how directly the standard supports the implementation of an EHM system. This is defined in terms of integrating system and software components including sensors, data acquisition, prognostics and diagnostics and enterprise systems.

The MIMOSA standards of OSA-CBM and OSA-EAI Open System Architecture for Enterprise Application Integration have been developed specifically to support condition based maintenance and EHM system technologies along with IEEE-1451 to standardize sensor systems. Open Applications Group Integration Specification OAGIS, though mature, is more focused on supply chain management.

4.3 System Specification - Design and Performance Requirements

The EHM system designer and the operator/customer/OEMs (airframe, engine, and avionics) will normally create a system specification that defines both the design and performance requirements of the overall system. The specification should comply with standard configuration management practices necessary to identify all supporting hardware and software design and performance elements and requirements.

Both the EHM system requirements and their validation should be specified as part of the system specification. Specifications should include performance capabilities such as: acceptable probabilities of detection, confidence levels, life tracking/cycle counting capabilities, diagnostic capabilities, prognostic capabilities, and key implementation requirements (i.e., system integration, hardware, and software). In each case, it is important that the system specification clearly identify the requirements so the system configuration and approach are selected to ensure the requirements are met. The specification should also address requirements to establish airworthiness and continued airworthiness, as applicable.

4.3.1 System Integration

The integration of the EHM functions on the aircraft should be clearly identified in the system specification. The EHM system designer is tasked with showing that the performance of the complete system justifies any changes in requirements at the aircraft level.

There are four primary options for onboard integration of EHM functions: (1) integrate the EMS function in an aircraft system, (2) integrate the EHM function in an engine system, (3) introduce standalone airplane equipment for an EHM function, or (4) introduce standalone engine equipment for an EHM function. The business case will typically encourage the integration of EHM function with other existing or planned aircraft or engine systems. Dependency on other systems has to be considered in the design and testing of the EHM system and will have an effect on the reliability and validity of the overall system.

Implementation decisions will arise for functions integrated (for EHM or otherwise) in the same equipment. Functions may be partitioned (logically or physically) from other functions that do not require the same level of software assurance. Alternatively, all functions in the equipment may be developed at the same level of integrity. The former is more complex. The latter adds cost but may be more conducive to EHM maintenance credit utilization. As such, the system specification should deal with this additional consideration.

For onboard and off-board integration issues, Interface Control Documents (ICD) referenced by the system specification should ensure proper data handling between the EMS, other related aircraft/ground support equipment, engine, and logistics systems.

As stated above, ground-based integration issues will likely include making data available to or receiving data from other operator systems for consumption. An open format that includes descriptive attributes of the data is recommended for this data exchange.

The system specification should also identify how the EHM information and data will be integrated into and used in the engine's operational and maintenance procedures. The specification requirements here will be directly derived from the ConOps and Use Cases developed for the EHM system.

The specification should indicate the signals required at each sub-system interface along with details such as their frequency, resolution, type, and units. This is true whether the interface supports an onboard or ground-based function. The specification should identify attributes that each data/parameter should have. These attributes should, to the greatest extent possible, be driven up into all systems that produce data that the EHM system might consume. In any case, a definition of the mapping between the parameter attributes assigned by the existing systems and the EHM system data/parameter attributes should also be included in the specification. Every effort should be made to assign common/standard definitions to data/parameters within the EHM system and existing systems. This standardized data dictionary will enable a consistent understanding and appropriate use of the data.

4.3.2 Onboard Hardware Design and Performance Requirements

The decision for what elements of the EHM system are to be incorporated onboard the aircraft should be made utilizing the ConOps discussed in 3.2.5, 4.1, and the regulations of the appropriate airworthiness authority. The general specification requirement for the onboard EMS is that hardware elements should be replaceable/interchangeable without additional adjustments or degradation of measurement accuracy. Additionally, the design and performance specifications for all onboard EMS hardware should address the following key areas to provide long term stability for ensuring:

- High integrity/high reliability of the EMS components used for alerting the crew during flight. This is important where EHM functions are integrated with other functions in the same equipment. Hardware or physical partitioning is a recommended means to protect safety related hardware from non-essential hardware components.
- Reliability of data transfer from the aircraft to the ground based system as influenced by hardware, media, handling, related procedures, etc.
- EMS design robustness so that failure of any one of the interfaces will not adversely affect the communication and performance of the remaining interfaces.

- EMS continued operation in the degraded mode. In general, the EMS should recognize normal and abnormal operating conditions. In case of abnormal operating condition, such as intermittent failure of a sub-component (e.g., power supply or wiring) or lightning strike, the EMS should not output false information. Abnormal operating conditions should not result in a “babbling” EMS component or one that intermittently outputs valid and invalid data for long periods. A typical requirement is to have the EMS continue to output the last measured valid data set for a short time followed by setting an invalid data flag. After the normal conditions resume, the EMS should continue operating in normal mode.
- Sufficient tolerance bands between components and their installation to include variance that could occur as a result of changing suppliers during the production phase.
- Timing requirements between digital signal processors for integration of specified timing between sensing elements, recording elements, signal processing, and control elements to properly interpret the data.
- Redundancy of parameters/functions that may be implemented in shared engine/aircraft systems which can benefit the EMS.
- Environmental Performance in which the components operate and are stored influences reliability of the EMS. The environmental requirements are usually stated in the specification and should include applicable parameters for environments addressed in commercial or military documents such as RTCA/DO-160, MIL-STD-810/461/464, and ADS-37.

4.3.2.1 Power Supplies

EMS power supply specifications should address the various power supply conditions (e.g., steady state, transients, voltage spikes, interruptions) that may be encountered during operation. During the design phase, environmental requirements defined in the specification are analyzed and the equipment is either designed to meet the specification during the various power supply conditions, or measures are taken to reduce load on the components of the system (Reference DO-160, MIL-E-7016, and MIL-STD-704).

4.3.2.2 Sensors

- The design and performance specifications relating to the reliability of the EMS sensors, especially to those that are internally mounted in the engine, should be sufficient to preclude replacement of the sensors between shop visits. The sensor design and associated engine interface features should prevent incorrect installation on the engine. Sensor specifications should be tailored to the specific application and environment, such as range, bandwidth, dynamic response, accuracy and resolution.
- Sensor failures can be generally characterized as “soft” and “hard”. Each of these failure types requires unique specification language as to how they are to be handled by the EMS. Most modern signal conditioning designs properly detect sensing system “hard” faults due to loss of signal typically indicating a sensor or harness problem. A good design practice is to detect out-of-range (low or high) readings by electronic processing. “Soft” failures manifest themselves with inaccurate readings from issues like low or high in-range indications and in-range noise. These types of failures can be detected by software design techniques if there is a redundancy of the measured parameter or the sensed value can be correlated with other parameters.

Sensors using digital output protocol often implement self-calibration, built-in-test (continuous, automatic, or manually initiated), data processing and compression capabilities. Such sensors can provide a failure message in digital output. Design and specification provisions should be made to prevent the loss of communication between multiple sensors with digital outputs and the electronic unit. Design and specification provisions should also be made so failure of a single sensor does not disrupt communications.

For recommended practices in developing detailed design and performance specifications on sensor parameters and signals, refer to Appendix B.

4.3.2.3 Data Buses

Most modern aircraft, commercial and military, have flight critical data buses. In some cases, it is possible to design the transmission of EHM data on these buses or to acquire data already on the bus. However, the sources and destinations of the EHM data must comply with the existing bus interface requirements. In other cases, a bus may be entirely "off limits" and a new data bus should be specified for engine health management. In either case, data bus specification requirements should establish:

- **Bus Capacity:** The primary considerations of a candidate bus to handle engine management data necessary for EHM function are:
 - Availability of labels or addresses for the desired EHM data
 - Impact on growth margin for the primary bus users
 - Resolution and update rate requirements of the EHM and primary user data
- **Bus Configuration and Routing:** The primary considerations for adequate EMS bus configuration and transmission media routing are:
 - Ability of the bus structure to accept necessary terminals.
 - Ability of the bus protocol to accept necessary terminals and labels.
 - Impact on Electro-Magnetic Interference (EMI), External Radio Frequency Environment (ERFE), and lightning protection and/or re-routing of transmission media.
 - Impact on cost and weight of additional and/or re-routing of transmission media

4.3.2.4 Cabling and Connectors

Specifications for EMS cabling and connectors should designate proper ratings and stipulate the type of signal transfer and environment capability required. For wire transmission media, the type of signal, voltage, current, charge and frequency employed, usually dictates cable shielding, grounding, routing and installation requirements.

- Connector installation and cable routing is important to be addressed via specifications (e.g., inadequate clamping of cabling can lead to noise in vibration signals). Connector specifications are addressed in various standards. When selecting and specifying connectors the following should be considered:
 - Location (e.g., correct temperature rating, vibration, strain relief)
 - Sealing against moisture and contaminants such as oil and hydraulic fluid
 - Special high mating force connector contacts in critical areas
 - Pin size (e.g., number 20 or larger)
 - Integral leads where temperature rated connectors are not available
 - Arranging and grounding spare contacts where mixing of different signal types in the same connectors is unavoidable (e.g., vibration with thermocouple signal or speed with other frequency or pulse signals)
 - Unique keying configurations where connectors are similar to each other