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Aircraft Gas Turbine Engine Health Management System Guide

RATIONALE

ARP1587B has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) examines the whole construct of an Engine Health Management (EHM) system. This keystone document gives a top-level view and addresses EHM description, benefits, and capabilities, and provides examples. This ARP purposely addresses a wide range of EHM architectures to demonstrate possible EHM design options. This ARP is not intended as a legal document and does not provide detailed implementation steps, but does address general implementation concerns and potential benefits. Other SAE documents (Aerospace Standards, Aerospace Recommended Practices, and Aerospace Information Reports) address specific component specifications, procedures and "lessons learned".

1.1 Purpose

The purpose of this ARP is to provide an Aircraft Gas Turbine Engine Health Management System Guide for commercial and government operators, aircraft manufacturers, engine producers and equipment suppliers. This guide is provided for program managers to obtain a sufficiently detailed understanding of EHM systems to make funding decisions. Similarly, it can be used by design personnel to obtain a systems perspective as well as references to guides on detail design of all aspects of an EHM system.

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 724-776-4970 (outside USA), www.sae.org.

The following SAE documents provide more detail on the various aspects of EHM systems:

General:

AIR1871B	Lessons Learned from Developmental & Operational Turbine Engine Monitoring Systems
AIR1873	Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines
AIR4176	Cost Versus Benefits of Engine Monitoring Systems
AIR5120	Engine Monitoring Systems Reliability & Validity

Life Usage:

AIR1872B	Guide to Life Usage Monitoring & Parts Management
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Performance Monitoring:

AIR1900A	A Guide to Temperature Monitoring
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Condition Monitoring:

AIR1828B	Guide to Engine Oil System Monitoring
AIR1839B	A Guide to Aircraft Turbine Engine Vibration Monitoring Systems
AIR4986	Engine Electrostatic Gas Path Monitoring
AS8054	Airborne Engine Vibration Monitoring (EVM) System Minimum Performance Standard for
AIR5317	A Guide to APU Health Management
AIR4174	Guide to Powertrain Monitoring Techniques

Diagnostics & Prognostics:

AIR5871	Prognostics for Gas Turbine Engines
AIR4985	Engine Fault Detection & Isolation Definitions & Metrics
ARD50069	Neural Networks Applications for Engine Condition Monitoring

On-board & Ground-based Data Management:

AIR4061A	Integration of EM with On-board Systems
AIR4175	A Guide to the Development of a Ground Station for Engine Condition Monitoring
AS4831A	Standard Software Interfaces for Ground Based Monitoring Systems
AS5395	HUMS Data Interchange Specification

2.2 Related Publications

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

- [1] Abernethy, R. B., Thompson, J.W., 1973, Uncertainty in Gas Turbine Measurements, AIAA Paper 73-1230.
- [2] Bishop, C.M., Neural Networks for Pattern Recognition, Clarendon Press, Oxford, 1997.
- [3] DePold, H.R., Gass, D.F., 1998, The Application of Expert Systems and Neural Networks to Gas Turbine Prognostics and Diagnostics, ASME 98-GT-101.
- [4] DePold, H., Volponi, A., Siegel, J., Hull, J., Validation Of Diagnostic Data with Statistical Analysis and Embedded Knowledge, ASME 2003-GT-38764.
- [5] Duda, R.O., Hart, P.E., and Stork, D., Pattern Classification, John Wiley & Sons, New York, 2000.
- [6] Volponi, A., DePold, H.R., Ganguli, R., Daguang C., 2000, The Use of Kalman Filter and Neural Network Methodologies in Gas Turbine Performance Diagnostics: a Comparative Study, ASME 2000-GT-547.
- [7] Volponi, A., 1994, Sensor Error Compensation in Engine Performance Diagnostics, ASME 94-GT-58.

- [8] Volponi, A., 1983, Gas Path Analysis: An Approach to Engine Diagnostics, Time-Dependent Failure Mechanisms and Assessment Methodologies, Proceedings of the 35th Symposium, Mechanical Failures Prevention Group, Gaithersburg, MD, Cambridge University Press.

2.3 Terminology and Definitions

The following list defines the terms used in this ARP.

AI: ARTIFICIAL INTELLIGENCE: An area of research that deals with automated machine learning that mimics the principles of intelligence and evolution.

AERONAUTICAL RADIO, INCORPORATED (ARINC): An avionics service provider.

CONDITION BASED MAINTENANCE (CBM): A set of maintenance processes and capabilities derived from real-time assessments of the equipment condition obtained from embedded sensors and/or external tests and measurements. The goal of CBM is to perform maintenance only upon evidence of need in a non-reactive sense. As such, the evidence needs to provide an indication that a certain time interval exists in which a specific maintenance action should be performed prior to the occurrence of a given fault or failure.

DEGRADATION: The mechanism by which the performance and ability of a system, piece of equipment, component or subassembly diminishes, usually as a function of time or usage.

DIAGNOSIS: The active process, through the analysis of data from a system, piece of equipment, component or subassembly, by which a symptom is investigated to understand its cause.

EGTM: EXHAUST GAS TEMPERATURE MARGIN: The difference between the actual exhaust gas temperature (EGT) for an engine and its certified EGT limit. The actual EGT is projected to full power takeoff and flat rated (or worst case) environmental conditions prior to being compared to the EGT limit. EGTM provides (1) a common point for comparing relative health among other engines of the same type, and (2) an indication of life remaining (in terms of EGT limit).

EHM: ENGINE HEALTH MANAGEMENT: 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

EHMS: ENGINE HEALTH MANAGEMENT SYSTEM: A complete system approach that includes some or all of the techniques listed under EHM (see above).

EM: ENGINE MONITORING. The general discipline or techniques to detect and observe data from a system, piece of equipment, component or subassembly through the use of sensors, data collection, data processing, data analysis, and the human decision process.

ETOPS: EXTENDED (RANGE) TWIN (ENGINE) OPERATIONS: Extended range operations with two engine airplanes. An ICAO rule adopted by regulating authorities permitting operators to fly two-engine commercial air transports on routes in which the distance to the nearest diversion airfield is greater than 60 flying minutes. Additional deviations of 75-minutes, 120-minutes, 180-minutes, and 330-minutes have been granted to some aircraft. The diversion is assumed to be conducted at the approved single engine inoperative cruise speed under standard conditions in still air.

FAILURE: A functional status or physical condition characterized by the inability of a system, piece of equipment, component or subassembly to fulfill its design purpose; the most severe degree of malfunction or degradation.

FMECA: FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS: A clinical, logical study of the ways in which a system, piece of equipment, component or subassembly can fail, the follow on effects of that failure on the surrounding system(s) and the impact of the failure on the system as a whole.

FAULT: A condition whereby a system, piece of equipment, component or subassembly is not able to perform as per specification. A fault may be indicative of an impending failure (see failure above).

HCF: HIGH CYCLE FATIGUE: Component material life usage incurred by experiencing a large number ($>10^5$) of oscillatory cycles but of relatively low amplitude (e.g., vibration, resonance, etc.).

HUMS: HEALTH AND USAGE MONITORING SYSTEM: A data acquisition, analysis, and information processing system that uses the aircraft parametric and utilization data to determine the integrity of components and subsystems.

IEEE: INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS: An electronics industry standards organization.

IFSD: IN FLIGHT SHUT DOWN: An event in which an engine is shut down in flight because of a fault, malfunction or severe degradation.

IP: INTERNET PROTOCOL: A means to establish a data link in real-time.

IVHM: INTEGRATED VEHICLE HEALTH MANAGEMENT: The general discipline or techniques for detection, accommodation, diagnosis and prognosis of degradation or failure of any systems, piece of equipment, component or subassembly and offering a maintenance action or decision support to address the degradation integrated for an entire air vehicle.

LIFE: A defined period of time during which a system, piece of equipment, component or subassembly is expected to operate safely and/or within specification. The term can be used to define an inspection or overhaul limit or a finite life limit (at which point the item is discarded).

LCF: LOW CYCLE FATIGUE: Component material life usage incurred by cyclic stress excursions ($<10^5$ cycles) and usually of high amplitude (e.g., rotational speed changes within the range zero to max rpm)

LRU: LINE REPLACEABLE UNIT: A piece of equipment or assembly that may be replaced at the first (flight line) level of maintenance.

MSG: MAINTENANCE STEERING GROUP: An ATA (Air Transportation Association) sponsored study group which publishes recommended methodologies and analytical procedures for developing a maintenance plan for aircraft, engines and systems.

NRIFSD: NON-RECOVERABLE IN FLIGHT SHUT DOWN: An in-flight shut-down that is non-recoverable, that is, the engine cannot be restarted after it shuts down.

ON CONDITION (see Primary Maintenance Processes).

PRIMARY FAILURE: A failure that is not a result of another failure and is generally the failure that triggers other failures or damage (see FMECA), also known as incipient or root cause failure.

PRIMARY MAINTENANCE PROCESSES: Three primary maintenance processes are defined and published by the Maintenance Steering Group (e.g., MSG-3) for classifying the way in which a particular aircraft element is maintained. These primary maintenance processes are:

- a. **Overhaul Time Limit or Part Life Limit (Hard Time):** This is a preventive primary maintenance process. It requires that a part be periodically overhauled in accordance with the operator's maintenance manual or that it be removed from service.
- b. **OCM: ON Condition Maintenance:** This is a preventive primary maintenance process requiring that a part be periodically inspected or checked against some appropriate physical limit to determine whether it can continue in service. The purpose of the limit is to remove the unit from service before failure occurs. These limits can be adjusted based on operating experience or tests as appropriate.
- c. **CM: Condition Monitoring:** This is a maintenance process for items that have neither "Hard Time" nor "On Condition" maintenance as their primary maintenance process. CM is accomplished by having appropriate means of data collection and analysis by which an operator obtains information from the whole population of a system or item in service and uses this information to allocate resources.

PROGNOSIS: The forecast of future functional status and condition of a system, piece of equipment, component or subassembly based on current and accumulated inputs. 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.

RCM: RELIABILITY CENTERED MAINTENANCE: A disciplined, structured process to identify cost effective and technically sound engine maintenance policies. With consideration to overall system reliability, RCM not only addresses components requiring specific maintenance but also those surrounding components that are worth inspecting/replacing/maintaining based on component reliability and criticality. As an example, during maintenance, a non-failed component is exposed and it may be more cost effective to replace the component than to risk the component failing or requiring maintenance within a pre-defined period of operation. The policies adopted involve maintenance at the flight line, intermediate maintenance and depot/overhaul as well as supply, training, engineering operator procedures and technical data.

RELIABILITY (+ MISSION/DISPATCH RELIABILITY): A measure of the likelihood that a system, piece of equipment, component or subassembly will perform its required functions for a specified duration or usage. Reliability is often expressed as a probability of achieving the expected performance or "Mean Time Between Failures (MTBF)".

SECONDARY DAMAGE: Additional damage resulting from a primary failure (see primary failure).

SITA: SOCIETE INTERNATIONALE DE TELECOMMUNICATIONS AERONAUTIQUES: An avionics services provider.

SYMPTOM: A measurable difference from nominal in some sensed output of a system, also referred to as an anomaly, i.e., not normal.

SYMPTOMATICS: The analysis of data from sensors, and/or periodic inspections, to determine an item's state of degradation, progression along a path towards failure, or the sensing of a symptom of abnormal condition.

3. DESCRIPTION

As EHM evolves, definitions that were appropriate a few years ago are no longer satisfactory and must be updated so that they are again representative. At its heart, EHM concerns the pre-emption, postponement and accommodation of gas turbine engine degradation, faults and failures. Furthermore, it should be considered in a broad context, from the sensing of properties on the engine to determining the effectiveness of any actions taken.

The guidelines of this document focus on an Engine Health Management system, that is, the system monitors are for engine gas-path and accessory systems. These principals are equally valid for an Integrated Vehicle Health Management (IVHM) system. In this case, the system monitors cover all airplane systems. Current EHM systems are part of an IVHM system. The integration with the air vehicle health management system typically occurs at the functional level of data storage, off-board transmission and decision support as described in Section 5 below. Each new generation of IVHM systems will employ system monitors that apply across traditional system boundaries, moving this traditional integration boundary. An extra level of rigor is required for the design of the IVHM system to assure that the integrated system provides an optimum solution.

3.1 Degradation, Faults and Failures

Degradation, faults and failures are changes in an engine's condition that compromise its ability to perform as required. Degradation implies a gradual change between the period when the item is performing its function satisfactorily and the period when it is not. A good example is the loss of efficiency of an engine component over time such as the compressor, through wear, leading to an increase in blade tip clearance until the engine is unable to provide sufficient take-off thrust (military) or EGT margin (commercial).

The nature of a fault implies a clear delineation between the period when an item is performing its function and the period when it is not (i.e., when it fails). The distinction between failure and fault is not always clear, but EHM specialists tend to refer to 'fault to failure progression', using the term fault to refer to an incipient condition reached on the route to failure. Indeed, the term 'failure' frequently refers to a sudden change such as a blade, bearing or disk failure.

3.2 Life

From an EHM perspective, it is useful and consistent to think of a 'life' as being a finite value of usage or 'life consumption' (whether measured in hours, cycles or some other damage accrual factor) at which a component would be deemed no longer serviceable. A 'life limited' item is one where this value has been specified.

3.3 Reliability and Dispatch/Mission Reliability

Reliability is usually specified as a probability of failure within a given timescale or a 'mean time between failure'. In this sense, EHM can affect reliability if it can modify an item's environment, for example by smoothing throttle demand. It cannot affect the intrinsic material behavior of a component.

Mission reliability is described as the probability that an item will be available to perform its required functions for the duration of a specified flight or mission. The intrinsic reliability of the system's components affects Mission Reliability after a mission or flight has begun. If an EHM system predicts degradation, faults or failures of a component that would cause a flight cancellation, turn-back or mission failure, the component may be replaced beforehand, thus having a direct impact on mission reliability (although still not affecting the responsible component's intrinsic reliability).

Mission Reliability is affected before a flight or mission not only by the system's component reliability but by the ability to accommodate failures. This is addressed by design redundancy and the use of off-design capability (e.g., a commercial dispatch deviation guide allows dispatch with some components not performing their intended function). EHM systems can provide advance notice of failures (occurring in the previous flight or predicted to occur in the future) such that, again, the indicted component can be replaced without impact on mission reliability. Sentence with a reference to AIR5120.

3.4 The Elements of an EHM System

A useful construct for understanding the functions of an EHM system identifies four essential elements: 'symptomatics', diagnostics, prognostics and prescriptive action. See Figure 1.

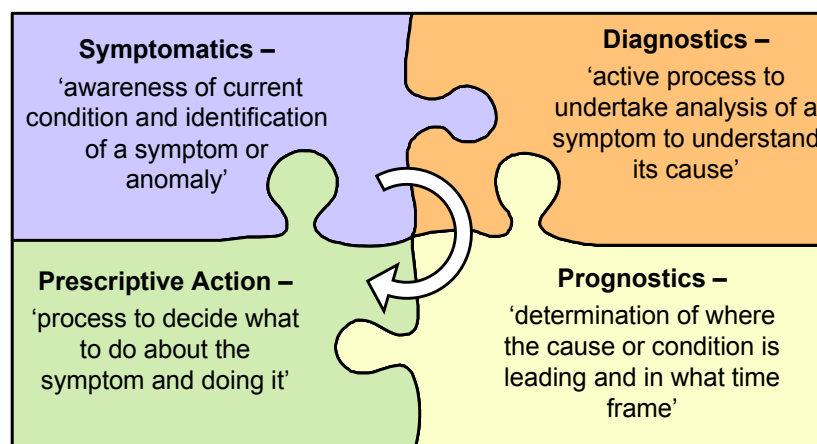


FIGURE 1 - THE ELEMENTS OF EHM

3.4.1 'Symptomatics'

The term 'symptomatics' addresses the first step of the EHM process and is the 'awareness of current condition and identification of a symptom or anomaly'. The medical parallel is an individual's awareness of how they feel, which may or may not prompt them to take the next step to diagnostics. Other terms that have been used to describe 'symptomatics', or that form a part of it, include 'state awareness', 'symptom identification', 'abnormality or anomaly detection', and 'condition monitoring'.

'Symptomatics' involves analysis of data from sensors, and/or periodic inspections, to determine an item's state of degradation, progression along a path towards failure, or the sensing of a symptom of abnormal condition. This functionality is sometimes included in the meaning of 'diagnostics' but, again following the medical analogy, there is often a distinct 'diagnostic' step that is required. For instance, an anomaly detection technique may be used to identify when an engine is performing abnormally without making an attempt to identify (i.e., diagnose) the cause or origin of the abnormality.

'Symptomatics' can take two broad approaches, which may be combined. The first is the 'life-based' approach, which estimates current condition by answering the question 'what was our starting state?' and 'what path did we follow to get where we are now?'. This approach is based on sensing parameters that estimate the damage input to a component. The principal route is through integration of the usage or damage accumulation history accrued by a part, as is traditionally used for low cycle fatigue (LCF) management of turbomachinery disks. An allied, simplified route might involve use of thresholds for highlighting significant exceedences such as over-temperatures or over-speeds.

The second approach is based on determining the condition of a component by sensing its behavior or output parameters. Examples of traditional implementations of these include monitoring vibration levels, or wear debris quantity and quality. The state-of-the-art would employ more sophisticated techniques to determine whether a condition was normal, probably using some form of artificial intelligence or a model to analyze data, based on physics, statistics, neural networks, Kalman filtering, fuzzy logic, Bayesian belief theory, multidimensional feature analysis and tracking, probabilistics or some other form of reasoning.

3.4.2 Diagnostics

The second EHM element is diagnostics, which is the 'active process to undertake analysis of a symptom to understand its cause'. The need for diagnostics implies that there is some uncertainty about the current condition. Thus, it is likely to involve some fault tracing or fault isolation to determine the underlying cause. More involved root cause analysis may be required for complex fault causes. Moreover, if a symptom calls for non-trivial diagnostics, the implication is that the fault is complex and this would suggest that prognosis would also be difficult. Diagnostics invariably requires a sound knowledge of the system in question; much of this knowledge is built into an engine's Failure Modes, Effects and Criticality Analysis (FMECA), which is a powerful diagnostic tool.

3.4.3 Prognostics

This is the third element of EHM and is the 'determination of where the cause or condition is leading and in what time frame'. In essence it is about predicting where degradation is heading, or what fault or failure will occur and when. This also implies a need to determine what effect this degradation, fault or failure will have on engine operation, or more specifically whether it will be critical or impact the aircraft's ability to carry out its mission. It is essential that the prognostic output provide meaningful information in the time domain, and it must also be based on some understanding or assumption of how the engine will be used. Historically, prognostics has been built into inspection limits, for instance in the allowable damage on turbine or compressor blades, where the projection is that the blade will last at least up until the next scheduled borescope inspection. The intention for the future is that increasingly accurate predictions should be made, reducing the reliance on regular time-consuming manual checks and inspections.

It is useful to consider more than one prognostic 'horizon'; see Figure 2. Short-term or 'near-horizon prognostics' gives a view of the near future and answers questions like 'will the engine complete the sortie/flight?' or 'will I need to change the engine in the next two weeks?'. These timescales are particularly useful to the pilot or a local engineering manager or commander; and high accuracy for individual engines is important. 'Mid-horizon' prognostics (between perhaps two weeks and two months) is of greatest use to the logistic chain so that spares may be moved into place, and for engineers to plan maintenance or prepare engines to avoid unnecessary failures and component changes early in deployments. 'Far-horizon' prognostics gives a longer-term view that is of greater value to the commercial or military headquarters for planning and provisioning purposes; high accuracy for individual engines is of less importance, the collective view being paramount here.