AEROSPACE INFORMATION REPORT

AIR5120

Issued 2006-11
Reaffirmed 2014-05

Engine Monitoring System Reliability and Validity

RATIONALE

AIR5120 has been reaffirmed to comply with the SAE five-year review policy.

TABLE OF CONTENTS

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1. SCOPE

1.1 Purpose

For Engine Monitoring Systems to meet their potential for improved safety and reduced operation and support costs, significant attention must be focused on their reliability and validity throughout the life cycle. This AIR will provide program managers, designers, developers and customers a concise reference of the activities, approaches and considerations for the development and verification of a highly reliable engine monitoring system.

When applying the guidelines of this AIR it should be noted that engine monitoring systems physically or functionally integrated with the engine control system and/or performing functions that affect engine safety or are used to effect continued operation or return to service decisions shall be subject to the Type Investigation of the product in which they'll be incorporated and have to 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 Engine Critical Parts would be included in the Type Investigation but most trend monitors and devices providing information for maintenance would not.

1.2 Introduction

An Engine Monitoring System (EMS) adds value by providing real time or near real time information on the functional and physical condition of gas turbine engines. This information is used to alert operators to conditions that could impact safe operation, schedule inspections and repairs to improve functional performance, forecast spares requirements, and manage warranties.

The elements that comprise an EMS are discussed in ARP1587. When discussing the reliability and validity of an EMS, the entire system needs to be considered, (i.e., design philosophy, software, hardware, sensors, operating procedures, training, service introduction and field support). The reliability and validity of the EMS is only as strong as its weakest sub-element.

Prior to the advent of EMS, engine operational information was obtained from flight crew and maintenance personnel observations gathered during operation or inspection. While there is no known quantification by a regulatory authority of the reliability and validity of these manually based approaches, they have evolved into the procedures and regulations that are currently considered the reliability baseline. Today, most EMS automate and enhance some or all of the manual processes to increase equipment safety and reduce operating cost.

Many early attempts to introduce EMS have lacked total success for a number of reasons. One of the major factors was a general lack of reliability. This reliability shortfall has come, in part, from the inherent unreliability of the system hardware elements. More importantly, however, reduced reliability was often due to the unreliability of the information provided by the system. History is replete with examples of false alarms, ranging from false chip detector lights to more sophisticated systems producing many false fault codes per flight. The inability of early EMS to provide reliable information has caused many to be extremely cautious in deciding how or when to implement a 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.

ARP1587 Aircraft Gas Turbine Engine Monitoring System Guide

AIR4985 A Methodology for Quantifying the Performance of an Engine Monitoring System

2.2 Definition of Terms

Detailed definitions of some of the terms below are given in AIR4985.

BIT: Built in Test

EIS: Entry into Service

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

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

CORRECT DETECT: The correct indication by the EMS that a problem exists.

EMS RELIABILITY: $\frac{[\text{Total Indications - False Alarms - Missed Detections}]}{\text{Total Indications}} * 100$

FIR: $\frac{[\text{No. of faults isolated}]}{\text{No. of faults indicated}} * 100$

ENGINE MONITORING SYSTEM (EMS): An EMS is defined as the complete system involved in the monitoring and indication of engine health. Included are the component level and subsystem level health status indications. Such indications are obtained through the use of sensor input, data collection, data processing, data analysis, and the human decision process. A complete system approach consists of an integrated set of hardware, software and logistical process. It can be manual, computer aided or fully automated.

COULD NOT DUPLICATE (CND): The inability to duplicate a problem detected by an EMS during subsequent testing. CNDs can be classified in two ways and can be difficult to separate:

1. A problem does not exist (False Alarm)

2. A problem does exist but is not detectable during the current test, i.e., no fault found, NFF. The principle cause of CNDs is the absence of a failure mode symptom during test conditions. In such cases, maintenance and operations personnel should take the appropriate action based on their experience. The suspected cause can be addressed by replacing components or the system can be returned to service with no maintenance action to see if the indicated fault returns.

LIFE CYCLE COST (LCC): LCC refers to the cost of the engine system of which the EMS is an integrated part. One of the main drivers behind most EMS is a reduction in engine system LCC. Included in the LCC is the cost of the EMS system and all additional hardware and software. The reduction in the LCC achieved as a result of the benefits derived from the EMS should be greater than the added cost of the EMS. From a general perspective the following gives the LCC Return on Investment (ROI).

$$\text{Life Cycle Cost} = \begin{matrix}\text{Cost of EMS} + \text{Cost of Engine System} + \text{Cost of Operation Over Life} \\ \text{ROI} = [\text{Benefit of EMS (\$)/Cost of EMS}] \text{ x } 100\end{matrix}$$

Where Benefit of an EMS can be defined as

Cost of Operation without EMS - Cost of Operation with EMS = EMS Cost Benefit

When an EMS is applied to a system already in service, consideration must be included for the years of remaining service. Depending upon the business aspects, it may be necessary to conduct a more in-depth financial analysis of the system to include a break-even analysis or spending profile projections as required by the business managers. The details of such analysis activity will generally be specific to the company but will generally follow the above indicated concept.

3. GENERAL CONSIDERATIONS

3.1 Overview

One of the fundamental reasons for incorporating an EMS is to improve the Life Cycle Cost (LCC) of the monitored system through operational and maintenance benefits. In most cases, the EMS 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. Unreliability of the EMS will adversely affect the ROI and could make the EMS a cost burden. The technology that is available for integration into an EMS 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 EMS such as analysis techniques, sensors, hardware and software.

It is preferable to start planning for an EMS early in the requirements development phase during the period where the customer, aircraft manufacturer and engine manufacturer have the flexibility to optimize content while maximizing reliability and ROI. Input from the customer's operational functions as well as the maintenance personnel who will use the system daily will provide an early understanding of the level of functionality required of the EMS and how it will be used. It is important at this stage to produce a risk assessment of technologies and to prepare maturation plans for those considered which offer high benefits as well as high risk. Consideration of these points up front should allow the EMS to be integrated into the total system architecture as outlined in Section 4.

A requirement may exist to retrofit an EMS, possibly to address a particular problem with the engine and its maintenance. Delayed introduction of an EMS to in-service engines will be more costly and may result in a less than desirable EMS capability but still yield a substantial return on investment and positively impact maintenance, logistics, safety, and operations. Retrofit of an EMS is by far the most complicated method of improving an existing system. Experience shows that for in service aircraft the cost of additional hardware, such as wiring and transducers to provide data for the EMS, may outweigh the benefits. In this case the best approach is to retrofit during a scheduled upgrade of the engine or airframe, particularly if wiring and sensors are to be added. The reliability requirements and considerations are the same as for the ideal case. However, the added complexity of integration into service, operational equipment and practices has to be considered in the risk assessment.

Human factors are an important element of EMS reliability. Since humans must ultimately interface with the system the risk of inducing human error exists and the associated impact on reliability. Section 4.5 details Human Factors and methods to mitigate their effects.

The entry into service and use of an EMS should be planned during the design phase. The EMS is likely to have an impact on the maintenance and operating procedures of the engine. The planning will include consideration of training and operation and maintenance procedures for the EMS itself and also for the engine. This is covered in 4.6.

Testing is a fundamental requirement to demonstrate EMS reliability and validity. Recommended test procedures to improve EMS reliability and validity are presented in Section 5 of this AIR together with their roles in terms of improving reliability and validity.

The functionality and use of the EMS should be integrated into the appropriate operational and maintenance practices for the air vehicle to improve the perceived and actual reliability of the EMS. Considerations for introduction of the EMS into service are addressed in Section 6.

The entry into service and support and maturation of an EMS will affect the reliability and validity of the system. If use of the functions is not fully integrated into the in-service environment, the overall reliability and validity of the system will be compromised. Issues related to integration into service and support and maturation are addressed in Sections 6 and 7.

3.2 General Validity and Reliability Requirements

EMS reliability needs to be evaluated at the system functional level in contrast to evaluating the inherent reliability of each hardware and software element. An EMS cannot be more reliable than its most unreliable hardware or software element. This is still true if the system includes redundancy to accommodate element malfunction.

EMS reliability is a function of 'false alarms' and 'missed detections'. False Alarms lead to time and money being spent verifying or trouble shooting a problem that does not exist. Although specific requirements are system and operator dependent, the target EMS false alarm rate on some of today's applications is no more than 2% of all the messages/alarms generated as a result of the faults monitored by the EMS. Provisions should be made during the requirements phase to consider the impact on the ROI and optimize accordingly.

EMS 'missed detections' result in equipment problems that go undetected. Missed detections generally have less impact than 'false alarms' since most equipment is designed to degrade slowly and equipment problems are eventually detected by the EMS or by the operating or maintenance crews. EMS 'missed detections' only become significant if the problem causes severe secondary damage or catastrophic equipment failure. Failure modes associated with severe or catastrophic failure usually make up only a small percentage of the equipment failure rate. Typically, these failure modes are well scrutinized during the EMS system design to avoid missed detections. This scrutiny is driven by the criticality of these failure modes and usually results in the EMS functions for these failure modes becoming part of the flight critical crew alerting system.

False Alarms have a far greater potential of negative consequences than Missed Detections. Therefore, as a guiding principle, EMS designers should focus considerable effort on avoiding false alarms even to the extent that missed detections are tolerated. As will be discussed later in this document, the EMS designer (in conjunction with the OEM) must make many decisions during the system and hardware/software design phases that directly impact reliability.

4. DESIGN AND DEVELOPMENT ACTIVITIES

4.1 System Specification

The operator/customer/OEM, in conjunction with the EMS designer, will normally create a system specification that defines the requirements of the overall system. It is recommended that EMS reliability and validity requirements be specified as part of the system specification. Specifications should include acceptable false alarm and missed detection rates, detection and diagnostic capabilities, and key implementation requirements (i.e., hardware, software and system integration). In each case, it is important that the system specification clearly identifies the requirements so that the system configuration and approach are selected to ensure that the requirements are met. The integration of the EMS with other existing or planned aircraft or engine systems such as the engine control, aircraft busses, and logistics management systems should also be clearly identified. Dependency on other systems has to be considered in the design and testing of the EMS and will have an effect on the reliability and validity of the system.

The system specification should also identify how the EMS information and data will be integrated into and used in the engine's operational and maintenance procedures. The reliability of the EMS in meeting the target improvement in LCC will be affected by how the data and information is used. Particular attention should be paid to interface architecture since different suppliers or organizations are often responsible for portions of the system to be integrated. All these activities have to be carried out with the engine Design Authority (DA/OEM).

Each specific application will carry slightly different reliability and validity goals determined by safety, cost and ROI considerations. These reliability and validity goals need to be established in the early stages of the design process and can then be used by the EMS designer to determine the implementation, hardware and software architectures, and testing levels.

The Acceptance Test Specification should be developed once the system specification has been prepared. This should include testing to address the reliability and validity requirements.

4.2 Hardware

EMS hardware reliability depends on the reliability of the EMS components and architecture. The correct hardware architecture of the EMS may improve functional reliability and validity of the detection capability and diagnostics. The separation of the functional requirements of the EMS for monitoring and acquisition should be considered during the definition of the EMS architecture.

The following key points should be specifically addressed:

- High reliability for the on-board components of the EMS, used for alerting the crew during flight.

- Reduced reliability may be acceptable for ground based elements of the EMS since the reaction to the information presented is not as critical in the post-process mode as it is for the real time on board mode. There is potential for additional ground based verification of the result. This practice is not recommended, however it may be used as a cost-effective solution.

- Reliability of data transfer from the airborne to ground based system is influenced by hardware, media, handling, related procedures, etc.

- The communication between the EMS and other related aircraft, engine and logistics systems.

- EMS needs to be designed sufficiently robust so that failure of any one of the interfaces will not adversely affect the communication and performance of the remaining interfaces and the EMS should continue operation in the degraded mode.

- Allow sufficient tolerance bands between components to include variance that could occur as a result of changing suppliers during the production phase.

- Match timing requirements between digital signal processors.

Although the redundancy of the sensors, communication lines and processing electronics will positively influence functional reliability of the EMS it is not general practice to have redundant components of the EMS or redundant processing electronics. Redundancy of some of the measured parameters may be implemented in the Engine Electronic Control or Full Authority Digital Electronic Control, EMS can benefit from this data.

The environment in which the components operate influences reliability of the EMS. The environmental requirements are usually stated in the specification and include such parameters as:

- Mechanical load - vibration, shock - single, multiple, linear acceleration, acoustic noise.

- Temperature - high, low operating/maximum short time/survival temperature, rate of change of temperature.

- Atmosphere - atmospheric pressure, rate of atmospheric pressure change, humidity, condensed humidity.

- Resistance to salt spray, sand and dust, fungus, working liquids, water, internal icing.

- Electromagnetic - atmospheric electricity, high intensity radiated fields (HIRF), lightning strike - single and multiple, multiple burst.

- Power Supply - normal, abnormal power supply conditions.

During the design phase environmental requirements defined in the specification are analyzed and the equipment is either designed to meet the specification, or measures are taken to reduce load on the components of the system:

- The mechanical loads are usually reduced by installation in an area with lower vibration levels or by means of shock absorbers.
- Operating temperature of the units can be reduced by cooling - forced cooling by air, fuel or natural cooling by convection.
- Operating temperature of the units can be increased by heating or by better heat dissipation inside the unit.
- Electromagnetic protection is usually provided by the whole EMS, including sensors, cable assemblies, and electronic unit(s). Special attention is paid in this case to proper shielding and grounding. The electronic unit(s) itself should also survive certain levels of interference induced by lightning, electromagnetic interference (EMI) or high intensity radiated fields (HIRF). For very demanding military environments fibre optic transmission of signals and communication may be required.

In general EMS should recognize normal and “abnormal” operating conditions. In case of abnormal operating condition such as intermittent power supply or lightning strike, the EMS should not output false information. Depending on the requirements, it should either keep silent or continue to output the last measured valid data set for a short time, as defined in the specification. After the normal conditions resume, the EMS should continue operating in normal mode.

The general requirement for the EMS is that elements should be replaceable without additional adjustments or degradation of measurement accuracy. The hardware design should provide long term stability.

4.2.1 Electronics

The following design practices increase functional reliability of the EMS electronics:

- Shielding, grounding and impedance matching.
- Separation of power and sensitive data lines.
- Operating below the power rating of the components.
- Burn in, aging processes during assembly and testing of the units.
- EMI protection on the input, output and power supply interfaces of the EMS.
- Separation of the “clean” and “dirty” zones within the electronics unit.
- Provision of a ground test (maintenance) connector with buffered signals to allow monitoring of the units operation during development, troubleshooting and other maintenance actions.
- Incorporation of spare computation power of at least 30 to 50% and spare memory of at least 20 to 50% is highly recommended to preclude potential reliability issues related to future growth of the EMS.
- Provisions for on board software or configuration upload to allow continuing upgrade and maturation of the EMS.
- System integration testing prior to and as part of final design verification testing preferably in a phased approach that gradually steps up the level of integration. (i.e., bench test to engine test to aircraft test) (refer to Section 5).

4.2.2 Sensors

The requirements 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. Sensor specifications should be tailored to the specific application and environment, such as range, bandwidth, dynamic response, accuracy and resolution.

Sensor failures can be characterized as “soft” and “hard”. “Hard” sensor failure modes indicate an engine system problem when the real fault is in the sensor itself. Most modern signal conditioning designs properly detect sensing faults when the fault is a total loss of signal. A good design practice is to detect out-of-range (high) readings by processing electronics. “Soft” failures manifest themselves with low or high in-range indications. These types of failures can be detected by software techniques if:

- There is a redundancy of the measured parameter.
- It can be correlated with other parameter.
- It can be calculated using a model.

Sensors using digital output protocol often implement self-calibration, built-in-test, data processing and compression capabilities. Such sensors can provide a failure message in the digital output. Provision should be made to prevent the loss of communication between multiple sensors with digital outputs and the electronic unit. Provisions should also be made so that failure of a single sensor does not disrupt communications.

The design of the sensor and the associated engine interface features should prevent incorrect installation of the sensor on the engine.

4.2.3 Cabling/Connectors

The cabling and connectors should be properly rated for the type of the signal transferred, as well as for the environment where they are located. The type of the signal, voltage, current, charge and frequency, usually dictates the requirements for the cable including shielding, grounding, routing and installation.

For improved common mode rejection capability and signal to noise ratio of measured signals, twisted pairs of the wires inside a common shield should be used. The signal leads should be fully shielded over the entire cable length. Double shielded cables are frequently used when the EMI requirements are very stringent. The additional shield acts as mechanical and electrical protection. When double shields are used, it is recommended to ground the outer shield as often as possible, i.e., normally at every connector via the connector backshells and at every clamping point. The inner shield however must be fully isolated from the outer shield, and at connectors be carried through via one of the contacts. The inner shield should be grounded at only one point, which is usually the signal conditioner chassis ground (similar to the single shield concept).

Installation of the connectors and routing of the cables is an important issue, e.g., inadequate clamping of cabling can lead to noise in vibration signals.

Connector issues are addressed in various standards. When selecting connectors the following should be addressed:

- Location, e.g., correct temperature rating, vibration, strain relief, etc.
- Sealing against moisture and contaminants such as oil and hydraulic fluid
- Special high mating force connector contacts in critical areas
- Pin size should number 20 or larger.
- Integral leads may be used where sufficiently temperature rated connectors are not available.

- Care should be taken when mixing different signal types in the same connectors, e.g., vibration with thermocouple signal, speed with other frequency or pulse signals… Where this is unavoidable then spare contacts should be grounded and arranged accordingly.

- Where connectors are similar individually unique keying configurations should be used.

4.3 Software

The reliability of the software itself is a significant aspect of the overall system reliability. The software design, configuration, development and verification/validation testing should be meticulously planned and rigorously controlled.

4.3.1 Design

A robust yet flexible architectural definition of the software will mitigate many of the historical problems associated with reliability. Currently there are two basic approaches, the closed architecture concept and the open architecture concept. Both approaches will need to consider the level of 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 easily allows enhancements and the inclusion of third party components. These benefits can be offset by the increased effort and complexity required to ensure the interface is sufficiently robust to prevent reliability and operability problems. Closed architecture concepts on the other hand are generally better integrated and more reliable but lack the flexibility of the open approaches. Some additional considerations that tend to improve reliability are:

- Place all variables in data tables.

- Segregate different levels of software (i.e., level C [required] and level E [pure maintenance])

- Where software is uploadable, consider including a means to identify the software upload (part number and/or version number) in a unit sitting on the shelf with no power applied. This can be accomplished with a Self Ident. System (SIS). A SIS can be implemented in many different ways one of which may consist of a small EPROM within the unit that can be powered by a handheld device.

In both the airborne and ground based portion of the system it is essential to properly plan for and control the database. Consideration must be included in the preliminary design phase for the following:

- How the various parts of the database will interface.

- What the data will be used for.

- How the data will be accessed.

- When it will be accessed.

- By whom it will be accessed

- What levels of manipulation will be allowed and by whom.

4.3.2 Data Validation

Before data is processed by EMS diagnostic algorithms, it must be checked against certain validity criteria to ensure algorithm reliability is achieved.

There are many ways to validate data collected by an EMS. Validation techniques include:

- Range checks, within the expected operating limits.
- Rate of change checking based on the capabilities of the measured engine parameter.
- Spike detection and rejection using statistical methods.
- Comparison of dual sensor or channel readings.

4.3.3 EMS Algorithms

Anomaly Detection

Identification of abnormal conditions from the EMS data can be a difficult activity since the designer may not have physical models that can accurately predict the resulting symptoms of a fault. The designer either must use empirical data from similar systems, rig testing to determine failure symptoms, or use an approach that detects deviation from normal behavior. The deviation from normal condition is the most frequently used method of monitoring. It is important to eliminate false alarms that are related to a change of the engine or aircraft operation.

The following are examples of anomaly detection techniques:

- Fault flags.
- Limit exceedance.
- Deviation from model based predictions.

Diagnostics

For increased reliability, detection and isolation of a fault should not be based on any single parameter input or information source. In some instances comparison of multiple engines, operating in the same conditions on the same aircraft can increase reliability of the fault detection and isolation. On a single engine application, the use of different but inter-related parameters to confirm the anomalous behavior can be used. In either single or multiple engine applications care must be exercised to prevent the inadvertent establishment of feedback paths within circuits that require segregation.

The following are examples of diagnostic techniques:

- Fault Filtering
- Trending
- Fault Modeling
- Data Fusion
- Pattern recognition

Prognostics

Diagnostics enables isolation of the type of fault, prognostics is the prediction of that incipient failure condition based on its progression to determine when maintenance or remedial action will be required.

Diagnostic and prognostic algorithms will need to be updated as new and different failures are discovered. This process can provide large improvements to the reliability of an EMS once it is fielded. When an EMS is fielded its algorithms are based on the present knowledge at that time. As a system is flown a large amount of data is collected. New failures may occur which could not have been predicted during design or produced in a test cell. In addition, changes to an algorithm library may be required to account for different flight regimes and envelopes. Lastly, as systems are used in the field and the airframe ages, algorithms may have to be 'tuned' to account for changes in areas such as vibration limits.

If the EMS has been developed with flexible limits it can easily be changed to acquire data at lower or higher thresholds allowing some control of the amount of data analyzed. Limits in the software can be used to control the level at which a failure is reported.

4.4 EMS BIT

It is general practice that BIT is implemented in the EMS. This should test not only the hardware of the electronic units and the correct performance of the software but also sensors, cabling and power supplied to the EMS.

Good design practice should include:

- BIT performed:
    - Routinely during EMS power-up.
    - Periodically during normal operation.
    - On demand, initiated by operator/pilot/higher level system.
- BIT that checks:
    - Open and short circuit of the sensor lines.
    - Power supply of sensors.
    - Validity of the measured signals.
    - All internal power supply sources.
    - Outputs via readback.
    - Input and output circuitry using injection of test signals on the input and wrap around of output information.
    - Proper operation of program cycle using watch dog timer that resets hardware in case of intermittent program cycle failure.
    - Memory – PROM, EPROM, EEPROM, RAM memory by means of Cyclic Redundancy Code (CRC), checksum, read/write cycle.
    - Bus communication by protecting labels or words with parity bit or CRC, periodically transmitting predefined message, and checking for stale (not refreshed) data.
    - Proper operation of Analog to Digital Conversion by injection of reference signal.

- Proper operation of timers by comparison with reference frequency.

- Non-volatile memory allocated for failure records that may include parameter values and time stamping.

- Several consecutive confirmations of the failure before a fault is declared by the EMS.

4.5 Human Element Factors

4.5.1 Introduction

Human factors are those elements of a design that are involved when humans and machines interface. These elements can and often do occur at many different design levels and incorporate physical as well as non-physical considerations.

The success of an EMS is dependent upon its acceptance by the user community. How well the human factors are integrated into the EMS will define to a large extent the level of acceptance by the user community. (The reader is encouraged to refer to ARP1587 for definition of the user community.)

This section will briefly discuss the human factor elements that need to be considered when focusing on the reliability and validity of an EMS. It is not the intention to cover all of the human factors but to present an overview of the more prevalent factors, their impact and how they are accommodated.

4.5.2 Non Physical Factors

Of all the elements that comprise an EMS, the most critical yet variable is the human element. Since humans ultimately turn information into action, the human element must be dealt with properly or performance of the system may be compromised.

There can be significant differences between people when viewed individually but as a group, people tend to fit a set of general patterns. These patterns will vary from group to group and even from culture to culture but are generally a constant across any one group at any single point in time.

It is important to define early in the design process the group or groups of individuals who will be using the system. These groups can include pilots, maintenance crews or the logistical community. Once the groups are defined it becomes necessary to develop an understanding of how they view the EMS, what they think about it and how they understand and intend on using the information it produces. It also becomes fundamental to also understand how they best perceive presented information and why they make the decisions they do in the way they do.

As simple as it may sound these tasks are difficult not just from a technical standpoint but also from a schedule standpoint. Invariably management will be pushing to move on with design and generally not allow adequate time for the assessment of these factors. As a result, a concurrent engineering approach generally provides the best compromise.

Many non-physical factors affect the thinking, informational processing and rationale development capabilities of the group that will be using the EMS. These include but are not limited to the following.

- The acceptance/resistance to change

- The subconscious need for recognition

- The willingness to accept technology

- The subconscious need to be needed

- The conscious and subconscious need for self-preservation

- The level of competitiveness within the work place

- The subconscious level of vulnerability to attack

- The degree of personal and job security
- The need to please/desire to do a good job
- The need for self-preservation
- Previous experiences with what is perceived to be a similar system
- The degree of need for control
- The perceived level of control and authority
- Reaction to sudden stimulus under stressful conditions
- The intellectual (comprehensional) capability of the user community

The above listed factors should not be looked upon as good or bad but should be used to evaluate the group dynamics and reactions. The manifestation of each of these non-physical factors are themselves the subject of numerous textbooks. The reader is encouraged to consult the various textbooks in the field for a deeper understanding of the subject material.

Each of the above factors and how they work within the user group needs to be considered when developing the various mental models (see below) upon which the EMS is built. Proper consideration will create an EMS that plays to the strengths of the user group and stays away from the weaknesses. This will in turn reduce the man-induced errors which will increase the reliability of the EMS.

Since not all groups have the same cultural background or level of bias and experience, the degree to which the above character traits and behavior patterns manifest themselves will vary with age, maturity level, culture and from situation to situation. Because of this the human factors aspect is constantly in a state of flux and the “design” is never solidly set but it can be predicted based on a large population. It is this predictability that provides the EMS designers with the knowledge necessary to minimize the related problems, maximize the effectiveness of the human link and boost the reliability and validity of the EMS.

When assessing the above listed factors it is best to immerse oneself as deeply as possible into the environment in which the users are working. This will afford the EMS designer the ability to think somewhat like the user and not the engineer at a desk 2000 miles away. When doing the environmental immersion, the surveyor should become involved with as many different individuals as possible so as to average out the different personalities. One must be careful not to become too deeply involved with any one individual due to the possibility of encountering extreme opinions. The goal of the assessment is to understand where the mean behavior pattern is and the width of the tolerance band surrounding the mean. This will assist in understanding what information should be presented, when it should be presented and most importantly how to present it.

Those programs that enjoy a long service life are also likely to see a shift in the behavior patterns of the people involved over a period of time as the business environment and demographics of the users group changes. In order to maintain a high level of reliability and validity one must be prepared to make adjustments in the system and the underlying philosophies to account for the changes.

4.5.3 Physical Factors

Understanding the non-physical factors opens the door to build the process models upon which the EMS is built. Once the mental models are built implementation of the physical human factors can occur.

The typical models that are built and used (either on paper or in the EMS designer's mind) fall into the categories described below.

- An operational model that defines the functions that are included: both routine functions and extreme functions.
- An operator usage model that defines how the various operators will use the system.
- A fault definition model that defines the faults that could be encountered.
- A fault location and isolation model that defines cause and effect and how the faults will be found.
- A data utilization model that defines how the data will be used and what it will be used for.
- A physical definition model that defines how the various parts of the machine interact.
- A life usage consumption model that defines how life consumption will be calculated.

Given the increasing level of sophistication within monitoring systems this list should be considered only as a starting point.

The physical factors include elements which can be controlled by altering some element of the design. They include but are not limited to the following list.

- Intellectual level of the data being presented
- Amount of data being presented at any one time
- Simplicity of data presentation
- Format of the data being presented (output)
- Level of user customization and interaction
- Degree of integration into higher level systems
- Physical size of the interfacing devices
- Data recording, continuous or triggered
- Data transfer media, type and frequency
- Enunciator types and locations
- Operator workloads
- Previous training - type, frequency and priority
- EMS training - type, frequency and priority

- Cockpit interfaces
- Language utilization
- Cultural preferences and considerations
- False alarm tolerance
- Missed alarm tolerance
- Supporting Equipment technology
- Data entry methods
- Data Download and analysis time
- Consequences of human error

Since the human link transforms the EMS data into action, the output format must present the data in an easily understood and credible manner. This will in turn maximize the reliability and validity of the monitoring system by reducing the likelihood for misinterpretation.

The environment in which the EMS user works within can often be a very different world from that of the EMS designer. In the previous section it was recommended that the EMS designer be immersed into the user environment so that the designer can come to understand the non-physical human factors. Since the findings obtained during user environment visits are subject to interpretation, a connection to the user environment should be maintained during system development and where possible, the implementation of the system should be tested a piece at a time, and users should have an opportunity to test and comment. User interaction promotes a series of small mid course corrections instead of a major redesign at the last minute should something not work and maintains a stronger continuity of design and a greater level of reliability.

Most of today's EMS are built with multiple levels of capability. It is important to keep the users capability and level of understanding on the same level as the data being displayed. With the tendency to incorporate more and more advanced technology this becomes a greater and greater problem. However, if the output information is presented in a relatively easy to understand format and the support is available in the event that a deeper probe of the information is needed, the incorporation of advanced technology will work.

One of the possible approaches adopted by modern EMS is to include the capability to provide different levels of data/information to different "levels" of user. These types of approaches must be considered carefully so as to prevent the perception that one level of user is policing the lower levels. Should the perception of policing develop, the usage of the EMS could be diminished and the overall reliability would suffer.

4.5.4 Training Impacts

Often the above mentioned factors will become compromised during the design process. It is necessary to have a good training program if the maximum benefit is to be obtained from the EMS. A good training program built by those who understand not just training techniques but also the inner workings and models upon which the EMS is built will minimize the negative effects of the compromises made during design. Unfortunately most company management, training departments, and trainers do not see EMS training any differently than component or engine overhaul training.

Generally, EMS has a more concentrated mix of physical and non-physical human factors than any other part of the engine it is monitoring. The basic functions of EMS are built on the models derived from detailed study of the human factors at work in the user community. No other component of the engine has such a high level of human factors consideration built in.

A good training program will accomplish the following:

- It will monitor the changes in the behavior patterns so early intervention can minimize the adverse impacts of a shifting set of demographics and behavior patterns.
- It will stabilize the behavior patterns within the user community.
- It will educate potential users in the thought processes used to build the system creating a wider base of user acceptance.
- It will reduce the spread of the behavior tolerance band.

Improper assessment of, or a change in the human factors during the course of design or use of the system will result in a mismatch between the user community and the system they are using. A small amount of mismatch should be expected due to minor variations in personnel but a large mismatch will create frustration and discontent among the user community, which will exhibit itself in reduced usage and an increase in the number of errors. A large mismatch will create doubt and a lack of confidence in the entire system, and may adversely affect the perceived reliability of the system.

4.6 Operational Design Considerations for Introduction and Support of the EMS

Reliability concerns during the entry into service phase are primarily focused on establishing successful transmission of the EMS information from its source to the ultimate destination and then using the information to prompt appropriate action.

To ensure this occurs, the methods of transmission must be established and proper procedures put in place to both use and maintain the system as a whole. Although not typically considered when evaluating the reliability or validity of a system, the procedures established for its usage are vital in obtaining reliable and valid results. This section will focus mainly on the procedures for operating and maintaining the EMS hardware as well as the methods for disseminating and using the information provided by the EMS.

The following responsibilities and strategies should be considered during the EMS design phase.

- Design Authorities roles and responsibilities.
- User's roles and responsibilities - including any special support or operational roles (maintenance or flight crew etc.).
- Organizational communications - within the user's organization and with other required bodies, e.g., engine DA etc.
- Introduction to service strategy - to include how functions will be enabled (e.g., phased enabling to ensure reliability per function rather than total EMS at one time), whether operational and maintenance procedures associated with the EMS will be audited during this phase to ensure they allow the goals to be met etc.
- Support strategy - once the EMS is fully enabled and operational how will it be supported, how will the benefits be assessed to ensure that perceived reliability is not affected by external influences.
- System performance assessment - metrics that will be used to enable the performance to be measured and improvements/enhancements (see 4.3) made to provide the reliability and capability required.
- Information needs analysis - who needs what information and when.

4.6.1 Documentation

Clear and complete documentation is the key to facilitating a smooth entry into service of an EMS. Smooth entry into service will maintain the reliability and validity that was designed into the EMS. The documentation should include descriptions of:

- The underlying operational concepts (models) the EMS is built on (reference 4.5.3).
- The Physical and functional hardware elements of the EMS at a system and component level.
- The gas turbine, which is being monitored and the interface between it and the EMS.
- Routine and periodically conducted manual operations related to EMS along with related detailed procedures.
- Routine and periodically conducted computer aided operations along with related detailed procedures.
- Routine and periodically conducted automated operations along with the back-up procedures in case of system failure.
- System software installation instructions.
- Post processing data handling procedures.

The documentation may be in either paper or electronic form per the system specification. Menu driven or on-line user aids can increase the ease of access to reference, training and procedural information but care needs to be taken to ensure consistency between forms. It is also recommended that back-up paper copies be available in case of corruption or failure of the electronic copy.

A suggested top-level format for the User Manual is as follows:

- Table of Contents
- Introduction
- Engine System Description
- Engine Hardware Description
- EMS System Description
- EMS Hardware Description
- EMS Software Description
- EMS Hardware Installation and Operation
- EMS Software Installation and Operation
- Inputs/Outputs and Messages
- Interpretation of Data
- Identification, Configuration Control and Revision Provisions

- Nomenclature
- References

The software section needs to include information on the parameter data stream and potential error messages.

4.6.1.1 Procedures for Operation and Maintenance

Tasks required to perform an operational evaluation include:

- Evaluation group assessment
- Required personnel skills validation
- Software enhancement and configuration management
- Maintenance benefits assessment
- Mission and operational effectiveness
- Engine condition and EMS output correlation
- EMS hardware reliability assessment and improvement
- Maintenance and logistic support documents evaluation
- Baseline production configuration and integrated maintenance concept recommendation

Manuals must be available which contain the procedures necessary for the use and maintenance of the system. Prior to full-scale introduction of the system, a dry run should be performed to allow maintenance personnel to step through the procedures. This will allow time to revise the process as needed if unforeseen problems arise. These procedures should cover, at a minimum, instructions for:

- Removal and replacement of any removable data storage devices (e.g., PCMCIA cards, Optical disks, Tapes, etc.)
- Configuration and set-up of the removable media
- Extracting data from the system and removable media
- Modifying and loading software to the on-board unit(s)
- Interpreting system output

The final item listed, interpreting system output, is discussed in more detail in the next section.

4.6.1.2 Procedures for Interpreting System Output

There are two basic categories of system output that the operator must be able to interpret and act upon. They are the ‘engine health output’ and the ‘system maintenance output’.

ENGINE HEALTH OUTPUT: This system output provides the main function of the EMS and is the information that is used to monitor the health of the engines covered by the system. Procedures must be available that clearly document how to interpret all possible scenarios of output (e.g., trend shifts, alerts, flags, etc.) and what actions should be taken in response to the data signatures.

SYSTEM MAINTENANCE OUTPUT: This is the system output that is used to maintain the EMS systems functionality. For example, this information can be in the form of fault messages, panel indications, or crew alerts. Lack of data is another form of system fault indication. Procedures must be available that clearly document both how to interpret and how to respond to any status or fault indications that the system provides.

4.6.2 Data Flow

The function of an EMS is to provide information that guides some sort of action. The flow of this information throughout the organization is as critical as the data itself in providing an effective overall system. The entry into service phase provides the final opportunity to validate the data flow through the organization and ensure that the EMS information is being provided to the proper organizations for action.

4.6.2.1 On-board Aircraft

From the operator's perspective, there are two main types of data flow on-board the aircraft: that which requires flight-crew action, and that which occurs in the background and is invisible to the flight-crew.

FLIGHT CREW RESPONSE: The flight crew can be involved with the EMS in two basic ways. They can either provide data to the system or respond to data provided by the system. Systems that require flight-crew input must provide specific instruction to the crew for collecting data. These instructions must be adapted to the specific instrumentation available for their use. Stabilization requirements and any other special instructions must also be included. Care must be taken during the development phase to ensure that the crews will be able and willing to provide the necessary input. For example, takeoff data is generally not available from the crew due their heavy workload during these conditions. As a general rule, overall EMS reliability is higher when the design does not require any input from the flight crew during any phase of the flight. This improvement occurs as a result of the elimination of the potential for human error that could be basic to all data collected during the flight. In some cases, the requirement to input data by the flight crew can require the addition of another flight crew member and in austere operational environments is not likely to happen. Such an event would tend to result in the reduction of EMS reliability. However, with some legacy systems, options may not always be present.

BACKGROUND DATA HANDLING: Although the data handling in this case is accomplished automatically, the algorithms used as triggers must be carefully defined and verified. These triggers prompt the system to record information about a specific event. Also, the operator must define triggers that determine how often data reports are taken during normal operation. This is typically defined by the operator's specific maintenance program and it should be based on OEM recommendations as a minimum. However, the quantity of data should not be so frequent as to mask longer-term trends.

At a minimum, the following items should be considered:

- Stabilization criteria
- Periodic sampling triggers (e.g., for trending normal operation)
- Abnormal event triggers (e.g., for surges or limit exceedences)
- Sample rate
- Sample size
- Flight phase coverage
- Data volume & Storage
- Report format and content

These items define the type of data that will be supplied by the system and must fulfil the requirements of the analyst and end-user.

4.6.2.2 From Aircraft to Ground-Based System

The amount, the method and the frequency of data to be transmitted or transported from the aircraft to the ground infrastructure must also be considered. For data that is transmitted, the timing of the reporting must match the urgency of the data. Immediate reporting may be accomplished via systems such as ACARS or satellite transmission; however, systems providing immediate access to the data are typically the most costly and may not be implemented.

Care must be taken to ensure that the data flow from the aircraft to the ground-based system, as defined during design phase, is validated and adjusted during entry into service.

One method of improving efficiency is to compress all data from a flight into a single end-of-leg report that is transmitted at the completion of the flight. This method however increases the time between the data recording and its availability. This must be considered when deciding which methods to use. Finally, the continuous recording or rolling history data is typically used only in the situation that a fault occurs. This type of data provides additional information for troubleshooting the event. However, for the data to be useful, an appropriate quantity of data surrounding any possible event must be recorded. In addition, infrastructure must be in place to quickly access and analyze this information.

4.6.2.3 Within Ground-Based System

Once the data reaches the ground-based system, procedures must be available to guide the data analysis and the recommended actions. These procedures must clearly document the operation of any ground-based software and guide the operator in interpreting the results to accomplish any necessary action.

The entire data stream should be tested with sample data or seeded faults to ensure that the proper analyses can be performed and appropriate actions initiated. Both accuracy and timeliness of responses should be evaluated.

4.7 Development and Technology Insertion

In certain applications the specified requirements of the EMS functionality or system implementation are outside the capabilities of mature computational techniques and systems but are yet known to exist. Implementation of the enhanced techniques or technologies is therefore known to be required at some point in the EMS life cycle. This may be in the form of new hardware such as sensors or electronic units or software. In some cases advanced software techniques that improve data interpretation and correlation may achieve the specified requirements.

When developing an EMS, consideration of both the initial and long term reliability and the associated development path is important. Proactive management of that growth activity must also be included during the development process to maximize systems validity and reliability.

All of the reliability and validity considerations for hardware and software development mentioned previously apply during the development and insertion of maturing technology. Two potential benefits that may exist during this phase that may not have existed during the original development phase are the existence of actual operational data and an operational platform on which final verification testing can be executed. Such actual data can facilitate a more reliable system.

The process will typically include:

- Review of the available signal data, analysis and correlation procedures
- Identification of new analysis, processing and correlation and integration techniques
- Testing of the new techniques on existing data, covering healthy and faulty engine conditions
- Initial assessment of diagnostic and prognostic capabilities
- Initial assessment of False Alarm Rates and probability of detection