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AIRCRAFT GAS TURBINE ENGINE MONITORING SYSTEM GUIDE

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PREPARED BY

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AIRCRAFT GAS TURBINE ENGINE MONITORING

1. PURPOSE: The purpose of this Aerospace Recommended Practice (ARP 1587) is to provide an Aircraft Gas Turbine Engine Monitoring System Guide for commercial and government users, aircraft manufacturers, engine producers and equipment suppliers. This ARP is not intended for use as a legal document but only as a system guide. Other SAE documents (Aerospace Standards, Aerospace Recommended Practices and Aerospace Information Reports) address, or will address, specific component specifications, procedures and "lessons learned".

2. SCOPE: This ARP is a system guide for Engine Monitoring System (EMS) definition and implementation. This keystone document addresses EMS benefits, capabilities and requirements. It includes EMS in-flight and ground applications of people and equipment, and recommends EMS requirements that are a balance of selected benefits and available capabilities. This ARP purposely addresses a comprehensive EMS. The intent is to provide an extensive list of possible EMS design options.

   NOTE:

   - Section 3 describes an EMS.
   - Sections 4 and 5 outline benefits and capabilities that should be considered for study purposes to define EMS baselines for how much or how little engine monitoring might be required.
   - Section 6 provides implementation requirements that should be considered for an EMS after study baseline levels of EMS complexity are selected.

3. DESCRIPTION: An EMS includes the people, equipment and procedures used to provide engine monitoring data (Fig. 1). An EMS collects, processes and displays data to assist engine design, management, safety, operation, maintenance and logistics. EMS data are acquired, recorded and processed in-flight and on the ground. EMS data are available for timely use by flight crew and ground support personnel. EMS data lead to actions taken on the basis of judgments made from directly measured or inferentially determined information. An EMS can be manual, computer aided or automated. A manual data acquisition system is utilized in most operational aircraft as part of the engine maintenance plan. An EMS can enhance the engine maintenance plan and also can complement aircraft and engine operations.

   EMS functions can be performed by dedicated people and equipment, or can be integrated and shared with the functions of other systems. An EMS is versatile and continuously evolving. Applied EMS capability grows or declines as determined by changing engine monitoring requirements.

   An EMS configuration can allocate different hardware and software distributions among installed engine and aircraft elements as well as among ground based, on-site and remote EMS elements. An effectiveness evaluation is required to determine partitioning of EMS hardware and software and in-flight and ground functions. While each EMS can be unique, EMS design, development and implementation methodology should be consistent and commensurate with engine monitoring needs.

   An EMS is part of the engine management system. As a source of information an EMS is at the center of the communication network required to implement an effective engine support and maintenance program. EMS data handling information requirements merit particular attention including:

   - what information is generated
   - why and when is information utilized
   - how and by whom is information communicated and used
   - where is information recorded, displayed, stored and retrieved
   - what equipment routines and personnel procedures are applied

   EMS equipment should not be addressed exclusive of human factors. A cooperative effort involving all EMS participants is recommended.

4. BENEFITS: Projected benefits of an EMS can include reduced cost of engine and aircraft ownership, increased availability, reliability and improved safety.

Requirements for an EMS cost benefit analysis are presented in Section 6.4. EMS effectiveness evaluation requirements are presented in Section 6.5.1.

EMS benefits can accrue in different ways including:

4.1 Safety: Safety related requirements and benefits of an ESM will vary between military and commercial applications. For military applications, especially for single engine aircraft, an EMS may be an operational requirement. For commercial applications, engine instrumentation to meet minimum safety requirements is approved by governing regulatory bodies.

4.2 Cost Savings: Applying EMS data to better determine and manage engine operation, condition, life usage and life remaining can provide cost savings in five areas: hardware, labor, fuel, operations and logistics.

Hardware cost savings can result from life extension of life limited components (Fig. 2) and also can result from early failure detection and elimination or reduction of secondary damage. Labor cost savings at different maintenance levels can result from reductions in hardware repair, time for fault isolation and time for fault correction and repair.

Fuel cost savings can result from early detection and correction of performance deficient engine modules and from a reduction of engine running for trim and troubleshooting. Operations and logistics cost savings can include a reduction in flight delays, bookkeeping of engine records, spare parts provisions and storage and shipping costs for spare engines and modules. The increased troubleshooting effectiveness afforded by EMS data can favorably impact aircraft turnaround time and availability and can reduce logistics costs associated with engine and component removals for unconfirmed causes.

4.3 Operational: An EMS can improve engine and aircraft availability and mission completion rates. Accurate and continuous engine monitoring can cause a beneficial reassessment of engine allowable limits and "red line" operational limits which traditionally include a margin for human factors. Accurate engine operational usage monitoring, long term correlation of parts consumption and maintenance man-hours can provide a basis for a reassessment of component life limits or an updating of the criteria used to maintain parts; e.g., removal based upon "hard time", "on-condition" maintenance or "condition monitoring" maintenance.

4.4 Flight Deck: EMS flight crew support can be manual, computer aided or fully automated. EMS benefits to the flight crew can include a determination of abnormal engine conditions.

4.5 Line and Station Maintenance: Engine condition and component life usage EMS data can assist scheduled and unscheduled maintenance. Rapid acquisition and presentation of EMS data can reduce the time required for fault isolation, assist in defining required maintenance and assess the availability of an engine for aircraft use. EMS data also can verify the correctness of maintenance actions.

4.6 Depot and Main Base Maintenance: An EMS can improve:

- maintenance forecasting and scheduling
- turnaround time
- fault isolation and identification of repair requirements
- compatability of personnel skill levels with maintenance requirements

4.7 Logistics: An EMS can improve:

- inventory management of spare engines and parts
- scheduling and utilization of people and equipment
- opportunistic and convenience engine removals, repairs and overhauls
- energy conservation

4.8 Engine Management: Better engine management decisions can be achieved by analysis, correlation and feedback of EMS detected engine problems, parts consumption and usage data. With the increased practice of warranties and incentives for both commercial and military engines, an EMS can be used to quantify user and supplier liabilities and cost savings shares.

An EMS can improve:

- engine product improvement programs
- allocation of tasks, labor and funds
- understanding of operational engines by users and manufacturers
- personnel training and learning
- future engine designs

5. CAPABILITIES: An EMS is an information system that can provide the following capabilities:

- assessing engine usage
- determining life remaining and engine operational readiness
- improving engine trim procedures
- detecting and isolating engine problems and verifying correction
- trending engine condition and tracking life limited hardware
- supporting engine management and logistics decisions

The distinction between EMS capabilities and benefits varies among EMS participants. EMS participant perspectives of end product benefits and monitoring capabilities are not mutually exclusive. Some overlap exists. Return On Investment (ROI) is considered an end product benefit of an EMS. Additional end product benefits can include increased engine and aircraft availability and reliability.

Requirements for an EMS cost benefit analysis are presented in Section 6.4. EMS effectiveness evaluation requirements are presented in Section 6.5.1.

For convenience, EMS capabilities are classified into three categories: short term, intermediate and long term engine monitoring. The following EMS capabilities are classified only once. Some of these engine monitoring capabilities can apply to more than one category.

5.1 Short Term: Short term EMS capabilities can include:

5.1.1 Safety: If an EMS is installed to provide safety benefits (Section 4.1), timely warnings can direct flight and ground crew attention to problems affecting mission integrity or leading to engine failure.

5.1.2 Pre-Flight: EMS indications of potential failures and warnings of a precautionary or advisory nature can aid pre-flight checks.

5.1.3 In-Flight: If installed to provide safety benefits (Section 4.1) an EMS can provide real time monitoring of engine condition. An EMS can provide appropriate warnings to the flight crew. Provision for data recording of critical events, either automatically or on pilot command, also can be included.

5.1.4 Post Flight: Regarding items specifically monitored by an EMS, a GO/NO GO indication of engine availability for the next flight is an EMS capability. NO GO causes can be indicated to the module level, line replacement unit (LRU) or lower more detailed level. EMS data can assist in troubleshooting and clearing pilot reports.

5.1.5 Engine Limit Exceedances: An EMS can indicate engine limit exceedances; e.g., over-temperature and overspeed.

5.1.6 Lubrication System: EMS data can indicate a lubrication system problem; e.g., oil contamination, low oil quantity, excessive oil consumption, low oil pressure or high oil pressure.

5.1.7 Vibration Data: An EMS can collect and process vibration data to indicate an engine problem. Vibration analysis techniques can fault isolate to the engine component and modular level. Vibration analysis techniques can range from total level trending and signature tracking to more detailed frequency and amplitude analysis. EMS vibration data can support on-the-wing engine rotor trim balance.

5.2 Intermediate Term: Intermediate term EMS capabilities can include:

5.2.1 Event Analysis: An EMS can provide data to analyze an event caused by a limit exceedance detected in flight or on the ground. Storage of steady state and transient aricraft and engine data prior to and subsequent to an event can be provided. The causes and factors leading to an event and the extent of possible resultant problems can be analyzed.

5.2.2 Trim Condition: Engine out-of-trim indication and data for corrective trim action is an EMS capability.

5.2.3 Gas Path Performance Analysis: An EMS can provide data to indicate and project engine and module performance level and extent of degradation. Engine as well as non-engine accessories that affect performance can be monitored to better distinguish gas path performance degradation from gas path performance changes due to other than engine causes; e.g., bleed airflow and power extraction.

5.2.4 Trending: An EMS can provide data to support engine trending routines and programs and also can indicate and project overall engine condition as well as module condition. EMS trending capability can include engine performance and mechanical condition.

5.2.5 Accessory Components: An EMS can provide event detection and isolation to the accessory component level. Engine as well as non-engine accessories and components can be monitored; e.g., bleed air-flow and power extraction.

5.2.6 Non-Destructive Inspection and Testing: Non-Destructive Inspection and Testing (NDI and NDT) can be contributing EMS elements. NDI and NDT techniques available for monitoring and evaluating engine condition include borescoping, radiography, eddy current, ultrasonic inspection, liquid penetrants, thermal paints and acoustics.

5.2.7 Additional: Additional engine and non-engine EMS capability can be provided; e.g., monitoring of gearboxes, powertrains, fuel and thrust management.

5.3 Long Term: Long term EMS capabilities can include:

5.3.1 Data Validity, Self Calibration, Check and Correction: An EMS can provide a continuous self calibration and self check of its hardware and software; e.g., sensor signal credibility, computation and calibration checks and Built-In-Test Equipment (BITE). (If an EMS provides cockpit indication, the EMS should indicate to the flight crew when it has malfunctioned).

Capability should be provided for EMS data information integrity. Satisfactory EMS operation can be provided when one or more EMS faults are present. An EMS can provide data validation and cross reference to cockpit instrumentation for flight crew and ground personnel.

5.3.2 Off-Line Maintenance Information: EMS capability can include indication of engine degradation and engine usage life history; e.g., engine hours, starts, low cycle fatigue (LCF) and hot section usage.

5.3.3 Flexibility and Growth: A modular EMS hardware and software design can meet anticipated and un-anticipated total system needs and can better integrate additional existing or advanced EMS technology.

5.3.4 Data Feedback: A capability of transmitting and confirming EMS data to commercial and governmental users, aircraft manufacturers, engine producers and equipment suppliers can be provided.

5.3.5 Life Usage Tracking: An EMS can provide data of accrued usage of life limited engine modules, components and parts. Cold and hot section engine life usage EMS data can be provided; e.g., low cycle fatigue (LCF), creep and wear. EMS data can be collected for life remaining projections.

5.3.6 Mission Profile and Engine Usage: EMS data can be collected for engine usage severity determination; e.g., engine throttle excursions and aircraft mission profiles.

5.3.7 Record Keeping: EMS data can be collected for configuration status of engines, engine modules and components. Actuarial data can be recorded and maintained to support a fleetwide engine management system.

6. IMPLEMENTATION REQUIREMENTS: EMS requirements are a result of a balance of selected benefits and available capabilities. EMS requirements are determined by an analysis of aircraft and engine operational environment, maintenance concept and user organization. To meet user requirements, an EMS can be configured with different levels of hardware technology and can be executed with various degrees of software sophistication. EMS requirements are assessed in terms of development, acquisition, operation and support costs.

Requirements for an EMS cost benefit analysis are presented in Section 6.4. EMS effectiveness evaluation requirements are presented in Section 6.5.1.

Early development and use of an EMS as an integral part of the engine bill-of-material and aircraft specification should be considered. An EMS program should parallel new engine and aircraft programs. Delayed introduction of an EMS to in-service engines can be more costly and can result in a less than satisfactory EMS capability. An engine retrofit program can require different mixtures of EMS responsibilities, interfaces and program milestones (e.g., existing engine sensors and maintenance concepts during a retrofit program generally are established and cannot be easily modified to more fully benefit from EMS capabilities).

Implementation of an EMS requires the application of several well structured and phased methodologies. Every EMS should proceed to some degree through all of the steps presented below.

6.1 Program Phases: The phased program milestones as shown in Fig. 3 depict the design, development and qualification of a typical EMS through production introduction for a new engine/application program.

Retrofit and accelerated EMS development can require a compressed program schedule; e.g., adaption of an EMS to engines in current production to take advantage of in-service experience will require different phasing and scheduling.

The software development task should be carried out concurrently with the outlined program phases. The software development task includes:

- manpower and time required to develop and validate the EMS software
- availability and timely accessibility of data processing equipment
- time elements involved in distributing EMS data products

The typical EMS new engine/application program schedule of four years shown below can vary considerably, depending upon the degree of system complexity, availability of off-the-shelf hardware and the number of monitoring functions.

Phase I	System Definition	6 mos.
Phase II	Prototype Development and Qualification	18 mos.
Phase III	Flight Test and System Integration	12 mos.
Phase IV	Operational Evaluation (includes possible redesign and requalification)	12 mos.
Phase V	Production Introduction	*
	Elapsed Calendar Time	48 mos.

*Phase V starts during Phases III or IV and continues after completion of Phase IV

An EMS is assumed to include aircraft and engine recording and also is assumed to include ground data computation, print-out and analysis.

Resulting EMS characteristics are most influenced by Phases I and IV. Phase I establishes the system capabilities and sets hardware boundary limitations. Phase IV demonstrates the original design concept and allows for both software refinement and an operational characteristics evaluation.

6.1.1 System Definition (Phase I): The definition of an EMS for a particular application should be a balance between system complexity, available capabilities, projected benefits and required Return on Investment (ROI). Fig. 4 illustrates a relationship between EMS complexity and ROI. A recommended methodology to be followed to achieve a cost effective EMS is presented by Fig. 5. EMS definition methodology to select a preferred EMS includes:

- defining the engine monitoring requirements
- defining several alternative EMS configurations
- performing a cost benefit analysis evaluation to select a preferred EMS

EMS definition requirements include:

- establishing maintenance concepts
- identifying engine problems from historical and predicted data
- selecting projected benefits (Section 4.0) and available capabilities (Section 5.0) to define an EMS
- analyzing how an EMS does or can benefit the engine maintenance plan
- establishing desired level of engine monitoring
- reviewing personnel and material resources for establishing configuration, use and support of an EMS

- ground processing capability to support an EMS in a timely manner
- quantity and quality of personnel to operate and maintain an EMS
- support equipment needed for an EMS

- reviewing software requirements (Section 6.6.2) to establish the levels of processing needed for both on-board and ground based equipment

EMS equipment selection should be performed following cost benefit analyses using requirements of Section 6.4. These analyses should include costs of program Phases I through V.

System definition of EMS equipment should consider:

- alternative configurations that meet engine monitoring requirements
  - on-board equipment (Section 6.6.1.1)
  - ground equipment (Section 6.6.1.2)
- ground support equipment needed for maintaining on-board and ground based equipment
- manpower requirements to operate and maintain equipment including data retrieval, processing, analysis and distribution

6.1.2 Prototype Development and Qualification (Phase II): Phase II uses and extends Phase I System Definition results to provide an EMS detailed design. Phase II EMS design activities should result in prototype hardware and software that is debugged and tested. Completion of Phase II requires that:

- the EMS has been successfully assembled and tested, including individual testing of hardware components and software modules and system testing both off and on an engine with live signal input together with an accompanying evaluation of engine condition relative to EMS output
- supporting EMS installation and development concepts are established
- the EMS concept is ready for transition to Phase III, System Integration and Flight Test

EMS requirements should include as a minimum:

- sensor specification and procurement
- sensor engineering test and evaluation
- bracketry, wiring and plumbing design
- signal conditioning specifications and procurements
- algorithm sensitivity analysis
- parameter limits
- software development
- data recording specification and procurement
- display equipment specification and procurement
- data base program development
- equipment qualification tests
- diagnostic algorithm development
- user manuals
- software effectiveness tests

- software validation and documentation
- hardware qualification tests
- logistics analysis
- installation design, drawings and interface definitions
- support analysis

6.1.3 System Integration and Flight Test (Phase III): The System Integration and Flight Test Program phase provides for EMS field installation and design confirmation. Installation, electrical, functional and environmental tests are required to verify that the EMS is ready to proceed to Phase IV, Operational Evaluation.

An EMS requires unique testing, recognizing the particular characteristics of aircraft and engine electronic interfaces. Required testing also includes sensor repeatability, sensor drift, applications software debugging, establishment of software threshholds for engine constants and sensitivity to spurious electronic noise and transient inputs.

EMS software "fine tuning" requires a continuing assessment of engine monitoring algorithm decision criteria limits and is assisted by the expanded engine data base acquired during Phase III.

System Integration and Flight Test requirements include:

- installed ground tests
- software effectiveness validation and modification
- integration with engine maintenance and logistics programs

6.1.4 Operational Evaluation (Phase IV): The Operational Evaluation program phase demonstrates EMS performance in the user environment. It is a functional test and operational evaluation of EMS capabilities and benefits. Operational evaluation data require detailed analyses, with criteria for measuring EMS effectiveness to assure user confidence in Phase IV results.

Tasks to perform an Operational Evaluation of program goals and objectives include:

- assignment of an evaluation group
- software improvement integration
- maintenance benefits documentation
- mission and operational suitability
- redesign and requalification
- engine condition correlation with EMS output
- EMS hardware reliability assessment
- logistic support package

6.1.5 Production Introduction (Phase V): Production Introduction requires emphasis to be placed upon producing an EMS in volume without degrading demonstrated capabilities. Production and logistic support considerations for an EMS are the same as those required for the introduction of other major systems. Requirements include:

- system documentation completion
- configuration control
- quality assurance procedures
- long lead time procurement
- vendor interfacing
- program scheduling
- manufacturing support planning
- product support programs
- training

Cost control is required during EMS production and deployment such that these costs, combined with those incurred by Phases I through IV, do not exceed original cost projections. Careful consideration of organizational hierarchies and personnel skill levels is required for the successful deployment of an EMS.

6.2 Responsibility Requirements: A program manager is recommended to direct an EMS program. A coordinated approach is required between EMS participants including commercial and government users, aircraft manufacturers, engine producers and equipment suppliers. System, equipment and procedure specifications are required to define on-board and ground based EMS responsibilities.

The user has prime responsibility for the operational facets of an EMS including procedures, facilities and skill levels.

EMS requirements should be specified, normally by the engine producer and the user. This includes required EMS functions, identification of required parameters to be monitored, sensor resolution and accuracy and repeatability, scan rate requirements, readout and processor resolution and accuracy requirements.

Philosophy and requirements for ground based hardware and software should be defined by the user with assistance from the aircraft manufacturer and engine producer. The equipment supplier should be responsible for supplying hardware to meet these requirements. The equipment supplier should define and supply hardware for system test support. The user should supply common ground support equipment.

6.2.1 System Integration:

6.2.1.1 Coordination: Coordination is required for EMS participants: equipment suppliers, engine producers, aircraft manufacturers and commercial and government users. Coordination is required to be responsive to varying EMS personnel and equipment capabilities. Many EMS coordination requirements can be performed by more than one EMS participant. To reduce duplication and to improve EMS management, it is essential that each EMS participant establish and concur with coordination arrangements.

6.2.1.2 Human Factors: The success of an EMS is dependent upon its acceptance by user personnel. The EMS user is responsible for the definition of EMS data presentation formats. These user data presentation formats should be confined to displays to which user personnel can react.

The application of EMS data for self incrimination is discouraged. Use of EMS data for disciplinary purposes should be limited to significant and constructive criticism; e.g., personnel safety, training.

6.2.1.3 Interfaces: EMS interfaces can include engine-aircraft, engine-ground, aircraft-ground and ground base-central processing station. An EMS should interface with existing maintenance programs including:

- engine maintenance data collection system; e.g., scheduled and unscheduled removals, shop findings, bench checks and reliability reports

- performance tracking of in-service propulsion systems

- control system for changing aircraft and engine design and maintenance procedures

As part of the engine management program, an EMS should interface with each level of engine maintenance. Typical examples include:

- level 1: line, field or organizational maintenance performs turn-around checks and servicing, identifies potential problems, provides minor repairs, LRU removal and replacement and engine change

- level 2: intermediate or support maintenance changes engine modules and incorporates minor changes and modifications

- level 3: depot, repair facility or overhaul maintenance tears down, overhauls and rebuilds engines, engine modules and components, and incorporates major changes and modifications

6.2.2 User and Supplier Responsibility: The following identifies general areas of responsibilities among the participants who develop, supply and use an EMS.

6.2.2.1 System Requirements: The EMS user has the responsibility for identifying system requirements. The aircraft manufacturers and the engine producer have the responsibility for assisting in the justification of these requirements. For general aviation and small operators, the aircraft manufacturer may assume the responsibilities of the user.

6.2.2.2 Parameter Selection: The engine producer has prime responsibility for selecting the parameters to meet the desired functional requirements established by the EMS user.

6.2.2.3 Engine Sensors: The engine producer has prime responsibility for selecting and qualifying engine supplied sensors to meet EMS functional requirements. The aircraft manufacturer is responsible for the QEC (Quick Engine Change) package. Equipment supplier responsibilities can include engine sensor signal conditioning. The engine producer and aircraft manufacturer have responsibility for the accessibility of engine installed EMS components.

6.2.2.4 Aircraft Sensors: The aircraft manufacturer has prime responsibility for providing non-engine producer supplied sensors required by an EMS. The engine producer provides recommendations to support this activity. The equipment supplier should be informed and can be responsible for special signal conditioning requirements.

6.2.2.5 Manual Inputs Provisions: Manual inputs should be coordinated between EMS participants. The user should define manual input requirements. The engine producer should provide manual input requirements in support of their algorithms.

6.2.2.6 Software and Algorithms: The engine producer has prime responsibility for identifying, developing and supplying diagnostic and prognostic algorithms necessary to meet user EMS requirements. As an additional service, the engine producer may provide software support to implement the algorithms.

EMS software and algorithms can be supplied by equipment suppliers. Aircraft manufacturers and users also can develop and supply additional software and algorithms for specific EMS data handling tasks. The following further delineates responsibilities for EMS software programs and algorithms:

- Operating Executive Program

  On-board executive software should be provided by the equipment supplier. Ground executive software can be supplied by either the user of the equipment supplier.

- Output Format Program

  On-board: the user should define requirements and the equipment supplier should develop the program.

  Ground Station: the user should define requirements and either the user or equipment supplier should develop the program.

- Application Programs

  Engine algorithms and data analysis programs should be developed, supported and maintained by the engine producer. In some cases, the equipment supplier can use information from the engine producer to generate algorithms and develop a data analysis program.

  New installations and changes to engine monitoring application programs should be reviewed and developed by the engine producer and EMS user. EMS program revisions by the user without the written consent of the aircraft manufacturer, engine producer and equipment supplier should be the responsibility of the user.

6.2.2.7 Aircraft Avionics: Requirements for aircraft avionics should be coordinated between user, aircraft manufacturers, engine producer and equipment supplier.

The equipment supplier should be responsible for developing and supplying hardware. For new aircraft and engines the aircraft manufacturer should provide installation requirements, contracting specifications and test demonstrations. For retrofit aircraft and engines the EMS user should provide installation requirements, contracting specifications and test demonstrations.

6.3 Design Considerations:

An EMS design requires consideration of the following:

- user objectives
- benefits and capabilities
- manual and computer aided provisions
- failure mode, effects and criticality analysis
- weights and envelopes
- installation compatibility
- historical data
- life cycle cost analyses
- maintenance and logistics
- available resources
- parameter selection and accuracy measurement
- program reviews
- reliability and maintainability analyses
- safety and hazard analyses
- power requirements
- human factors
- trade studies
- test requirements analyses
- sensitivity analyses

6.3.1 Engine Maintenance Management Plan: The engine maintenance management concept determines requirements for an EMS. A plan should be established covering the maintenance management information required to support the engine during its operational life. The plan should indicate the complexity level of EMS required. Engine monitoring parameters required should be indicated. Required engine provisions for an EMS also should be indicated; e.g., bosses, sensors. Categories of engine monitoring and related parameters include:

- Mission Usage

  Parameters required to provide average mission usage indication for computation of engine component lives should be specified. This requirement generally is needed for only a statistically significant number of engines in the fleet

- Parts Tracking

  Actuarial data with parameters that are necessary to be monitored continuously on every engine (e.g., engine speeds, temperatures, pressures, time) and that are converted to indices of performance degradation or life consumption should be specified.

- Maintenance

  Parameters to provide fault detection, diagnosis and isolation of engine modules and components to desired maintenance levels based on wearout or failure should be specified. Fault isolation to the engine LRU, module or lower (more detailed) level might be required as indicated by failure modes and effects analysis, cost effectiveness analysis and MSG-2 type analysis.

- Performance

  Parameters (primarily gas path related) acquired manually or automatically that are analyzed to provide overall engine performance and deterioration trends should be specified. First level performance parameters should indicate overall engine health and can include a requirement for engine removal. Second level performance parameters might be used to isolate malfunctions to engine modules. Fault isolation requires a more complete list of performance parameters. Second level performance parameters might be obtained with ground test instrumentation.

6.3.2 EMS Analyses and Constraints: An existing or projected aircraft and engine maintenance concept definition is required for EMS design purposes. After an EMS design is formulated, it requires a conceptual integration into the existing or projected aircraft and engine maintenance concept such that methodologies can be applied to determine EMS cost and benefit trades.

Analyses are required to define engine subsystems and components to be monitored. This effort should start with historical records of problems previously experienced on similar engines used for the application under consideration. Failure modes and criticality analyses, test equipment analyses and MSG-2 type analyses are important to EMS design considerations. The early inclusion of an EMS in these analyses requires pre-planning in many areas not directly related to EMS.

Constraints should be considered with EMS trades. Constraints frequently determine boundary conditions that limit the use of an EMS and should limit its design; e.g., existing or projected organizational constraints can limit available skill levels at different levels of engine maintenance while finite resources (people, equipment, funds) can limit a timely application of EMS.

6.4 Cost Benefit Analysis: Establishment of aircraft and engine life cycle costs (LCC) for various EMS configurations with different benefit savings for a specific engine application allows iterative cost benefit trade-off analyses to be performed. Too much or too little EMS complexity can prevent achievement of LCC savings, Fig. 4. An analysis criterion is to maximize ROI by matching an appropriate EMS to a particular set of projected cost savings. There should be a convergence through the cost benefit trade-off analyses toward a preferred EMS that meets user requirements.

The objective of the cost benefit trade-off analyses is to determine levels and methods of implementation of engine monitoring that is cost effective, Fig. 5. Typically, EMS savings are not realized until after the engine is operational and its design and development are completed, Fig. 6. Cost benefit trade-off analyses require a comparison between two major cost elements:

- Life Cycle Cost (LCC) of the aircraft and engine
- LCC and savings attributable to the implementation of an EMS

Return on Investment (ROI) is an underlying justification for an EMS. Labor and material EMS costs should be identified, projected and tracked to assess ROI benefits. Safety benefits should be included and, for emphasis, can be weighted. Other benefits, such as improved engine availability and part scheduling, also can be weighted for emphasis.

In some cases, the costs of ownership are not accurately known for large aircraft and engine fleets; e.g., projected costs for a proposed EMS can be more accurate than the estimated cost of ownership for an aircraft and engine fleet, Large cost drivers that impact cost of ownership might not be known or admitted; e.g., unknown component life limits and service related deficiencies. When performing EMS cost benefit trade-off analyses, these possible system cost inconsistencies should be considered and might be balanced with appropriate weighting factors.

6.4.1 Costs: Life cycle cost elements of an EMS are similar to those of other aircraft or engine systems, and include:

- development costs
- production costs
- operational and support (O&S) costs

Development EMS costs include:

- design
- development
- qualification

Production EMS costs include:

- aircraft and engine EMS hardware, including spares
- EMS ground support and data processing equipment

Operational and support EMS costs include:

- maintenance labor and material
- fuel consumed due to the weight of engine monitoring hardware
- labor and material for transmission, processing and analysis of EMS data
- cost of unnecessary engine maintenance due to EMS false alarms

6.4.2 Benefits: Knowledge of system benefits is required for EMS cost benefit analyses. Section 4 presents projected EMS benefits. These benefits should be quantified to estimate and determine EMS savings. Analyses of EMS benefits should consider:

- projected reduction in maintenance manhours per flight hour
- fuel savings through reduction of ground test runs
- fuel savings through recognition of inefficient degraded engines
- time savings through confirming pilot reports and maintenance repair actions
- time saving by fault isolation to specified malfunction
- reduction in required spare parts through elimination of unnecessary repairs
- reduction in unnecessary engine and component removals
- engine hardware savings by increased engine and module availability
- capability of "on-condition" maintenance to decrease hardware and labor maintenance costs
- early identification of unexpected fleet deterioration
- reduction in secondary engine damage
- fewer mission aborts
- ability to predict and schedule future maintenance

6.5 General Requirements: The following EMS general requirements apply to most aircraft gas turbine engine applications:

6.5.1 Effectiveness Evaluation: An evaluation is required to assess the effectiveness of the development, production and operation of an EMS. Overall system effectiveness can be measured by observing and projecting the impact of an EMS upon user established parameters. Hand calculations, computer simulations, ground and flight tests and operational records are sources of estimates and data for EMS effectiveness evaluations. Examples of effectiveness indices include:

- maintenance manhours per flight hour
- aircraft and engine readiness
- engine removal rate
- turnaround time
- repair actions at each maintenance level
- material cost per repair action
- time between removals
- engine mean time between failures
- EMS mean time between failures
- EMS maintenance manhours per flight hour

Effectiveness indices frequently are normalized and can provide additional EMS effectiveness assessments; e.g., percent mission completion, percent aircraft availability.

The following defines evaluation factors, applicable to on-board equipment that provide a GO/NO GO engine status indication at the end of each flight for items specifically monitored by the on-board EMS equipment, Fig. 7. Similar factors can be developed for other EMS equipment and procedures. If the EMS incorporates Built In Test Equipment (BITE) then the EMS itself becomes one of the monitored systems; i.e., success or failure in detecting EMS faults can be treated similar to the success or failure in detecting engine faults. Typical evaluation factors for on-board EMS equipment can be defined as follows:

1. GOOD (correct assessment): The on-board EMS equipment indicates a correct assessment of no engine discrepancy and the engine is operational and capable of making a subsequent flight without maintenance (on-board EMS engine status indicator GO).

   - Type one: The crew or support personnel along with the EMS did not note any discrepancies that would prohibit a subsequent flight.

   - Type two: The crew or support personnel report a discrepancy that on-board EMS equipment is programmed to detect; however, no problem is indicated. The engine discrepancy reported by the crew or support personnel is found to be not engine related and is unconfirmed by subsequent trouble shooting.

2. HIT (correct assessment): An engine discrepancy has occurred and is correctly identified by on-board EMS equipment (on-board EMS engine status indicator NO/GO).

   - Type one: On-board EMS equipment alone correctly detects an engine discrepancy which requires immediate corrective maintenance action.

   - Type two: On-board EMS equipment along with the crew or support personnel detects an engine discrepancy which requires corrective maintenance action.

   - Type three: On-board EMS equipment correctly identifies an engine discrepancy (usually a limit exceedance) but severity and duration of the problem does not warrant immediate maintenance action based upon a judgment decision by authorized personnel. Such discrepancies can be designated "precautionary" or "watch" items.

3. MISS (incorrect assessment): On-board EMS equipment indicates no engine discrepancy even though a discrepancy for which it was programmed did occur. The engine discrepancy is reported by other EMS means. Verification of the discrepancy is a prerequisite to confirm a MISS and in some cases requires suspect component inspection and teardown (on-board EMS engine status indicator GO).

4. FALSE ALARM (incorrect assessment): On-board EMS equipment incorrectly indicates an engine discrepancy when none has occurred. Verification of engine GO status is made by other EMS means and in some cases requires suspect component inspection and teardown (on-board EMS engine status indicator NO GO).

5. OUT OF SCOPE: An engine discrepancy has occurred but is not programmed to be detected by on-board EMS equipment (on-board EMS engine status indicator GO or NO GO).

All engine discrepancies fall into one of the above five categories, Fig. 7. The ratio of each category to the total number of flights provides a measure of on-board EMS equipment effectiveness. The number of misses that were not programmed might be considered by the evaluation so that intentional out of scope design limitations do not unduly bias an assessment of on-board EMS equipment.

Fault detection success ratios include:

Success Ratios	Ideal Goals
$\frac{\text{GOODS + HITS}}{\text{Total Flights}}$	approach 1
$\frac{\text{MISSES}}{\text{Total Flights}}$	approach 0
$\frac{\text{FALSE ALARMS}}{\text{Total Flights}}$	approach 0
$\frac{\text{OUT OF SCOPES}}{\text{Total Flights}}$	approach 0

EMS fault detection ratios are cumulative values for the time interval of the effectiveness evaluation. Results of an EMS fault detection effectiveness evaluation should be compared to previous calculated estimates and test data. Consideration should be given to relating the contribution of EMS fault detection effectiveness to other aircraft and engine effectiveness parameters. These results should be used to quantify an EMS's contribution to safety and increased engine and aircraft availability and reliability with reduced cost of ownership (Section 6.4).

6.5.2 Identification and Configuration Control: Labeling of EMS hardware and software, data, instructions and procedures is required.

EMS use of actuarial data, identification codes, nameplates and titles should be sufficient to distinguish between similar but different EMS elements, events and personnel. Both hardware and software configuration control is recommended for an EMS.

6.5.3 Engine Stations and Symbols: ARP 755 is recommended for consistent engine station identification and related symbol usage (Section 8.1).

6.5.4 Power Protection Provisions: Power interrupt, power down and power polarity EMS protection is required. Occurrence of power interrupts should be flagged.

6.5.5 Checkout and Substantiation: An EMS, in addition to engine monitoring, also should monitor itself. Manual, computer aided and automated EMS checkout and substantiation requirements should be considered. A back-up plan for EMS failures is recommended (Section 6.5.8).

6.5.6 Revision Procedure: EMS revision procedures for on-board and ground hardware and software are required. Revision procedures for EMS personnel instructions also are required.

EMS revisions by the user without written consent of the aircraft manufacturer, engine producer and equipment supplier should be the responsibility of the user. Revision procedures should be consistent with EMS identification and configuration control provisions (Section 6.5.2).

6.5.7 Options and Customized Provisions: Requirements for EMS options should be considered. Customized EMS provisions require additional consideration and coordination with EMS participants.

6.5.8 Back-up Plan for EMS Failures:

A back-up plan should be developed to account for EMS failures. Development of the back-up plan is essential if engine monitoring integrity and engine usage history are to be maintained. Fall back provisions can include a cycle count based on engine hours, data from another engine or manual input based on crew records or operational experience.

6.5.9 Documentation: Documentation of manual, computer aided and automated EMS hardware and software is required. Documentation of EMS personnel instructions and procedures should be compatible with EMS hardware and software documentation.

User Manuals should be prepared and delivered to the EMS user. The User Manuals should include a description of on-board, on-site and remote (off-site) interactions between EMS personnel and equipment and computer programs.

The following information should be contained in the EMS User Manual:

1. Introduction

2. Table of Contents

3. Engine Description

   A general description of the engine(s) being monitored by the EMS should be provided. This description should include the type of engine(s) and engine configuration(s) with performance and operational characteristics. The engine description should be sufficient for user understanding required to achieve EMS objectives.

4. Hardware Description

   A general description of EMS hardware and its interfaces should be provided.

5. Software Description

   A general description of EMS software and its interfaces should be provided.

6. System Description

   A general system description of EMS personnel instructions should be provided. The system description should include a flow chart definition of organizational relationships of personnel and equipment required for EMS operation. This section also should describe provisions for engine management, maintenance and monitoring, and should delineate EMS functional support of these engine provisions.

7. Hardware Installation and Operation

   User personnel instructions and information needed to operate EMS hardware should be provided. This section also should describe tests that the supplier provides for hardware checkout by the user.

8. Software Installation and Operation

   User personnel instructions and information needed to operate EMS software should be provided. A flow chart with sufficient information to install the computer program(s) should be provided with programming instructions for modification of software computer program(s), limits and coefficients.

   This section also should describe the test cases that the supplier provides for software checkout by the user. Test case inputs and printouts should be supplied with the software computer program(s) listings.

9. Inputs/Outputs and Messages

This section should describe each EMS input and output in sufficient detail to avoid ambiguity and should list the units of all input and output parameters. This section also should list and explain each EMS message.

10. Options

This section should enable the user to better understand the full capabilities of the EMS and should describe specific EMS options, limitations and other features.

11. Identification, Configuration Control and Revision Provisions

An EMS hardware parts list and an EMS software programs list should be provided. EMS identification, configuration control and revision provisions should be delineated. User Manual update provisions also should be included in this section.

12. Nomenclature

This section should include terminology, definitions and other information required to understand the EMS and its User Manual.

13. References

This section should include a listing of background documents used in the preparation of the EMS User Manual.

6.6 Hardware and Software Requirements: An EMS can be configured with various degrees of manual, computer aided or automated hardware and software capabilities to meet different user requirements. Allocation of hardware and software requirements can vary with respect to installed aircraft systems and ground based, on-site and remote operating system elements (Fig. 8 and 9). Equipment should be designed to meet applicable on-board and ground base environmental and functional requirements.

Required EMS parameters are a function of engine complexity, the level of monitoring required and the engine maintenance plan. Fig. 10 presents a typical EMS parameter list. The EMS parameter list can be more or less extensive; e.g., multi-engine and single engine aircraft. The parameter list can be different for different applications; e.g., helicopter engine parameters such as torque and power turbine speed (Ref. ARP 1217, Section 8.1).

The effectiveness of an EMS to detect events depends upon parameter measurement. EMS parameter measurements are the output of several successive functions beginning at the engine and proceeding through transducer and electronic hardware. A sensitivity analysis is required to assure that EMS error is understood and properly controlled. Potential sources of uncertainty are:

- probe and sensor location(s)
- single and multiple probes
- probe and sensor design
- probe line length and volume
- transducer errors
- electronic errors; e.g., signal conditioning accuracy
- software; e.g., sample rate, engine algorithms
- compensation; e.g., engine transient operations
- interfaces

6.6.1 Hardware: EMS on-board and ground based hardware configuration depends on system architecture as defined by the overall system functional requirements.

EMS hardware requirements should consider the following:

- compatibility with installation environments; e.g., vibration, temperature and contamination
- modular packaging techniques to facilitate future system changes
- service life and reliability
- space and weight
- compliance with applicable standards and specifications
- physical compatibility with other aircraft engines and ground based systems
- capability for automatic bench testing
- built in test equipment (BITE)

6.6.1.1 Installed Equipment: Requirements for installed EMS equipment should include:

- signal accuracy, repeatability and resolution
- desirability of avoiding installed calibrations
- environmental compatibility and maintainability
- data source integrity; e.g., EMS data taken from aircraft or engine data sources should not degrade data source signal (s)

Data Transmission:

- multiplex signal transmission consistent with applicable specifications; e.g., 1553, MIL-STD ARINC 429
- protection from electro-magnetic and lightning interference
- separation of power and sensitive data lines
- use of standard data formats
- installed environment; e.g., vibration, contamination, temperature and pressure
- shielding, grounding and impedance matching
- achievement of high signal quality and minimization of line losses

Data Acquisition:

- input and output
- circuit isolation
- signal conditioning for multiple input signal types
- signal sampling and conversion to appropriate format
- capability for different data sampling rates
- signal accuracy, repeatability and resolution

Data Processing:

- storage and processing capacity and speed and format compatability with EMS algorithms and software programs

- power interrupt, power down and reverse polarity protection, and flagging of power interrupts on data bus

- security of data in commercial and government operations

- data accuracy requirements; e.g., 8 bit or 16 bit

Data Output and Storage Devices: One or more of the following data output and storage devices are recommended to present the results of EMS on-board recording and processing:

On-Board Ground Data Link:

- data format
- data transmission rate
- data storage capacity
- signal buffering

Visual Displays and Annunciators:

- type display; e.g., CRT, LED
- type of presentation; e.g., alpha/numeric, graphic, bar graph
- automatic and manual call-up provisions
- on-board and ground reset provisions
- audible alarms and voice annunciators

Printers:

- printing speed and format
- duplicate copy capability
- line length and capacity
- low acoustic noise level

Recorders and Other Data Storage Devices:

- type; e.g., solid state, cassette, disc, permanent tape
- recording and playback speed
- computer and other interface compatible formats
- continuous and incremental recording
- data storage capacity
- recycling and overwriting capability

6.6.1.2 Ground Based Equipment: On-site and remote (off-site) requirements for ground based EMS equipment should include:

Data Collection and Storage

- type of data transfer technique from on-board EMS equipment; manual, magnetic tape, cassette, telemetering links

- storage type and capacity

Ground Processing and Analysis

- manual, computer aided and automated
- output format requirements
- storage and computing power

Peripherals

- output type; e.g., visual, hard copy

Engine Ground Test

- installed and uninstalled
- compatibility with EMS on the ground and installed
- type of test; e.g., trim diagnostic, post repair, maintenance, overhaul

Engine Inspection

- type and method of engine inspection; e.g., borescope, X-ray, isotope, eddy current
- fuel and oil system inspection; e.g., screen checks, oil analysis
- requirements for engine access ports

EMS support

- calibration and verification requirements
- fault diagnostic and prognostic considerations
- portability

6.6.2 Software: EMS software includes the procedures for data handling programs and related EMS documentation, Fig. 11. EMS data are processed by calculations, algorithms and logic procedures either manually, computer aided or automatically. To the extent that they are computer programmed, they are currently called computer software. Coordination of software requirements between EMS participants is recommended.

Allowed variability in such parameters as Mach number, altitude, total air temperature and aircraft and engine geometry should be stated. Certain EMS applications might not encounter the desired engine and aircraft steady state conditions frequently enough to ensure proper monitoring results; e.g., aircraft auto-throttle, thrust management. Consideration should be given to establishing specific criteria for data recording and to statistical treatment of data.

6.6.2.1 Computer Programs: Automatic data processing with data interpretation and presentation comprises a computer program. EMS data interpretation should be guided by installed and uninstalled engine characteristics supplied by handbooks and algorithms published by the aircraft manufacturer and engine producer. These engine characteristics should be valid for applicable operation modes and should include sub-system and off-design operational effects.

Where practical, each set of output data should be dated and should indicate identification of the original computer program with subsequent changes. Computer program source codes should provide a user with information regarding software revision status of the installed program. The user should be informed of the effects of program modifications and updates.

Providing self-check for screening invalid mathematical operations should be considered. This preventive action can preclude invalid operations from being transferred to the user's supplied subroutines. The use of numerical status indicators to clearly define the validity of the output is recommended. The program should be capable of continuing with the next case provided the user's subroutines and computer operating system do not override this capability. The computer memory should be cleared when the program is loaded. The highest level of compiler optimization operationally available to the program supplier is preferred, but requires coodination between user and supplier.

An EMS computer program should be capable of operating in a stand alone mode as well as in a subroutine mode. The subroutine mode should be available as a one subroutine call. An EMS computer program should be capable of interfacing with other application computer programs and data sources.

An EMS computer program might interface with AIDS (Aircraft Integrated Data Systems) and other user supplied programs with such monitoring features as:

- total aircraft performance
- crew proficiency
- environmental system performance
- autoland system performance

Automated interpretation of EMS data requires that its computer program provide:

- normalization of EMS data to common base conditions; e.g., sea level static standard day conditions, cruise flight conditions

- data selection at steady state conditions

- application of proper data corrections and time synchronization for characteristics such as air bleed, inlet configuration, power extraction, exhaust nozzles, parasitic flows, liquid injection, variable geometry, sensor effects, Mach number and Reynolds number effects

- detection of duration and extent of limit exceedances as defined by the engine operating instructions and limits

- trending of periodically acquired data to present deviations from a baseline of normal operation analysis for engine condition changes

- provisions for inclusion of aircraft monitoring system results and time synchronizations with EMS analysis

- avoidance of ineffective data gathering modes by sensing their occurrence and rejecting data sampled; e.g., engine performance assessment during windmilling or with anti-ice bleed

- isolation of duration sensitive events where time at the condition is meaningful; e.g., time at temperature

- recording of incidents and events requiring a time history of parameters pertinent to such engine transients as flameouts, auto accelerations, compressor stalls and limit exceedances

- data validation checks

- monitoring of parameter divergence of one engine as compared with other engines installed in the same aircraft

The keeping of historical records on a per engine per aircraft bases involves the storage and time synchronization of data either raw or analyzed for decision making. These data might need further analysis for the decision making process. Computer program data items generally stored are:

- cumulative life cycles and low cycle fatigue data
- reduced power take-off occurrences and levels
- performance trend data
- engine identification and location
- module and configuration identification
- installation and removal histories
- maintenance action records
- pilot reports
- engine usage
- spectrographic oil analysis
- oil consumption and debris contamination
- vibration history
- total operating time on engine
- engine modules and components
- documentary data; e.g., calendar time, geographical location

6.6.2.2 Computer Programming Considerations: Execution times and computer capacity can limit EMS computer programs. Program execution times depend on where the data are processed (on-board, on-site or remote site), the complexity involved in the monitoring programs, the type of computer, the program execution priority levels and the amount of program sharing. In programming a special purpose computer, there should be spare memory and computational capacity to accommodate inevitable program revisions, additions and updates.

Computer hardware and software differences (e.g., word length, compiler and operating system) should be considered and can cause output difficulties from otherwise identical programs. Computer and computer program suppliers should ensure that the polarity of incoming signals is preserved.

6.6.2.3 Data Handling: Data handling involves decision making with regard to data acquisition, correction, organization, transfer and display. EMS data handling occurs not only internally in the computer program but also externally in other areas, Fig. 11. EMS data handling requires:

- definition of functional parameter relationships between data sources and engine conditions
- collection of data at appropriate sample rates for selected parameters under specified conditions
- proper identification of data sets whenever data are transferred
- data verification by means of comparison with predetermined limits, check ranges, other parameters or established reference conditions and synthesis of parameters
- formatting of data for displays, hard copy prints and recording media
- data feedback and correlation to substantiate corrective actions

7. TERMINOLOGY AND DEFINITIONS: The following list is the result of a survey of terminology and definitions commonly used in various EMS disciplines. The list is typical and is not necessarily complete or universally used.

1. Actuarial Data - Refers to the type of information used to define the subcomponents of an engine or system (e.g., serial numbers) and often includes the bookkeeping of data that indicate the life usage on these subcomponents (e.g., operating hours, LCF counts, hot section usage).

2. Aircraft Integrated Data Systems (AIDS) - The broad term to identify a family of systems that acquires, processes and records data that are used to determine the functional status and condition of various commercial aircraft systems, including engine and engine components.

3. Algorithm - A step by step procedure for solving a problem or accomplishing some end.

4. Baseline - A quantifiable physical condition or level of performance from which changes are measured.

5. Built In Test Equipment (BITE) - Equipment built into a unit to provide a self test capability for the unit.

6. Classification - Implies a decision rule where data or information may be identified and grouped (e.g., waveforms or signatures) to be an indication of a particular status, discrepancy or failure mode.

7. Damage Factor - A relative number assigned to indicate a defined amount or unit of engine component or piece part life usage; e.g., LCF counts, hot section factors.

8. Degradation - The condition or status indicating impaired or deteriorating condition, function or physical state.

9. Diagnostic - An analysis result pertaining to the detection and isolation of a malfunction or discrepancy.

10. Diagnostic Routine - A sequence of tests or fault tree logic designed to use data inputs and predetermined standards or operational limits to establish condition status and locate a malfunction or discrepancy.

11. Diagnostic Sensitivity - A measure of the threshold level at which a change of condition or functional status yields symptomatic indications with a given diagnostic routine or technique. The threshold level is an accumulation of all error contributions which input into the diagnostic routine or technique.

12. Discrepancy - Deviation from an expected condition.

13. Engine Accessory - A part or assembly usually driven by the engine but not required to operate the engine.

14. Engine Component - A part or assembly that is fundamental to the operation of the engine.

15. Engine Health Monitoring - The general discipline or technique for indication of status of the mechanical or functional condition of an engine or engine components; sometimes referred to as Engine Condition Monitoring.

16. Engine Monitoring System (EMS) - An EMS is a complete system approach to define engine, engine component and sub-system health status through the use of sensor inputs, data collection, data processing, data analysis and the human decision process. This system approach can consist of an integrated set of hardware and software and several separate engine monitoring system elements and can be manual, computer aided or automated.

17. Failure - A functional status or physical condition characterized by the inability of an engine, engine component or sub-assembly to fulfill its design purpose; the most severe degree of malfunction.

18. Failure Detection - The process or technique of identification of engine, engine component or subsystem failure.

19. Failure Mode - The particular manner or sequence of events that is indicative of a specific engine, engine component or sub-system failure.

20. Failure Path - The chain of events or set of circumstances that result in an engine, engine component or sub-system failure because of interrelationships between components and sub-systems.

21. Fault Detection - The process, technique or capability of identification of a discrepancy.

22. Fault Isolation - The process, technique or capability of the specific identification of engine component, sub-system or piece part causing a discrepancy.

23. Fault Tree - An expression for a logic path used to establish engine, engine component or subsystem functional status and condition.

24. Incipient Failure - A functional status or condition which is existing at the beginning of a failure of engine, engine component or subsystem.

25. In-flight Engine Status - In-flight indications (real time or near real time) of potential failures and warnings of a cautionary or advisory nature; e.g., high vibration. (Warnings to the cockpit should be those only to which the flight crew can react. Event detection and exceedance documentation should be provided).

26. Limit Exceedances - Parameter excursions beyond pre-established values.

27. Long Term Trending - Tracking of engine, engine components or subsystem degradation on a periodic basis, often by flight. This type of tracking indicates a deviation of monitoring data from an established trend (Ref. Trend Analysis).

28. Low Cycle Fatigue (LCF) - Component material life usage incurred by cyclic stress excursions.

29. Line Replaceable Unit (LRU) - Propulsion component or assembly that may be replaced at the lowest level of maintenance, sometimes called a Weapon Replacement Assembly (WRA).

30. Malfunction - Abnormal condition or status of an engine, component or sub-system.

31. Measurand - A physical quantity, force, property or condition which is to be measured.

32. Monitoring - The act or technique of establishing functional status or condition.

    a. Inflight Monitoring - Monitoring by on-board equipment during the period from engine start to engine shut down.

    b. On Site Monitoring - Utilization of data on site. Ground test of engines using on-board or portable ground test equipment.

    c. Remote Monitoring - Utilization of data at a remote (off site) location.

33. Maintenance Steering Group (MSG) - 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.

34. Off Line Maintenance Information - Data to indicate long term engine degradation through trend monitoring and tracking of engine usage history; e.g., engine hours, starts, LCF counts, and hot section usage.

35. On Condition - A term used to indicate maintenance based upon the functional, structural or other condition of the unit or part, as differentiated from time schedule maintenance (Ref. Primary Maintenance Processes).

36. Operational Limit - A pre-established reference for engine, engine component or sub-system operation.

37. Parameter - A measurable or calculated quantity which varies over a set of values.

38. Performance Degradation - The condition or status indicating impaired or deteriorated engine gas path performance as referenced to some established or predetermined condition.

39. Post Flight Engine Status - An immediate GO/NO GO indication of engine availability for next flight and if in a NO GO status situation, indication of required maintenance action as appropriate.

40. Power Interrupt - A momentary loss of power to the engine monitoring equipment resulting in possible loss of data.

41. Pre-Flight Engine Status - Cockpit indications to aid in pre-takeoff checks; e.g., thrust check.

42. Primary Failure - A failure which is not a result of another failure.

43. Primary Maintenance Processes - Three primary maintenance processes are recognized and defined by MSG-2 for classfying the way in which a particular aircraft element is maintained. These primary maintenance processes are:

   - Overhaul Time Limit or Part Life Limit (Hard Time): This is a preventive primary maintenance process. It requires that an engine or part be periodically overhauled in accordance with the operator's maintenance manual or that it be removed from service. These time limitations may be adjusted based on operating experience or tests as appropriate.

   - On Condition Maintenance (OCM): This is a preventive primary maintenance process. It requires that an engine or part be periodically inspected or checked against some appropriate physical limit to determine whether it can continue in service. The purpose of the standard is to remove the unit from service before failure during normal operation occurs. These limits can be adjusted based on operating experience or tests as appropriate.

   - Condition Monitoring (CM): 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.

44. Prognosis - The forecast of future functional status and condition based on current and accumulated inputs.

45. Quick Engine Change (QEC) - A package or kit of hardware items not included on the engine as delivered by the engine producer but required in the build-up of the engine prior to installation in an aircraft.

46. Safety of Flight Event - An engine, engine component or sub-system functional status or condition that could seriously jeopardize flight integrity.

47. Safety of Flight Warning - Timely crew warning to permit in-flight correction of problems seriously affecting flight integrity or leading to catastrophic engine failure. (The intent is to provide either real time crew warning or post-flight maintenance indication for all engine discrepancies that could cause an unsafe flight situation).

48. Secondary Damage - Damage resulting from a primary failure.

49. Sensor - A mechanical, electrical, optical or fluidic device that provides data inputs; e.g., transducers, position indicators, discretes.

50. Sensor Output Format - The form of the signal or waveform supplied by the sensor; e.g., analog, pulse frequency, digital.

51. Short Term Trending - Tracking of engine, engine component or sub-system operational degradation by noting data on a particular flight or ground check and comparing with a pre-established trend (Ref. Trend Analysis).

52. Signature - A signal or combination of data inputs that are characteristic of an individual engine, engine component or subsystem that can be used to indicate functional status and condition.

53. Sonic Vibration - Refers to the dynamics of mechanical vibration waveforms in the frequency range up to 20KHz.

54. Transducer - A hardware sensing device which measures a physical phenomenon (e.g., pressure, temperature, position) and outputs a calibrated signal.

55. Trend Analysis - A technique to utilize deviation of recorded data and signature characteristics with respect to time to diagnose and prognosticate a malfunction or failure.

56. Trim Condition Data - Data to indicate an out of trim engine condition and to implement a corrective action to return to scheduled trim.

57. Ultra Sonic Vibration - Refers to the dynamics of mechanical vibration waveforms in the frequency ranges of more than 20KHz.

8. BIBLIOGRAPHY:

8.1 SAE Documents: The following documents are available from the Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096:

1. ARP 755 - Turbine Engine Performance Station Identification and Nomenclature

2. ARP 1217 - Instrumentation Requirements for Turboshaft Engine Performance Measurement

3. SP 478 - Society of Automotive Engineers ARP 1587 and Aircraft Gas Turbine Engine Monitoring Systems

8.2 ARINC Documents: The following documents are available from Aeronautical Radio, Inc. (ARINC) Specifications, 2551 Rivas Road, Annapolis, Maryland 21401:

1. ARINC 429 Mark 33 Digital Information Transfer System

2. ARINC 453 Very High Speed Data Bus

3. ARINC 563 Aircraft Integrated Data System (AIDS Mark 1)

4. ARINC 573 Aircraft Integrated Data System (AIDS Mark 2)

5. ARINC 597 ARINC Communication Addressing & Reporting System (ACARS)

6. ARINC 600 Air Transport Avionics Equipment Interfaces

7. ARINC 717 Digital Expandable Flight Data Acquisition and Recording System (DEFDARS - AIDS Mark 3)

8.3 Other: It is recommended that an EMS document and literature search be conducted. A suggested literature source is:

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161

The following documents are examples of typical EMS information that is available:

1. Abernethy, R. B. et al., Pratt & Whitney Aircraft, and Thompson, J. W. Jr., ARO, Inc., "Uncertainty in Gas Turbine Measurements." February 1973, available from NTIS. AIAA No. 73-1230, AIAA/SAE 9th Propulsion Conference, Las Vegas, Nevada, November 5-7, 1973. AIAA Library, 750, 3rd Avenue, New York, New York 10017.

2. Pettigrew, James L., "Is EMS the Key to Operational Readiness for Less Money with On-Condition Maintenance?" Proceedings 14th Annual International Logistics Symposium, August 14-16, 1979, available from SOLE (Society of Logistics Engineers), International Headquarters, Suite 922, 303 William Avenue, Huntsville, Alabama 35801.

3. Byrd, K. F. and Tall, W. A., "Engine Life Definition Technique - An Approach to Logistics Support Management/Planning," ASME Technical Paper, Presented at the Winter Annual Meeting, San Francisco Ca., 10-15 December 1978, available from ASME (American Society for Mechanical Engineers), United Engineering Center, 345 E. 47th Street, New York, N.Y. 10017.

4. Nowlan, F. S., "A Current Turbine Engine Maintenance Program and the Experience and Logic Upon Which It is Based," ASME Technical Paper 73-GT-81, presented at the Gas Turbine Conference and Product Show, Washington, D. C., 8-12 April 1973, available from ASME.

5. Snowball, H. M., "Engine Aids and the Metrologist Syndrome," Instrumentation for Airbreathing Propulsion, Progess in Astronautics and Aeronautics, V.34, Cambridge, Mass., The MIT Press, 1974. PP 505-514, available from MIT Press, 28 Carlton Street, Cambridge, Mass. 02142.

6. Sisson, James G., MD; Schoonmaker, Eric B., MD; Ross, Jon C., MD; "Clinical Decision Analysis - The Hazard of Using Additional Data", JAMA 236: 1259-1263, September 13, 1976, available from AMA (American Medical Association), 535 North Dearborn Street, Chicago, Illinois 60610.

7. Urban, Louis A., "Gas Path Analysis Applied to Turbine Engine Condition Monitoring", AIAA Journal of Aircraft, Vol. 10., July 1973, PP 400-406, available from AIAA (American Institute of Aeronautics and Astronautics), 1290 Avenue of the Americas, New York, N.Y. 10019.

8. Murphy, J. A., "Diagnostic System Requirements for Helicopter Propulsion Systems", AIAA Journal of Aircraft, Vol. 15, June 1978, PP 333-338, available from AIAA.

9. Belrose, Thomas C., "Testing of Propulsion System Diagnostic Equipment", AIAA Paper 77-895, July 1977, available from AIAA.

10. Urban, Louis A., "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines," ASME Paper No. 74-GT-62, available from AIAA.

11. Hamilton, Keith R. and Chopin, Matthew H., "Diagnostic Engine Monitoring for Military Aircraft", Proceedings 1975 Annual Reliability and Maintainability Symposium, available from IEEE (Institute of Electrical and Electronics Engineers, Inc.), 345 East 47th St., New York, N.Y. 10017.

12. Scott, B.C., Peth, R. H. and Rosomer, B.K., "F-15/F100 Engine Diagnostic Systems", AIAA Technical Paper 79-1201, presented at AIAA/SAE/ASME 15th Joint Propulsion Conference, Las Vegas, NV. 18-20 Jun 1979.

13. George, P.T. and Parker, A.T., "An Evaluation Technique for Determining the Cost Effectiveness of Condition Monitoring Systems" ASME Technical Paper 78-GT-166, presented at the Gas Turbine Conference and Product Show, London, England, 9-13 April 1978.

14. Danielson, S.G. and Dienger, G., "A European View on Gas Turbine Engine Monitoring on Current and Future Civil Aircraft", AIAA/ASME/SAE 15th Joint Propulsion Conference, June 18-20, 1979, Las Vegas, Nevada, paper 79-1200.

15. Driessen, Ed. A. and Vermeulen, A.C., "Use of Recorders in Future Aircraft Operations" AIAA 64-352 1st AIAA Annual Meeting, Washington, D.C., June 29-July 2, 1964 and Journal or Aircraft Volume II, No. 3, 1965, pp. 176-184.

9. ILLUSTRATIONS: To clarify the narrative several illustrations are provided. All illustrations are contained in this final section and are listed in the Table of Contents.

Background material for this document can be found in SP-478, "Aircraft Gas Turbine Engine Monitoring Systems".

FIGURE 1.
ENGINE MONITORING SYSTEM (EMS)

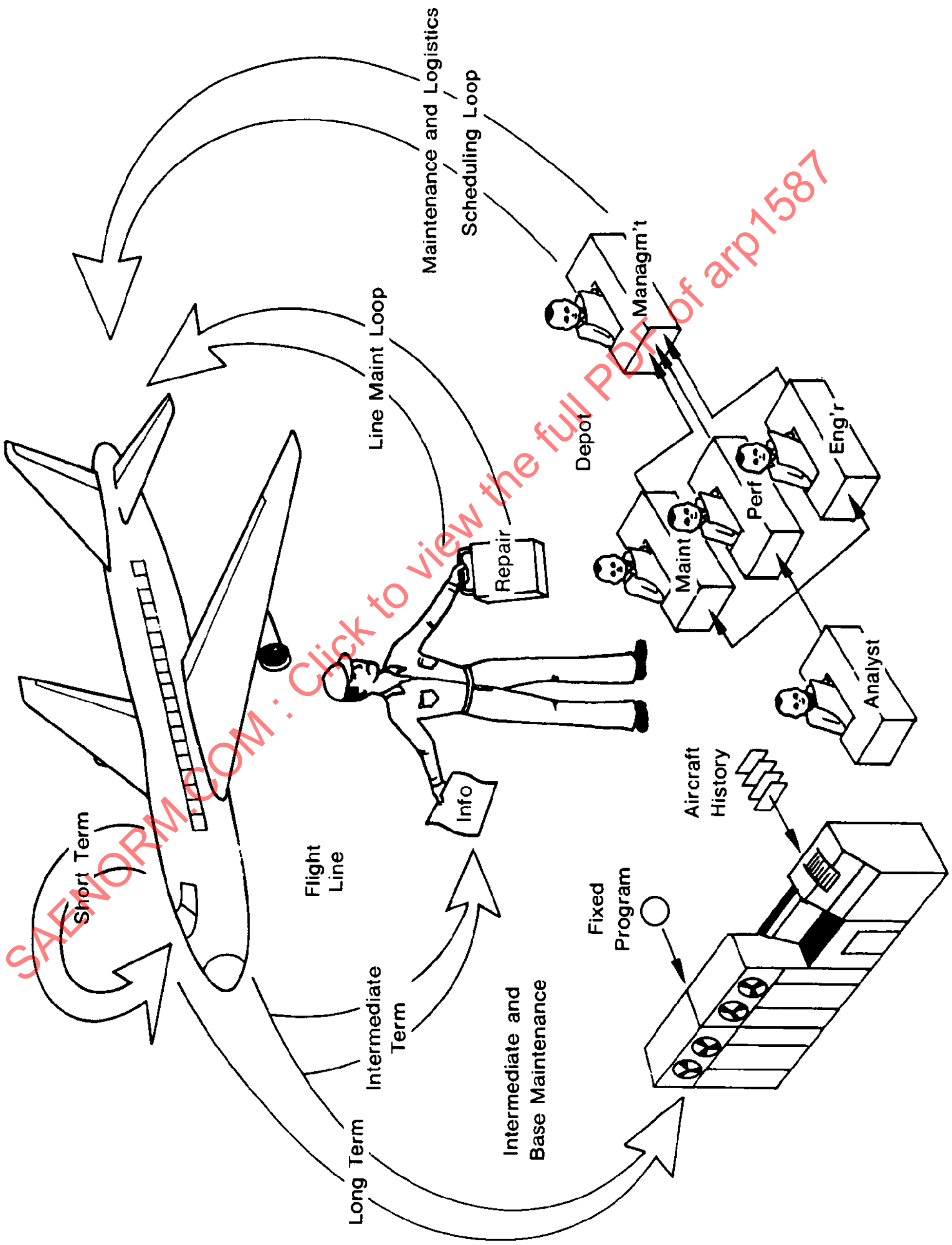

FIGURE 2.
ENGINE LIFE TRACKING WITH AN EMS