SAE Aerospace
An SAE International Group

AEROSPACE INFORMATION REPORT

SAE AIR4985

Issued 2005-01
Reaffirmed 2012-10

A Methodology for Quantifying the Performance of an Engine Monitoring System

RATIONALE

AIR4985 has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE:

The purpose of this SAE Aerospace Information Report (AIR) is to present a quantitative approach for evaluating the performance and capabilities of an Engine Monitoring System (EMS). The value of such a methodology is in providing a systematic means to accomplish the following:

1. Determine the impact of an EMS on key engine supportability indices such as Fault Detection Rate, Fault Isolation Rate, Mean Time to Diagnose, In-flight Shutdowns (IFSD), Mission Aborts, and Unscheduled Engine Removals (UERs).

2. Facilitate trade studies during the design process in order to compare performance versus cost for various EMS design strategies, and

3. Define a "common language" for specifying EMS requirements and the design features of an EMS in order to reduce ambiguity and, therefore, enhance consistency between specification and implementation.

The techniques used for this methodology borrow from those used for testability analysis and are modified to apply to the unique aircraft supportability definitions in item 1 above. While the discussion and examples in this document focus on aircraft engines and their components, the methods and terms in this AIR are applicable to other systems. For example starting systems can be considered to be within the scope of the document.

It will be noted that many of the terms and measures used in the document reflect a military bias. It is anticipated that the methods described will either apply directly to commercial aviation measures or can be readily adapted.

2. REFERENCES:

2.1 Related Publication:

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

2.1.1 SAE Publication: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AIR1872	Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines

3. DEFINITION OF TERMS:

The following set of definitions provides the framework for building the analytical methodology. Many of the following engine supportability terms are well known and whose definitions are generally accepted throughout the industry; however, others are used frequently but lack specificity. In order to enforce standardization these latter terms are given specific definitions for this methodology and a few others have been created to implement concepts attendant to the purposes of this document.

EMBEDDED SYSTEM: EMS features that are on-board the aircraft and perform their functions automatically. The "complete" EMS may be embedded in a single "box" or the system may be distributed among several components that are either on the engine or the aircraft.

EMS: The set of features and capabilities that is allocated for detection and isolation of component failures and monitoring of engine health and usage. An EMS can refer strictly to those automatic features incorporated into embedded electronics or it may include all means used to detect and isolate failures including ground support equipment, personnel and procedures. For the purposes of this AIR, EMS will refer specifically to those features that have been included in the engine (or aircraft) and ground station to aid in detection and isolation of engine component failure, performance deterioration, abnormal engine operation as well as usage. These functions, therefore, may be included in "on-board" equipment as well as ground processing computers.

EMS SCOPE: The subset of engine functions, components, modules, etc. that the EMS is intended to monitor and support. For example the evaluation of EMS performance may be for the entire engine or it may only address those components that interface with a digital control. The EMS scope defines the components and, therefore, the associated failures that the system will be required to address and against which its performance is measured.

FAILURE RATE: The rate at which an engine component fails to perform its proper function. Expressed in events/million engine flight hours.

FALSE ALARM RATE: This parameter measures the rate at which the EMS "detects" events that are not actual engine problems. This may be caused by several problems; however, flawed EMS logic and lack of understanding of actual engine behavior are chief among them. The EMS is held responsible only for those events and failure modes that it was designed to detect and/or isolate. This can be expressed as a percentage of total detected events or a true rate based on total flight hours.

FDR% FAULT DETECTION RATE: Percentage of engine/component faults occurring within the EMS Scope that the EMS is able to detect.

3. (Continued):

FIR% FAULT ISOLATION RATE: The percentage of engine/component failures occurring within the EMS Scope that the EMS is able to unambiguously isolate to a single component or module. A component or system may have several modes of failure; the FIR% will address all failure modes of all components within the EMS scope. Although an EMS may be given target rates for both unambiguous and ambiguous categories, in this document FIR% will address only unambiguous fault isolation. In general an ambiguous fault isolation group would include only two, or perhaps three, specific components.

FLIGHT DELAY: Commercial aviation term referring to equipment-caused departure delay exceeding a specified time threshold. Delays are generally expressed as a rate (Delays/1000 flight hours or Delays/1000 Flight Legs). While this AIR does not address specifically how an EMS may impact Flight Delays, the same approach used for Mission Aborts (or Air Turn Back) and In-flight Shutdowns can be applied.

FMECA - FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS: A reliability engineering process that results in a document which identifies all failure modes for defined engine components and allocates a failure rate to each. The failure rate generally includes both inherent (natural failure modes) and induced (caused by other effects such as improper maintenance, foreign object damage, etc.) rates. The potential effects of each failure are also documented. The overall failure rate of the engine as well as identification of critical failure modes is provided by the FMECA. The FMECA is the basis of establishing the failure modes (and associated rates of occurrence) that the EMS must address.

GROUND STATION: The system that performs the EMS functions that are allocated to ground computation and analysis. Generally the ground station is a computer or computer system with specialized software for performing its functions. The source of data for a ground station will be some form of data transfer media from the embedded portion of the EMS.

IN-FLIGHT SHUTDOWN (IFSD) RATE: The rate at which engine failures result in shutting an engine down while the aircraft is in flight, whether it is done by the pilot, the control system or because of an inability to operate. Expressed in events/million (or events/thousand) engine flight hours.

MISSION ABORT (MA) RATE: Rate at which engine failures, either inherent or induced, cause a mission to terminate prematurely. Expressed in events/million flight hours. MA is a military term. The commercial aviation industry uses Air Turn Backs (ATB) and Rejected Takeoffs (RTO).

MTTD - MEAN TIME TO DIAGNOSE: For all component failures within the EMS scope the average failure rate weighted time required by a maintenance crew to isolate or diagnose the cause of the failure symptoms. An EMS that focuses on improving troubleshooting will drive the MTTD down. Expressed in minutes or hours.

3. (Continued):

PROGNOSTICS: EMS functions that address the detection and/or isolation of future component failures, degradation, etc. before that failure or deterioration causes the engine to fail to adequately perform its intended function. An example of this is a lubrication oil debris monitor that checks for the presence of debris from failing bearings or other components in the oil. The component may continue to operate satisfactorily for many hours, yet the debris, characterized by elemental analysis, indicates that complete failure may occur at some point in the future. While this document does not address prognostics as a separate EMS function, the techniques and methods defined in this AIR and applied to Fault Detection/Isolation are equally applicable to prognostics.

SVR - SHOP VISIT RATE: The rate at which engines are removed from the aircraft to have unscheduled and scheduled maintenance performed. Expressed in visits/thousand flight hours.

UER - UNSCHEDULED ENGINE REMOVAL: Any unplanned removal of an engine from an aircraft for either engine caused or non-engine caused engine failures/conditions. Expressed in events per thousand engine flight hours.

4. UNDERSTANDING THE EMS IMPACT ON SUPPORTABILITY MEASURES:

An EMS can potentially improve several of the "bottom line" supportability measures of an engine. The methodology presented in this AIR is a design (and specification) tool that enables a systematic assessment of this impact. The performance requirements for an EMS may be expressed in many ways; however, impact on supportability parameters is perhaps the most frequently used. Understanding how an EMS can affect these measures and how to quantitatively assess this impact is the objective of this AIR. The following paragraphs describe, qualitatively, how this impact and its attendant benefits may be realized. A quantitative definition of these concepts follows.

4.1 Fault Detection Rate and Fault Isolation Rate:

One of the primary objectives of an EMS is to provide information that improves fault detection and isolation accuracy. A well designed EMS can significantly reduce the number of components that are removed and returned for repair when, in fact, nothing is wrong with them; terms describing this condition are No Fault Found (NFF), Retest OK (RTOK) and Cannot Duplicate (CND). Improvements in the NFF rate are difficult to quantify, consequently no provision is included in the methodology of this AIR to take credit for this capability. However, while not quantified, good fault isolation will reduce unnecessary maintenance as well as maintenance induced events. Additionally, the EMS has the potential to reduce spare parts inventories and the costs associated with returning good components to Original Equipment Manufacturers (OEM) or depot facilities for testing and repair. The greatest improvements in fault detection and isolation rates are realized when an EMS detects and isolates those engine failure modes or effects that occur most frequently (i.e., have the highest failure rate).

4.2 Mean Time to Diagnose:

By improving the Fault Detection and Isolation rates an EMS can reduce the amount of troubleshooting required to identify faulty components or other engine anomalies; this reduction in troubleshooting time translates directly to a lowering of the engine's MTTD. An EMS design which is targeted at decreasing the MTTD would focus on fault isolating those failure modes which require significant troubleshooting, both from the point of view of frequency of occurrence as well as troubleshooting complexity.

4.3 In-Flight Shut Downs and Mission Aborts:

Some component failures that drive the IFSD and Mission Abort rates may have incipient failure modes that can be detected, but do not initially cause an IFSD or MA. An EMS designed to detect these early failure symptoms has the potential to reduce the IFSD and MA rates of the engine. An example of this is a lubrication debris detection system: particles generated by certain failure modes of engine bearings can be detected many hours before actual failure. While detection of this form does not preclude maintenance it can eliminate the MA or IFSD impact of the failure as well as the degree of maintenance that may be required if complete failure had occurred. An EMS that is designed to reduce IFSDs and MAs must be designed to detect those incipient failure modes associated with components or subsystems whose complete failure can precipitate these events. The predicted IFSD and MA rates can then be adjusted based on the ability of the EMS to provide early detection and thus avoid these incidents. In some cases an IFSD or MA can result from signal failures which are not due to physical damage, but which deceive the crew into believing that a mechanical problem exists that demands an engine shutdown or abort. For example an oil pressure transmitter may fail to indicate any pressure, the pilot would need to secure the engine even though the engine in actuality is operating normally.

4.4 Unscheduled Engine Removals and Shop Visit Rate:

In general the SVR is the sum of the UER rate plus the scheduled engine removal rate. The UER rate can be reduced if the EMS is able to detect engine or component failures before they drive an engine "off-wing". Detection of early symptoms of failure can significantly reduce the cost of secondary damage. If a prognosis of a future event is presented, and results in a scheduled removal prior to failure, then a UER is converted to a planned shop visit, and secondary damage avoided. In fact, the reduction in secondary damage is the single largest element of savings provided by an EMS. Another EMS feature that improves the SVR is usage monitoring (reference AIR1872). Usage monitoring of life-limited components makes it possible to keep such parts on-wing longer because precise tracking of the life used avoids the excessive conservatism that would otherwise be required if part usage is tracked by gross measurements such as hours. The

4.4 (Continued):

"life consumed" of critical engine parts is typically done by counting life usage indicators (LUI), such as low cycle fatigue (LCF) counts. Tracking the actual LCF cycles accumulated can enable critical parts to stay in service longer than if tracked by hours since using hours requires making conservative assumptions in the life usage per hour or flight. Hence, use of parts life tracking (PLT) systems can reduce the scheduled removal component of the SVR.

4.5 False Alarm Rate:

While the false alarm rate is a significant EMS performance metric, it results, in general, from shortcomings in the EMS design or its implementation and as such is not a parameter that can be calculated in advance. Field or bench testing must be used to identify these shortcomings and determine the false alarm rate. As previously stated the false alarm rate is a measure of the system's generation of alerts or fault indications to the flight and/or maintenance crews that are not real problems. What is a false alarm and what isn't needs careful definition before measurements are made. An EMS may detect conditions that it was designed to identify, but which may not, in practice, turn out to be conditions that merit maintenance or crew attention. An example of this might be the capability to detect abnormal fluctuations in engine parameters, when in fact fluctuations or shifts in parameters occur as the engine responds to input to the engine's Full Authority Digital Electronic Control (FADEC) from various aircraft systems and not the engine throttles.

5. QUANTITATIVE METHODOLOGY:

For the terms discussed above, the analytical methodology for computing the impact of an EMS is presented below. In each case new terms are introduced, which are described and defined, that provide the basis of EMS performance assessment methodology. In addition to a mathematical description of the various EMS performance parameters, some discussion of the issues and means of determining each are also included. Associated tables illustrate the calculation methodology for each metric.

5.1 Fault Detection Rate and Fault Isolation Rate:

FR_i: The total failure rate of the i^{th} component or frequency of occurrence of an anomaly (events/million engine flight hours). This data can be extracted from an engine or component FMECA and will usually include several failure modes, each with their individual failure rates. Generally the inherent failure rate for the component is used, but the induced failure rate may be included as well.

FR_t: The sum of the failure rates/frequency of occurrence for all components/causes included in the EMS scope ($FR_t = \Sigma FR_i$).

FFR_i: The rate of an individual component's failures as a fraction of the total failure rate for all components in the EMS scope ($FFR_i = FR_i / FR_t$).

FD_i: For a given component (or event cause) the fraction of that component's failures that is detectable by the EMS. To make this determination two important pieces of information are necessary: (1) a set of well defined EMS requirements (i.e., functionally specific) and (2) a knowledge or understanding of the potential symptoms for each failure mode of the component. The FMECA will contain a set of potential symptoms for a specific failure mode. However, in many cases the stated symptoms will require a complete or major failure before being manifest. For instance a slow oil leak could eventually cause low oil pressure if the oil level was never checked. However, for a leak to result in a low oil pressure event during a single mission it would have to be substantial. FMECA generated failure rates do not distinguish between the degree of failure required to produce the stated symptoms; therefore, some consideration must be given to what percentage of a given component failure mode will actually produce EMS detectable symptoms. This analysis may be somewhat qualitative, but field experience, if available, can be used to determine realistic percentages. For new engines these judgments must be based on engineering analysis coupled with the experience of more mature systems. FD_i is determined by summing the failure rate of each component failure mode multiplied by its probability of detection by the EMS. This sum is then divided by the total failure rate for the component.

($FD_i = \Sigma[FRm_j \cdot FDm_j] / FR_i$, where FRm_j is the failure rate associated with the j^{th} failure mode of a component, and FDm_j is the fraction of times that the j^{th} failure mode will be detected by the EMS).

FDR%: The percentage of all component failures (or event causes) within the EMS scope that are detectable by the EMS ($FDR\% = \{ \Sigma[FR_i \cdot FD_i] / FR_t \} \cdot 100$). This is the total (failure rate weighted) fault detection rate for the EMS and, as such, is one of the key performance parameters.

5.1 (Continued):

FI_i: For a given component (or event cause) the fraction of that component's failures that the EMS is able to fault isolate unambiguously. As with FD_i it is necessary to know the specific functional elements of the EMS and the symptoms associated with each failure mode in the EMS scope that will enable isolation. In order for isolation to be unambiguous the EMS must be able to discern failure mode symptoms or characteristics that are unique to the component. This task is easiest to perform when parameters are available to the EMS directly from the component or subsystem that are clear indicators of its failure. However, to incorporate sensors for many components would be impractical from a cost, complexity and reliability viewpoint. Consequently, most monitoring systems utilize parameters that are more generally available and reflect the overall health of the engine and its primary subsystems, but do not enable a high degree of unambiguous fault isolation, since the detectable symptoms may be inherent to several different component failure modes. FADECs, however, enable a relatively high degree of fault isolation of the FADEC itself and of the components with which they interface electronically. ($FI_i = \Sigma[FRm_j \cdot FIm_j]/ FR_i$, where FRm_j is the failure rate associated with the j^{th} failure mode of a component, and FIm_j is the fraction of times that the j^{th} failure mode can be unambiguously isolated by the EMS).

FIR%: The percentage of all component failures (or event causes) within the EMS scope that the EMS is able to unambiguously isolate ($FIR\% = \{\Sigma[FR_i \cdot FI_i] / FR_t\} \cdot 100$). This is the total (failure rate weighted) fault isolation rate for the EMS and is a primary system performance parameter.

These basic terms provide the foundation for performing an analysis of an EMS design from a fault detection and fault isolation perspective. In practice it is useful to break the fault detection and isolation capabilities of the EMS into its various components. For example an "embedded" or on-board system might consist of operational event detection algorithms (over-speed, over-temperature conditions, stalls, etc.) as well as Built In Test (BIT) as part of a FADEC's capabilities. The total EMS may also include a ground station that can provide some portion of the fault detection and isolation capability. This introduces some additional terms.

$FD(BIT)_i$: For a given component (or event cause) the fraction of that component's failures that is detectable by BIT included as part of the EMS.

$FD(EM)_i$: For a given component (or event cause) the fraction of that component's failures that is detectable by the embedded detection features of the EMS, not including BIT.

$FD(GS)_i$: For a given component (or event cause) the fraction of that component's failures that is detectable by the ground station portion of the EMS.

5.1 (Continued):

$FI(BIT)_i$: For a given component (or event cause) the fraction of that component's failures that can be unambiguously isolated by BIT included as part of the EMS.

$FI(EM)_i$: For a given component (or event cause) the fraction of that component's failures that can be unambiguously isolated by the embedded isolation logic of the EMS, again not including BIT.

$FI(GS)_i$: For a given component (or event cause) the fraction of that component's failures that can be unambiguously isolated by the ground station.

As represented in the expressions below, the total fault detection and unambiguous fault isolation capability of a system (FDR% and FIR%, respectively) is the sum of its constituents. Since each component of an EMS is generally designed separately, it is useful to define the performance separately, enabling a clearer picture of how the fault detection and isolation capability of the system is distributed. By design, a different EMS scope may be applicable to each component of the EMS detection and isolation suite. In this case it may be appropriate to express the FDR% and FIR% for each EMS scope, however, the computational methodology would be identical to that of a single EMS scope, which is the case for the expressions below.

$$FDR\% = (\{ \sum[FR_i \cdot FD(BIT)_i] + \sum[FR_i \cdot FD(EM)_i] + \sum[FR_i \cdot FD(GS)_i] \} / \sum FR_i) \cdot 100$$

$$FIR\% = (\{ \sum[FR_i \cdot FI(BIT)_i] + \sum[FR_i \cdot FI(EM)_i] + \sum[FR_i \cdot FI(GS)_i] \} / \sum FR_i) \cdot 100$$

In some cases, particularly related to fault detection, there can be some overlap between methods. For instance, FADEC BIT may detect failures within the control system components that may also be detected as operational abnormalities by the embedded system. It is important that only one of these detection methods is credited, otherwise the calculated FDR% will misrepresent the actual FDR%.

Sample Calculation: Fault Detection Rate (FDR%)

Table 1 illustrates calculation of the FDR% for an EMS scope consisting of only those components that interface electronically with the engine's FADEC. This analysis indicates that for the defined EMS scope a fault detection rate of approximately 78% is predicted. An explanation of the engine component acronyms used in Table 1 is found in Table 2.

5.1 (Continued):

TABLE 1 - Sample Calculation of FDR%

Component	FR_i	$FD(BIT)_i$	$FD(EM)_i$	$FD(GS)_i$		$FR_i \cdot FD_i$
FADEC	400	0.95	0.00	0.00		380.00
Main Fuel Control	177	0.37	0.41	0.00		138.06
CVG Actuator	61	0.23	0.12	0.05		24.40
FVG Actuator	61	0.23	0.12	0.00		21.35
Igniter & Lead	55	0.00	0.00	0.00		0.00
Ignition Exciter	43	0.12	0.00	0.00		5.16
Lube/Scavenge Pump	78	0.00	0.66	0.19		66.30
VEN Pump	33	0.29	0.37	0.14		26.40
VEN Actuators	21	0.35	0.22	0.05		13.02
Lube Tank	49	0.00	0.57	0.15		35.28
T2 Sensor	80	0.79	0.13	0.08		80.00
T25 Sensor	75	0.88	0.05	0.07		75.00
Fan Speed Sensor	12	0.90	0.00	0.00		10.80
Anti-Ice Valve	58	0.76	0.00	0.00		44.08
T5 Harness	87	0.83	0.11	0.00		81.78
PS3 Line	14	0.71	0.00	0.12		11.62
FR_t (= Σ FR_i) =	1304			Σ (FR_i x FD_i) =		1013.25
FDR% =	77.7					

TABLE 2 - Component Descriptions

Component Name	Description
CVG	Compressor Variable Geometry (moveable guide vanes in the compressor)
FVG	Fan Variable Geometry (moveable guide vanes in the fan)
Igniter	Spark Plug type device used to start the engine
Exciter	Electrical box which provides energy to the engine's igniter
Lube/Scavenge Pump	Engine oil pump
VEN	Variable Exhaust Nozzle or variable diameter exhaust cone
Lube Tank	Engine Oil Tank
T2 Sensor	Engine inlet air temperature sensor
T25 Sensor	High speed compressor inlet air temperature sensor
T5 Harness	Thermocouples and wiring for measuring turbine exhaust gas temperature
PS3 Line	Tube for piping compressor exit pressure (PS3) to a transducer

Table 3 illustrates the type of analysis used to implement the quantitative method, described in 4.1, for two components (FADEC & VEN Actuators) in Table 1.

5.1 (Continued):

TABLE 3 - Sample FDR% Analysis Logic

Component	Detection Method	Analysis Logic for Quantitative Detection Performance
FADEC	BIT	Based on testability analysis performed on the entire FADEC, the FADEC BIT has been determined to have a 95% fault detection rate for the FADEC itself
	Embedded	There are many operational faults that are detectable by the embedded portion of the EMS that can be caused by FADEC failure. Examples might include over-speed, over-temperature, flameout, etc., however each FADEC failure mode that would cause these events is detectable by the FADEC, hence the embedded portion of the EMS gets no credit for fault detection of the FADEC.
	Ground Station	The ground station enables analysis of data captured by embedded detection algorithms and trending of various engine parameters, such as engine health or performance, vibrations and oil pressure. In the case of the FADEC the ground station does not detect any additional failures that the FADEC BIT cannot detect.
VEN Actuators	BIT	The FADEC interfaces electronically with the VEN actuator through an electro-hydro servo valve (EHSV), which controls the position of the actuator. Testability analysis indicates that all failure modes associated with this EHSV can be detected by the FADEC and that these failures account for 35% of the actuator failures.
	Embedded	Some hydro-mechanical failures of the VEN Actuator are not detectable by the FADEC, however such failures can result in events detectable by the embedded system such as AB No-Lights, Blowouts, engine stalls, etc. Analysis indicates that an additional 22% of the VEN actuator failures are detectable in this way.
	Ground Station	A small percentage of hydro-mechanical failures (estimated to be about 5%) are expected to be detectable by excessive variation in engine trended performance parameters.

Sample Calculation: Fault Isolation Rate (FIR%)

The methodology for calculating Fault Isolation Rate percentage is exactly the same as that for FDR%; however, the analysis focuses on the EMS' capability to unambiguously identify faults. Table 4 illustrates the quantitative methodology for the same EMS Scope as Table 2, resulting in approximately a 52% first-time fault isolation rate. Table 5 demonstrates the logic for assessing the EMS performance details that go into Table 4.

5.1 (Continued):

TABLE 4 - Sample Calculation of FIR%

Component	FR_i	$FI(BIT)_i$	$FI(EM)_i$	$FI(GS)_i$		$FR_i \cdot FI_i$
FADEC	400	0.72	0.00	0.00		288.00
Main Fuel Control	177	0.37	0.10	0.00		83.19
CVG Actuator	61	0.15	0.06	0.05		15.86
FVG Actuator	61	0.15	0.06	0.00		12.81
Igniter & Lead	55	0.00	0.00	0.00		0.00
Ignition Exciter	43	0.12	0.00	0.00		5.16
Lube/Scavenge Pump	78	0.00	0.00	0.00		0.00
VEN Pump	33	0.20	0.00	0.00		6.60
VEN Actuators	21	0.25	0.00	0.05		6.30
Lube Tank	49	0.00	0.00	0.00		0.00
T2 Sensor	80	0.68	0.13	0.00		64.80
T25 Sensor	75	0.78	0.05	0.00		62.25
Fan Speed Sensor	12	0.90	0.00	0.00		10.80
Anti-Ice Valve	58	0.50	0.00	0.00		29.00
T5 Harness	87	0.73	0.11	0.00		73.08
PS3 Line	14	0.55	0.00	0.00		7.70
FR_t (= Σ FR_i) =	1304			Σ (FR_i x FI_i) =		676.35
FIR% =	51.9					

TABLE 5 - Sample FIR% Analysis Logic

Component	Isolation Method	Analysis Logic for Quantitative Detection Performance
FADEC	BIT	FADEC testability analysis indicates that 72% of internal FADEC failures can be isolated to the FADEC itself.
	Embedded	No FADEC failures can be isolated by the embedded portion of the EMS
	Ground Station	The ground station software can isolate no FADEC failures.
VEN Actuators	BIT	Control system testability analysis indicates that most of the VEN Actuator electrical component failures can be unambiguously isolated by the FADEC; this accounts for 25% of all the VEN actuator failures.
	Embedded	Analysis indicates that the EMS embedded logic will not enable direct isolation of any VEN Actuator failures.
	Ground Station	Evaluation of the performance trend characteristics of one specific VEN failure mode suggests that because of the uniqueness of the signature the ground station software can unambiguously isolate the failure.

5.2 Mean Time to Diagnose:

TTI_i: Time to isolate the i^{th} component in the EMS scope. The TTI is a complex parameter to estimate since its determination is primarily qualitative and is dependent on experience with many types of fault isolation methodologies, automated and otherwise. Determination is based on the following information:

1. Knowledge of the failure modes of a component and the symptoms associated with each,

2. Ambiguity of components or causes that will be associated with any failure mode of a component, based on the symptoms associated with that failure mode,

3. Troubleshooting practices that will be used with the engine, when they will be used and the times associated with using them. Examples of various methods include: use of special support equipment (i.e., borescope, electronic testers, etc.), visual inspection, engine runs (to duplicate symptoms), "shot gunning" or removal and replacement of components until the faulty one is found. While these methods do not use EMS capabilities, in order to assess the impact of an EMS on the MTTD it is necessary to determine the MTTD with and without the EMS, which demands the knowledge and experience described above.

In order to make the determination of TTI manageable, simplifying assumptions will be necessary. The following are sample assumptions:

1. Assign a fixed mean time to each type of troubleshooting method that represents a reasonable average for that method. The table below illustrates this concept.

TABLE 6 - Mean Time for Troubleshooting Methods

Troubleshooting Method	Average Time to Isolate	Comments
1. EMS Fault Code	2 min	Time to check fault display
2. Visual Inspection	10 min	Check inlet/exhaust, doors
3. EMS Ground Station	30 min	Use Ground Station to fault isolate
4. Ground Run	90 min	Set up and run engine
5. Special Checks	90 min	Use of support equipment
6. Remove & Replace	$30 \cdot (X + 1)/2$ min	X = number of ambiguities

5.2 (Continued):

2. Assume a sequence of troubleshooting tasks for each component failure and only include in the TTIi the time for those steps that will occur prior to isolating the failure.

The most significant reduction in MTTD occurs as the FIR% increases, however improvements in MTTD can be realized even when the FIR% is low. An EMS may reduce the ambiguity groups associated with failures and, therefore, reduce the average troubleshooting time required for each. Credit for this appears in the Remove & Replace method, where a smaller number of components (X in the equation above) will need to be replaced until the defective one is identified.

In the table above, it is recognized that after a flight step 1 will always be done, since checking fault codes is part of every post flight maintenance activity. If that alone identifies the faulty component, then troubleshooting ends at that point and the TTI_i would be 2 minutes. For most Line Replaceable Units or LRUs (components which can be removed from the engine while it is installed in the aircraft) visual inspection will only catch leaks, ruptures, low fluid levels, visual flags or buttons changing state, and other similar types of symptoms that may be indications of failure.

$TTI_i = \sum (FRm_j \cdot TTIm_j) / FR_i$, where FRm_j is the failure rate associated with the j^{th} failure mode of a component (or event cause) and $TTIm_j$ is the corresponding time to isolate that component for the j^{th} failure mode and will be one of the values in Table 6. Note that the appropriate $TTIm_j$ for a given failure mode will depend on the troubleshooting method by which that component failure is most readily isolated. TTI_i can also be expressed in the form: $TTI_i = \sum (FFR_k \cdot TTI_k)_i$, where FFR_k is the fraction of a component's failures that can be isolated by the k^{th} fault isolation method (from Table 6.) and TTI_k is the associated isolation time in Table 6 for the i^{th} component in the EMS scope.

$MTTD = \sum\{FR_i \cdot \sum[FFR_k \cdot TTI_k]\} / \sum FR_i$

If achieving a specific MTTD is a requirement for the EMS, then customer agreement may be required on the assumptions used to determine the TTI's for each isolation technique. However, assumptions may not have to be as rigorous if the purpose of the analysis is to show relative differences in the MTTD and perform benefit analyses with and without various EMS features.

5.2 (Continued):

Sample Calculation: Mean Time To Diagnose (MTTD)

Table 7 demonstrates the methodology for determination of the MTTD, utilizing the same EMS scope as the previous examples. For each of the possible troubleshooting methods an assumed time to diagnose appears in the table as AVG Time. For this example the MTTD is determined to be 47 minutes. Table 8 illustrates the analysis that goes into allocation of troubleshooting among the different methods available for a single component.

TABLE 7 - Sample Calculation of MTTD

Component	FR_i		FFR_i	FFR_i	FFR_i	FFR_i	FFR_i	FFR_i	X	TTI_i	$FR_i \cdot TTI_i$
			Code	Visual	G. Stn	G. Run	Sp Ck	R & R		min	
			2	10	30	90	90	30(1+X)/2			
FADEC	400		0.72	0.00	0.00	0.00	0.00	0.28	2	14.0	5616
Main Fuel Control	177		0.47	0.00	0.00	0.15	0.25	0.13	2	42.8	7574
CVG Actuator	61		0.21	0.30	0.05	0.32	0.00	0.12	2	49.9	3045
FVG Actuator	61		0.21	0.35	0.00	0.30	0.00	0.15	2	51.2	3120
Igniter & Lead	55		0.00	0.00	0.00	0.00	0.00	1.00	2	135.0	7425
Ignition Exciter	43		0.12	0.00	0.00	0.00	0.00	0.88	3	158.6	6822
Lube/Scavenge Pump	78		0.00	0.25	0.00	0.00	0.25	0.50	4	137.5	10725
VEN Pump	33		0.20	0.12	0.00	0.00	0.00	0.68	3	124.0	4092
VEN Actuators	21		0.25	0.40	0.05	0.15	0.00	0.15	2	39.8	835
Lube Tank	49		0.00	0.65	0.00	0.00	0.35	0.00	0	38.0	1862
T2 Sensor	80		0.81	0.00	0.00	0.00	0.00	0.19	2	27.3	2182
T25 Sensor	75		0.83	0.00	0.00	0.00	0.00	0.17	2	24.6	1846
Fan Speed Sensor	12		0.90	0.00	0.00	0.00	0.00	0.10	2	15.3	184
Anti-Ice Valve	58		0.50	0.00	0.00	0.35	0.00	0.15	2	52.8	3060
T5 Harness	87		0.84	0.00	0.00	0.00	0.16	0.00	0	16.1	1399
PS3 Line	14		0.55	0.00	0.00	0.00	0.00	0.45	2	61.9	866
FR_t (= Σ FR_i) =	1304										60651
$\Sigma(FR \cdot TTI_i)/FR_t$ = MTTD =	47	minutes									