



AEROSPACE INFORMATION REPORT

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Superseding AIR5317

(R) A Guide to APU Health Management

RATIONALE

This SAE Aerospace Information Report (AIR) provides insight and guidance into the best practices for implementing a health management capability for Auxiliary Power Units (APUs) installed on commercial or military aircraft. With the considerable advancement of prognostics and health management (PHM) tools and capabilities in the past 10 years, operators expect that the value proposition for such a system can easily be demonstrated for APUs. This AIR aims to assist operators in building the PHM capability such that the value can be achieved.

AIR5317A has been reaffirmed to comply with the SAE Five-Year Review policy.

TABLE OF CONTENTS

1.	SCOPE.....	3
1.1	Purpose.....	3
2.	REFERENCES.....	3
2.1	Applicable Documents	3
2.1.1	SAE Publications.....	3
2.1.2	SAE ISBN Publications	4
2.1.3	U.S. Government Publications.....	4
2.2	Definitions	4
3.	GENERAL DESCRIPTION OF HEALTH MANAGEMENT CAPABILITIES.....	6
3.1	Elements of a Health Management Capability.....	6
3.2	Background of APU Health Management.....	8
3.3	Current State of APU Health Management.....	8
4.	COSTS AND BENEFITS FOR IMPLEMENTING AN APU HEALTH MANAGEMENT CAPABILITY	9
4.1	Costs	9
4.2	Benefits	10
5.	TECHNICAL REQUIREMENTS FOR IMPLEMENTING AN APU HEALTH MANAGEMENT CAPABILITY	12
5.1	Failure Detection	12
5.1.1	Detect APU Failures Currently Seen in the Field.....	12
5.1.2	Detect APU Failures Based on Failure Mode and Effects Analysis	13
5.2	Data Collection.....	14
5.2.1	Sensors and Measurements	14
5.2.2	Data Collection Events.....	16
5.3	Data Transmission	17

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5.4	Data Analysis	18
5.4.1	Symptoms	18
5.4.2	Diagnostics.....	18
5.4.3	Prognostics	19
5.4.4	Analysis Techniques	19
5.4.5	Corrective Action.....	26
5.4.6	Implementation.....	28
5.4.7	ETOPS Considerations	30
6.	EXAMPLES OF CURRENT APU HEALTH MANAGEMENT CAPABILITIES	31
6.1	Commercial ETOPS Operator	31
6.2	Military Operator.....	31
6.3	Commercial Maintenance Service Agreements.....	31
7.	CONCLUSION	32
8.	NOTES.....	32
8.1	Revision Indicator.....	32
Figure 1	Four segments of data analysis	18
Figure 2	EGT trending	21
Figure 3	Oil temperature trending	22
Figure 4	Oil level trending	24
Figure 5	Oil consumption monitoring	24
Table 1	Typical APU functional FMEA.....	13
Table 2	Equations for correcting measured parameters.....	20

1. SCOPE

AIR5317 establishes the foundation for developing a successful APU health management capability for any commercial or military operator, flying fixed wing aircraft or rotorcraft. This AIR provides guidance for demonstrating business value through improved dispatch reliability, fewer service interruptions, and lower maintenance costs and for satisfying Extended Operations (ETOPS) availability and compliance requirements.

1.1 Purpose

As aircraft technology has evolved, the ability and the desire to monitor the health of the APU has also evolved. This report will identify the unique characteristics of a successful APU health management capability and the best practices for establishing such a system. The purpose of this report is to guide the development and use of a successful APU health management effort in a practical, cost effective method.

This report will:

- Identify the costs and benefits associated with developing an effective APU health management capability
- Identify the best practices and technologies for developing and implementing an APU health management capability
- Identify the best practices for using APU health management to prevent failures and disruptions to operations
- Identify a recommended collection of data, including recommended measurements and recommended events

2. REFERENCES

These references contain useful information that may have been used in this report or may be beneficial in understanding the subject.

2.1 Applicable Documents

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

2.1.1 SAE Publications

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

AIR1828	Guide to Engine Lubrication System Monitoring
ARP1587	Aircraft Gas Turbine Engine Monitoring System Guide
ARP1839	A Guide to Aircraft Turbine Engine Vibration Monitoring
ARP4176	Determination of Costs and Benefits from Implementing an Engine Health Management System
ARP4754	Certification Considerations for Highly Integrated or Complex Aircraft Systems
ARP5120	Aircraft Gas Turbine Health Management System Development and Integration Guide
ARP6275	Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System
ARP6803	IVHM Concepts, Technology, and Implementation Overview

2.1.2 SAE ISBN Publications

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

ISBN 978-0-7680-6432-2	Integrated Vehicle Health Management - Perspectives on an Emerging Field, Jennions, I.K., editor, 2011
ISBN 978-0-7680-7645-5	Integrated Vehicle Health Management - Business Case Theory and Practice, Jennions, I.K., editor, 2012
ISBN 978-0-7680-7952-4	Integrated Vehicle Health Management - The Technology, Jennions, I.K., editor, 2013
ISBN 978-0-7680-8067-4	Integrated Vehicle Health Management - Essential Reading, Jennions, I.K., editor, 2013
ISBN 978-0-7680-8088-9	Integrated Vehicle Health Management - Implementations and Lessons Learned, Jennions, I.K., editor, 2014

2.1.3 U.S. Government Publications

Copies of these documents are available online at <http://quicksearch.dla.mil>.

FAA AC 120-42B Extended Operations (ETOPS) of Multi-Engine Airplanes

FAA CFR §25.1322 Code of Federal Regulations

2.2 Definitions

ACARS: Aircraft Communications Addressing and Reporting System.

ACMS: Aircraft Condition Monitoring System.

AMBIGUITY GROUP: A group of two or more components that are identified as the potential cause of an APU failure.

APU: Auxiliary Power Unit - A small gas turbine engine installed on aircraft to provide auxiliary pneumatic airflow and auxiliary electrical power on the ground and in-flight, allowing the aircraft to be autonomous of external sources.

ARINC: Aeronautical Radio, Incorporated.

AVAILABILITY: A measurement of how often an APU is capable of performing its full functionality. An APU whose performance has degraded may not be capable of providing sufficient electrical power or pressurized air to the aircraft; hence, the APU is not available.

BASELINE: A quantifiable physical condition or level of performance from which changes are measured.

BCV: Bleed Control Valve - An internal APU valve used to regulate the airflow extracted from the APU to supply the airplane pneumatic system.

BIT: Built-in Test - A self-initiated test performed by the APU controller software to validate internal circuits, input/output signal conditioning, and external interface circuits.

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

DEGRADATION: The mechanism by which the performance and ability of the APU system reduces as a function of time or usage.

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

DOD: Domestic Object Damage - Damage caused by an APU system component.

ECS: Environmental Control System - The aircraft system which regulates the pressure and temperature in the cabin, cockpit, and cargo compartments. The ECS also regulates the air supplied to the aircraft exterior surfaces to control ice buildup.

EGT: Exhaust Gas Temperature - The temperature measured at a specific point in the APU gas path aft of the combustor.

EHM: Engine Health Management - The general process of evaluating the overall health of a gas turbine engine by comparing measurements during normal operations to a model of the expected values or to a baseline. The process includes identifying trends that indicate pending failures that may impact the availability of the engine in near future operations.

ETOPS: Extended Operations - An International Civil Aviation Organization (ICAO) rule adopted by regulating authorities permitting multi-engine commercial air transports to fly routes in which the distance to the nearest diversion airfield is greater than a specified flying time in minutes, such as 120 minutes.

FAILURE EFFECT: The impact of an APU failure on operations and/or on revenue.

FAILURE MODE: A condition in which the APU may become unavailable to perform its full functionality.

FAULT ISOLATION MANUAL: A controlled manual that provides operators with a set of recommended maintenance procedures for determining the root cause of an APU failure.

FMEA: Failure Modes and Effects Analysis - A means of ranking the APU system failures using numerical assignments for severity of effects, for probability of occurrence of a cause, and for the ability to detect a loss before it is encountered. A failure mode may be severe only if it impacts the operation or results in a loss of revenue. The cause of the failure mode may be associated with a particular APU model. The cause of some failure modes may be preventable through normal practices while other modes are not preventable. The cause of some failure modes may be easily detected while others are not predictable. Each failure mode implies a different risk to the continued successful operation of the aircraft.

FOD: Foreign Object Damage - Damage caused by an object that is not an APU system component.

GSE: Ground Support Equipment - (1) Owned or rented equipment that supports operations while aircraft are on the ground, such as electrical generators. (2) Ground-based software used to support data analysis.

IGV: Inlet Guide Vane - An internal vane in an APU that controls airflow through the APU and into the aircraft pneumatic system.

LRU: Line Replaceable Unit - Equipment attached to, or functionally associated with, an APU, which can be replaced by maintenance personnel within the operational schedule of the aircraft.

MEL: Minimum Equipment List - The Federal Airworthiness Regulations require that equipment installed on an aircraft required for compliance with the Airworthiness Standards and the Operating Rules must be operative. However, the rules also permit the publication of an MEL where compliance with certain equipment requirements is not necessary. Experience has shown that with various levels of redundancy designed into the aircraft, operation of every system or installed component may not be necessary when the remaining operative equipment can provide an acceptable level of safety. The MEL authorizes the release of aircraft for flight with inoperative equipment. In order to maintain an acceptable level of safety, restrictions in the form of placards, maintenance procedures, and crew operating procedures are specified in the MEL.

MES: Main Engine Start - The process of starting the main engines with pneumatic air supplied by the APU.

MSA: Maintenance Service Agreement - A contractual agreement between a commercial operator and the APU manufacturer where the operator pays the manufacturer a fixed price per hour of APU operation in lieu of a maintenance charge for labor and materials. An MSA is commonly referred to as a Power-by-the-Hour agreement.

MTBUR: Mean Time Between Unscheduled Removals - A reliability measurement typically calculated as the total flying hours during the time period, divided by the number of unscheduled removals that occurred during the same period.

NFF: No Fault Found - The finding noted by licensed personnel when an APU or an LRU is tested to a specific test procedure and no defects are found. Also, referred to as No Trouble Found (NTF).

NVM: Non-Volatile Memory - The space allocated in a data acquisition unit or an APU controller for storing measurements and fault information.

OEM: Original Equipment Manufacturer - The OEM is the original manufacturer of a piece of equipment, such as an APU or an aircraft, who completed the development, testing, and certification of the equipment.

PCMCIA: Personal Computer Memory Card International Association - A small removable memory device used for data storage.

POR: Point of Regulation - The physical location in the generation system where the demand is controlled.

PROBABLE CAUSE: A probable cause is a known cause that is likely to result in an identified failure mode. For example, 'worn starter motor brushes' is a probable cause of a "Fail to Crank" fault.

PROGNOSTICS: The forecast of future functional status and condition of a system, piece of equipment, component or subassembly based on current and accumulated inputs. The forecast can be expressed as remaining useful life (RUL), or time to reach a specific degradation level, or time to reach a point at which the risk of component failure is unacceptable.

QAR: Quick Access Recorder - A memory device used to store continuously recorded data, such as full flight data.

RTL: Ready To Load - The point in which an operational APU is capability of providing electrical power or pressurized air to the aircraft.

SATCOM: Satellite Communications.

SCV: Surge Control Valve - An internal APU valve used to control airflow through the core to avoid an APU from surging or experiencing reverse flow.

SITA: Societe Internationale Telecommunications Aeronautiques - An aviation community owned organization that manages the world's largest telecommunications system, provides the ground transfer of aircraft communications between ARINC and the airlines, and provides direct communication between the aircraft and the airlines.

STC: Supplemental Type Certificate - Regulatory approval to modify an aircraft after its initial design certification, such as installing new hardware or modifying existing hardware.

3. GENERAL DESCRIPTION OF HEALTH MANAGEMENT CAPABILITIES

3.1 Elements of a Health Management Capability

The data flow through a health management capability is typically described as a five-stage process: Sense, Acquire, Transfer, Analyze and Act (SATAA). These data flow processes are described in detail in ARP5120.

Sense

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

Manual actions such as inspection observations (view of a physical part, reading data hand-written on paper or from a computer terminal, etc.) or audit results (verifying existence of hand-written or computer-generated data records, validation of results, etc.) may also be considered Sense elements.

Acquire

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

Transfer

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

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

Analyze

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

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

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

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

Act

The Act element involves providing output in a form that the operator can use to make maintenance, logistics, or operational decisions. The key objective of this process is to ensure that specific trouble-shooting and maintenance support advice is given to the operator in time to manage or avoid potential events (this likely requires a Transfer element).

The Act element then is to carry out the task as described by that operational decision whether this is maintenance in the form of removal and replacement of the APU or components, or performance of an inspection (e.g., boroscope).

Because flight crew action is not normally required by health management systems, the output information typically is not provided to the flight crew during flight operations. If a flight crew action is required, existing FAA standardized definitions and regulations for cockpit warning, caution, and advisory alerting systems can be found in CFR §25.1322. All elements of a system that generate this type of annunciation are to be developed using the guidance of ARP4754.

3.2 Background of APU Health Management

The role of the APU is to provide auxiliary electrical power and auxiliary pneumatic airflow to the aircraft. While APU failures may result in operational delays, unscheduled maintenance, or cancellation of ETOPS routes, they rarely result in an impact to aircraft safety. When an APU failure occurs, the operator has the ability to defer the APU on the Minimum Equipment List (MEL) until the APU malfunction can be corrected or the APU removed.

As such, the desire to monitor and manage the health of the APU was not widely seen until the past 15 years. This change was brought about by the increased reliance on an operational APU as part of an airworthy ETOPS configuration. On legacy aircraft, the ability to monitor the health of the APU has been limited by the ability to record the data needed to assess the health of the APU. This ability has improved as legacy aircraft have been retrofitted with data acquisition systems. Newer technology aircraft have been designed and delivered with the capability at entry-into-service. Even with data acquisition systems, APUs generally lack additional instrumentation beyond what is required to control the operation of the APU. The health management capability must rely on the limited set of parameters and the output from the Built-in-Test (BIT) to detect any anomalies in the health state of the APU.

Data availability, proven success of Engine Health Management (EHM) systems for main engines, the need to reduce operating costs, and the ever-increasing power of technology is bringing new possibilities and larger acceptance to the idea of APU health management.

3.3 Current State of APU Health Management

The need to show immediate cost savings and the limitations of legacy systems is often a barrier for establishing an APU health management capability. Most operators have a mixed fleet of older and newer aircraft that include a mixed fleet of APUs. Inconsistencies between the fleet capabilities and the need to have separate health management tools add to the increased expense of implementation. Many older large transport and most regional aircraft lack the data acquisition systems to record data onboard and transmit that data off aircraft automatically, making APU data retrieval a manual process. While most APUs store parametric data and fault history records in the controller's non-volatile memory (NVM), the data retrieval process typically involves maintenance personnel manually retrieving and downloading the NVM using the manufacturer's supplied tool. Larger aircraft typically have an Aircraft Condition Monitoring System (ACMS) that will record APU data at specific operating conditions and then transfer that data in the form of a report to the Aircraft Communications Addressing and Reporting System (ACARS).

Once the APU data is retrieved, a health management tool is needed to analyze the data. If the aircraft manufacturer or the APU manufacturer does not supply this tool, few operators will undergo the expense of developing a program in-house. If the aircraft or APU manufacturer does supply the tool, many operators lack sufficient personnel to review the data and will rely on the APU manufacturer to assess the health of their fleet.

Some observations on the current state of APU health management are:

1. On legacy aircraft, an APU health management capability is limited due to the availability of data and the perceived need to perform such tasks.
2. Larger commercial aircraft have an Aircraft Condition Monitoring Systems (ACMS) that will record APU data at specific operating conditions and then transfer that data in the form of a report or recording file.
3. On new technology aircraft, an APU health management capability is expected due to the availability of data and the need to reduce schedule interruptions.
4. The decision analysis for implementing an APU health management capability is usually focused on dispatch reliability.
5. APU BIT has greatly improved the operator's ability to properly diagnose and repair the APU, but has done little to prevent failures from causing schedule disruptions.

6. With the exception of ETOPS, aircraft can usually be dispatched with an APU inoperative; therefore, loss of revenue due to cancellation is not a major consideration. Maintenance actions to address the APU failure are postponed to times that are more convenient.
7. The ability to defer APU maintenance per the MEL makes it difficult for operators to see the business value of APU health monitoring capability.
8. Airplane and APU manufacturers have not required the APU to publish data beyond that which is required for control on the data bus for access for the ACMS.

4. COSTS AND BENEFITS FOR IMPLEMENTING AN APU HEALTH MANAGEMENT CAPABILITY

Quantifying the costs and benefits of an APU health management capability is instrumental to its success. To determine whether an APU health management capability is financially viable, the operator must consider the costs and benefits associated with implementing and sustaining such a program. A Cost Benefit Analysis (CBA) is a commonly used process to compare the costs to the benefits to determine the long-term value of such a program. Performing a CBA will expose the economic feasibility of introducing and integrating the capability with the legacy installation. In the case of new design aircraft, the CBA will be the determining factor for many integration issues. ARP4176, ARP6275, and *"Integrated Vehicle Health Management - Business Case Theory and Practice"* (Jennions, 2012), provide useful insight into how to create a CBA and facilitate the justification for implementing a health management capability.

This section describes some of the potential costs and benefits of implementing and sustaining an APU health management capability. The operator should use their internal costs for labor, delays and cancellations, and materials when performing the CBA.

4.1 Costs

The costs and difficulty in implementing an APU health management capability will vary depending on the fleet and the infrastructure already in place. For example, it may be cost prohibitive to implement a program for a legacy fleet that lacks the communication capabilities to record and transmit APU information. Further, if the infrastructure is not already in place to communicate the APU information to the appropriate personnel, the benefits of an APU health management capability will not likely offset the cost of implementation.

For newer fleets, the availability and reliability of the APU is a significant driver when selecting an APU for a particular airframe. As a result, the APU manufacturers have improved the reliability and the fault isolation capability to meet the demands of the operators. Hence, an APU health management capability for a new, highly reliable APU model must also be economically justified.

Some of the costs associated with implementing APU health management include:

- non-recurring, licensed, or contractual cost associated with obtaining or internally developing ground-based APU health management software and the purchase of an associated host server.
- non-recurring cost of purchasing and installing data acquisition hardware on the aircraft, including the cost of a Supplemental Type Certificate (STC).
- recurring expense for supporting an APU health management capability on a website, local or wide area network, or cloud.
- recurring expenses including: data transmission costs, APU health monitoring software server and internet support costs, labor cost for software support, labor cost for the APU health management analyst or engineer, labor cost to manually enter APU performance numbers into the analysis software (if not automated), and the software maintenance fees, if applicable.

4.2 Benefits

When considering whether to establish an APU health management capability, the operation must tie the perceived benefits to their organizational values (for example, profit margin, cash flow, customer satisfaction index, or employee satisfaction index). There must be a clear perception of how these values will be improved with a successful APU health management effort. The following metrics are used by operators to measure the benefits of a new activity:

- Reduction in the life-cycle cost of the APU
- Reduction in maintenance effort to support the fleet
- Reduction in the number of service interruptions, such as a delay or cancellation
- Reduction in the number of unscheduled component removals
- Reduction in the number of spare components needed due to improved trouble-shooting
- Reduction in the use of rental equipment, such as huffers
- Improvement in the utilization of support equipment

An APU health management capability can help operators improve on these metrics in the following ways:

a. Improve Customer Satisfaction

An APU health management capability can improve customer satisfaction by enabling operators to predict impending failures and mitigate the risk of those failures prior to flight. In hot and humid climates, the APU may be used to cool the aircraft while on the ground and in cold climates, the APU may be used to warm the aircraft. If the operator is unable to obtain electrical or pneumatic power from the gate or from Ground Support Equipment (GSE), the level of comfort in the cabin will greatly be diminished. Advanced indication will allow operators to make alternate decisions to ensure passenger satisfaction and comfort is achieved.

b. Reduce the Number of Delays, Cancellations, and Schedule Disruptions

An APU health management capability can reduce the number of delays, cancellations, and schedule disruptions by enabling operators to predict impending failures, such as a failure in a redundant system (a Speed Sensor or EGT thermocouple) or in a clogged oil filter or oil cooler, or core degradation and load compressor degradation. By predicting impending failures, maintenance can be scheduled and performed at times which do not impact flight schedules and do not require expensive contract maintenance. Some of the cost of delays and cancellations include the loss of passenger goodwill and the cost of accommodating displaced passengers, the cost of disrupting airport operations, and the cost of contract maintenance.

Further, the impact of service interruptions due to degraded engine performance may be alleviated by using the APU to operate the air conditioning packs during take-off. By using the APU rather than the engines to supply pneumatic air to the air conditioning system, the engines can be operated at a lower power setting (reduced EGT), thus potentially extending life, or at a higher power setting (without risk of EGT exceedance) to achieve the required take-off thrust.

c. Reduce the Frequency of Renting Ground Equipment

An APU health management capability can reduce the frequency of having to use or rent GSE to supply electrical or pneumatic power to an aircraft when the APU is not available. The ground handling time for GSE can result in a schedule delay. The cost of renting equipment can be very high, especially at outstations, and often the minimum rental period is for one hour. By predicting or diagnosing failures, maintenance can be scheduled and performed prior to dispatching the aircraft to an outstation.