

A Guide to APU Health Management

RATIONALE

This guide was developed to assist Auxiliary Power Unit (APU) operators in identifying the key steps in establishing and maintaining a successful APU health management program that meets both the economic and the technical requirements of their business. This guide was developed for all APU operators or life-cycle owners, such as commercial operators, Original Equipment Manufacturers (OEM), equipment suppliers, and military transport units.

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1. SCOPE

The SAE Guide to APU health management establishes the foundation for developing a successful APU health management program at any aircraft or APU operator, such as an airline, an OEM, an equipment supplier, or a military transport unit. This guide identifies the best practices for using an APU health management program to improve dispatch reliability and to satisfy Extended Operations (ETOPS) availability requirements.

1.1 Purpose

There have been many attempts to institute APU health management programs but most programs were modeled after the pre-existing main engine programs. These models often overlooked special considerations that are necessary to make an APU health management program successful. This report will identify the unique characteristics of a successful APU health management program and the best practices for establishing 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 program
- Identify the best practices and technologies for developing and implementing an APU health management program
- 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

The General Description in Section 3 is intended to provide a high level overview of the background and the current state of APU health management. The Costs and Benefits in Section 4 is intended to provide a high level overview of the costs and benefits associated with establishing an APU health management program. The Technical Requirements in Section 5 is intended to provide detailed information regarding best practices, recommended data collection and monitoring, maintenance correlation, and implementation.

2. REFERENCES

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

AIR1828A	Guide to Oil System Monitoring
AIR1839B	A Guide to Aircraft Turbine Engine Vibration Monitoring
AIR4061A	Guidelines for Integration of Engine Monitoring Functions with On-board Systems

AIR4175	A Guide to Development of a Ground Based Station for Engine Condition Monitoring
AIR4176	Cost versus Benefits of Engine Monitoring Systems
AIR4985	A Methodology for Quantifying the Performance of an Engine Monitoring System
ARP1587B	Aircraft Gas Turbine Engine Monitoring System Guide
AS4831	Software Interfaces for Ground-Based Monitoring Systems

2.1.2 Government Publications

Available from http://www.airweb.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/

FAA AC 120.42 Extended Operations (ETOPS) of Multi-Engine Airplanes

2.1.3 Other Publications

Richard A. Wade, "A Need-focused Approach to Air Force Engine Health Management Research", US Air Force Research Laboratory, Wright-Patterson Air Force Base, OH

2.2 Terminology and Definitions

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 on the aircraft that provides auxiliary electrical power on the ground and in-flight. Most APUs also provide pressurized air to operate Environmental Control Systems (ECS) and pneumatic systems for icing and main engine starting.

ACARS: Aircraft Communications Addressing and Reporting System

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.

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

DIAGNOSTICS: The process of using data and other measurements to determine the cause of an APU malfunction or discrepancy. The second element of health management; the active process to undertake analysis of a symptom to understand its cause.

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.

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.

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

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 60 flying minutes. Additional deviations of 207 minutes have been granted to some aircraft and longer deviations are being evaluated. Historically, ETOPS referred to twin-engine aircraft but has since been extended to include multi-engine aircraft. ETOPS drives additional APU reliability and availability constraints.

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

FAILURE EFFECTS: The effect an APU failure has on operations and/or on revenue.

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

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 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 process of predicting the future condition and availability of an APU, using the current condition and a model of a failure mode. The third element of health management; the determination of where the cause or condition is leading and in what time frame.

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.

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.

SMOOTHING: An algorithm intended to reduce the scatter in trended data due to normal variations in the raw data. A widely used smoothing algorithm is the 95% weighting of "old data" and 5% weighting of new data. Another widely used smoothing algorithm is the 30-day rolling average.

SYMPTOMS: The first element in health management; the awareness of current condition and identification of a symptom or anomaly.

USB: UNIVERSAL SERIAL BUS - An external bus standard that supports data transfer rates up to 12 Mbps.

3. GENERAL DESCRIPTION

3.1 Background

The role of the APU is to provide auxiliary electrical power and auxiliary pneumatic airflow to the aircraft. Historically, APU failures have resulted in operational delays, unscheduled maintenance costs, and cancellation of ETOPS routes, but have rarely resulted in an impact to aircraft safety. As such, the idea of an APU health management program to target these issues has only recently (within the past 10 years) become interesting. Given the perceived successes of engine health management programs, it would seem natural to extend an engine health management program directly to an APU fleet. However, since an APU is typically operated under different safety, logistical, and economical constraints, few operators actually practice APU health management.

Typically, when an APU failure occurs, the operator defers the APU on the Minimum Equipment List (MEL) until the APU malfunction can be corrected or the APU removed. The cost of removing and replacing an APU is relatively inexpensive compared to a main engine.

The "Fly to Failure" practice is sustained by the fact that most APU data is not readily available to the aircraft data acquisition systems. Historically, APU controllers were only designed to control the parameters necessary to safely start and operate the APU throughout all operating modes. In the 1980s, Built-in-test (BIT) capability was added to the controllers to improve the detection and trouble-shooting of APU malfunctions. More recently, the calculation of health parameters and the storage of diagnostic data to further aid in trouble-shooting and diagnostics were added to the controllers. In parallel, aircraft data infrastructures were expanded to include a centralized maintenance computer for processing and viewing digital fault data from the controllers as well as from other electronic equipment. Aircraft Communications Addressing and Reporting Systems (ACARS), Satellite Communications (SATCOM), and data service provider networks have made access to this increasing amount of data easier than ever before.

Data availability, the success of main engine health management programs, the desire to reduce operating costs, and the ever increasing power of computing resources is bringing new possibilities and larger acceptance to the idea of APU health management.

3.2 Current State

The need to show bottom-line cost savings and the limitations of historical systems is often prohibitive in operating an APU health management program. Some operators chose not to monitor their APU fleet due to the lack of a manufacturer-supplied program. Most operators have a mixed fleet of older and newer aircraft that include a mixed fleet of APUs. Inconsistencies between the fleet capabilities make justifying the expense of an APU health management program difficult.

Many older aircraft and APUs lack the instrumentation and the data acquisition systems to transmit data automatically, making APU data retrieval a manual process. While most APUs store fault history records in the controller non-volatile memory (NVM), the data retrieval process involves maintenance personnel manually retrieving and downloading the NVM using the manufacturer's supplied tool, which is not tied to the aircraft systems in most aircraft. Further, if the APU manufacturer does not supply an APU health management program, few operators will undergo the expense of developing a program in-house. If the APU manufacturer supplies an APU health management program, many operators lack sufficient personnel to review the APU data and rely on the APU manufacturer to review their data for them. However, since many operators lack the infrastructure to deliver the APU data to the manufacturer real-time, the benefit of real-time analysis and trending is replaced by after-the-failure analysis and trouble-shooting.

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

1. APU health management is an addendum to a propulsion engine health management. The implementation has been linear, with few special APU features incorporated into the monitoring system. As a result, implementing and supporting an APU health management program may cost the same as implementing and supporting a propulsion engine health management program. Further, health management software analysis tools customized for most APUs are not readily available on the market, as opposed to the multitude of tools that are available for the propulsion engines from the OEM or from third party vendors.
 2. The decision analysis for main engines is aimed at reliability and the cost of ownership. Until ETOPS, APU health management was focused on dispatch reliability.
 3. APU BIT has greatly improved the operator's ability to properly diagnose and repair the APU, but has done little to improve dispatch reliability or reduce schedule disruptions.
 4. With the exception of ETOPS, aircraft can usually be dispatched with an APU inoperative; therefore, loss of revenue is not a major consideration. Maintenance actions to address the APU failure are postponed to times that are more convenient. The ability to defer the APU makes it difficult for operators to justify the expense to perform APU health monitoring based solely typical flight delay justification costs.
 5. Health monitoring will rarely catch random LRU failures so dispatch reliability may not be the best way to justify the expense of an APU health management program.
- #### 4. COSTS AND BENEFITS

Quantifying the costs and benefits of an APU health management program is instrumental to its success. To determine whether an APU health management program is financially viable, the operator must consider the costs and benefits associated with implementing and sustaining such a program. A Net Present Value (NPV) Model is a commonly used tool for comparing the costs to the benefits to determine the long-term value of such a program.

This section describes some of the potential costs and benefits of implementing and sustaining an APU health management program. The operator should use their internal costs for labor, delays and cancellations, and materials when populating the NPV Model. AIR4176 may provide additional insights into identifying costs and benefits of a health management system.

4.1 Costs

The costs and difficulty in implementing an APU health management program 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 program 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 procedures to meet the demands of the operators. Hence, an APU health management program for a new, highly reliable APU model must also be economically justified.

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

- The non-recurring, licensed, or contractual cost associated with obtaining or internally developing APU health management software and the associated host server
- The recurring expense for supporting an APU health management program on a web site or on a local or wide area network
 - Typical recurring expenses include: the data transmission costs, the APU health monitoring software server and internet support costs, the labor cost for software support, the labor cost for the APU health management analyst or engineer, the labor to manually enter the 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 program, 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:

- On-time flights
- Maintenance effort to support the fleet
- Cost of unscheduled removals
- Cost of spares
- Cost of rental equipment
- Utilization of support equipment
- Life-cycle cost of the APU

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

a. Reduce the number of Delays, Cancellations, and Schedule Disruptions

An APU health management program 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. 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.

b. Reduce the Frequency of Renting Ground Equipment

An APU health management program can reduce the frequency of having to use or rent Ground Support Equipment (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.

c. Avoid Excessive Trouble Shooting/Testing:

An APU health management program can reduce extensive trouble-shooting and testing by assisting operators in identifying the cause of an APU failure more quickly and accurately, thus reducing the cost of mechanic labor-hours and the cost of fuel used during testing. When the cause of an APU failure is not known, mechanics may perform extensive trouble-shooting and testing of the system in an attempt to determine the cause of the failure.

d. Avoid Unnecessary APU and LRU Removals

An APU health management program can reduce the quantity of unnecessary APU and LRU removals during trouble-shooting by enabling operators to isolate the cause of the failure more quickly and accurately. When the cause of an APU failure is not known, mechanics may attempt to reduce the time required to trouble-shoot an APU failure by replacing multiple LRUs at one time. This practice results in additional costs for unnecessary component removals and dramatically reduces the ability to accurately track the reliability of the LRUs. Operators may remove an APU prematurely if trouble-shooting is not successful in determining the cause of the failure or when removing the APU requires less time than trouble-shooting or replacing components or LRUs. The costs associated with a premature removal may include aircraft unavailability, labor costs, transportation costs, and Repair Shop costs. By trending the health of the APU, operators will be able to maximize on-wing utilization of the APU and reduce unnecessary premature removals. Further, expensive last minute transportation costs for an unscheduled replacement and associated labor costs will be avoided.

e. Improve Repair Shop Failure Analysis

An APU health management program can assist a Repair Shop in determining the cause of a failure of an LRU or an APU. Most LRUs are returned to a Repair Shop with little information regarding why the LRU was removed and the reason for removal of an APU is often too general. For example, a common reason for removal of an APU is "Fail to Start" or "APU FAIL" message displayed in cockpit. Both reasons for removal may be sufficient for an aircraft logbook but neither reason is sufficient for effective trouble-shooting in the Repair Shop. As a result, extensive trouble-shooting, including complete teardown, is often necessary to determine the cause of the failure. Extensive trouble-shooting leads to the replacement of components prematurely and negatively impacts the statistical reliability analysis of the components. An APU health management program can assist the Repair Shop in identifying the reason for removal and the corrective action needed without extensive trouble-shooting and teardown.

f. Reduce Secondary or Consequential APU Damage

An APU health management program can greatly reduce the occurrence of secondary or consequential damage to APU internal components and LRUs due to an APU failure that can be predicted or detected. For example, turbine degradation can be tracked by monitoring key parameters, such as EGT under a known load condition. An APU can be scheduled for removal when the EGT reaches a certain threshold that correlates to a turbine degradation level. Early APU removal may eliminate the damage caused by a failed turbine blade, or other component, had the APU remained on the aircraft until failure.

g. Reduce Excess Inventory

An APU health management program can reduce inventory levels by enabling operators to reduce unnecessary component and LRU removals and to track the reliability of components and LRUs. Unnecessary component and LRU removals may result in excessive inventory levels for spares. Tracking the reliability of components and LRUs enables the operators to strategically purchase and stock spares.

h. Avoid ETOPS Disruption

An APU health management program can enable operators to predict impending failures, track oil servicing levels, and diagnose failures that can be addressed prior to the ETOPS mission. Prior to dispatch for an ETOPS mission, the APU must be functional. If the APU fails the pre-flight checks or fails during the ground operations prior to departure, the ETOPS mission will likely be delayed. If the cause of the failure cannot be quickly identified and corrected, the ETOPS mission will likely be cancelled. In addition to the costs of canceling or delaying a flight, an ETOPS cancellation may also include the cost of ferrying an aircraft to the location of the out-of-service aircraft to transport the passengers to a new location. Ferry flights provide no revenue and are very costly.

i. Eliminate Hard Time Requirements for Components and Maintenance Inspections

An APU health management program can eliminate or extend the need for hard time requirements for removal or inspection of certain components. Hard time requirements are typically based on operating hours or cycles. For example, the requirement to inspect the oil filter every 2000 hours may be eliminated or extended if an APU health management program can detect when the filter is clogged by trending the pressure drop across the filter. Eliminating or extending hard time requirements can result in savings in labor and material costs.

4.3 Reliability

An APU health management program can assist an operator in improving their APU system reliability. The Mean Time Between Unscheduled Removals (MTBUR) is a typical measurement of reliability. An APU health management program can effectively improve trouble-shooting and reduce the number of unnecessary LRU removals, thus improving the MTBUR rate.

APU reliability can be enhanced by health monitoring of the entire APU system. Traditional reliability performance metrics are impacted greatly through unscheduled removals. Maximizing on-wing utilization through the better use of APU health management tools for troubleshooting and for tracking core performance degradation will directly improve the unscheduled removal rate. However, APU health monitoring will not be effective in improving the inherent reliability of the APU system without modification of the OEM original design through service bulletin or other regulatory document. Through effective modification of the design, the MTBUR will improve, regardless of health monitoring.

An APU health management program can assist operators in realizing further benefits in their reliability programs if approved by their regulatory authorities. Operators can use the data collected from health management systems and maintenance corrective actions to use as justification to improve their aircraft maintenance programs, such as changing maintenance task intervals. Data can also be collected by operators through their reliability programs to provide to the APU manufacturers. The APU manufacturers can use the data collected to improve the basic core reliability and system reliability or to make improvements to the trouble-shooting manuals. The data collected can also be used to focus on maintenance training problem areas, component upgrades, and maintenance or flight crew procedural changes, which will improve the overall reliability of the component and aircraft dispatch reliability at the fleet level.

5. TECHNICAL REQUIREMENTS

The technical requirements for an APU health management program must be derived from a fundamental understanding of how the condition of the APU impacts an operator's business model. Once the impact is understood, the requirements for data collection, data transmission, and statistical methods to assist in the detection and characterization of APU failures can be developed.

A successful APU health management program requires development on the aircraft side and development on the ground support side. Identifying what data must be collected from the aircraft and then communicating that data to the ground support system is the first step in developing a program. Once the data is available to the ground support system, developing the methods for identifying the APU failures modes is the next step. Finally, an implementation plan must be in place to process the data and to integrate the APU health management program into the current business systems.

5.1 Best Practices for Establishing an APU Health Management Program

5.1.1 Detect APU Failures Currently Seen in the Field

For an operator that wishes to establish an APU health management program for an existing fleet, the best practice may be to identify which failures most frequently impact the operation and then develop the methods for detecting these failures. Most operators track the cause of mission delays and cancellations due to APU failure. From this list, the top reasons for failure can be derived. Upon further drill-down, the root cause of the failure can be identified through maintenance actions and shop findings. The operator can develop their APU health management program to detect these root cause failures.

Currently, some of the APU failures, which frequently impact operations, are:

- The APU fails to start due to ignition system faults
- The APU fails to start or accelerate due to fuel control system faults
- The APU fails to supply pressurized airflow to support Environmental Control System (ECS) and pneumatics due to bleed control system faults
- The APU fails to supply pressurized airflow to support ECS and pneumatics due to APU core deterioration
- The APU fails to maintain scheduled Speed due to Foreign Object Damage (FOD) or Domestic Object Damage (DOD)

5.1.2 Detect APU Failures Based on Failure Mode and Effects Analysis

For an operator that wishes to establish an APU health management program for a new fleet, the best practice may be to develop methods for detecting functional failures by the Failure Modes and Effects Analysis tool. The FMEA tool gives the operator the ability to evaluate their maintenance and economic objectives to determine how each type of failure should be treated. The FMEA tool can be used to describe each failure mode and the effects of each failure mode. From this analysis, the operators will be able to decide whether to accept the risk of these failures or to mitigate them with an APU health management program. For a commercial operator, the FMEA may resemble Table 1:

TABLE 1 - TYPICAL APU FUNCTIONAL FMEA

Failure Mode	Probable Causes	Possible Symptoms
APU is slow to start or fails to start in 3 attempts	Core degradation, bearing or other significant mechanical failure, starter motor failure, power not available to APU controller, controller failure, fuel system failure, ignition system failure, harness failure, inlet blockage	High EGT and Fuel Flow, slow starts
APU shuts down	Core degradation, loss of power to the APU controller, APU controller failure, fuel system failure, harness failure, inlet blockage	APU shuts down, BIT message
APU cannot start one or more main engines	Core degradation, bearing or other significant mechanical failure, IGV cutback, bleed system failure, harness failure	High EGT and Fuel Flow, slow starts, IGV cutback, low bleed pressure
APU cannot deliver air to maintain cabin temperature	Core degradation, load compressor degradation or FOD, IGV cutback, bleed system failure	High EGT and Fuel Flow, slow starts, IGV cutback, low bleed pressure
APU cannot drive the generator to provide electrical power in-flight	Core degradation, load compressor degradation or FOD, APU controller failure, generator failure, harness failure	High EGT and Fuel Flow, slow starts

The intended use of the functional FMEA is to identify those APU component failures that represent the greatest risk to the normal operation and aircraft availability, such as:

- APU start and operation
- Main Engine Starting (MES)
- Ability to provide minimum generator load at altitude after a main engine fails.

For example, if the APU fails to start, the functional FMEA may indicate that the starter motor degradation represents a significant risk to performance of the operation. Therefore, it may be of value for the operator to have an APU health management program that detects starter motor degradation and predicts the eventual failure of the starter motor. The APU health management program should include trend monitoring for a starter motor health parameter, which means that the data measurements, the algorithms, and the correlation trends must be identified. Data acquired during the APU development and certification programs may be useful in defining a good quality correlation.

APU starting represents the biggest risk to the ETOPS operation. If the operator is performing altitude cold soak starts (for periodic ETOPS operations checks or other need), data collected at altitude may need to be normalized and trended differently and separately from start data trended for normal operations. Knowing that the electrical load can be carried by the APU would help to reduce risk only after the higher risk of starting was addressed. In order to reduce the risk that the APU may not be capable of carrying the electrical load, the 'causes' listed would be the focus of a new activity in the APU health management program.

5.2 Recommended Data Collection

5.2.1 Measurements

Data collection considerations are a significant step in establishing an APU health management program. For existing fleets, APU measurements, which enable the operator to identify the condition of the APU system, may be available to the aircraft cockpit displays. However, not all of these measurements are available to the aircraft data acquisition system. Below are some suggested measurements and analytical functions that are available from the APUs on current aircraft:

- Hours and Cycles - used to track reliability and service bulletin incorporation.
- Inlet Temperature - used to normalize APU data to standard day conditions.
- Initial Inlet Temperature - used to differentiate between ground and in-flight during APU starting.
- Inlet Pressure - used to normalize APU data to standard day conditions (establishes altitude and adjustments to fuel schedules).
- Initial Inlet Pressure - used to differentiate between ground and in-flight during APU starting.
- Load Compressor Discharge Temperature - used to trend load compressor degradation.
- Load Compressor Discharge Pressure - used to trend load compressor degradation.
- Time to reach "Ready To Load" - used to evaluate how long the APU takes to reach a Speed that will allow a load, such as electrical or pneumatic. Excessive time to reach RTL may indicate core degradation, such as the compressor or turbine.
- Time to Start - used to evaluate how long the APU takes to reach a specific Speed. Excessive Start Time may indicate drag or core deterioration. Time to Start should be tracked separately for ground starts and in-flight starts as well as for warm starts and cold soak starts.
- Peak EGT during APU Starting - used to determine core degradation or inlet blockage.
- Speed at Peak EGT during APU Starting - used to normalize Peak EGT for APUs that do not operate at a constant mechanical Speed.
- EGT at a Functional Load - used to determine APU core degradation, such as during MES, in-flight starting, or while supplying a known ECS load.
- Speed at Max Load - used to normalize EGT at Maximum Load for APUs that do not operate at a constant mechanical Speed.
- Inlet Guide Vane Position/Angle - used to determine APU core degradation and functional capability to provide pneumatic air. The APU controller will cutback the IGV angle or position to protect the APU from an EGT exceedance. IGV cutback may indicate APU core degradation or LRU failure.
- Bleed Pressure - used to determine the ability of the APU to supply pneumatic air to the aircraft system. Low bleed pressure may indicate a deteriorated compressor, a deteriorated core, or a bleed system malfunction.
- Battery Voltage and/or Current - used to determine why an APU fails to start or shutdowns due to loss of power to the controller.

- Starter Current - used to determine why the APU is slow to start or fails to start.
- Oil Temperature - used to determine if the oil cooler is clogged or failing and if the generator is failing.
- Oil Pressure - used to determine oil pump failure or degradation.
- Differential Pressure across Fuel Filter - used to determine contaminants in the fuel system, which may have caused fuel nozzle clogging and resulted in fail to starts.
- Differential Pressure across Oil Filter - used to determine contaminants in the oil system, which may be indicative of a bearing, gear, seal, or a generator failure.
- Oil Debris Collection - used to determine magnetic contaminants in the oil system, which may be indicative of internal failures, such as bearings, bearing races, gears, generator, and insulation.
- Oil Debris Detection - used to determine magnetic and non-magnetic contaminants in the oil system, which may be indicative of internal failures, such as bearings, bearing races, gears, generator, and insulation. Early debris particle counting may enable scheduled removal of the APU prior to incurring secondary damage.
- Vibration - used to determine FOD damage, blade damage, bearing or gear failures, LRU failures, and build problems resulting in rotor component shift.
- Generator Load or Demand - used to normalize APU data to standard operating conditions.
- Fuel Flow - used to determine APU core degradation.
- Fuel Servo Current - used to determine core degradation when Fuel Flow is not a measured parameter.
- Time between maximum Fuel Manifold Pressure and EGT rise - used to determine Fuel Nozzle clogging, which may be causing APU fail to starts.
- Rundown Time - used to determine APU bearing and gear degradation.
- Hydraulic Pressure - used to determine the ability of the APU to drive hydraulic pumps, in particular for a helicopter.

The instrumentation most common on an APU is the engine control instrumentation, such as Speed and EGT. The health management analysis that has often been supplied in APU controllers utilizes this instrumentation to produce calculated parameters useful for discovering some types of degradation, not necessarily those types commensurate with the most common failures observed by the maintenance crews. Both the raw sensor data and calculated parameters are often broadcast to other aircraft subsystems via a data bus.

Extending the APU health management capability may be accomplished by considering other measurements and correlations not originally intended for health monitoring. Additional parameters may be available on the aircraft digital data bus, which are accessible to the maintenance crew but were not available to the APU manufacturer when the health management program was created. Integrating the measurements from these various aircraft sources can lead to extended knowledge about a new, unanticipated situation or failure mode. Integration must be done in the ground-based system to take advantage of the additional data sources.

5.2.2 Events

When to collect APU data is the next consideration when establishing an APU health management program. For the prognostic analysis, APU data should be collected when the APU is performing its required functions. The frequency of the data collection will vary depending on the function and the need of the operator. For example, during a Main Engine Start, one operator may choose to collect data during every main engine start while another operator may choose to collect data once every 10 main engine starts. Other operators may record data on every flight but only retain data from every 10th historical flight. Examples of events where APU data can be collected for prognostics are:

- APU Starting
- Main Engine Starting
- ECS Operation (normal operations)
- APU Maximum Load Operations
- APU with Electrical Load and no ECS
- APU Idle Unloaded
- APU Rundown

For diagnostic analysis, APU data should be collected during an event, such as a Protective Shutdown or a Speed or EGT Exceedance. Examples of events where APU data can be collected for diagnostics are:

- Protective Shutdown
- Starting Failure (Fails to Start, Fails to Accelerate, Fails to Light, Fails to Crank)
- IGV Closed During ECS Demand
- BCV Failure
- APU Limit Exceedance (soft or hard limit)
- APU Rapid Rundown

Examining the APU health during each event requires may also require collecting data from all of the APU controller inputs and outputs in order to properly normalize the data. For example, gathering data from other aircraft systems, such as the flight conditions, the generator, ECS, and main engine controllers, will assist in trending the data to a common baseline.

5.3 Recommended Communication

Data communication for APU health management is similar to, if not integrated into, the communication methods for propulsion engine health management. Communication of collected data typically depends on the method of collection (manual or automatic), transmission capabilities, and budget. Data can be communicated automatically by data link service providers, such as ARINC or SITA via ACARS (VHF radio transmission) or through satellite communications (SATCOM). Data can also be communicated when the aircraft is on the ground through removable media, through wireless broadband communications, or through a laptop computer. Many aircraft are currently capable of off-loading data to a digital storage device, such as an optical disk, a PCMCIA card, or a USB card. Newer aircraft may be capable of off-loading data to a wireless broadband ground network. However, most regional aircraft are only capable of off-loading data through an intermediate device, such as a laptop computer. In the worst scenario, many aircraft have no off-load capability and the only method to communicate data is to manually transfer the data from hard copy records to the health management program.

Since APU health management communications are typically integrated into the same communications procedures, details will not be repeated here and can be found in previously issued SAE documents, ARP1587B and ARP4175A.

5.4 Best Practices for Developing an APU Health Management Program

Developing an APU health management program can be complicated and expensive if not implemented in a focused, disciplined manner. The aim of this section is to provide some best practices and lessons learned in order to facilitate the creation of an APU health management system that meets the needs and restrictions of the preceding sections. The amount of detail in a monitoring program must be selected to satisfy the objectives of the operator's business model, and the budget available for the implementation, execution and maintenance of the health management program.

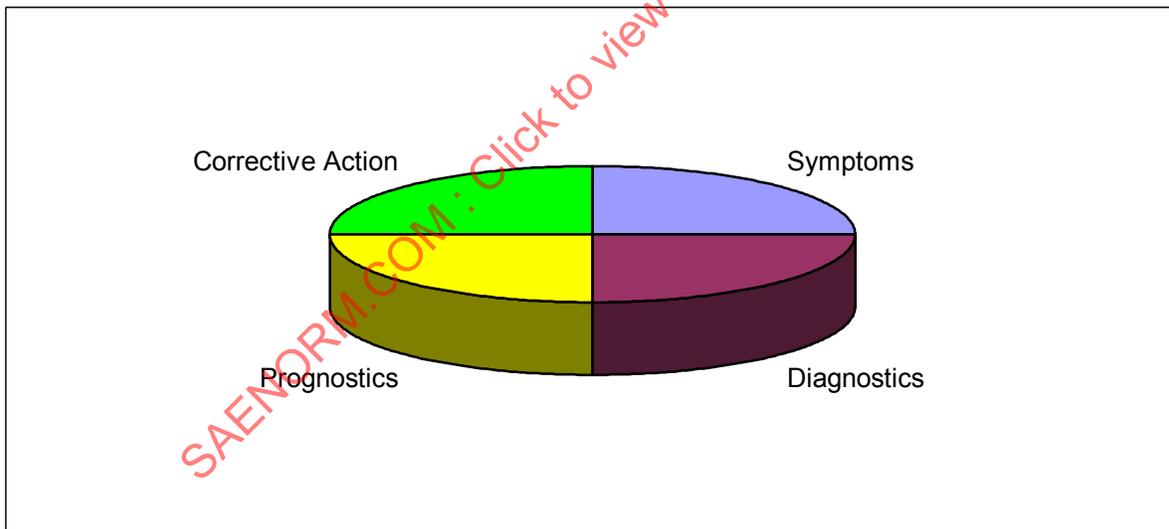


FIGURE 1 - FOUR ELEMENTS OF APU HEALTH MANAGEMENT

The technical aspects of an APU health management system can be divided into four major segments: Symptoms, Diagnostics, Prognostics, and Corrective Action. This section covers each of these elements as they apply to APU health management. The more practical aspects of software implementation and user interface considerations are important to consider in planning and executing an APU health management program and are addressed in the following sections.

5.4.1 Symptoms

The first element of health management is 'symptoms' and refers to the 'awareness of current condition and identification of a symptom or anomaly.' A condition that is identified as an anomaly may be a symptom of abnormal operation due to a failure. The abnormal operation may or may not be a cause for alarm. However, further analysis of data from sensors or from inspections may be required to determine if the abnormal operation is indicative of a failure condition.

For the purpose of the top-level discussion, consider a component as a subsystem, like "APU Starting System," or "Main Engine Starting System" or "Environmental Control System." At this level, the common maintenance actions may be trouble-shooting or replacing the APU. No attempt needs to be made to find a root cause of the failure mode, so diagnostic and prognostic capabilities are not required. The operator simply needs an indication of degradation in APU health in order to take action. This level of health management should require very low health management effort, and should expect a clear, but not optimized, cost benefit from an effective application of this health management to the APU.

Comparing APU parameters to fixed thresholds is an easy way to highlight a change in APU health. EGT, APU Start Time, and oil temperatures can all be monitored in this way.

5.4.2 Diagnostics

The second element of health management is 'diagnostics,' which is the 'active process to undertake analysis of a symptom to understand its cause.' When an abnormal operation is detected based on symptoms and the analysis of data, the process to determine the root cause of the abnormal operation is diagnostics. Diagnostics typically involves fault isolation and knowledge of the APU system based on FMEA. If diagnostics determines that a failure condition exists, further action will likely be required, such as a protective shutdown.

Effective diagnostics will recognize the distinction between a failed LRU and a failed APU. If the diagnostics can isolate the cause of the failure to an ambiguity group of LRUs, replacement of these LRUs is usually faster and cheaper than extensive trouble-shooting or replacing the APU. Diagnostics involves more analysis and knowledge and may include a mixture of discrete BIT data and APU health management data to find the true root cause of the failure. Since LRUs are the number one cause of APU function failure, the added effort of analyzing APU health data may be easy to justify if the success rate is high enough.

5.4.2.1 Protective Shutdown Troubleshooting

Symptom and diagnostic capabilities have been built into the control system of many APU models. The protective shutdown is one manifestation of those capabilities. The presence of a protective shutdown implies that an anomaly has been detected by the APU control system and that the APU has been disabled to prevent excessive or secondary damage. Many times the APU control system will provide diagnostic information in the form of fault codes and shutdown reason information derived from diagnostic algorithms embedded in the APU control system. Additional information about the aircraft system is also useful in diagnosing the root cause leading to an APU protective shutdown.

Capturing APU data prior to the protective shutdown event provides additional information to support the diagnosis of an APU symptom. The transient state of parameters listed in 4.2.1 is useful in determining the root cause of an APU protective shutdown.

5.4.3 Prognostics

The third element of health management is 'prognostics,' which is 'the determination of where the cause or condition is heading and in what time frame.' Prognostics is the process of predicting the future functional capability or condition of the APU by identifying trends in the APU data that either diverge from the normal APU operation or are consistent with a known APU failure condition. Prognostics includes knowing the effect of the failure condition and knowing how the failure will impact the APU functionality and availability.

Despite completing the FMEA during the APU design phase, the probability of occurrence for each failure condition will not be known for the mature APU for several years after entry into service. Therefore, the health management program must provide a means to change the monitoring process to analyze new failures as they occur.

5.4.3.1 Performance Trending and Control Charting

The performance of the APU and the measured parameters exhibit normal day-to-day variations. Many intermittent or rapidly developing symptoms indicate APU failures that can be diagnosed by comparing past parameter values to current values. The frequency of the data recording may influence how quickly a symptom can be diagnosed. Infrequent data will capture slow deterioration trends but may not provide sufficient information to diagnose rapid deterioration.

Control Charting, also known as Fingerprint Charting, is a useful tool for identifying these APU health symptoms and for correlating these symptoms to a failure mode. There are many published works explaining control chart theory and mechanics. A few examples follow.

Control charts are useful for:

- Establishing baselines of the mean and variation of APU health parameters
- Identifying statistically significant changes in parameter variation
- Identifying shifts in mean value of a parameter
- Developing a Run Chart
- Identifying ignition system degradation
- Identifying APU start system degradation

To determine when the APU performance is diverging from normal operation, the current performance is typically compared to a baseline trend. The baseline trend may be derived by the APU manufacturer during controlled, installed APU performance testing or the baseline trend may be established during in-service APU operations. A baseline trend may also be established for ground and in-flight operations. The following paragraphs describe how a baseline trend can be established to identify deviations from normal operation for various components and parameters.

5.4.3.1.1 Core APU Deterioration Trending

The key APU parameters for monitoring core performance degradation are EGT and Fuel Flow. As the APU core deteriorates, the loss in efficiency of the turbine and compressor will result in an increase in the required Fuel Flow to run the APU to the control Speed. The increase in the required Fuel Flow will result in an increase in EGT. The increase in EGT and in Fuel Flow can be monitored as a delta from the baseline trend.

A baseline trend for EGT and Fuel Flow should be established when the APU has minimum operating hours (20-50 hours.) If the baseline dramatically changes after an APU is overhauled, a second baseline should be established. The baseline trend should reflect the expected EGT and Fuel Flow levels as a function of an APU control parameter, such as Corrected Speed.

For new APU programs, the baseline for APU performance can be established by running multiple APUs in a test cell under known, controlled, stabilized conditions. Each APU test should be conducted over a range of Shaft Load (pneumatic and electrical load) with a known installation configuration. The data should be corrected for ambient conditions and for Shaft Load. The Shaft Load correction can be established by conducting tests under various known load conditions, if possible in the test cell, and deriving a relationship between no load and load. If possible, data should be collected during extended development testing to establish a change in EGT and Fuel Flow as a function of operating hours.

For existing APU programs, a baseline can be established from data collected from APUs that have remained on-wing for the expected life of the APU core. A Delta EGT can be established over the operating life of the APU. The difficulty in using field data is the lack of control over the data collection process. The data must be corrected for Shaft Load differences, ambient conditions, and Speed differences. In addition, the utilization of the APU may differ from aircraft to aircraft. One APU may be utilized on short routes, which will increase the APU cycles relative to the APU hours. Another APU may be utilized on long routes, which will decrease the APU cycles relative to the APU hours. An APU with a higher cycles-to-hours ratio is likely to degrade at a more aggressive rate than an APU with a lower cycles-to-hours ratio.

Data collected for APU core deterioration trending must be corrected for ambient conditions. The following equations are standard for correcting APU data for ambient conditions.

TABLE 2 - EQUATIONS FOR CORRECTING MEASURED PARAMETERS

Parameter	Description (units)	Calculation
EGTK	Corrected EGT (°C)	$[(EGT + 273.15) / \theta] - 273.15$
WFK	Corrected Fuel Flow (Kg/h)	$Wf / (\delta \sqrt{\theta})$
SHPK	Corrected Shaft Load (kW)	$SHP / (\delta \sqrt{\theta})$
RPMK	Corrected Speed (%)	$RPM / \sqrt{\theta}$
OILTK	Corrected Oil Temperature (°C)	$OILT - TINLET$
PBR	Bleed Pressure Ratio	$PT / PINLET$
LCDTK	Corrected LCDT (°C)	$[(LCDT + 273.15) / \theta] - 273.15$

where:

TINLET = Inlet Temperature (in degrees Celsius)

PINLET = Inlet Pressure (in psia)

PT = APU Bleed Discharge Pressure (in psia)

$\theta = (\text{Inlet Temperature} + 273.15) / 288.15$

$\delta = \text{Inlet Pressure} / 14.7$

$SHP(kW) = \text{Generator Demand}(kVA @POR) * \text{Power Factor} / (1 - \text{Line losses}) * \eta_{gen}$

LCDT = Load Compressor Discharge Temperature (in degrees Celsius)

EGT is a measured APU parameter and can be easily corrected to ambient conditions using the above equation. In addition to normalizing EGT, the value should be corrected for deviations in electrical (SHP) and pneumatic loads (ECS). Algorithms for normalizing EGT are proprietary to the APU manufactures and are not provided in this document.

Once the corrected and normalized value is calculated, the delta from the baseline should be calculated. For example,

$DELTA\ EGT = EGTK_{normalized} - EGT_{baseline}$

An example of a DELTA EGT trend is provided in Figure 2.

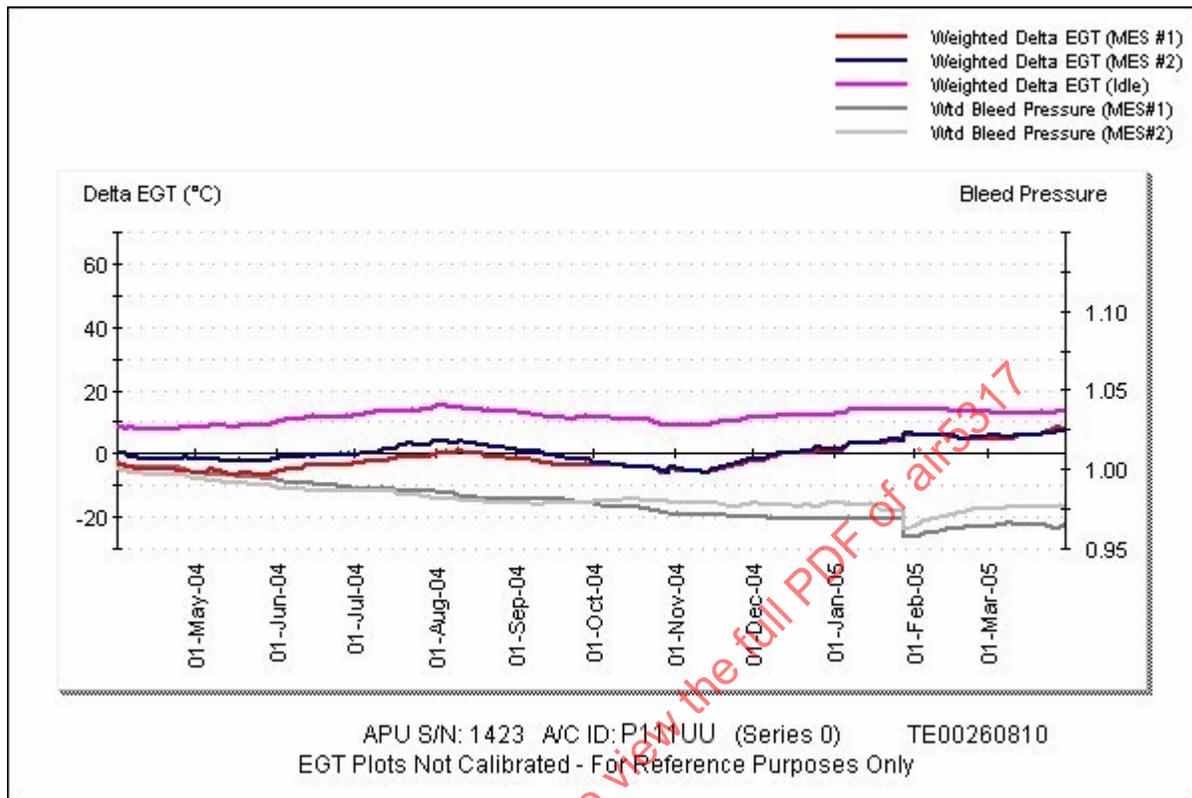


FIGURE 2- EGT TRENDING

Fuel Flow is not normally a measured APU parameter. If a Fuel Flow meter is not installed on the APU, Fuel Flow may be calculated from the Fuel Servo Current (mA), assuming that parameter is available from the APU controller. An increase in the Fuel Servo Current usually indicates an increase in the Fuel Flow required to run the APU to the control Speed.

The Electrical Load, or Shaft Horsepower (SHP), is not a measured APU parameter but can be calculated from the above equation using Generator Demand, Generator Efficiency, and a typical Power Factor. Generator Demand is typically a measured parameter. However, Generator Efficiency and Power Factor are not measured parameters and must be obtained from the APU manufacturer, the Generator manufacturer, or the aircraft manufacturer.

Data collected for trending should be normalized for variations in SHP. The equations for normalizing the data for SHP are generally derived from the APU manufacturer's performance model and are proprietary to the APU manufacturer. The performance model is a tool that has been calibrated and validated against engine test data and, thus, provides information on typical behavior of an APU for any considered operating condition. An algorithm for normalizing data for differences in electrical load can be derived by running the APU performance model and varying the electrical load while maintaining a constant pneumatic load. Likewise, the equation for normalizing data for differences in pneumatic load can be derived by running the APU performance model and varying the pneumatic load while maintaining a constant electric load.

5.4.3.1.2 Oil Temperature Trending

Oil Temperature trending is used to indicate a failure of the Oil Cooling System or a failure of the Generator. An increase in Oil Temperature may indicate a blocked Air/Oil Cooler. The blockage may be due to dirt or debris in the Air/Oil Cooler inlet. A baseline trend is not necessary for Oil Temperature trending but an alert limit should be established. For example, if the APU controller generates a fault at 130 °C, an Oil Temperature alert limit should be set at 120 °C, to allow maintenance time to schedule an inspection of the Air/Oil Cooler. An example of an Oil Temperature trend is shown below:

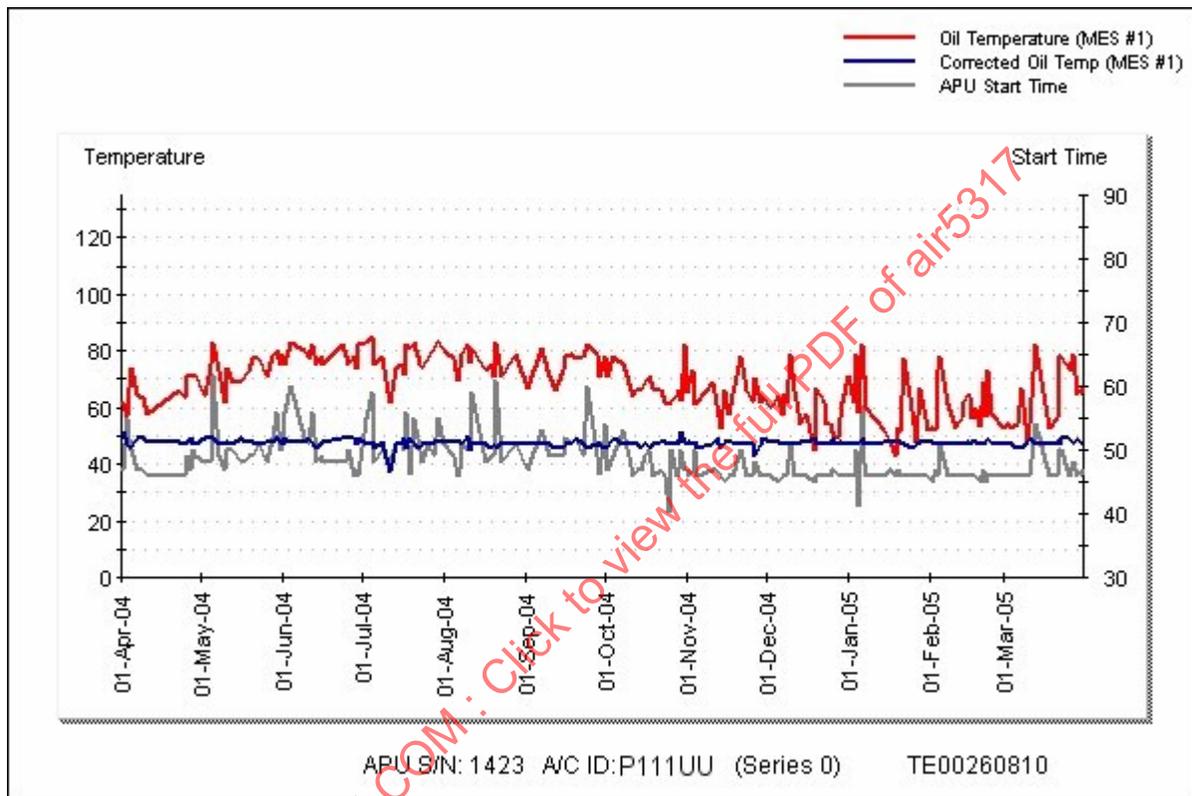


FIGURE 3 - OIL TEMPERATURE TRENDING

5.4.3.1.3 Time to Start, Time to RTL, and Time for MES Trending

Trending the time it takes for the APU to Start (to reach a specified Speed, such as 95%) or the time it takes for the APU to reach the "Ready To Load" (RTL) state (capable of supplying electrical and/or pneumatic power) can indicate APU degradation. For example, if the Time to Start, which normally takes 60 seconds for a particular APU, suddenly increases to 90 seconds, it is likely that the APU is experiencing performance degradation due to a deteriorated compressor or turbine or an open bleed valve. A significant increase in time may or may not be detected by the flight crew. Many operators move their flight crew between various aircraft as well as various fleets. Normal APU operation on one aircraft may not be normal on a different aircraft, leading to erroneous logbook entries and to missed anomalies. Trending the Start Time will show gradual increases that can be detected long before the flight crew will ever notice.

A deteriorated APU may take longer to start a main engine. Therefore, trending data during a MES may reveal that a deteriorated APU may take a longer time to start a known good engine.

5.4.3.1.4 Rundown Time Trending

Trending the Rundown Time, which is the time required for spool down from fuel cutoff to shutdown, can indicate an APU bearing or gear degradation or a mechanical failure resulting in deterioration or rubbing. For example, a normal APU may take 30 seconds to spool down to 0%. If the Rundown Time significantly decreases, a condition known as Rapid Rundown, the APU may have a failed bearing or gear, causing the rundown time to be abrupt and not smooth and consistent. A Rapid Rundown may not be detected by the flight crew since the crew is typically engaged in other activities at the time of APU shutdown. Therefore, trending the Rundown Time can help prevent an on-wing failure through early prognosis.

5.4.3.1.5 Oil Differential Pressure Trending

The differential pressure across oil filters, depending on the location of the oil filters and the configuration of the oil lubrication system, can be trended to determine bearing, gear, or generator failure. For example, an APU with two generators will typically have an oil filter downstream of each generator. Normally, the pressure decrease across the two filters should be similar. However, if the differential pressure across one filter increases while the differential pressure across the other filter does not, this may indicate that one generator is failing. The drawback to this analysis is that some contaminants will remain in the lubrication system (not captured by the oil filter or by the chip collector) and will cause the differential pressure to increase across the oil filter downstream of the non-failing generator.

5.4.3.1.6 Bleed Pressure Ratio Trending

The pressure at which pneumatic air is supplied from the APU to the aircraft system can be trended to determine load compressor degradation or failure. As degradation occurs, the ratio of the Load Compressor Pressure to the Inlet Pressure (Bleed Pressure Ratio) will gradually decrease. FOD will cause a rapid decrease in the Bleed Pressure Ratio. Bleed Pressure Ratio should be normalized to a reference bleed pressure to correct for variances in Speed and ambient conditions. The following represents a typical normalization equation:

$$\text{PBR} = (\text{PT}/\text{PINLET})/\text{PBR}_{\text{reference}} \quad (\text{Eq. 1})$$

5.4.3.1.7 IGV Monitoring and BCV Monitoring

The APU that supplies pneumatic bleed will close the Inlet Guide Vane (IGV) system or the Bleed Control Valve (BCV) to protect the APU from an EGT exceedance. This phenomenon is known as IGV Cutback or BCV Cutback. If the cutback occurred due to high EGT, the probable cause will likely be a deteriorated core or load compressor. However, if the cutback occurred without high EGT, the probable cause will likely be a failure of a bleed system component or a failure to supply fuel muscle pressure. Since one of the most common APU failure modes is the inability to supply pneumatic air, an APU health management system is one of the best sources for trouble-shooting. If the APU health management system indicates that an APU has high cycles and hours, the EGT is trending high, and IGV or BCV cutback is a frequent disruption, the recommendation will likely be to remove the APU. If the APU health management system indicates that the APU has low cycles and hours, the EGT is trending normal (at or near baseline), and the cutbacks are infrequent or previously non-existent, then the likely recommendation would be to further trouble-shoot the bleed system components.

Since cutback events tend to skew the smoothed, trended data, data collected during a cutback event should be excluded from the trend calculation. For example, if a 95/5 smoothing algorithm is used, then the data collected during a cutback event should be excluded from that smoothing calculation. The raw level should be shown to ensure that the event is not overlooked.

5.4.3.1.8 Load Compressor Temperature Trending

For an APU that supplies pneumatic air, the discharge temperature of the load compressor can be trended to determine load compressor deterioration or damage. As degradation occurs, the LCDT will gradually increase. A more rapid increase may be indicative of a compressor failure. LCDT should be corrected for ambient conditions.

5.4.3.1.9 Oil Consumption Monitoring

Oil Consumption monitoring is used to indicate high oil usage due to a deteriorated APU or due to an Oil System leak. The ability to perform Oil Level monitoring is dependent on the sensor used to indicate the Oil Level. Most APUs have an Oil Level Indicator installed, which provides a visual indication of whether the Oil System is Full or whether Oil should be added. The resolution of an Oil Level Indicator coupled with the manual effort to document how much oil is indicated and how much oil is added, make Oil Consumption monitoring difficult. If the APU has an Oil Level Sensor, which communicates to the APU controller and indicates Oil Level in quarts, the ability to perform Oil Consumption monitoring is greatly enhanced. However, Oil Consumption monitoring will require integration with aircraft maintenance actions so that the quantity of oil added can be compared to the quantity of oil sensed.

Oil Consumption monitoring is a requirement for ETOPS. See 4.46 for information regarding ETOPS.

5.4.3.1.10 Oil Debris Monitoring

Real-time Oil Debris monitoring can provide early detection of impending bearing failure, gear failure, or other component failures within the lubrication system. The same technology used for main engine Oil Debris monitoring can be applied to APUs. However, since an Oil Debris monitoring system is expensive and adds weight for the sensor and the signal-conditioning box, many operators may find that a real-time system may be difficult to justify financially. As technology evolves to where a separate signal-conditioning device is no longer needed, the additional weight of an Oil Debris monitoring system may become less of a barrier.

Various technologies exist for detecting particles within the lubrication system. Some of the existing capabilities include detecting non-ferrous and ferrous particles, counting the number of particles, and determining the size of the particles. The number of particles and the size of the particles can be trended to establish a timeline from initial debris detection to actual failure of a component. This trend can be used to schedule the APU for removal prior to failure.

Oil Debris monitoring can help minimize the secondary damage caused by a bearing or gear failure. However, since the existing damage as indicated by the presence of debris in the lubrication system will likely result in a major repair to the APU, the advantage of an Oil Debris monitoring system is the ability to schedule maintenance and potentially avoid a service disruption.

For more information regarding Oil Debris monitoring, see SAE AIR1828A.

5.4.3.1.11 Vibration Monitoring

Vibration monitoring can provide early detection of rotor imbalance, bearing degradation, combustor failure, pump failure, and gearbox failure. The same technology used for main engine vibration monitoring can be applied to an APU with appropriate modifications. Vibration monitoring can be applied to almost any failure mode that results in a change in frequency. However, developing the algorithms and the alarm limits to detect the change in frequency for specific components requires extensive development testing by the APU manufacturer in a representative installation and may be difficult to justify financially.

Reluctance to invest in Vibration monitoring has been fueled by past experience with poorly designed Vibration monitoring systems. Fortunately, the accuracy of Vibration monitoring has improved with new technology and with the placement and the frequency resolution of the vibration sensor. Sensors that are appropriately located to detect vibration in a specific frequency range for a certain component will provide the most accurate and early indication of a failure.

APU Vibration monitoring can be performed with a limited number of sensors. For example, two sensors could be installed in sensitive locations and algorithms could be developed to monitor for imbalance and for bearing frequency changes. Changes detected by Vibration monitoring should be correlated to Oil Debris Collection and Monitoring and a borescope inspection before further action is taken.

Vibration monitoring sensors lead to higher cost and weight. In addition, if the signal filtering function is not integrated with the aircraft or the APU controller system, a separate signal conditioning box is needed, which also leads to higher cost and weight.

For more information regarding Vibration monitoring, see AIR1839B.

5.4.3.1.12 Fuel Nozzle Trending

For APUs that have extensive data collection capabilities, the time from Fuel Manifold Filled to Light-Off (EGT rise) can be trended to determine if the fuel nozzles are clogged. Typically, the fuel manifold requires a certain amount of time to fill. The fuel manifold pressure will reach a peak value before EGT begins to rise, indicating Light-off. The time from peak manifold pressure to EGT rise will increase if any of the fuel nozzles are clogged.

5.4.3.1.13 Additional Trending

Additional algorithms and limits that can be developed and used for trending are:

- Deviation of electric starter current (or voltage) from the expected E-I curve during APU start.
- Monitoring of Speed and EGT during APU Start from cranking to RTL.
- Increase in Time to starter cut-out.

5.4.3.2 Filters, Smoothing Algorithms, Statistical Analysis, and Compression

A filter should be applied to the APU data to reduce the scatter due to normal statistical deviations in the data measurements. The filter selected should be sensitive to the difference between an isolated point and a shift in the data. For example, data recorded during IGV Cutback will likely fall outside the normal distribution of the data. However, data recorded during IGV Cutback is significant and needs to be retained.

In addition to correcting the APU data for ambient conditions and for filtering for statistical deviations, a smoothing algorithm should be applied to the APU data to further reduce the scatter. A common smoothing algorithm is the 95/5 weighting, in which the new trend point is calculated from 95% of the previous value and 5% of the new value. For example,

$$\text{DELTA EGT}_{\text{smoothed}} = 0.95 * \text{DELTA EGT}_{\text{prior}} + 0.05 \text{ DELTA EGT}_{\text{new}}$$

Another common smoothing algorithm is to trend the data on a 10-day or a 30-day rolling average:

$$\text{DELTA EGT}_{\text{smoothed}} = (\sum \text{DELTA EGT}_n) / 10, \text{ where } n= 1 \text{ to } n=10 \text{ (useful for start data)}$$

$$\text{DELTA EGT}_{\text{smoothed}} = (\sum \text{DELTA EGT}_n) / 30, \text{ where } n= 1 \text{ to } n=30$$

Statistical analysis can be incorporated into APU health management program to help mitigate the normal fluctuations in the data measurements and to establish deviations from the trend that require attention. For example, action may not be necessary until the Oil Temperature trend exceeds the normal standard deviation. The best curve fit of the data should be determined when establishing the baseline trends for each parameter. The best curve fit through the data may not be linear.