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

RATIONALE

This document is being cancelled because there has been no progress since 2003 and the committee has no one to lead a WG to update it. Engine OEMs and Certification Authorities are concerned it could be used to develop a new system against that would no longer meet current standards.

NOTICE

This document has been declared "CANCELLED" as of September 2011. By this action, this document will remain listed in the Numerical Section of the Aerospace Standards Index.

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INTRODUCTION

The idea of engine monitoring is not new. For years, military aircraft have used cycle counters, and pilots in military and commercial sectors have manually recorded cockpit parameters in order to enable maintenance and engineering personnel to detect signs of trouble. Changes in maintenance philosophies in the 1970's, from hard-time to on-condition, were accompanied by a requirement for a more sophisticated monitoring capability. Technological advances, made possible by the rapid development of digital electronics, have enabled comprehensive, automated monitoring to become the norm.

In recent years, increasing priority has been given to the development of life usage monitoring by both commercial and military operators. This action has been motivated not only by the continuing need to prevent failures but also to reduce life cycle costs through more effective utilization of engine parts. In military operation, the diversity of mission profiles amplifies the need and complicates the task of life usage tracking. However, the same basic requirements for monitoring life usage apply to both commercial and military operators. Monitoring includes on-board data collection, on-board processing, ground-based processing and data management.

Because of user interest and need, SAE Committee E-32 has developed this Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines.

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1. SCOPE:

The effectiveness of Engine Life Usage Monitoring and Parts Management systems is largely determined by the aircraft-specific requirements. This document addresses the following areas:

- a. Safety
- b. Life-limiting criteria
- c. Life usage algorithm development
- d. Data acquisition and management
- e. Parts life tracking
- f. Design feedback
- g. Cost effectiveness

It primarily examines the requirements and techniques currently in use, and considers the potential impact of new technology to the following areas:

- a. Parts classification and control requirements
- b. Failure causes of life-limited parts
- c. Engine life prediction and usage measurement techniques
- d. Method validation
- e. Parts life usage data management
- f. Lessons learned
- g. Life usage tracking benefits

1.1 Purpose:

SAE ARP1587 provides general guidance on the design considerations and objectives of monitoring systems for aircraft gas turbine engines. A major function of these Engine Monitoring Systems is to monitor the usage of life-limited parts in order to maximize available life and to enhance aircraft safety.

The purpose of this document is to review the current approaches to Engine Life Usage Monitoring and Parts Management. The document also serves to provide a summary of the many varied requirements of aircraft turbine engine life usage monitoring and parts management (see Appendices A and B) and a description of the means by which these requirements can be achieved more effectively through the use of engine monitoring systems.

1.2 General Considerations:

- 1.2.1 Life Usage: The failure of an engine part may be due to inherent causes such as the accumulation of damage due to cyclic and steady-state stresses resulting from temperature, speed, differential pressure, and vibration. In many cases, the effects of these stresses can be estimated and, therefore, the amount of life used or life remaining in a part can be approximated with reasonable confidence.

For these inherent failure causes, the approach generally used to determine the initial design life estimate of an engine part is to:

1.2.1 (Continued):

- a. Submit the proposed design to heat transfer, stress, and life analyses
- b. Subject sample parts to rig testing
- c. Subject production standard engines to full-scale simulated service endurance tests

These steps are supplemented by further analyses in the laboratory and flight test investigations to confirm or modify initial design estimates of failure resistance and operating environment, respectively.

Life usage monitoring depends on two key aspects:

- a. Life Prediction, whereby the finite life is determined against a life criteria (creep life, LCF life, etc.)
- b. Life Measurement, by which the rate of life consumption is determined

Analytical techniques are widely used to predict the service life of gas turbine engine parts. However, the actual life of parts in service depends upon the severity of cyclic or steady-state operation or both. In the absence of quantitative life usage data, the initial life usage assumptions are necessarily conservative to assure engine integrity. These initial assumptions are later re-evaluated using data acquired primarily from lead-the-fleet sampling programs. This includes, but is not limited to, subjecting service run parts to rig tests.

The simplest method of measuring life usage is to record engine running time. A slightly more sophisticated approach is to record both running time and mission profile, which recognizes that some flights are more severe in terms of fatigue than others. More complex methods include use of airborne data acquisition systems, which provide complete usage records for a fleet of aircraft, and microprocessor-based Engine Monitoring Systems capable of calculating life usage in real time. Clearly, the chosen degree of sophistication depends on the required life measurement accuracy and this, in turn, will typically be determined by perceived cost savings and safety requirements. The optimum is to be able to measure, on an engine-by-engine basis, all parameters which impact life consumption and, using accurate life algorithms, determine usage for individual fracture critical components. To gain a worthwhile benefit, the life prediction and life measurement systems adopted need to have a similar degree of accuracy.

1.2.2 Parts Management: During the life of a gas turbine engine, occasional removals from service are required to facilitate scheduled and unscheduled repair/overhaul.

In order to minimize engine down-time during repair, parts are often replaced with new or repaired parts conforming to equivalent or improved design standards. Consequently, parts that are removed for rework or inspection are sometimes re-allocated to other engines undergoing repair. Thus, after several engine rebuilds, the constituent parts can be very different from the initial complement supplied by the manufacturer. For modular engines, the ability to exchange complete modules tends to compound this further.

1.2.2 (Continued):

This degree of interchangeability demands the use of well organized asset management systems to track the utilization of life-limited parts. These systems may range from simple card index systems to computer-based information management systems capable of interfacing with airborne engine monitoring systems via specialized data transfer equipment.

2. REFERENCES:

2.1 Applicable Documents:

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

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

ARP1587	Aircraft Gas Turbine Engine Monitoring System Guide
AIR1873	Guide to Limited Engine Monitoring Systems for Aircraft Gas Turbine Engines

2.1.2 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-STD-1783

2.1.3 Other Publications:

RB.211 Propulsion Systems Manual, Chapters 70-01-10 (Maintenance) and 5-10-01 (Time Limits)
(Available from Rolls-Royce)

3. PARTS CLASSIFICATION AND CONTROL REQUIREMENTS:

Engine parts that have finite lives are identified early in the engine design process. If these parts were allowed to continue indefinitely in service, they would eventually fail at some point in time, possibly causing significant damage to the engine or airframe. These parts are accordingly given service life-limits that are not to be exceeded in order to assure safe operation.

A Failure Modes, Effects, and Criticality Analysis (FMECA) is used to determine the sensitivity of an engine to parts failures. This FMECA is part of the Reliability Centered Maintenance (RCM) process. If the failure of a life-limited part is likely to affect safety of flight, it is then classified as a "critical life-limited part". Parts that rotate and are subject to significant Low Cycle Fatigue (LCF) are generally classified as critical parts. Similarly, if the FMECA shows that the failure of a life-limited part does not affect safety of flight but nevertheless is likely to seriously affect engine performance, reliability, or operating costs or both, it is then classified as a "non-critical life-limited part".

3. (Continued):

Critical life-limited parts for a particular engine type would generally remain common for single and multiengine aircraft applications. However, parts that are listed as noncritical for a multiengine aircraft may be listed as critical for a single-engined aircraft.

Most engine parts, life-limited or otherwise, require inspection throughout their service lives to check for signs of damage due to cracks, impact, corrosion, erosion, etc. Moreover, life-limited parts require strict adherence to rigorous control procedures to ensure that no component continues in service beyond its safe life-limit. For critical life-limited parts, regulations require that each part be traceable throughout its service life history and that complete inspection records be maintained. Therefore, each critical life-limited part is marked accordingly with a unique serial number for identification.

4. FAILURE CAUSES OF LIFE-LIMITED PARTS:

An engine part is life-limited if it is likely to fail through extended usage under normal design operating conditions. In general, safe life-limits are imposed across the fleet if the failure mode is inherently related to engine usage. Inherent failure causes can include one or any combination of the following:

- a. Low cycle fatigue
- b. High cycle fatigue
- c. Thermal fatigue
- d. Creep

In addition to these inherent failure causes, other causes can lead to the premature failure or rejection of a component. These non-inherent causes are mostly related to external factors not normally encountered by all engines in the fleet. These causes include:

- a. Foreign object damage
- b. Handling damage by operators
- c. Corrosion
- d. Erosion
- e. Fretting
- f. Rub, wear, friction
- g. Material defects
- h. Manufacturing defects
- i. Maintenance mishandling
- j. Acoustics/operating environment

In many cases, premature failures can be avoided by better component design, engine/component health monitoring and detailed inspections. Within the scope of health monitoring, fault detection and diagnosis is not discussed further in this document (see AIR1873).

4.1 Low Cycle Fatigue (LCF):

Low cycle fatigue is normally associated with significant stress excursions caused by repeated cycling between different stress levels within the material's elastic limit, eventually leading to failure. It is widely agreed that LCF failure occurs in less than 10^5 cycles, where a cycle is usually defined as an excursion from min to max stress and back to min. Excursions within the min to max stress range will typically occur more frequently during a component's operating life and, while not as significant as a complete cycle, these partial cycles nevertheless contribute to LCF and should, therefore, also be measured.

LCF stresses can be caused by centrifugal loads, torsional loads, gas pressure loads, and thermal gradients; each can act independently or in combination with one another, and produce the net stresses for a specific engine operating condition. The majority of rotating parts, in particular shafts and disks, are subject to LCF.

Non-rotating parts such as pressure vessels, mounts, and supporting structure also experience LCF stresses from recurring loads due to pressures and maneuvers/inertia.

For most rotating parts, the predominant load is centrifugal and, therefore, RPM dependent. Because centrifugal load is proportional to RPM^2 , the stress change due to an RPM change at or about the takeoff rating is substantially greater than that due to an equal RPM change at or about engine idle. Correspondingly, throttle movements in higher RPM bands are substantially more damaging than comparable throttle movements in lower RPM bands. Consequently, military engines usually exhibit higher LCF usage rates than commercially operated engines because of the large number of high-power throttle movements required for military aircraft.

4.2 High Cycle Fatigue (HCF):

Compared with LCF, high cycle fatigue is caused by lower stress amplitudes but at a much greater frequency ($>10^5$ cycles). Typical causes of HCF are vibration and flutter. An HCF stress is often superimposed on an LCF stress and is accounted for by applying a percentage factor to the LCF damage, thus further reducing the overall life. At the design stage, efforts are made to ensure that HCF will not occur under normal operations, or at the very least, characterize it sufficiently to ensure that the stresses will not be the life limiting failure mode of any component. Typically, this involves ensuring that components do not resonate either alone or through interaction with neighboring components. Knowledge of modal vibrations is obviously key in this task. However, aircraft, especially military, often operate in different roles and regimes than were originally defined. Thus, HCF can be unknowingly introduced into day-to-day operations. While HCF tends not to initiate cracks, a flaw in a component (typically a blade) could quickly propagate to failure under the effects of HCF. Understanding HCF failure modes requires a thorough knowledge of component stresses (both steady-state and cyclic), temperatures, and material properties. Although HCF is well recognized, it is not well understood, is difficult to model and measure, and its detection using on-board engine monitoring systems is currently under development.

4.3 Thermal Fatigue:

Thermal fatigue stresses are induced by thermal gradients and differential expansions. Thermal fatigue is similar to LCF in that relatively large stress levels can be induced, which can augment or negate the mechanically originated stresses in a part. The largest thermal stresses usually occur during transient temperature conditions as, for example, during engine start-up or rapid power changes. Accelerations and decelerations are the prime contributors toward thermal fatigue because, in these conditions, the rate of change of the gas temperature is rapid and generates high thermal gradients, particularly in hot section parts.

Many engine parts directly experience high gas temperatures, either by total immersion in the gas stream as in the case of turbine blades and vanes, or locally through partial immersion as in the case of high pressure compressor and turbine disks. In either case, thermal gradients will occur, which cause thermally induced stresses. This is because the geometric configurations of many engine parts cause different heating and cooling rates that, in turn, cause differential expansions within the part. For this reason, thermal fatigue is sometimes seen as a subset of LCF but, in this document, it is kept separate for clarity.

4.4 Creep:

For aircraft that fly mission profiles with long cruise segments and/or long periods at high power settings, creep can become a more life-limiting criterion than LCF. In commercial airlines, creep is generally not a problem in cruise but would be more prevalent during the takeoff and climb transients.

Under application of a sustained load at elevated temperatures, metals can show a gradual but permanent dimensional change. This is the result of slip occurring along crystal structures in the crystal itself, together with flow of the grain boundary material. The ramification of this process is the possible change in dimensions of a turbine component, to the point where the load bearing area of the component can no longer withstand the peak operating stresses. If allowed to continue unchecked, this condition will result in failure.

It is generally agreed that when plastic strains are introduced, the operating life of the component depends on the plastic strain and the high temperatures in which these strains are experienced. However, the maximum operating temperature is the single most important variable. Increasing the maximum temperature for a given temperature range will significantly reduce the remaining life to failure. For example, at elevated metal temperatures, the creep life of a part can be halved for a metal temperature increase of only 15 °C. Time duration at maximum temperature is another variable that greatly impacts creep life. As with HCF, common design practice is to eliminate creep as a life limiting factor during normal operation. Unlike HCF, however, creep is well understood, more easily modeled and predicted and therefore more easily eradicated as a life-limiting feature.

5. ENGINE LIFE PREDICTION AND USAGE MEASUREMENT:

Since the failure of certain engine parts is, at the very least, hazardous and potentially catastrophic, the application of effective failure prevention methods is imperative. A traditional methodology is to correlate engine life usage with time in normal operation to derive the time before next scheduled removal. At overhaul, some engine parts may be removed for cause, while others may be removed because of the statistical probability that failure will occur before next overhaul. These statistical probabilities are necessarily weighted for safety reasons; and therefore, parts are often removed with useful life remaining. Moreover, life drivers tend not to correlate closely with operating time. Thus, for reasons of maintaining safety and improving economy, the development of life usage monitoring systems incorporating accurate algorithms is necessary to determine the appropriate discard time for critical and non-critical components, particularly for military applications where the flight profiles can vary significantly.

5.1 Design Methodology:

As mentioned earlier, common design practice is to eliminate HCF and creep as life-limiting factors for normal operations. Abnormal operation, however, such as failure-induced flutter, over-temperatures or over-speeds can cause HCF or creep to become the life limiting factor. For this reason, many modern condition monitoring systems are designed to detect these abnormal conditions and alert the maintenance personnel. The remaining life-limiting factor, LCF, cannot be avoided as it occurs during normal operation. The approach normally used by engine manufacturers to verify the longevity of a life-limited part for a new engine design includes:

- a. Definitions of material properties and their distributions.
- b. Stress and heat transfer analyses of the proposed design using computer modeling techniques having various degrees of sophistication, including the estimation of pressure and temperature environments and the stresses they impose. These data are then used together with correlated test data to produce an initial life prediction.
- c. Bench, rig, and spin pit tests to verify the stress analysis data and to confirm life estimates. However, the difficulty of simulating real engine conditions and the lack of statistical significance of the number of test articles places more reliance on analytical methods.
- d. Instrumented bench and flight development engine testing to verify the estimated environmental conditions and stress levels.

The safe life of a critical life-limited component is the estimated life to first measurable crack. It can also be expressed as a proportion of the life for a crack to propagate to a critical crack size. The data provided by stress analysis are combined with empirical Stress/Cyclic (S/N) data, range-mean relationships and cumulative damage laws to produce an estimate of life to first crack. Rig and engine testing are helpful in validating fatigue life-limits and in determining whether life-limit adjustments are necessary. This analysis continues after an engine is in production so that parts life data are accrued ahead of service experience.

5.1 (Continued):

This work has been put on a more quantitative basis through the use of the science of fracture mechanics. The fact that all alloys contain impurities, flaws and defects to some extent forms the basis for fracture mechanics. The theory of fracture mechanics is that these impurities can develop into cracks that grow as a function of crack type and fluctuations in repetitive stress.

A crack in an engine part is stable up to a certain critical length, at that point it propagates to failure. The critical length depends on the particular material, but is always inversely proportional to the square of the stress. Thus, for an increase in stress, there is a corresponding decrease in critical length.

A stress intensity factor is used to relate the gross area or overall stress field to the physical geometry of the crack. Using the stress intensity factor, the material properties are generated which give the amount of crack growth for each applied cycle. This growth can then be summed to permit a calculation of crack size at any time in the life of an engine part. The critical condition occurs when the stress intensity factor reaches the fracture toughness value or the vibratory threshold value, at which point the crack will become unstable and propagate through the part.

Fracture mechanics relies on Non-Destructive Examination (NDE) to find cracks before engine assembly and during engine inspections. To verify defect size and distribution, quantification of sub-surface defects is done before engine development. Applying fracture mechanics to the design of an engine part, based on the part having a sub-surface defect just below the level that can be readily detected with accurate NDE techniques, then enables the life of the part to be calculated. The cycles remaining before the critical condition is reached can then be calculated. Based on this calculation and verification by test, the re-inspection and/or retirement of a part can be scheduled. Records must be kept of cyclic usage in service.

5.2 Derivation of Service Life Usage:

At initial production, the widely used method of determining the service life of life-limited parts is based on estimates of engine usage rates for mission type and mission mix. Analytical predictions are used to set the inspection interval and the retirement fatigue life. Because it is not currently possible to detect or measure cracks in most parts while installed in the engine, the calculated crack propagation phase is usually not included in the estimate of fatigue life. The fatigue life of critical parts is thus based on time to crack initiation and must therefore be reliably established in order to avoid not only uneconomical premature retirement but also failure during engine operation. This is accomplished by evaluation of high time parts and refinement of analytical techniques. These parts are taken from bench development engines, accelerated service test engines, and production engines and are sometimes tested to destruction. These test programs can be used as evidence in support of life-limit recommendations that are reviewed periodically and, if appropriate, adjusted accordingly. With analytical support, favorable test and service experience may lead to life extensions. Conversely, if experience indicates that life-limits are too high, they may be reduced.

5.2 (Continued):

Recommendations for life usage monitoring are based upon the need to accumulate data on service history and associated mission profiles for specific engine parts. Such data banks enable the assessment and correlation of life prediction with actual engine usage. This approach usually involves the recording and analysis of engine usage data during service operation. This can result in the adjustment of service lives and inspection intervals. This procedure is already practiced for military engines and provides a monitor on fleet trends should service usage change.

Recent advances in analytical techniques, coupled with the advent of lightweight on-board computers, have created the conditions for a more accurate and individual treatment of engine life usage prediction.

5.3 Mission Profile Analysis:

Missions are composed of common basic modes including engine start-up, taxi, takeoff, climb, cruise, landing, and shut-down. Other elements may need to be considered if the engine is used for VTOL or thrust reversing. Engine life usage must be determined for each flight mode. The life usage during each of these flight modes will depend on the type of aircraft and whether it is performing in a military or commercial role.

Mission profile analysis is typically performed by:

- a. Recording the relevant in-service engine and aircraft parameters to refine the initial theoretical mission profile.
- b. Reconstructing, analytically, the mission ingredients until they have a high statistical probability of fitting a large percentage of actual mission profile data, including extreme points.

The collection of data for different classes of aircraft can have additional benefits including the establishment of design goals for new engine types.

5.4 Life Optimization:

Most engine manufacturers have service life extension programs for life-limited parts. This is achieved by re-analysis of stress data, inspection of high-time service parts, and sampling and testing of parts from lead-the-fleet engines parts where available.

The initial life of a particular engine part is declared when the predicted safe life has been substantiated through detailed analysis, rig testing or service sampling programs or both. If increases to life are established, the manufacturer amends his overhaul manual to reflect this.

5.4 (Continued):

If engine operation is less severe than that on which the initial life-limits are based, then benefits, in addition to the general 'life growth' program of the engine manufacturer, can be enjoyed. Both hourly and cyclic life benefits can be realized for the components that reach their peak stress levels during takeoff. By using an appropriate life factor, agreed to by the manufacturer for the specific engine power level, extended use of critical life-limited parts can be achieved. Conversely, where an engine is subjected to high stress levels, for example, crew training or operating above maximum rated power, the critical part life usage must be increased in accordance with the rules of the engine manufacturer and appropriate regulatory agencies.

Examples of the application of life adjustments for commercial airline operators of one particular engine type are:

- a. When takeoff power is limited to between 90 and 95% of normal takeoff rated power (i.e., 5 to 10% de-rated), a rotating component life factor of 0.93 may be applied to both the cyclic usage and the hourly usage, thus providing a life dividend to the operator.
- b. When the actual takeoff power used is greater than the normal takeoff power rating, it is necessary to record this flight as being equivalent to six cycles at normal takeoff power rating. (Note that each OEM will recommend their own penalty, for their particular engine type, to the airline operators.)
- c. Conversely, when rotor speed or temperature limits are exceeded, operators are obligated to remove the engine for dimensional or metallurgical inspection. Further usage of affected parts is dependent on the degree of limit exceedance, duration of event and inspection findings. Parts may be returned to service at a decreased remaining life or scrapped depending on the manufacturer's recommendation.

To benefit from using reduced power takeoffs, it is necessary to keep detailed records of the power used for each flight. This can be an enormous data capture task for any recording system, but lends itself readily to analysis using an engine monitoring system. This approach requires the agreement of the engine manufacturer.

5.5 Life Usage Measurement

With current, mature technology, it is feasible to measure engine life usage with engine monitoring systems. However, it is necessarily over-conservative because many approximations and assumptions are made. New and emerging technology, such as fast on-board computing capabilities and artificial intelligence, enables a much more accurate measurement to be made. This section discusses the requirements for computing engine life usage during flight in real-time or post-flight in a ground station using recorded flight data.

- 5.5.1 Low Cycle Fatigue: Any discussion of LCF life usage monitoring would be incomplete without mentioning the stresses caused by thermal gradients, differential expansions and centrifugal loads. Currently, work in the area of thermally induced LCF represents a major part of routine stress and life analysis of rotating parts. However, for simplicity, this document concentrates on mechanical LCF

5.5.1 (Continued):

If it is assumed that the most damaging stress levels in an engine part are primarily due to mechanical effects (that is, centrifugal forces due to rotor speed), then the main life usage parameter for that part is mechanically induced LCF. This would be true for a fan disk where thermal effects are negligible in comparison to centrifugal stresses. Figure 1 shows a schematic of the process used to determine the life usage of an engine part that is subjected to mechanically induced LCF. This procedure requires the use of an appropriate mathematical function that converts a speed cycle to fatigue, and a cycle counting technique that recognizes the major and minor speed cycles. The equivalent reference count is then calculated.

A reference cycle is usually defined as an excursion from zero to maximum RPM and back to zero as depicted in Figure 2. The reference line in Figure 2 defines the relationship between equivalent usage in reference cycles and peak rotor speed for a given zero-max-zero rotor speed excursion. Other lines define the usage in equivalent reference cycles for non-zero minimum rotor speeds. The usage for any one cycle can, thus, be computed.

In the very simple rpm/stress profile shown in Figure 3A, it is necessary to extract the major and minor cycles (Figure 3B) in terms of equivalent reference cycles (Figure 3C).

There are several methods for extracting the cycles from a LCF stress profile, but the Rainflow method is the most widely accepted and successful method. The success of the Rainflow method evolves from its ability to count all cycles, and to identify the minimum and maximum stresses and strains for each cycle. The variation of mean stress as well as the variation of the stress/strain range must also be identified. This is conveniently achieved using the Rainflow method, which calculates the mean of each cycle by averaging the highest and lowest peaks of each cycle.

To understand the principle of the Rainflow method, the time-history stress or strain profile is turned through 90° so that the time axis is vertically downwards (see Figure 4). The profile is now imagined to be a series of pagoda roofs, falling to the ground. The rainflow must stop if it begins at a peak that is a local maximum, and if it falls on another maximum peak that is more positive than the originating peak, as shown in case /1/. Similarly, if the rainflow begins at a peak that is a local minimum it must then stop when it falls on another minimum peak that is more negative (case /2/). The rainflow must also stop if it meets the rain from a roof above (case /3/).

For mechanically induced LCF, rotor speed alone is sufficient to determine the usage. However, cycle counting methods more sophisticated than the Rainflow method are needed to deal with thermally induced LCF because of the possibility of negative stresses, although Rainflow still works if the parameter used is calculated stress.

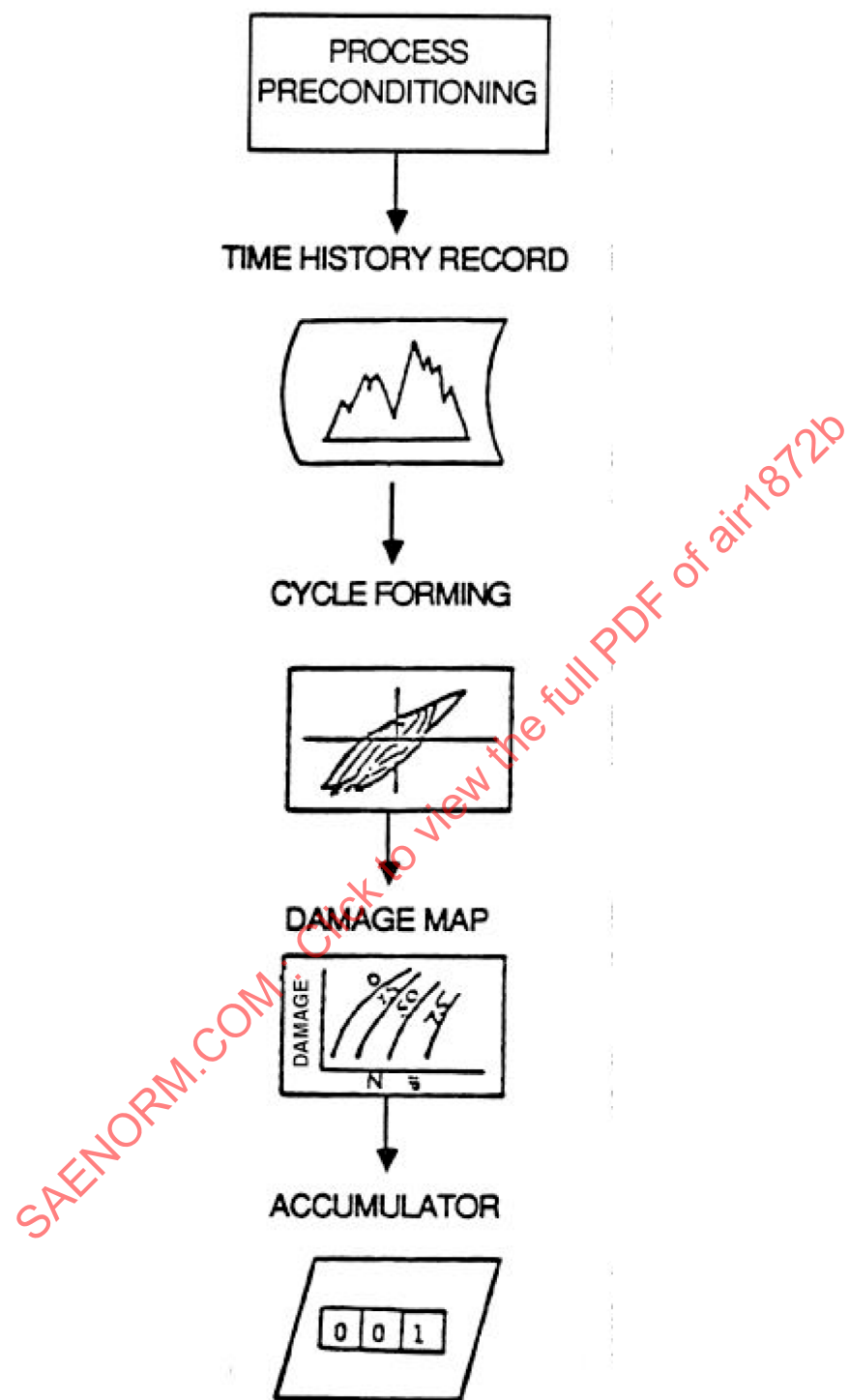


FIGURE 1 - Mechanical LCF Algorithm

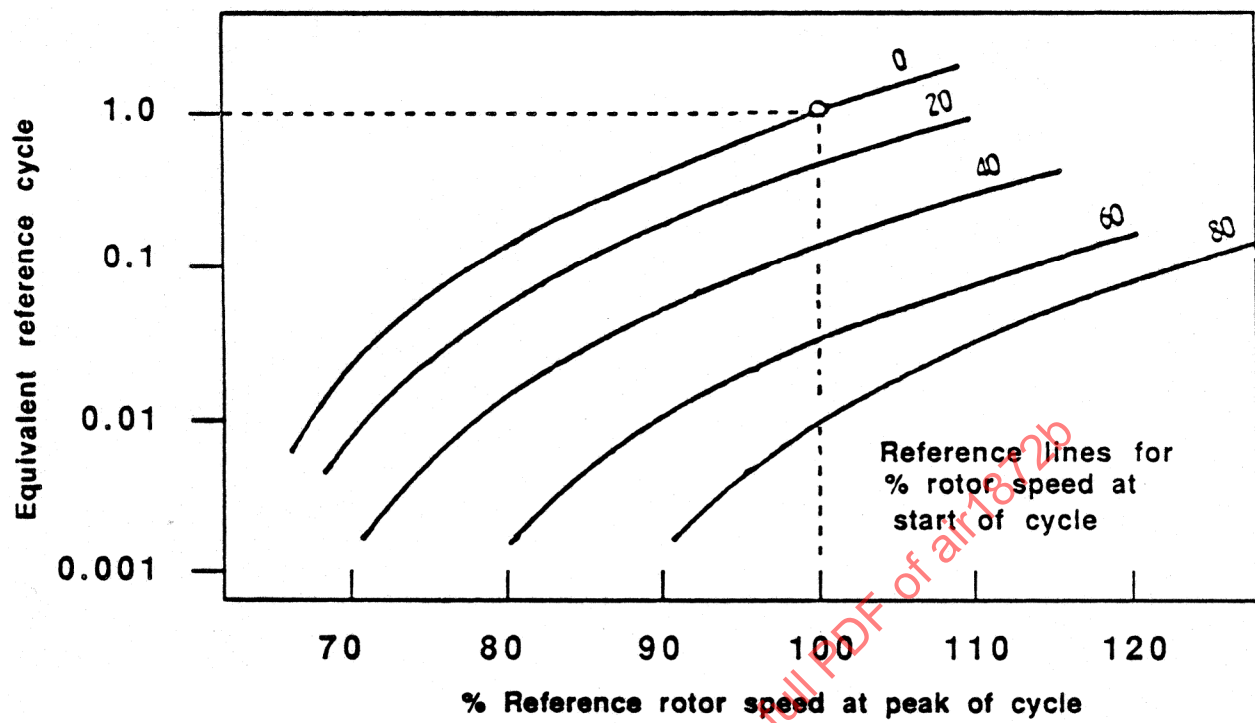


FIGURE 2 - Typical Map Structure

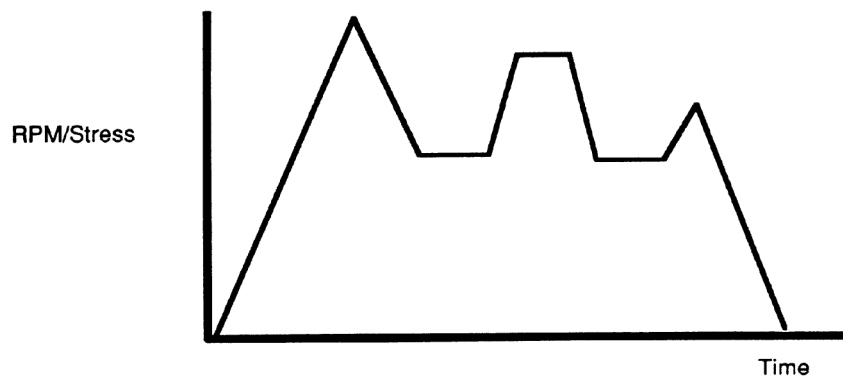


FIGURE 3A

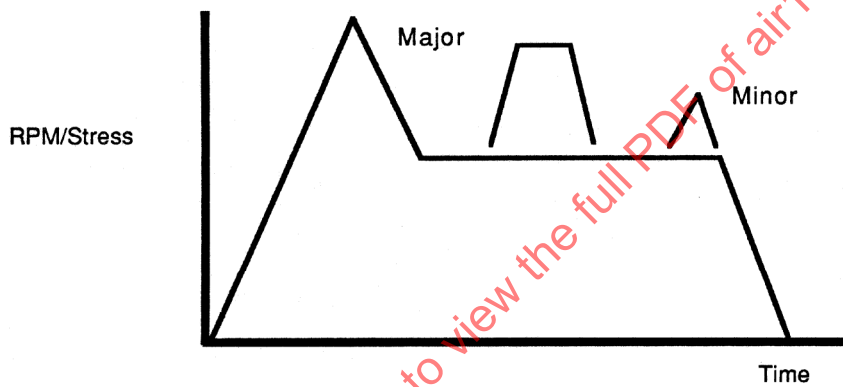


FIGURE 3B

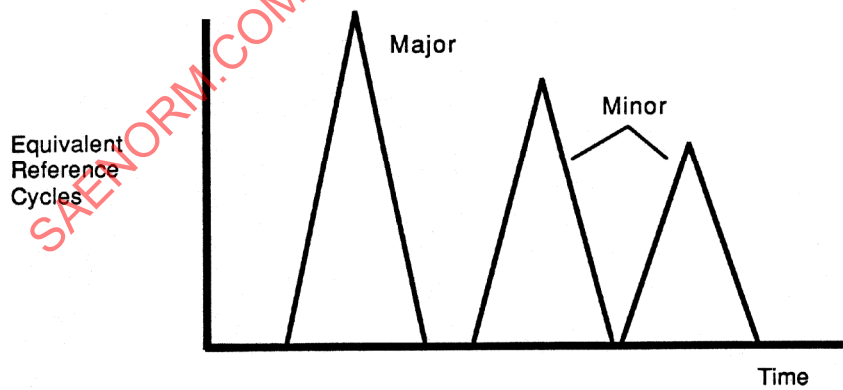
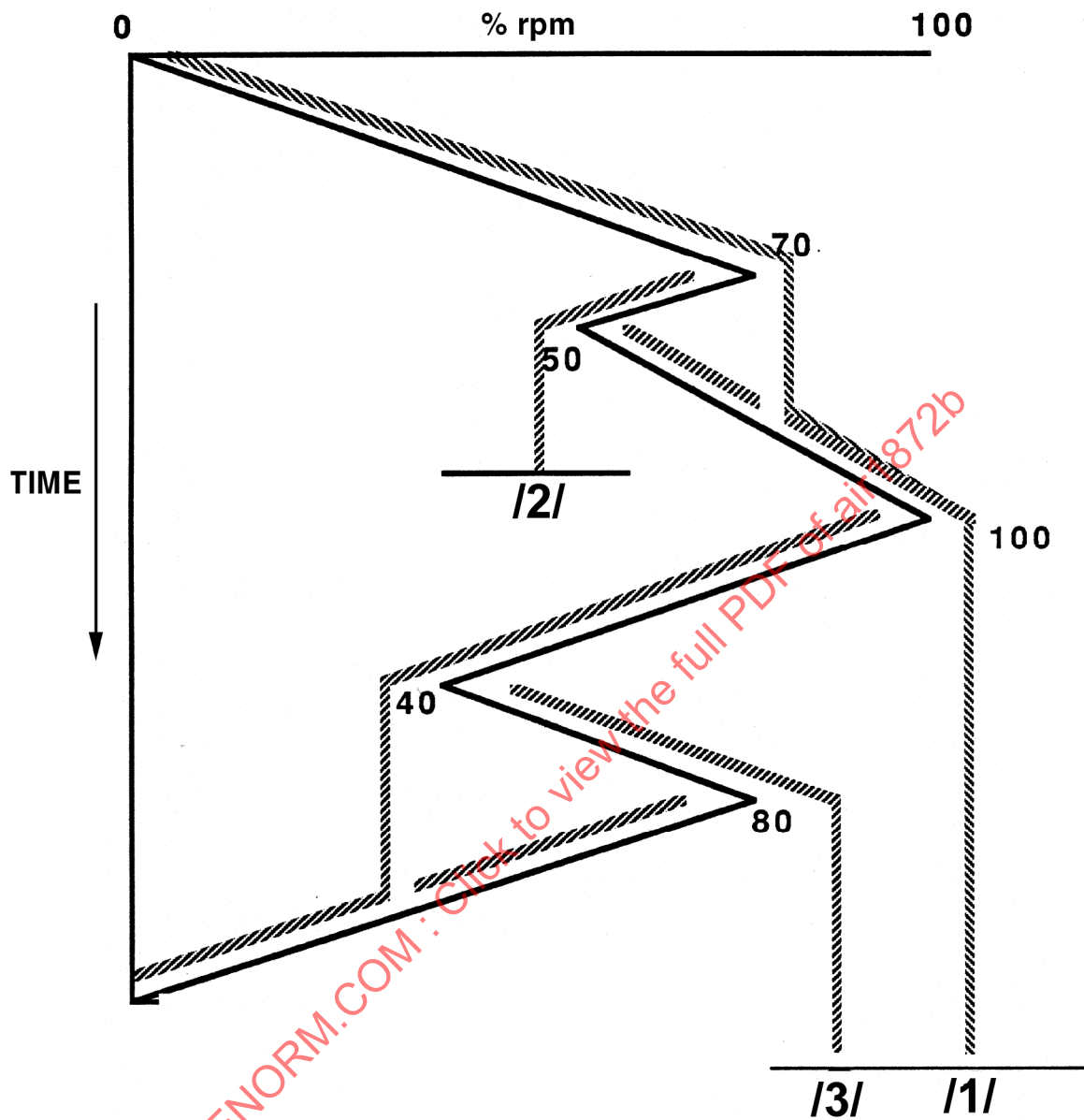


FIGURE 3C

FIGURE 3 - Major and Minor Cycles



/1/ = MAJOR = 0 - 100 - 0

/2/ = MINOR = 70 - 50 - 70

/3/ = MINOR = 40 - 80 - 40

FIGURE 4 - Rainflow Method

- 5.5.2 Thermal Fatigue: Thermal fatigue is characterized by rapid changes in stress/strain due to mechanical and thermal loading on relatively thin material sections. This situation occurs during rapid engine throttle transients where large temperature gradients exist due to non-uniform thermal storage capacity (wall thickness) and non-uniform heat flux on the surface.

Accurate life prediction, therefore, requires accurate knowledge of the metal temperatures during both steady-state and transient operations. These data can be acquired during engine testing and from heat transfer predictions. Additionally, data from extensive laboratory LCF specimen tests, conducted over the engine operating ranges of transient induced temperatures and strains, is required.

Life prediction and usage measurement, in each case, is condensed to a Miner's Rule summation for several types of recurring and damaging cycles. A unique damage factor is assigned to each cycle that is established by specimen tests. Therefore, the usage measurement process for thermal fatigue limited components is similar to that for LCF limited components.

- 5.5.3 Creep: Establishing creep life limits provides the 100% life-limit reference to be used in the monitoring system for a turbine component. The percentage of life usage then is a function of the stress, temperature, and the length of time at various stress levels. Analysis and development tests provide the necessary correlations, based on temperature and rotational speed, to determine the stress and strain levels. The precise method utilized in combining partial percentages, that is, the percent of life used during different operating segments of each flight, can vary depending on the basic method of combining increments.

The chosen method will depend on the type of engine operation being considered. All methods will be in terms of the stress levels resulting from engine speed and time at operating temperature. Approaches used for military missions will focus primarily on creep as a function of cyclic fatigue stress factors related to speed. On the other hand, commercial type operation will require approaches focused more towards strain that relates to accumulated time at temperature.

A typical function for estimating percentage life usage for a turbine component is presented in Figure 5. A figure such as this would be utilized for the most critical component in any turbine section (low pressure turbine, high pressure turbine, etc.). Creep life increases with decreasing turbine temperature as depicted in Figure 5.

- 5.5.4 Limit Exceedance/Incident Recording: Although not directly connected, limit exceedance recording constitutes an important aspect of life usage monitoring of engine components. Most life usage algorithms only cater for normal engine operating conditions. It is crucial to monitor the behavior of the engine for limit exceedances because they seriously impact the service life of a component.

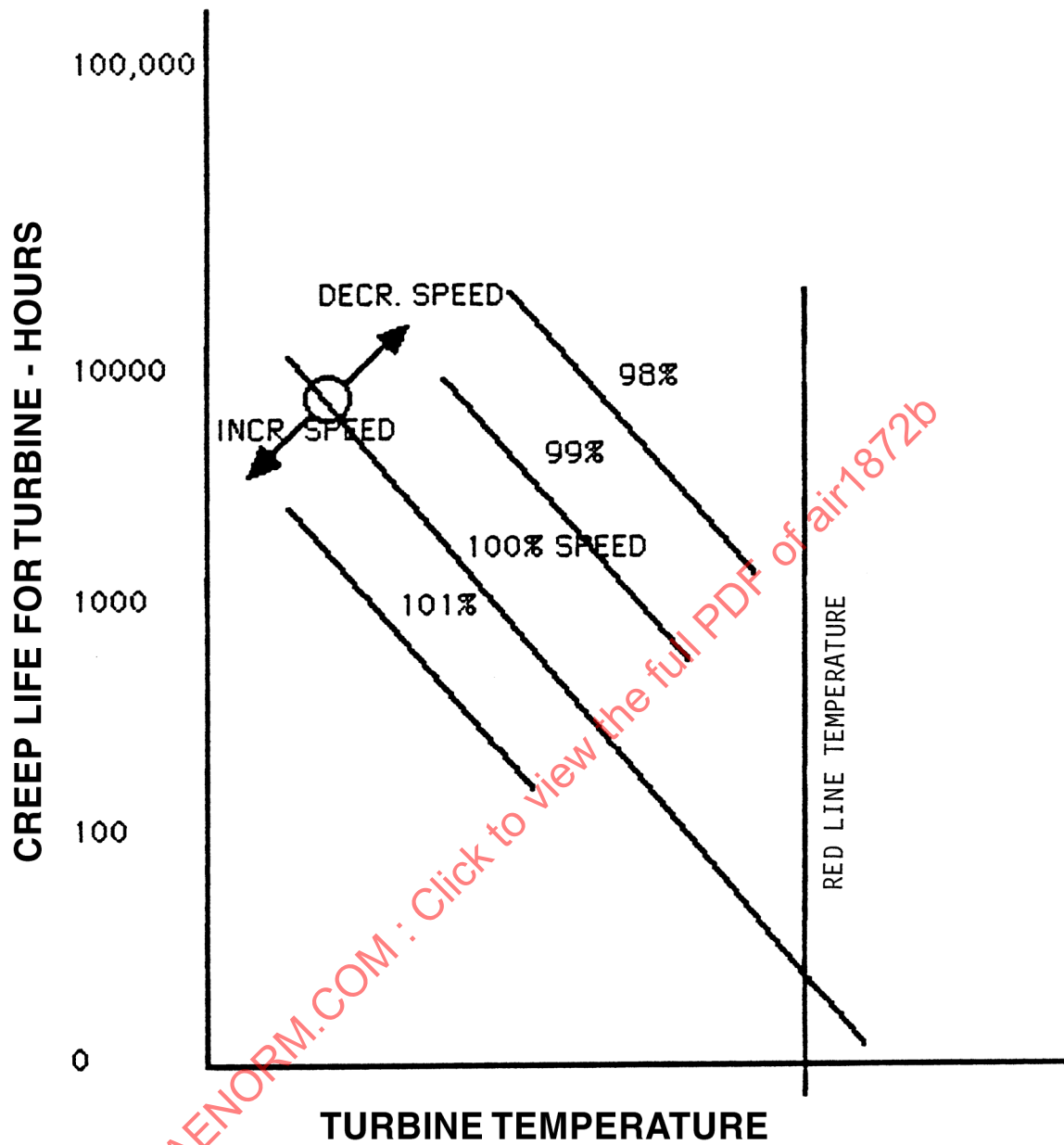


FIGURE 5 - Percent Life Usage Implementation

5.5.4 (Continued):

Typical exceedances include:

- a. Rotor overspeed
- b. Turbine over-temperature
- c. Surge/stall
- d. Hot start
- e. Vibration

Limit Exceedance/Incident Recording is usually performed by configuring the software in the EMS to recognize specific conditions and to trigger recording of the data bracketing the exceedance for subsequent diagnosis. This post exceedance analysis can result in engine removal or reduction in the remaining operational life of the affected components.

5.6 Parameter Requirements:

The parameter measurements required for life usage monitoring are determined by engine manufacturers at the time the algorithms are defined. The stresses that actually consume life cannot be monitored directly; therefore, relational measurable parameters are used to derive them. The more common directly-measurable parameters for engine life usage monitoring are:

- a. Rotor speed (for all spools)
- b. Exhaust gas temperature
- c. Torque
- d. Pressure altitude
- e. Indicated air speed
- f. Time
- g. Power/Throttle Lever Angle (to determine Afterburner usage)

If ground-based algorithms are used, sampling rates must be high enough to enable unambiguous recovery of the time variation of each input parameter and to avoid aliasing errors, but not so high as to generate too much data.

5.7 Read-Across Factors:

Each life-limited part should ideally be monitored separately by the EMS. However, for cost and logistic reasons, it may be prudent in some applications to consider reducing the number of monitored parts to only the most critical ones. A widely used method is to monitor only one or two parts on each rotating shaft and to derive the life usage on the unmonitored parts by applying relational 'read-across' factors. This derivation technique has proved very successful for measuring LCF life usage, but is only practical when the life usage relationship between parts is linear. This is usually more feasible where thermal stresses are absent or negligible.

Read-across equations are derived by analyzing flight-recorded mission profile data. The updating of life usage records that utilize read-across factors becomes more practical with the use of automatic ground processing management systems than with on-board systems.

5.8 Data Integrity:

Integrity of EMS is related to the ability of the equipment to recognize and highlight poor input data and to ensure that life calculations are reliably performed. Thus, data quality is a major consideration. Key design considerations for integrity may, therefore, be identified as:

- a. System hardware validation
- b. Input data validation
- c. System software validation

There are a number of basic checks that can be used to verify signal integrity by identifying and rejecting erroneous input data. These include but are not limited to the following:

- a. Out-of-range
- b. Rate-of-change
- c. Parameter interrelationships
- d. Transducer drift

It is necessary to flag maintenance personnel when the EMS receives erroneous data from its sensors during the previous flight. Relevant information can usually be displayed by the EMS built-in-test (BIT) facility. The EMS requires extensive BIT capability to ensure that internal computational routines are operating within defined limits. In the event of an EMS failure, the affected module or card should be identified and the effect of failure on recorded data should be considered. Additionally, manual input of the cycles consumed but not recorded should be performed either in accordance with a simplified algorithm or a "worst-case" scenario to ensure that the components have not consumed more life than is recorded.

5.9 Other Factors to Consider:

One can never be sure that the monitoring and analysis of engine operating data is providing a completely accurate representation of reality. For example, are the effects of auto-throttle and reverse thrust being taken into account sufficiently; are any factors being overlooked completely and could engine manufacturers improve the way in which they calculate the lives of their engines. Additionally, the accuracy of the measured parameter is important and has a significant effect on the subsequent life usage calculations.

- 5.9.1 Autothrottle: A change of rpm is more damaging at higher mean rpms. For example, an increase of 200 rpm, from 2000 to 2200 rpm causes a change in stress of 2000^2 to 2200^2 or 4 to 4.84. This represents a stress change of 21% but the absolute value changes by 0.84 units. If the same rpm change is considered at 4000 rpm (i.e., from 4000 to 4200) then the stress change is 4000^2 to 4200^2 which is 16 to 17.6. This is only a stress change of 10% but the absolute value changes by 1.6 units. Thus the change in the stress range is greater at the higher mean speed. Use of the auto throttle system generally only results in minor changes in spool speeds during the cruise phase and this phase is not considered to have a major effect on fracture critical component lives.

- 5.9.2 Reverse Thrust: Obviously, use of reverse thrust has some detrimental effect on component lives. However, most fracture critical component life is used during the takeoff (highest torques) and climb phases of the flight when spool speeds are at their greatest. Some flight profile monitoring systems extract spool speeds during takeoff, climb and reverse thrust and the ground-based software determines the corresponding usage from this data. Analysis of data from many flights, has shown that spool speeds (and, therefore, stress levels) encountered during reverse thrust are highly predictable such that they can be incorporated into the life usage systems without separate monitoring.
- 5.9.3 Areas for Further Improving Component Life Predictions: Unlike military flights which may consist of many hundreds of different phases and great variation from one flight to another, commercial flights follow a regular pattern (i.e., takeoff, climb, cruise, descent, approach, landing, reverse thrust, taxi) which is largely repeatable in nature. The frequency weighted average flight profile system (used by Rolls-Royce) is a simple and cost-effective system in terms of the lives it offers in relation to the degree of monitoring required to support it. On more recent engines, operators can use a datum flight profile (a typical worst case scenario) and "extended" flight plans which reflect lower levels of engine use and correspondingly offer higher lives for the fracture critical parts. Use of these lives require that operators carry out flight profile monitoring to confirm that they are operating within the extended profiles which assume greater use of de-rated takeoffs and climbs. This flexible approach is discussed in more detail in Appendix C. For commercial operations, this multiple flight plan system offers the opportunity to use fracture critical components more effectively and efficiency without jeopardizing safety. However, it is predicated on usage being much more predictable than is possible in military engine operation. Indeed, the variety of usage is so large in the military that R&D programs are currently on-going to calculate life usage in real-time (on-board), based on the already measured parameters of engine temperatures, speeds, etc. The totality of factors affecting life usage would be incorporated directly into designer's life usage algorithms and the transformation of running hours or number of takeoffs into "cycles" (with the inevitable safety factors, and read-across factors) would no longer be needed. For example, the severity of the takeoff conditions that each engine experienced would be calculated as a percentage of total life available on the various fracture critical components within the engine. The calculations would take account of outside conditions (e.g., Alaska versus Florida) so that the amount of "de-rating" could be accurately computed and the dividend accurately applied to the component lives. Similarly, the severity of use throughout the mission would be constantly monitored, calculated and clocked up on the component "life meters". While this development is currently not worth pursuing in the commercial market (because their usage tends to be much more predictable), it might be worth incorporating on commercial engine fleets once the technology is fully developed and mature. The pay-off would first need to be established but, in the military, the cost benefits are clearly immense. Within such an on-board system would be a means to input and extract the lives of components being replaced and removed. This is especially important on modular engines where some rotating components are exchanged without the need for substantial tear down.

6. METHOD VALIDATION:

Prior to the introduction of a life usage monitoring system to operational service, it is necessary to validate the technique that the system will use. This validation process involves two distinct tasks.

- a. Validation of the life usage monitoring algorithm
- b. Validation of the life usage monitoring system

Method validation qualifies the life usage monitoring capability of the EMS. This can be achieved by correlating the calculated component life usage with actual physical condition and then by verifying the EMS software implementation of the algorithm.

6.1 Algorithm Validation:

Full qualification of a life usage algorithm will usually require a significant amount of service experience in order to develop a large enough database to establish accurate correlations. However, for military engines, initial information in support of this objective can be acquired through Accelerated Simulated Mission Endurance Tests (ASMET). Commercial engines are subjected to certification and endurance tests that provide similar life usage information.

Defining an ASMET duty cycle begins with an intensive survey of flight records together with pilot interviews at Training and Operational Wings. These surveys help to determine the number of mission profiles for the particular aircraft involved, depending on whether the aircraft is new or an existing design and for military or commercial use.

Existing aircraft are sometimes used to produce particular mission profiles. Analysis of these data provides information on the frequency of changes between different levels for each parameter, an initial and final throttle position matrix, and computed times at various throttle position, altitude, and airspeed conditions.

Results often show marked differences when compared with the older engine specification endurance qualification test cycles. For example, the time spent at high power or idle settings might have changed, or there might be more cyclic variation per flight hour. Regular comparison of actual mission profiles with the originally defined duty cycles helps to monitor changes in usage so that the appropriate corrections to cyclic safe lives can be made.

6.2 System Validation:

A life usage algorithm is generally developed on a computer by the engine manufacturers' stress analysts, using simulated or test data. The actual implementation of the algorithm in an engine monitoring system can lead to software code differences. Therefore, it is important that the EMS code emulates the original algorithm as closely as possible to ensure that the differences between various implementations are kept within acceptable tolerances. In the past, differences of up to 5% have been accepted, but it should now be possible to achieve a much better correlation.

6.2 (Continued):

The procedure for performing comparative testing usually involves the use of data records which, collectively, can exercise all aspects of the algorithm. If the final life usage results meet expectations it is not sufficient to simply accept them, even though it is a good indicator that the software conforms to specification. A more complete correlation is achieved by comparing the values of the derived stresses and other critical parameters after every calculation for the complete set of recorded data.

7. PARTS LIFE USAGE DATA MANAGEMENT:

In order to readily determine the parts life usage and life remaining, accurate quantitative data must be collected and processed in a logical and convenient manner. This section describes the acquisition, storage, processing, and display of data for parts life usage management.

7.1 Management Decisions:

Management decisions based on parts life usage or life remaining are made at all levels of the engine maintenance support structure. User requirements for engine monitoring data are dependent upon the management decisions being made at the specific support levels. Typical maintenance levels are:

- a. Flight line, on-wing (Organizational (O) level maintenance)
- b. Engine shop (Intermediate (I) level maintenance)
- c. Depot and overhaul facilities (Depot level maintenance)
- d. Manufacturer (might not be a level of maintenance or is combined with c)

Note, however, that the USAF is in the process of reorganizing to a two-level maintenance concept, whereby the I level maintenance is deleted. Under this system, an installed engine which is deemed to have in excess of 8 h maintenance to remedy a known fault is removed and dispatched to Depot level, which could be several thousand miles from the operating base. The following explanation, however, assumes a traditional three-level maintenance concept.

In the engine shop, life usage related decisions are usually supported by time, temperature, and cycle data acquired on-board and down-loaded to the ground processing stations. Actual usage data are used to update the master records which back and update life. As a result of this update, the useable parts and remaining life for each part are available to engine shop personnel. In addition, calculated engine removal forecasts by calendar date are prepared for the engine shop chief. These reports assist him/her in scheduling the manpower and resources necessary for the forecasted maintenance.

An engine or module is transported to the depot level or overhaul facility if the flight line or engine shop cannot isolate the fault, or the repair is beyond local capability, or if technical orders specify the return based on the low remaining life. At this level, maintenance decisions are made based on historical data, removal reason, and engine/module records. Items that cannot be repaired at the shop or depot are sent to the manufacturer or contractor for repair or are scrapped. Also, depot level management requires fleet average calculations for planning purposes.

7.1 (Continued):

The engine manufacturer also has an interest in engine historical and usage data so that he/she may provide improved maintenance support for in-service engines. He/she can also provide expertise to identify reliability and maintainability problems that can be solved by engine design improvements. Acquired cycle/time data, that has been input to the ground system data base, also enables the life usage analysis to be carried out on parts not originally considered to be life-limited, or for re-assessing life usage of parts. The record-keeping staff analyzes engine removal data and failure statistics to determine spares stocking requirements and distribution to operating locations.

7.2 Data Acquisition:

The previous sections of this document have shown the necessity for accumulating data on gas turbine engine service history and mission profiles. Data capture is relatively easy, assuming that the required parameters can be sensed or calculated from other sensed data. The more challenging aspects include capturing the optimum amount of data and, more importantly, the use and analysis of the captured data. Until now, data has been captured during flight and subsequently down-loaded at the end of the day for up-load into a ground-based facility. This facility processes the data and often produces trends to assist in fault diagnosis as well as the required life usage information. It also reduces the data to an acceptable summary for archiving. In order to maximize the benefit of these data, the time period between data down-loading and further processing must be kept as short as possible. This is also necessary for maintaining accurate and up-to-date engine records.

Faster computing times and lightweight, state-of-the-art, hardware is promoting efforts to move towards a complete on-board data analysis. The advantages of on-board processing include reduced labor intensity, an immediately available output, and reduced possibility of data loss, as no pre-processed data transfer is needed.

7.3 Data Base Management System:

Design of record-keeping systems for information feedback requires data management and bookkeeping techniques that must be carefully planned, executed, and integrated with the maintenance process. Access to life usage data along with historical engine performance and maintenance data and fleet averages provide information for the following:

- a. Monitoring of fleetwide life usage.
- b. Determination of next scheduled engine removal.
- c. Support of On Condition Maintenance (OCM) including resource scheduling, opportunistic maintenance, and removal predictions.
- d. Spare part provisioning and logistic support.

7.3 (Continued):

- e. Correlation of maintenance history with mission profiles, and life usage operating environments.

In addition, all system software must be sufficiently flexible to handle inputs from a wide range of monitoring systems. Generic processing, data base architecture, and data management logic are desirable. Acceptable software designs should avoid customization to specific application hardware whenever possible. However, the logic should be designed primarily to manage engines, modules and parts. The data structure should be designed for rapid, efficient data through-put and real-time retrieval of reports containing information frequently requested for display.

Database maintenance must also be performed to ensure data accuracy and database integrity. Daily backups of the database are recommended. Data that fall outside the storage window should be stored on archive tapes. These procedures improve database integrity.

The system must be flexible enough to accept changes to life-limits and other parameters without extensive software modifications and to support introductions of new/improved component designs. Configuration management requirements must be considered for the software and the hardware.

Finally, there should be flexibility to easily change read across factors in the system. It is thus important to store raw usage data counts in the database.

7.4 Data Retrieval and Analysis:

To successfully implement a parts life usage and engine performance management system, the data retrieval procedures must be quick, timely, and easy to operate. User friendliness can be achieved by systematically structuring the on-line query. A flexible query structure with automatic report generation can support users at all levels.

It is imperative that data integrity be maintained. Gaps in the data must be identified and resolved. Also, manual transcription should be kept to a minimum. Ideally, engine plate data should be maintained automatically and the system should provide stringent rejection criteria to avoid a proliferation of erroneous data recording.

7.5 Hardware Characteristics:

The hardware configuration must be designed and developed cost-effectively to provide managers with information in a suitable format at the appropriate time to assist in their decision-making process. Items of concern include multi-user capability, real-time operational tasks, and interactive graphics. Standardization of software, hardware, and interfaces achieves low-cost implementation, replication, and ease of maintenance.

A computer processor for engine management, capable of supporting access by a large number of users, is recommended. The hardware configuration should be tailored to data base access, transfer and display requirements. The terminal equipment may provide graphics and must be appropriately interfaced with both the computer processor and data acquisition units.

7.6 Information Interfaces:

On-line displays can be graphic, tabular or both. Plots, histograms and statistics should be available. The raw, calculated and forecast data should be presented in tabular form when accurate information, not available with graphic pictorials, is preferred. Data should be available in multiple output formats tailored for a specific application.

The data management system must support the display terminal, hardcopy printer and other hardware interfaces. Terminals must be designed for data entry and preparation, information display in tabular and graphic formats, data communication between acquisition units, and centralized storage locations, and time-sharing operation. Easy access of data acquisition systems is critical to the engine management system success. Terminals can be made available for the engine shop, depot, manufacturer, and command organizations and should be installed in convenient locations.

8. BENEFITS:

The application of engine life usage monitoring and parts management systems can make significant contributions to reducing life cycle costs, and enhance logistics planning for the engine, while maintaining or improving flight safety. Current life predictions are sometimes conservative because the measurement system does not directly account for all the parameters which affect life usage, and how they interact. Data accrued from an airborne life usage measurement system provides information on critical components (LCF and hot end factors), enabling a more efficient use of life remaining in modules and engines. Not only does this improve hardware management decisions on cost grounds, but can improve safety of flight by preventing failures of critical components. The comprehensive fleetwide data base that is produced makes significant inputs into component improvement programs, assists in analysis of mission profiles, and provides important data feedback to the engine manufacturer. Of equal importance, life usage monitoring systems can provide the basis for warranty decisions of engines in the future. Improved engine management decisions are achieved by using the processed data with parts tracking systems to ensure more efficient deployment and scheduling of engines and parts.

An accurate and well-maintained parts life tracking system can have very positive influences on the overall maintenance concept for the engine. Some examples are as follows:

a. Cost:

USAir has been able to quantify benefits of using flight profile monitoring as a requisite for making full use of the PSCL (Published Safe Cyclic Life) for the life limiting rotating parts in the Rolls-Royce Tay engine which powers the Fokker 100 aircraft. Life cycle usage is based on the equivalent life cycles in accordance with a datum flight profile envelope that shows the limit of frequency and amplitude of rpm excursions during a flight cycle. The operator is required to monitor the actual flight profile relative to the datum flight profile. If the operator chooses not to monitor the actual flight profile for whatever reason, then the operator may have to forfeit as much as 25% of the PSCL life based on the manufacturer's life limited parts program. To USAir, this means forfeiting \$3,745,760 (1991 dollars) worth of disk life for a fleet population of 80 engines if

8. (Continued):

the decision were made not to monitor actual flight profiles. On an annual basis, at the life usage of 2500 cycles per year, this equates to a yearly saving of \$468,220 of usable disk life that is gained by conducting flight profile monitoring. One has to weigh against this the software charge of \$28,000 to modify the on-board DFDAU (Digital Flight Data Acquisition Unit) to generate the "LCF Reports" that are down linked to the ground station. These reports are used to verify the actual flight profile to the engine manufacturer which verifies the datum flight profile so that maximum use can be made of the PSCL. More details on this system are in Appendix B.

b. Provisioning:

With an accurate assessment of future missions, and a knowledge of life consumed on prior missions, an accurate prediction can be made relative to future spare parts requirements, allowing inventory to be optimized.

c. Opportunistic Maintenance:

Improved knowledge of component life remaining allows discretionary replacement of parts when the engine is in the maintenance shop for other reasons.

d. Deployment:

In deployment situations, the number of aircraft required and their anticipated missions are usually known. With a parts life tracking system, an evaluation of remaining life can be made on all candidate aircraft, and aircraft with the best chance of completing the deployed mission without major maintenance can be selected for deployment. This minimizes spares that would have to be part of the deployment and provides additional assurance that all deployed aircraft shall be operational.

e. Efficient Personnel Utilization:

Depending on the sophistication and automation of the parts life tracking system, accurate and timely data can be provided to the maintenance facility without the labor-intensive effort associated with manually supported systems. This can release maintenance personnel to spend time on other tasks or could result in accomplishing the job with fewer people.

EMS data can play an important part in engine development, product improvement, and engineering support. Usage data accumulated from a fleet of engines can provide valuable information inputs for current engine product improvement programs and the design decisions being made for the next generation of engine design. This design feedback can be provided in terms of mission analysis data, actual usage data for specific engine component types, and changes in operational usage rates. This design feedback can impact engineering management decisions on the development and implementation of specific proposed engineering changes. More efficient use of limited product improvement funds can be achieved by using fleet-generated EMS life usage data. The design of new engines and engine components can be better effected through operational usage data provided from the current generation of EMS equipped engines.

8.1 Life Usage Tracking for Warranty:

Logistics support, in the form of maintenance concepts and data acquisition capability, has a significant impact on establishing warranty requirements. An engine designed for modular maintenance requires special tracking and administrative procedures for individual modules. Life usage tracking capability can dictate the scope of coverage. The user must be able to validate and document warranty claims while maintaining mission effectiveness.

One approach to warranty is to cover the individual components (parts life warranty). This requires a system to track and document the components' history. The extent of coverage shall depend on the approach used to warranty the engine. Its effectiveness shall depend on how substantial the tracking capabilities are in the system and the interpretation of data generated by the system.

The role of an EMS in a warranty program is to provide the parts life tracking capability by accounting for the number of accumulated cycles and by providing other component data. The optimum situation would be for certain items to be tracked within the data system that is programmed to permit use of a warranty symbol while the item is under warranty and to automatically delete the warranty symbol when the warranty period expires. Should warranty action be required, the part number, serial number, and operating time of the failed component would be made available as it is in a maintenance action.

For example, the US DoD uses Total Accumulated Cycles (TAC) to implement warranty tracking on most new engine programs. TAC was originally defined as a means to track damage on LCF limited components for complete engines. However, the use of specific life usage algorithms such as LCF, thermal fatigue and creep are actually a more sensitive means to track component parts usage.

$$\text{Number of TACs} = \text{LCFC} + (\text{FTC}/4) + (\text{PTC}/40) \quad (\text{Eq.1})$$

where:

LCFC = Low cycle fatigue cycles: Intermediate and above and back to Off as measured by the EMS. A start-up and shut-down thus equals one LCF cycle.

FTC = Full throttle cycle: Idle to Intermediate and above and back to idle as measured by the EMS.

PTC = Part throttle cycle: Cruise to Intermediate and above and back to cruise as measured by the EMS.

In order for an EMS to have a significant impact on engine warranty, the system should operate at all times. Data on engine usage are required for adequate engine life cycle management; therefore EMS should be considered for inclusion on any minimum equipment list for flight. This does not necessarily imply required system redundancy but a requirement for a firmly established procedure to substitute other satisfactory data or methods to record life usage during any EMS inoperative period, for example, flight hours.

8.1 (Continued):

For example, a Navy warranty states that the government shall service each engine in accordance with the prescribed maintenance manuals and maintain operational and maintenance records, including EMS data. In the event of EMS failure, other satisfactory proof of engine life usage may be substituted.

9. NOTES:

The change bar (I) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document.

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APPENDIX A ENGINE STRUCTURAL INTEGRITY PROGRAM (ENSIP)

ENSIP is an organized approach to the structural design, analysis, test development, production and life management of gas turbine engines with the goal of:

- a. Ensuring safety
- b. Eliminating the occurrence of structural durability problems during production, acceptance testing, and service operations
- c. Reducing life cycle costs

ENSIP contains all of the structural requirements necessary to develop an engine and manage it throughout its useful life, with an emphasis on durability and damage tolerance (see Figure A1). It requires that certain critical parts, i.e., those parts whose failure could result in loss of an aircraft, be designed to crack growth criteria and that the initial flaw sizes required to ensure safe operation for twice the required inspection interval be not less than the NDE minimum flaw size capability. Presently, engines are being designed for inspection intervals that are half the life of the engine, the eventual goal being equal to the life of the engine.

During engine design and development, past engine usage data are combined with future expectations of how the system will be used so as to determine a series of mission profiles. These profiles are then examined and used in analysis procedures to design engine components with specific lives and inspection intervals. To verify that these lives and inspection intervals are met, extensive component and systems testing is done. All testing is set-up such that the testing simulates actual expected usage as defined by the mission profiles. Following these tests, Accelerated Mission Testing (AMT) is performed on engines to ensure overall engine durability. These AMT tests are derived from the mission profiles by removing all of the non-damaging portions of the missions, such as extended steady-state cruise time. This results in an acceleration rate from 2 for a trainer mission to up to 10 for a bomber mission. Because test time is shortened by a significant amount, the engines can be tested in a test cell for the full design life time, to the design mission, before the engine ever gets into production.

This type of testing may provide for a safer system by revealing potential problems during development testing rather than during actual usage years later. The potential for cost savings over the life of the system is tremendous since problems can be solved during Full Scale Development (FSD) instead of after production has started, or possibly ended, and retrofitting existing engines is necessary. Critical assets are saved and safety is improved since fewer aircraft are lost to unexpected problems.

After Operational Capability Release (OCR), actual usage data are collected and used to recalculate the system life. If a residual life is significantly different than what was planned, then inspection intervals are changed to ensure safe and cost-effective usage.



INTRODUCTION TO ENSIP THE ENSIP TASKS



TASK I	TASK II	TASK III	TASK IV	TASK V
DESIGN INFORMATION • ENSIP MASTER PLAN • DESIGN SERV. LIFE & USAGE REQUIREMENTS • DESIGN CRITERIA	DESIGN ANAL. COMPNT. & MAT. CHARAC. • DESIGN DUTY CYCLE • MAT'L'S AND PROCESSES DESIGN DATA CHARACTERIZED • STRUCTURAL/THERMAL ANALYSIS • MFG. AND QUALITY CONTROL	COMPONENT & CORE ENG. TESTING • STRENGTH TESTING • DAMAGE TOLERANCE TESTS • DURABILITY TESTS • THERMAL SURVEY • VIBRATORY STRAIN & FLUTTER BOUNDARY SURVEY	GROUND & FLIGHT ENG. TESTS • ENVIR. VERIF. TESTING • (AMT) TEST SPEC. DERIV. • DURABILITY TESTS (AMT) • DAMAGE TOL. TESTS • FLIGHT TEST STRAIN SURVEY • UPDATED DURA. & DAM. TOL. CONTROL PLAN • PERFORM. DETERIOR. STRUC. IMPACT ASSESSMENT • CRITCL. PART UPDATE	PROD. QUAL. CONTROL & ENG. LIFE MGT. • PROD. ENG. ANALYSIS • STRUC. SAFETY & DURAB. SUM. • ENG. STRUC. MAINT. PLAN • MONV. ENG. TRACKING • LEAD THE FORCE PROG. (USAGE) • DURA. & DAM. TOL. CONTROL PLAN IMPL. • TECHNICAL ORDER UPDATE

FIGURE A1 - Engine Structural Integrity Program

During the life of the system, support cost is further reduced if Retirement for Cause (RFC) is used to determine if a part has been used for its full life (time to crack initiation-LCF). RFC requires that the critical parts be inspected to the minimum flaw size capability of the NDE equipment that must be smaller than the minimum design flaw size. All parts found to be free of cracks are returned to service for another inspection interval. Those parts that contain cracks are either retired or, if the cracks are small enough, authorized repairs may be accomplished and the part returned to service. All of these parts would have been retired at the -3 sigma life if LCF was used for parts life management. By using RFC, these parts can be used as much as 10 times longer (see Figure A2). The risk associated with RFC is much higher and is only being implemented on a very limited basis.

From the above it should be clear that ENSIP not only plays a role in the design and development of the engine but is meant to be used throughout the life of the system to obtain a safer, more cost-effective and more reliable engine. This is accomplished by using parts to their full lives and by testing in FSD to detect problems early in the program as well as considering failure modes not addressable by earlier methodologies. Engine usage monitoring is also necessary to indicate deviations that could extend inspection intervals or point to potential safety problems. Additional information is available in greater detail in MIL-STD-1783.

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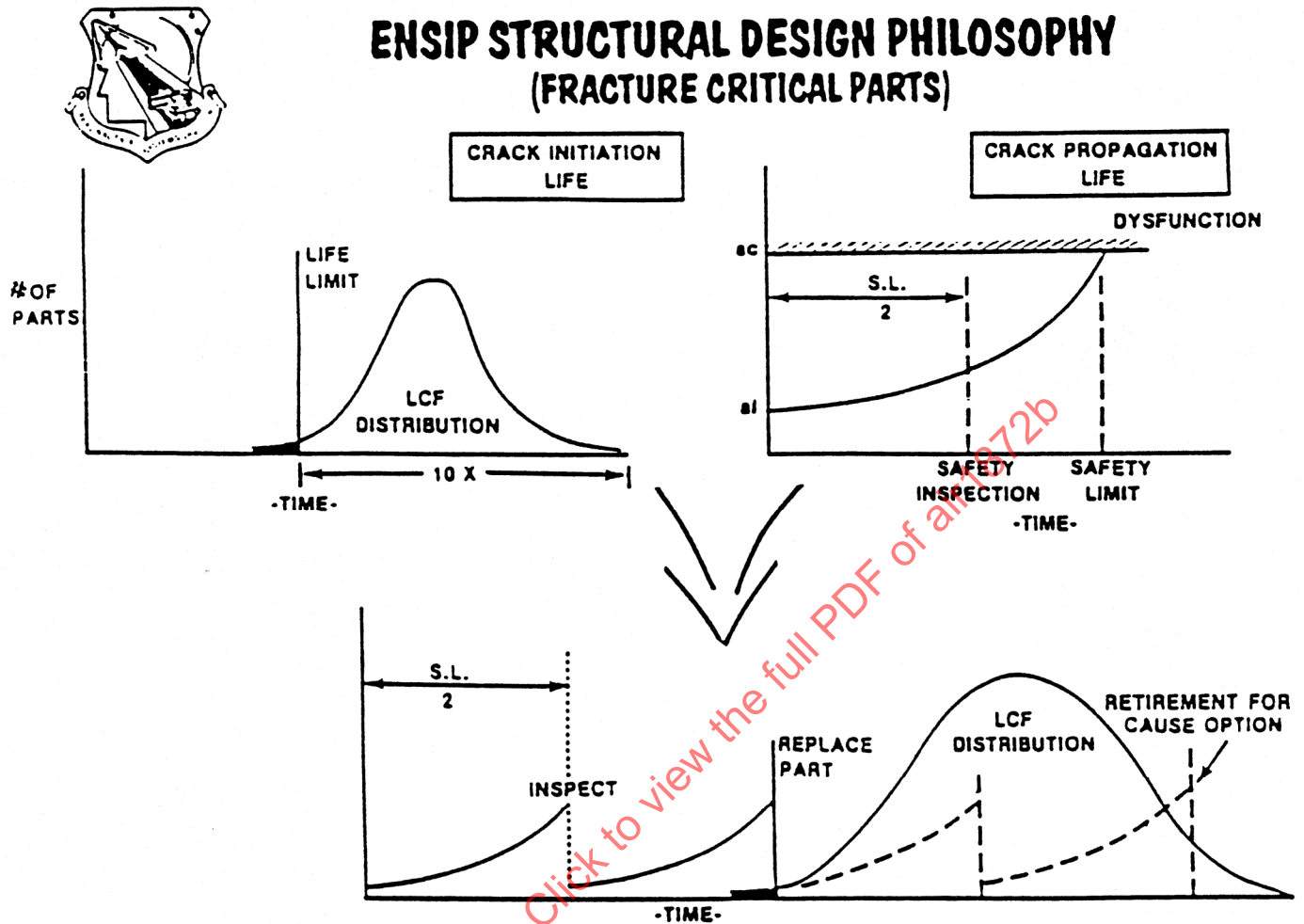


FIGURE A2 - ENSIP Design Philosophy

APPENDIX B LIFE USAGE AND PARTS MANAGEMENT SYSTEMS

B.1 LIFE USAGE MONITORING SYSTEMS:

For many years the military community has employed a variety of approaches to the measurement of usage of life-limited components. Systems range from simple time/temperature recorders to comprehensive condition monitoring systems, utilizing dedicated on-board computers that calculate fatigue damage in real-time, allowing maximization of available life, and progressing toward the adoption of on-condition maintenance practices.

After a decade or so of limited applications, and the proving of techniques and technology, the military is beginning to specify monitoring systems for new aircraft, and has also embarked on extensive retrofit programs. Some examples illustrating use in the military fixed wing and rotary wing applications, and in commercial airline applications are listed and amplified below:

a. A Commercial Airline Perspective:

Typically, commercial airline operators want to operate an "on-condition" policy for their engine maintenance. Nowadays, this is the norm rather than the exception although "power by the hour" is also an attractive and acceptable means of operation. Generically, operators use FADEC and an on-board EMS unit to collect data. They also retrieve the data and interpret it to make day-to-day maintenance decisions. They maintain an operational data base for each of their engine fleets and monitor the life usage of their individual engines through limit exceedances, estimates of life used and prediction of remaining life.

When an engine is released from overhaul, the remaining cycles of the life limited parts are stored in an engine life cycle counting program. After installation into an airplane, actual data from the central aircraft flight hour and cycle counting program is fed in to the engine life cycle program so that there is always a full picture of when the engine must next be pulled. This information is also fed into an engine removal forecast which is issued weekly.

For condition monitoring, a routine trend monitoring program analyzes engine operating data. The aircraft condition monitoring system (ACMS) generates three different report types (Takeoff, Cruise, and Exceedance) on-board the aircraft and these are downlinked via ACARS to the on-ground programs (GEM and COMPASS) where the data is analyzed on-line.

- (1) Takeoff reports provide information on the overall health of the engine. After installation of the engine, five consecutive reports are generated to establish a good initial point. Thereafter, the degradation of the initial point value will show the deterioration in engine performance. In addition the initial point is compared with Test cell results for correlation/validation. If there is not a good correlation, then investigative action is taken. With everything normal, a takeoff report is generated every week for trending and to ensure that every engine always has sufficient takeoff exhaust gas temperature (EGT) margin to meet all rating requirements. Looking at EGT margin and the deterioration rate of the initial point value gives a good estimate for forecasting eventual removal.

B.1 (Continued):

- (2) Cruise reports are generated every 4 h and contain gas path, oil system, controls and vibration data. After analysis of each data point, the data go through a trend recognition function which is designed to alert the analyst to trend deviations. This ensures a successful early detection and helps to minimize operational irregularities and engine removals "down-route".
- (3) Exceedance reports are generated whenever a predefined limit is exceeded. The report is issued independently of the flight phase and is brought to the immediate attention of the analyst.

b. F100 Events History Recorders:

The F100 Events History Recorder (EHR) is an engine-mounted device used to monitor certain engine parameters and provide ground crews with a direct readout of these parameters.

The EHR records N2 cycles, Fan Turbine Inlet Temperature (FTIT) and a discrete signal, all from the electronic engine control. Measurement of rotor speeds is a more accurate parameter for counting cycles on engine components than power settings from the pilot's lever angle (PLA). It has been found that when PLA data is used in the EMS, cycles are overcounted by approximately 20%.

Engine history data provided include accumulated time at certain conditions, event counts, and fault flag indications. Total engine time, two levels of hot section time and LCF cycles are provided with direct digital readouts. One-time flag indications are provided for two levels of overtemperature and for a hot start. Additional diagnostic information is provided by the EHR in the form of a flag indication from a signal supplied by the electronic engine control (EEC). For an EEC, the signal indicates an N1 sensor failure. On Digital Electronic Engine Control (DEEC) equipped engines, the flag indicates that a failure has occurred in one of the LRU components. This flag shows that maintenance is necessary; however, further troubleshooting is required to isolate the fault.

An improved unit has been developed and incorporated to replace the original version. The new EHR provides improved reliability and additional life tracking parameters. Operationally, it is unchanged. All of the above readouts remain and two diagnostic parameters are added. One is an internal EHR failure indication; the other reports an FTIT probe failure. The new EHR has electronic memory and stores all the information presently on display, plus two additional levels of hot section time, two additional types of LCF cycles and the accumulated total of fault flag indicators.

The benefits of the EHR include engine parts life management and fault detection. It is the only means of determining when timed maintenance must be performed or engine overhaul is required. The N1 sensor failure flag and DEEC System fault indication provide visual displays for the control's diagnostic capability.

B.1 (Continued):

The following table provides a summary of the EHR parameters and the recording criteria.

TABLE B1 - EHR Table of Operation

Parameter	Criteria
1. Engine Time	FTIT 500 °F
2. Hot Section Time Level I	FTIT 1692 °F
3. Hot Section Time Level II	FTIT 1755 °F
4. Overtemperature "B"	FTIT 1780 °F for 2 min or 1816 °F for 31 s or 1834 °F for 6 s or 1868 °F for 3 s
5. Overtemperature "C"	FTIT 1834 °F for 2 min or 1868 °F for 31 s or 1906 °F for 6 s 1943 °F for 1.5 s
6. Low Cycle Fatigue	N2 increases from 10,250 to 12,500 rpm
7. Hot Start	FTIT 1548 °F and N2 6500 rpm
8. N1 Sensor/DEEC System Fault	Discrete signal from control
9. EHR Failure	Internally generated
10. Low Cycle Fatigue Type I	N2 increases from 6500 to 11,800 rpm
11. Hot Section Time Level III	1655 °F FTIT 1755 °F
12. Hot Section Time Level IV	1715 °F FTIT 1755 °F
13. FTIT Probe Failure	If N2 decreases from 10,250 to 7300 rpm and FTIT 900 °F and 5 of 7 samples of FTIT input resistance to ground show 1000 Ω
14. Low Cycle Fatigue Type IV	N2 increases from 11,500 to 12,500 rpm

B.1 (Continued):

c. F101 and F110 Engine Life Usage:

The F101-GE-102 engines for the B-1B, the F110-GE-100 for the F-16 and the F110-GE-400 for the F-14 all incorporate on-engine life usage recording. In the case of the F101, it is incorporated into the Central Integrated Test System (CITS) Processor and, in the case of the F110, into the Engine Monitoring System Processor (EMSP). Both units perform essentially the same function, that is, signal conditioning, conversion of signals from analog to digital, validity testing and counting engine life usage functions and indices. Both Air Force systems, B-1B CITS and F-16 EMS, transfer this life usage information to other Air Force analysis programs for any further Engine Life Usage or Parts Life Tracking computations. The F-14 Navy system performs a simple computation of TACs on the aircraft, and a parts life tracking program is being designed for use in the ground station at the equivalent of intermediate maintenance level.

In the military engine examples, (b and c) the following functions or indices are counted:

- (1) Engine Operating Time
- (2) Low Cycle Fatigue Cycles
- (3) Full Thermal Cycles
- (4) Cruise-Intermediate-Cruise Cycles
- (5) Augmentor Operating Time
- (6) Augmentor Cycles
- (7) Five (5) Times at Temperature (Based on HPT Blade Temperature)

Three of these functions are used either on the ground or airborne to calculate TACs, primarily for engine warranty purposes.

$$\begin{aligned} \text{Total Accumulated Cycles} = & \text{Low Cycle Fatigue Cycles} + 1/4 \text{ Full Thermal} \\ & \text{Cycles} + 1/40 \text{ Cruise-Intermediate-Cruise Cycles} \end{aligned} \quad (\text{Eq.B1})$$

All of the functions are subsequently used on the ground to calculate parts life tracking parameters. They are:

- (1) Engine Operating Time
- (2) Equivalent Low Cycle Fatigue Cycles
- (3) Equivalent Time-At-Temperature
- (4) Augmentor Operating Time
- (5) Augmentor Cycles

The life of each of the life-limited parts is dependent on one or more of the tracking parameters. Unique constants ("K" Factors) are developed for each part that is limited by either equivalent low cycle fatigue cycles or equivalent time at temperature. The Air Force tracks in excess of 80 critical parts, and a similar list is being developed for the Navy.

B.1 (Continued):

d. T700 History Recorders:

The T700 History Recorder is an electromechanical unit attached to the right side of the engine. The box has four digital display windows, which provide the following life usage parameters:

The first window shows a count of the number of mechanical stress-related cycles experienced by the engine. A cycle is recorded when the engine exceeds 95% core speed; the core speed must then drop below 50% and then increase to 95% again before another cycle will be registered.

Temperature related stress events are displayed in the second window. As with LCF, this counter is indexed each time the engine exceeds 95% core speed; however, for additional counts to be recorded, core speed must drop below 86% and then increase to 95%.

The third window shows the cumulative effect of time at temperature and this is monitored by indexing the counter based on time at power turbine inlet temperature. Indexing occurs faster as the turbine gas temperature rises.

Running time in hours is displayed in the fourth window. Operating time is accumulated once the engine core speed exceeds 50% and stops when the speed falls below 40%.

Data provided by the history recorder must be manually transcribed into a log book, where it becomes available for life usage calculations.

e. Low Cycle Fatigue Reports (USAIR F100 Commercial Engines):

The engine's N1 and N2 speeds are monitored during flight. One report is generated per flight leg after landing. The data in the report consists of the following:

- (1) Powerback is indicated by both reverser deploy discretes "ON" and both N2 >55% at any time in Start Mode, Idle Mode or Ground Run.
- (2) Maximum N1 and N2 engine speeds during Takeoff mode.
- (3) TAT value at entry point of Takeoff Mode.
- (4) Maximum N1 and N2 engine speeds during Climb Mode.
- (5) Minimum N1 and N2 speeds during descent Mode.
- (6) Use of reverse thrust during Landing Mode, only if reverse power is greater than idle. YES/ NO to be indicated by both reverser deploy discretes = "ON" and both N2>55% at any time in Landing Mode.
- (7) Maximum N1 and N2 engine speeds during reverse thrust.

B.1 (Continued):

f. F404 Inflight Engine Condition Monitoring (IECMS):

IECMS provides continuous monitoring of the F404-400 (F-14) engine for failures and exceedances; software capabilities are resident in the aircraft mission computer. In addition to event detection and data recording functions the life usage indices defined below are also monitored.

Full and partial core speed cycles are continuously monitored and accumulated in the mission 58.9 to 92.2% back to 58.9%, while a partial cycle is defined from 76.1 to 92.2% back to 76.1%. Because of the consistency of the relationship between N2 and N1, the N2 counts are also used to provide N1 (fan) speed counts.

Full and partial compressor discharge pressure cycles provide LCF counts for life calculations of combustor module structures. Full cycles are defined from 70 to 405 back to 70 lbf/in² (absolute); partials are recorded from 70 to 340 to 70 lbf/in² (absolute).

Using Throttle Position, Ambient Pressure, Inlet Temperature, Mach Number, and HPT exhaust gas temperature, IECMS calculates a blade trailing edge metal temperature, which is then used to generate counts related to life used.

Continuously monitored Throttle Position, Ambient Pressure, Mach Number and Inlet Temperature are used to calculate an HPT blade leading edge temperature. A cycle count proportional to blade damage is then determined based on the maximum blade temperature achieved every time the throttle is advanced above 60°.

IECMS continuously sums engine operating time with the throttle at or above 80 degrees; counts relative to this time are accumulated and stored.

Counts proportional to the time the engine is operated above 58.9% core speed are accumulated and stored.

g. United Kingdom (UK) Military Engine Usage Monitoring System:

The Engine Usage Monitoring System (EUMS) was developed in the mid-seventies for a more accurate assessment of the LCF life usage of major rotating engine parts in service operation. The system was developed for installation in a small representative sample of operational squadron aircraft. Two versions of EUMS are in use with the British Royal Air Force.

Both EUMS I and II are designed to accept inputs from standard aircraft transducers, utilizing existing sensors and transducers in most installations. The parameters that are typically recorded include engine shaft speeds and inlet and exhaust temperatures. Some installations also record other parameters to meet a wider objective of condition monitoring.

B.1 (Continued):

The airborne equipment is comprised of a Data Acquisition Unit (DAU) and a Quick Access Recorder (QAR). The QAR stores continuously recorded data, in digital format, on a compact tape cassette. Cassettes are replayed on a ground based data processing station where the LCF damage is computed and overall fleet usage rate determined.

EUMS I has been installed on a variety of Royal Air Force fighters, transport aircraft and USMC AV-8A aircraft and has provided the data necessary to achieve beneficial component life extensions on several engine types.

The application of EUMS II is less widespread, but has been effective in very specific situations. The main advantage of EUMS II is its ability to process data on-board using algorithms defined by the engine manufacturers. Another significant advantage of EUMS II is the ability to monitor and record engine and airframe parameters at higher sampling rates than EUMS I. This enhanced capability has facilitated low cost development support for more advanced life usage algorithms and monitoring systems.

h. F402/AV-8B Engine Monitoring System (EMS):

All Pegasus MK 105 and F402-RR-406 engines in AV-8B type aircraft are to be monitored for life usage and condition. The EMS life usage functions include LCF of major engine parts and creep/thermal fatigue of HP turbine blades. The algorithms, defined by Rolls-Royce, utilize many of the methods described in the body of this document.

Initially, only six parts are monitored for LCF life usage including the combustion chamber outer case. The remaining components are tracked by use of read-across factors. It is intended that more advanced life usage algorithms will be applied to account for thermal transients. When this change is implemented, all major parts will be monitored without the need for read-across.

The EMS is configured to form part of an engine maintenance concept and is supplemented by a comprehensive information management system and organizational level diagnostics capability.

The EMS is based on an on-board Engine Monitoring Unit (EMU), which incorporates computational facilities, input/output interfaces and limited data display capabilities. Detailed data recorded by the EMU are extracted on the ground using a Data Retrieval Unit (DRU).

The main functions of the EMS are to perform the following operations on line:

- (1) Count LCF cycles
- (2) Measure HPT blade life usage
- (3) Detect and quantify limit exceedances
- (4) Perform vibration frequency analysis
- (5) Produce incident records

B.1 (Continued):

With an EMS in every aircraft, it will be possible to keep track of LCF life and turbine blade life to maximize time between overhaul.

Data stored in the EMU must be available to maintenance personnel in a meaningful form. This information mostly concerns limit exceedance summaries and life usage counts, but more detailed information is required on occasions where further analysis would assist troubleshooting.

For routine interrogation of exceedance summaries and life usage counts, these data may be presented in the cockpit. However, this display option is not suitable for the larger amounts of data that can be stored in the EMS incident memories; therefore, a Data Retrieval Unit (DRU) is provided.

The DRU is a small, ruggedized GSE unit suitable for use on land or ship. Its primary use is that of a data transfer system to extract data from the EMS and pass it to an interface unit for subsequent input to a ground computer. The ground computer is equipped with a video terminal, printer and plotter for direct readout, hard-copy and parameter/time plot output capability.

The DRU is used to update the parts tracking system records, thus avoiding human transcription errors that are inherent in manual data transactions. In order to support a comprehensive life usage and parts tracking system, a facility for inserting documentary engine data relating to a particular engine is provided.

The UK requirement for continuously recorded flight data (as in the EUMS program) remains for algorithm development and component usage correlation purposes. Provisions are being made in the EMS for a bulk data storage unit. The EMS has already been successfully flight tested on an AV-8B Harrier and will be installed in all Royal Air Force GR5 and AV-8B aircraft.

i. USAF Comprehensive Engine Management System:

The Comprehensive Engine Management System (CEMS) was implemented by the Air Force to achieve high levels of force readiness in peacetime and force availability during wartime at low cost. Rising fuel, manpower and equipment costs caused the Air Force to shift maintenance policies toward "On-Condition Maintenance" (OCM). To support the information-intensive processes associated with OCM, the Air Force responded by fielding automated systems and procedures for logistics and maintenance management of aircraft and critical aircraft subsystems, particularly engines. The fielded system was CEMS, which was developed in four increments:

(1) Increments I and II perform life-limit management

(2) Increment III performs engine status tracking, pipeline analysis, actuarial projections and engine stock measurement/control