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GUIDE TO LIFE USAGE MONITORING AND PARTS MANAGEMENT FOR AIRCRAFT GAS TURBINE ENGINES

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1. INTRODUCTION:

The idea of engine monitoring is not new. For years, military and commercial aircraft have used cycle counters, and pilots in both sectors have manually recorded cockpit parameters in order to enable maintenance and engineering personnel to discern 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 both paralleled and complemented philosophical and technological changes in military and commercial engine maintenance programs. As electronic chips came along, it was a natural evolution for automated monitoring to begin taking big steps.

In recent years, increasing priority has been given to reviewing life usage monitoring by both commercial and military operators. This action has been motivated by the occurrence of failures and by the need for improved economy through more effective life 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 this interest and need, SAE Committee E-32 has developed this Guide to Life Usage Monitoring and Parts Management for Aircraft Gas Turbine Engines.

1.1 Purpose: SAE Aerospace Recommended Practice 1587 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 AIR 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 I and II) and a description of the means by which these requirements can be achieved more effectively through the use of engine monitoring systems.

1.2 Scope: The effectiveness of Engine Life Usage Monitoring and Parts Management systems is largely determined by the aircraft-specific requirements. This AIR 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.

1.2 (Continued):

This AIR primarily examines the requirements and techniques currently in use, including:

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.

2. GENERAL CONSIDERATIONS:

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 and pressure changes. In many cases, the effects of these stresses can be monitored, 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:

a. submit the proposed design to heat transfer and stress 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.

Analytical techniques are widely used to predict the service life of gas turbine engine parts. The actual life of parts in service shall depend 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.

Recommendations for monitoring life usage range from the selective application of airborne data acquisition systems, which provide complete usage records for small groups of aircraft, to the fleetwide application of microprocessor-based Engine Monitoring Systems capable of calculating life usage in real time.

2.2 Parts Management: During the life of a gas turbine engine, there will be occasions when it is necessary to remove it from service to facilitate scheduled repair/overhaul and unscheduled repair.

In order to minimize engine unavailability during repair, parts are often replaced with spare parts conforming to equivalent or improved design standards. Parts that are removed for rework or inspection shall be subsequently re-allocated as spares for subsequent engine repairs. 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.

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.

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 (see Appendix III). 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". Thus, life-limited parts can be grouped in to these two categories.

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

Most engine parts, life-limited or otherwise, require regular 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 for predetermined reasons. 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, either by decreasing failure resistance or by introducing new rejection criteria. These non-inherent causes are mostly random, because they are related to external factors not normally encountered by all engines in the fleet. These causes include:

a. Foreign object damage.
b. Engine mishandling (that is, overtemperature, overspeed).
c. Corrosion.
d. Erosion.
e. Fretting.
f. Wear.
g. Material defects.
h. Manufacturing defects.

In many cases, premature failures can potentially be avoided by better component design, appropriate condition monitoring and detailed inspections. However, condition monitoring with respect to these non-inherent failure causes are not discussed further in this document.

4.1 Low Cycle Fatigue (LCF): Low cycle fatigue is normally associated with significant stress amplitudes caused by repeated cycling between different stress levels within the material's elastic limit, eventually leading to strain hardening (or in some cases, strain softening) and failure. It is widely agreed that LCF failure occurs in less than 50 000 cycles, where a cycle is usually defined as an excursion from zero stress to a maximum datum stress and back to zero.

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, thereby increasing or decreasing the net stresses depending upon the specific engine operating condition. The majority of rotating parts, in particular shafts and discs, are subject to LCF.

LCF stresses also arise from recurring loads due to pressures and maneuvers/inertia and affect the life of non-rotating parts such as pressure vessels, mounts and airframe structures.

4.1 (Continued):

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 take-off 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 relatively large number of high-power throttle movements required for military aircraft.

4.2 High Cycle Fatigue (HCF): High cycle fatigue is caused by lower stress amplitudes than those that cause LCF. Failure due to HCF usually occurs in more than 50 000 cycles. A HCF stress (possibly due to vibration) may in some circumstances be superimposed on a LCF stress and accounted for by use of a percentage factor applied to the LCF damage, thus reducing the overall life. This type of fatigue is difficult to predict in the initial design stage and may not appear either in development testing or initial service of a production engine. Understanding this failure mode requires a thorough knowledge of component stresses (both steady-state and cyclic), temperatures and material properties. Although HCF is well recognized as a failure mode it is difficult to measure, and a means of implementing this capability in engine monitoring systems has not, as yet, been adopted.

4.3 Thermal Fatigue: Thermal fatigue stresses are induced by thermal gradients and differential expansions. Accels and decels 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 exit guide vanes, or locally through partial immersion as in the case of high pressure compressor and turbine discs. 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.

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.

4.4 Creep: For aircraft that fly mission profiles with long cruise segments, creep can become a more life-limiting criterion than LCF.

Under application of a sustained load at elevated temperatures, metals can show a gradual 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. The second parameter that is most influential on remaining life due to creep is time duration at the maximum temperature.

5. ENGINE LIFE PREDICTION AND USAGE MEASUREMENT:

Since the failure of certain engine parts is at least hazardous and, in certain military applications, 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 Overhaul (TBO). 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. Thus, for reasons of maintaining safety and improving economy, the development of life usage monitoring systems incorporating accurate algorithms is justified. Because of the repeatability of some civil application flight profiles this justification becomes less clear.

5.1 Design Methodology: The approach normally used by engine manufacturers to verify the longevity of a life-limited part for a new engine design includes:

a. Accurate definitions of material properties.

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 places more reliance on analysis methods.

5.1 (Continued):

d. Instrumented bench and flight development engine testing are used to verify the estimated environmental conditions and stress levels.

The safe life of a critical life-limited component is the estimated life to first measureable crack or to a proportion of the life to a critical crack size. The data provided by stress analysis are combined with empirical Stress/Cyclic (S/N) data, range-mean relationshps and cumulative damage laws to produce an estimate of life to first crack. Rig and engine testing is 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.

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 in to cracks that grow as a function of repetitive stress fluctuations and the type of crack.

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. Quantification is generally destructive.

The application of fracture mechanics in the design of an engine part enables the calculation of life based on the part having a defect just below the level that can be readily detected with accurate NDE techniques. The cycles remaining to the critical value 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: A widely used method of determining the service life of life-limited parts is based on theoretical estimates of engine usage rates for mission type and mission mix. Because it is not possible to detect or measure cracks in most parts while installed in the engine, the crack propagation phase is usually not included in the estimate of fatigue life. The fatigue life of critical parts must therefore be reliably established in order to avoid both uneconomical premature retirement and 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.

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, take-off, climb, cruise, landing and shut-down. Other elements may also be considered if the engine is used for VTOL or thrust reversing. Engine life usage must be determined for each flight mode by mission analysis. 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 performed by:

a. Recording the relevant in service engine and aircraft parameters to refine the initial theoretical mission profile.

b. Reconstructing the mission profile analytically until it has a high statistical probability of fitting a large percentage of actual mission profile data.

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 life increases are established, the manufacturer shall amend his overhaul manual to reflect this.

Commercial operators, in addition to the general 'life growth' program of the engine manufacturer, can in some cases benefit further where engine operation is less severe than that on which the initial life-limits are based. Both hourly and cyclic life benefits can be realized for the components that reach their peak stress levels during take-off. 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 take-off power is limited to between 90% and 95% of normal take-off rated power, a rotating component life factor of 0.93 may be applied to both the cyclic usage and the hourly usage.

b. When the actual take-off power used is greater than the normal take-off power rating, it is necessary to record this flight as being equivalent to six cycles at normal take-off power rating.

c. 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 dependant on the degree of limit exceedance, duration of event and inspection findings. Parts may be returned to service at a decreased life rating or scrapped depending on the manufacturer's recommendation.

To benefit from using reduced power take-offs, it is necessary to keep detailed records of the power used for each flight. This can be an enormous task for any records 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 present technology, it is feasible to measure engine life usage with engine monitoring systems in a sufficiently reliable and accurate manner. This section shall discuss 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: It is recognized that any discussion of LCF life usage monitoring would be incomplete without at least a mention of the stresses caused by thermal gradients and differential expansions as well as stresses due to 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.

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 disc where thermal effects are negligible in comparison to centrifugal stresses. Fig. 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 relates a speed cycle to fatigue and a cycle counting technique that selects 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 Fig. 2. The reference line in Fig. 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 count in equivalent reference cycles for non-zero minimum rotor speeds. The usage count for any one cycle can, thus, be computed.

In the very simple rpm/stress profile shown in Fig. 3a, it is necessary to extract the major and minor cycles (Fig. 3b) in terms of equivalent reference cycles (Fig. 3c).

There are several methods for extracting the cycles from a LCF stress profile, but the most widely accepted and successful method is the Rainflow Method. Success of the Rainflow Method evolves from its ability to count all cycles, identifying 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 when cycles are defined according to the Rainflow Method, where the mean of each cycle is simply the average of 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 deg so that the time axis is vertically downwards (see Fig. 4). The profile is now imagined to be a series of pagoda roofs, falling to the ground, except that if the peak where rainflow begins is a maximum then it must stop if it falls opposite a max peak that is more positive than that from where it began. Similarly, if the rainflow begins at a peak that is a minimum it must then stop when it falls opposite a minimum peak that is more negative. The rainflow must also stop if it meets the rain from a roof above.

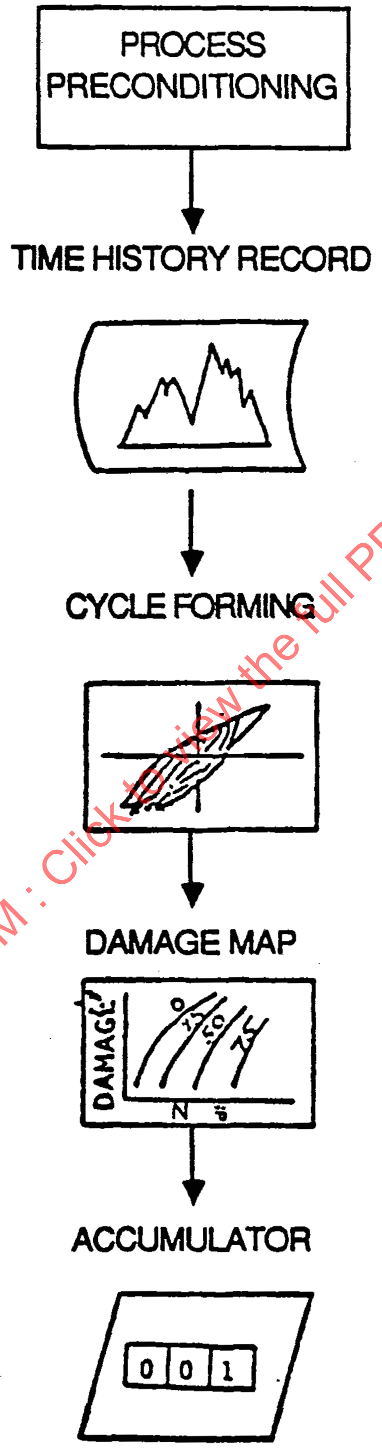


FIGURE 1 - Mechanical LCF Algorithm

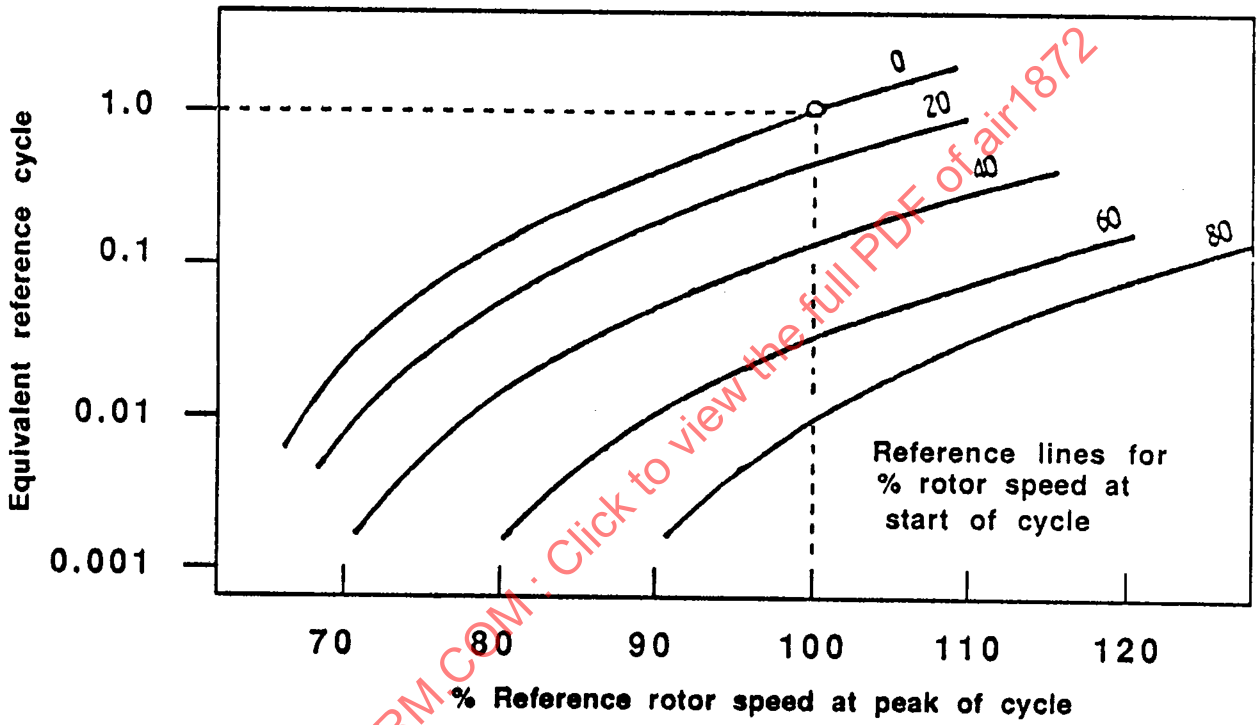


FIGURE 2 - Typical Map Structure

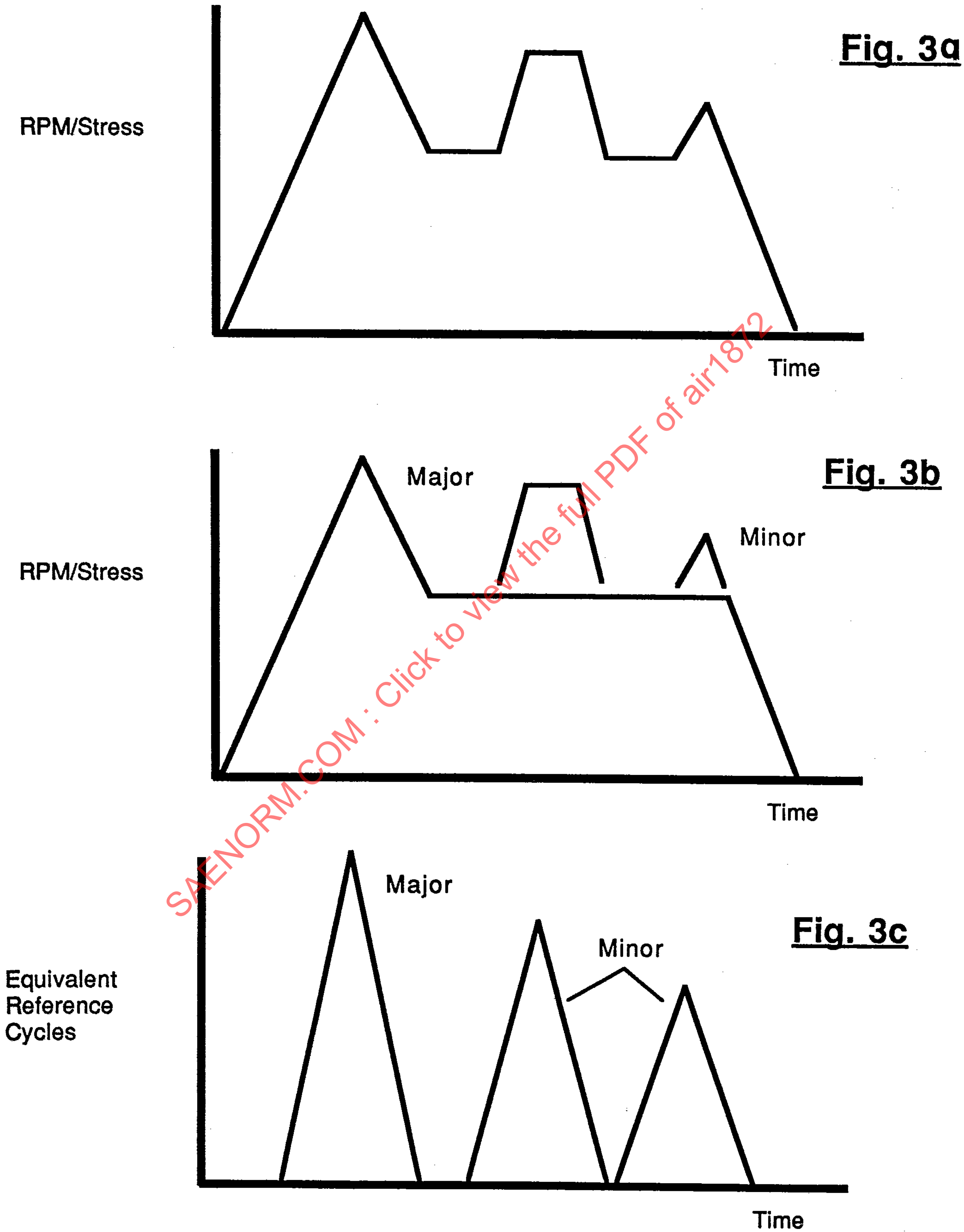
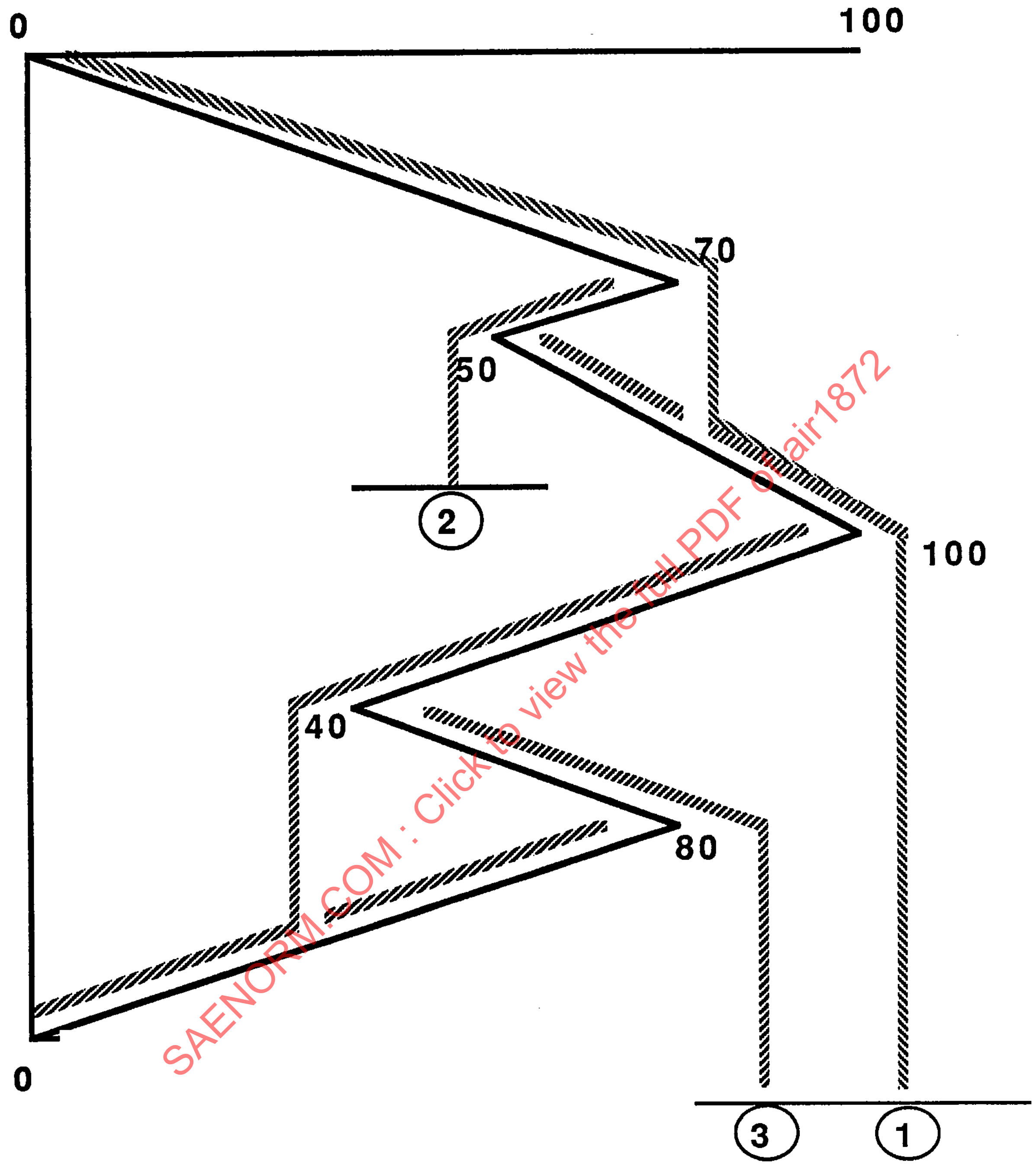


FIGURE 3 - Major and Minor Cycles



1 = MAJOR = 0 - 100 - 0
2 = MINOR = 70 - 50 - 70
3 = MINOR = 40 - 80 - 40

FIGURE 4 - Rainflow Method

5.5.1 (Continued):

For mechanically induced LCF, rotor speed is all that is required. It should be noted however, that 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 suitable for mechanically induced LCF, evidence indicates that more sophisticated cycle counting methods need to be developed to operate in conjunction with thermally induced LCF because of the likelihood of negative stresses as well as positive stresses.

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. In this situation, during steady state and rapid engine throttle transients, large temperature gradients occur 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 are acquired by extensive measurement of temperatures during engine testing and by heat transfer predictive models. Also required are extensive laboratory material LCF specimen tests conducted over the range of transient induced temperatures and strains that occur in the component during engine operation.

Life prediction and usage measurement, in each case, is condensed to a Miner's Rule summation for the 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 components limited by thermal fatigue is similar to that for conventional LCF.

5.5.3 Creep: Establishing the 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 the various stress levels. Analysis and development test experience provide the correlations necessary to determine the stress and strain levels based on temperature and rotational speed. 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 methods used will depend on the type of engine operation being considered and will be in terms of 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.

5.5.3 (Continued):

A typical function of implementing percentage life usage for a turbine component is presented in Fig. 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 Fig. 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 are designed to operate under normal engine operating conditions. It is crucial to monitor the behavior of the engine for limit exceedances that can seriously affect the service life of a component and sometimes result in extensive damage to critical areas of the engine.

Typical exceedances include:

a. Rotor overspeeds.
b. Turbine overtemperature.
c. Surge/stall.
d. Hot starts.
e. Vibration.

Limit Exceedance/Incident Recording is usually performed by configuring the software in the EMS to recognize specific conditions and trigger the recording of data surrounding the exceedance for subsequent diagnosis.

5.6 Parameter Requirements: The parameter measurements required for life usage monitoring are determined by the engine manufacturers at the time 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 speeds.
b. Exhaust gas temperature.
c. Torques.
d. Pressure altitude.
e. Indicated air speed.
f. Time.

Sampling rates must be such that for each input parameter the frequencies are high enough to enable unambiguous recovery of the time variation of that parameter and to avoid aliasing errors, but not so high as to generate an unnecessary excess of data.

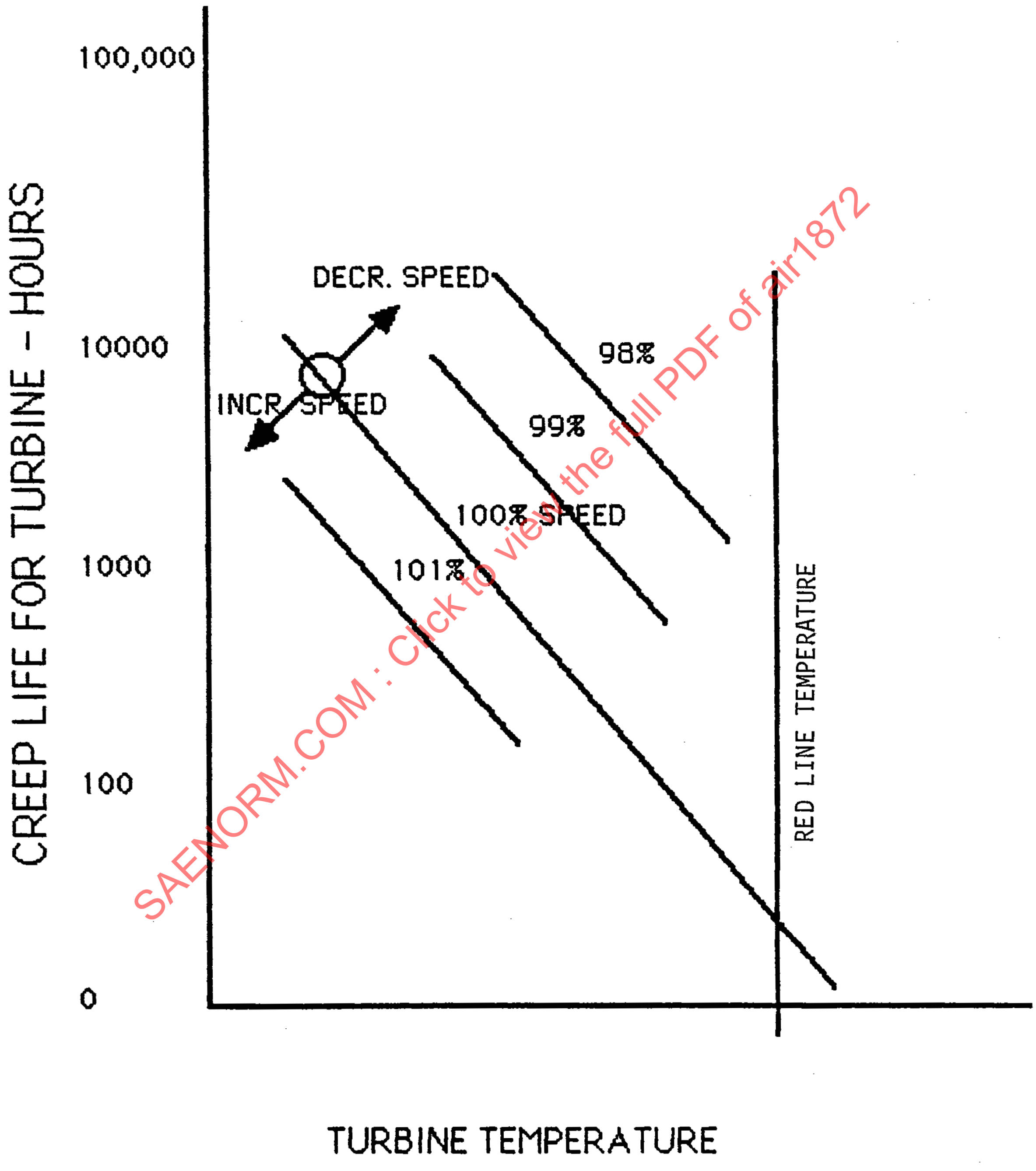


FIGURE 5 - Percent Life Usage Implementation

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 where 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 any lifeing 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 as a function of 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.

6. METHOD VALIDATION:

Prior to the introduction of a life usage monitoring system to operational service, it is necessary to validate the technique that is to be employed. 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 ensures the qualification of the life usage monitoring function 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 of correlative evidence. However, initial information in support of this objective for military engines can be usefully acquired through the use of a simulated mission endurance test (SMET). Similarly, commercial engines are subjected to certification and endurance tests. These too can be used to acquire information on life usage.

Defining a SMET duty cycle begins with an intensive survey of flight records together with pilot interviews at Training and Operational Squadrons. These surveys result in the definition of the required number of mission profiles for the particular aircraft involved, depending on whether it is for military or commercial use and a new or existing aircraft.

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 dramatic differences from the older engine specification endurance qualification test cycles. For illustration there may be less time at high power, very much more time at idle and significantly more cyclic variation per flight hour than demanded by some older test requirement.

6.2 System Validation: A life usage algorithm shall generally be developed on a mainframe or mini-computer in the engine manufacturers' Stress Analysis area, using simulated or test data. The translation of the algorithm for use in an engine monitoring system can lead to the possibility of slight differences between the two software implementations. Therefore, it is important that the EMS data processing emulate the original software implementation as closely as possible to ensure that the differences are kept within acceptable tolerances. Differences of 5% have been accepted in some past developments, but it should be possible to achieve a much better correlation.

The procedure for performing out the comparative testing usually involves the use of a number of selected data records, which collectively can exercise all aspects of the algorithm. Simple acceptance of the final life usage results, although useful, is a good indicator that the software conforms to specification but is not entirely adequate. A more complete correlation is achieved by comparing the values of the derived stresses and other critical parameters after every execution of the 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. The user requirements for engine monitoring data are dependent upon the management decisions at specific support levels. Typical maintenance levels are:

a. Engine shop.
b. Depot and overhaul facilities.
c. Manufacturer.

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 parts life records. 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 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, the repair is beyond local capability, or if technical orders specify the return based on 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 for repair. Also, depot level management requires fleet average calculations for planning purposes.

The engine manufacturer also has an interest in engine historical and usage data so that he may develop improved maintenance support for in-service operation and provide expertise in the identification of 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 shall also enable the life usage analysis of a part not originally considered to be life-limited, or for re-assessing life usage of a part. 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 AIR have shown the necessity for accumulating data on gas turbine engine service history and mission profiles. This requirement has led to the development of on-board monitoring systems for data acquisition. Some of these systems provide complete mission usage data for small groups of aircraft, while others provide real-time calculations of life usage for large fleet applications.

These on-board data acquisition and processing systems collect a significant amount of data. To track the utilization of life-limited parts from engine to engine, these data must be down loaded into a ground-based facility for further processing, decision making and archiving.

7.2 (Continued):

In order to maximize the benefit of these data, the time period between data down-loading and further application must be kept as short as possible. This is also necessary for the maintenance of accurate and up-to-date engine records.

7.3 Data Base Management System: Design of record-keeping system software for information feedback requires that the implementation of data management and bookkeeping techniques 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 engine overhaul.

c. Support of On Condition Maintenance (OCM) including resource scheduling, opportunistic maintenance and removal predictions.

d. Spare parts provisioning and logistics support.

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. It is desirable that the processing, data base architecture and data management logic be general. Acceptable software design should avoid customization to specific application equipment whenever possible. However, the logic should be designed primarily to manage engine, modules and engine 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. Nightly backups of the database are recommended, and data that falls out of the storage window should be stored on archive tapes. These procedures ensure database integrity.

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

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 is achieved by systematically structuring the on-line query command language. A flexible command structure with automatic report generation supports users of all levels of sophistication.

It is imperative that data integrity be maintained. Gaps in the data must be identified and resolved. It is imperative that manual transcription 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 as a cost-effective system for providing managers with information in a suitable format at the appropriate time to assist in their decision-making process. Items of concern in selecting an operating system include multi-user capability, real-time operational tasks, and interactive graphics. Standardization of software, hardware and interfaces achieves low-cost implementation, replication and system maintenance.

A computer processor, which shall support a large number of user partitions for engine management, 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 the computer processor and with data acquisition units.

7.6 Information Interfaces: On-line displays for engine management can be graphic, tabular or both. Plots, histograms and statistical displays are generated by graphics software. 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 the specific application.

The data management system must have support software to handle 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. Use of engine monitoring 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. At these sites they 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, enhancing logistics planning for the powerplant, while maintaining or improving flight safety. Current life predictions are sometimes applied conservatively. Data accrued from an airborne life usage measurement system shall provide information on critical components (LCF and hot end factors), enabling more efficient use of life remaining in modules and engines. Not only shall this improve hardware management decisions on cost grounds, but could improve safety of flight by preventing failures of critical components. The comprehensive fleetwide data base that is produced shall have significant inputs into component improvement programs, assist in analysis of mission profiles, and provide 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. Provisioning

With an accurate assessment of future missions to be flown, 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 minimized.

b. Opportunistic Maintenance

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

c. 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.

d. 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.

8. (Continued):

EMS data can play an important part in engine development, product improvement and engineering support programs. Usage data accumulated from a fleet of engines can provide valuable information inputs into current engine product improvement programs and into 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: The U.S. Joint Logistic Command Ad Hoc Group on standard military engine warranties suggests in the draft of their development guide that logistics support is a factor necessary to establish meaningful warranty objectives. This 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. The TAC cycle was originally defined as a means to provide warranty tracking 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. TAC is based on the following relationship:

$$TAC = LCFC + (FTC/4) + (PTC/40)$$

8.1 (Continued):

where:

LCFC - Low cycle fatigue cycles:
Intermediate and above and back to Off as measured by the EMS.

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 as a candidate for any minimum equipment list required for flight. This does not necessarily imply required system redundancy but instead 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.

For example, one Navy warranty notes 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.

APPENDIX I

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 insuring safety and eliminating the occurrence of structural durability problems during production, acceptance testing, service operations, and 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 Fig. 6). It requires that certain critical parts, 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 insure 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 shall be used 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 setup 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 nondamaging portions of the missions, such as extended steady-state cruise time. This results in an acceleration rate from 2 - 10 for a trainer mission to a bomber mission, respectively. 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 insure safe and cost-effective usage.

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

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INTRODUCTION TO ENSIP

THE ENSIP TASKS

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

FIGURE 6 - Engine Structural Integrity Program

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 Fig. 7). 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.

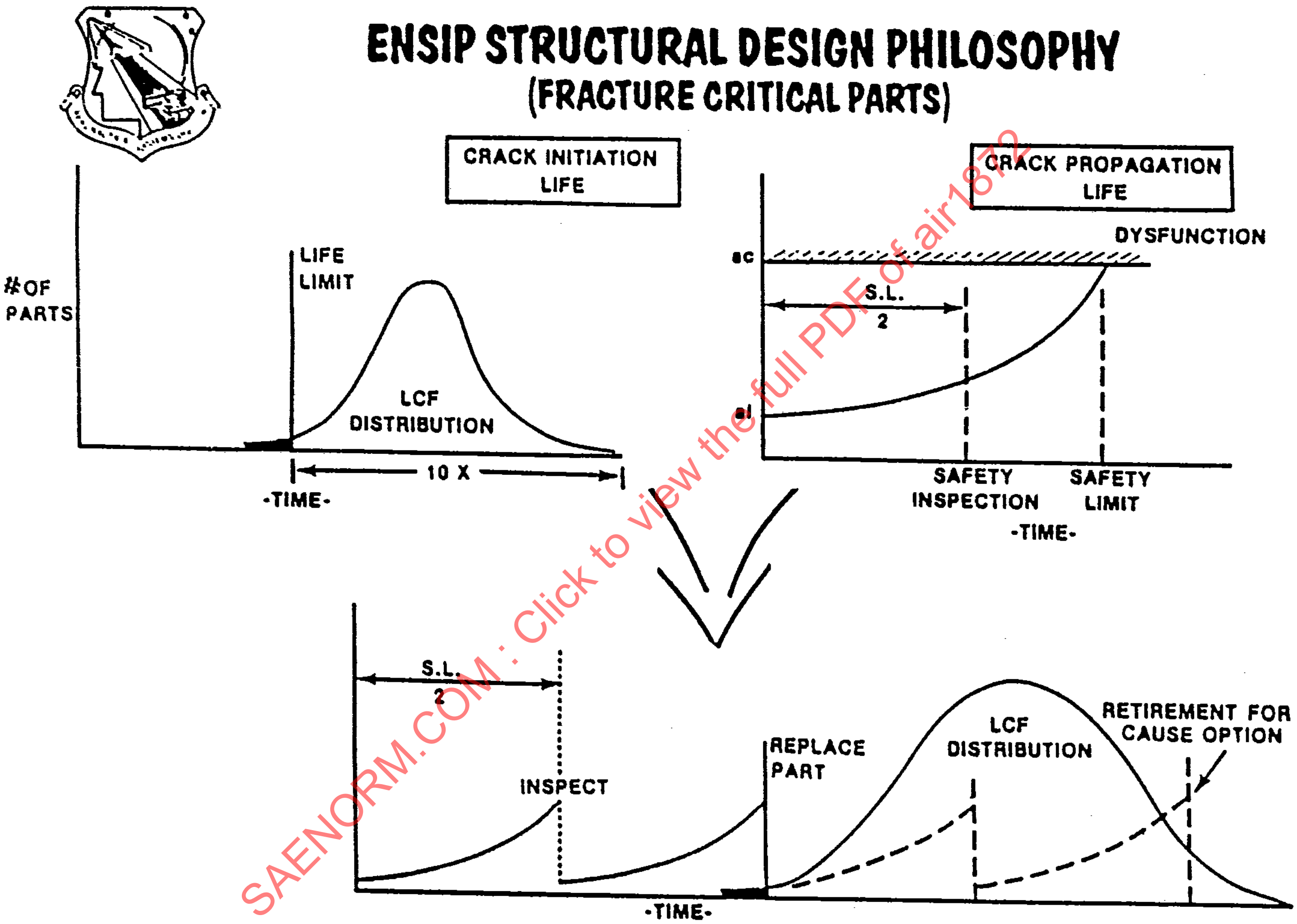

FIGURE 7 - ENSIP Design Philosophy

APPENDIX II

Life Usage and Parts Management Systems

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 realtime, 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. The following sections describe some of the (current) systems and others that are in development.

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, FTIT and a discrete signal, all from the electronic engine control.

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.

A redesigned unit has been developed and incorporated to replace the original version. The primary reason for a new EHR is improved reliability. 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 controls diagnostic capability.

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

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 65 000 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 ohms
14.	Low Cycle Fatigue Type IV		N2 increases from 11 500 to 12 500 RPM

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 all of the above applications, the following functions or indices are counted:

a. Engine Operating Time
b. Low Cycle Fatigue Cycles
c. Full Thermal Cycles
d. Cruise-Intermediate-Cruise Cycles
e. Augmentor Operating Time
f. Augmentor Cycles
g. 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.

1 Total Accumulated Cycle = 1 Low Cycle Fatigue Cycle
+ 1/4 Full Thermal Cycle
+ 1/40 Cruise-Intermediate-Cruise Cycle

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

a. Engine Operating Time
b. Equivalent Low Cycle Fatigue Cycles
c. Equivalent Time-At-Temperature
d. Augmentor Operating Time
e. 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.

TF-30 Jet Engine Monitor

The JEM (Jet Engine Monitor used on A-7C aircraft with TF30-P-408 engine) monitors a number of critical in-flight engine parameters and automatically presents a readout of engine health status to ground maintenance personnel.

The primary purposes of the JEM system are the following:

a. Engine Speed and Temperature Over-Limit

During engine starting and sustained operation, the duration that turbine inlet temperature (TIT) exceeds preset levels is recorded. The preset levels are those established by the engine manufacturer above which certain maintenance action is required. The extent of maintenance is determined by the severity (duration and magnitude) of overtemperature. A coded overtemp maintenance requirement is displayed along with the overtemp data to indicate the extent of maintenance required. Similarly, the duration of high compressor rotor speed (N2) above preset levels is also recorded. In the event of multiple excursions of TIT and N2 above a given preset level during a single engine run, only the highest exceedance and its duration is retained and recorded by the JEM.