



LIFE PREDICTION AND EXTENSION OF LEGACY GAS TURBINE AERO ENGINES THROUGH REENGINEERING AND NOVEL TECHNIQUES: A SAFETY AND RISK-BASED ANALYSIS

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ABSTRACT

Gas Turbines are subjected to inherent degradation and deterioration due to their environmental & operational conditions, and Legacy Gas Turbine Aero Engines (LGTAEs) are no exception and more so with their increased age. This results not only in reduced performance but also in increased SFC, the cause of the emissions. Moreover, with no support from OEMs, the LGTAEs have almost all become obsolete and defunct leading to premature loss. The primary purpose of this paper is to analyze and improve the life prediction and extension of LGTAEs through Reengineering, novel techniques, and methods. The Reengineering in this context incorporates Novel Design, Manufacturing, and Maintenance techniques/methods wherever required. Exploratory and descriptive research analysis has been used to identify the Current and Novel Techniques that can be applied to accurately predict and extend the Life of LGTAEs. The paper identified the application of Current and Novel Techniques as an Integrated Approach to LGTAEs has a greater scope in accurate prediction and extension of LGTAEs. This is demonstrated by carrying out a critical analysis of the Novel Techniques and illustrating how these Techniques and Methods when applied in real-time incidents produce significant positive results. The Novel Techniques studied and analyzed in this paper are Engine Systems and Component Analysis, Gas Path Analysis, Reliability, Availability, and Maintainability (RAM) Analysis, Digital Twins, Risk Based Maintenance (RBM) Analysis, Fatigue Analysis, Safety by Inspection, and Corrosion Prevention Techniques. Finally, the paper studies and investigates the investment recovery of the investors and operators of LGTAEs through Reengineering, Novel Techniques/Methods, and Upgradation/Modification.

Keywords: Legacy Gas Turbine Aero Engine (LGTAE), Reengineering, Systems and Component Monitoring, Gas Path Monitoring, and Analysis, Fatigue, Life Limited Parts (LLPs), Reliability Centered Maintenance (RCM), Reliability, Availability, Maintainability, Risk Based Maintenance, and Analysis, GHG Emissions, Safety, Lean Maintenance, SCM

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1. INTRODUCTION

The modern turbo engine is one of the finest examples of engineering ingenuity, complexity, and usefulness. The turbo-engine, whether used in land-based power-generating equipment or aircraft propulsion, has profoundly impacted our lives. Increased air travel, rising fuel prices, and environmental concerns have all combined to increase the need for more fuel-efficient engines [5]. Although the reliability of engines has improved considerably, many legacy engines continue to operate. The maintenance of legacy engines is a major burden for their operators owing to the high cost involved, and the engines pose a high risk to flight safety. LGTAEs suffer degradation in performance with usage. With the usage of the engine, the condition of the engine components degrades. Due to this degradation, the performance of the used engine does not match the prediction methods and analysis unless accurate performance testing methods are in place. The analysis of the gap between the performance prediction of LGTAEs and the actual measurement is critical for flight safety and reliability [4]. The primary aim of RCM which includes Maintenance, Diagnostics, and Prognostics (HUMS, EHM, and PHM) is to estimate the performance degradation of LGTAEs.

Like any other gas turbine, fatigue, and creep are the most common problems that LGTAEs might encounter. Fatigue crack initiation and propagation are common defects in turbine components. Turbine casing may encounter thermal fatigue phenomena, which is Low Cycle Fatigue (LCF) that appears because of time-variable temperature gradients during turbine working cycles. Some LGTAEs and their casings are very susceptible to cracking at critical points. According to studies, thermal fatigue is specified as the main reason for the creation of cracks.

Modern gas turbine engines are not only powerful but also very reliable. Owing to improvements in materials and the type of coating in combination with developments in cooling technologies, the normal operating parameters have changed to such an extent that currently, the inlet temperature of the engine turbine can exceed 1000°C. Paradoxically, increased reliability makes risk assessment more difficult because engine failures seldom occur. There is a pressing need to evaluate the risk of failure and the effective implementation of the corresponding maintenance actions because engine failure can have catastrophic results. The projected risk has wide prediction bounds owing to the dearth of failure data which could be a reason for the slow evolution of prognostic technologies.

The operations of LGTAE are in a critical state with high downtimes, low availability, and high maintenance lead time resulting in huge losses to the operators. The Serviceable and Operational Life of LGTAE is decreasing over time because of older metallurgy used, primitive/outdated Diagnostics and Prognostics Integration, and non-availability of serviceable spares. Moreover, it is identified that the amount of research carried out in improving the Prediction and Extension of Life of LGTAE is far less compared to CEO Engines.

It is argued unless the operators employ a Re-engineering approach for accurate prediction and extension of the Life of LGTAE, there would be more premature losses of LGTAE leading to the Grounding of all LGTAEs resulting in big losses to the operators/industry. This paper tries to enhance the awareness of LGTAE operators on the scope of extension of the Life of LGTAE through the application of Integrated Re-engineering on LGTAEs. The Integrated Re-engineering comprises the usage of Novel Techniques on LGTAEs through an integrated approach for the extension of the Life of LGTAEs.

This Paper is more of a Technical Analysis of Potential Solutions from Existing and Emerging Technologies that can be applied to LGTAEs to predict and extend their Life. It is found there has been a significant amount of research carried out on Gas Path Analysis to improve the Predictive Maintenance of LGTAEs, but it is observed from the Literature Survey that there is less research done on Aero-Engine Systems Monitoring that focuses on the Extension of Life of LGTAEs. This Paper aims to explore Aero-Engine Systems Monitoring along with the application of Emerging Novel Techniques to enhance the RUL of LGTAEs. The following sections will delve into the analysis of various novel concepts and techniques that can become potential solutions to the current issues encountered by LGTAEs.

2. RELIABILITY CENTERED MAINTENANCE

RCM may be defined as a process to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context. RCM is a maintenance strategy to increase Reliability & Availability cost-effectively [11].

2.1. RELIABILITY

Reliability is a design feature and even with the best of the maintenance techniques, it can only be restored to the design level [11]. An increase in reliability requires high developmental costs and then to maintain this reliability with time, good maintenance techniques are required (Fig. 4). Often a Reliable Gas Turbine can be let down because of inadequate installation and/or auxiliaries. The reliability/cost relationship is given below (Fig. 4). It is seen that though the resultant cost of achieving high reliability reduces with an increase in reliability, the cost of achieving and maintaining this rises rapidly. There is thus a compromise between reliability and cost and equipment cannot be designed for 100% reliability [11].

Since reliability decreases with age, there is a requirement to restore it to the designed value, which can only be achieved through proper maintenance techniques [11]. It is not only desirable to have a good maintenance technique, but this should be achieved at the minimum possible cost. Reliability may be defined as the probability of not being forced out of service when the unit is needed including forced outage hours (FOH) while in service, while on reserve shutdown, and while attempting to start normalized by period hours (PH)- units are %:

Reliability = $(1 - \text{FOH/PH}) * (100\%)$ where FOH = total forced outage hours, PH = period hours

2.2. AVAILABILITY

Availability: Probability of being available, independent of whether the unit is needed- includes all period hours and mean time between failures - units are %

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{Downtime}}$$

MTBF = Mean Time Between Failure and depends on Reliability
Downtime = Outage Hours

The relationship between availability, downtime, and MTBF (related to reliability) is given below (Fig. 1).

One sees that for the same MTBF the availability is inversely proportional to the downtime, and for the same downtime, it varies directly with MTBF, and hence reliability[11]. Of these MTBF is influenced by the same factors as reliability, whereas downtime is influenced by such factors as whether the gas turbine design is modular, whether the instrumentation provided and diagnostic capability is adequate, and whether access for inspection (for example, sufficient borescope holes) and for change out of components is good. Design aspects will affect downtime and factors such as spare provisioning, documentation, trained personnel, and ready access to suitable specialist facilities will also affect the downtime (Table. 1).

Factors (Design and Maintenance Planning) Affecting Downtime of LGTAEs
Modular Construction
Advanced Instrumentation
Diagnostic Capability (Advanced HUMS)
Access for Inspection
Spares Provisioning
Documentation
Buffer Availability
Availability of Tools, Testers, and Ground Equipment (TTGE)
Trained/Skilled Personnel
Specialist Facilities
Lean Aviation Maintenance

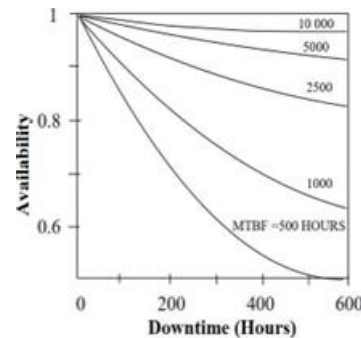


Table 1 Factors Affecting Downtime of LGTAEs

Figure 1 MTBF, Downtime, and Availability [11]

2.3. MAINTAINABILITY

Maintainability is the ease at which an airplane or an aero-engine can be kept airworthy by the operator. Maintainability is directly related to ease of manufacturing. Complicated manufacturing processes can result in an aircraft that is both hard and costly to maintain. Maintainability also extends to the ergonomics of repairing. Are expensive tools required? Will the mechanic need to contort like an acrobat to replace that part? Will it take 10 hours of labor to access a part that will take 5 minutes to replace? Maintainability describes how quickly and easily your technicians can perform necessary repairs and get assets back to their normal operating conditions [17]. An asset with low Maintenance Time To Repair (MTTR) is highly maintainable.

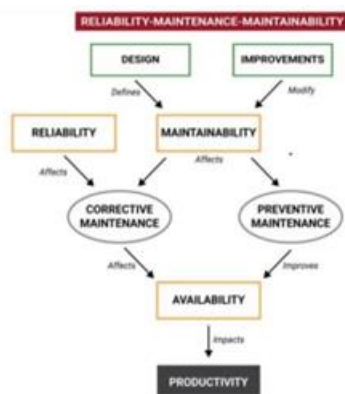


Figure 2 Maintainability and its relation with Reliability and Maintenance [17]



Figure 3 Reliability, Availability, and Maintainability (RAM) [17]

2.4. RAM ANALYSIS AND ITS IMPACT ON THE LIFE OF LGTAEs

Reliability, Availability, and Maintainability (RAM) are design attributes of a system or an asset (Fig. 3). They hold great importance, not just to Design & System Engineers, but to Operators and Maintenance Professionals as well (Fig. 2). Collectively, these parameters are leveraged to improve the productivity of the asset over its life cycle by reducing waste, maximizing profit, and ultimately, optimizing its overall life cycle costs (LCC).

Reliability, Availability, and Maintainability have to be studied together, analyzed, and applied to improve the Lives of LGTAEs and CEO Engines [17]. This is because these parameters are interdependent and often in conflict with each other. In other words, improving one parameter will likely result in the deterioration of the other two. For example, in case one, if we introduce a complicated diagnostics system to an LGTAE, which can improve its inherent reliability, however, complicating the design or the modification can proportionally increase the time maintenance technicians have to spend on routine maintenance, reducing its maintainability. In case two, the maintenance instructions can be made overly simple. For example, you can increase maintainability by reducing the number of items to sign off on your preventive maintenance checklists. However, this will likely result in some parts of the machine not being properly inspected, increasing the probability of failure and decreasing its reliability.

The application of RAM Analysis throughout the equipment life cycle will have a significant impact on the Performance and Life of an Equipment/LGTAE. RAM Analysis is generally performed at the design stage by a team composed of Design, Systems, and Reliability Engineers [17]. However, the analysis can be repeated throughout the life cycle of an asset by Maintenance and Service Reliability Engineers who have key information on Performance and Health and Usage Monitoring Systems (HUMS). It is even found from the research that a Safety component has to be added to the RAM Analysis making it RAMS analysis to achieve increased life of the Equipment/LGTAE with improvement in safety levels. The usage of RAM Analysis during the Service Life of an Equipment/LGTAE/CEO Engine will have a greater effect on the evaluation of the current state/condition of the asset/LGTAE as assets rarely operate in ideal operational and environmental conditions and each LGTAE has a unique life experience.

2.5. STUDY OF VARIATION IN THE LIFE OF TWO SIMILAR LGTAEs/CEO ENGINES

It is found in the study and observed from operations that Two identical assets that are installed in different operating environments may perform differently and have very different lengths of useful life [17]. This difference and variation could be due to a range of factors such as Extreme Weather/Operating Conditions, Manufacturing Deviations, Diversity in Training, Competency of Staff Operating and Maintaining the equipment, Adherence to maintenance procedures and practices as per Service Manuals issued by the OEM, and the Quality of Spare Parts fitted in the CEO Engines/LGTAEs (Table. 2).

The above-mentioned factors conclude and confirm that assets/LGTAEs will have varying failure rates [17]. Therefore, RAM analysis during the operations phase should include and account for the operating and environmental conditions the individual/particular engine is subjected to assess the associated failures/failure rates. The corresponding loading actions/life cycles are carefully examined and investigated to identify the cause of the failure and the extent of damage.

FACTORS CONTRIBUTING TO VARIATION IN THE LIFE OF TWO SIMILAR LGTAEs
Extreme Weather/Operating Conditions
Manufacturing Deviations
Diversity in Training
Competency of Staff Operating & Maintaining the Equipment
Adherence to Maintenance Procedures & Practices of OEM
Quality of Spare Parts Fitted in LGTAEs

Table 2 Factors Contributing to Variation in the Life of Two Similar LGTAEs [17]

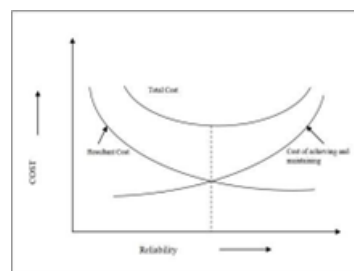


Figure 4 Cost/Reliability Relationship [11]

3. LGTAE CONDITION MONITORING THROUGH CRITICAL ENGINESYSTEMS AND COMPONENTS MONITORING

Aircraft engines constitute a complex system, requiring adequate monitoring to ensure flight safety and timely maintenance [12]. During Aircraft and Engine Operations, Cockpit displays indicate engine performance through vital information such as rotational speeds, engine pressure ratios, exhaust gas temperatures, etc. Oil supply to critical parts, such as bearings, is vital for safe operation. For monitoring fuel and oil status, indicators for quantity, pressure, and temperature are used. In addition to these crucial parameters, vibration is constantly monitored during engine operation to detect possible unbalance from failure of rotating parts, or loss of a blade. Any of these parameters can serve as an early indicator to prevent costly component damage and/or catastrophic failure, and thus help reduce the number of incidents and the cost of maintaining aircraft engines [12].

This is facilitated by Engine Monitoring Systems (EMS), which have become standard in the last two decades with advances in aircraft engines and computer technology. The current state of Practice focuses on using some form of EMS on all aircraft, especially military ones [12]. However, the LGTAEs, with older technology are equipped with Primitive EMS that have access to limited data, which is not so accurate to monitor their performance and rely more on Preventive Maintenance. Integration of Advanced and Augmented EMS to LGTAEs will help LGTAEs to identify impending failures in advance to prevent catastrophic accidents and extend their life. However, the Integration of Augmented EMS to LGTAEs may make the system complex and require additional training for the operators to operate the LGTAEs with the Augmented Technology, but the benefits associated with it far exceed the limitations.

The critical engine systems and components monitoring including key parameters that act as indicators of developing defects due to GT Faults and impending failures because of inherent degradation and deterioration are reviewed in this paper. Engine performance monitoring, a current trend in monitoring the gas turbine engine's day-to-day condition, is proving to be very effective in providing early warning information of ongoing or impending failures, thus reducing unscheduled delays and more serious engine failures. Nonetheless, the presence of primitive prognostics and limited monitoring systems in LGTAEs has a significant impact on the Safety & Reliability of LGTAEs and demands for Augmented Prognostics. Moreover, with old metallurgy, the LGTAEs are subjected to a higher amount of Fatigue than CEO & NEO engines in operation and require the replacement of current devices and sensors with augmented technology to improve their Safety & Reliability. The Research of critical engine systems and component monitoring of LGTAEs using advanced technology, sensors, and devices would contribute to early warning and accurate Life Prediction of LGTAEs resulting in extending their life.

3.1. TYPICAL PARAMETERS FOR EMS (INSTALLED ENGINE AND UNINSTALLED ENGINE)

The Typical Parameters recommended for monitoring both the Installed Engine and Uninstalled Engine are given below (Table. 3). The number of parameters monitored on the engine varies both in the installed and uninstalled condition. These parameters will reflect the condition of not just the Critical Gas Path Components, but also the Critical Engine Systems, which helps in assessing the performance and condition of CEO/NEO Engines or LGTAEs.

The number of parameters monitored in the Installed Engine Testing is less because of limitations in data capturing, space for EMS, etc., and does not give a clear picture of the damage and snag to the engine, whereas, with the Uninstalled Engine Testing problem does not arise due to scope for more data capturing and absence of such limitations. The condition and Engine Health Monitoring (EHM) becomes more accurate.

TYPICAL ENGINE PARAMETERS MONITORED			
INSTALLED ENGINE PARAMETERS (COCKPIT)	UNIT (MEASUREMENT)	UNINSTALLED ENGINE PARAMETERS (ENGINE TESTBED CONTROL ROOM)	UNIT (MEASUREMENT)
N1/NL (PORT)/(STBD)	% RPM	OUTSIDE AIR TEMPERATURE (OAT/T ₀)	°C
N2/NH (PORT/STBD)	% RPM	T1, T2, T3, T4, T5, T6	°C
EGT (PORT/STBD)	°C	(TEMP AT VARIOUS ENG STATIONS)	
EPR (PORT/STBD)	DIMENSIONLESS	AMBIENT PRESSURE (P ₀)	PSI/BAR/KPA
FUEL QUANTITY INDICATION (FQI)	KG	P1, P2, P3, P4, P5, P6, P7, P8	PSI/BAR/KPA
FUEL FLOW (FF)	KG/MIN	(PR AT VARIOUS ENGINE STATIONS)	
OIL QTY	KG/LTR	MASS FLOW (M1)	KG/SEC
OIL TEMP	°C	FUEL FLOW (FF)	KG OR LB/SEC
OIL PR	PSI/BAR	NL - LP SHAFT SPEED	% RPM
VIB - N1/NL (PORT/STBD)	MICRONS	NH - HP SHAFT SPEED	% RPM
VIB - N2/NH (PORT/STBD)	MICRONS	THRUST (Xg)	lbf/KN
		FUEL TEMP (FLOW METER/SPRAY NOZZLE)	°C
		VIBRATION (TANGENTIAL/RADIAL)	MICRONS
		OIL QTY	KG
		OIL TEMP	°C
		OIL PR	PSI/BAR

Table 3 Typical Aero-Engine Parameters Monitored

3.2. BENEFITS OF CONDITION MONITORING AND DIAGNOSIS

Certain kinds of engine failures will result in specific changes in the parameters being monitored. The standard means of monitoring parameters involves the comparison of parameters to reference levels or evaluating shifts through time by trending [12]. Some parameters that exceed the operating limit are recorded for future use and operating limits for such are typically set by the engine manufacturers based on design performance models and by operators based on field experience from other aircraft and engines.

Condition monitoring helps in identifying the most probable cause of the exceedance of the parameter and estimating the possible damage. Establishing Troubleshooting procedures and expert system diagnostics by the operators of LGTAEs will address the technical snags efficiently with minimal time to recovery. The design of Advanced Diagnosis methods and techniques will help in discriminating between data characteristics from an acceptable condition and trends that are associated with developing faults. Advanced Diagnostics aims to replace the standard threshold setting and fault detection process by enhancing the feature extraction capabilities. Automated and advanced diagnosis tools aim to provide the automatic generation of more meaningful and accurate fault diagnostic information [12].

3.3. ENGINE SYSTEMS MONITORING

The Engine Systems monitoring is generally done both online and offline. The online monitoring is carried out during the Flight by the Pilot and Flight Test Engineer and any anomalies, deviations, and abnormalities can be recorded and passed to the Maintenance Line. In contrast, Offline monitoring is being done during Maintenance, Diagnostics, and Prognostics by the Maintenance Personnel. In both monitoring methods, the Visual Monitoring technique is mostly employed apart from Advanced Diagnostics, Prognostics, and Digital Twins which are used, to be used and developed in the Operations and Maintenance of GT Engines. Online monitoring involves Fuel, Oil, Air, Starting, Ignition, Vibration, Fire Systems, etc, whereas offline involves all systems being monitored during Preventive Maintenance and Diagnosis (Corrective Maintenance) visually. The online monitoring consists of Fuel Consumption, Fuel Flow, Fuel Pressures, Temperatures, Oil Consumption, Pressures, Temperatures, Starting and Ignition Procedures, Fire Warnings, etc. The offline consists of Oil System Debris Monitoring using Magnetic Chip Detectors, Fuel, and Oil Filters, Physical Checks, etc.

It is found in the Literature Survey and from the Operations of GT Engines that the Control Systems, Fuel, and Oil (Lubrication) Systems experience more technical snags than the other systems (Table. 4). The Control Systems consist of a Full Authority Digital Engine Controller (FADEC), Electronic Engine Controller (EEC), Engine Control Amplifier (ECA), Throttle Control System (SIFCO, Cam Rods, Box, etc), Bleed Systems (Bleed Valve), Fuel Control Unit (FCU), Afterburner Fuel Control Unit (ABCU) etc. The Research observed and found apart from the Engine Main Fuel System issues concerning fuel control and regulation units in the Control Systems, the Aircraft Fuel System in particular Fuel Tanks experiences outages in the form of Fuel Blockages, Failure to transfer fuel to the Main Engine Fuel System (Table. 4). The Lubrication (Oil) System also confronts the same number of snags in particular Bearing issues, Debris Accumulation, and Oil Pressure Warnings.

Table 4 Engine Systems and Components ranking by Forced outage rate and Forced Outage Total Downtime [11]

Outage Rate	%	Outage Total Down-Time	%
Control System	24.2	Generator	17.0
General gas turbine	19.2	Turbine	16.4
Fuel System	13.1	Compressor	12.0
Lubrication	11.1	General Gas Turbine	12.0
Combustion	8.3	Lubrication	11.5
Generator Control	6.5	Power Distribution	9.6
Power Distribution	5.4	Combustion	7.9
Generator	4.8	Control System	7.5
Cooling System	3.8	Fuel System	4.7
Compressor	1.8	Generator Control	2.2
Turbine	1.1	Cooling System	0.9
Exhaust System	0.6	Exhaust System	0.3

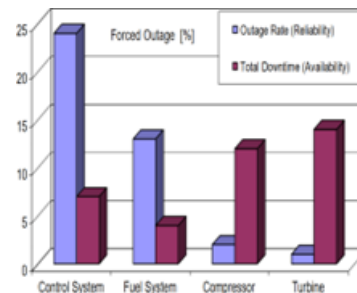


Figure 5 Engine Systems and Components ranking by Forced Outage Rate and Forced Outage Total Downtime [11]

The largest contributors to forced outage rates are often engine support systems such as control and fuel systems (Table. 4 and Figure. 5). It is observed the Fuel System Reliability is very low with an Outage Rate of 13.1 %, however, the availability is high with a downtime of 4.7 %.

The lower Reliability of the Fuel System is largely because of Aircraft Fuel System and Main Fuel and Afterburner Fuel System Control Unit issues. It is interesting to note that the Reliability, as well as the Availability, is less with the Lubrication System with Bearing, Oil Pressure, and Debris issues (Table. 4). The downtime associated with these systems can be managed to acceptable levels by design redundancy and the holding of appropriate spares. Advances in instrumentation and microprocessor-based controllers can be expected to contribute to further improvements in the availability of engine support systems [11].

3.4. GAS PATH COMPONENT MONITORING

The GT Faults such as Fouling, Erosion, Corrosion, Rubbing Wear, etc will have a significant impact on the Component Degradation, and Efficiency which affects GT Efficiencies and Power Output (Fig. 6 and 7). The Component Degradation has a consequential effect on GT Exhaust Temperature variation (Fig. 8). Also, GT Faults affect component mass flows which affect component efficiencies remarkably (Table. 5). Gas turbine rotating components undergo significant excursions in both centrifugal and thermal loads (the latter being time-dependent) and inherently experience thermal stresses and metallurgical fatigue to some extent [11]. Hence some major components such as shafts, discs, and blades, which are subject to cyclic stresses induced centrifugally and thermally, are life-d [11]. These components are very critical to engine safety and may not be contained after fatigue failure. The life of these components is determined by creep and Low Cycle Fatigue (LCF) and they must be replaced after a fixed number of cycles. Generally, the life is calculated based on the assumption that the parts are subject to a mission of fixed severity. In reality, the profile of gas turbine operation is quite different from that assumed.

Accurate profile assumption provides the basis for accurate life estimation. Creep, plastic deformation from prolonged high-temperature operation, is one of the common modes of blade failure and is a function of stress, temperature, and time while thermal fatigue is related to the temperature gradient within the blade. Knowledge of the operating load history is very important to determine thermal stresses which change in a complex manner due to transient differential heating and cooling effects. During design, component LCF life is calculated based on thermal stresses arising from the assumed load history.

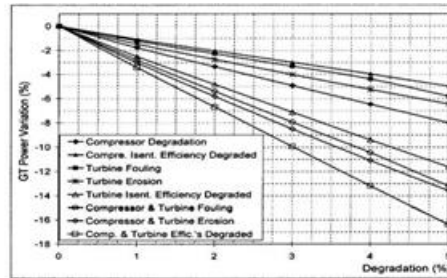
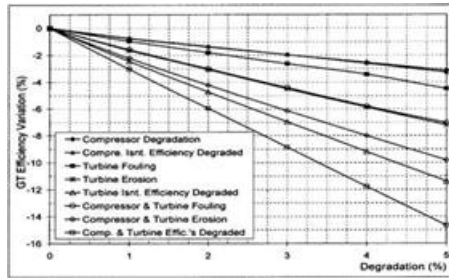
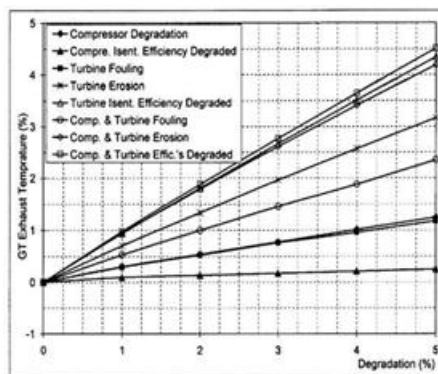


Figure 6 Gas turbine efficiency variation due to component degradation **Figure 7** Gas turbine power variation due to component degradation

However, the actual operating load excursions may be quite different than those assumed. An accurate assessment of the operating characteristics of the engine can help extend hardware inspection intervals, preclude premature removal of parts from service, and prevent excessive conservatism in future design. On the other hand, severe loads warrant shorter inspection intervals and limited-service life [11].



Fault	Represented By	Range
Compressor Fouling	Drop in Γ	0.0 – (-5.0%)
	Drop in η_c	0.0 – (-2.5%)
Compressor Erosion	Drop in Γ	0.0 – (-5.0%)
	Drop in η_c	0.0 – (-2.5%)
Turbine Fouling	Drop in Γ	0.0 – (-5.0%)
	Drop in η_T	0.0 – (-2.5%)
Turbine Erosion	Rise in Γ	0.0 – (+5.0%)
	Drop in η_T	0.0 – (-2.5%)
FOD	Drop in η_c and η_T	0.0 – (-5.0%)

Figure 8 Gas turbine exhaust temperature variation **Table 5** Representation of Component Degradation [11] due to Component Degradation [11]

In contrast to the Engine Fuel System, the major gas path components such as compressors and turbines have high reliability (Table. 4 and Fig. 5). However, when a forced outage is caused by the failure of one of these components, the downtime experienced can be large (Table. 4 and Fig. 5). It is observed that the Outage Rates of the Compressor and Turbine are 1.9 % and 1.1 % respectively, which is considered Highly Reliable, nonetheless, the Availability of the Compressor and Turbine is less with a high Downtime Rate of 12 % and 14 % respectively (Table. 4 and Fig. 5). Both, the high cost of such components, and the low likelihood that they will be required means that they are often not held as spares. Poor assumption of the Loads used during the Design of Critical Components such as Compressor and Turbine, and failure to define an accurate buffer based on the Process, Failure, and Historical (Statistical) Data have a significant impact on the Availability, Maintainability, and Operations of GT Engines/LGTAEs.

3.5. EXTENSION OF POTENTIAL FAILURE TO FUNCTIONAL FAILURE (P-F) INTERVAL USING CONDITION MONITORING

The potential-to-functional failure interval (P-F interval) is one of the most important concepts when it comes to performing Reliability-Centred Maintenance (Fig. 9). Remarkably, the P-F interval is also one of the most misunderstood RCM concepts. The failure mode analysis becomes even more complicated when you are dealing with several P-F intervals for one failure mode [17]. A functional failure is the point where an asset fails to perform a required function. The failure can be a complete or partial failure of any primary or secondary asset function. An example of a complete failure is a Ball or Radial Bearing leading to an Aero Engine/LGTAE In-Flight shutdown or Flameout. An example of a partial failure is a worn impeller in a fuel or oil pump of an Aero Engine/LGTAE that still pumps fluid but not to the required level. Either a complete or partial failure will have an operational impact and will need to be corrected. In some cases, when safety is a concern, the functional failure may not be the actual failure point but a predetermined point that should not be exceeded due to the risk involved. An example of this would be the preset oil temperature of an oil system in an aero engine. This temperature is lower than the point where the aero engine would sustain critical damage. The actual failure would be the loss of the aero engine, but the catastrophic nature of that failure requires an identification before the point of shutdown. This becomes the functional failure of the engine.

A detectable symptom or warning sign that a functional failure is in the process of occurring is a potential failure [17]. Functional failures can have many different potential failure symptoms before the actual functional failure. These potential failure symptoms can occur at different times and are detectable by different methods (Fig. 9). Some of the symptoms include heat, vibration, smell, and cracking (Fig. 9). An example of a potential failure is the increased temperature in a ball or radial bearing before bearing damage. The importance of the potential failure characteristic in RCM is to use an inspection to detect the potential failure before the functional failure occurs. The method of potential failure detection is dependent on the symptom and the methods available and employed. Mostly Prognostics Health Management and Advanced Predictive Maintenance Technologies are employed apart from Physical Checks carried out on LGTAE. In many cases, we can still find the symptoms far enough in advance using physical and visual checks to correct the impending failure even though a predictive technology can detect the failure sooner [17]. Some of the more popular predictive technologies are thermography, vibration analysis, oil analysis, debris analysis, engine usage analysis, and ultrasound.

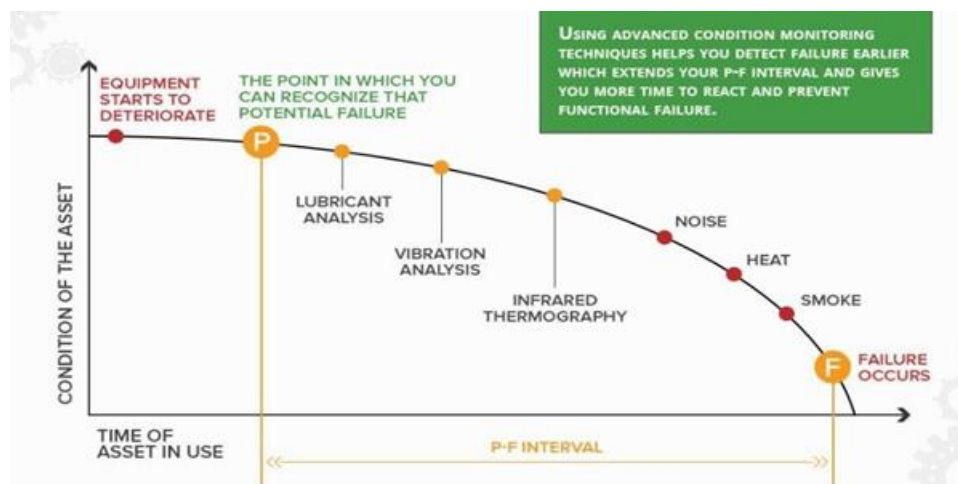


Figure 9 Performance Deterioration of an LGTAE from Potential Failure to Functional Failure [17]

TIMING – A KEY AND CRITICAL ELEMENT IN THE P-F INTERVAL GRAPH

The P-F interval is the time or cycles between the initial detection of the potential failure condition and the time of the actual functional failure (Fig. 9). Most failures do not take the same amount of time to fail after the symptom is detected, so the P-F interval is expressed as an average amount of time or cycles [17]. The P-F is critical in designing the right maintenance task to prevent functional failures. A general example would be to set the task interval for inspection at half of the P-F interval. The Mean Time Between Failure (MTBF) related to the failure is not important when designing the maintenance task because it gives no reference to the time of a symptom of the failure. A graphical representation of the P-F interval is displayed above (Fig. 9). The vertical axis is the functional capability of the asset, and the horizontal axis is the operating age or number of cycles. As the life of the asset goes along, it will come to a point where the symptom appears. This is the potential failure. After the symptom appears, there will be a period until the functional failure occurs. This period is the P-F interval.

MULTIPLE SYMPTOMS

Failure modes that have multiple symptoms of impending failure offer a great deal of flexibility in the choice of tasks to perform for detecting impending failure. Each of these potential failure conditions has a different P-F interval, and it is important to not treat them as equals in the analysis [17]. Every symptom will arise at different times concerning functional failure. An example of this would be a bearing failure. The first symptom may be unusual vibration detectable by vibration analysis around six months. The second symptom may be sound detectable at three months using airborne ultrasound. The third symptom may be increased heat detectable one month before the bearing fails [17]. Treating these symptoms as similar P-F intervals and inspection methods can lead to extensive downtime due to the use of the wrong tool at the wrong time. A graphical representation of multiple P-F intervals is displayed above (Fig. 9).

The probability of detection is the probability of detecting a potential failure condition in one inspection if it exists at the time of inspection. The probability of detection when using any inspection technique will vary depending on certain factors. First, there is the location of the failure and how accessible it is to the professional performing the task. Complex pieces of equipment or small, confined areas create difficulties in performing tasks. Some Unit Components, Sub Systems, and Systems are remotely located and have less accessibility for the inspection and detection of potential failure. Second, the task is complex and the skill level of the professional conducting the task is critical. When determining the task to perform, consider the skill level of the professional who will be normally performing the task. This will help determine the probability of detection. Finally, if there is a technology used to perform a task, it could have limitations that need to be considered. The bottom line is that the lower the probability of detection, the more often you have to inspect to increase your chances of detecting the potential failure.

FAILURE MONITORING

Failure monitoring is the act of continued inspections at an increased level and focus after a potential failure is detected. This allows you to get maximum life out of the asset while still keeping the risk to a minimum [17]. The possibility of monitoring can only be effective if the P-F interval is very predictable and long enough to allow time for monitoring the symptom. In many cases, the monitoring task is a shorter interval than the original task because a potential failure condition exists. Also, remember that it is best not to perform monitoring if the functional failure has safety or environmental consequences.

The Mean Time to Repair (MTTR) is the average time it takes to repair a failure condition. Consider this when looking at the task interval. The MTTR can vary depending on the type of failure - potential or functional. MTTR for the functional failure is used for determining the P-F interval adjustment. In some cases, the MTTR can be very extensive due to repair complexity, lead-time on parts, or availability of skilled service people. In cases where the MTTR is a significant length of time, that amount of time is taken off the P-F interval to increase the task interval, providing a greater possibility of correcting the problem before the functional failure.

RELEVANT MAINTENANCE TASK SELECTION FOR IMPLEMENTATION

Choosing tasks for a specific interval is dependent on several factors [17]. It can be a simple decision process or done with a cost-benefit analysis. The first factors to identify are what tasks can be used to find potential failures and how often the tasks have to be performed. Second, you must identify the resources available to perform the tasks and the possibilities of attaining other resources. Rule out the tasks that will not be options and choose the task or tasks from the remaining options available based on the acceptable impact of the task on safety and operations. A cost-benefit analysis is a powerful tool to perform the selection process, but it is not always necessary.

It is observed apart from RAM Analysis, Condition Monitoring of LGTAEs helps in extending the P-F Interval thus increasing the Life of the LGTAEs. During Infant Mortality, when the Failure Rate is decreasing, the maintenance or inspection levels may not be sufficient to keep the LGTAEs in optimal operating condition. Similarly, during the wear-out zone, when the failure rate starts increasing again, the maintenance levels may again fall short. It concludes that the maintenance levels cannot be kept constant from the Installation of an LGTAE to its Grounded.

Ideally, you will have systems such as Health and Usage Monitoring Systems (HUMS), Component Maintenance Management Systems (CMMS), Component Life Record (CLR), Engine Log Book, Engine Log Cards, etc to monitor the health of the Engine Component as well as the Engine to determine the actual failure rates of the asset. The actual maintenance level could be adjusted corresponding to the failure rates and failure pattern while taking into account the desired trade-off between Reliability, Maintainability, and Availability.

It is advised that the Operating and Maintenance Establishments of LGTAEs and CEO Engines incorporate Advanced Condition Monitoring Systems that provide Real-Time Data about the onset of Potential Failures before they turn into actual functional failures. Asset/Engine Condition Monitoring is a well-known and proven technique for reducing the Failure Rate and extending the P-F interval. The only way to do that is to have the right data and analyze it in the proper context. The P-F Interval is a critical analysis technique to prevent premature losses of LGTAEs and contributes to the accurate prediction and extension of the Life of LGTAEs.

4. GAS PATH ANALYSIS OF A GT AERO-ENGINE

As Aero Engines/LGTAEs operate in harsh working conditions (High Temperature, Pressure, Load, Stresses, etc) repeatedly, the performance of each aero engine/LGTAE will degrade gradually from the time it is put into use, and such performance degradation will increase the risk of aircraft incidents (Fig. 6) [16]. The Gas Path System is the core of an aero-engine. Research shows that gas-path faults cause more than 90 % of aero-engine failures, and the repair and maintenance cost of the gas-path system accounts for about 60 % of an aero-engine's total repair and maintenance cost [16]. The capability of detecting anomalies in the aero-engine in time is essential for the health monitoring of the engine gas-path system. If anomalies in the aero-engine/LGTAE can be detected early, the maintenance team will have enough time to make a sound maintenance plan (Fig. 6 and 8).

The Gas Flow Path of any engine is susceptible to encountering a wide variety of physical problems (GT Faults) such as Erosion, Corrosion, Fouling, Built up dirt, FOD, Missing Blades, Plugged Nozzles, etc. These physical problems/GT Faults result in degraded component performance and produce changes in measured parameters (Fig. 6 and Table. 5). The changes in measured parameters allow the isolation of degraded GT Components and permit the correction of physical problems/GT Faults [11].

4.1. FAULT TREE AND FAULT MATRIX

To monitor for the GT faults various analytical techniques have been devised (Table. 6). Among the more popular are the Fault Tree and Fault Matrix techniques (Fig. 10 and Table. 7). The fault tree examines increases and decreases in various parameters, leads the mechanic through a decision tree, and finally offers a probable fault at the end of the path (Fig. 10) [11]. Similarly, the Fault Matrix method relies on observing changes in engine parameters and comparing them with tables depicting deviations in these parameters for possible engine faults to determine the statistically most probable single fault (Table. 7). These techniques share the limitation that only one fault can be detected within the engine and the technique is unable to offer a solution if two or more faults are simultaneously present within the engine. In addition, these techniques are unable to identify the magnitude of the degradation and therefore they only give qualitative rather than quantitative assessments.

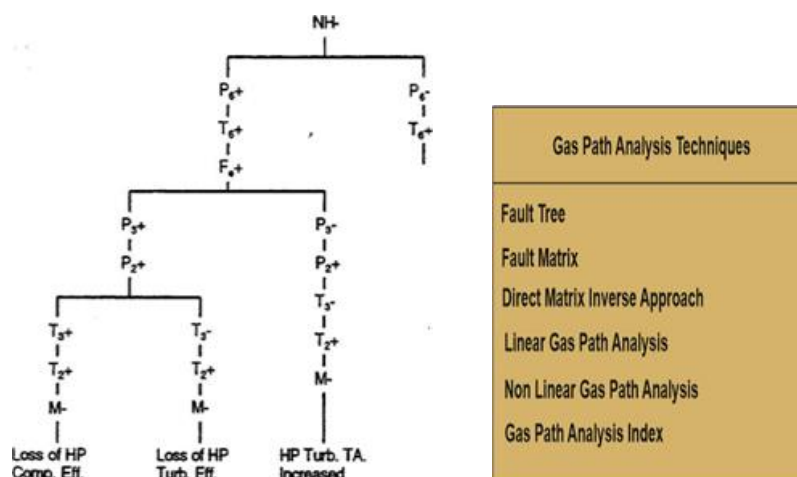


Figure 10 Example of a Fault Tree [11]

Table 6 Gas Path Analysis Technique

Gas Path Analysis (GPA), or more generically, simultaneous multiple fault diagnostics, was first introduced by Urban in 1967. Gas path analysis can be performed using data acquired during routine service on the wing [11]. The on-wing analysis has access to data at some fixed interval. This permits an examination of each new reading to prior readings from the same engine. Deterioration can be recognized as the change in performance from when the engine was new. The objective of the on-wing analysis is to decide when an engine should be removed for overhaul and what the overhaul work scope should be. Gas path analysis is also accomplished using test cell data obtained during an acceptance or in-bound run (Table. 3). The engine's and component's performance levels must be inferred from one or more readings that are obtained at a fixed instant in time. Usually, the test analysis is based on an outbound acceptance run. If the engine satisfies its acceptance limits, there is little interest in the results of the analysis. When the engine fails the acceptance requirement, the data are reviewed to try to determine the minimal rework to correct the problem [11]. Occasionally, an engine removed from service will be run in a test cell to help define its required work scope. This approach, generally called Gas Path Analysis (GPA) first introduced by Urban in 1967 [11].

Apart from, Fault Tree and Fault Matrix Analytical Techniques, some of the other Techniques and Methods that can be employed for Gas Path Analysis of an Aero Engine/LGTAE are given above (Table.6).

Also, the quality of the deterioration calculations is greatly affected by the availability of data. Ideally, it would be best to have a host of dependent parameter measurements available. However, as mentioned at the outset the more complex the system the greater the potential for unserviceability. Therefore, when one is limited to the number of sensors available to measure the data, the selection of which measurements will be taken becomes of vital concern.

Type	Fault	TIT	SHP	m_1	CPR	Vibration	Indication
Turbine (Generator)	Rotor Damage	↑	↑	↑	↑	Yes	η_i Low
	Nozzle Erosion	↑	↑	↑	↓	No	$m\sqrt{T_3}/P_3$ High
Turbine (Power)	Rotor Damage	0	↓	0	0	Yes	η_i Low, EGT High
	Nozzle Erosion	↓	↓	↓	↓	No	$m\sqrt{T_4}/P_4$ High
Compressor	F.O.D.	↑	↓	↑	↓	Yes	η_c Low, m_1 Low
	Dirty	↓	↓	↓	↓	No	η_c Low

Table 7 Example of a Fault Matrix [11]

Each engine and each fault that you are trying to predict will have its own optimum set of measured dependent parameters for accurate deterioration predictions. As such, programs and software such as Pythia and Gas Turb allow us to determine which set of measurements will best predict the faults that we wish to monitor before selecting and installing a sensor suite onto your engine.

4.2. SIMULATED GPA DIAGNOSTICS APPROACH

The use of GPA techniques requires quality engine data for baseline and deteriorated performance [11]. Because of the difficulties of acquiring such data, clean and deteriorated engine performance data has been simulated with the component-matching method. Deteriorated performance data was obtained by imposing degradation on component characteristics and “rematching” the engine [11].

The assumed or implanted faults on various engine components are given below (Fig. 11). The fault range between 2 and 6 % has been chosen because it represents the size of the fault which may result in maintenance action. As an example, fouling causing a 5 % reduction in inlet massflow will reduce not only compressor efficiency but will also cause a 10 % power output loss [11]. With a given set of “monitored” dependent parameters, the linear GPA diagnostics was able to detect the implanted faults by correctly identifying the tendency and giving a reasonable estimate of the magnitude. The non-linear GPA showed a considerable improvement and was always able to accurately detect single or multiple faults [11]. If the choice of monitored parameters is poor, then a proper detection of faults is not possible. The success of identifying a given fault set depends greatly on the set of monitored parameters i.e. the set of instrumentation.

The benefits of gas path analysis (GPA) can be achieved with appropriate instrumentation that thermodynamically correlates with the desired faults [11]. Furthermore, an optimal selection of instrumentation set would allow for simultaneous correct diagnosis of multiple faults. Knowledge of optimum sensor sets would also prove indispensable to diagnostic engineers/developers. Experience shows that the use of a non-linear GPA approach to instrumentation set selection provides a significant improvement when compared with the linear GPA because it addresses the non-linear nature of the problem [11].

The successive application of linear GPA either diverges from or converges to an exact solution depending on the choice of instrumentation used. The accuracy of the diagnosis is different if a different instrumentation set is used. It is also found from the research that over-instrumenting the engine may not necessarily provide a better diagnosis but rather could lead to an increase in cost arising from the installation and maintenance of such redundant instruments [11].

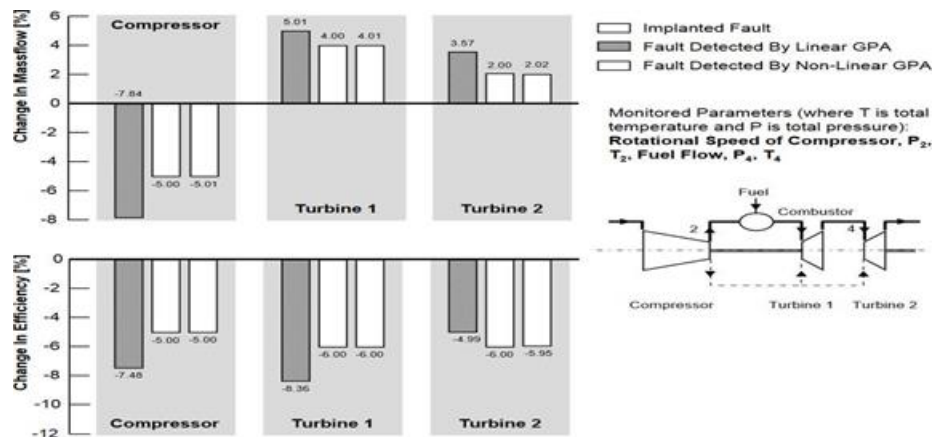


Figure 11 Well-Defined Gas Path Analysis Diagnostics Approach [11]

5. DIGITAL TWINS APPLICATION – IMPACT ON PREDICTIVE MAINTENANCE OF LGTAES/CEO ENGINES

Aero-engine is one of the most important components of an aircraft. The development of maintenance has undergone the transition from “post-event maintenance” and “preventive maintenance” to “predictive maintenance”, and the future development direction is precise maintenance, which aims to ensure operational safety and reduction of operating costs [21]. The aero-engine operational safety is affected by environment, time, conditions, and degradation or failure of various components. Unpredictable component failures may occur during operation. If failures cannot be resolved promptly, catastrophic accidents are likely to happen. At present, the annual global aircraft maintenance cost is about \$31 billion, while the aviation engine maintenance cost accounts for 60% or more of the total cost [21]. Accurate predictive maintenance can ensure transportation safety and reduce operating costs, as well as improve equipment operation reliability and safety, reduce maintenance time, and extend aero-engine lifetime [21].

Current predictive maintenance methods mainly include reliability statistics and physical model-based and data-driven methods. These traditional research methods are usually reactive and heuristic and fail to diagnose the fault or assess potentially risky operation in time, let alone make timely adjustments to civil aircraft’s and aero-engine’s safe operation. The current predictive maintenance of the aero-engine in use is not effective and unable to predict failures accurately due to the complexity of system structure, different failures occurring simultaneously, or the occurrence of a failure resulting from a combination of multiple reasons, a large amount of data generated during operation, which has the characteristics of multi-modality, multi-source heterogeneity, multidimensional, and complex distribution. All these drawbacks of the current predictive maintenance system increase the difficulty and cost of predictive maintenance.

With the development of artificial intelligence technology, digital twin (DT), as a technical means to implement these advanced concepts, provides an effective solution for precisely intelligent predictive maintenance of equipment. A Digital Twin (DT) is an instantaneous, real-time, virtual copy of a physical system, procedure, or product.

With an ability, to collect, collate, store, analyze, and feedback data, a DT can be made to provide continuous evaluation of its physical entity.

5.1. DT – DRIVEN PREDICTIVE MAINTENANCE APPROACH FOR AERO-ENGINE/LGTAE

The real physical aero-engine and its operating environment are the basis of DT architecture for aero-engine predictive maintenance [21]. The aero-engine operating data is collected in real-time by its sensors, and simulation data forms the DT of the aero-engine. Data is the core of the model, and a lot of data will be generated during the operation of the aero engine. Two data consists of physical aero-engine operation data (Dp), and virtual aero-engine data (Dv), which mainly refers to the data mined by building aero-engine DT. Service data (Ds), which is feedback data for applying DT, such as fault diagnosis and life prediction, knowledge data (Dk), which is civil aviation domain knowledge, and derivative data (Df), which is fusion data composed of Dp, Dv, Ds, and Dk [21]. Through the mapping of data assets, the DT model has evaluation, optimization, prediction, and other functions, such as condition monitoring, fault diagnosis, intelligent maintenance, and RUL prediction of aero-engine [21]. A constructed conceptual model driven by DT for intelligent predictive maintenance of the aero-engine is displayed (Fig. 12 and 13) to make the reader understand the workflow of the DT-driven predictive maintenance model [21]. With the predictive maintenance model, it is possible to monitor the state of the aero-engine and obtain real-time information about the system, subsystems, and key components by forming a closed-loop system of physical aero-engine, aero-engine DT model, DT Data, and intelligent predictive maintenance. The mutual feedback of system information and iterative optimization make predictive maintenance more accurate and efficient.

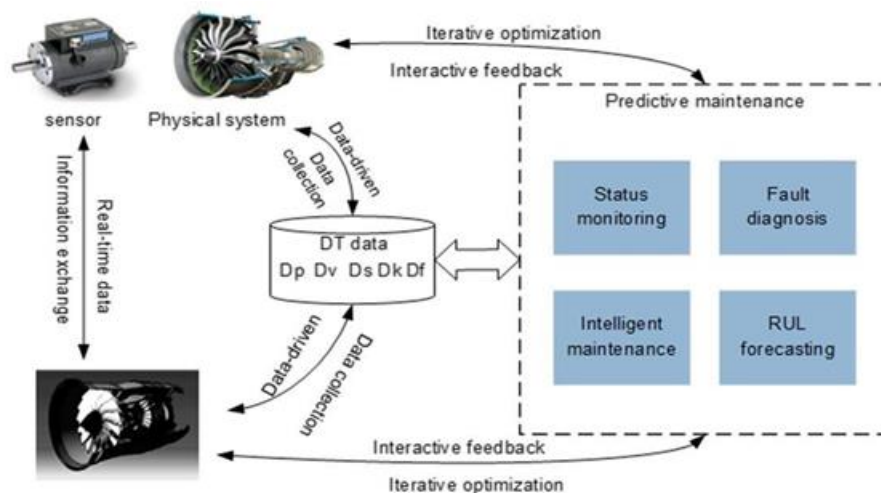


Figure 12 DT-Driven Intelligent Predictive Maintenance Build Model Applied to LGTAE/CEO Engines [21]

OPERATION OF DT-DRIVEN INTELLIGENT PREDICTIVE MAINTENANCE

The DT collects data from the Physical Aero-Engine which includes sensor data, equipment operation data, and signal data [21]. After reducing data noise, data features are extracted and finally used for predictive maintenance of the Aero-Engine (Fig. 12). With the continuous interaction of physical-virtual world information, the actual running status of the physical aero-engine is visualized in the DT model. For example, the real-time mapping of data assets (including maintenance information, running environment, component information, and subcomponent information) is collected by sensors, and these multidimensional data are further mapped to a certain parameter, so that engine performance degradation, physical degradation, and simulation can be fed back to DT in time.

Through continuous iterative optimization, the engine fault detection and diagnosis run better. The model is simulated and compares the simulation results with the actual results until the error is small enough to verify the DT method's effectiveness. Finally, deep learning methods are used to complete the precise predictive maintenance of aero-engine [21].

The Health Factor/Health Index (HI) generated by the DT model along with Long Short Term Memory (LSTM), which is employed to perform in-depth feature extraction on a large amount of data composed of multi-sensor performance parameters can be used to evaluate and monitor the degradation process of the aero-engine in the life cycle, conduct Prognostics Health Management (PHM), fault detection, and use deep learning methods to predict the remaining life (Fig. 13) [21]. The incorporation and integration of DT technology to the LGTAE/CEO Engines is key in Precise Intelligent Maintenance and helps in the timely maintenance of Aero Engine to ensure its normal operation smoothly. Although challenges such as an increase in System Complexity and Data Management exist in the introduction and adoption of DT Technology to Maintenance and Operations of LGTAE/CEO/NEO Engines, the benefits it offers far exceed the challenges by improving existing underperforming condition monitoring and Prognostics Health Management (PHM) technologies with enhanced visualization, faster data computation, and accurate predictive analysis contributing to Life extension of LGTAE/CEO/NEO Engines.

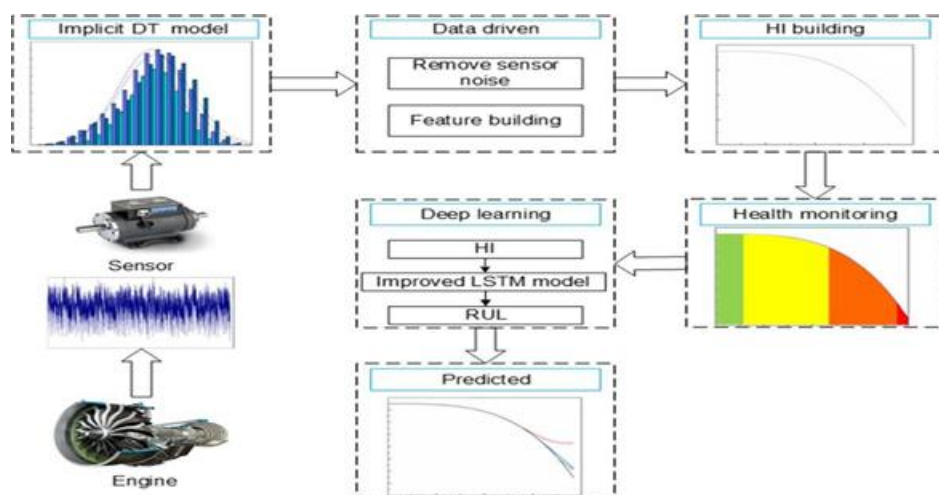


Figure 13 DT – Driven Predictive Maintenance Approach for Aero Engine/LGTAE [21]

6. RISK-BASED MAINTENANCE ANALYSIS, CORROSION PREVENTION AND CONTROL PROGRAMS (CPCP), AND SAFETY BY INSPECTION

The Integrity and Reliability of the LGTAE/CEO Engine are critical to the Safety of the Aircraft. Although the reliability of engines has improved considerably, a large number of legacy engines continue to operate unsafely in an unsafe operating environment.

Risk is usually interpreted as the chance or probability of a failure event occurring in a population over some time [20]. An alternative interpretation of risk is that it is the instantaneous chance or probability of a failure event occurring in a population. In the case of aircraft and engine structures, the instantaneous failure rate is often defined in terms of per hour or per unit flight time. For deteriorating structures, the probability of the deterioration level exceeding a certain failure threshold can be considered as a risk. The risk of failure must be kept below an acceptable level for continuous safe operation.

6.1. RISK-BASED MAINTENANCE (RBM) ANALYSIS

Life extension of LGTAE/CEO Engines can be achieved by employing RBM Analysis although in some cases the life of the entire aero engine cannot be extended, however, the life of some components can be increased by carrying out RBM Analysis. In general, some of the methods that can be employed or are currently used in RBM Analysis to increase the life of Aero-Engines are the Probabilistic Approach/Analysis, Crack Growth Analysis, and Cost Analysis.

PROBABILISTIC ANALYSIS

Owing to uncertainties in fatigue crack initiation and growth, a probabilistic approach is used for risk analysis. The probabilistic approach can identify the source of variables posing a risk to the fatigue life and fatigue strength of a structure while eliminating over-conservatism that maintains safety [20]. As part of the Probabilistic Analysis, the damage-tolerance method is used to see if we extend the life of certain components. The damage-tolerance method is based on a fracture mechanics-based design philosophy, and it determines the ability of a structure with a crack to maintain integrity. Crack growth life is defined as the service time required for an initial crack that is readily detectable using NDI methods to fail in damage-tolerance methods for design and life management. The extension of the life of the components depends on the Probability of Failure to damage tolerance using Non-Destructive Testing (NDT) [20]. The life of a component is managed via inspection intervals scheduled to detect cracks. The inspection interval is computed using deterministic fracture mechanics or Probabilistic Risk Analysis. The RBM philosophy uses risk rating as a measure for decision-making, and the risk rating is a combination of the probability and severity of a risk event. Events with a high probability but low severity may result in a lower risk rating. The converse is also true. For example, risk events such as fractures in rotating components of an engine can lead to catastrophic consequences (i.e. high severity), but such incidents rarely occur (i.e. low probability). However, because the severity is a vague concept and is difficult to quantify, for its comparison with probability, the probability of failure (POF) alone is used as the risk criterion in aircraft aero-engine structural risk assessments.

CRACK GROWTH ANALYSIS

Crack Growth Analysis of a component or a module during corrective and preventive maintenance is critical to decide on the extension of service life of the module/component or replacement of it. The estimation of crack size, crack length, and crack growth rate are conducted to measure the extent of damage to the material/module, and based on that a decision is made whether to extend the life of the component/module. The fatigue crack growth rate is normally predicted by empirical models. Generally, Paris Law is used to calculate fatigue crack propagation and fatigue life [20]. The equation is as follows.

$$\frac{da}{dN} = C (\Delta K)^m \quad (1)$$

where a is the crack size, da/dN is the fatigue crack growth for load cycle N , C is the crack growth constant, ΔK is the stress intensity factor range (maximum and minimum), and m is an exponent. When the stress intensity factor range reaches a critical level, material fracture occurs because of fatigue. The fatigue crack growth behavior can be divided into three stages. In the first stage, a fatigue crack begins to grow when the stress intensity factor range exceeds a threshold level. The logarithm of the rate of fatigue crack growth shows a linear dependence on the stress intensity factor range. The Paris law in equation (1) models only the second stage. Therefore, equation (1) may exaggerate the fatigue crack growth rate during its early stages and underestimate the rate of fatigue crack growth in the later stages.

Most of the fatigue life is spent in the near-threshold crack growth for the high cycle fatigue problem of smooth specimens; hence, disregarding the unstable crack growth will not result in a significant error.

Equation (1) can also be written as

$$dN = C^{-1} (\Delta K)^{-m} da \quad (2)$$

Integrating both sides, the fatigue life N can be obtained as

$$N = \int_0^N dN = \int_{a_i}^{a_c} C^{-1} (\Delta K)^{-m} da \quad (3)$$

Where a_i is the initial crack length and a_c is the critical crack length. To accelerate the computation of equation (3), the crack sizes are estimated using the Master Crack Growth Curve (MCGC) shown below (Fig. 14). A back extrapolation method which was developed by Yang and Manning based on measurable crack lengths with a known loading history is used to obtain the initial crack-length distribution [20]. This method has been used here for the Probability Risk Analysis (PRA). The MCGC technique is widely used for aircraft and aero-engine structural integrity programs where a mean or median crack growth curve is used for backward crack growth analysis [20]. The use of back-extrapolation would be valid where the loading history of engines in the same fleet is similar. The MCGC (Shift/Curve) is shifted for back-extrapolation from the fatigue lives of the samples that did not fail. The intersections (Fig. 14) between the shifted curves and the vertical line at the time of inspection are the crack lengths at the time of inspection (6000 cycles in this case) [20].

The fatigue reliability can be assessed concerning the following limit state function for the failure event with equation (3)

$$g = a_c - a(t)$$

where $a(t)$ is the crack size at time t . The critical crack size is treated as a deterministic constant in the assessment of fatigue reliability owing to its insensitivity to fatigue service life. The computation of the corresponding probability $\Pr(g \leq 0)$ is straightforward.

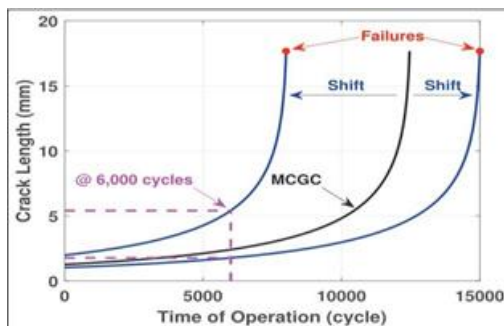


Figure 14 Crack growth model showing the shifting of MCGC [20]

Material Properties of AM355 Martensitic Stainless Steel	
Material Properties	Material Limit
Modulus of elasticity	190-210 Gpa
Poisson ratio	0.27-0.30
Yield stress	1070 Mpa
Ultimate stress	1170 Mpa

Table 8 Material Properties of AM355

EXAMPLE OF A FMECA – CT7-9C ENGINE FAILURE

The CT7-9C engines (Fig. 15a) of the Republic of Korea Air Force (ROKAF) power CN-235 transport aircraft, and each CN-235 aircraft is equipped with two CT7 engines [20]. Recently, the CT7 engine failed but recovered during flight, which subsequently resulted in the precautionary landing of the aircraft [20]. It was found that the fracture of the compressor (Fig. 15b) first-stage blisk was the direct cause of failure. A blisk is an engine component in which the blades and disc are machined as a single component and a single first-stage blisk consists of a total of 20 blades. Failure modes, effects, and criticality analysis (FMECA) followed by risk analysis was conducted to optimize the maintenance strategy of the CT7 engine.

The damage to the blisk blades manufactured by using AM355 martensitic stainless steel is shown below (Fig. 16) and its material properties are listed in (Table. 8). Damage was observed at all stages from the inlet guide vane to the impeller and no evidence of foreign object damage was found, moreover, several blades of the first blisk were found partially fractured [20]. Figure 17(a) shows an optical microscope image of the fractured blade. Part of the airfoil from the trailing edge (TE) to the tip near the leading edge (LE) was fractured, and its size was 20 mm x 21 mm. A fractographic analysis of the fractured blade was performed (Fig. 17(b)–(d)). A fatigue crack (approximately 7 mm long) initiated on the concave surface penetrated the convex surface (Fig. 17(b), region I of Fig. 17(a)) and propagated approximately 19 mm diagonally to the tip near the LE (Fig. 17(c), region II of Fig. 17(a)). Finally, an overload fracture occurred and caused a dimple on the left surface, as shown in Figure 17(d) and region III of Figure 17(a), indicating that cracking started from the concave surface, which is the pressure side of the blade, near the TE and grew toward the tip of the LE.

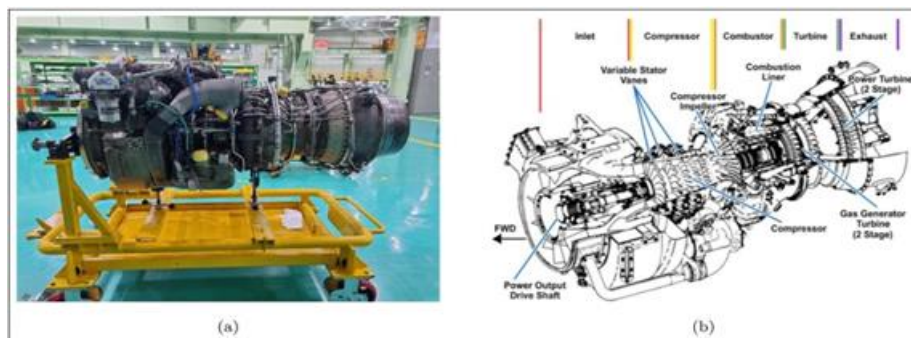


Figure 15 (a) view of a CT7-9C engine and (b) a cutaway diagram [20]

Because no traces of external impact, corrosion, or abnormal operation were found on the fractured blade surface, it is highly likely that an increase in tensile stress (Fig. 16(c) I), which was dominant on the concave surface during operation, accelerated crack initiation. The fact that the initial fatigue cracks (Fig. 17(b), region I of Fig. 17(a)) propagated simultaneously from the concave surface supports this hypothesis. In many cases, rubbing between the blade tip and casing (Fig. 16(c) II) caused premature failure. The contact of the tip with the case was placed at the top of the list of factors that caused premature fatigue cracking. Small fragments of the fractured blades could cause damage to the components in the subsequent stages and eventually lead to compressor failure. Therefore, the criticality of a blade-tip fracture is very high for the CT7 engine.

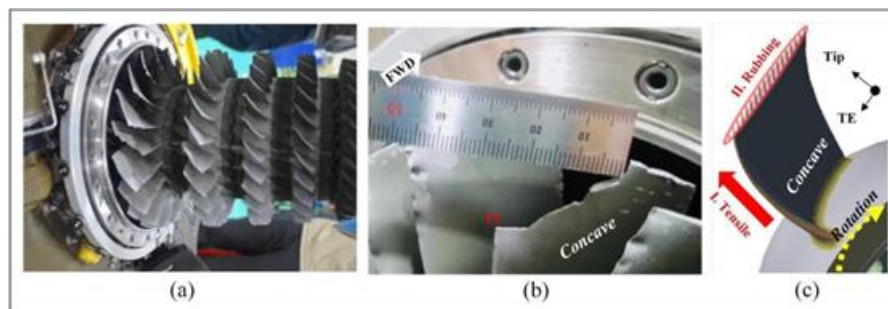


Figure 16 CT7-9C engine compressor blisk damage: (a) from first to fifth stages, (b) in the first stage (a metric ruler was placed), and (c) diagram illustrating fatigue crack initiation [20]

Two severity factors related to Non-Recoverable In Flight Shut Down (NRIFSD) and Engine Related Loss of Aircraft (ERLOA) events were derived from the failure data and historical landing factors. The current case is the only initiating event that was not followed by an NRIFSD event. Assuming that a subsequent initiating event causes NRIFSD, an NRIFSD severity factor of 1/2 can be viewed as conservative.

Historically, two successful single-engine landings have been reported. Similar to the NRIFSD severity factor, an ERLOA severity factor of 1/3 was used for the risk projection.

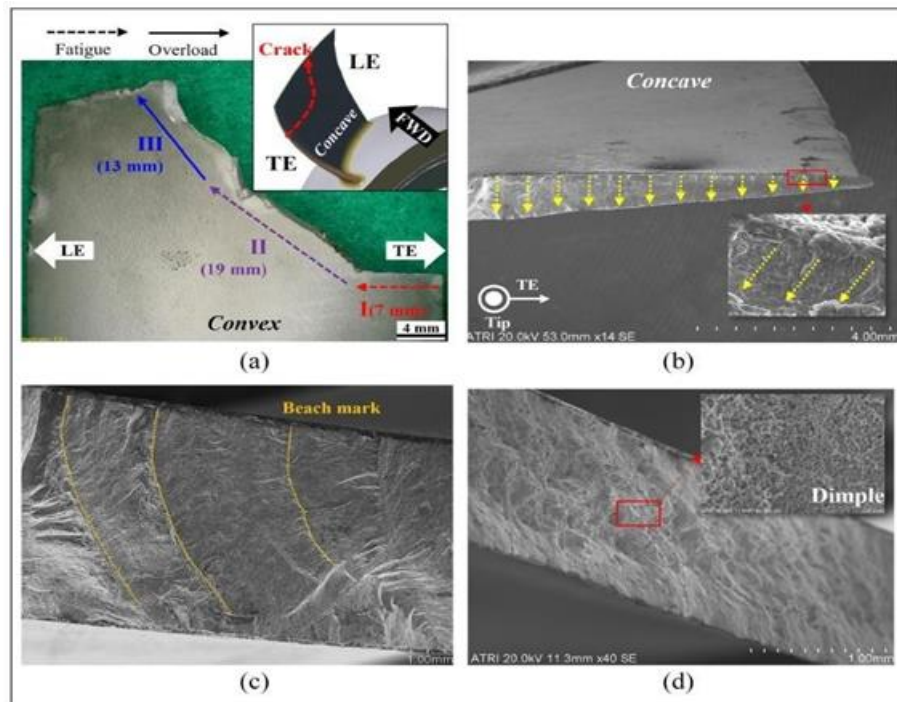


Figure 17 Failed blisk microscopic analysis showing: (a) the crack propagation path, (b) initiation sites (region I), (c) beach marks (region II), and (d) dimples (region III) [20]

LESSONS FROM CT7-9C ENGINE FAILURE

It is important for the Maintenance Engineers and Technicians that engines are to be thoroughly inspected for crack development, nicks, dents, etc. during Daily Inspection and Preventive Maintenance, in particular, the first few stages where the Maintenance Personnel have more access although the Vibration and Acoustic Sensors capture any fatigue development in the latter stages of the compressor section from the inaccessible places where there is less access for Maintenance Personnel. This applies to the Turbine Section too, however, the access to the Turbine Stages for the Maintenance Personnel during Daily Inspection is in the reverse order. It is important to note in this case the fatigue crack growth developed and occurred in the first stage of the compressor section could have been very well avoided had it been thoroughly inspected during the Daily Inspection. The integrity of maintenance personnel during inspection and maintenance is critical for safe flight, and safety of aircraft, crew, and passengers.

COST ANALYSIS

In general, the expected life-cycle cost for optimal replacement cycles comprises the following: (a) inspection cost, (b) repair cost, and (c) risk cost, where (a) and (b) are considered maintenance costs. The longer the optimal replacement cycle, the lower the maintenance cost (inspection and repair costs) and the higher the risk cost (in contrast to the maintenance cost) [20]. Optimized solutions to problems related to inspection and replacement timing are important for life extension programs in aging aircraft. By considering both the risk and cost, the aging fleet can continue operations beyond its design life safely and economically.

6.2. CORROSION PREVENTION AND CONTROL PROGRAMS (CPCP)

The CPCP is one of the Novel Techniques that is being employed in Aero-Engine Maintenance Establishments across the world in particular Aircraft operating in coastal areas to contain corrosion development and extend the RUL of Aero-Engines. Some Research-Based Organizations focus on support for Maintenance rather than the development of new materials because approximately half of through life cost of a military/civil aircraft/aircraft engine is spent on maintenance [23]. This effort not only reduces maintenance costs but also significantly increases the Remaining Useful Life (RUL) of Aircraft/Aero-Engine. These research activities prolong the service life of an aircraft/aircraft engine providing large benefits by delaying the purchase of a replacement aircraft engine. Acquisition costs are also large, at approximately one-third of the through-life cost of an aircraft fleet. It is found the Aeronautical Research Laboratory (ARL) of the Defence Science and Technology Organization (DSTO), Australia has made significant progress in extending the RUL of Aircraft/Aircraft Engine through CPCP and Safety by Inspection Technique/Method [23]. Initially, potential problems of aging aircraft/LGTAEs have been evaluated and accordingly technologically feasible life extension measures have been developed.

The external environment to which aircraft are generally exposed consists of atmospheric moisture including rain, and airborne contaminants such as chlorides, sulphates, and nitrates. The internal environments in aircraft/aircraft engines will be different in different areas of the structure, and some locations will be more corrosive than others. Hence it is not unreasonable to expect that different corrosion prevention and control procedures may be required for different areas of an aircraft/aero-engine. Water Displacing Corrosion Preventatives (WDCPs) have been used by the aircraft industry for many years as a relatively inexpensive way of temporarily controlling corrosion [23]. With the economic drive to increase the lives of aircraft/aircraft engines, wider use of WDCPs in the future may allow a more flexible and cost-effective approach to corrosion control in aging aircraft/aircraft engines. Unfortunately, very little systematic laboratory or field research has been undertaken to provide the necessary technical background to support the wider usage of WDCPs [23]. Work at ARL has been concerned mainly with assessing the effectiveness of WDCPs under various environmental conditions, and determining the useful life of these compounds in service environments, especially the highly corrosive environments experienced by the RAAF P-3C Orion Maritime Surveillance Aircraft.

The loss of weight with time of 7075-T651 aluminum alloy specimens continuously immersed in a corrosive environment of 0.1M NaCl solution is shown below (Fig. 18). In the research experiments of ARL, the WDCPs were applied once only before immersion, and this was sufficient to inhibit corrosion for up to 23 days [23]. Similar results have also been obtained with other aluminum alloys and with mild steel. In another series of tests, the WDCP was added to the NaCl solution (at 10% by volume), before 2024-T351/T651 aluminum alloy specimens were immersed. The presence of the WDCPs significantly reduced the corrosion rate over an exposure time of 42 days (Fig. 19). These data suggest that WDCPs can provide corrosion protection even in the presence of a corrosive environment (Fig. 18).

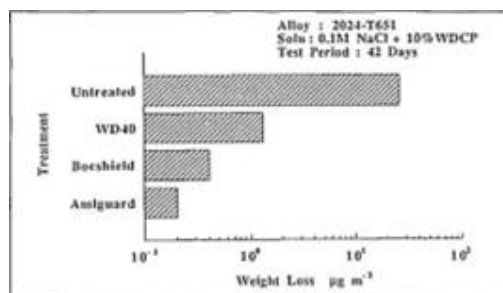
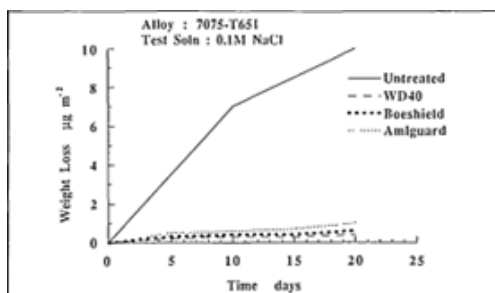


Figure 18 The effect of Pretreatment with WDCPs On Corrosion of 7075-T651 Al Alloy in NaCl Solution test Solution on the Corrosion of 2024-T351 Al Alloy

Additional results indicate that WDCPs are very effective inhibitors of galvanic corrosion (Fig.20). The corrosion current flowing between a galvanic couple of 7075 aluminum alloy and graphite fiber-reinforced epoxy resin, when immersed in a NaCl solution is given below (Fig. 20). However, it is found its WDCPs effect reduces when it is used in aircraft/aircraft engines operating in coastal sites/locations due to an environment containing airborne salt carried by on-shore winds, which is very corrosive (Fig. 21). The ARL research has identified that efficacy probably depends on the type of WDCPs, the thickness of the coating, the severity of the environment, and the elapsed time between applications [23].

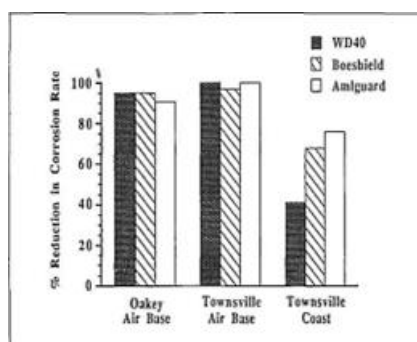
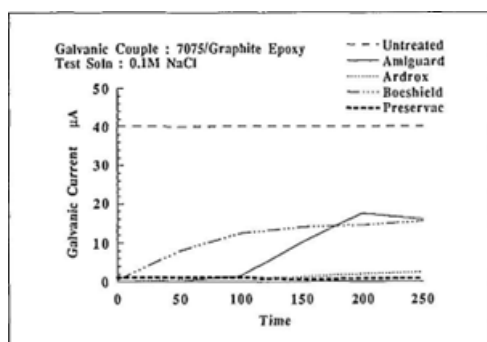


Figure 20 The effect of Pretreatment with WDCPs on the GC of 7075-T651 Al Alloy in contact with graphite epoxy In NaCl Solution [23]

Figure 21 The Effect of Pretreatment with WDCPs on the Corrosion of Wire on Bolt Specimens Exposed at Outdoor Sites in Queensland [23]

6.3. SAFETY BY INSPECTION

Safety by Inspection is one of the methods/techniques that is being employed by the Industry to extend the life of aging aircraft/aero-engine and which is being researched extensively across the world. ARL, in their research on Safety by Inspection and its application on RAAF Military Aircraft/Aero-Engine, has made significant progress in extending the life of Military Aircraft/Aero-Engine. Probably the most significant feature of this procedure is the fact that the aircraft is allowed to continue in service even after cracks are detected, a philosophy that is considered alien both during the design and operation stages [24]. The employment of Safety by Inspection can extend the useful service life of aging aircraft/aero-engine beyond the planned service life using Non-Destructive Inspection (Safety by Inspection) to ensure that cracking or other deterioration does not approach a critical level. The concept of using repeated inspections to allow continued safe operation is shown below (Fig. 22).

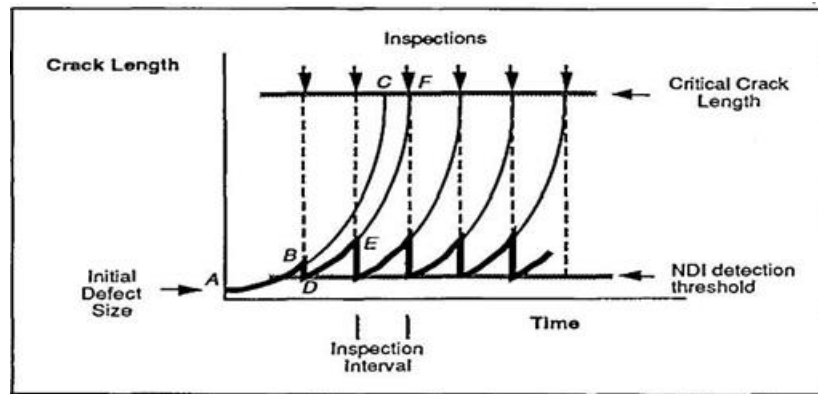


Figure 22 The Crack Growth and Inspection Interval upon which Safety by Inspection is based [24]

In this method/approach, a series of fatigue tests are conducted on the specimen, and based on that crack growth rate and critical crack length are determined from the specimen tests. An acceptable safe crack length limit (a reject condition) is then defined, using knowledge of the fracture toughness and operational loads. A suitable inspection interval was then determined from the crack growth curve, with sufficient redundancy to ensure that there would be several opportunities to detect the crack. The safety-by-inspection approach allowed the extension of certain component lives from the original 1,200 hours to as much as 3,300 hours [24]. It is important to emphasize that the problem of aging aircraft/aero-engine, aircraft/aero-engine which are to exceed their original design life applies to the whole structure/engine; concentrating on only one aspect, however critical, without considering other potentially degraded areas will lead ultimately to loss of aircraft/aero-engine. If continued airworthiness is to be based on regular use of Non-Destructive Inspection (NDI), it will be necessary to develop an NDI plant that covers all areas of likely deterioration. The wider use of NDI is also inevitably going to be a major means of managing critical parts in aging civil aircraft/aero-engine.

DETECTION OF CRACK AND CORROSION

Safety by Inspection includes crack detection methods such as Eddy Currents, Ultrasonics, Magnetic Methods, Dye Penetrants, Radiography, and Visual NDI (Fig 23). Many of the procedures have been refined in a technical sense and are now much more sensitive and reliable than was the case some years ago. Deterioration in aging aircraft is by no means confined to crack development; corrosion, in its various forms, can produce dangerous reductions in component sections, and can be a precursor to cracking, or can effectively limit aircraft/aero-engine life by requiring expensive disassembly and component replacement [24].

The early detection of corrosion is extremely desirable, since it may allow the corrosion to be blended out, the surface to be re-treated, and the component returned to service. In addition, early detection prevents the build-up of the corrosion product which since it occupies much more volume than the original material, can lead to distortion of the surrounding parts, or fracture of fasteners. Unfortunately, corrosion occurs at edges or surfaces and joints, leading to inherent difficulties with NDI methods which are sensitive to these features. This, in conjunction with the need for early detection, represents one of the major challenges for NDI.

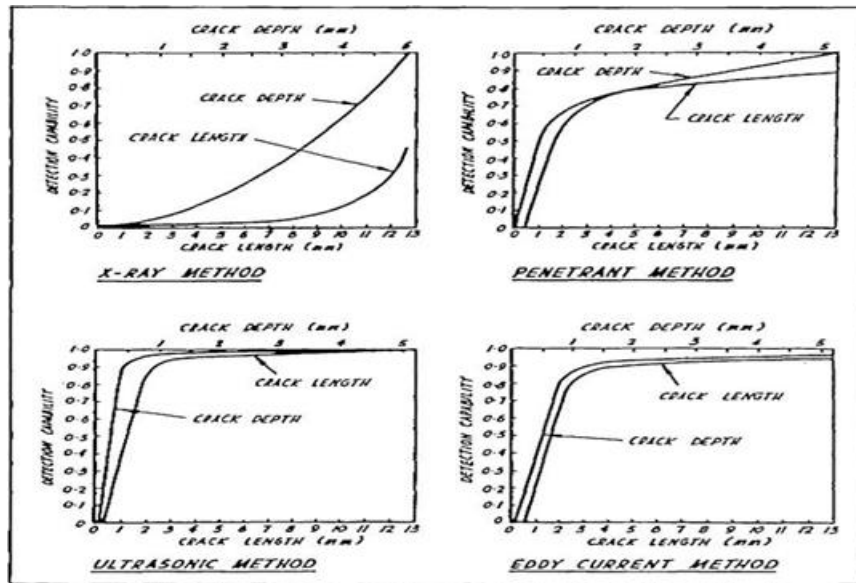


Figure 23 Detection Capability of Crack for Various NDI Methods [24]

There are many potential methods available for the detection of corrosion. Some of the methods available for corrosion detection are Ultrasonic, Eddy-Current, X-radiography, Neutron Radiography, Acoustic Emission, and Thermography [24]. These methods provide a means of detecting hidden corrosion if that corrosion is near an accessible surface. Where the corrosion lies deeper in the structure, then most of these techniques have limited application, and it will be necessary to fall back on radiographic methods, with their inherent contrast problems, or on eddy-current methods, in which discriminating corrosion from other features is difficult. Overall, the use of several different methods to tackle any particular problem would appear to provide obvious advantages. A variety of other NDI approaches offer some promise for the detection of hidden corrosion; further laboratory development is necessary, however, before they can be applied in service.

In summary, the extension of service life beyond an originally planned or certified life will require additional effort in NDI; for the detection of single cracks in defined locations, many methods are currently available, although the detection of cracks at fastener holes might require the use of significant manpower or expense [24]. The methods available for corrosion detection are considerably more limited, the more promising approaches include the use of more extensive visual methods, assisted with advanced borescopes and CCD camera systems, and the use of improved eddy-current methods. The use of several complementary methods, to improve the detectability of corrosion would appear to be promising, and for large-area scanning, the need for automated methods to reduce operator fatigue and error is now significant.

Overall, however, the most important message is that detecting cracks or corrosion in areas that have been demonstrated to be suspect is not the complete solution; the whole aircraft/aero-engine is aging, not just specific parts, and failure to consider all areas of potential deterioration will eventually result in loss of aircraft/aero-engine. Research and Development into maintenance-related areas such as corrosion protection and applied NDI offer substantial benefits across a range of aviation applications, including both Military and Civil Aviation Fields. Careful introduction of the procedures and techniques in both fields could permit the extension of lives of aging aircraft/Aero-Engines or LGTAEs.

7. FATIGUE (LCF AND HCF), ITS IMPACT ON LGTAE LIFE AND METHODS FOR REDUCTION OF FATIGUE

LGTAEs/CEO Engines are very susceptible to cracking and fatigue failure at critical points. There have been numerous cases where Fatigue reduced the Service Life of LGTAEs and led to catastrophic failures of LGTAEs leading to premature loss of Aero-Engines. Fatigue may be defined as the progressive deterioration of a material that is subjected to cyclic stress loads, usually less than the yield stress until failure occurs [3]. Fatigue generally occurs due to non-steady loading fluctuations in stress and strain. Under conditions of cyclic loading local regions of high stress start to develop and because of the non-uniform orientation of the crystals one or more crystals will suffer slippage. Slippage will cause a fracture to some micro-element which spreads to the whole section and leads to failure.

Phases of Fatigue

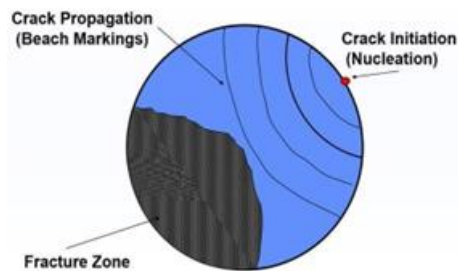


Figure 24 Phases/Stages of Fatigue Development [3]

Fatigue Specimens

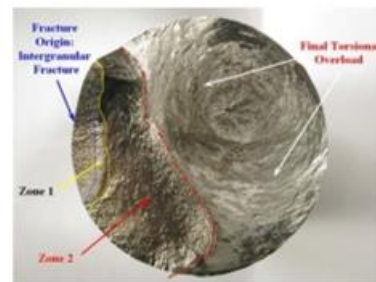


Figure 25 Fatigue Specimens with Zones [3]

The stages/phases of Crack Growth are Crack Initiation, crack growth on planes of high shearstress (Stage I), crack growth on planes subjected to high tensile stresses (Stage II), and Fracture (Fig 24, 25, 26). The components that are susceptible to Fatigue Failure in LGTAEs are Blades, Vanes, Discs and Spacers, Air Seals, Cases, and Housing [3]. The Approximate Failure Percentage in terms of a Pie Chart is illustrated below to understand the breakdown of Fatigue Failure of LGTAE components (Fig 27).

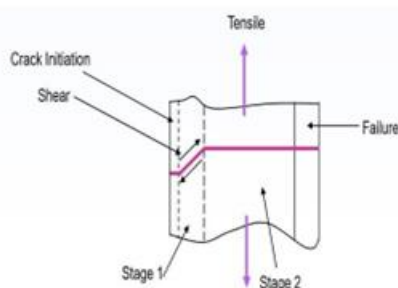


Figure 26 Crack Growth with Tensile and Shear Stress

Susceptibility to Fatigue Failure

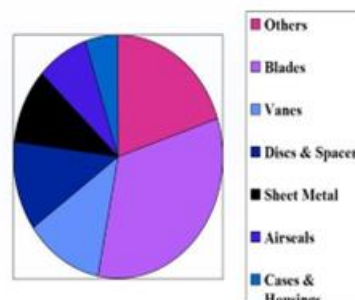


Figure 27 Breakdown of Components Susceptibility to

Fatigue Failure [3]

LOW CYCLE FATIGUE (LCF)

Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) are two distinct types of fatigue failure that occur in materials subjected to cyclic loading (Fig 28). LCF involves a relatively small number of cycles to failure, typically in the range of hundreds to thousands of cycles. LCF occurs at higher stress levels compared to HCF. The stress amplitudes in LCF are typically high enough to cause plastic deformation in the material during each loading cycle [3].

In LCF, failure is often characterized by the accumulation of plastic strain and the formation of cracks at stress concentrations or defects in the material. These cracks propagate relatively quickly until catastrophic failure occurs. LCF is commonly associated with cyclic loading conditions involving large variations in stress or strain, such as thermal cycling or mechanical loading during startup and shutdown of equipment. LCF is often encountered in components subjected to transient loading conditions, such as turbine blades in aircraft engines, where frequent temperature changes occur during startup and shutdown.

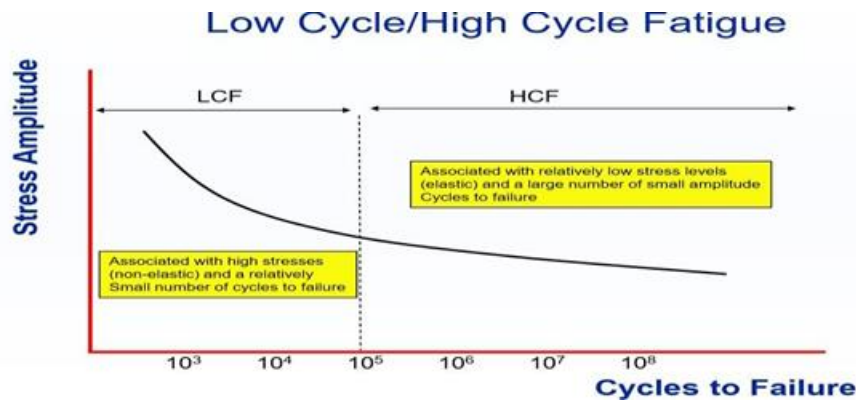


Figure 28 S-N Diagram of LCF and HCF [3]

HIGH CYCLE FATIGUE (HCF)

HCF involves a large number of cycles to failure, typically in the range of thousands to millions of cycles (Fig. 28). HCF occurs at lower stress levels where the material remains predominantly elastic throughout the loading cycle, meaning it returns to its original shape after each cycle.

In HCF, failure is primarily due to the propagation of cracks initiated at stress concentrations or defects in the material. These cracks propagate slowly over time under cyclic loading until they reach a critical size, leading to sudden catastrophic failure. HCF is associated with cyclic loading conditions involving smaller variations in stress or strain, such as cyclic vibrations or dynamic loading during normal operational conditions [3]. HCF is more prevalent in components subjected to cyclic loading at high frequencies, such as rotating machinery components like gears, shafts, and bearings. Both HCF and LCF are critical considerations in the design, maintenance, and operation of aircraft engines. Engine manufacturers employ various techniques such as material selection, design optimization, and advanced testing procedures to mitigate the risk of fatigue failure and ensure the reliability and safety of aircraft engines. Regular inspections, maintenance, and monitoring of engine health are also essential for detecting and addressing fatigue-related issues on time.

Some of the factors affecting Fatigue are Type of loading, Size, Surface finish, Stress concentration, Mean stress, and Environment [3]. Type of Loading such as Bending, Axial, and Torsional will have a significant impact on the Fatigue rate. The size of the material or component also affects fatigue development, a larger diameter has a lower fatigue limit and fails earlier. The surface finish such as Surface Roughness, Polishing, Case Hardening, and Rolling will have a significant impact on Fatigue Strength. When the surface roughness decreases the fatigue limit of the specimen increases. The fatigue strength of a component highly depends on its surface quality. Mean stress effects significantly influence the fatigue life of components. In general, tensile mean stresses are known to reduce the fatigue life of components, whereas compressive mean stresses increase fatigue life.

7.1. ENVIRONMENTAL EFFECT ON FATIGUE

Environmental Conditions such as Corrosion, Fretting, and Temperature have a significant effect on Fatigue [3]. Corrosion fatigue is produced by the simultaneous effect of cyclic load and chemical attack, elevated temperature produces interactions between environment, creep, and fatigue, and Low temperature severely reduces fracture toughness. Corrosion Fatigue is caused by repeated loading in a corrosive environment. It usually reduces fatigue life and increases the rate of corrosion, however, immersion in a corrosive medium does not always reduce fatigue life and fatigue loading does not always increase the rate of corrosion. The medium weakens the inter-atomic bonds, causing small cracks. Corrosion attacks the material via the small cracks, which is mitigated either by a reduction in stress amplitude or by improvement of corrosion resistance. Fretting is the result of slight movement in joints that are not designed to move [3]. The debris caused by the movement is retained in the joint and produces small cracks that can lead to fatigue failure. Fatigue developed at High Temperatures decreases Fatigue resistance, accelerates Crack propagation, and increases Creep.

7.2. METHODS FOR REDUCTION OF FATIGUE

Reducing material fatigue in LGTAEs is crucial for enhancing the longevity and reliability of components, which contributes to the Life Extension of LGTAEs. Some effective ways to achieve this are the usage of stronger, advanced, and more capable materials, reducing the margin of errors during assembly and manufacture, employing Advanced Fatigue Life Prediction Technologies as discussed earlier in the paper, Regular Inspections, and Repairs such as Regular Bearing Replacement, Cold and Hot Section Rotor Blades Replacement along with Stators and NGVs.

REDUCTION OF CORROSION FATIGUE AND FRETTING

Reduction of Corrosion Fatigue Damage can be achieved by Reducing amplitude of cyclic motion, Increasing material resistance to corrosion, Shot-peening, cold-working or nitriding, Anodic coatings (Zn and Cd on steel), Paint, oil, polymer or ceramic surface coatings, Cladding of high strength Al alloys with a pure Al surface layer – Alcladding, Coating with corrosion resistant chemical film – chromates and dichromates [3]. Some of the common coatings are Electroplating on Steel Compressor Blades, epoxy resins on steel, chromating and epoxy resin on Mg Alloys, anodizing and epoxy resin on Al Alloys, and Aluminide coatings on Nickel Chromium Turbine Blades to prevent hot corrosion above 900°C. Fretting can be mitigated by using anti-fretting compounds, eliminating relative motion, and surface hardening of fretting surfaces.

8. DISCUSSION

LGTAEs although highly reliable during their time, face several operational and maintenance challenges and issues as they age over a period leading to premature withdrawals resulting in loss of investment to the owners/operators. Over some time, LGTAEs experience a decline in performance due to wear and tear, Degradation, and Deterioration caused because of GT Faults. Components like compressor blades, combustion chambers, and turbine blades may suffer from fouling, erosion, corrosion, and fatigue, leading to reduced efficiency and thrust output. Maintaining LGTAEs can be costly and challenging as Maintainability falls due to the usage of older materials, poor manufacturing processes, scarce availability of spare parts, and specialized knowledge that is required for repairs, which will have a significant impact on therepair time. Operators often struggle with high maintenance costs and extended downtime. Maintainers have to use costly tools and testers to get back LGTAEs into service and the downtime affects huge losses to the operators. As engines age, the risk of unexpected failures increases. Components may fail due to material fatigue, cracks, or other issues. Ensuring flightsafety becomes a critical concern for operators of LGTAEs.

LGTAEs lack advanced control systems, making it harder to optimize performance, fuel efficiency, and emissions. Legacy engines are less fuel-efficient compared to modern designs. Improving fuel efficiency requires significant modifications or replacement with newer engines. Older engines emit more pollutants, contributing to air quality issues and climate change. LGTAEs are not equipped with advanced Performance Analysis and HUMS, which reduces their safety, reliability, and efficiency.

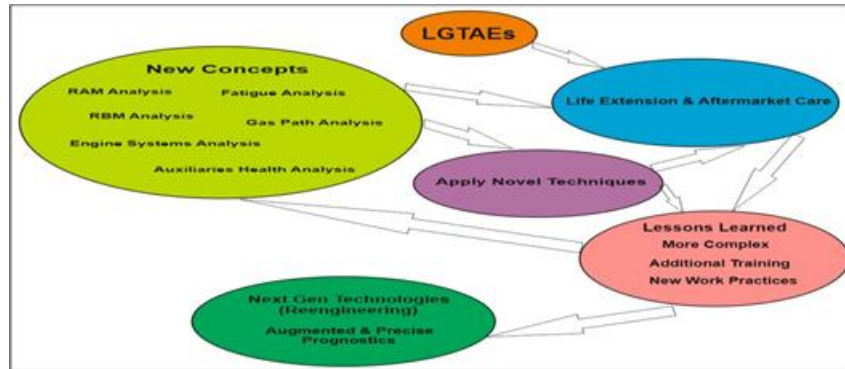


Figure 29 Life Prediction and Extension of LGTAEs Through Reengineering

It is important to note that the performance and deterioration of each LGTAE of the same variant varies due to a range of factors such as operating and environmental conditions and there is a variation in the failure time of each LGTAE of the same variant from the initial detection of potential failure to actual functional failure. In this work, it is found RAM Analysis, Engine Systems, and Component Monitoring, P-F Interval Analysis, and Gas Path Analysis are highly effective in containing deterioration as well as extending the P-F interval of LGTAE. Timely Engine Systems Analysis that includes Oil/Lubrication, Vibration, Debris, and Acoustics Analysis will have a significant impact on the RUL. The performance of LGTAEs increases significantly with the introduction of the above-mentioned techniques through Reengineering. It requires the integration and installation of some Advanced HUMS to the LGTAEs. In addition to this, RBM Analysis which includes Crack Growth and Cost Analysis are effective ways to enhance RUL cost-effectively. Also, the environmental effects of Fatigue contribute to further damage to the Life of LGTAE. This research work illustrates how fatigue and corrosion development can be addressed using CPCP, advanced materials, advanced manufacturing processes, coatings, and smart materials that not only sense the Fatigue but also negate it. CPCP and Safety by Inspection contribute to the extension of Original Design Life/Planned Service Life using NDI methods. It allows the LGTAE to continue its service life even after detecting cracks without compromising on safety.

The amount of Loads an LGTAE experiences is huge and has a significant impact on Fatigue development (Table. 9). An example of Time to Failure of an Aero Engine Turbine Blade made up of Nimonic 80A when subjected to High Temperatures and High Stresses during various Flight Conditions is given below using Larsen Miller Parameter (LMP) Equation/Formula (Table. 9).

$$P = \frac{T}{1000} (\log t_f + 20)$$

Where, P = LMP obtained from LMP Charts, T = Temperature in Kelvin, t_f = Time to Failure and 20 is a Constant for most applications but varies in some cases according to the application[19].



	Time (min)	$T^{\circ}K$	Stress (MPa)	P	t_f (hours)
Take-off	1.5	1000	300	22.8	631
Climb	15	1100	200	23.9	53.4
Cruise	103	950	150	24.5	615848
Low Ratings	30	925	100	25.3	224569800
Reverse Thrust	0.5	1000	300	22.8	631
Total	150				

Table 9 Example of Turbine Blade (Nimonic 80A) Time to Failure Subjected to Varying Flight Conditions [19]

Despite adhering to the above-mentioned Novel Techniques, the maintainers and operators fail to diagnose the technical snags, and deterioration, and predict RUL accurately. This paper demonstrates how to accurately predict RUL and Potential Failures by employing Digital Twins exploiting the development of Artificial Intelligence, and the benefits associated with it. Also, apart from the above discussed, this paper suggests the introduction of Lean Aviation Maintenance (LAM), Japanese Work Ethics, and Blockchain can have a significant impact on the reduction of downtime. It is found although there is a higher reliability of certain modules and components of LGTAEs, the downtime is high because of the Non-Availability of Critical Modules attributed to the absence of LAM in the Aviation Maintenance Establishments. Emerging Technologies like Blockchain and LAM will contribute to Effective Supply Chain Management through improvement in Forecasting, Provisioning, Buffer Availability, and Timely Despatch of Critical Spares. In summary, LGTAEs face challenges related to performance, maintenance, safety, and environmental impact. Operators must carefully manage these issues to ensure the continued safe and efficient operation of LGTAEs by employing an Integrated Approach of the Re-engineering Techniques discussed to enhance the RUL of LGTAEs and Return on Investment to the operators (Fig. 29).

9. CONCLUSION

The safety and integrity of the aircraft and engine are paramount and largely depend on the effective Design of an aircraft and engine and maintenance strategies. The efficient design of an engine foreseeing the ease of maintenance reduces downtime increasing maintainability. This paper suggests a design modification of an LGTAE cost-effectively through Re-engineering not only improves performance but also RUL. The modifications could be an integration of Advanced HUMS or replacement of a Critical Module with a modified one or both. This paper recommends the introduction of RAM Analysis, Engine Systems Analysis, RBM Analysis, and Safety by Inspection can be highly effective with the extension of RUL of LGTAEs. With the Continuous Evolution in the Technology Development and Integration of Artificial Intelligence (AI), the application of DT can be effective by enhancing accurate prediction of the condition of LGTAEs. Furthermore, this paper suggests Derisking of Ancillary Components fitted in Auxiliary/High-Speed Gear Boxes of LGTAEs with Augmented Prognostics will contribute to significant improvement in the Life of LGTAEs. It is found in the research there have been incidents/accidents where non-adherence to Maintenance Procedures and practices contributed to the loss of LGTAEs, which could have been avoided. Therefore, this paper suggests Adherence to Maintenance Procedures and Practices not only prevents accidents and huge losses to the owner but also contributes to the improvement in performance. This Research recommends the introduction of Novel Techniques discussed in the paper as an Integrated Re-Engineering Approach, which can be impactful in the accurate prediction and extension of RUL of LGTAEs. The LGTAEs are older Aero-Engines with older technology that underperform with minimum Life, Safety, ROI, and higher levels of emissions.

Therefore, the Application of an Integrated Re-Engineering Approach using Novel Techniques and Methods not only improves the Performance, Safety, and ROI of LGTAEs but also contributes to the reduction of emissions resulting in the development of a Sustainable Greener Society and Environment.

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AUTHORS BIOGRAPHIES



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Dr. Craig Law is an Associate Professor in Fluid and Aerodynamics at the University of Witwatersrand, South Africa. His research focuses on the dynamics of flows with vortices covering everything from trailing vortex behavior to lift distribution control and combustion mixing. He also uses Model-Based Systems Engineering as an investigational tool (applications include everything from Air Traffic Management to the application of smart materials in missile flight control systems). Dr. Craig Law completed his BSc(Eng.)(Aero.) and PhD (in the flow research unit) at the University of Witwatersrand, South Africa. He has served as a reviewer for the Aerospace Science and Technology Journal and Measurement Science and Technology among others. He is also active as a reviewer, moderator, and interviewer for professional and qualification evaluations for the Engineering Council of South Africa. Also, he has published more than 15 Research Papers in International Journals.

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