Gas turbine maintenance– aero engines

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Abstract

In this paper, we discuss the history, background, and evolution of gas turbine maintenance of aero engines. The types and levels of maintenance have been discussed to develop an understanding of the reader on Aero Engine Aviation Maintenance. The layout, facilities, and the typical composition of a Gas Turbine Maintenance Establishment (GTME) of Aero Engines has been emphasized to provide an insight into the workflow in a typical GTME of Aero Engines. The role of effective logistics and supply chain management and its impact on the serviceability of the engines in a typical GTME of Aero Engines has also been covered in this paper. The challenges and the problems of the technicians, maintenance engineers, and maintenance set up and how they affect the high serviceability levels of Aero Engines have been highlighted. The current and future state of GTME have also been included in this paper. The scope for introduction and development of lean maintenance in GTME of Aero Engines to achieve high serviceability levels has also been looked into considering the increase in demand for civil aircraft for passenger and cargo service and for military aircraft for security in the next decade.

Keywords: Gas Turbine Maintenance Establishment; Maintenance Control Centre; Reliability Centered Maintenance; Supply Chain Management; Lean Maintenance

Nomenclature

AOG	***Aircraft on Ground***	***LP***	***Low Pressure***
BRD	***Base Repair Depot***	***MCC***	***Maintenance Control Centre***
DOD	***Domestic Object Damage***	***MCD***	***Magnetic Chip Detector***
DR	***Defect Report***	***MRM***	***Maintenance Resource Management***
EOG	***Engine on Ground***	***MRO***	***Maintenance Repair Overhaul***
FOD	***Foreign Object Damage***	***MTBF***	***Mean Time Between Failure***
FOH	***Forced Outage Hours***	***OEM***	***Original Equipment Manufacturer***
GTME	***Gas Turbine Maintenance Establishment***	***PWR***	***Premature Withdrawal Report***
GTS	***Gas Turbine Starter***	***RCM***	***Reliability Centered Maintenance***
HUMS	***Health Usage Monitoring System***	***SCM***	***Supply Chain Management***
JIT	***Just In Time***	***VSM***	***Visual Stream Mapping***

1. Introduction

High and dependable serviceability is critical for efficient operation of aircrafts both in commercial and military aviation. Almost every Military aviation of the World is beset with long delays when carrying out depot-level maintenance. The requirement of high efficiencies/production is more in high demand and less density fleets. The maintenance is also based on the foundations of efficiency and efficacy of the logistics and product.

Supply chain efficiency and prompt supplies are crucial for the sustainability of adequately high levels of serviceability [1]. The increasing age of aircraft, high operational demands, reduced manpower and overall lack of fiscal resources further compound the problem to the extent that previous solutions provided to address aircraft availability shortfalls have been found insufficient.

The paper focuses on the workflow and facilities of a typical GTME. The levels and types of Maintenance have been explained to develop an insight on the kind and the amount of work that is carried out and the skill that is required to carry out that work in a typical maintenance set up of a type of Aero Engine. Different generations of Aviation Maintenance have been covered to describe the evolvement and development of Aviation Maintenance in terms of checks, inspections, servicing, advancements in tools and testing, workforce requirement, reliability, automation, ease of maintenance, safety, and security. Gas Turbine Deterioration which includes gas turbine faults and component degradation and Gas Turbine Condition Monitoring which comprises Oil System Monitoring, Visual Condition Monitoring, Vibration Monitoring, and Acoustics Monitoring has been mentioned to explain how the engine is assessed, engine condition is monitored, engine faults are diagnosed and rectified, and how the engine is maintained using Health Usage Monitoring System (HUMS). Reliability Centered Maintenance (RCM) which defines the entire maintenance and Maintenance Control Centre (MCC) which maintains the records of aero engines and monitors the life of the engine and its components have been emphasized. Finally, the role of logistics and supply chain and its impact on the maintenance and serviceability have been dealt.

2. Typical gas turbine maintenance establishment- aero engines

Due to the increasing importance of aviation safety and airworthiness of aircraft, maintenance, repair, and overhaul, (MRO) has become the key division in aviation industry [13]. Maintenance, repair, and overhaul (MRO) in the aeronautical industry is a complex process that has strict and precise requirements defined by airworthiness authorities to guarantee the safety of passengers and aircrew. MRO may be defined as " all actions that have the objective of retaining an item in or to a state in which it can perform its required function. The actions include the combination of all technical and corresponding administrative, managerial, and supervision actions”.

Aircraft maintenance is the overhaul, repair, inspection or modification of an aircraft or aircraft component. Aircraft maintenance checks are periodic inspections that have to be done on all commercial/civil aircraft after a certain amount of time or usage; military aircraft normally follow specific maintenance programs which may or may not be similar to those of commercial/civil operators. The first generation of Aviation maintenance consisted of servicing aircraft and aircraft equipment, preflight and daily inspections, minor repairs, adjustments, and replacements. All essential tools and equipment had to be air transportable. The second generation of Aviation maintenance included in-depth servicing of aircraft and equipment, periodic preventive inspections, repairs, and replacements, engine changes. The majority of second-generation equipment had to be air-transportable though some support elements required ground transportation.

The third generation Aviation maintenance included repairs and replacements that required mobile machinery and other equipment that had to be moved by ground transportation. The technicians were highly specialized with an emphasis in field repairs and salvage, removal, and replacement of major units, assemblies, fabrication of minor parts, and minor repairs to aircraft structures and equipment. This generation specialized in heavy field repairs within a limited time. The fourth and present generation includes operations needed to completely restore worn out or heavily damaged aircraft to a condition of tactical serviceability and also included the periodic major overhaul of engines, unit assemblies, accessories, and auxiliary equipment.

Maintenance types:

Generally, there are three types of maintenance in use:

a) Preventive Maintenance:

It is the maintenance where the equipment is maintained before breakdown occurs. It is performed in an attempt to avoid failures, unnecessary production loss, and safety violations. Preventive maintenance is effective in preventing age-related failures of the equipment. For random failure patterns which amount to 80 percent of the failure patterns, conditioning monitoring proves to be effective. The effectiveness of a preventive maintenance schedule depends on Reliability Centered Maintenance (RCM) Analysis which it was based on, and the ground rules used for cost-effectivity.

b) Corrective Maintenance:

Corrective maintenance can be defined as the maintenance which is required when an item has failed or worn out to bring it back to working order. Corrective maintenance is the program focused on the regular task that will maintain all the critical machinery and the system in optimum operating conditions. The major objectives of the corrective maintenance program are to eliminate breakdown, eliminate deviation, eliminate unnecessary repairs, and optimizie all the critical planned system.

c) Predictive Maintenance:

Predictive maintenance can be defined as the maintenance which is done using advanced equipment like digital and computerized testers to make the system serviceable.

RCM

Reliability-centered maintenance is an engineering framework that enables the definition of a complete maintenance regime. It regards maintenance as the means to maintain the functions a user may require of machinery in a defined operating context. It enables maintainers to monitor, assess, predict and generally understand the working of their physical assets.

Composition of a gas-turbine maintenance establishment (aero engines):

Today's typical GTME comprises of the following:

a) Maintenance Control Centre:

MCC is an important section of GTME as it plans, controls, directs, records, monitors and analyzes the servicing of the aircraft and engine. It is divided into four sub-sections

- Planning Section- It monitors the aircraft and aero engines falling due for different periodic checks based on flying hours and calendar life and accordingly prepares the schedule servicing plan. It also prepares Aircraft on Ground (AOG) build up plan as per requirement. Special Technical Instructions and Servicing Instructions are also monitored.
- Direction and Controlling Section- It issues the work order to second line maintenance for scheduled servicing (preventive maintenance) of aircraft and aero engines and task order for unscheduled servicing (corrective maintenance) of aircraft and aero engines. Concessions, limitations, and extensions of servicing are also looked after.
- Records & Analysis Section- Snag trend analysis of different systems are recorded and analyzed by this section. Premature Withdrawal Report (PWR) and Defect Report (DR) are also recorded and maintained by this section. Warranty, AOG, and cannibalization are also recorded.
- Document Section- It keeps the documents of all the aircraft and is responsible for the custody and maintenance of all the documents.

b) First Line or Flight Line Maintenance:

The FLM includes the maintenance that is carried out in the operational units. It involves the routine maintenance of the aircraft. The maintenance consists of Daily Inspections which include preflight, Turn Around, and after-flight/Last flight inspections, minor repairs, rectifications, and replacements. This servicing is done as per OEM servicing/maintenance publications. The specialized aviation maintenance personnel is deployed in the flight line according to their specialized trades (Figure 1) to carry out the maintenance activities. The maintenance personnel is supervised and monitored by aeronautical engineering officers specialized in mechanical and electrical systems (branches).

Specialised System Trade	Function
Airframe /St ruct u re	Daily Inspectio n , Minor repairs, rectificatio n , and replaceme nts related to structure and associated systems
Propulsio n	Daily Inspection, Minor repairs, rectification, and replacements related to Propulsio n and associated systems
Systems	Daily Inspection, Minor repairs, rectification, and replacements related to Electrical, Instrument, and associated systems
Avionics	Daily Inspectio n , Minor repairs, rectificatio n , and replaceme nts related to Avionics (Radar & Radio) and associated systems
Weapon/A rma men t	Daily Inspection, Minor repairs, rectification, and replacements related to Weapon/Arma ment and associated systems

Figure 1. First Line Specialised System Trades and Its Function

c) Second Line Maintenance:

Second Line Maintenance includes both rectification (corrective maintenance) and periodic servicing (preventive maintenance) of the aircraft. It involves removal and replacement of major units, assemblies, fabrication of minor parts, and minor repairs to aircraft structures and equipment. The periodic servicing is classified as A-Check, B-Check, and C-Check. Each check is carried at certain flying hours as prescribed by OEM in the publications. Each of the checks varies from aircraft to aircraft and is decided by the OEM of the aircraft. These checks can also be classified in some countries as primary, primary star, minor, and minor star. The team composition is similar to flight maintenance, but the type of service carried out varies. The time consumed for each check also varies from aircraft to aircraft and engine to engine.

d) Base Repair Depots/Service Support Centers:

Third and fourth line maintenance is undertaken by BRDs to carry out D-Check or major servicing of aircraft. This is the most comprehensive and demanding check for an airplane. It takes the entire plane and engine apart for inspection and overhaul. The paint of the aircraft is also removed for further inspection on the structure of the aircraft. It also requires the most space of all and is the most expensive maintenance check of all. In the absence of BRDs at the base level, some AMRO establishments have service support centers which carry out most of the major servicing of the aircraft.

3. Maintainability, availability, and reliability

Maintenance costs and availability are two of the most important concerns to the equipment operator. For a maintenance program to be effective, the operator must develop a general understanding of the relationship between his operating plans and priorities for the plant, the skill level of operating and maintenance personnel, and the manufacturer's recommendations regarding the number and types of inspections, spare parts planning, and the major factors affecting component life and proper operation of the equipment. A well-planned maintenance program will result in maximum equipment availability and optimal maintenance costs.

The failure rate/time relationship for most of the equipment has traditionally been represented by the bath-tub curve (Figure 2).

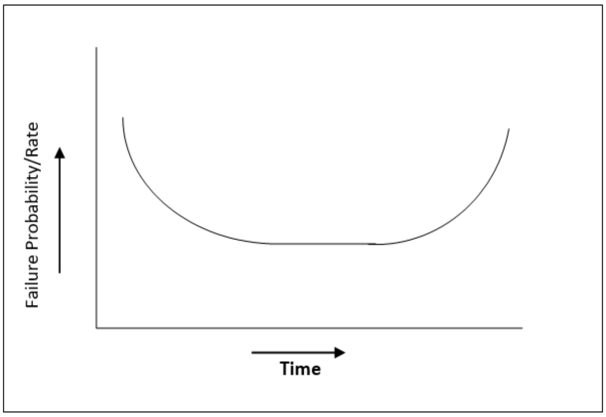

Figure 2. Bath-Tub Curve

The first stage of the curve represents the running in period characterized by falling failure rate. During this period, manufacturing and minor design mistakes are corrected. The next stage is one of constant failure rate, the level of which depends on the intensity and efficiency of maintenance assuming that after repair the equipment is restored to as good as new conditions. The third part of the curve represents the wear out stage, which is characterized by sharp increase in the overall failure rate of the system.

a) Reliability

Engine reliability is a function of engine design, manufacture, operating environment and quality control. Failure is related to reliability and availability. A user needs to assess the economic and operational aspects of engine availability and reliability. Probability of not being forced out of service when the unit is needed includes 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 -FOH/PH) * (100%)

Where FOH = total forced outage hours, PH = period hours

Reliability is basically a design feature and even with the best of the maintenance techniques it can only be restored to the designed level. Design influences reliability via such considerations as stress margins used, margins to critical speeds, margins to blade and vane vibration frequencies, and environmental conditions including fuel, air and oil specifications. The simplicity of the design, the design maturity and established design and development procedures along with redundancy make an important contribution to engine reliability. Manufacture, quality control and experience also make a major input. Often a reliable gas turbine can be let down because of inadequate installation and/or auxiliaries. An increase in reliability requires high developmental costs and then in order to maintain this reliability with time, good maintenance techniques are required.

b) Availability

Availability is a function both of mean time between failure (MTBF) which is related to reliability and downtime defined by the maintenance organization and inherent maintainability. The largest contributors to forced outage rates are often engine support systems such as control and fuel systems. The down-time associated with these systems can be managed to acceptable levels by design redundancy and the holding of appropriate spares. Advances in instrumentation and micro-processor-based controllers can be expected to contribute to further improvements in the availability of engine support systems. Probability of being available, independent of whether the unit is needed- includes all period hours and mean time between failures- units are %:

$$\text{AVAILABILITY} = \frac{\text{MTBF}}{\text{MTBF + DOWNTIME}}$$

Gas turbine faults

In service performance deterioration of gas turbine engines is inevitable. Gas turbine engines operate over a wide range of temperature, speeds, power and environments. All these causes a deterioration of the gas turbine performance which can be defined as the cumulative effect of the performance degradation of various modules that constitute the engines. The various gas turbine faults are

(a) Fouling (Deposition)

(b) Corrosion

(c) Rubbing Wear

(d) Labyrinth Seal

(e) Foreign object damage (FOD) and Domestic Object Damage (DOD)

(f) Hot End Component Damage

Ability to identify the cause of the fault and the type of fault helps in reducing the maintenance time and employing relevant testing equipment and service procedure to address the issue.

Systems monitoring

(a) Oil System Monitoring

(b) Debris Monitoring

(c) Vibration monitoring techniques

(d) Engine Usage Monitoring Techniques

(e) Visual Condition Monitoring Techniques

(f)Turbine exit spread monitoring

(g) Limited Transient Monitoring

(h) Acoustic Monitoring

Constant monitoring of systems as mentioned in the maintenance manuals helps in identifying the deterioration or degradation of a particular system and preventing premature failure and flame out of the engine. Condition monitoring and Health Usage Monitoring Systems (HUMS) using advanced testing equipment can help in assessing the condition of the engine and taking relevant corrective action to increase the engine life. The breakdown of the different faults and failure of systems indicate lubrication system has the highest faults and failure (Figure 3) than the other systems. This is because of the damage caused to the bearing and seals of the bearing compartment due to the kind of loads and stresses the engine experiences which results in leakage of oil and may eventually lead to premature failure and flame out of the engine. This can be avoided through regular cleaning and inspection of the oil pressure filter, debris monitoring using Magnetic Chip Detector (MCD) debris analysis with the most advanced digital debris testers and adhering to correct maintenance practices mentioned in the publications of the OEM. Regular monitoring of all the systems as integrated diagnostic testing (Figure 4) helps in the Early Failure Detection of the problems.

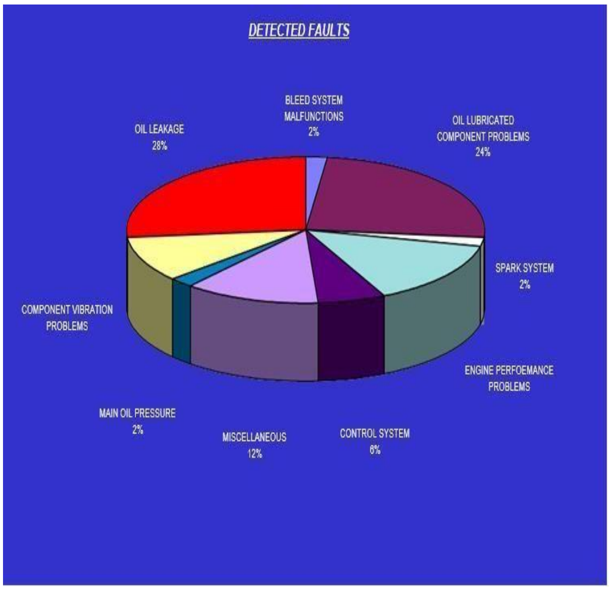

Figure 3. Breakdown of faults detected for a typical gas turbine

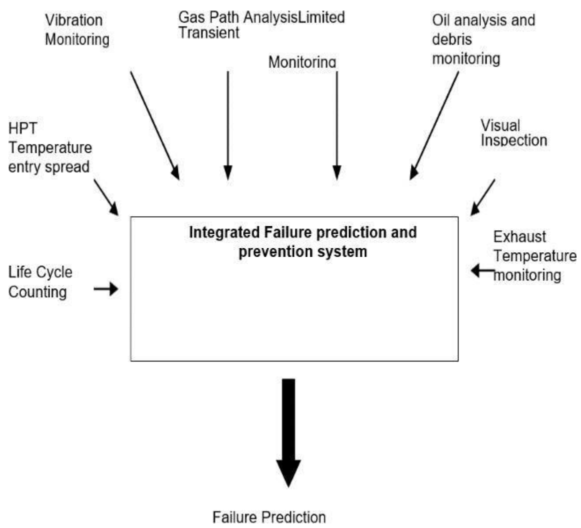

Figure 4. An Integrated Diagnostic System

4. Supply chain support

Generally, supply chain members include suppliers, Manufacturers, Distributors and End Customers. With regards to GTME, the supply chain includes Sub-Tier Suppliers, System Suppliers, Aircraft OEMs, MRO (GTME) Services/Repair Shops and Operators (End users or Customers). The focus of GTME is on Reduced Turn-Around Time (TAT), Product Availability, Reliability, Quality, Cost, Flexibility, and Safety. In order to achieve the above, researchers have felt that the introduction and application of lean in GTME is not enough, but it should be extended to the extended enterprise (supply chain) of GTME. Supply chain integration involves dealing with other supply chain members as extended members of Manufacturers/MROs. Supply chain integration helps in achieving continuous flow on shop floors, low inventory, effective demand management which are ultimate objectives of lean application in GTME establishment through effective communication, information sharing, and coordination between supply chain members.

Role of logistics in the GTME supply chain

The term logistics in civil usually refers to supply chain functioning related to flow of goods for meeting customers' requirements. Military logistics, on the other hand, covers a far wider scope of functions. The 'whole' military function can be understood simply as comprising two main elements, operations, and logistics. Every function excluding operations and operational training from the whole can be considered a part of logistics. Logistics in the context of military includes all functions performed on material and transportation of personnel. The material function comprises of design, development, acquisition, maintenance, upgrade, storage distribution and disposal. An aircraft is made of millions of parts. The role of logistics is to procure and track each and every part that is not available at the base as per the demand of the maintainer.

Benefits of lean introduction and adoption at GTME

Lean In the physical sense can be described as lightweight, thin, speedy, and agile. In a way this is a correct description of the principles of LEAN. However, LEAN Goes further than that. It is also a certain discipline, a way of doing things and responding to situations. Lean principles are the mechanism for process improvement developed by Womack and Jones based on the original work done by Ohno of the Toyota Motor Corporation to optimize production by eliminating waste [6].

Many of the authors agree that the identified benefits are linked to lean management practices such as value chain analysis, waste elimination, system organization, operator (end customer) focus, problem-solving, strong and effective relationships. Implementation of just-in-time and pull production will reduce the surplus (unnecessary) inventoryand increase the product (serviceable product) availability for servicing the aircraft/aircraft system. The authors view flexibility as the ability to respond to the dynamic situation in terms of volume, different types of product (systems) and delivery. The improvement in a supply chain can be achieved through implementation of lean principles, practices, and techniques. Implementation of principles requires implementation of corresponding practices which in turn requires implementation of corresponding techniques. The most common principle applied is value stream mapping, which maps value to expose and eliminate waste. Strong and effective relationships, value chain analysis and waste reduction are the most acknowledged practices for implementation of lean in the supply chain. JIT, VSM and supplier integration are very popular techniques in the implementation of lean in a supply chain.

5. Minor star preventive maintenance of a military aircraft at a typical military GTME

The responsibility of various types other than corrective maintenance rests with the MCC. The corrective maintenance is carried out at the airline operating/operating unit level whenever an aircraft or aero-engine experiences snag or problem. The typical minor star preventive maintenance activity is carried out at 1000 Hrs. of flying of the aircraft. Whenever an aircraft is due for a servicing, the MCC informs and directs the operating unit to hand over the aircraft to the shop floor Bay accordingly. The aircraft is received by the shop floor bay from the operating unit and carry out the acceptance/induction checks. The problems and abnormalities observed during the acceptance checks are recorded. Thereafter the Bay personnel will carry out the remaining activities in sequence. The activities will be carried out as per the service procedures and instructions mentioned in the manuals of the OEM. The increase in lead times and non-value-added time of the maintenance than the mentioned time in publications of the OEM is due to unavailability of spares, tools, testers, ground equipment, and lack of skilled workforce. Once the servicing is done, the shop floor bay informs the MCC which in turn directs the operating unit to receive the aircraft for operations. The various activities and process times (Figure 5) of a minor star preventive maintenance of a military aircraft at a typical GTME are mentioned below.

1. Engine LP Fuel Filter Removal, Cleaning, Examination, and Fitment
2. Dry and Wet drain outlet leak rate check
3. Jet Pipe Removal and Inspection
4. Insulation Blanket Removal, Inspection, & Fitment
5. Jet Pipe Fitment
6. Oil Pressure Filter Removal, Inspection, Cleaning, and Fitment
7. Throttle Teleflex control undercarriage and engine bay degreasing and greasing (XG-287)
8. Throttle Valve Control rod bearing lubrication by OX-27 Oil.
9. Shut off valve control rod bearing lubrication by OX-27 oil
10. Air Filter Element- Removal, Cleaning, Examination and Fitment
11. Fuel Strainer Left & Right mainplane examination
12. LP Cock Pull up Load Check
13. Refueling Connector lugs & slots check for wear & tear by wear gauge
14. Fuel Pipes & attachments/Fittings left and right undercarriage bay examination for damage, chaffings
15. GTS oil tank- Examination & Replenishment
16. GTS oil tank outlet filter removal, cleaning & Fitment
17. GTS LP Fuel filter Removal and afterbay maintenance
18. Gravity filler cap Examination
19. LP Compressor Wash
20. Engine Static & Dynamic Ground Run Checks

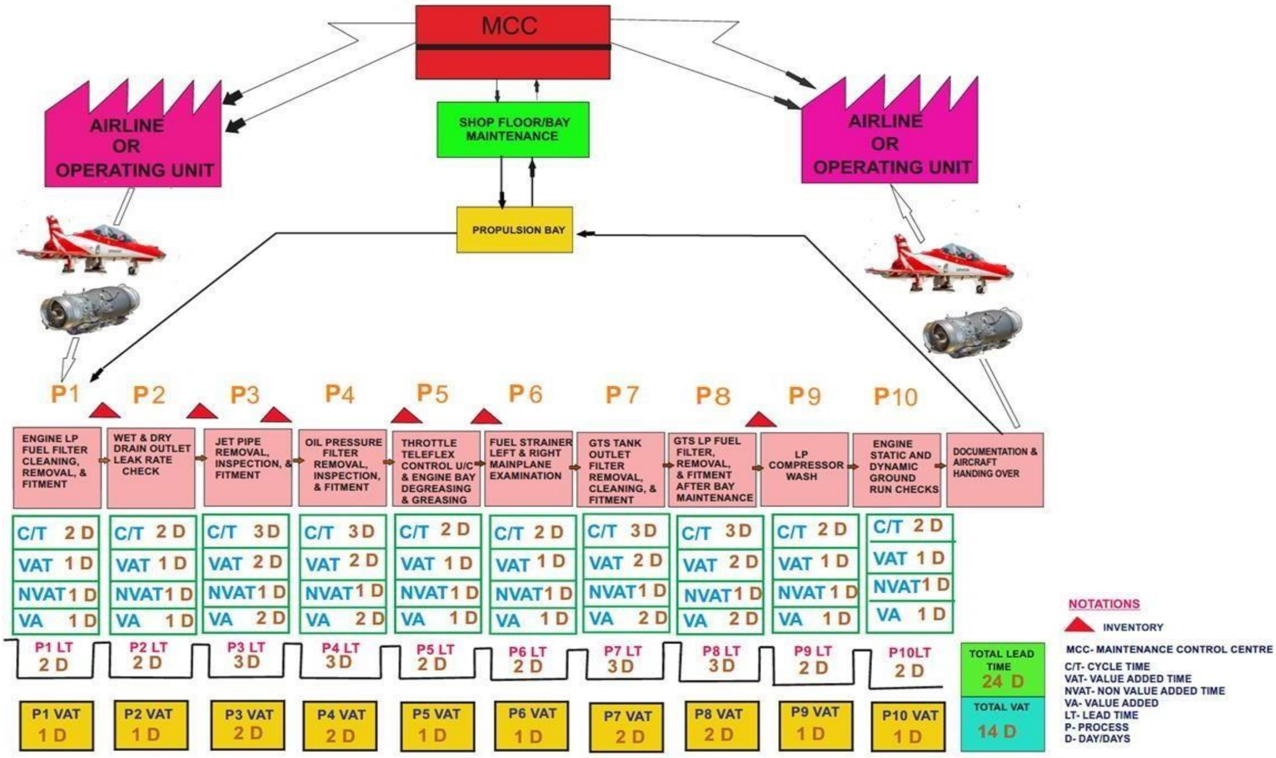

Figure 5. Minor Star Preventive Maintenance (Aero Engine)

Ergonomics in Maintenance:

While many people assume that human factors in maintenance refers to the actions of mechanics, the Maintenance Resource Management (MRM) which was formed by aviation industry admits to several major areas where maintenance errors can occur [3]. These areas are (a) equipment design and manufacture;(b) manufacturers' documentation and procedure writing; (c) airline procedures and work areas (d) mechanic training and performance.

The airframe and equipment manufacturers have implemented Human Factor programs to improve design such that maintenance can be performed more easily and reduce the number of possible errors that can be made. Improvements in maintenance manuals and other documents are also under manufacturer's scrutiny and certain academics are looking into the problem of Human Error. But the Airlines also have a responsibility to monitor the processes and procedures they employ and to modify those with respect to human error reduction. The training organization should modify courses to accommodate any changes necessary to meet the Human Factors aspect and is also required to develop and implement a Human Factor Maintenance course [3].

Problems of Technicians and Engineers:

The biggest problem of GTME globally is the unavailability of spares and TTGE, which put mental and physical pressure on the technicians and engineers to meet the ever-increasing operational demands of the airliners. The increasing age of aircraft and the continuation of old aircraft due to low fuel prices and lack of interest to replace the old ones is putting a lot of burden on the technical manpower to work on the aged aircraft to achieve the required levels of lead times due to the inherent degradation of the condition of the aero engine and aircraft. Also, the shortage of manpower is affecting the lead times and serviceability of aero engines. The fusion of maintenance and supply chain management can address the above problem to some extent.

Safety:

Safety, as has been said by so many other, is everyone's job or business and is paramount [3]. Communication is key to ensuring everyone's safety. It is the responsibility of GTME to provide safe and sanitary working conditions. Technicians, supervisors, and engineers should watch for their own safety and for the safety of others working around them [3]. The hangars or sheds used for storing the support equipment should be clean and of the highest standard. Signs should be used for segregating dangerous and hazardous equipment from the other equipment. Also, signs should be used to provide the location of first aid kit and fire equipment. Wearing or use of safety equipment like gloves, safety glasses, ear defender can protect the user from hearing loss and injury during aircraft operations and maintenance. The maintenance personnel should comply with the safety procedures mentioned in the publications of the OEM to prevent injuries and accidents while carrying out maintenance activities.

6. Conclusion

The safety of the aircraft and passenger largely depends on the effective maintenance of the engines and aircraft. Adherence and Compliance to service procedures mentioned in the manuals can not only prevent accidents but also increase the life of the engine and aircraft. Most of the Maintenance Establishments across the world are facing common problems like Aircraft on Ground (AOG), Engine on Ground (EOG), high lead times, down times, poor serviceability levels etc. These problems are mostly due to unavailability of spares, tools, testers, ground equipment, lack of skilled workforce. Effective Supply Chain Management and the introduction of Lean Maintenance and Blockchain Strategy canaddress the problems and challenges of supplies. Continuity training regarding service procedures, safety, and engine systems will contribute to effective maintenance and developing a skilled workforce. Correct Maintenance practices can prevent duplication of work, accidents and help in increasing the safety of aircraft, technicians, and engineers. Any airlines or military aircraft operating unit is as good as the maintenance of its aircraft, technicians, and engineers. From the military perspective, in order to make a military combat aircraft to fly for two hours, the maintenance time is approximately 13 hours. The amount of hard work that goes into the aircraft is huge and deserves due respect to the technicians and engineers who make the aircraft fly high safely.

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