

Engine Maintenance Concepts for Financiers

Elements of Turbofan Shop Maintenance Costs



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Abstract

Commercial aircraft maintenance cost can be divided into three main areas; airframe, engines, and components. These three areas represent the majority of the aircraft's maintenance exposure over its service life. Of these three costs, engine maintenance expenditures will often represent the most significant, and consequently will have an important impact to the market value of the entire aircraft at any given time.

The purpose of this paper is to discuss the primary factors that influence engine maintenance costs. The material presented herein is intended to be both a guide and a resource tool for those interested in gaining a better understanding of what factors influence engine maintenance cost and how these factors can be managed.

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1. INTRODUCTION

The predictability in assessing an engine's shop Direct Maintenance Cost (DMC) is largely a result of the significant reliability improvements inherent in today's engine technology and as a result of the introduction of on-condition maintenance practices. Engine on-condition maintenance does away with "hard-time" intervals and prescribes routine monitoring of key operational parameters such as Exhaust Gas Temperature (EGT), fuel flow, vibration, oil consumption, and rotor speed. Degradation in any of the parameters beyond OEM specified limits often warrants removal of the engine for maintenance.

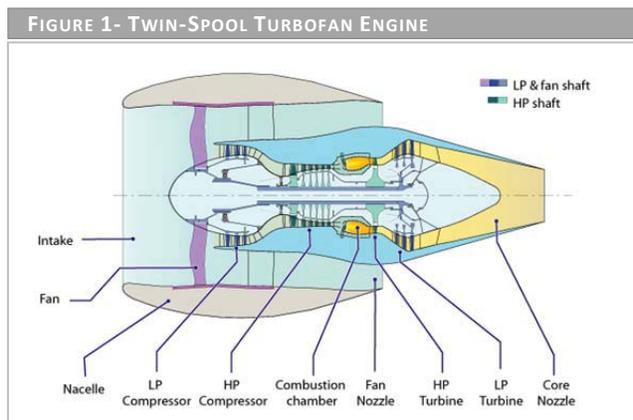
A by-product of reliability improvements and on-condition maintenance philosophy is greater reliance on condition-monitoring software and statistical analysis to predict the frequency of engine shop visit events and their corresponding shop visit costs. Estimating an engine's shop DMC therefore, requires careful forecasting of the equipment's on-wing life as well as accurate assessment of its shop visit costs at each phase during its life-cycle status.

An engine's on-wing life is heavily influenced by its thrust rating, operational severity (e.g., average flight leg, take-off derate, environment), and maturity (e.g., first-run or mature-run). Factors influencing an engine's shop visit cost consists of time on-wing considerations as well as business considerations. The aim of this paper is to examine the off-wing elements of engine maintenance cost. The examples and data analyzed are based on a standard turbofan engine incorporating conventional design architecture.

2. TURBOFAN ENGINE

Aircraft turbine engines used on today's commercial jet aircraft are classified as turbofans – Figure 1. Relative to their turbojet predecessor turbofans develop much higher takeoff thrust, are much more fuel efficient, and considerably quieter in operation.

All turbofan engines currently in use are axial flow engines, meaning that the compression phase within the core is done axially (parallel to the axis of the engine) as the air flows through the compressor. The compressor is composed of several rows of airfoils that alternate among rotor blades and stator blades. Rotor blades are connected to the rotating shaft whereas stator blades are fixed and do not rotate.

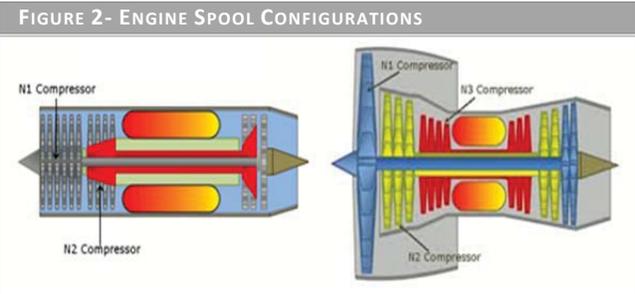


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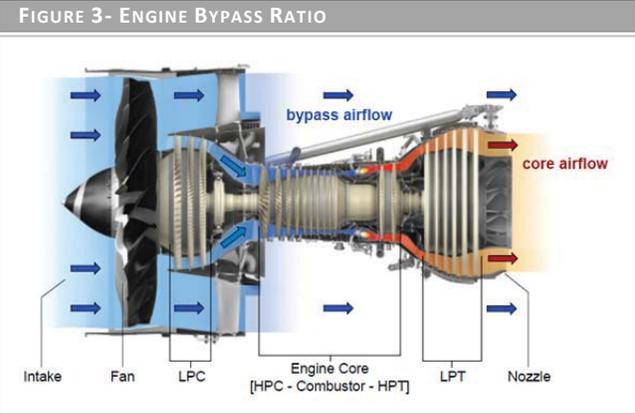
In a turbofan engine a large portion of the inlet air accelerated by the fan is bypassed around the core of the engine. The fan, in effect, is taking on the role of a propeller by generating supplemental thrust. The remaining portion of the inlet air continues into the core engine where it is compressed and mixed with fuel in the combustor. The resulting high temperature exhaust gas is used to turn (power) the turbine and generate thrust. A turbofan, therefore, generates a portion of its thrust from the core engine and most of its thrust from the fan.

Conventional turbofan engine design is based on either a twin-spool or triple-spool configuration – Figure 2. In a twin spool configuration the low-pressure compressor is driven by the low-pressure turbine, and the high-pressure compressor is driven by the high-pressure turbine. A triple-spool turbofan generally includes an additional (intermediate) compressor and turbine. Each spool generally rotates at different speeds in order to maintain high efficiency in all stages of compression.



Thrust growth on turbofans is usually obtained by increasing fan airflow, which is commonly achieved by increasing its bypass ratio. The bypass ratio is the ratio of the air that goes around the engine to the air that goes through the core – Figure 3. In high bypass engines, the core engine primarily acts as a gas generator providing high energy gas flow to drive the fan turbine. The fan alone produces anywhere from 50% - 85% of the total engine thrust depending on the engine model. In addition, high bypass engines burns fuel far more economically relative to lower bypass ratio engines.

Increasing the bypass ratio tends to increase core thermal efficiency as well as improve fuel efficiency. High bypass ratios are also correlated with lower noise, since the large flow of air surrounding the jet exhaust from the engine core helps to buffer the noise produced by the latter.



The turbofan market is dominated by General Electric, Rolls-Royce and Pratt & Whitney, in order of market share. GE and SNECMA of France formed a joint venture, CFM International, which manufactures the CFM56 family of engines. Rolls Royce and Pratt & Whitney also have a joint venture, International Aero Engines (IAE), which manufacturer the V2500 family of engines.

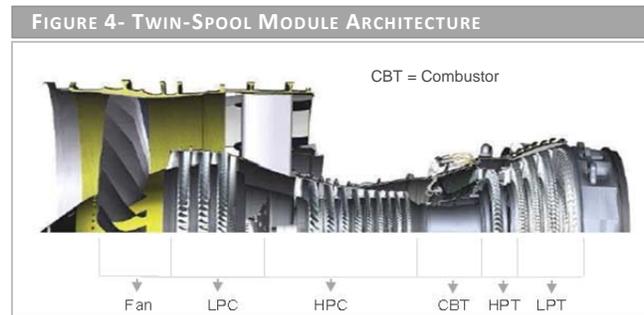
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3. ENGINE MODULE DESIGN CHARACTERISTICS

Today's engines are built from a number of individual assemblies known as modules, each of which has its individual identity, service history and inspection thresholds. Any of the constituent modules can be replaced as an entire unit during a shop visit. Key benefits gained from a modular construction are: a.) Decreased turn-time, and b.) Reduced spare engine holdings.

Figure 4 illustrates a modular architecture of a conventional twin-spool turbfan engine. Turbofans that are based on triple-spool design architecture also include an Intermediate Pressure Compressor (IPC) module and an Intermediate Pressure Turbine (IPT) module. A brief description of each of the major modules is summarized below.



3.1 Fan / Low Pressure Compressor (LPC) - The Fan / LPC module is the first component on the engine. The key components of the fan module consist of the fan blades, fan disk, and compressor case. Today's fan blades are generally made of titanium, however a number of newer generation models also use high strength composites.

3.2 High Pressure Compressor (HPC) - The HPC module is made up of a series of rotor and stator assemblies whose main function is to raise the pressure of the air supplied to the combustor. The rotor assembly key components are the axially mounted compressor blades, while the stator assembly key components are the compressor vanes.

3.3 Combustor - The combustor is where fuel is added to the cycle to create thermal energy. Most of today's modern turbfan engines employ an annular combustion system. The key components of a combustor consist of the inner & outer casings, fuel nozzles, and the high pressure nozzle guide vanes.

3.4 High Pressure Turbine (HPT) - The HPT module is aft of the compressor rear frame and forward of the LPT stator case. The HPT module is made up of the HPT rotor and nozzle guide vane assemblies, which act to extract the combustion thermal energy for driving the high-pressure compressor and accessory gearbox.

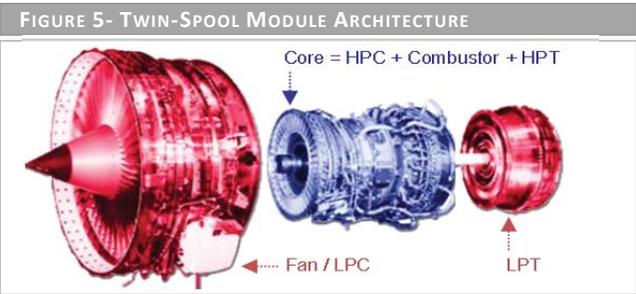
3.5 Low Pressure Turbine (LPT) - The LPT module is downstream of the HPT module. LPT components include the LPT rotors, LPT nozzle stator case and turbine rear frame. The LPT extracts the remaining combustion thermal energy to drive the fan and low-pressure compressor rotor assembly.

3.6 Accessory Drive - The accessory drive section is usually attached to the engine core or fan case. The accessory drive transfers mechanical energy from the engine to drive the basic engine & aircraft accessories (e.g. generators and hydraulic pumps) mounted to the accessory gearbox.

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An engine's core section, also referred to as the hot section, consists of the HPC, combustor, and HPT – Figure 5. During operation it is this section that will be subject to most demanding conditions with respect to temperature, pressure, and rotational speed. It will therefore be this assembly of the engine that will deteriorate fastest, and core refurbishment will more likely need to be performed at every shop visit to regain lost performance.

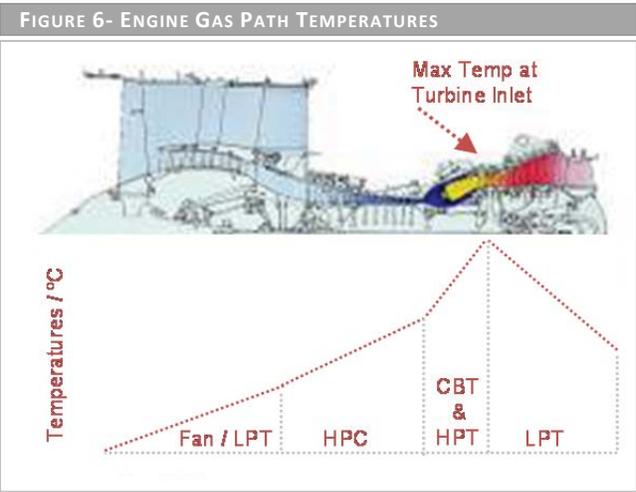


4. ENGINE OPERATING TEMPERATURES

High thermal efficiency is dependent on high turbine entry temperatures. Figure 6 shows the temperature rise through the engine gas flow path. Today's engines can experience turbine inlet temperatures in excess of 1,500°C. To put this into perspective, at approximately 1,500°C components in the turbine are operating eight times hotter than a typical domestic oven.

The primary limitation to higher turbine inlet temperatures is the availability of exotic materials that can withstand these higher temperatures. The general trend is that raising the turbine inlet temperature increases the specific thrust of the engines with a small increase in fuel consumption rate.

The combination of a higher overall pressure ratio and turbine inlet temperature improves thermal efficiency. This, together with a lower specific thrust (better propulsive efficiency), leads to a lower specific fuel consumption.



5. ENGINE KEY OPERATING PARAMETERS

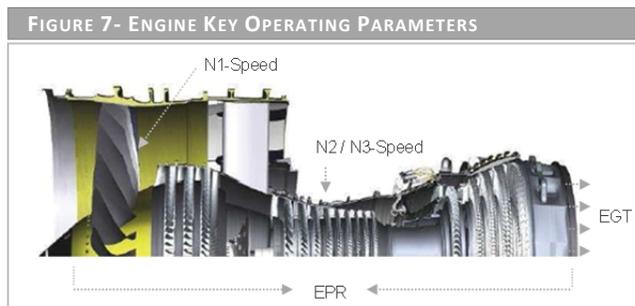
The primary engine operating parameters are illustrated in Figure 7, and consist of fan speed (N1-speed) and Exhaust Gas Temperature (EGT). Fan speed is commonly used for thrust indication whereas EGT is a common condition (or health) monitoring parameter. Some engine models also make use of Engine Pressure Ratio (EPR) and N2/N3-speed for thrust monitoring. The following is a brief discussion of each of these performance parameters.

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5.1 Engine Pressure Ratio (EPR) - is defined to be the total pressure ratio across the engine, and is computed by taking the ratio of the total pressure at the exhaust (or turbine exit) to total pressure at the front of the fan/compressor. This is used by some engine manufacturers to measure engine thrust.

5.2 N1-speed - N1-speed is the rotation speed of the fan (or low pressure compressor depending on the engine type) and is typically presented as percentage of design RPM. Rapidly fluctuating N1 or EPR can be a sign of an engine stall whereas as low EPR or N1-speed can be a sign of a flameout. N1-speed is also a primary parameter used to measure thrust.



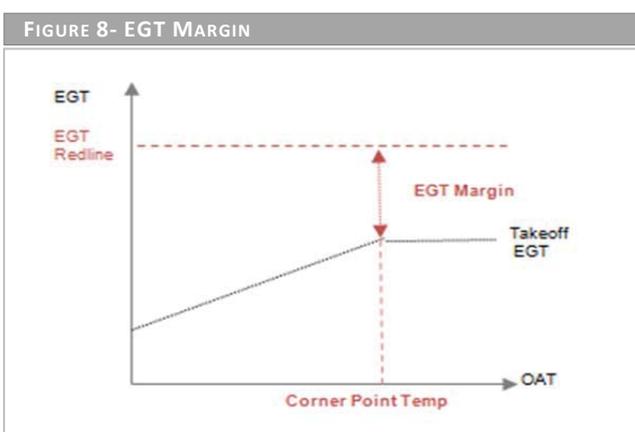
N2-speed (or N3-speed if the engine is a three spool configuration) is the rotation of the high or intermediate pressure compressor and is also presented as percentage of its design RPM. Rapidly fluctuating N2/N3-speed can be a sign of an engine stall.

5.3 Exhaust Gas Temperature (EGT) - expressed in degrees Celsius, is the temperature at the engine exhaust and a measure of an engine's efficiency in producing its design level thrust; the higher the EGT the more wear and deterioration affect an engine. High EGT can be an indication of degraded engine performance. An exceedance in EGT limits can lead to immediate damages of engine parts and/or a life reduction of engine parts. With this in mind it then becomes absolutely important to keep the EGT as low as possible for as long as possible.

5.4 EGT Margin - Normally EGT reaches its peak during take-off, or just after lift-off. The difference between the maximum permissible EGT (red-line) and the peak EGT during takeoff is called the EGT Margin - Figure 8. EGT margin is expressed mathematically as follows:

$$\text{EGT Margin} = \text{EGT Redline} - \text{EGT Gauge Reading}$$

In general, EGT margins are at their highest levels when the engines are new or just following refurbishment. Theoretically an engine can remain in operation until its EGT margin has reduced to zero. EGT margin is also sensitive to changes in Outside Air Temperatures (OAT). As the OAT increases so does EGT for a given thrust setting. This is because most engine power management systems are designed to maintain constant



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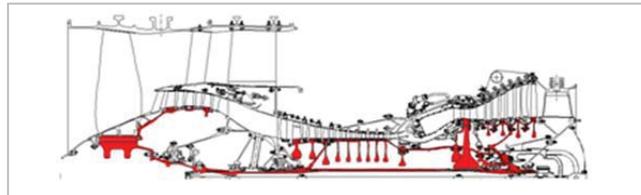
take-off thrust with rising OAT.

The rise in EGT is traditionally linear up to the design corner point temperature at which point the EGT becomes controlling. The corner point temperature is where the EGT is highest when operating at maximum thrust conditions. Operating at a higher OAT beyond the corner point temperature is possible, however the thrust must be reduced (de-rated) to avoid an EGT redline exceedance.

6. ENGINE LIFE LIMITED PARTS (LLPs)

Within engine modules are certain parts that cannot be contained if they fail, and as such are governed by the number of flight cycles operated. These parts are known as critical Life-Limited Parts (LLP) and generally consist of disks, seals, spools, and shafts – Figure 9.

FIGURE 9- ENGINE LIFE LIMITED PARTS



In most cases, the declared lives of LLPs are between 15,000 - 30,000 cycles, and a complete set will represent a high proportion (greater than 20%) of the overall cost of an engine. If the engine is operated over a long-range network, LLPs may never need to be replaced over the life of the engine. Over short-range routes however, LLPs may need to be replaced two or three times and, consequently, contribute a relatively high cost.

Certain LLPs can have shorter lives imposed on them by airworthiness directives (ADs) or other technical issues such as a decrease in fatigue characteristics or strength capability. Additionally, some engine manufacturers certify ultimate lives of LLPs at the time they certify an engine model. Other manufacturers certify the lives of LLPs as experience is accumulated. In these scenarios ultimate lives are reached after one or several life extensions.

The term stub-life is used to represent the engines shortest life remaining of all LLPs installed in a specific engine. Not all stub-lives are consumed during operation, and quite often the range of life remaining on an individual LLP at the time of replacement can vary from 3 to 15 percent of total cyclic life. Invariably, a considerable amount of value can be wasted when LLPs are replaced.

A number of engine models also contain static LLPs. Although these parts are not classified to be critical rotating parts they do fall under the category of parts whose failure could create a hazard to the aircraft. Such parts often consist of shrouds and frames.

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7. ENGINE MAINTENANCE PLANNING CONCEPTS

7.1 Engine Maintenance - Maintenance describes the work required during the engine's service life to ensure it operates safely, reliably, and cost-effectively. Aircraft maintenance costs represent approximately 10% - 15% of an airline's operating expenses, of which 35% - 40% are engine-related – Figure 10.

Material replacement is the most significant item in engine maintenance and, typically, can account for 60% - 70% of the engine's direct maintenance cost. It is caused simply because parts wear out and have to be either replaced or repaired.

Engine maintenance is required for three principal reasons:

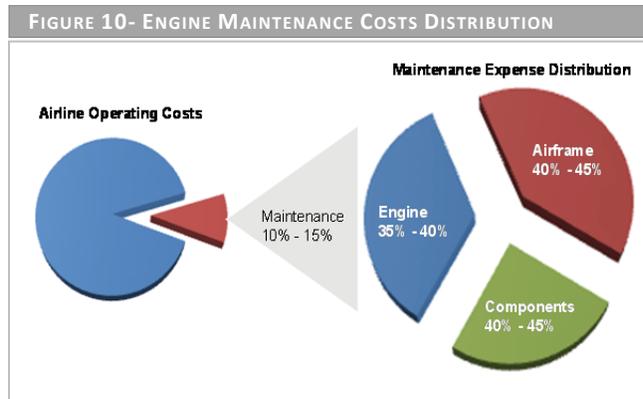
1. Operational: To keep the engine in a serviceable and reliable condition so as to generate revenue
2. Value Retention: To maintain the current and future value of the engine by minimizing its physical deterioration throughout its life.
3. Regulatory Requirements: To meet at least the minimum standards of inspection and maintenance required by the regulatory authorities.

An engine removal is classified as a shop visit whenever the subsequent engine maintenance performed prior to reinstallation entails either: a.) Separation of pairs of major mating engine flanges, or b.) Removal/replacement of a disk, hub or spool

7.2 Engine Shop Maintenance Elements - Engine shop maintenance includes two primary elements:

- Performance Restoration: The core engine deteriorates as parts are damaged due to heat, erosion, and fatigue. As an engine is operated the Exhaust Gas Temperature ("EGT") increases, inducing accelerated wear and cracking of the airfoils, which further decreases performance. Based on the engine materials and their properties, a critical EGT is established by the OEM, attainment of which necessitates a performance restoration shop visit.

During a performance restoration, the core module is traditionally dismantled and airfoils (rotors & stators) are inspected, balanced, and repaired or replaced as necessary. Service Bulletins and Airworthiness Directives are often incorporated during such visit.

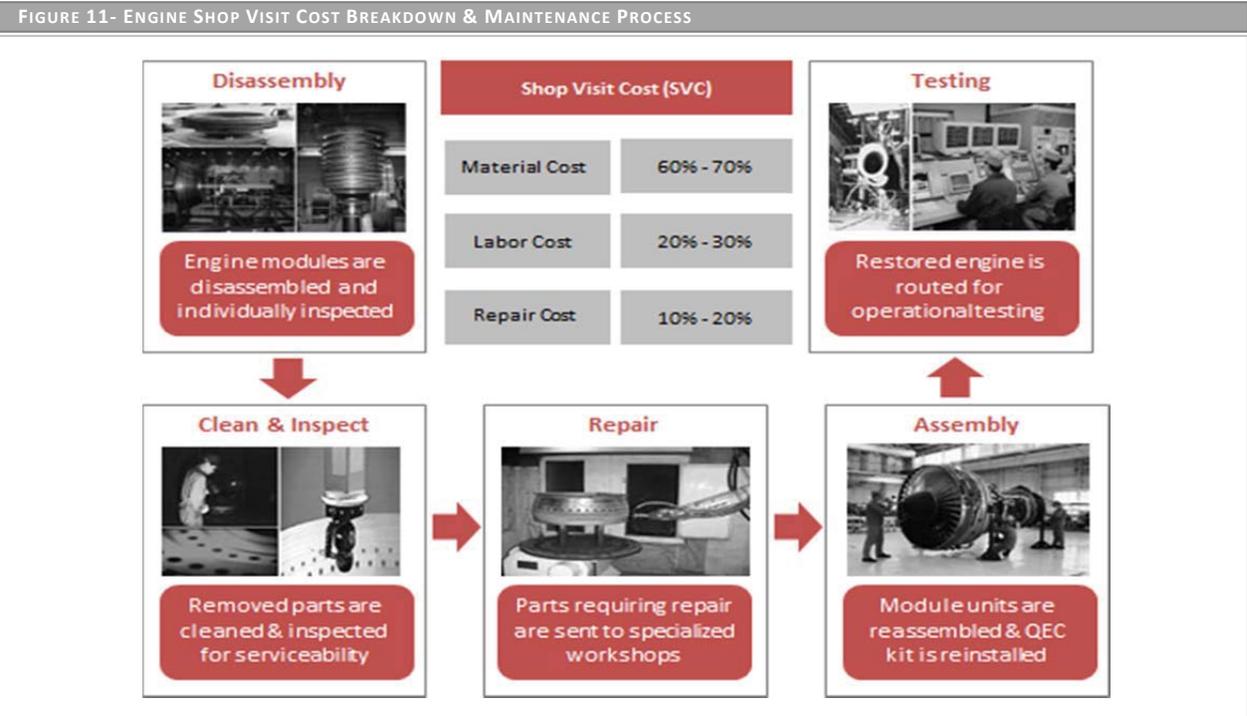


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- Life Limited Part Replacements: The rotating compressor and turbine hubs, shafts, or disks within the engine have a specifically defined operating life, at the end of which, the parts must be replaced and not used again.

The breakdown of an engine’s shop visit costs and maintenance process is detailed in Figure 11. The primary cost driver of engine shop maintenance is material cost. Approximately 60% - 70% of the cost of an engine shop visit is due to replacement of material. If life-limited parts (LLP) require replacement the material cost will increase further. Direct labor will account for approximately 20%-30% of total cost, while repairs will account for 10%-20%.



The biggest portion of material cost is attributable to airfoils – blades & guide vanes. Individual vane segments in the turbine modules can cost as much as \$10,000, while turbine blades can cost as much as \$8,000 each. A full shipset of High Pressure Turbine (HPT) blades can total between 60 – 80 blades and costs \$400,000 - \$700,000. And a full shipset of High Pressure Compressor Blades (HPC) can cost \$150,000 - \$300,000. Typically, the largest portion of parts repair cost is also associated with airfoils given that these parts require high tech equipment to make them serviceable again.

Engine on-condition monitoring and workscope management are becoming increasingly important and sophisticated aspects of maintenance management. The following sections discuss these two key components in greater detail.

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7.3 Engine On-Condition Monitoring - Historically, engines were removed and overhauled after a fixed time interval, often referred to as a hard-time interval. The main disadvantage of this process is that engines which were operating safely and satisfactorily had to be removed prematurely.

The modern trend is to maintain engines on an on-condition monitoring basis, wherein engines are removed only when an internal component reaches its individual life limit, or when performance monitoring suggests that the engine is operating outside manufacturers suggested parameters.

In order to monitor the performance of an engine, regular detailed measurements are taken of the engine's operating speed, temperature, pressure, fuel flow and vibration levels. The measurements are tracked by special software in order to identify deteriorating trends. By closely monitoring these trends it is possible to identify a potential problem with the engine and rectify the problem before it becomes serious.

One means to monitor the physical condition of internal engine parts is through use of a borescope. Borescopes are easy-to-use optical diagnosis instruments that view, magnify and illuminate hard-to-reach areas. They are used to inspect the internal parts of the engine for defects such as cracks, stress fractures and corrosion.



FIGURE 12- ENGINE MAINTENANCE COSTS DISTRIBUTION

The most commonly used form of the borescope is the video borescope, which consists of a handheld unit and a long, flexible, fiber-optic cable as shown in **Figure 12**. Current borescope technology now allows for the accurate measurement of voids and defects such that the serviceability of an engine can be determined immediately by the inspector.

7.4 Engine Workscope Planning - The primary objective of the workscope is to restore the engines performance, and to build the engine to a standard that minimizes long-term engine direct maintenance cost, or cost per flying hour. This process, however, can be quite challenging given parts and modules have different rates of deterioration.

Most repair shops will assess the life remaining on LLPs when an engine is inducted for maintenance and will manage time limited components to coincide with subsequent shop visits. Ideally, the repair shop will ensure that LLP stub-lives closely match the expected time on-wing from EGT margin erosion. So, for example, if an engine's LLP stub-life is 10,000 FC then the repair center will ensure that the engine has sufficient EGT margin to stay on-wing for 10,000 FC. The 10,000 FC would then be called the engine build standard.

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An engine’s Workscope Planning Guide (WPG) is a maintenance planning guide published by each engine manufacturer that details the suggested level of required maintenance on each module as well as a list of recommended Service Bulletins. Engine manufacturers generally specify three levels of worksopes consisting of: 1.) Minimum Level, 2.) Performance Level, and 3.) Full Overhaul Level. – Figure 13.

FIGURE 13- EXAMPLE: ENGINE WORKSCOPE PACKAGE

Major Module	SV1 Workscope Level	SV2 Workscope Level	SV3 Workscope Level
Fan & LPC	Minimum Level	Performance Level	Minimum Level
Core	Performance Level	Full Overhaul	Performance Level
LPT	Minimum Level	Performance Level	Minimum Level
Accessory Drive	Minimum Level	Performance Level	Minimum Level

Minimum Level Workscope – Typically applies to situations where a module has limited time since last overhaul. The key tasks accomplished with this workscope level are external inspections, and to some extent, minor repairs. It is not necessary to disassemble the module to meet the requirements of a minimum level workscope.

Performance Level Workscope - Will normally require teardown of a module to expose the rotor assembly. Airfoils, guide vanes, seals, and shrouds are inspected and repaired or replaced as needed to restore the performance of the module. Cost-effective performance restoration requires determination of the items having the greatest potential for regaining both exhaust gas temperature (EGT) and Specific Fuel Consumption (SFC) margin.

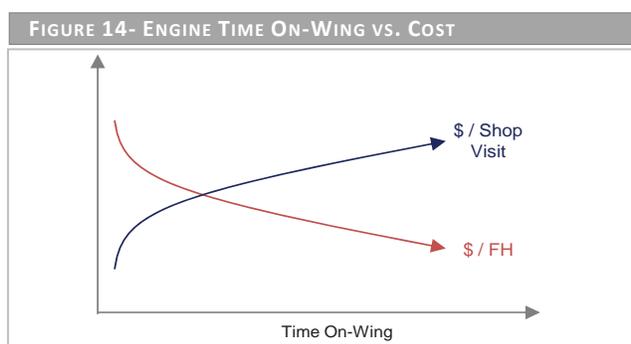
Full Overhaul Workscope - Full overhaul applies to a module if its time / cycle status exceeds the recommended (soft-time) threshold, or if the condition of the hardware makes full overhaul necessary. The module is disassembled to piece-parts and every part in the module receives a full serviceability inspection and, if required, is replaced with new or repaired hardware.

The level of workscope to be performed on an engine is dependent on the time accumulated on the engine modules and observed hardware condition. The key determinants that affect the workscope inputs vary by operator but generally can be categorized as being influenced by either; 1.) Time on-wing considerations, or 2.) Business considerations.

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Time On-Wing Considerations – As illustrated in Figure 14, an engine's time on-wing plays a dominant factor in both shop visit cost and shop DMC. The amount of work performed at each shop visit varies with TOW, but generally increases as TOW increases. With greater TOW most modules will require higher levels of maintenance to address part repair & replacement.



Time on-wing considerations are affected by several factors key among them are the engine's operational profile and LLP management considerations. Engines operating on short-haul networks tend to accrue higher flight cycles. Engine LLPs are therefore replaced at frequent intervals and represent a higher proportion of total engine maintenance costs. Common shop visit practice for mature engines is to establish build standards such that its performance potential matches its LLP life limits.

Engines on medium to long-haul networks engine are exposed to higher levels of wear and deterioration. This leads to a higher degree of parts being replaced and/or repaired, and greater degree of module re-work, particularly on the core modules. Engine LLP replacement is often required only during alternating shop visit intervals, and in extreme cases, an entire set of LLPs will require replacement once during its service life.

Business Considerations - An operator's financial status often dictates their policies towards investments in engine shop visit maintenance. Cash constrained operators may view the cost associated with an optimized workscope as being cost prohibited, and instead will opt to minimize their liabilities by scaling down the engine's build standard.

7.5 Parts Manufacturer Approval (PMA) - The FAA defines Parts Manufacturer Approval (PMA) as a combined design and production approval for modification and replacement parts. As defined in FAR 21.303, the applicant for a PMA must apply in a form and manner prescribed by the FAA. The PMA process is the primary legal basis for approved replacement parts. It allows a manufacturer to produce and sell these parts for installation on type certificated commercial aircraft. **Order 8110.42** prescribes the approval procedures for FAA personnel and guides applicants in the approval process.

The standard legal requirement for replacement & modification parts is the PMA. OEM-produced parts are actually just an exception to the PMA requirement. In the FAA's view, there is no drop off in status from the OEM part to the PMA part. Both have equal standing. Additionally, the certification standards for the PMA part are exactly the same as for the original part.

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PMA Design Approval Process - As noted, the FAA must approve both the design and the manufacturing process for PMA parts. To do this they have two separate types of organizations, the Aircraft Certification Offices (ACOs) and the Manufacturing Inspection District Offices MIDOs. The ACOs are responsible for determining that a PMA applicant's part meets the airworthiness standards that apply to the type-certificated product on which the part is to be installed. The MIDOs audits the manufacturing facility that produces PMA parts to ensure that it has the production and quality systems necessary to reliably produce an aerospace quality part per the design. Only when both the design and production system are approved will the Parts Manufacturer Authorization be issued by the FAA.

PMA Part Suppliers - There are generally two standards of PMA suppliers. Licensed PMA suppliers cooperate with the OEMs to produce parts for aircraft. Since the OEM is providing a design that has already been approved by the FAA to the PMA applicant, there is no requirement for the FAA to provide design approval. Licensed parts meet the following requirements:

- Same parts as production
- Same quality and process control as original equipment
- License meets PMA by FAA identity classification

Competitive PMA suppliers actively compete with OEMs. These suppliers use test & computation (reverse-engineering) as the means to prove the PMA part is equal to or better than the approved original part. Most PMA parts now use test & computation for design substantiation.

PMA Part Classification - Once the applicable airworthiness requirements are identified and basis for design approval satisfied, the PMA applicant must now identify the criticality of the part. This is done by means of a failure modes & effects analysis for the particular part in addition to the part's next higher assembly. Every possible way the part could fail is examined and the consequences of the failure are assessed. Based on this analysis the part is classed as critical / complex (possibly affecting the performance of either the aircraft or engine), or non-critical (all the rest). A part is often considered critical if the assessment shows hazardous condition from the effects of failure. In general, most PMA parts fall under the non-critical classification – see Figure 15.



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Once a part has been classified, an applicant often obtains a representative sample of the OEM parts and analyzes them to establish a benchmark that must be equaled or bettered by the PMA part. Advances in materials, processes, and manufacturing since the original product certification combined with airline experience with OEM part durability may enable the PMA supplier to provide a design that is superior to the original part.

The final step to PMA acceptance is for the applicant to demonstrate that they have inspection and repair procedures for their parts. They can either state that the PMA part can be maintained in accordance with OEM maintenance manual procedures, or if the part is different from the OEM, the PMA supplier must provide current instructions to an operator on how to inspect and repair the PMA parts.

PMA Issues & Concerns - As attractive as PMA parts are from a cost savings standpoint, the acceptance as an alternative to Original Equipment Manufacturer (OEM) parts can be an issue especially when a PMA part is assembled with an OEM mating part. OEM's are now restricting how they will provide technical support and warranty coverage when the PMA is used. The other risk in using PMA parts is if they were installed by a non-OEM shop and at the next shop visit the operator/owner sends the engine to an OEM shop. In this scenario the PMA parts become exposed and more than likely quarantined. This will then force the

Most aircraft owner/lessors recognize that there is already positive momentum building towards greater acceptance of alternate parts. However, many of these constituents continue to highlight key concerns regarding PMA parts. The primary concerns relate to asset: 1.) Remarketability & transferability, and 2.) Residual value impairment

1. Asset remarketability and the ability to seamlessly transition aircraft between regulatory jurisdictions are often cited as the leading factors that drive aircraft lessor's aversion to PMA parts.
2. Residual value impairment, both related to decreased marketability and due to perceived lower cost PMA parts.

A third concern faced by lessors relates to engines that contain PMA parts. Many engine OEMs will typically refuse to reassemble PMA parts back into an engine, and will subsequently mandate their replacement with OEM parts. This can significantly increase the cost of an engine shop visit. For this reason, as well as the fact that many engine PMA parts are classed critical, most lessors will make a clear distinction between non-critical PMA parts installed on airframe (and certain components) versus engines.

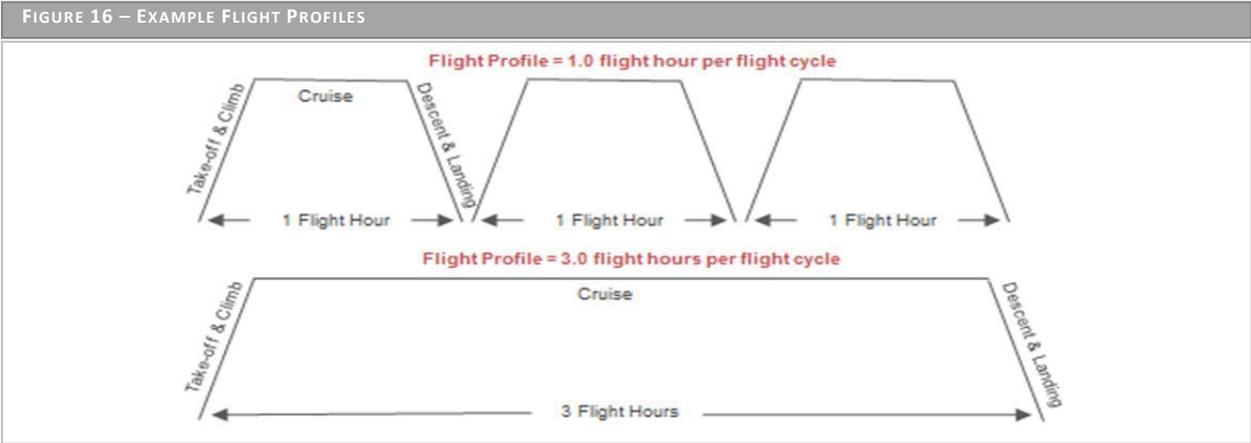
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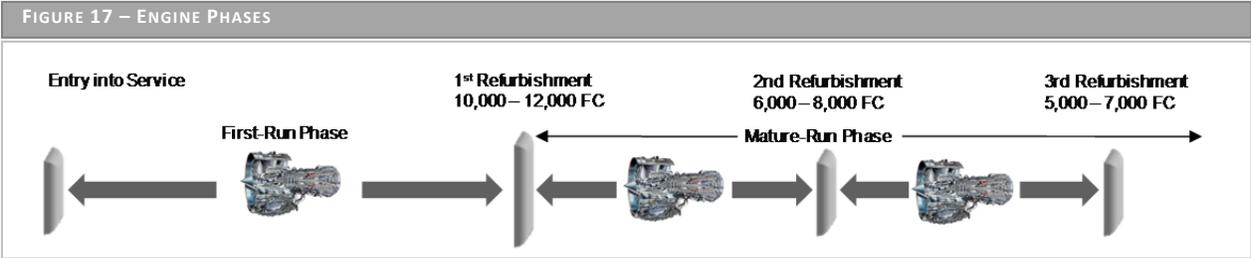
Another popular alternative used for cost reductions is the use of repaired parts. Roughly 60% - 80% of replaceable parts in an engine consist of airfoils. These piece parts also happen to be some of the most expensive engine parts. Through investment, research and development, and process improvements, much of this hardware can be repaired to the new part specification, reducing the requirement for new spare hardware.

7.6 Engine Utilization - The measurement of length of time an engine remains in service is often quantified in both flight hours and flight cycles. The Flight Hour (FH) represents one hour of flight, whereas Flight Cycle (FC) represents one aircraft take-off and subsequent landing. Flight hours are generally the unit of measurement used as a charging basis for engine restoration events, while flight cycles are used for engine LLPs.

Figure 16 illustrates the comparison between two flight profiles. An aircraft’s flight profile can be represented by the ratio of the aircraft’s flight hour to flight cycle – terms such as flight length, utilization, and hour-to-cycle ratio are often used to describe an aircraft’s operational profile.



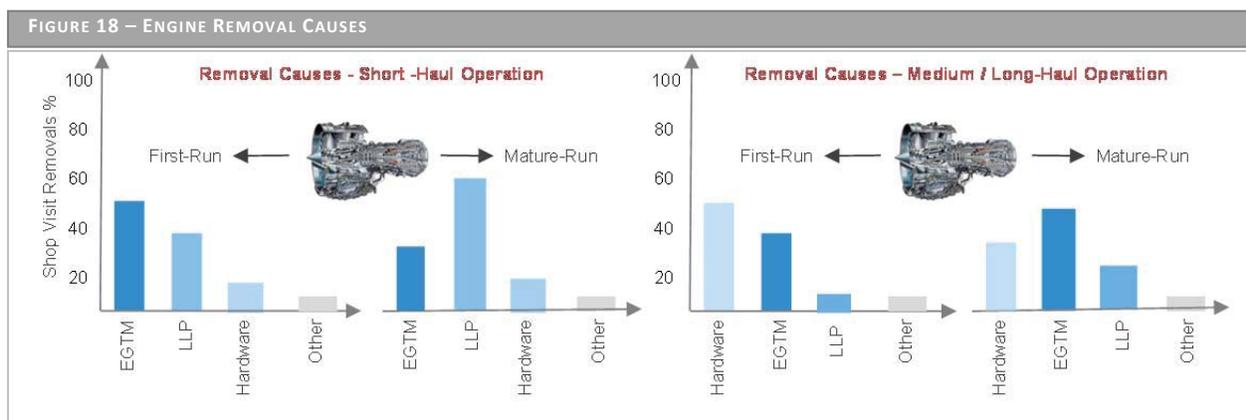
7.7 Engine Phases - First-run is the initial operating years, often referred to as the “honeymoon period”. First-run engines will traditionally last longer on-wing than subsequent run engines. Depending on the engine type, mature-run begins after the first core restoration shop visit, or after all engine modules have been restored – Figure 17.





8. PRIMARY CAUSES OF ENGINE REMOVALS

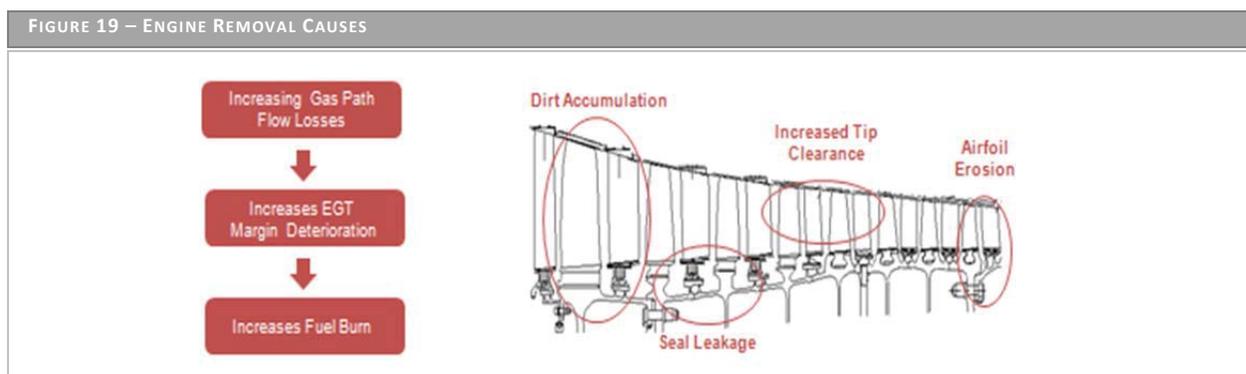
As illustrated in Figure 18, the causes of engine removals depends heavily on the type of operation an engine is exposed to. Engines operating on short-haul operations experience higher removals due to EGT margin deterioration and LLP expiry. In contrast, engines operating on medium-to-long haul flights tend to have a higher percentage of removals due to hardware deterioration and EGT margin deterioration. Other unscheduled removal causes result from Foreign Object Damage (FOD), High Oil Consumption (HOC), and engine vibration.



The following is a description of the major causes of engine removals.

8.1 EGT Margin Deterioration - EGT margin deterioration is often the primary driver of engine removals, particularly for engines operating on short-haul missions. It is well known that a major factor in deterioration of engine efficiency is the gradual increase in the clearance between the turbine blade tips and surrounding static seals or shrouds.

Figure 19 illustrates the primary causes of EGT erosion. Deterioration of the tip clearances increases the amount of flow losses and leakage of working fluid between blade tips and the surrounding shroud of both the turbine and compressor stages. Such leakage reduces overall engine efficiency hence raising the total specific fuel consumption.



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The EGT margin deterioration cycle is illustrated in Figure 20. As the engine accumulates more time on-wing efficiency erodes and more fuel loading is required to achieve the same required thrust level. Ultimately the EGT increases to the point where there is little margin remaining and the engine has to be removed for refurbishment.

The rate of EGT margin deterioration is affected by how the engine is operated. Engines operating on short cycle legs experience higher rates of deterioration than those operating high cycle legs. Actual rates of deterioration will vary with thrust rating in addition to other operational factors, such as engine derate and average flight length flown. Additionally, engines operating in hot & dusty environments experience greater EGT margin erosion than those operating in cool & temperate environments.

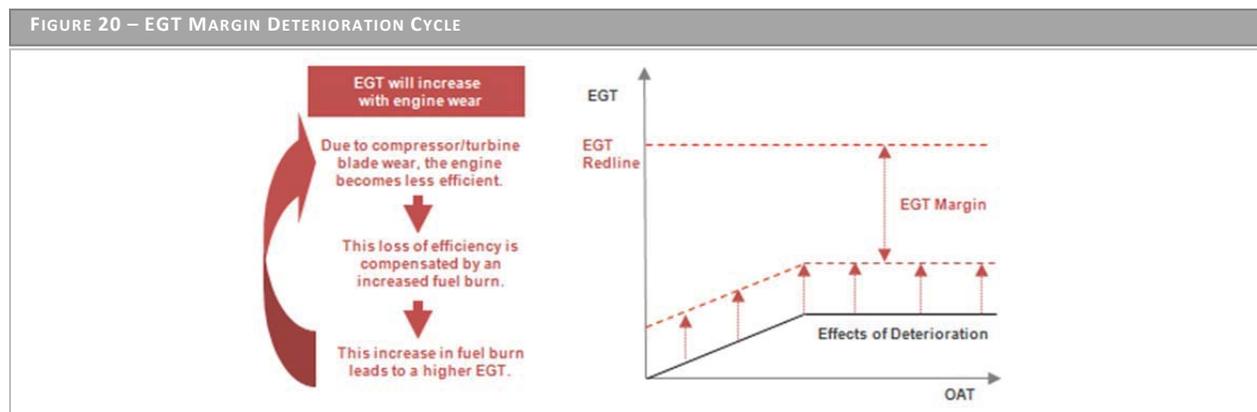
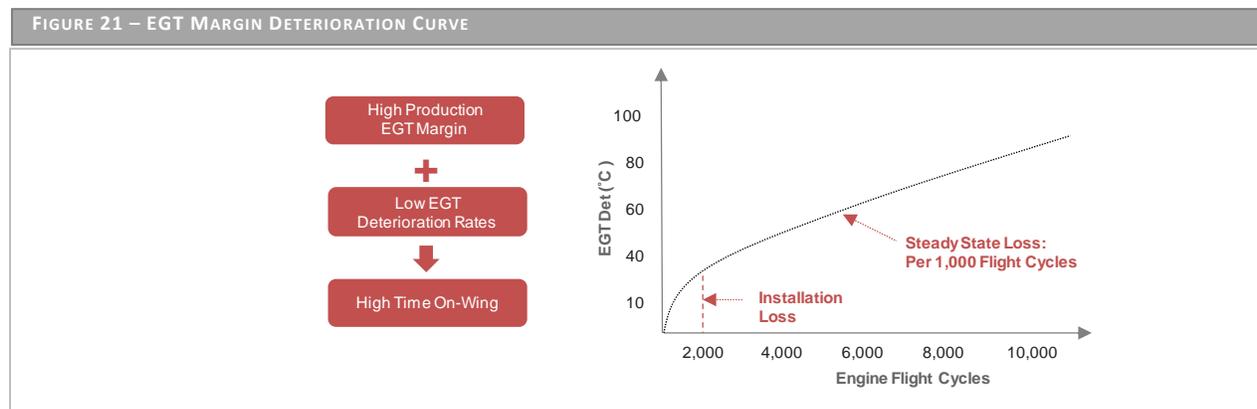


Figure 21 illustrates the relationship between EGT margin erosion and accumulated engine flight cycles. Rates of deterioration are highest in the initial 1,000 – 2,000 engine flight cycles of operation as the blade tips begin to wear. EGT Margin erosion rates stabilize after the initial loss and reach a steady state level that remains fairly constant until the engine is scheduled for removal.



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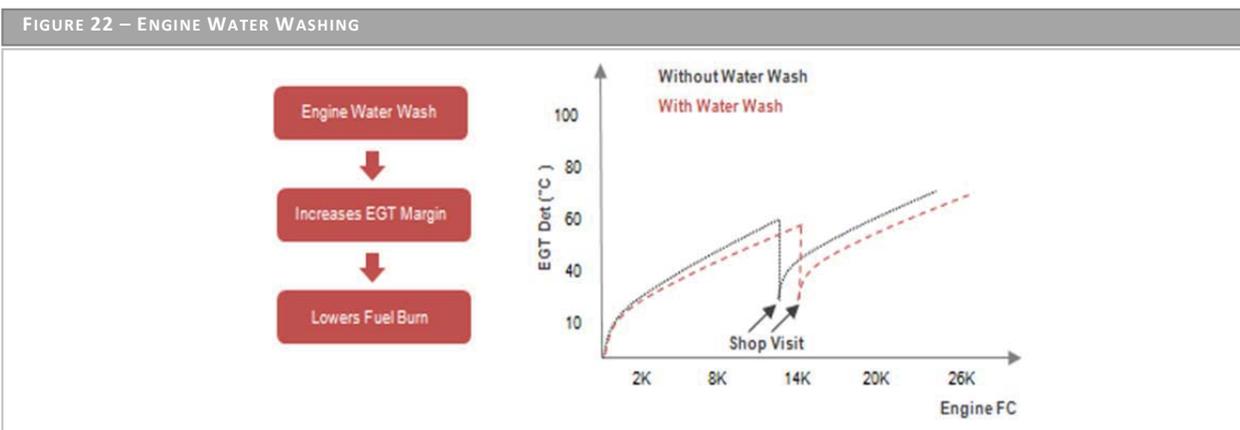
Engine manufacturers often publish the initial EGT Margins and the expected installation loss for their engines. With this data one can compute the engine's theoretical maximum time on-wing using the following equation:

$$\text{Theoretical Max TOW} = \text{Initial FC Loss} + (\text{Initial EGT Margin} - \text{Installation Loss}) / \text{EGTM Deterioration Rate}$$

For example, an engine rated at 24,000 lbs has an initial EGT Margin of 100 °C, and its installation loss is expected to range between 10-15 degrees Celsius per 1,000 flight cycles. Thereafter, rates of deterioration will stabilize to 4-5 degrees Celsius per 1,000 flight cycles. On this basis, the engine could theoretically remain on wing for 18,000-23,500 flight cycles.

EGT Margin Recovery Through Water Washing – All engines become contaminated during the course of normal operations. Over time, this contamination leads to performance deterioration which can be restored by regular engine wash. Figure 22 illustrates the effects of water washing on engine EGT margin erosion.

Engine washing is an on-wing, ground-based, process that pumps water and cleansing additives into the engine's intake while the engine is operating. The process fully penetrates the compressor and turbine to clean the airfoil surfaces. Engine wash provides increased EGT margin - thus longer on-wing life- and compressor efficiency resulting in reduced fuel burn. Keeping the gas path clean can reduce fuel burn by as much 1.2% and increase engine EGT margin by as much as 15 deg. C.



8.2 LLP Expiry - Many engines have high enough EGT margin to remain on wing beyond the limits of certain LLPs. In most instances these engines are operating on short-to-medium haul networks and accumulate enough flight cycles to bump-up against a LLPs stub-life.

8.3 Hardware Deterioration - Mechanical degradation problems typically emerge on certain parts after they have been exposed to extreme operating conditions for a prolonged period of time. The effects of hardware deterioration result in blade distress (particularly on HPT blades), parts cracking and chipping, and in extreme situations, part failures.

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8.4 Foreign Object Damage (FOD) - FOD results from ingestion of foreign objects. Sources of FOD include debris ingested while in the air (i.e. birds, ice, hail, ash, etc.) as well as runway debris that an engine ingests during take-off or landing. The effect of FOD on maintenance costs can be significant although many of today's modern turbofan engines are designed to avoid major core damage when FOD does occur.

9. ENGINE DIRECT MAINTENANCE COSTS (DMC)

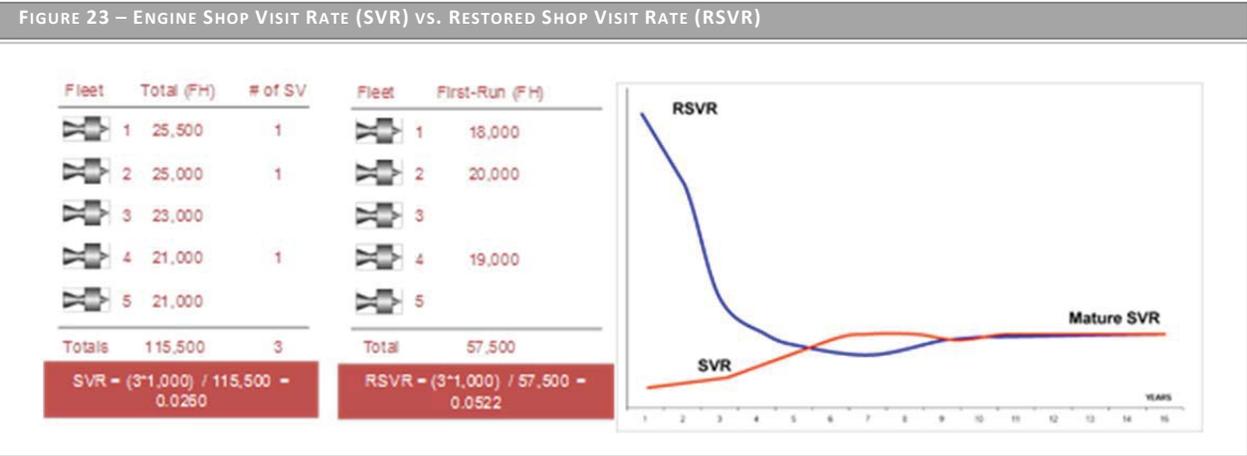
Engine Direct Maintenance Costs (DMC) are expenses for scheduled and unscheduled labor, material and outside services applied to meet the performance of the required maintenance that is directly related to the operation of an engine. The equation for calculating engine DMC is expressed as follows:

$$DMC = \text{Shop Visit Cost} / \text{Time On-Wing} - \text{measured in } \$ / \text{FH}$$

9.1 Calculation Method for Time On-Wing (TOW) - An engine's Time On-Wing can be estimated using two methodologies. The first method calculates TOW using an engine's Shop Visit Rate (SVR), which takes into consideration the reliability of all engine's in a fleet. The SVR is the ratio of total number of shop visits having occurred within a period to the total number of hours flown by all engines since new or entry into service. An engine's SVR is often presented on a 12-month rolling average basis to smooth out any statistical anomalies. Using an engine's SVR enables one to compute its Mean-Time-Between Shop Visit (MTBSV) as follows:

$$\text{Mean-Time Between Shop Visit (MTBSV)} = (1 / \text{SVR}) \times 1,000 - \text{measured in FH}$$

Another method in assessing engine TOW can be achieved through the use of the engines Restored Shop Visit Rate (RSVR). The RSVR is the ratio of total number of shop visits having occurred within a period to the number of hours flown by the involved engines since their last restoration shop visit. RSVR represents an average time on-wing between removals. Figure 23 illustrates the differences between engine's SVR and its RSVR.

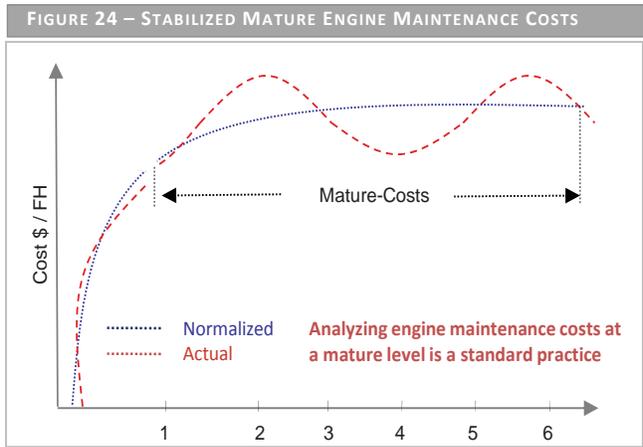


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Over the life of the engine both the SVR and RSVR eventually merge to into the engine's Mature SVR (MSVR). In addition, an engine's performance restoration costs tend to stabilize as it matures. This trend ultimately leads to stabilized DMC as well.

In an effort to normalize engine cost data, both engine and aircraft manufacturers report direct maintenance costs that are adjusted to a mature level – to reach this level there must be an ample population of in-service engines that have occasioned from three to four shop visits. This policy enables equipment manufacturers to make a fair comparison of stabilized maintenance costs – see Figure 24.

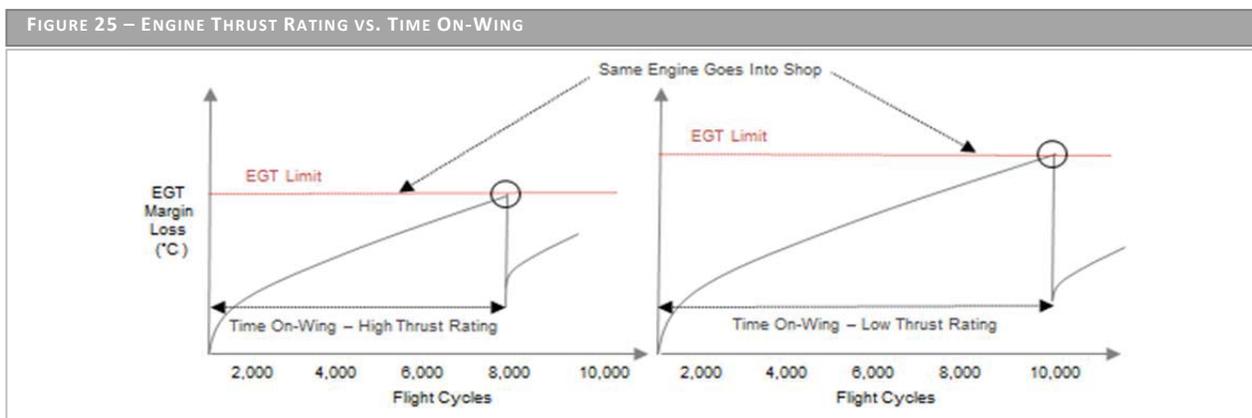


10. FACTORS INFLUENCING ENGINE COSTS & TIME ON-WING

An engine will occasion several shop visits during its life, however the rate of visits will depend on various operational parameters consisting of:

1. Thrust rating,
2. Operational severity
3. Age status
4. Workscope Management Policies

10.1 Thrust Rating - For a given engine variant, EGT margin deteriorates faster when operating at higher thrust levels – Figure 25. Higher thrust generates higher core temperatures, which exposes constituent parts in the engine to greater thermal stress. Reducing thrust will: a.) Slow EGT deterioration, b.) Reduces fuel-flow and c.) Lower maintenance costs by increasing time between shop visits.



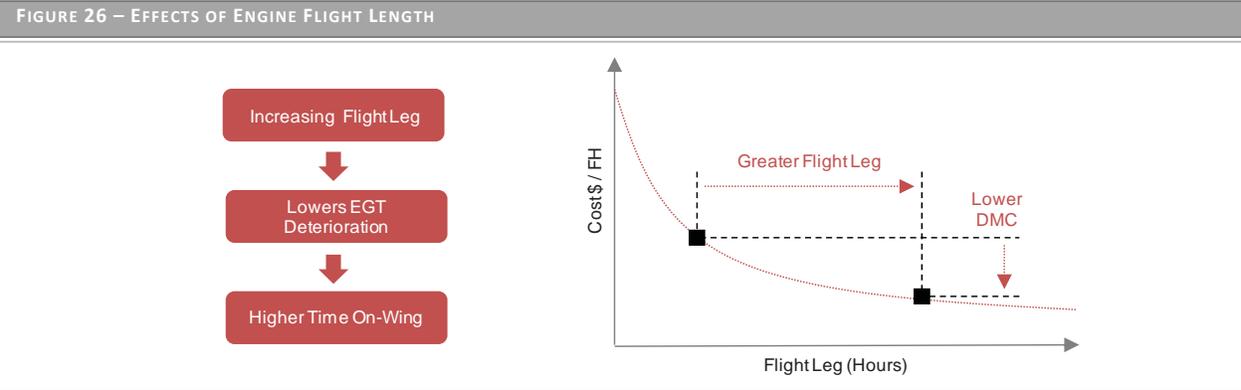
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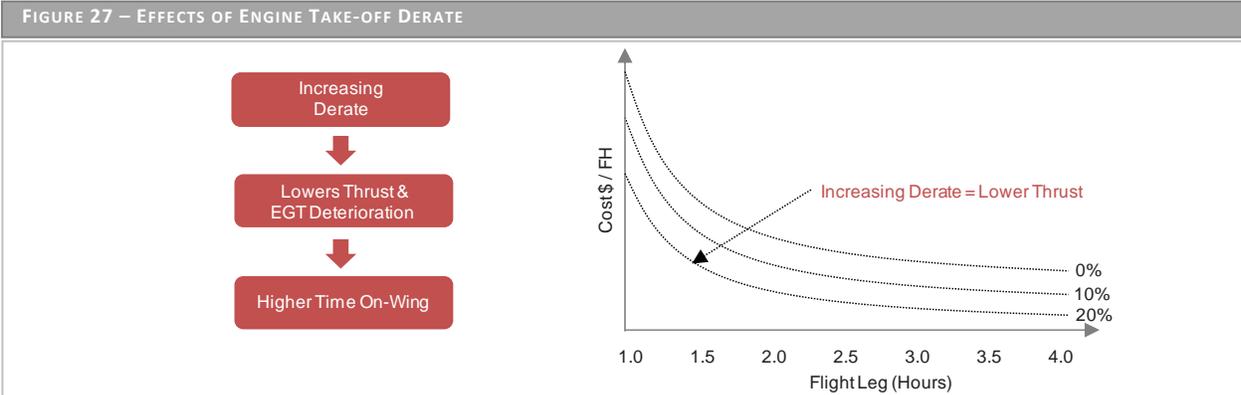
10.2 Operational Severity - An engine's DMC is heavily influenced by the severity of the operating environment it is exposed to. More demanding operating conditions will impose greater stress on engine parts and components. Operating severity comprises:

- i. Flight Length
- ii. Take-off Derate
- iii. Ambient Temperatures
- iv. Environment

Flight Length - As the flight length reduces an engine spends a larger proportion of total flight time using take-off and climb power settings. In most instances the effect of shorter stage length operation is more rapid performance deterioration leading to greater direct maintenance cost per flight hour - Figure 26. Conversely, longer sector lengths will lead to less wear and tear and an increase in the on-wing time of an engine.



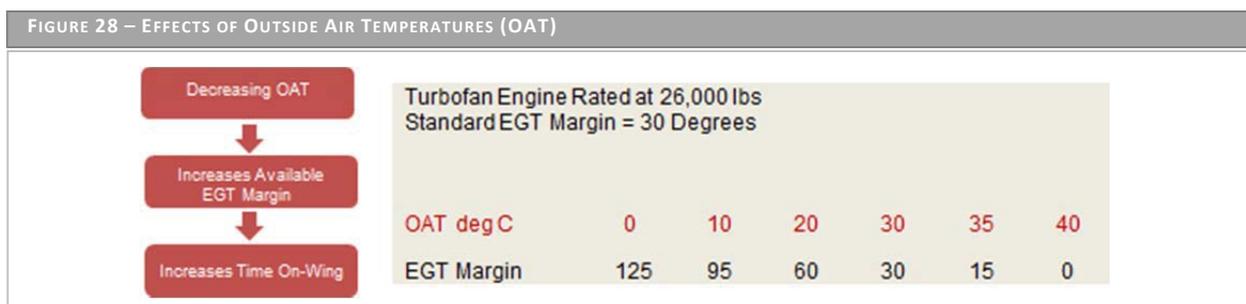
Take-Off Derate - Take-off derate thrust is a takeoff thrust setting that is below the maximum thrust level. A larger derate translates into lower take-off EGT and therefore enjoys a lower engine deterioration rate, longer on-wing life, and reduced cost per flight hour. Figure 27 illustrates engine derate and its effect on direct maintenance cost.



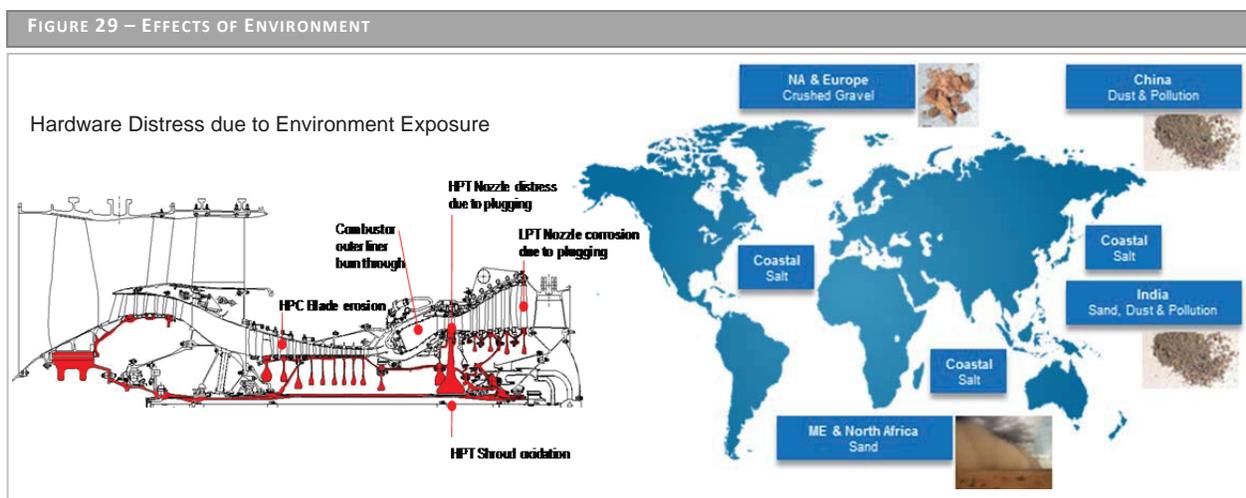
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Ambient Temperatures - Turbofan engines are normally flat rated to ambient air temperatures around International Standard Atmosphere (ISA) + 15°C, which is equivalent to 30°C at sea level conditions. The turbine entry temperature at max take-off and max climb rating increase as ambient air temperature increases, up to their limit value. Therefore, an engine exposed to high ambient temperatures will experience lower available EGT margin and greater performance degradation. Figure 28 illustrates the variation of available EGT margin deterioration as a function of Outside Air Temperature (OAT) for a sample turbofan engine rated at 26,000 lbs.



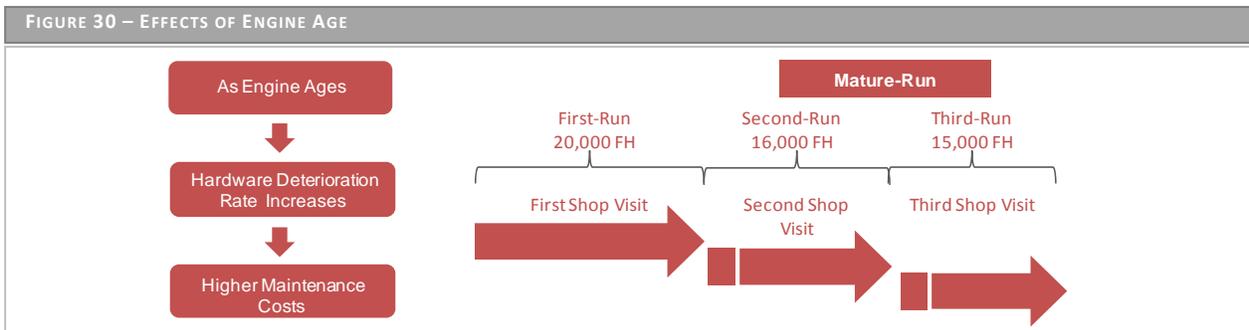
Environment - Engines operated in dusty, sandy and erosive-corrosive environments - Figure 29 - are exposed to higher blade distress and thus greater performance deterioration. Particulate material due to air pollution, such as dust, sand or industry emissions can erode HPC blades and block HPT vane/blade cooling holes. Other environmental distress symptoms consist of hardware corrosion and oxidation. For engines operating in hot/dry & erosive environments, EGT margin erosion rates are likely to be greater.



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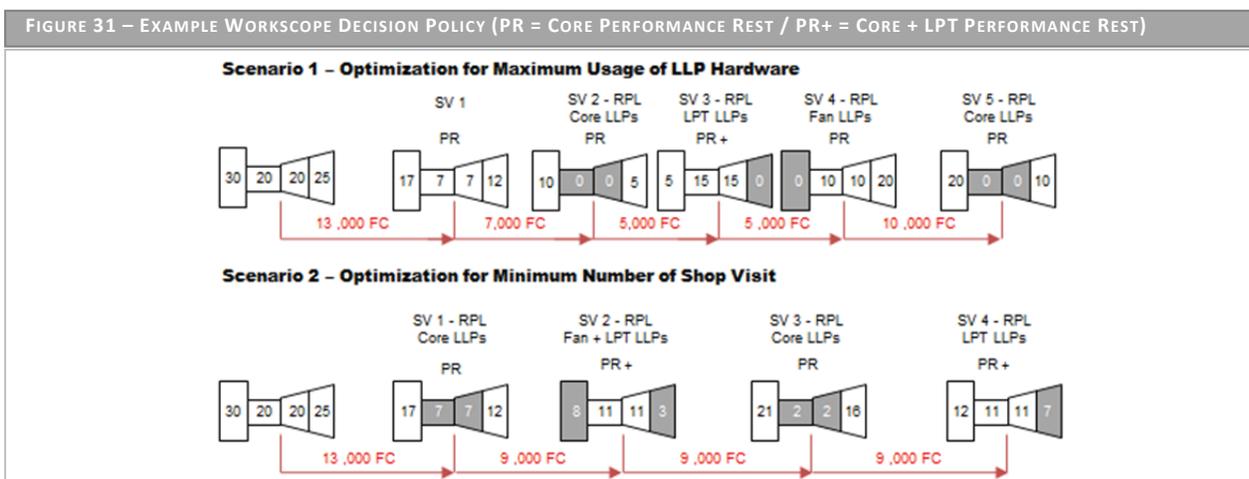


10.3 Engine Age - Older engines generally cost more to maintain than newer engines. As an engine ages its average time to shop visit lessens - Figure 30. First-run engines will last considerably longer on-wing than mature engines. In fact, it is not uncommon to see first-run engines remaining on-wing 20%-30% longer than mature run engines. As the engine ages a disproportionate amount of parts experience higher deterioration rates, higher scrap rates, and correspondingly higher engine maintenance cost.



10.4 Workscope Management Policies - The Workscope Planning Guide provides recommendations directed towards improving EGT outbound performance margins, improving the durability of the engine hardware, as well as improving the reliability of the engine. The guidelines outline recommendations only, and should not be interpreted as requirements. The level of workscope to be performed on an engine inducted in the shop is dependent on the removal cause(s), time accumulated on the engine modules, observed hardware conditions, trend data at removal, and airlines goals – see Figure 31.

The Workscope Planning Guide also highlights the key service bulletins that should be considered when the engine is inducted into the shop. As the fleet continues to age, and more shop visits are driven by performance, lessons learned from the shop visits will be incorporated into this guide. Work scope choice reflects the future time on wing of the engine. Minimal work scope is a short term strategy that drives lower time on wing. Extended work scopes can be costly and not achieve the lowest operating cost. Optimal work scopes need to be proposed and fit to operating requirements and long term strategy.



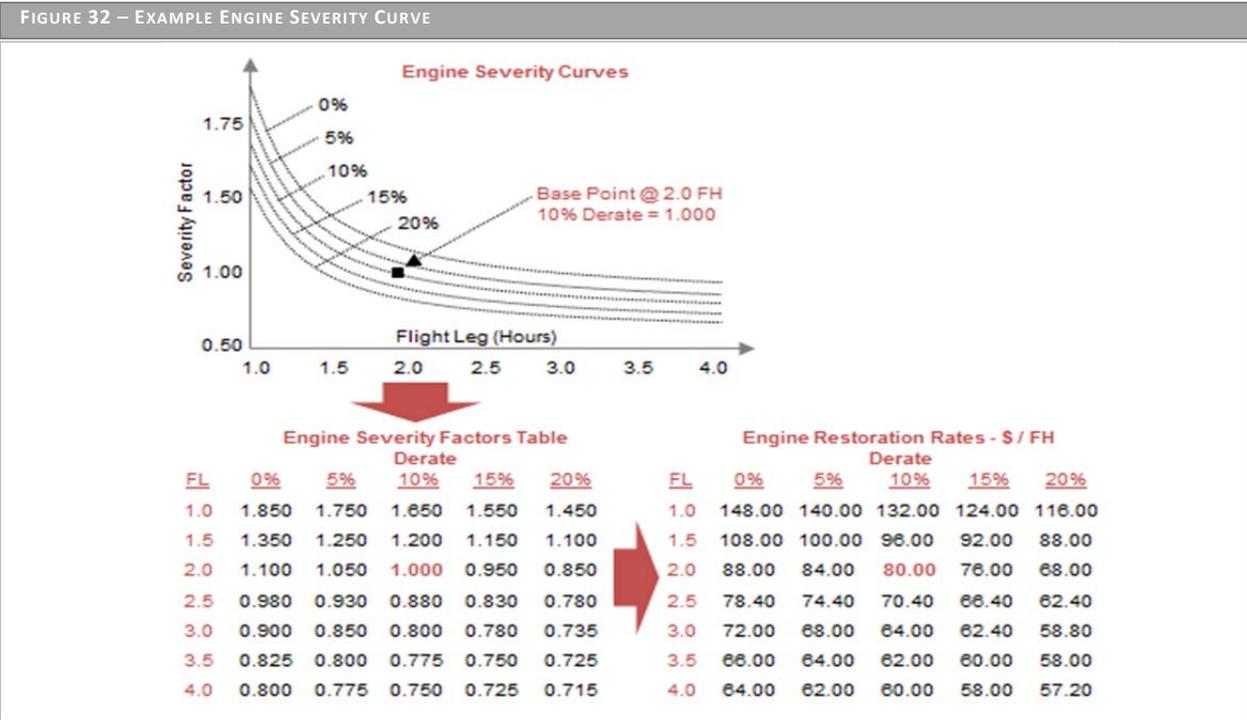
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11. ENGINE SEVERITY CURVES

Engine severity curves permit an evaluation of the effects that thrust, takeoff derate and flight length impose on engine direct maintenance costs. Engine manufacturers develop severity curves from statistical distributions that characterize expected restoration shop visit costs and time on-wing.

Engine manufacturers often develop severity curves for each engine model in production. Engine models with multiple thrust ratings will often have severity curves developed for each thrust rating, in addition to severity curves for different phase intervals (e.g., first-run or mature-run). Severity curves can provide a valuable resource for achieving the lowest cost of operation through sensitivity analysis. Figure 32 illustrates an example of severity curves that have been tabulated to produce the factors for multiple derates and flight length profiles.



12. ENGINE ASSET VALUE PROTECTION

Over the past 20 years, airlines have turned to operating leases for an increasing share of aircraft financing requirements. Today, approximately 40% of the world’s fleet is under operating lease and this percentage is expected to grow along with the growth in global demand for commercial aircraft.

As owners of commercial aircraft, lessors are significantly concerned about the residual value of their assets, and in particular engines since these assets represent a large percentage of overall maintenance exposure. There are two principal ways that lessors cover their engine maintenance exposure. This is accomplished through:

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1. Maintenance Reserves
2. Engine Flight-Hour Agreements (FHA)

12.1 Maintenance Reserves - The decision to require an operator to pay maintenance reserves is usually a credit-risk issue. Usually the owner of a leased aircraft or engine will perform some degree of financial due diligence on an operator in order to form a valid judgment as to whether an obligation to pay maintenance reserves is required. Separate reserves are set up for: a.) Performance restoration shop visits and, b.) LLP replacement. Payments are calculated on a flight hour and/or flight cycle basis, payable monthly in arrears. Leases mandate when the lessee may draw against the accrued amounts, and typically exclude:

- Routine servicing of the engine during normal operation
- Overhaul of Quick Exchange Units (QEC) external components
- Foreign object damage
- Operator misuse or abuse

Maintenance Reserves require the lessee to accrue funds for future maintenance by paying the lessor either throughout the lease or through an end-of lease term redelivery payments. Lessee typically has the work performed, pays the maintenance provider, and then claims a reimbursement from the lessor out of the accumulated reserve account.

As it applies to engines, the general intention for maintenance reserves is to achieve full-life economic condition of engine modules and LLPs. This requires compensation to be paid for any differential between both the full-life condition of the performance restoration status of engine modules and life remaining status of engine LLPs and the physical condition of these maintenance events. Mathematically this can be expressed as follows:

$$\text{Net Reserves} = \text{Full-life Value} - \text{Value of Life Remaining}$$

Repayment takes place only if payment into the reserve account is fully up to date, and only up to the total value of the specific reserve account. Thus if a particular eligible task is carried out, and the cost of that work exceeds the total in the specific reserve account, the excess cost is the responsibility of the lessee. Funds generally may not be transferred from other reserve accounts of the same engine (or other engines) to cover excess expenses incurred.

Maintenance reserves can be structured using three different alternatives, consisting of:

1. Hourly / Cash Maintenance Reserves
2. End of Lease Adjustment
3. Letter of Credit

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Hourly / Cash Maintenance Reserves - These are usually payments made on a regular, usually monthly, basis by the lessee to the lessor, and are generally based upon the age and expected utilization of the engine in question. Therefore, at the time an engine is taken out of service for maintenance, the lessor should already have funds to cover the cost of the overhaul.

End of Lease Adjustment - This option would expose a lessor to a greater risk of incurring maintenance costs and is thus usually only offered to better quality credits or airlines that have demonstrated a good track record of payment. If the engine is returned at the end of a lease in a worse than stipulated condition, the lessee must make an end of lease payment to the lessor. Conversely, if the engine is returned in a better than stipulated state, the lessor is obliged to pay the lessee. There are two types of end-of-lease payment structures:

- Mirror-In / Mirror-Out - A mirror adjustment can either be one-way, where the Lessee is required to pay an adjustment when an engine is returned with less time remaining than at delivery, or a two-way mirror whereby lessor may have to pay the lessee if the engine is returned in better condition than at delivery.
- Zero-Time or Full-Life - A payment whereby the lessor receives payment for time used since last overhaul or since new.

Letter of Credit - Maintenance Letter of Credit (LOC) is a bank guarantee that the lessee will return the asset to the lessor in the condition required by the lease. Often the LOC gets adjusted (increased or decreased) throughout the lease term as the engines accumulated time and incur maintenance shop visits.

12.2 - Engine Maintenance Reserve Development - As highlighted previously, separate reserves can be structured to cover the performance restoration of modules and LLP replacement. For engine restoration coverage, the lessors will either use the manufacturer's published rates, which are normally classified as "mature", or will they derive their own rates based on experience and/or research. Those lessors that do derive their rates will often do so for both an engine's first-run and mature-run phases.

Engine LLP rates - Figure 33 - are computed from the engine manufacturer's published life limits and piece part costs. Many lessors assume that each LLP will retain between 5%-15% of its stub life before being replaced. Accordingly, they will apply a stub factor to each LLP as a means to recoup the cost of the stub life lost.

FIGURE 33 - STABILIZED MATURE ENGINE MAINTENANCE COSTS

LLP	FC Limit	Cost \$	\$/ FC	10% Stub
1	30,000	180,000	6.00	6.67
2	27,600	120,000	4.35	4.83
3	30,000	100,000	3.33	3.70
4	20,000	50,000	2.50	2.78
5	20,000	80,000	4.00	4.44
6	20,000	110,000	5.50	6.11
7	20,000	30,000	1.50	1.67
8	20,000	240,000	12.00	13.33
9	20,000	200,000	10.00	11.11
19	20,000	180,000	9.00	10.00
11	20,000	90,000	4.50	5.00
12	20,000	60,000	3.00	3.33
13	25,000	100,000	4.00	4.44
14	25,000	150,000	6.00	6.67
15	25,000	70,000	2.80	3.11
16	25,000	90,000	3.60	4.00
17	25,000	80,000	3.20	3.56
18	25,000	70,000	2.80	3.11
		2,000,000	88.00	98.00

10% Stub = Cost \$ / (90% * FC Limit)

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The process for structuring performance restoration rates can be complex given the number of variables that influence engine DMC. Lessors will take into consideration a Lessee’s specific operation and the particular phase the engines are in (first-run or mature-run) before deriving the appropriate performance restoration reserve rates.

Many lessors derive restoration matrix’s, which provides a summary of reserve rates based on the key operating parameters such as flight leg, engine derate, and environmental conditions. The Table 1 & Table 2 below illustrates an example performance restoration matrix summarizing first and mature-run rates for 26,000 lbs rated engine assuming an average thrust de-rate of 10%.

Table 1 - Delivery through the first Performance Restoration of core Modules – US \$ / FH:

Flight Leg	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Temperate	142	111	85	83	82	81	80
Hot / Dry	159	124	95	93	91	90	89
Erosive / Corrosive	170	133	102	100	98	97	96

Table 2 - Following first Performance Restoration of core Modules – US \$ / FH:

Flight Leg	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Temperate	210	164	125	123	121	120	119
Hot / Dry	235	183	140	137	135	134	133
Erosive / Corrosive	252	197	150	147	145	144	143

12.3 Engine Flight-Hour Agreement (FHA) – Under a typical Flight-Hour Agreement (FHA) program the Original Equipment Manufacturer (OEM) covers all product and quality causes of shop visits. This generally will include coverage for failure, malfunction, and wear & tear of any engine part(s) causing the engine to be unserviceable and outside of defined limits.

All Airworthiness Directives (ADs) and target Service Bulletins (SBs) issued for the life of the program are also incorporated at the shop visit at OEM’s expense. Many FHA program’s coverage extends to even domestic object damage and Beyond Economical Repair (BER) costs. However, most programs will exclude LLP replacement in their coverage.

For many operators, particularly start-ups or operators with small fleets, the FHA can yield considerable financial benefits. The program assists operators in maintenance cost stabilization by providing greater degree of visibility in their costs.

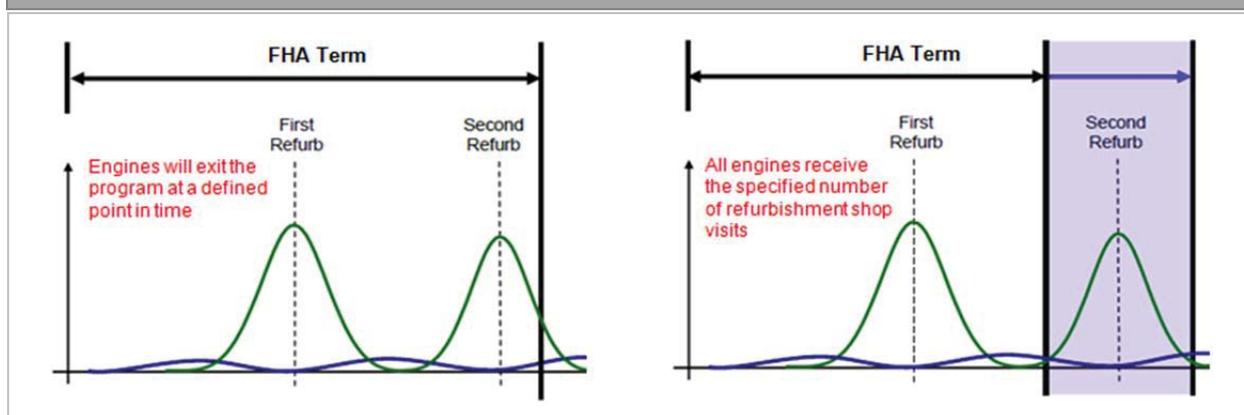
Because engines under maintenance oversight by the OEM are overhauled to the latest standards the operator can expect better engine reliability and greater residual value. FHA payment terms are offered as Pay as You Go (PAYG), whereby a rate is used to calculate a sum to be paid each month based on the engine flying hours in the month, or Pay at Shop Visit (PASV), whereby a rate is normally only applicable to the restoration shop visits.



The terms of Fleet-Hour Agreement will generally consist of one of the following alternatives:

1. Fleet Cumulative Term - Fixed period of time for the fleet: e.g. 12 years from EIS (entry into service) of first aircraft,
2. Per Engine Term - Fixed period of time for each engine: e.g. 12 years from EIS of each engine.
3. Fixed Shop Visit Term - Fixed number of Restoration Shop Visits (RSVs) per engine, e.g. term finishes for each engine after 2nd shop visit.

FIGURE 35 – FLEET-HOUR AGREEMENT TERM STRUCTURES



13. ENGINE ECONOMIC TERMINOLOGIES

13.1 Maintenance Status - One of the most important factors affecting an engine's value is the maintenance status associated with the engines modules and LLPs. Maintenance status is used to assess, in whole or part, the value of maintenance utility remaining. The key to quantifying maintenance status lies in making accurate assessment as to:

- a. Where each major engine modules are relative to their last and next shop visit, and
- b. What percentage of each modules next shop visit cost is remaining.

In order to monitor the performance of an engine, regular detailed measurements are taken of the engine's operating speed, temperature, pressure, fuel flow and vibration levels. The measurements are tracked by special software in order to identify deteriorating trends. By closely monitoring these trends it is possible to make accurate predictions as to when an engine's scheduled removal is warranted, and by correlation, the interval remaining to its next shop visit.

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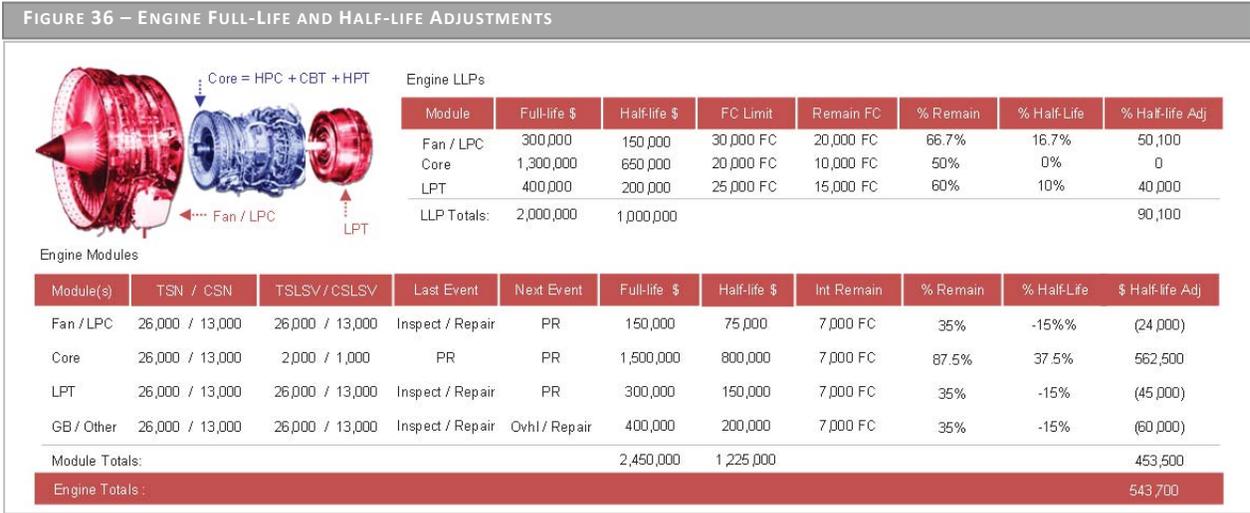
Depending on the aircraft type and age, the value of maintenance status can represent a significant proportion of an aircraft's overall market value. Where appraisers are responsible for ascertaining the market value of an aircraft, they use, as a baseline reference, three industry-standard terms to represent an aircraft's maintenance status. These terms consist of full-life, run-out, and half-life.

The Full-life condition means that the engine has just been completely refurbished and that the Life Limited Parts have their full certificated limits remaining. In practice this will not be the case, however if the engine is fully funded by maintenance reserves the combination of the potential life remaining on the Life Limited Parts and the time remaining to the next refurbishment complete with the maintenance reserves previously received means that the engine is effectively in a "Full Life" condition.

The Zero-life condition means that the engine has fallen outside its allowed operational parameters and requires refurbishment before it can return to commercial use. In addition, minimal life is usually left remaining on the Life Limited Parts. The Run-Out value of an engine will closely correlate to the cost of overhauling an engine, or for types that are being phased out, the value of the engine core.

The Half-life status assumes that the engine modules are half-way between major overhauls and that any life-limited part has used up half of its life. Engine market values are often adjusted for maintenance condition and the method for calculating this adjustment is as follows:

$$\text{Half-life Adjustment \$} = \text{Value Remaining} - (50\% * \text{Event Cost})$$



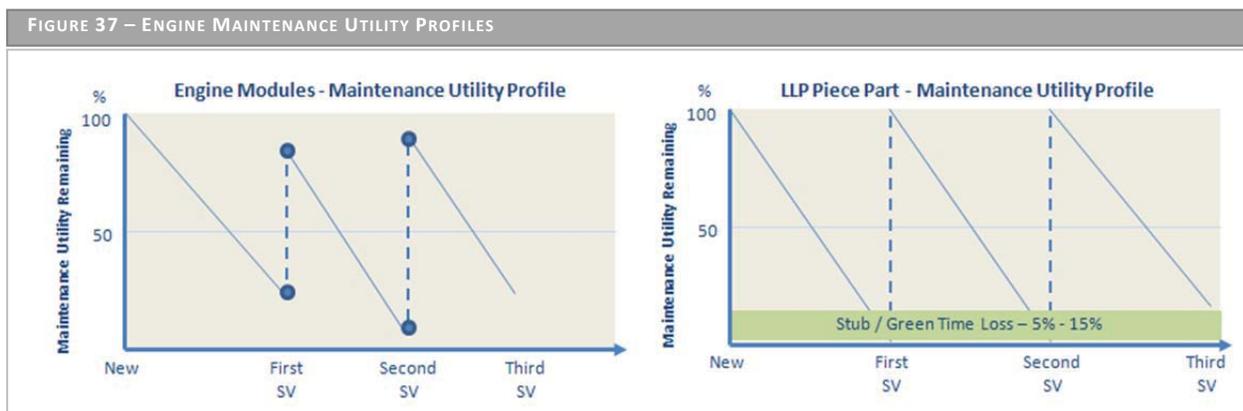
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13.2 Maintenance Utility – Maintenance utility describes the decline in maintenance value over time associated with a particular maintenance event. The decline in maintenance utility will follow a conventional saw-tooth pattern, however, depending on the nature of the maintenance event, the value may or may not fully amortize to zero nor does it fully re-capitalize to 100% of its market value. This is true for engine modules given they are subject to on-condition maintenance, and because rarely is every module fully restored to zero-time during a shop visit.

Although LLPs are subject to hard-time intervals most parts are removed prior to reaching their life limits. Most LLPs are removed with stub-lives (green-time) remaining, and depending on the engine type (narrow-body or wide-body) and the workscope being factored, the stub-lives will vary from 5% - 15% on average.

Figure 37 illustrates the traditional saw-tooth maintenance profile for engine modules and LLPs. The workscope performed on the engine will partially restore the maintenance value of modules. However, if all LLPs are replaced the LLP stack will have 100% of its value replenished, although this is rarely achieved if the LLP lives are staggered. Only when an engine has had a full overhaul and full LLP replacement at the same shop visit is its value replenished to near 100% of original maintenance value.



13.3 Engine Life Cycles - the economic life cycle of an engine can be divided into three phases.

1. Phase 1 starts at the introduction of the engine into regular and finishes when the production run of the aircraft it supports ceases. During this phase:
 - a) Engine demand grows and values tend to correlate to list prices;
 - b) The majority of engines have yet to occasion their first performance restoration;
 - c) New engine warranties still apply; and d.) Few engines are actively traded.

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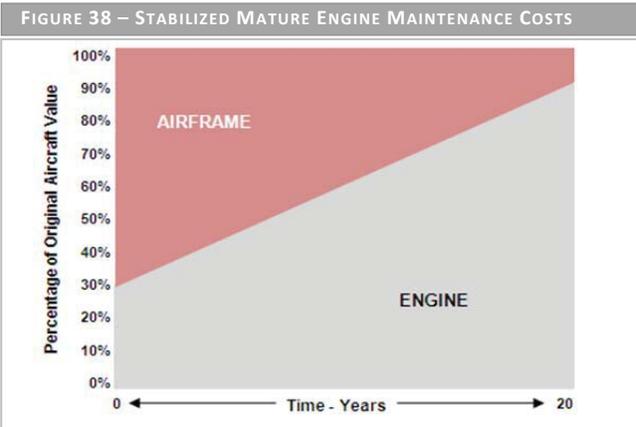
- 2. Phase 2 coincides with the termination of an aircraft's production. During this phase:
 - a) Engine values are generally stable;
 - b) Most of the engines are in their mature phase;
 - c) Stable rate of performance restorations;
 - d) Engine maintenance status becomes increasingly important.

- 3. Phase 3 represents the period of time following the withdrawal from service of aircraft types that engine's support. During this phase:
 - a) Demand for engines is much weaker and values start to approach the cost of overhaul;
 - b) Supply increases as aircraft are retired from service;
 - c) Remaining engines in the fleet are traded on the basis of maintenance "green time"

Of all the major equipment accounted for in the valuation of an aircraft, engines tend to retain their value more strongly as an aircraft ages. As discussed previously, an engine's maintenance value is a function of the cost of an engine's Life-Limited Parts (LLPs) and the cost of an engine performance restoration. Given the ability to restore value and useful life through maintenance processes, the economic value of an engine remains relatively firm throughout much of its economic useful life.

These factors play a vital role in the behavior of engine maintenance values because, whereas an airframe gradually deteriorates over time as flight hours and cycles accumulate, appropriate levels of maintenance can repetitively restore an engine to a near new condition and value.

Figure 38 illustrates the aircraft/engine value relationship. Since the value of an engine in the later stages of its economic life is strongly related to the operational green-time remaining, the maintenance status of engines has a growing impact on value. During the final phase of its economic life, when the serviceable engine is operated to the point where an engine shop visit is required, the engine owner must make a decision to either invest in an engine shop visit or disassemble the engine and sell the parts.



One caveat to engine values: young and popular engines can be relied upon to regain their original market value when they have maintenance. However, Investors should be wary of an engine entering into a phase of market decline when it starts to decrease in popularity. When the numbers of an aircraft type in operation starts to diminish, the fleet of engines supporting that aircraft fleet increases. The effect is an increasing ratio of spares to installed engines, which weakens their market value.

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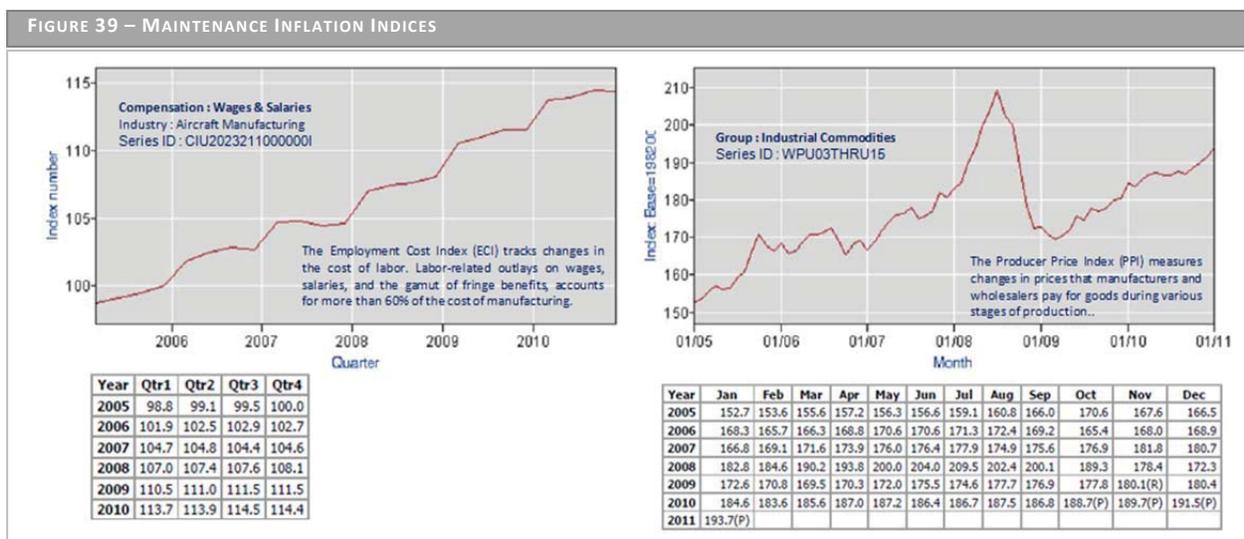


14. ENGINE MAINTENANCE INFLATION

The individual economy-driven factors affecting engine maintenance cost are mainly labor and material repair & replacement. Engine manufacturing wage rates increase over time because of overall changes in wages and prices throughout the economy, as well as changes in prevailing wages engine manufacturers must pay to retain skilled workers.

Material repair & replacement costs tend to exhibit higher price volatility due to: a.) Greater imbalances in supply/demand for these materials, and b.) Greater use of more advanced and expensive materials (e.g., titanium, nickel alloys, composites).

The proportion of total engine maintenance cost is on the order of 35% labor / 65% material. To measure and forecast changes to these cost inputs we need to factor the price escalations of key economic indices that correlate to them. These key indices are illustrated in Figure 39 and consist of: a.) Employment Cost Index (ECI) for aircraft manufacturing wages & salaries, and b.) Producer Price Index (PPI) for industrial commodities.



Actual indices can be obtained through the Bureau of Labor Statistics (BLS) website – Appendix 2.0 describes the procedures for generating this data. Forecasted indices can be obtained through use of third party services such as Economy.com and Global Insight. A method to calculate actual maintenance inflation can be accomplished using the following formula:

$$\text{Formula: } E_n = P_b * [0.35 \times (ECI_n / ECI_b) + 0.65 \times (PPI_n / PPI_b)]$$

P_b = Base Cost

ECI_b = Average of the ECI "Wages & Salaries" for the 11th, 12th, and 13th month prior Basic Date

ECI_n = Average of the ECI "Wages & Salaries" for the 11th, 12th, and 13th month prior Escalation Date

PPI_b = Average of the PPI "Industrial Commodities" for the 11th, 12th, and 13th month prior Basic Date

PPI_n = Average of the PPI "Industrial Commodities" for the 11th, 12th, and 13th month prior Escalation Date

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APPENDIX 1 – EXAMPLE CALCULATIONS

The examples that follow are based on a conventional turbofan engine rated at 27,000 lbs. The engine’s base operating parameters & costs, LLP limits & costs, and severity factors are illustrated in Table 1 below. The engine is projected to have an initial EGT Margin of 85 °C, and installation loss of 10-15 degrees Celsius per 1,000 flight cycles. Thereafter, rates of deterioration will stabilize to 4-5 degrees Celsius per 1,000 flight cycles.

TABLE 1 – SUPPORTING ENGINE METRICS												
Engine Base Information				Engine Severity Factors Table						Engine LLPs		
Base Point :	1.000	First-Run RSVR:	0.0500	<u>FL</u>	<u>0%</u>	<u>5%</u>	<u>10%</u>	<u>15%</u>	<u>20%</u>	<u>Module</u>	<u>Cost</u>	<u>FC Limit</u>
Rating :	27,00 Lbs	Mature-Run RSVR :	0.0625	1.0	1.850	1.750	1.650	1.550	1.450	FAN	\$400K	30,000
Annual FH :	3,000	First-Run Rest \$:	\$1.6M	1.5	1.350	1.250	1.200	1.150	1.100	HPC	\$500K	20,000
Annual FL :	2.0	Mature-Run Rest \$:	\$1.8M	2.0	1.100	1.050	1.000	0.950	0.850	HPT	\$500K	20,000
Derate :	10%	<u>Environment</u>	<u>Factor</u>	2.5	0.980	0.930	0.880	0.830	0.780	LPT	\$600K	25,000
Environment :	Temperate	Temperate	1.000	3.0	0.900	0.850	0.800	0.780	0.735			
		Hot / Dry	1.100	3.5	0.825	0.800	0.775	0.750	0.725			
		Erosive	1.200	4.0	0.800	0.775	0.750	0.725	0.715			

Example 1 - Theoretical Maximum Time On-Wing Calculation

Given: Initial EGT Margin = 85 °C
 Installation Loss = 10-15 °C per 1,000 flight cycles
 Steady State Deterioration = 4-5 °C per 1,000 flight cycles

Solution: Theoretical TOW Low = 1,000 FC + [(85 °C - 15 °C) / 5 °C] * 1,000 = 15,000 FC
 Theoretical TOW High = 1,000 FC + [(85 °C - 10 °C) / 4 °C] * 1,000 = 19,750 FC

Example 2 – Calculate the Base First-Run, Mature-Run, and Blended DMC Rates

The base operation for the above engine assumes flight leg operation 2.0, 10% take-off derate, and temperate operating environment.

Given: First-Run RSVR = 0.05 per 1,000 FH = 20,000 FH
 First-Run Restoration Cost = \$1,600,000
 Mature-Run RSVR = 0.0625 per 1,000 FH = 16,000 FH
 Mature-Run Restoration Cost = \$1,800,000

Solution: Base First-Run DMC=\$1,600,000 / 20,000 FH = \$80.00 / FH
 Base Mature-Run DMC=\$1,800,000 / 16,000 FH = \$112.50 / FH
 Base Blended DMC=(\$1,600,000 + \$1,800,000) / (20,000 + 16,000) = \$94.44/FH

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Example 3 – Calculate First-Run Restoration DMC Matrix

An aircraft lessor is requested to develop the first-run restoration rate matrix assuming 10% take-off derate operation in the following environments: a.) Temperate, b.) Hot/Dry, and C.) Erosive. The matrix will extend from flight operation ranging from 1.0 through 4.0.

Given: Base First-Run DMC=\$1,600,000 / 20,000 FH = \$80.00 / FH
 10 % Derate Factor = 1.000
 Temperate Factor = 1.000
 Hot/Dry Factor = 1.100
 Erosive Factor = 1.200

Solution: Adjust Rest Rate = (Base Rate)*(10% Severity Factor) * (Environment Factor)

	10% Factors	FL	10% Temperate	Flight Leg	1.0	1.5	2.0	2.5	3.0	3.5	4.0
80.00 \$/FH x	1.650	1.0	132.00	Temperate	132.00	96.00	80.00	70.40	64.00	62.00	60.00
	1.200	1.5	96.00	Hot / Dry	145.20	105.60	88.00	77.40	70.40	68.20	66.00
	1.000	2.0	80.00	Erosive	158.40	115.20	96.00	84.50	76.80	74.40	72.00
	0.880	2.5	70.40								
	0.800	3.0	64.00								
	0.775	3.5	62.00								
	0.750	4.0	60.00								

Hot /Dry Matrix = Temperate Matrix x 1.1
 Erosive Matrix = Temperate Matrix x 1.2

Example 4 – Calculate the Restoration DMC Adjusted for Operational Severity

An operator flying similar aircraft on different routes wishes to estimate his engine performance restoration DMC based on the following operational profiles:

Profile - 1
 Annual FH: 3,000
 Flight Leg: 2.0
 Derate: 20%
 Environment: Hot/Dry

Profile - 2
 Annual FH: 3,000
 Flight Leg: 2.5
 Derate: 5%
 Environment: Erosive

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Given: Base First-Run DMC=\$1,600,000 / 20,000 FH = \$80.00 / FH
 Profile 1 Severity Factor = 1.450
 Profile 2 Severity Factor = 0.980
 Hot/Dry Factor = 1.100
 Erosive Factor = 1.200

Solution: Adjust Restoration Rate= (Base Rate) * (Severity Factor) * (Environment Factor)

Environmental Factors		Severity Factor Table						First-Run Shop DMC –				
Environment	Factor	FL	0%	5%	10%	15%	20%	Base	Profile 1	Profile 2		
Temperate	1.000	1.0	1.850	1.750	1.650	1.550	1.450	1.) Base Rate (\$ / FH)	\$80	\$80	\$80	
Hot / Dry	1.100	1.5	1.350	1.250	1.200	1.150	1.100	Flight Leg	2.0	1.0	2.5	
Erosive	1.200	2.0	1.100	1.050	1.000	0.950	0.850	Derate	10%	20%	5%	
		2.5	0.980	0.930	0.880	0.830	0.780	2.) Severity Factor	1.000	1.450	0.930	
		3.0	0.900	0.850	0.800	0.780	0.735	Region	Temperate	Hot / Dry	Erosive	
		3.5	0.825	0.800	0.775	0.750	0.725	3.) Environment Factor	1.000	1.100	1.200	
		4.0	0.800	0.775	0.750	0.725	0.715	Shop DMC (\$ FH):	\$80.00	\$127.60	\$89.28	

Example 5 – Calculate the Restoration DMC Adjusted for Derate Severity

An operator flying similar aircraft, on average flies 2.0 hours / cycle and 10% average takeoff derate. If the operator's route structure allows for some degree of additional derate then the following DMC savings benefits can be estimated using the severity curves detailed above.

Given: Base Profile Severity Factor = 1.000
 Profile A Severity Factor = 1.550
 Profile B Severity Factor = 0.850

Solution: Restoration DMC Savings (%) = (Base Factor – Actual Factor) / Base Factor

Flight Time	Derate	Severity Factor	Calculation	DMC Savings
2.0	10%	1.000	Base	Base
2.0	15%	0.950	(1.00-0.95)/1.00	5%
2.0	20%	0.850	(1.00-0.85)/1.00	15%

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Example 6 – Effects of Flight Length & Derate on Engine SVR

Operators flying similar equipment but different operational profiles can compare their SVR using severity factors. Operator “A” operates 1.0 flight-leg at 15% average take-off derate. Operator “B” operates 3.0 flight-legs at 5% average take-off derate.

Given: Base Severity Factor = 1.000
 Base SVR = 0.050
 Profile A Severity Factor = 1.550
 Profile B Severity Factor = 0.850

Restoration DMC Savings (%) = (Base Factor – Actual Factor) / Base Factor

Solution: Multiplying the base SVR by 1.55 and 0.850 respectively will provide levels that can be directly compared to operator’s A & B SVRs

Operator	Flight Time	Derate	Severity Factor	Calculation	Ratio
Base	2.0	10%	1.000	Base	Base
A	1.0	15%	1.550	1.55 / 1.00	1.550
B	3.0	5%	0.850	0.85 / 1.00	0.850

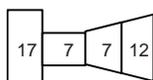
Example 7 – Engine Shop DMC – Adjusted For Workscope Management

An operator flying 3,000 FH per year at 2.0 flight leg and 10% derate would like to compare two workscope alternatives - detailed below - to assess the following: a.) Restoration DMC, and b.) Shop DMC.

Workscope 1:
 Build Goal: 7,000 FC
 Expected TOW = 14,000 FH
 Restoration Cost = \$1,650,000
 Restoration DMC = \$117.85 / FH
 LLP Cost = \$0
 Total SV Cost = \$1,650,000
 Shop DMC = \$117.85 / FH

Workscope 2:
 Build Goal: 10,000 FC
 Expected TOW = 20,000 FH
 Restoration Cost = \$1,800,000
 Restoration DMC = \$90.00 / FH
 LLP Cost = \$1,000,000
 Total SV Cost = \$2,800,000
 Shop DMC = \$140.00 / FH

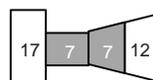
Replace
 No LLPs
 Build to 7,000 FC



Totals -----	
Restoration \$	1,650,000
- Total FC	7,000
- Total FH	14,000
- Restoration DMC	117.85 \$/FH
LLP \$	0

Total Shop Visit \$	1,650,000
Shop DMC	117.85 \$/FH

Replace
 Core LLPs
 Build to 10,000FC



Totals -----	
Restoration \$	1,800,000
- Total FC	10,000
- Total FH	20,000
- Restoration DMC	90.00 \$/FH
LLP \$	1,000,000

Total Shop Visit \$	2,800,000
Shop DMC	140.00 \$/FH

Engine Maintenance Concepts for Financiers

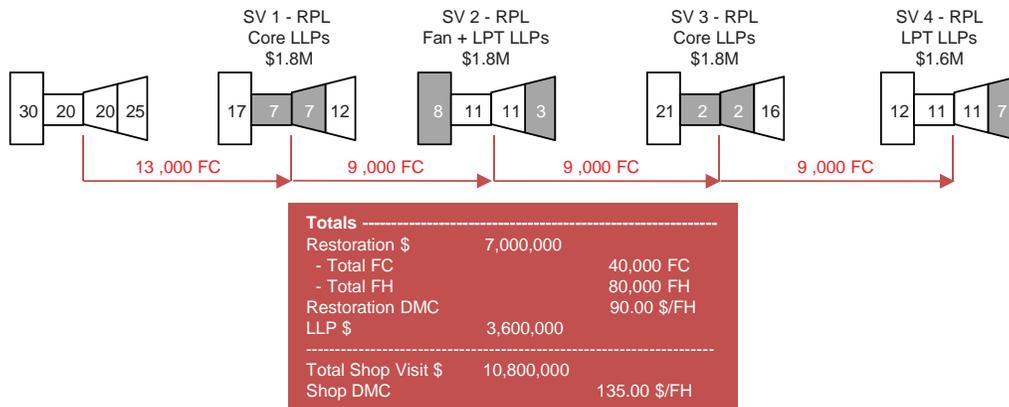


Example 8 – Engine Life-Cycle Shop DMC – Adjusted For Workscope Management

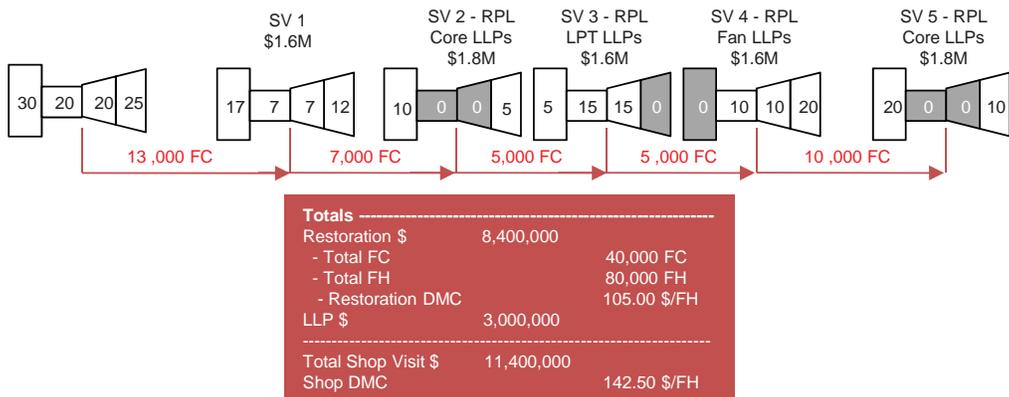
Engines generally go through patterns of workscope that vary based on time on-wing and business considerations. The examples that follow illustrate the unit shop visit cost versus shop DMC trade-off when adopting workscope management optimized for: a.) Maximum usage of LLP hardware, and b.) Minimum number of shop visits.

Scenario A: Optimized For Maximum Usage of LLP Hardware
 Build Standard Goal: Maximized to LLP stub-life.
 Annual FH: 3,000 / Flight Leg: 2.0 / Derate: 10% / Environment: Temperate

Solution: Maximizing usage of LLP hardware often leads to lower unit shop visit costs, whereas building engines for minimum number of shop visits allows one to achieve lower shop DMC.



Scenario B: Optimized for Minimum Number of Shop Visits
 Build Standard Goal: 10,000 FC
 Annual FH: 3,000 / Flight Leg: 2.0 / Derate: 10% / Environment: Temperate



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Example 9 – Engine Half-Time Valuation

An investor is conducting an aircraft market value analysis for a twin-engine turbofan aircraft. Part of the analysis requires assessing the aircraft's market value adjusted from half-time maintenance condition. Both engines have accumulated 10,000 FC / 20,000 FH since new, and the engine's first-run MTBSV interval is 25,000 FH.

Solution:

1. Engine restoration half-time adjustment = [(Percent Life Remaining – 50%) * Event Cost] ; where
 - a. Percent Life Remaining = 20%
 - b. Event Cost = \$2,000,000
 - c. Half-Time Adjustment Per Engine = (\$600,000)

2. Engine LLP half-time adjustment = [Value Remaining – (50% * LLP Stack Cost)]; where
 - a. Value Remaining = \$1,122,000
 - b. Event Cost = \$2,000,000
 - c. Half-Time Adjustment Per Engine = \$122,600

3. Total Engine Adjustment = 2*(\$122,600 – \$600,000) = (\$954,800)

Event	Expected TOW FH	Time Remain	%Time Remain	Expected Cost \$	Half-Time Adjust \$
Restoration	25,000	5,000	20%	2,000,000	(600,00)

LLP	Part Cost \$	Cycle Limit FC	Cycle Cost \$/FC	Remain Cycles	Remain Value \$
1	180,000	30,000	6.00	20,000	120,000
2	120,000	30,000	4.00	20,000	80,000
3	100,000	30,000	3.33	20,000	66,600
4	50,000	20,000	2.50	10,000	25,000
5	80,000	20,000	4.00	10,000	40,000
6	110,000	20,000	5.50	10,000	55,000
7	30,000	20,000	1.50	10,000	15,000
8	240,000	20,000	12.00	10,000	120,000
9	200,000	20,000	10.00	10,000	100,000
10	180,000	20,000	9.00	10,000	90,000
11	90,000	20,000	4.50	10,000	45,000
12	60,000	20,000	3.00	10,000	30,000
13	100,000	25,000	4.00	15,000	60,000
14	150,000	25,000	6.00	15,000	90,000
15	70,000	25,000	2.80	15,000	42,000
16	90,000	25,000	3.60	15,000	54,000
17	80,000	25,000	3.20	15,000	48,000
18	70,000	25,000	2.80	15,000	42,000
	2,000,000		87.74		1,122,600
					56.1%
				Half-Time Adjust \$	122,600

Example 10 – Engine Maintenance Cost Escalation

Calculate the escalated cost of an engine restoration shop visit in March 2009 assuming a base cost in March 2006 of \$1.8M. Refer to Appendix 2 for instructions on retrieving the required indices.

$$\text{Formula : } E_n = P_b * [0.35 * (ECI_n / ECI_b) + 0.65 * (PPI_n / PPI_b)]$$

P_b = Base Cost

ECI_b = Average of the ECI "Wages & Salaries" for the 11th, 12th, and 13th month prior Basic Date

ECI_n = Average of the ECI "Wages & Salaries" for the 11th, 12th, and 13th month prior Escalation Date

PPI_b = Average of the PPI "Industrial Commodities" for the 11th, 12th, and 13th month prior Basic Date

PPI_n = Average of the PPI "Industrial Commodities" for the 11th, 12th, and 13th month prior Escalation Date

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Step 1. Go the BLS web site at: <http://data.bls.gov/cgi-bin/srgate>

Step 2. Retrieve both the ECI - NAICS Wages & Salaries Aircraft Manufacturing indices and the PPI indices for the following periods:

- a) 11th, 12th, and 13th month prior to the base date (March 2006)
- b) 11th, 12th, and 13th month prior to the escalation date (March 2009)

ECI Series ID : ciu2023211000000i

Year	Qtr1	Qtr2	Qtr3	Qtr4
2006	101.9	102.5	102.9	102.7
2007	104.7	104.8	104.4	104.6
2008	107.0	107.4	107.6	108.1
2009	110.5	111.0	111.5	

PPI Series ID : wpu03thru15

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	168.30	165.70	166.30	168.80	170.60	170.60	171.30	172.40	169.20	165.40	168.00	168.90
2007	166.80	169.10	171.60	173.90	176.00	176.40	177.90	174.90	175.60	176.90	181.80	180.70
2008	182.80	184.60	190.20	193.80	200.00	204.00	209.50	202.40	200.10	189.30	178.40	172.30
2009	172.60	170.80	169.50	170.30	172.00	175.50	174.60	177.70	177.50	177.90	180.50	

Step 3. Calculate the indices averages.

ECI	Basic	From	To	ECI-11	ECI-12	ECI-13	ECI_Avg
ECI b	Mar-07			102.5	102.5	102.5	102.50
ECI 1		Mar-07	Mar-08	104.8	104.8	104.8	104.80
ECI 2		Mar-07	Mar-09	107.4	107.4	107.4	107.40

PPI	Basic	From	To	ECI-11	ECI-12	ECI-13	PPI_Avg
PPI b	Mar-07			168.8	166.3	165.7	166.93
PPI 1		Mar-07	Mar-08	173.9	171.6	169.1	171.53
PPI 2		Mar-07	Mar-09	193.8	190.2	184.6	189.53

Step 4. Calculate the escalated shop visit cost.

Summary Calculation :

$E_n = 0.35 \times (ECI_n / ECIB) + 0.65 \times (PPI_n / PPIb)$			
(ECI _n /ECI _b) =	1.0478	/	1.0000 = 1.0478
(PPI _n /PPI _b) =	1.1354	/	1.0000 = 1.1354
0.35 x (ECI _n / ECIB) =	0.3667		
0.65 x (PPI _n / PPI _b) =	0.7380		
E_n =	1.1047		
P_b =	1,800,000		
Escalated Cost of Engine Shop Visit :	1,988,516		

Engine Maintenance Concepts for Financiers



APPENDIX 3 – U.S. BUREAU OF LABOR STATISTICS DATA RETRIEVAL INSTRUCTIONS

1. Go to the BLS web site at: <http://data.bls.gov/cgi-bin/srgate>
2. You will then be prompted to enter the series ids for the data you wish to retrieve. You may select one or more series id's at a time. Below is a description of each series id.
 - a. **ciu2023211000000i** - NAICS Wages & Salaries Aircraft Manufacturing
 - b. **wpu03thru15** - PPI - Industrial Commodities Index
3. Type in the Series id, select the years you wish to view & click to retrieve data.

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