Engine Maintenance Concepts

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Agenda

1. Design Characteristics
2. Performance Characteristics
3. Maintenance Philosophy
4. Direct Maintenance Costs
5. Factors Influencing DMCs
6. Flight Hour Agreements

Appendix A Maintenance Costs & Reserve Rates
Appendix B Engine Major Module Description

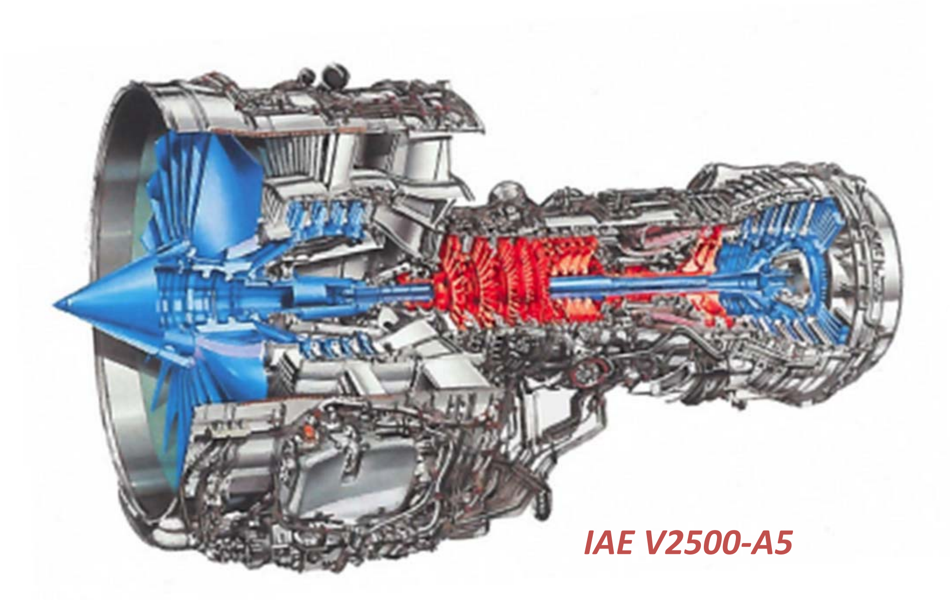
A modern engine often operates **25,000 hours** between major overhauls; equivalent to **13,500,000 miles** or flying to the moon and back over **27 times**.

1 - Design Characteristics

Conventional turbofan engine design is based on either a **twin-shaft** or **three-shaft** configuration.

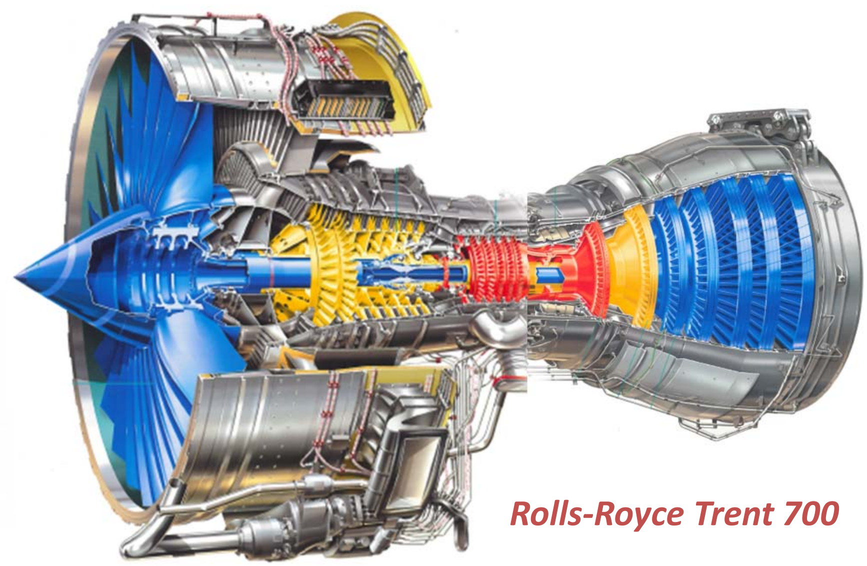
In a **twin-shaft** configuration the Fan/LPC is driven by the LPT, and the HPC is driven by the HPT. A **three-shaft** turbofan includes an additional, **intermediate** compressor and turbine section.

Example Twin-Shaft Engine



IAE V2500-A5

Example Three-Shaft Engine



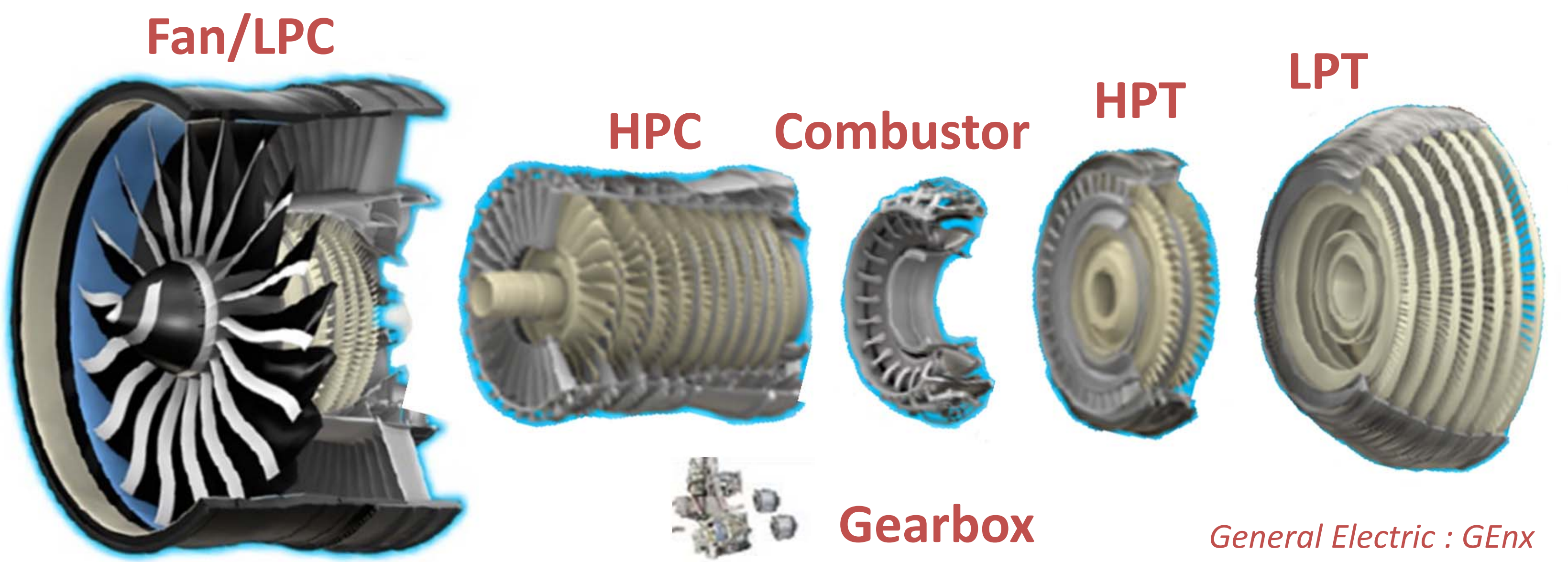
Rolls-Royce Trent 700

1 - Design Characteristics

Engines are designed as a series of **modules** for ease of assembly & subsequent maintenance

Each module has its **individual identity**, **service history** and **designated levels of work**.

Engine Module Breakdown (Twin-Shaft Engine)

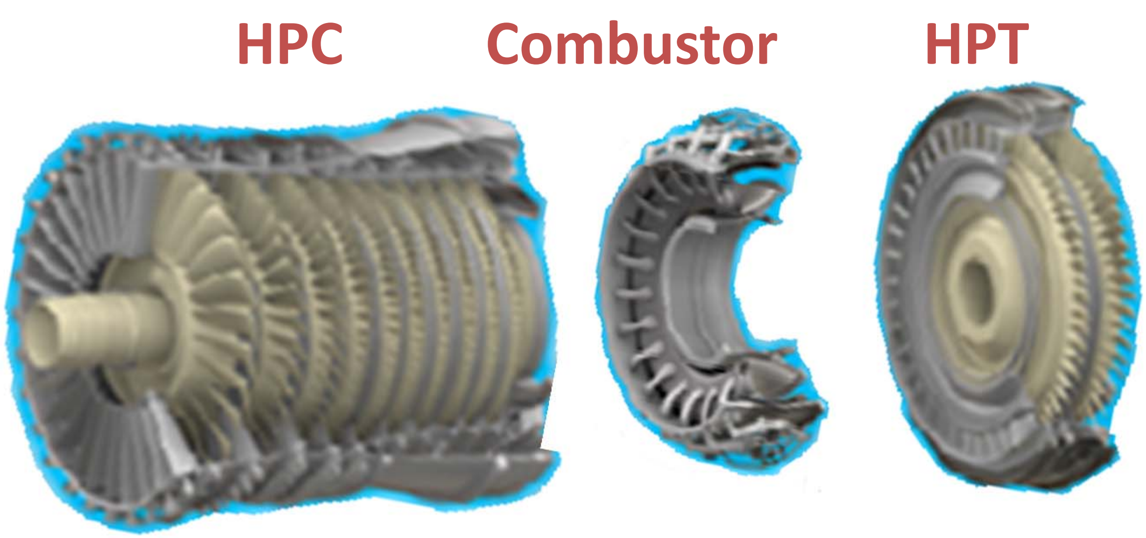


General Electric : GEnx

1 - Design Characteristics

The **Core Modules (Hot Section)** of an engine consist of the HPC, Combustor & HPT, and are generally restored at each shop visit.

Core Modules (Twin-Shaft Engine)

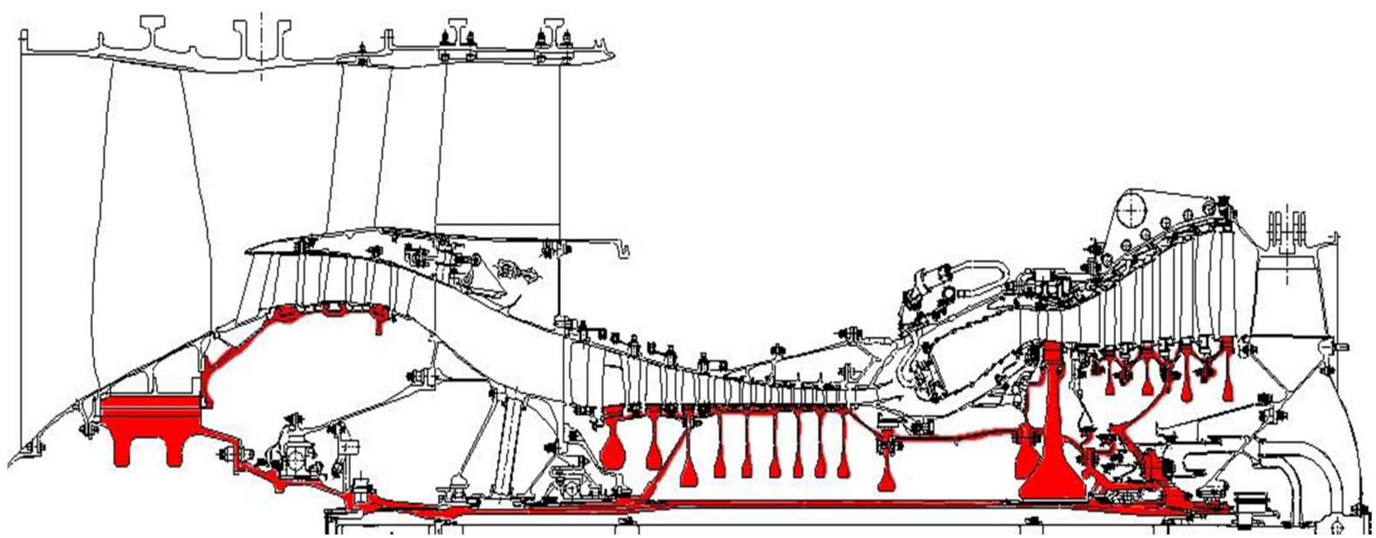


1 - Design Characteristics

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 **Life-Limited Parts (LLP)** and generally consist of disks, seals, spools, and shafts

LLPs are discarded once their useful lives are reached.

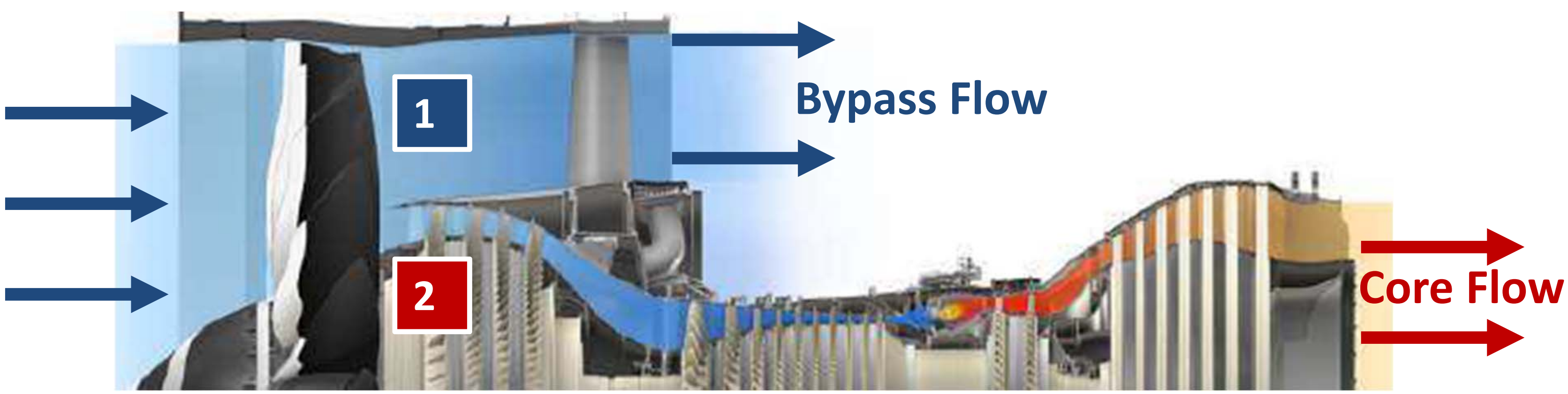


2 - Performance Characteristics

The **bypass ratio** is the ratio of the air that goes around the engine to the air that goes through the core

In high bypass engines, the core engine primarily acts as a gas generator and the fan produces anywhere from 60% - 80% of the total engine thrust.

$$\textbf{Bypass Ratio} = \frac{\text{Mass Flow } 1}{\text{Mass Flow } 2}$$



2 - Performance Characteristics

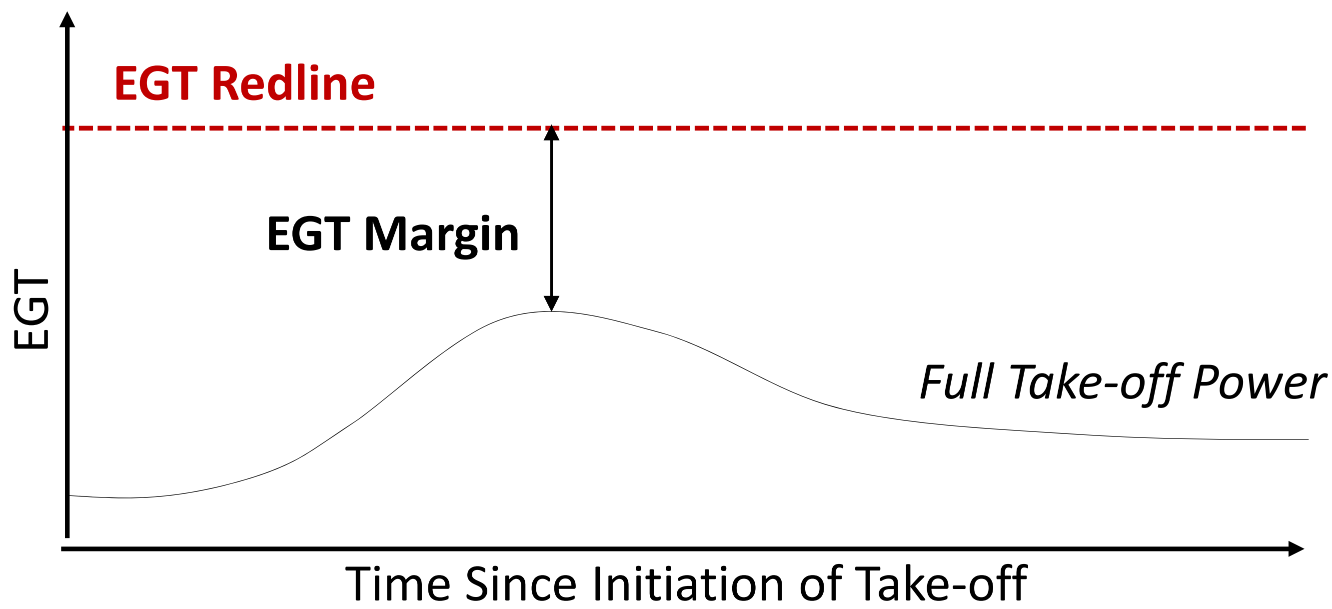
Exhaust Gas Temperature - EGT is a measure of the temperature of the gas as it leaves the turbine unit and is a primary indication of engine health.

Engines are certified with temperature limits that are enforced via a limit on maximum take-off EGT, referred to as the **redline EGT**.

2 - Performance Characteristics

EGT margin (EGTM) is the difference between the **peak EGT** incurred during take-off and the certified redline EGT. It is used to evaluate and track engine **time on-wing & health**.

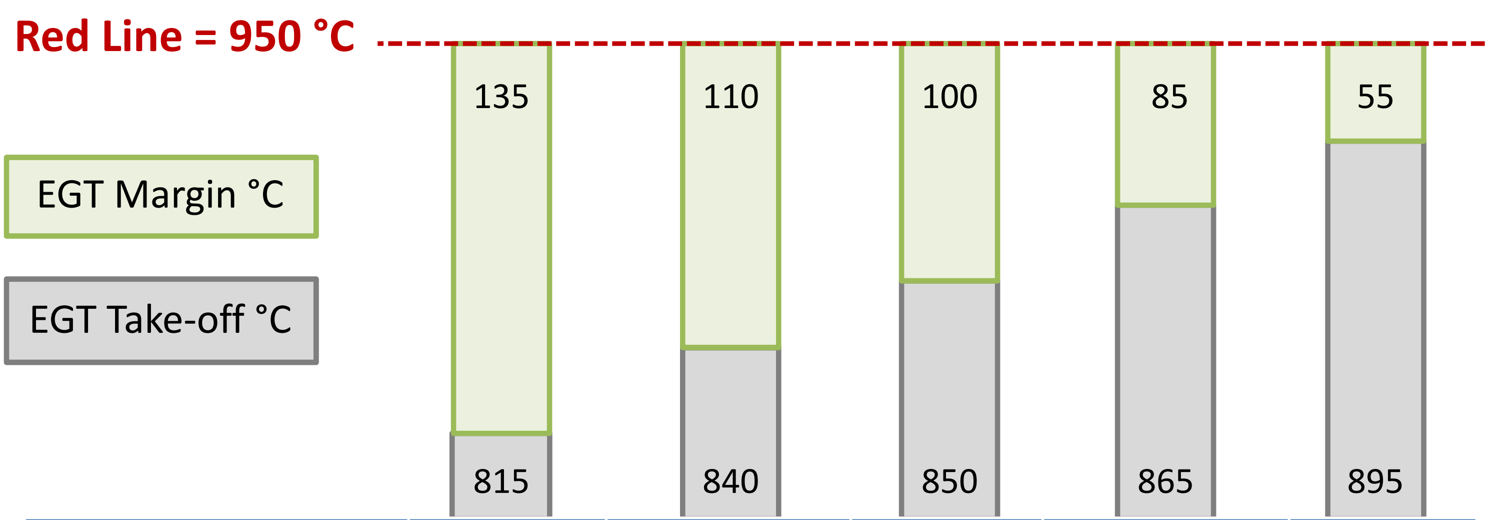
EGT Margin °C = EGT Redline – EGT Take-off



2 - Performance Characteristics

EGT margins (EGTM) are at their highest levels when the engines are new or just following refurbishment.

EGT Margins for new CFM56-7B Engines

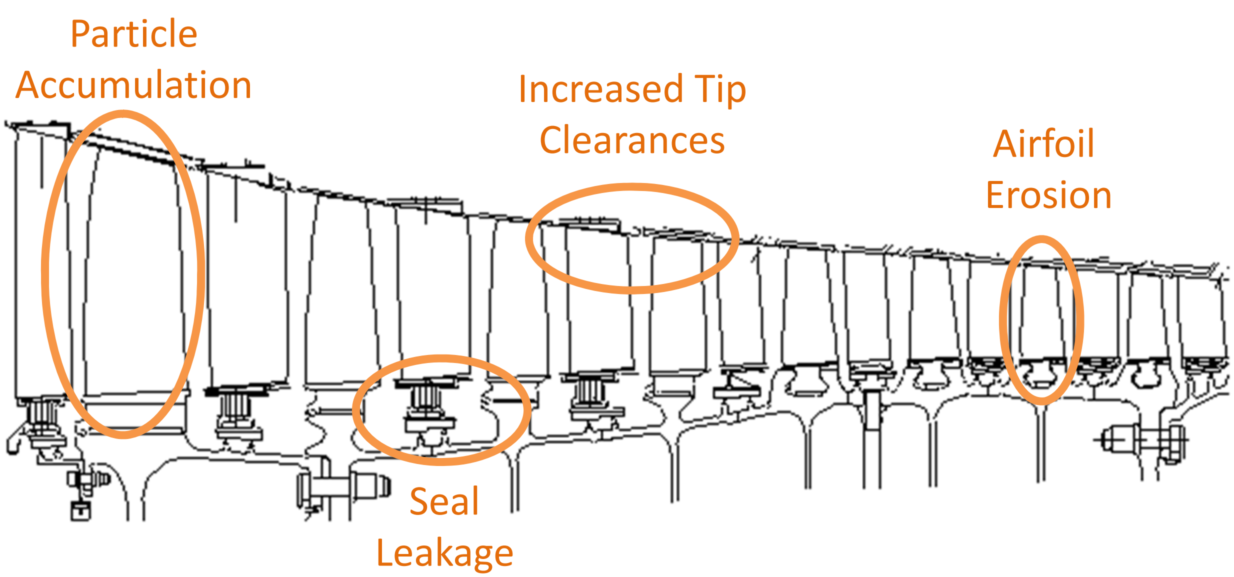


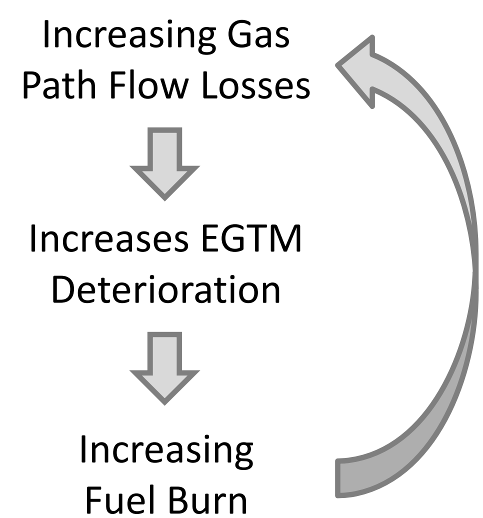
Engine Model	7B20	7B22	7B24	7B26	7B27
Takeoff Thrust	20,600	22,700	24,200	26,300	27,300

2 - Performance Characteristics

EGT margin deterioration largely results from **hardware distress** (e.g. gradual increase in clearance between the turbine blade tips & surrounding static seals or shrouds, and combustor distress)

EGT Margin Deterioration Cycle

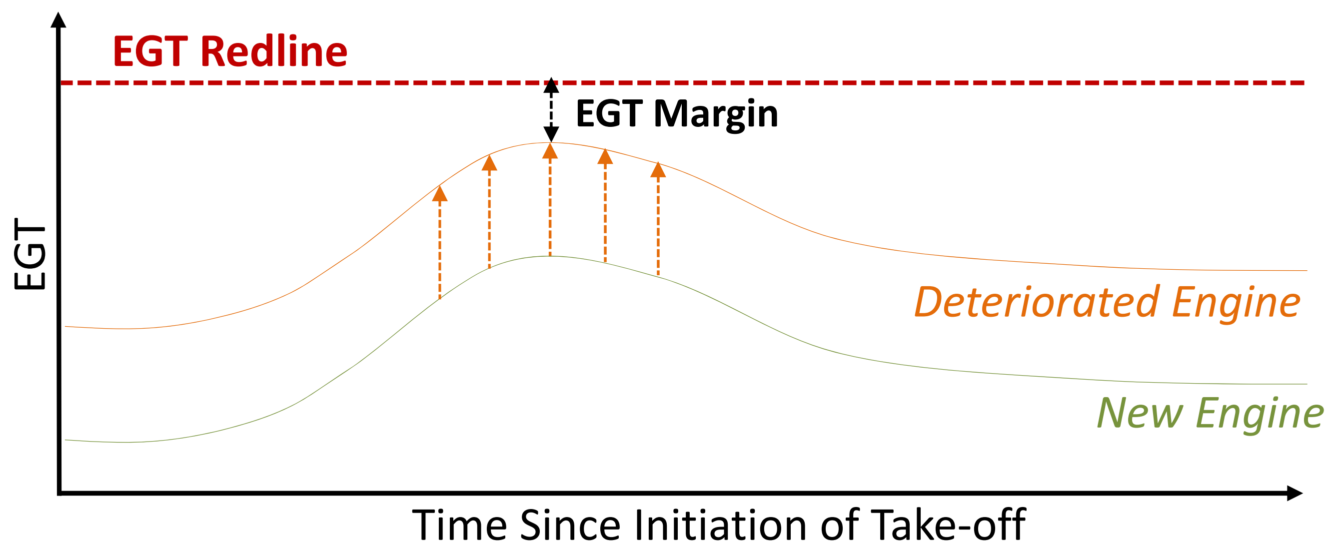




2 - Performance Characteristics

Rate of EGT margin deterioration is affected by how the engine is operated. Primary factors influencing the rate of deterioration consist of: a.) Flight operation (flight leg, derate, environment), b.) Age (first-run vs. mature-run) and c.) Workscope

EGT Margin Deterioration Cycle



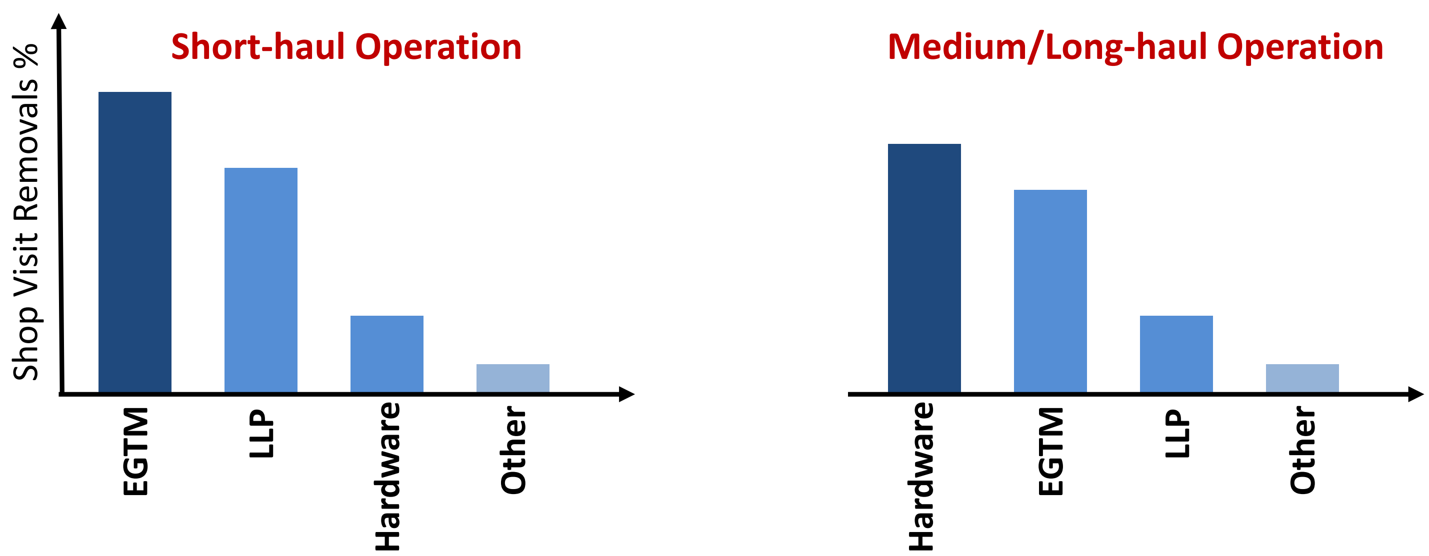
2 - Performance Characteristics

Engine Primary Removal Causes

Engines operating on **short-haul flights** experience higher removals due to: a.) EGTM deterioration & b.) LLP expiry.

Engines operating on **medium-to-long haul flights** experience higher removals due to deteriorating: a.) hardware & b.) EGTM.

Primary Removal Causes



3 - Maintenance Philosophy

On-condition maintenance

Engines are subject to **on-condition maintenance** whereby maintenance is undertaken only when **monitoring** shows that work is required.

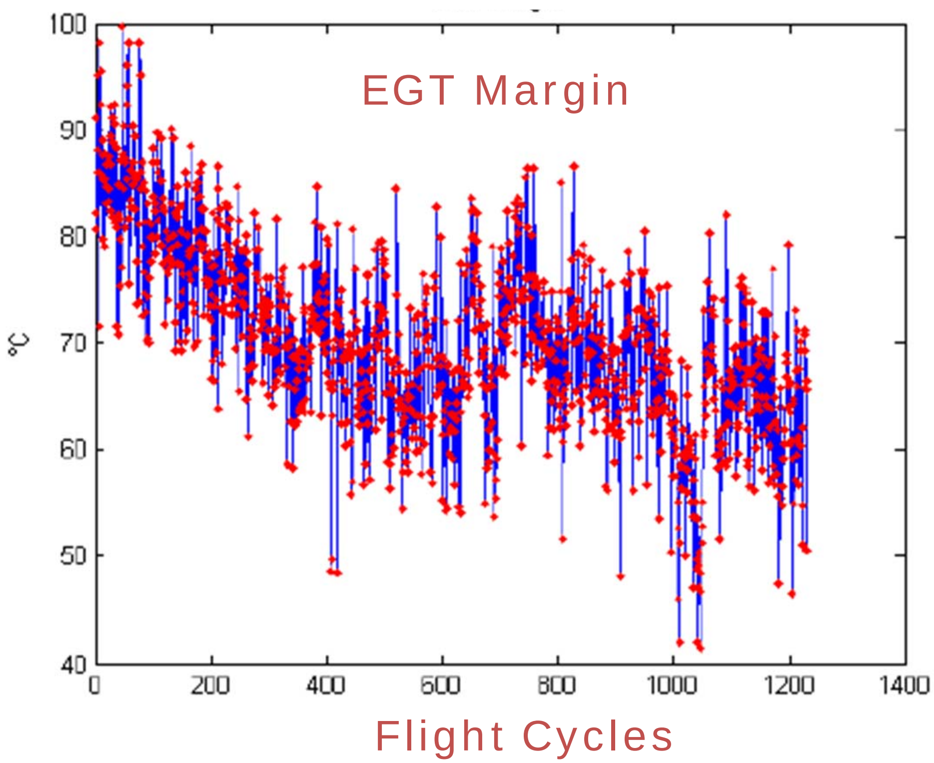
Typical Monitored Parameters:

- Exhaust Gas Temperatures (EGT),
- EGT Margin,
- Rotor (Shaft) Speed (e.g. N1 & N2),
- Fuel Flow,
- Oil Pressure, Temp & Consumption,
- Engine Vibration
- Metal in System (Chip Detector)

3 - Maintenance Philosophy

On-condition maintenance

Example - trend monitoring of EGT Margin looks at successive snapshots of observations to help analyze the wear trend of the engine.



3 - Maintenance Philosophy

Engine Workscoping

- The **Workscope Planning Guide (WPG)** is a manual that details suggested levels of required maintenance on each module as well as a list of recommended **Service Bulletins**.
- The WPG generally specify **levels** of workscopes - examples: 1.) Minimum Level, 2.) Performance Level, and 3.) Full Overhaul .

3 - Maintenance Philosophy

Engine Workscoping

- The workscope of an engine can be "**target-oriented**" to achieve:
  - Target on-wing time
  - Target shop visit cost
  - Target LLP stub-life / Restored EGT Margin
- Engine build goals are often influenced by business decisions.
  - Maximizing usage of LLP hardware, which often leads to lower shop visit costs but higher DMC ($ / FH), or
  - Building for minimum number of shop visits, which allows one to achieve lower shop DMC ($ / FH) but higher shop visit costs.

Engine Workscoping

Example Shop Visit (SV) Workscope Levels

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
Gearbox	Minimum Level	Performance Level	Minimum Level

3 - Maintenance Philosophy

Qualifying Engine Performance Restoration

– A qualified **Performance Restoration Shop Visit** occurs whenever the engine maintenance performed entails a performance or higher level of work, **which at a minimum**:

  ✓ Accomplishes a prescribed package of inspections, maintenance checks and major refurbishments on an engine's **Core Modules**

– This level of refurbishment does not specify 100% disassembly and 100% piece part inspection, but will generally :

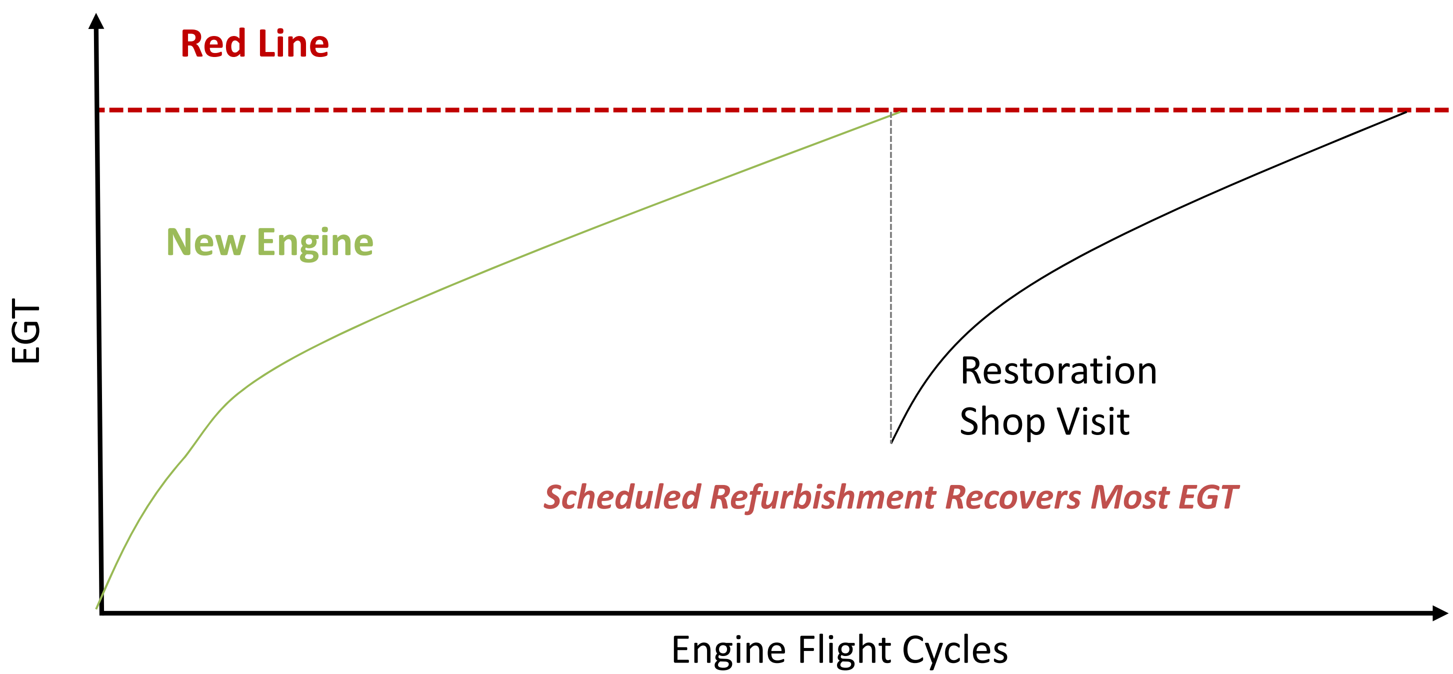
  ✓ Zero-time the **Core Modules** to the highest build specification,

  ✓ Obtain max time between shop visits with resultant lowest cost per flight hour & the greatest potential for regaining **EGT margin**.

3 - Maintenance Philosophy

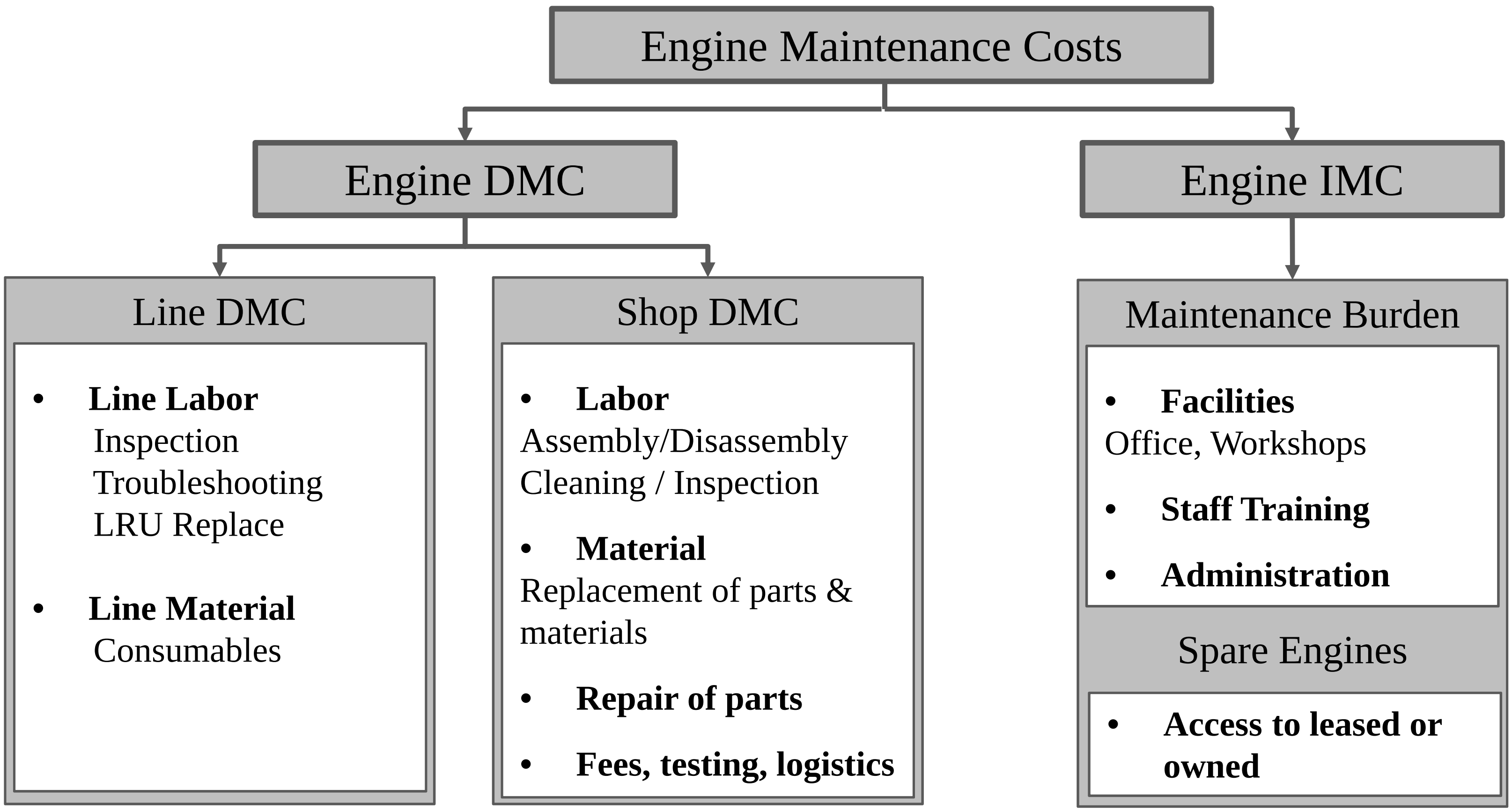
Performance restoration maintenance will restore hardware and clearances between blade tips and engine casings.

On average, **65% - 85% of the original EGT Margin will be restored** following a performance restoration.



4 - Direct Maintenance Costs (DMCs)

Components of Engine Total Maintenance Costs



DMC = Direct Maintenance Cost
IMC = Indirect Maintenance Cost

4 - Direct Maintenance Costs (DMCs)

Components of Engine Shop Direct Maintenance Costs

Shop DMC

- **Labor**
  Assembly/Disassembly
  Cleaning / Inspection
- **Material**
  Replacement of parts & materials
- **Repair of parts**
- **Fees, testing, logistics**

↓

Input for Performance Restoration Cost ($) and Time Since Refurbishment (FH)

DMC Breakdown

Material : 60% - 70%
Labor : 20% - 30%
Repair : 10% - 20%

5 - Factors Influencing Engine DMCs

Both restoration costs & time on-wing are influenced by:

- ✓ Engine Thrust Rating
- ✓ Engine Age (first-run versus mature-run)
- ✓ Flight Operation (flight leg, take-off derate, environment)
- ✓ Engine Workscope Decisions

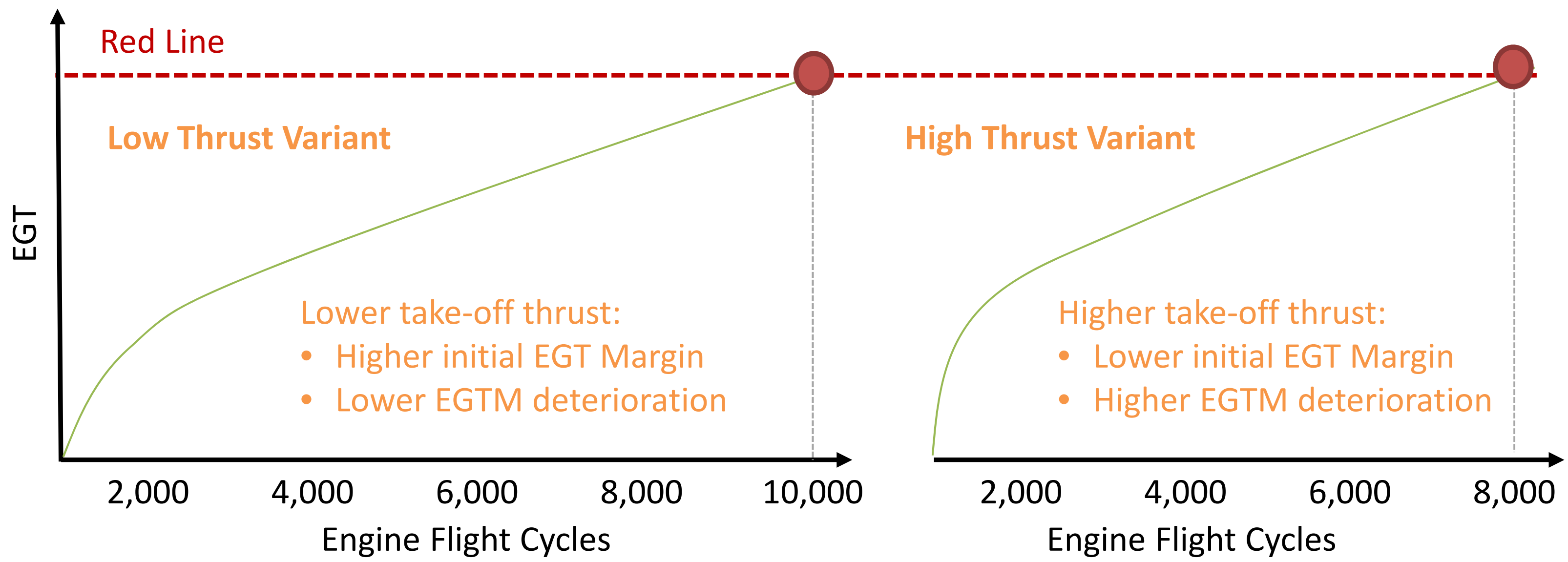
These factors directly affect the cost per-flight-hour, or maintenance reserve rates, charged by lessors.

5 - Factors Influencing Engine DMCs

Engine Thrust Rating

✓ Higher engine thrust rating = Higher EGT margin deterioration = Lower Time On-Wing

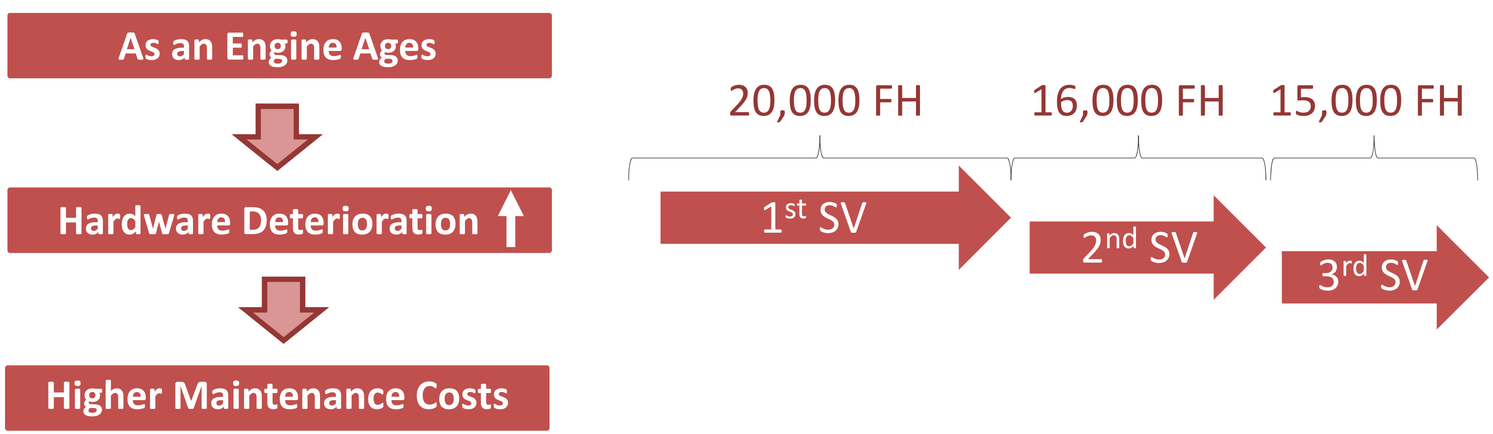
Same Engine Model Goes Into Shop



5 - Factors Influencing Engine DMCs

Engine Age

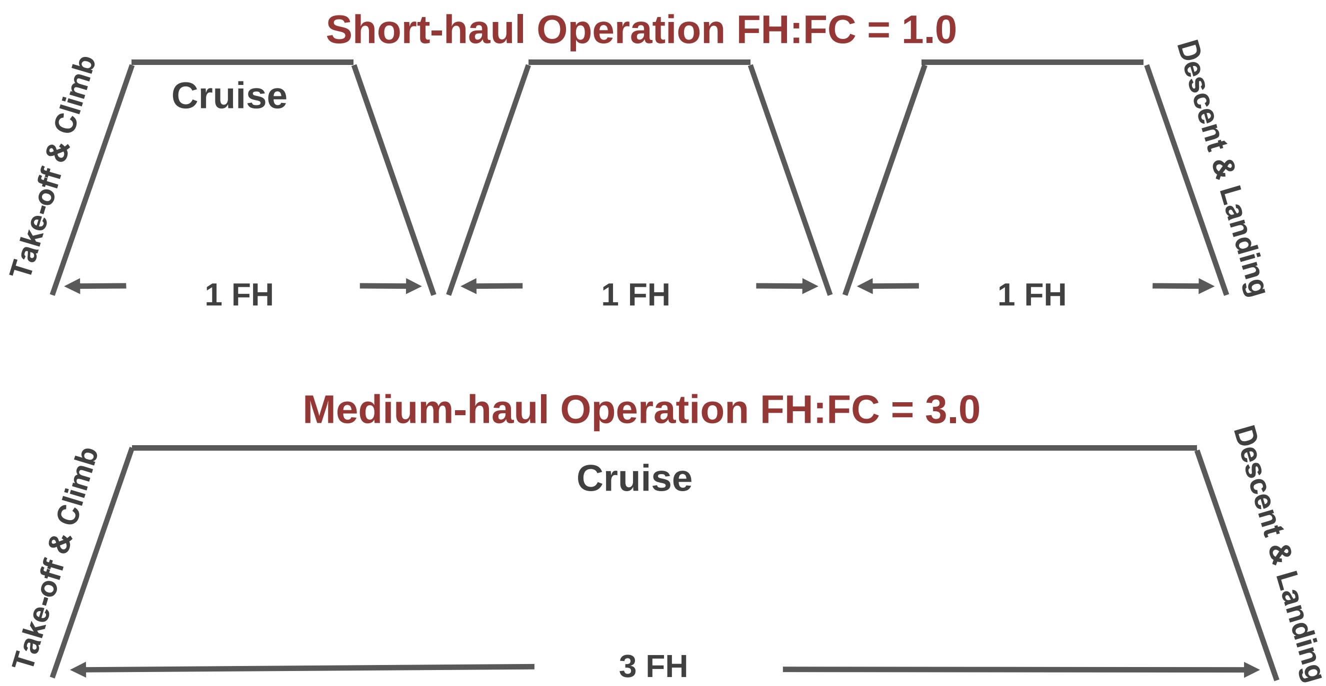
- ✓ **First-run** engines traditionally have longer time on-wing than subsequent run engines.
- ✓ **Mature-run** generally begins after the first core restoration shop visit, or after all engine modules have been restored



5 - Factors Influencing Engine DMCs

Engine Flight Leg

✓ The flight profile of an aircraft can be expressed by the **flight hour to flight cycle ratio** (FH:FC), also known as the **flight leg length** .



5 - Factors Influencing Engine DMCs

Engine Flight Leg

✓ The average FH:FC is an important parameter for the operational severity of an engine – greater flight legs equates to lower DMCs

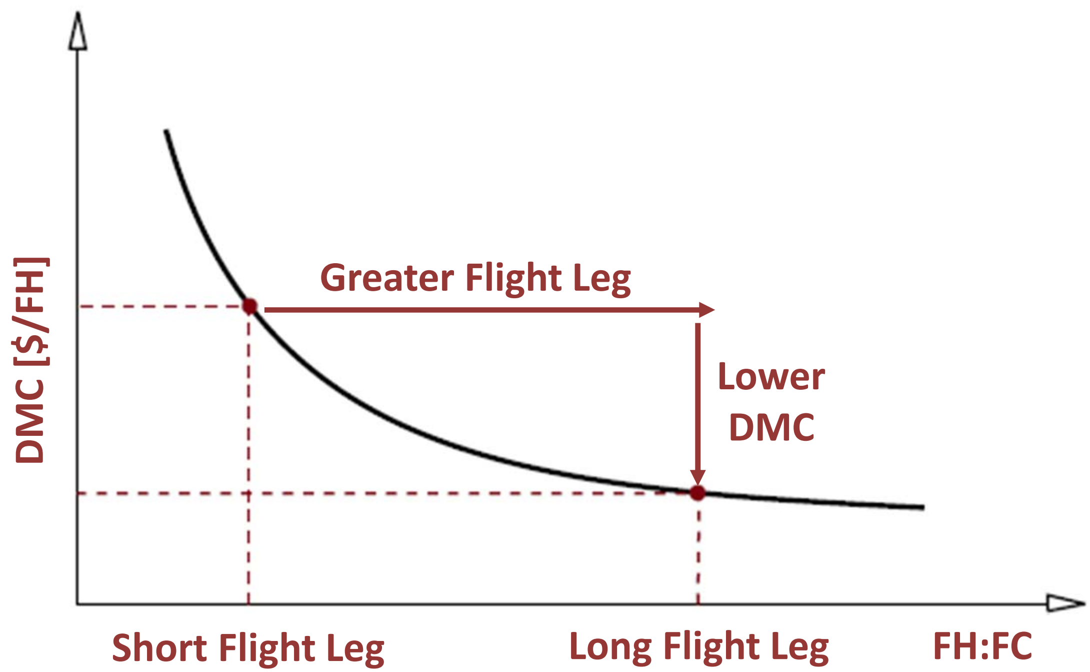
Increasing Flight Leg

⇩

Lowers EGT Deterioration

⇩

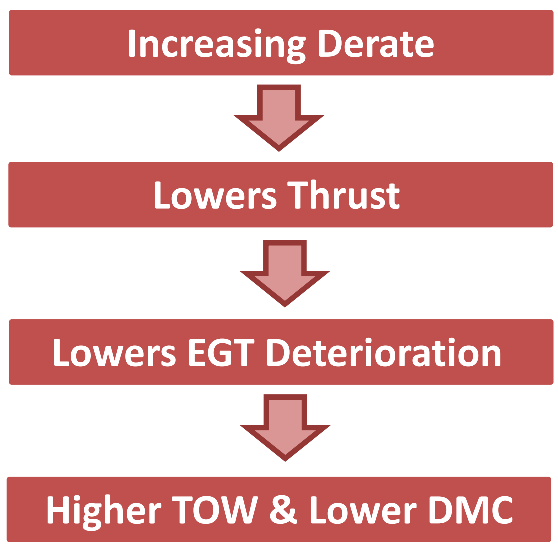
Higher TOW & Lower DMC

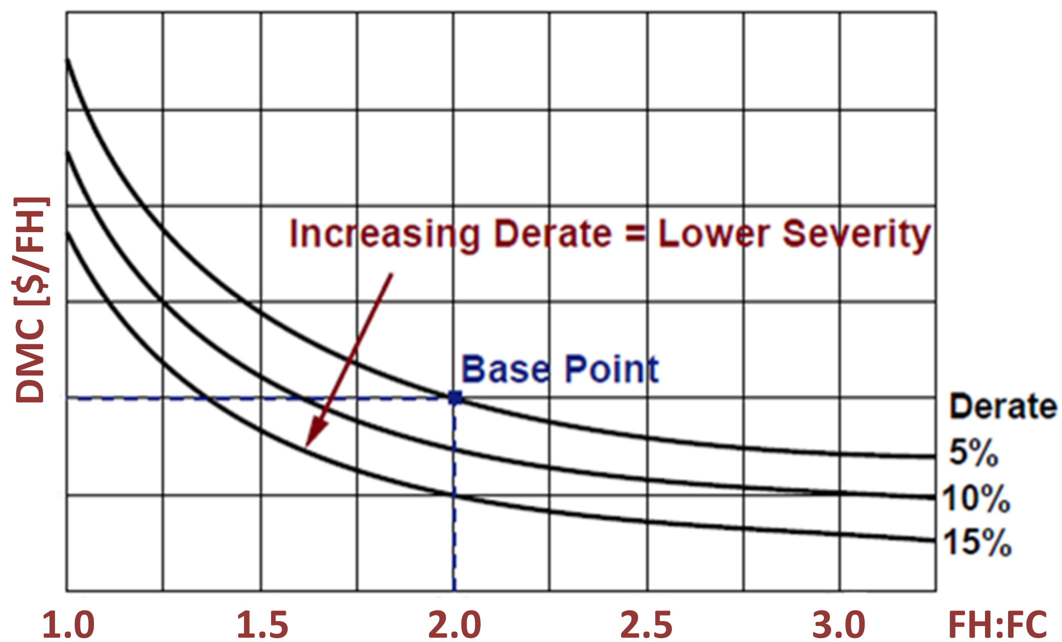


5 - Factors Influencing Engine DMCs

Engine Take-off Derate

- ✓ **Take-off derate thrust** is a takeoff thrust setting that is below the maximum thrust level.
- ✓ Larger derate translates into lower take-off EGT and lower engine deterioration rate, longer on-wing life & reduced cost per FH

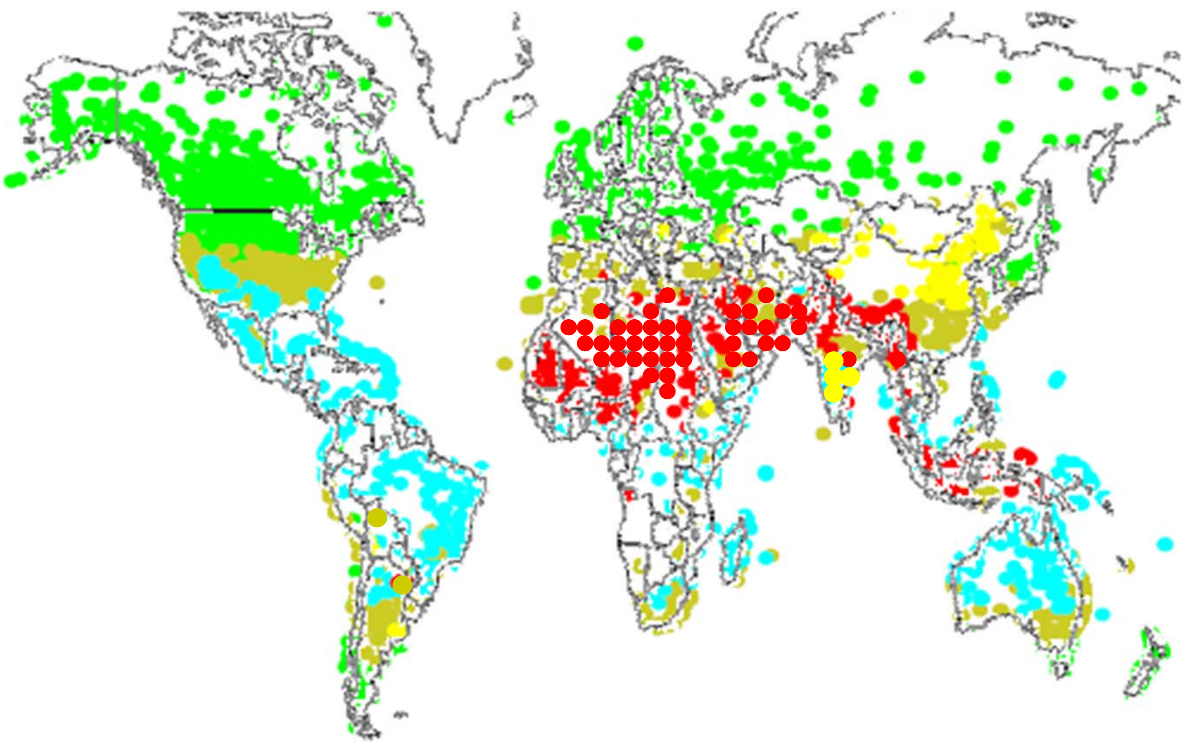




5 - Factors Influencing Engine DMCs

Operating Environment

✓ Engines operated in hot-dry and/or erosive-corrosive environments are exposed to **greater hardware deterioration** and thus greater performance deterioration.



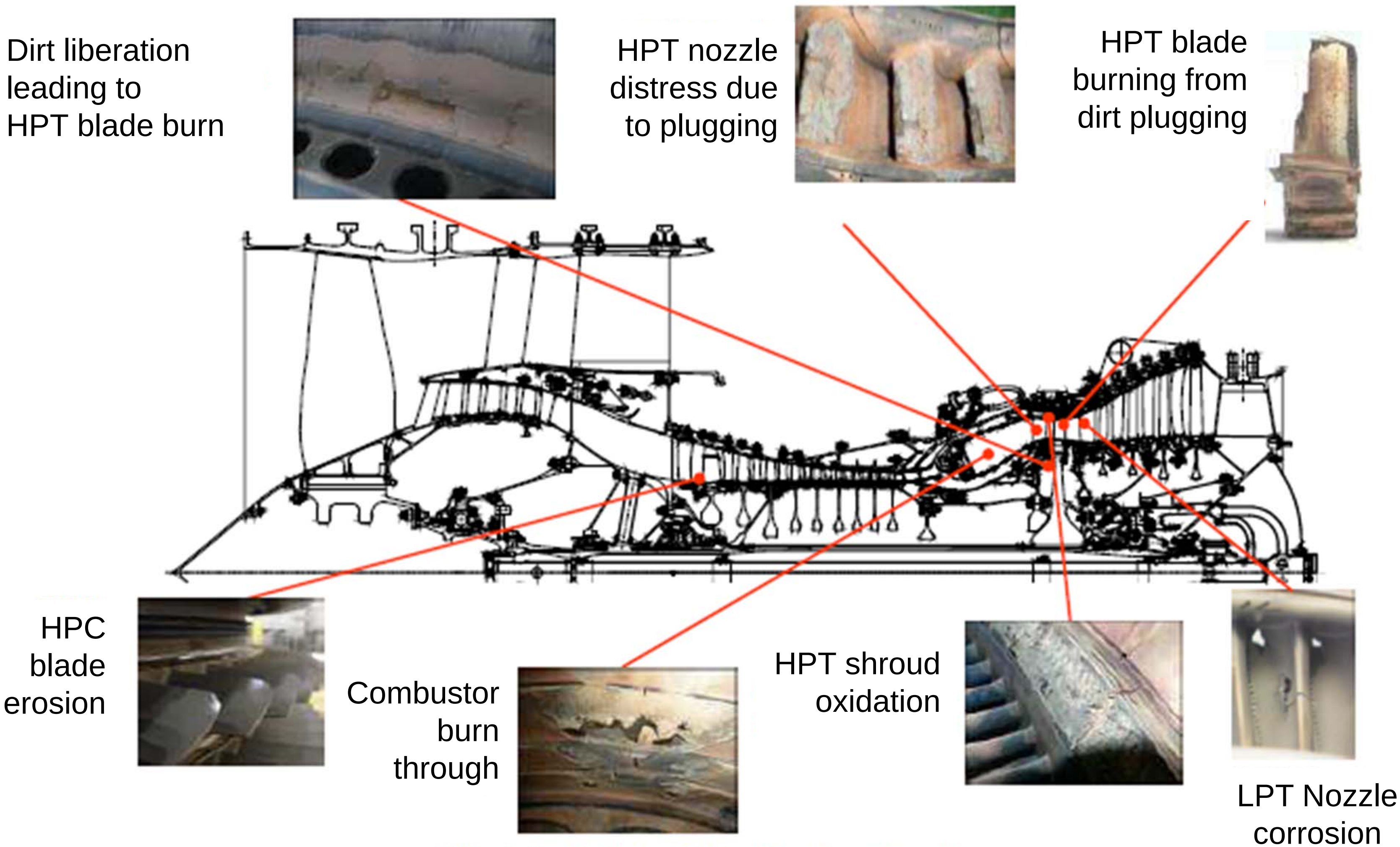
Colors highlight severity & rate of occurrence of distress

Three Categories:

- **Temperate**
  - Lowest
  - Medium / Low
- **Erosive-Corrosive**
  - Medium
  - High
- **Hot-Harsh**
  - Highest

5 - Factors Influencing Engine DMCs

Operating Environment – example hardware distress



5 - Factors Influencing Engine DMCs

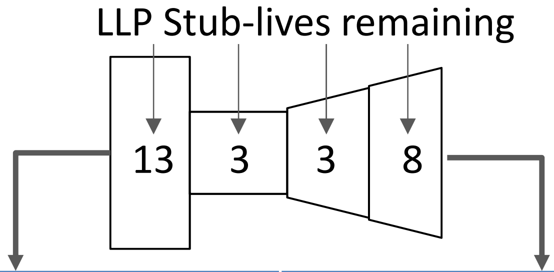
Engine Workscope Decision

- ✓ Engines generally go through patterns of workscopes that vary based on time on-wing and business considerations
- ✓ The level of workscope to be performed on an engine inducted in the shop is dependent on:
  - removal cause(s),
  - time accumulated on the engine modules,
  - observed hardware conditions,
  - trend data at removal, and
  - airlines goals

5 - Factors Influencing Engine DMCs

Example Engine Workscope Decision

Engine Enters Shop



	Scenario 1	Scenario 2
Workscope	Core + LPT Restoration	Full Overhaul
LLP Replacement	Core + LPT	Fan + Core + LPT
Build-Goal	13,000 FC	20,000 FC
Shop Visit Cost $	$3.0M	$3.75M
LLP Cost $	$2.0M	$2.5M
Projected $ / FH	$200 / FH	$163 / FH

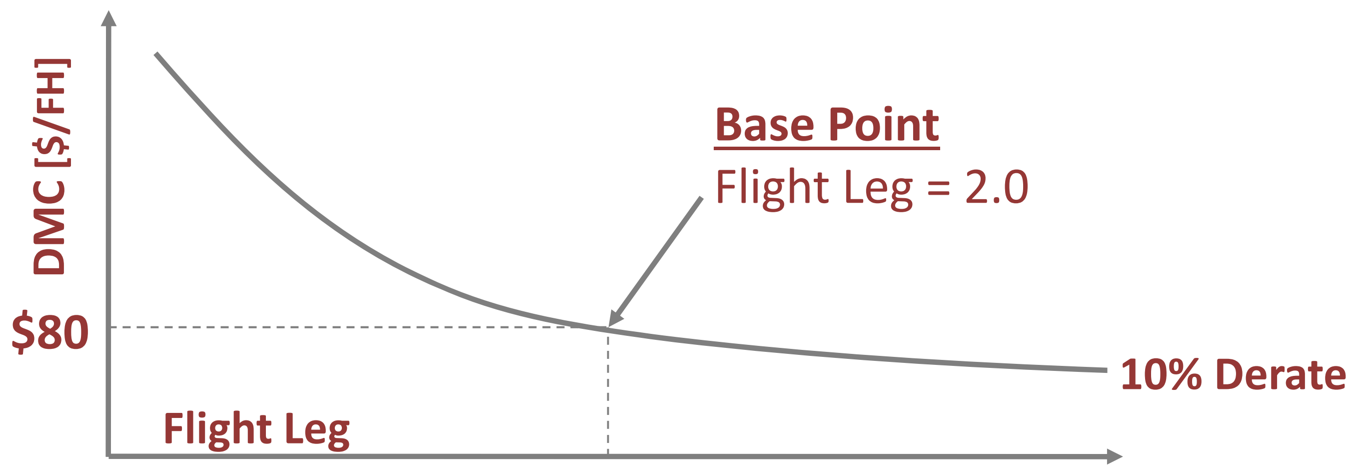
Engine Exits Shop

5 - Factors Influencing Engine DMCs

Engine DMC Development

- **Engine DMCs** are derived from OEM **severity curves.**
- These relative factors allow maintenance costs to be adjusted by the effects of flight length and takeoff derate.

Example Shop Visit DMC Severity Curve

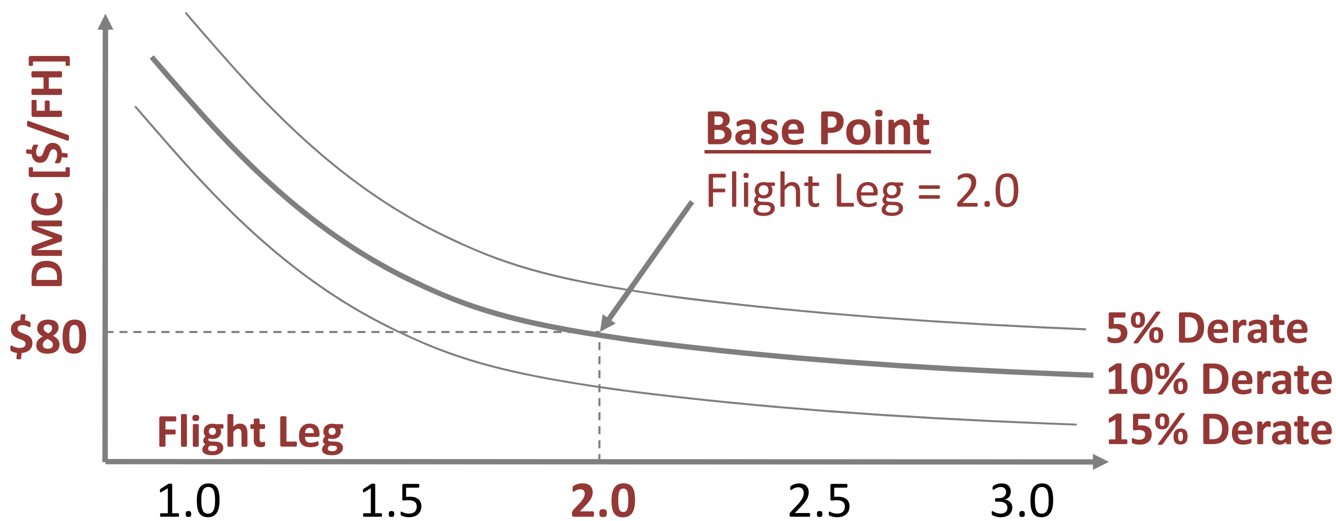


Flight Leg	1.0	1.5	**2.0**	2.5	3.0
10% Derate [$/FH]	$175	$135	**$80**	$78	$76

5 - Factors Influencing Engine DMCs

Engine DMC Development

Example Shop Visit DMC Severity Curve Expanded to Account for Additional Derate Settings



	1.0	1.5	2.0	2.5	3.0
5% Derate [$/FH]	$195	$150	$88	$86	$84
10% Derate [$/FH]	$175	$135	**$80**	$78	$76
15% Derate [$/FH]	$160	$120	$72	$70	$68

5 - Factors Influencing Engine DMCs

Engine DMC Development

Example DMC Matrix Expanded to Account for Engine Age & Operating Environment.

		1.0	1.5	2.0	2.5	3.0
First-Run	5% / Temperate	$195	$150	$88	$86	$84
First-Run	10% / Temperate	$175	$135	**$80**	$78	$76
First-Run	5% / Hot - Harsh	$215	$170	$100	$98	$96
First-Run	10% / Hot - Harsh	$225	$180	$110	$108	$106
Mature-Run	5% / Temperate	$235	$200	$135	$110	$100
Mature-Run	10% / Temperate	$225	$175	**$125**	$105	$95
Mature-Run	5% / Hot - Harsh	$275	$235	$200	$190	$180
Mature-Run	10% / Hot - Harsh	$250	$210	$180	$170	$160

5 - Factors Influencing Engine DMCs

Life-Limited Parts (LLPs)

- Engine LLP DMCs are computed from the engine manufacturer's published life limits and piece part costs.
- The term **stub-life** is used to represent the engines shortest life remaining of all LLPs installed in a specific engine.
- 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.

Item	Cost $	Life Limit FC	LLP $/FC	10% Stub
FAN				
DISK	$ 168,100	30,000	$ 5.60	$ 6.23
BOOSTER SPOOL	$ 248,300	30,000	$ 8.28	$ 9.20
SHAFT ASSY	$ 132,800	30,000	$ 4.43	$ 4.92

5 - Factors Influencing Engine DMCs

Life-Limited Parts (LLPs)

- LLPs accounts for a **high proportion** of maintenance costs for engines operating on short-haul missions because of shorter average flight legs and higher rate of cycle accumulation.

- LLPs accounts for a **low proportion** of maintenance costs for engines operating on long-haul missions because of higher average flight legs and lower rate of cycle accumulation.

6 – Flight Hour Agreements

Engine Flight Hour Agreement (FHA) Program

– Under a typical FHA program the engine manufacturer covers all product and quality causes of shop visits. In addition to coverage of performance restorations, it generally includes:

  ✓ Incorporation of all Airworthiness Directives (ADs) and target Service Bulletins (SBs) issued for the life of the program.

– 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 engine flying hours, or

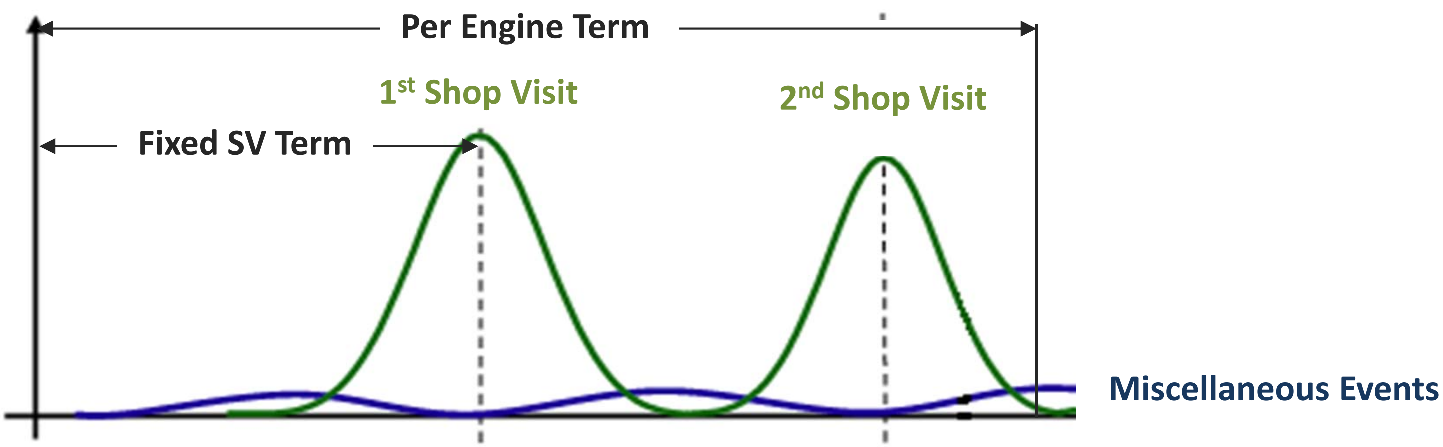
– **Pay-at-Shop-Visit (PASV)**, whereby a rate is normally only applicable to the restoration shop visits.

6 – Flight Hour Agreements

Engine Flight Hour Agreement (FHA) Program

– Terms of an FHA will generally consist of one of the following:

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



Appendix A - Maintenance Costs & Reserve Rates

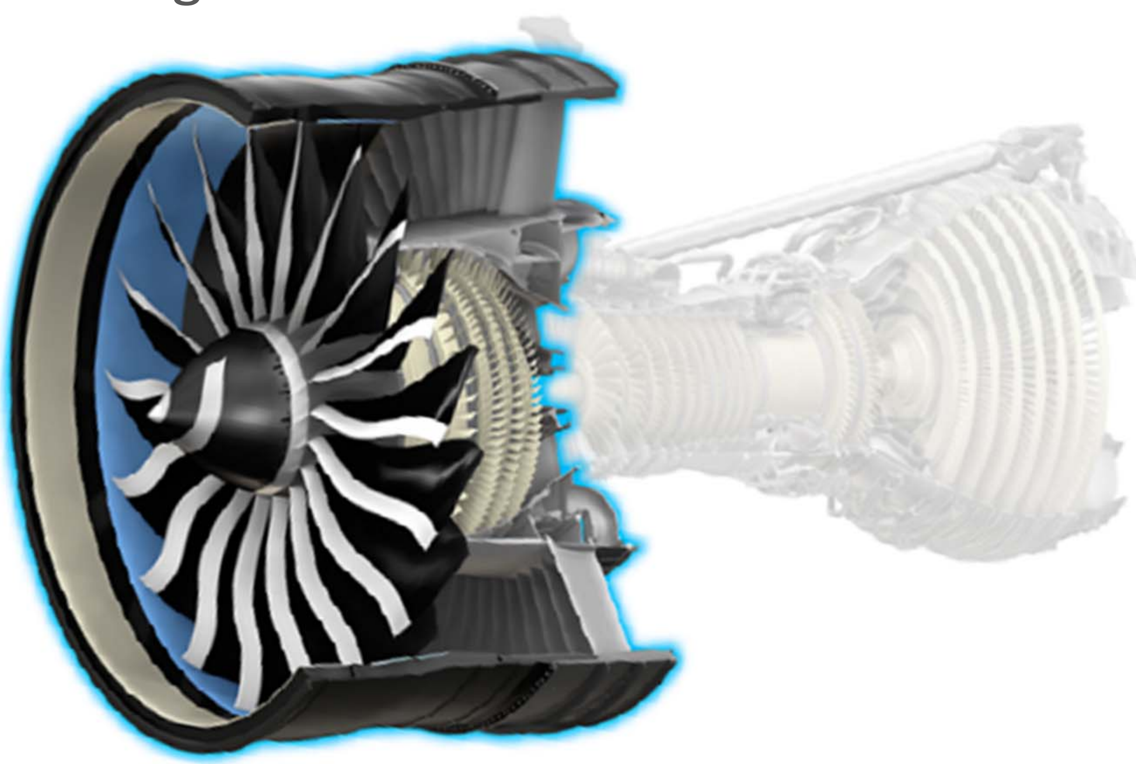
Engine	Thrust	Phase	Fl Leg	Time On-Wing (FC)	Costs 2014 $	Rate ($ / FH)
CFM56-5B6/3	23,500	First-Run	1.7	16,000 - 17,000	$2.2M - $2.4M	$78- $88
CFM56-5B4/3	27,000	First-Run	2.0	11,500 - 12,500	$2.2M - $2.4M	$95 - $105
CFM56-5B3/3	33,000	First-Run	2.0	8,000 - 9,000	$2.2M - $2.4M	$140 - $150
CFM56-7B24E	24,000	First-Run	1.7	16,000 - 17,000	$2.2M - $2.4M	$78- $88
CFM56-7B26E	26,300	First-Run	2.0	12,500 - 13,500	$2.2M - $2.4M	$88- $98
CFM56-7B27E	27,300	First-Run	2.0	11,000 - 12,000	$2.2M - $2.4M	$100 - $110
V2524-A5 S1	24,000	First-Run	1.7	15,500 - 16,500	$2.1M - $2.3M	$78 - $88
V2527-A5 S1	27,000	First-Run	2.0	11,000 - 12,000	$2.2M - $2.4M	$100 - $110
V2533-A5 S1	33,000	First-Run	2.0	8,500 - 9,500	$2.2M - $2.4M	$135 - $145
Trent 772	71,200	First-Run	6.0	3,500 - 4,000	$3.8M - $4.2M	$180 - $200
PW4068	68,000	First-Run	6.0	3,250 - 3,750	$3.4M - $3.8M	$185 - $205
CF6-80E1A4	70,000	First-Run	6.0	3,250 - 3,750	$3.4M - $3.8M	$185 - $205
GE90-115B	115,000	First-Run	8.0	2,250 - 2,750	$4.6 - $5.0M	$275 - $295

Appendix A - Maintenance Costs & Reserve Rates

Engine	Thrust	Phase	Fl Leg	Time On-Wing (FC)	Costs 2014 $	Rate ($ / FH)
CFM56-5B6/3	23,500	Mature-Run	1.7	12,800 - 13,800	$2.3M - $2.7M	$125- $145
CFM56-5B4/3	27,000	Mature-Run	2.0	9,500 - 10,500	$2.4M - $2.8M	$135 - $155
CFM56-5B3/3	33,000	Mature-Run	2.0	6,500 - 7,500	$2.4M - $2.8M	$190 - $210
CFM56-7B24E	24,000	Mature-Run	1.7	12,800 - 13,800	$2.3M - $2.7M	$125 - $145
CFM56-7B26E	26,300	Mature-Run	2.0	10,000 - 11,000	$2.4M - $2.8M	$130 - $150
CFM56-7B27E	27,300	Mature-Run	2.0	8,800 - 9,800	$2.4M - $2.8M	$135 - $155
V2524-A5 S1	24,000	Mature-Run	1.7	12,500 - 13,500	$2.3M - $2.7M	$125 - $145
V2527-A5 S1	27,000	Mature-Run	2.0	8,800 - 9,800	$2.4M - $2.8M	$135 - $155
V2533-A5 S1	33,000	Mature-Run	2.0	7,000 - 8,000	$2.4M - $2.8M	$190 - $210
Trent 772	71,200	Mature-Run	6.0	2,500 - 3,000	$4.6M - $5.2M	$340 - $390
PW4068	68,000	Mature-Run	6.0	2,500 - 3,000	$4.2M - $4.8M	$320 - $360
CF6-80E1A4	70,000	Mature-Run	6.0	2,500 – 3,000	$4.2M - $4.8M	$320 - $360
GE90-115B	115,000	Mature-Run	8.0	1,800 - 2,000	$5.4 - $6.0M	$420 - $460

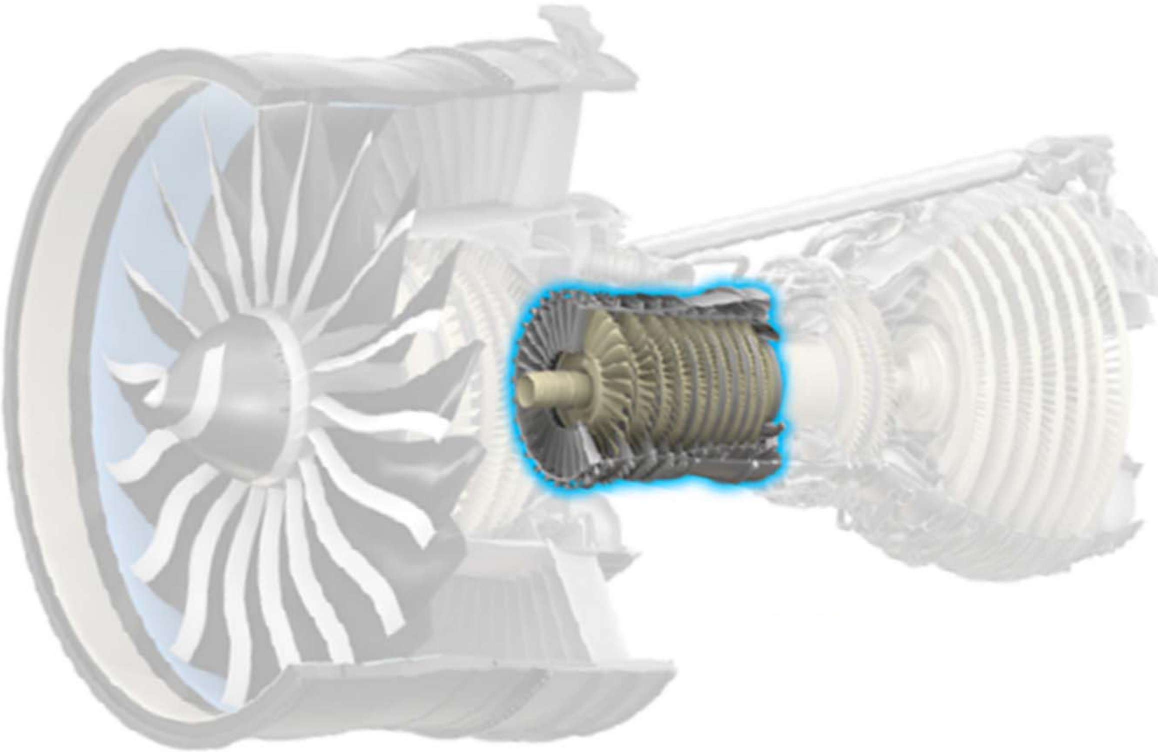
Appendix B – Engine Major Module Description

Fan/Low Pressure Compressor (LPC) – The Fan is responsible for producing majority of a typical turbofan's thrust. The LPC receives a burst of air from the Fan and begins to compress it to accelerate it through the engine.



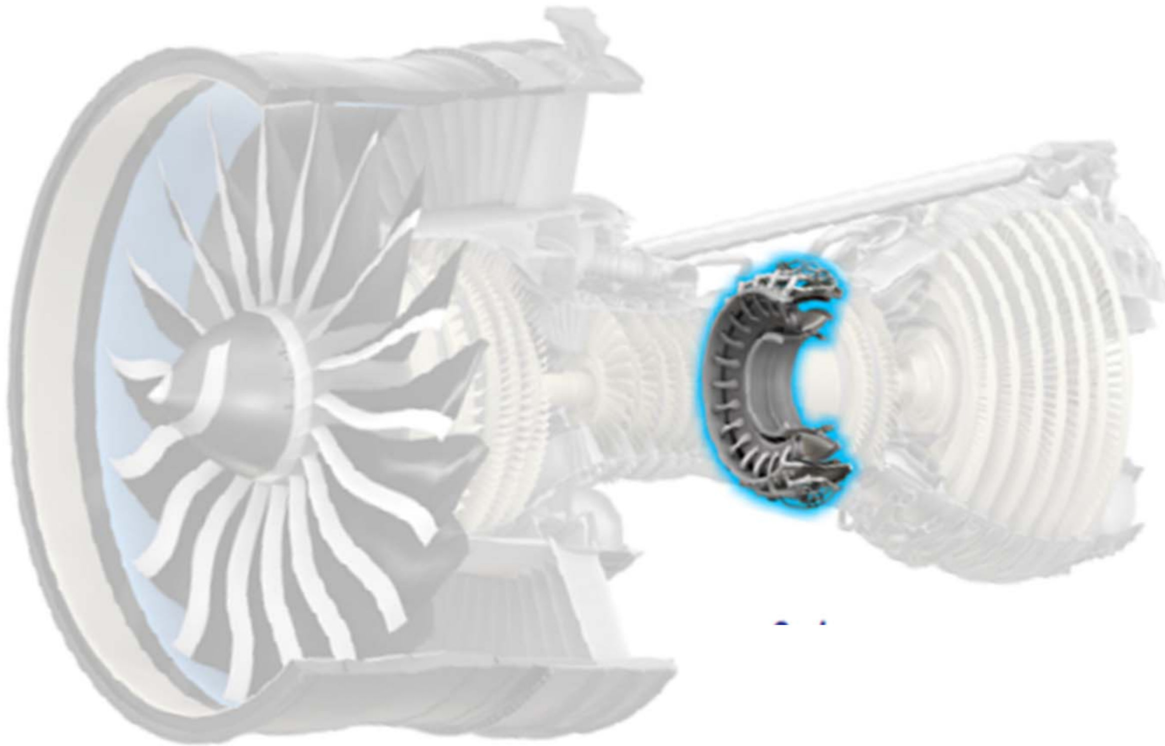
Appendix B – Engine Major Module Description

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.



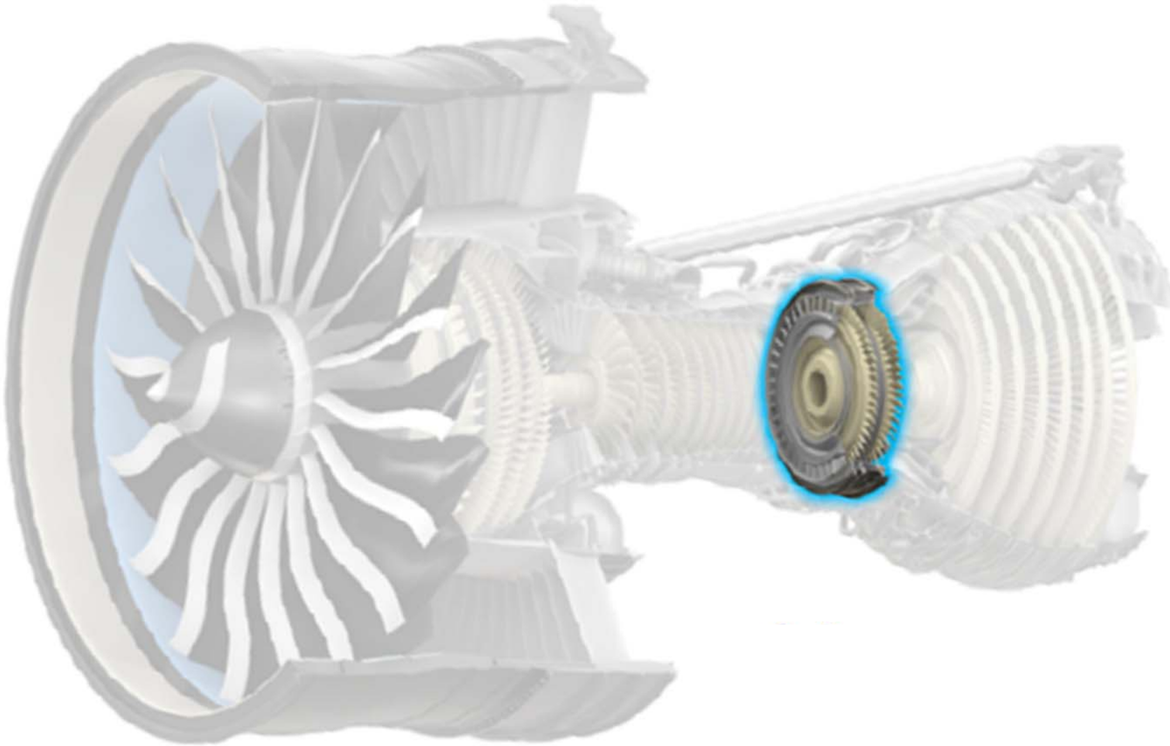
Appendix B – Engine Major Module Description

Combustor - The combustor is where fuel is added to the cycle to create thermal energy. Most of today's modern turbofan engines employ an annular combustion system.



Appendix B – Engine Major Module Description

High Pressure Turbine (HPT) - 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 HPC.



Appendix B – Engine Major Module Description

Low Pressure Turbine (LPT) - The LPT extracts the remaining combustion thermal energy to drive the Fan and Low-Pressure Compressor rotor assembly.