Engine Maintenance Management

Managing Technical Aspects of Leased Assets
Madrid, Spain / May 12th, 2015

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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.
Technical Drivers of Off-Wing Maintenance
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Technical drivers of off-wing engine maintenance can be broadly categorized into four areas:

1. EGT Margin Deterioration
2. Expiry of Life-Limited Parts (LLPs)
3. Hardware Deterioration
4. Other Removal Causes
Technical Drivers of Off-Wing Maintenance

1. **EGT Margin Deterioration**

**Exhaust Gas Temperature** - EGT is a measure of the **temperature** of the gas as it leaves the turbine unit.

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

![Diagram showing EGT and redline](image)
1. EGT Margin Deterioration

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.

\[
\text{EGT Margin} \degree \text{C} = \text{EGT Redline} - \text{EGT Take-off}
\]

\[
\text{EGT Margin} = 950 \degree \text{C} - 850 \degree \text{C} = 100 \degree \text{C}
\]
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

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

Example - EGT Margins for new CFM56-7B Engines

<table>
<thead>
<tr>
<th>Engine Model</th>
<th>7B20</th>
<th>7B22</th>
<th>7B24</th>
<th>7B26</th>
<th>7B27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff Thrust</td>
<td>20,600</td>
<td>22,700</td>
<td>24,200</td>
<td>26,300</td>
<td>27,300</td>
</tr>
</tbody>
</table>

Red Line = 950 °C
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

As the engine deteriorates, the EGT margin will rise until it reaches Redline EGT, or the absolute temperature limit which cannot be exceeded without damaging the engine.

EGT Margin Deterioration

![Diagram showing EGT Margin Deterioration]

- EGT Redline
- EGT Margin
- Deteriorated Engine
- New Engine

Time Since Initiation of Take-off

EGT °C
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

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

EGT Margin Deterioration Cycle

- Compressor Fouling
- Increased Tip Clearances
- Airfoil Erosion
- Seal Leakage
- Increasing Gas Path Flow Losses
- Increases EGT Deterioration
- Increasing Fuel Burn
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

Rates of EGTM deterioration are highest during initial operation & subsequently stabilize to reach a steady state level.

Relationship Between EGTM Deterioration & Engine FC

![Graph showing relationship between EGT deterioration and Engine Flight Cycles]

- **Steady State Loss**: Per 1,000 FC (e.g. 5 °C / 1,000 FC)
- **Installation Loss**: (e.g. 25 °C first 2,000 FC)
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

Rate of EGTM deterioration is influenced by:

**Flight Operations** - rate of EGTM deterioration increases as:

- Engine thrust rating increases
- Engine derate decreases
- Average flight leg decreases
- Operating environment becomes more severe

**Engine Age (Maturity)**

- **First-run** engines traditionally have higher EGTM and lower EGTM deterioration rates relative to mature engines
Technical Drivers of Off-Wing Maintenance

1. EGT Margin Deterioration

**EGTM trend monitoring** - trend monitoring of EGTM looks at successive snapshots to help analyze the wear trend of engines.
Technical Drivers of Off-Wing Maintenance

2. Expiry of 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 **Life-Limited Parts (LLP)** and generally consist of disks, seals, spools, and shafts. **LLPs are discarded** once their useful lives are reached.
Technical Drivers of Off-Wing Maintenance

2. Expiry of Life-Limited Parts (LLPs)

LLPs account for a high proportion of mx costs on short-haul missions due to lower avg. flight legs & higher cycle accumulation.

LLPs account for a low proportion of mx costs on long-haul missions due to higher avg. flight legs & lower cycle accumulation.
3. **Hardware Deterioration**

All engine components are exposed to different kinds of deterioration mechanisms. These include amongst others:

- Low and high cycle fatigue,
- Thermo-mechanical fatigue,
- Erosion / Corrosion / Oxidation

4. **Other Removal Causes**

Other removal causes include amongst others:

- Foreign Object Damage (FOD),
- Oil Leak / High Oil Consumption,
- Vibration,
- Airworthiness Directives
Technical Drivers of Off-Wing Maintenance

- 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.

Technical Drivers of Engine Removals by Operation

<table>
<thead>
<tr>
<th></th>
<th>Short-haul Operation</th>
<th>Medium/Long-haul Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGTM</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>LLP</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>Hardware</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>Other</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>
Commercial Considerations of Off-Wing Maintenance
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Commercial considerations are often influenced based on where an engine is in its economic lifecycle.

- **Entry Into Service (EIS)** - engine first enters into service.
- **Growth** – engine gaining acceptance & orders are increasing,
- **Stabilization** – engine sales are at a consistent, steady level.
- **Dispersion** - engine sales drop to a low level & are being sold for spare parts or scrap.
Commercial Considerations of Off-Wing Maintenance

Workscope Considerations: Phase 1–2 (Growth + Stabilization)

- Build for minimum number of SVs, which allows one to achieve lower shop DMC ($ / FH) but higher SV costs.
- Use OEM parts & repairs,
- Invest / Benefit from latest SB modifications & technology
- Build to maximize EGTM recovery and time on-wing
Commercial Considerations of Off-Wing Maintenance

Workscope Considerations :  Phase 3 (Dispersion)

- Maximizing usage of LLPs, which often leads to lower SV costs but higher DMC ($ / FH)
- Weigh benefits of purchasing replacement engine in lieu of performing a shop visit
- Weigh benefits of PMA parts and DER repairs
# Commercial Considerations of Off-Wing Maintenance

## Example Workscope Consideration:

**Engine Enters Shop**

<table>
<thead>
<tr>
<th>Workscope</th>
<th>Growth &amp; Stabilization</th>
<th>Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLP Replacement</td>
<td>Fan + Core + LPT</td>
<td>Core Modules</td>
</tr>
<tr>
<td>Build-Goal</td>
<td>20,000 FC</td>
<td>8,000 FC</td>
</tr>
<tr>
<td>Restoration Cost $</td>
<td>$2.50M</td>
<td>$2.0M</td>
</tr>
<tr>
<td>LLP Cost $</td>
<td>$2.50M</td>
<td>$1.5M</td>
</tr>
<tr>
<td>Total Shop Visit Cost $</td>
<td>$5.0M</td>
<td>$3.5M</td>
</tr>
<tr>
<td>Restoration $ / FH @ 1.5 FL</td>
<td>$83.33 / FH</td>
<td>$102.50 / FH</td>
</tr>
</tbody>
</table>

**Engine Exits Shop**

<table>
<thead>
<tr>
<th>LLP Stub-lives remaining</th>
<th>13 3 3 8</th>
</tr>
</thead>
</table>

Managing Technical Aspects of Leased Assets - May 12th, 2015
Lessor & Lessee Considerations of Off-Wing Maintenance
Engines installed on leased aircraft often times **have more constraints** and will depend on the:

- Delivery conditions
- Term of the lease
- Redelivery conditions

Commercial considerations within a lease **factor the mirror-in-mirror-out philosophy** whereby the status of engine redelivery conditions are used to establish delivery conditions.
Lessor & Lessee Considerations of Off-Wing Maintenance

Mirror-in-Mirror-out Philosophy:

Lessee 1 Returns & Lessor Accepts & Delivers Lessee 2 Accepts

Lessee 1 returns & lessor accepts engines meeting defined minimums per the lease (e.g. 6,000 FH / 4,000 FC)

Lessor delivers & lessee 2 accepts engines meeting defined minimums per the lease (e.g. 6,000 FH / 4,000 FC)
Lessor & Lessee Considerations of Off-Wing Maintenance

Lessors depend on **transferability & liquidity**, and **residual value protection** of their engines.

So parts and repairs installed during maintenance events have to be acceptable to all operators and regulatory jurisdictions.

That is why most lessors do not allow for:

- PMA parts to be installed, &
- DER repairs
Flight Hour Agreement (FHA) Programs
Flight Hour Agreement (FHA) Programs

Under an FHA an operator pays a service provider an hourly rate based on the number of engine hours flown & the engine OEM covers all product upgrades & shop visits during the FHA term.

**Advantages**

- **Cost Visibility** - Smoothing of expenditure designed principally to address the cost and timing uncertainties inherent in traditional time and material contracts

- **Greater Value** - Overhauled to the latest standards; all ADs and target Service Bulletins (SBs) issued for the life of the program are incorporated at shop visit at OEM’s expense

- **Reduced Infrastructure** - Relieves the operator of the need to purchase stocks of engines and accessories
Flight Hour Agreement (FHA) Programs

## Disadvantages

- **Access to Cash** – some packages don’t allow for any cash to be refunded at any point, only credits for future maintenance work will be provided.

- **Reduces Aftermarket Competition** – creating a situation where there is no aftermarket competition on any level; where the OEM controls all commercial aspects – spares, materials, repairs, etc.
Flight Hour Agreement (FHA) Programs

Payment Options

1. **Pay-as-you-go** – Payments are made to the service provider as the engines accrue time .......... most FHA contracts are PAYG
2. **Pay-at-shop visit** – Payments are made at shop visit based on a hourly rate provided by the service provider.

Term Options

1. **Per Fleet Cumulative Term** - Fixed period of time for the fleet: e.g. 12 years from 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. **Per Shop Visit Term** - Fixed number of Restoration Shop Visits per engine, e.g. term finishes for each engine after 1st SV.
## Appendix A - Maintenance Costs & Reserve Rates

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust</th>
<th>Phase</th>
<th>FL Leg</th>
<th>Time On-Wing (FC)</th>
<th>Costs 2015 $</th>
<th>Rate ($ / FH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5B6/3</td>
<td>23,500</td>
<td>First-Run</td>
<td>1.7</td>
<td>16,000 - 17,000</td>
<td>$2.25M - $2.5M</td>
<td>$80 - $88</td>
</tr>
<tr>
<td>CFM56-5B4/3</td>
<td>27,000</td>
<td>First-Run</td>
<td>2.0</td>
<td>11,500 - 12,500</td>
<td>$2.25M - $2.5M</td>
<td>$95 - $105</td>
</tr>
<tr>
<td>CFM56-5B3/3</td>
<td>33,000</td>
<td>First-Run</td>
<td>2.0</td>
<td>8,000 - 9,000</td>
<td>$2.25M - $2.5M</td>
<td>$140 - $155</td>
</tr>
<tr>
<td>CFM56-7B24E</td>
<td>24,000</td>
<td>First-Run</td>
<td>1.7</td>
<td>16,000 - 17,000</td>
<td>$2.25M - $2.5M</td>
<td>$80 - $88</td>
</tr>
<tr>
<td>CFM56-7B26E</td>
<td>26,300</td>
<td>First-Run</td>
<td>2.0</td>
<td>12,500 - 13,500</td>
<td>$2.25M - $2.5M</td>
<td>$90 - $100</td>
</tr>
<tr>
<td>CFM56-7B27E</td>
<td>27,300</td>
<td>First-Run</td>
<td>2.0</td>
<td>11,000 - 12,000</td>
<td>$2.25M - $2.5M</td>
<td>$105 - $115</td>
</tr>
<tr>
<td>V2524-A5 S1</td>
<td>24,000</td>
<td>First-Run</td>
<td>1.7</td>
<td>15,500 - 16,500</td>
<td>$2.25M - $2.5M</td>
<td>$80 - $88</td>
</tr>
<tr>
<td>V2527-A5 S1</td>
<td>27,000</td>
<td>First-Run</td>
<td>2.0</td>
<td>11,000 - 12,000</td>
<td>$2.25M - $2.5M</td>
<td>$105 - $115</td>
</tr>
<tr>
<td>V2533-A5 S1</td>
<td>33,000</td>
<td>First-Run</td>
<td>2.0</td>
<td>8,500 - 9,500</td>
<td>$2.25M - $2.5M</td>
<td>$140 - $155</td>
</tr>
<tr>
<td>Trent 772</td>
<td>71,200</td>
<td>First-Run</td>
<td>6.0</td>
<td>3,500 - 4,000</td>
<td>$5.5M - $6.0M</td>
<td>$230 - $250</td>
</tr>
<tr>
<td>PW4068</td>
<td>68,000</td>
<td>First-Run</td>
<td>6.0</td>
<td>3,250 - 3,750</td>
<td>$5.0M - $5.5M</td>
<td>$230 - $250</td>
</tr>
<tr>
<td>CF6-80E1A4</td>
<td>70,000</td>
<td>First-Run</td>
<td>6.0</td>
<td>3,250 - 3,750</td>
<td>$4.5M - $5.5M</td>
<td>$230 - $250</td>
</tr>
<tr>
<td>GE90-115B</td>
<td>115,000</td>
<td>First-Run</td>
<td>8.0</td>
<td>2,500 - 3,000</td>
<td>$6.5 - $7.5M</td>
<td>$280 - $300</td>
</tr>
</tbody>
</table>
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<table>
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<tr>
<th>Engine</th>
<th>Thrust</th>
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<th>Time On-Wing (FC)</th>
<th>Costs 2015 $</th>
<th>Rate ($ / FH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5B6/3</td>
<td>23,500</td>
<td>Mature-Run</td>
<td>1.7</td>
<td>12,800 - 13,800</td>
<td>$2.5M - $3.0M</td>
<td>$125 - $145</td>
</tr>
<tr>
<td>CFM56-5B4/3</td>
<td>27,000</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>9,500 - 10,500</td>
<td>$2.5M - $3.0M</td>
<td>$135 - $155</td>
</tr>
<tr>
<td>CFM56-5B3/3</td>
<td>33,000</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>6,500 - 7,500</td>
<td>$2.5M - $3.0M</td>
<td>$190 - $210</td>
</tr>
<tr>
<td>CFM56-7B24E</td>
<td>24,000</td>
<td>Mature-Run</td>
<td>1.7</td>
<td>12,800 - 13,800</td>
<td>$2.5M - $3.0M</td>
<td>$125 - $145</td>
</tr>
<tr>
<td>CFM56-7B26E</td>
<td>26,300</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>10,000 - 11,000</td>
<td>$2.5M - $3.0M</td>
<td>$130 - $150</td>
</tr>
<tr>
<td>CFM56-7B27E</td>
<td>27,300</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>8,800 - 9,800</td>
<td>$2.5M - $3.0M</td>
<td>$135 - $155</td>
</tr>
<tr>
<td>V2524-A5 S1</td>
<td>24,000</td>
<td>Mature-Run</td>
<td>1.7</td>
<td>12,500 - 13,500</td>
<td>$2.5M - $3.0M</td>
<td>$125 - $145</td>
</tr>
<tr>
<td>V2527-A5 S1</td>
<td>27,000</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>8,800 - 9,800</td>
<td>$2.5M - $3.0M</td>
<td>$135 - $155</td>
</tr>
<tr>
<td>V2533-A5 S1</td>
<td>33,000</td>
<td>Mature-Run</td>
<td>2.0</td>
<td>7,000 - 8,000</td>
<td>$2.5M - $3.0M</td>
<td>$190 - $210</td>
</tr>
<tr>
<td>Trent 772</td>
<td>71,200</td>
<td>Mature-Run</td>
<td>6.0</td>
<td>2,500 - 3,000</td>
<td>$7.0M - $8.0M</td>
<td>$380 - $440</td>
</tr>
<tr>
<td>PW4068</td>
<td>68,000</td>
<td>Mature-Run</td>
<td>6.0</td>
<td>2,500 - 3,000</td>
<td>$6.5M - $7.5M</td>
<td>$360 - $420</td>
</tr>
<tr>
<td>CF6-80E1A4</td>
<td>70,000</td>
<td>Mature-Run</td>
<td>6.0</td>
<td>2,500 – 3,000</td>
<td>$7.0M - $8.0M</td>
<td>$380 - $440</td>
</tr>
<tr>
<td>GE90-115B</td>
<td>115,000</td>
<td>Mature-Run</td>
<td>8.0</td>
<td>1,800 - 2,200</td>
<td>$10.5 - $11.5M</td>
<td>$480 - $560</td>
</tr>
</tbody>
</table>