There are more than 4,200 737NGs in operation, all powered by the CFM56-7B. The engine's high EGT margin means shop visit workscope and removal patterns are mainly based around LLP lives. Maintenance reserves for the optimal shop visit pattern for each variant are analysed.

Long-term CFM56-7B maintenance costs

There are now almost 4,200 737NGs in commercial airline and corporate jet operation. The CFM56-7B has therefore become one of the most numerous engine types in service. There are five main variants and 17 sub-variants in operation, with the number of installed and spare engines exceeding 8,500. The CFM56-7B's operation and maintenance costs have been studied and analysed *(see CFM56-7B maintenance analysis & budget, Aircraft Commerce, June/July 2008, page 18)*. After being in service for 16 years, it has now reached maturity. The engine's operation and maintenance requirements are re-assessed.

Fleet & operation

The five main variants of the -7B series have a nomenclature system that indicates each variant's thrust rating, with a two-digit suffix indicating the number of thousands of lbs of installed thrust, rounded up or down. The -7B20 is rated at 20,600lbs, the -7B22 at 22,700lbs, the -7B24 at 24,200lbs, the -7B26 at 26,300lbs, and the -7B27 at 27,300lbs.

There are also sub-variants within each variant. The base variant has no additional suffix in its name. There are three other sub-variants for each variant, indicated by a /3, an E and a /B1.

The /3 indicates an engine that has undergone CFMI's 'Tech Insertion' modification. "This was a package of upgrades that included the installation of 3-D aerodynamic blades and vanes in the high pressure compressor (HPC) and high pressure turbine (HPT)," explains Claus Bullenkamp, senior manager customer support at MTU Maintenance. "The Tech Insertion modification also included an enhanced singular annular combustor, and other improvements to airfoils. One major change was that CFMI wanted to have uniform lives for life-limited parts (LLPs) in all five main variants. This included having all core engine LLPs at a standard life of 20,000 engine flight cycles (EFC). Non-tech insertion engines had shorter and varied lives in the high pressure turbine (HPT) in the -7B26 and -7B27 engines. These varied lives compromised removal intervals and engine management."

The Tech Insertion modification has been standard in all new-built engines delivered since January 2008. It can also be installed in base engines when they go through a shop visit.

The /E is a production standard introduced in 2011 that has improved turbine hardware. Production of these have overlapped with the /3 engines.

A /B1 sub-variant is an engine powering a business or corporate jet 737NG model. Of the active 737NG fleet, only 14 aircraft have /B1 sub-variant engines.

Although there are four main 737NG variants, the fleet is dominated by the 737-800. This model has 2,838 active aircraft, 68% of airline 737NGs. There

The majority of CFM56-7Bs are operated on 737-800s. The largest number of engines powering the 737-800 are the -7B26, -7B26/3, -7B26/E, and -7B27.

CFM56-7B FLEET SUMMARY

737 Variant	-600	-700	-800	-900	TOTAL
CFM56-7B20	28	79			107
CFM56-7B20/3	1	8			9
CFM56-7B20E		1	5		6
TOTAL -7B20	**29**	**88**	**5**		**122**
CFM56-7B22	25	675			700
CFM56-7B22/3		58			58
CFM56-7B22E		16	3		19
TOTAL -7B22	**25**	**749**	**3**		**777**
CFM56-7B24		170	139	16	325
CFM56-7B24/3		18	230		248
CFM56-7B24E		8	60		68
TOTAL -7B24		**196**	**429**	**16**	**641**
CFM56-7B26		18	848	36	902
CFM56-7B26/3		10	777	107	894
CFM56-7B26E			263	44	307
CFM56-7B26/B1		2			2
TOTAL -7B26		**30**	**1,888**	**187**	**2,105**
CFM56-7B27		1	290		291
CFM56-7B27/3		1	171	7	179
CFM56-7B27E			18	6	24
CFM56-7B27/B1		1	9		10
TOTAL -7B27		**3**	**488**	**13**	**504**
UNKNOWN		1	25		26
TOTAL	**54**	**1,067**	**2,838**	**216**	**4,175**

are also 1,067 active 737-700s, 25% of the active 737NG fleet. The -600 and -900/-900ER account for just 54 and 216 aircraft respectively.

On the 737-700 fleet, the two main engine variants are the -7B22 (675 aircraft), and -7B24 (170) which power between them 79% of all 737-700s. The largest -7B22-powered fleets are operated by Southwest (416) and WestJet (48). Southwest operates its fleet with an average EFC time of 1.76 engine flight hours (EFH) from a range of 1.58-2.32EFH across its fleet and network.

Canadian low-cost carrier (LCC) WestJet operates its -7B22 fleet at an average of 2.14EFH per EFC.

There is also a relatively small number of high-rated -7B26 and -7B27, and /3 Tech Insertion engines, powering the 737-700 fleet.

There are seven main CFM56-7B variants powering the -800 fleet: the -7B24 (139), -7B26 (848), -7B27 (290), -7B24/3 (230), -7B26/3 (777), -7B26E (263), and -7B27/3 (171). These total 2,718 aircraft, 96% of all -800s in operation. Most of these, 2,349 aircraft, are powered by the high-rated -7B26 and -7B27 variants.

American Airlines has the largest -7B24/3 and -7B24E fleet with 101 aircraft, operated at an average EFC of 2.4-2.6EFH.

There are several large -7B26-powered fleets operated by American Airlines (49), Delta Air Lines (71), Qantas (33), Ryanair (97), Turkish Airlines (33) and United Airlines (108).

There are also some larger -7B26/3 and -7B26E fleets, operated by Ryanair (187), Norwegian (48) and Southwest (42).

Average EFC times for these biggest fleets are 2.44EFH for American, 1.80EFH for Delta, 1.90EFH for Qantas, 1.65EFH for Ryanair, 1.60EFH for Southwest, 2.1EFH for Turkish, and 2.9EFH for United.

There are also 107 737-900ERs powered by the -7B26/3 engine.

Another analysis reveals that the most popular main engine variant is the -7B26, which powers 2,105 aircraft, 51% of the fleet. This is followed by the -7B22 (777 aircraft) and the -7B24 (641).

Moreover, there are 2,609 aircraft with the highest rated -7B26 and -7B27 engines, and 1,540 aircraft powered by the medium and lower rated -7B20, -7B22 and -7B24 engines.

The 737NG is operated by more than 160 different airlines, and most EFC times range from 1.7EFH to 2.2EFH. The global average for the fleet is 1.9EFH.

Optimised maintenance

A large number of engines are now managed under power-by-the-hour (PBH) integrated services maintenance programmes. Nevertheless, airlines still manage the maintenance of a significant number of engines, maintained either in their own shops, or sent to third-party shops. Payment is made by a variety of methods, including time and material.

It is estimated that with the correct software systems in place, airlines can achieve lower overall maintenance costs per EFH for engines if they manage the removals and determine the shop-visit workscopes themselves. This involves optimising an engine's maintenance management, by matching the removal intervals as closely as possible to the engine's LLP lives. Maintenance costs are optimised if the workscopes requiring heavier and deeper work on a large number or all of the engine's modules coincide with the expiry of LLPs.

The main issues to consider in optimising maintenance cost per EFH will be: EFH:EFC ratio; exhaust gas temperature (EGT) margin and its erosion rate for each thrust rating; and rate of deterioration of engine hardware. These all affect probable or planned removal intervals, and ideally these should match the life of LLPs in each engine module.

The CFM56-7B generally has high EGT margins. EGT margin has been a main driver of engine removals for engines operated on short-haul operations. The relatively low EGT margins of earlier generation engines resulted in relatively short planned on-wing intervals. EGT margin loss and erosion generally relate to accumulated EFC on-wing. EGT margin is therefore a prime consideration for engines operated on short EFC times, and in turn accumulated EFC time is the main removal driver.

The high EGT margin of most CFM56-7B variants means that their removal intervals are less driven by EGT margin loss. Relatively long intervals are possible, and longer accumulated time on-wing, permitted by high EGT margins, reveals other issues with the engine that are related to deterioration of hardware. Moreover, the -7B is operated on longer

The CFM56-7B has high EGT margins, and only the -7B26 and -7B27 have loss of EGT margin and performance as prime removal causes. Most -7B20, -7B22 and -7B24 engines can usually remain on-wing until they reach the life limits of core engine LLPs at 20,000EFC.

average EFC times than earlier generation engines such as the CFM56-3 and JT8D. Longer EFC times mean that EGT margin loss is less of an issue than hardware deterioration, which is proportionate to accumulated EFH. EFH times tend to be more of a removal driver for engines operated at longer average EFC times.

LLP lives

The -7B has four main modules and a total of 18 LLPs. LLPs can be considered for the original, non-Tech Insertion and for the Tech Insertion engines. CFMI's target life limits were 30,000EFC for LLPs in the fan/booster module, 20,000EFC for LLPs in the HPC and HPT modules, and 25,000EFC for LLPS in the LPT.

Some of the parts in all four modules of higher-rated variants had lives shorter than the target lives. The list price for a full set of LLPs for non-Tech Insertion engines was $1.5 million in 2005. This had risen to $1.8 million by 2008, accounted for by $356,000 for the parts in the fan/booster, $921,000 for parts in the HPC and HPT, and $500,000 for parts in the LPT.

The current list prices for LLPs of Tech Insertion engines are a total of $2.52 million for a complete shipset, a 40% increase on the 2008 list price. This is split between $511,000 for the three parts in the fan and booster, $1.304 million for the LLPs in the two HP modules, and $706,000 for LLPs in the LPT.

The fan/booster module has three parts. The original life limits for the fan disk and booster spool were 17,900EFC and 23,600EFC. Only the fan shaft had a full life limit of 30,000EFC. Limits for new part numbers for the fan disk and booster spool were increased to 30,000EFC.

Tech Insertion engines, built from 2008, have all fan/booster LLPs at the full limit of 30,000EFC.

The HPC module has five LLPs, and the HPT module has four. These were at the full target life of 20,000EFC in the case of the -7B20, -7B22 and -7B24 variants in the original non-Tech Insertion engines. The exceptions were a part number for the HPC stage 1-2 spool, which had a life of 13,000EFC, the HPT rear shaft which had two part numbers with lives of 11,500EFC and 17,300EFC, and two other parts with lives of 17,300EFC and 18,600EFC.

The higher-rated -7B26 and -7B27 variants, however, had two to four LLPs limited to lives of 17,600-18,600EFC.

All variants of Tech Insertion engines have HPC and HPT LLPs at the full target life of 20,000EFC.

The LPT has six LLPs. As with fan/booster and HPC/HPT parts, some LLPs in the LPT of higher-rated -7B26 and -7B27 variants had lives limited to less than the target of 25,000EFC in non-Tech Insertion engines. Some parts were limited to lives as short as 16,300EFC, and others to 23,900EFC. Part numbers used in later-build non-Tech Insertion engines had lives of 25,000EFC. All Tech Insertion engine variants have LLPs with lives at the full target limit of 25,000EFC.

EGT margin

EGT margin (EGTm) is generally high for the three lower-rated main -7B variants. It is only at medium levels for the -7B26 and -7B27, however.

"The -7B20 has a very high installed EGTm of 130 degrees centigrade when new, while the -7B22 has a lower margin of 103 degrees," says Bullenkamp.

These are similar to margins seen by other specialist maintenance providers. Lufthansa Technik provides engine maintenance through a variety of programmes, including PBH and integrated services. "We generally see installed margins of 135 degrees for the -7B20 and up to 110 degrees for the -7B22," says Markus Kleinhans, propulsion systems engineer CFM56-7B at Lufthansa Technik.

The -7B24 has a margin of 100-105 degrees, just a few degrees lower than the -7B22.

The -7B26 also has a relatively high margin, when new, of 80-85 degrees.

Only the -7B27 has a relatively low margin of 52-55 degrees when new. This margin is small when EGTm erosion rates are taken into account, so this makes the engine's performance sensitive to EGTm.

These new margins are available up to the engine's corner point. That is, the outside air temperature (OAT) up to which the thrust is kept constant, and over which the engine's thrust is automatically reduced with rises in OAT to keep EGT constant. The standard corner point is 30 degrees centigrade for all five main variants. This means that the engines are therefore able to operate at maximum thrust in most operating conditions.

EGTm erosion

EGTm erosion rates are high during the first 1,000-2,000EFC on-wing of operation. "These will be 11-12 degrees per 1,000EFC for the first 2,000EFC on-wing for the medium- and high-rated -7B variants, which means a loss of 24-25 degrees," says Kleinhans. An important factor in EGTm loss rate, however, is take-off thrust de-rate. This averages at 15-20% in many cases, although it will depend on OAT and actual take-off weight. The 737NG's long-range capability means that low take-off weights are generally experienced. The

EFH:EFC ratio of some operators, such as United, means that de-rates will be lower.

"The lower rated -7B variants have initial EGTm loss rates of eight degrees per 1,000EFC, so about 16 degrees in the first 2,000EFC on-wing," says Kleinhans. "The EGTm loss or erosion rate then slows to a more stable rate of 2.5-4.0 degrees per 1,000EFC".

The stable EGTm erosion rates are 3.0 degrees per 1,000EFC for the lowest-rated -7B20. "They are higher at 4 degrees per 1,000EFC for the -7B22, and increase to 5.5 degrees per 1,000EFC for the -7B27," says Bullenkamp.

The -7B27 can therefore remain on-wing, for its first removal interval, for up to a maximum of 12,000EFC, and more likely to be 10,000EFC before EGTm is fully eroded.

The -7B26 can remain on-wing for a maximum of 16,000EFC for the first removal interval, with the typical range being 14,000-16,000EFC, before EGTm is fully eroded.

The -7B24, by comparison, can theoretically remain on-wing for at least 18,000EFC, and for more than 20,000EFC. The 20,000EFC life limits of LLPs in the HPC and HPT modules are likely to be reached before EGTm has fully expired.

"The -7B22 and -7B20 variants can remain on-wing beyond a total of 30,000EFC before all LLP life limits are reached," says Kleinhans. "Removal intervals will, however, be limited to a maximum of 20,000EFC by the HP life limits.

"Another positive feature of the -7B is that its fuel consumption is also relatively low because of the high initial EGTm," continues Kleinhans. "It also has low spool speeds and is able to maintain tight clearances. This in turn means that the engine has relatively low rates of hardware degradation."

The expiry of LLP life limits and erosion of EGTm will lead to an engine shop visit. At a minimum this will result in an engine core or performance restoration.

Restored EGTm

Restored EGTm will always be lower after all shop-visit workscopes than for new engines. Potential removal interval due to EGTm will therefore be shorter for all subsequent removal intervals. These restored EGTms have to be considered when planning to optimise the engine's maintenance costs over the course of two or three shop visits.

"It is usually possible to regain 70-80% of the engine's original EGTm for the second and subsequent on-wing runs," says Kleinhans.

Bullenkamp generally agrees, stating that this is the case whether or not the engines are Tech Insertion standard. Moreover, the EGTm erosion rates are not too different to those experienced during the first on-wing run.

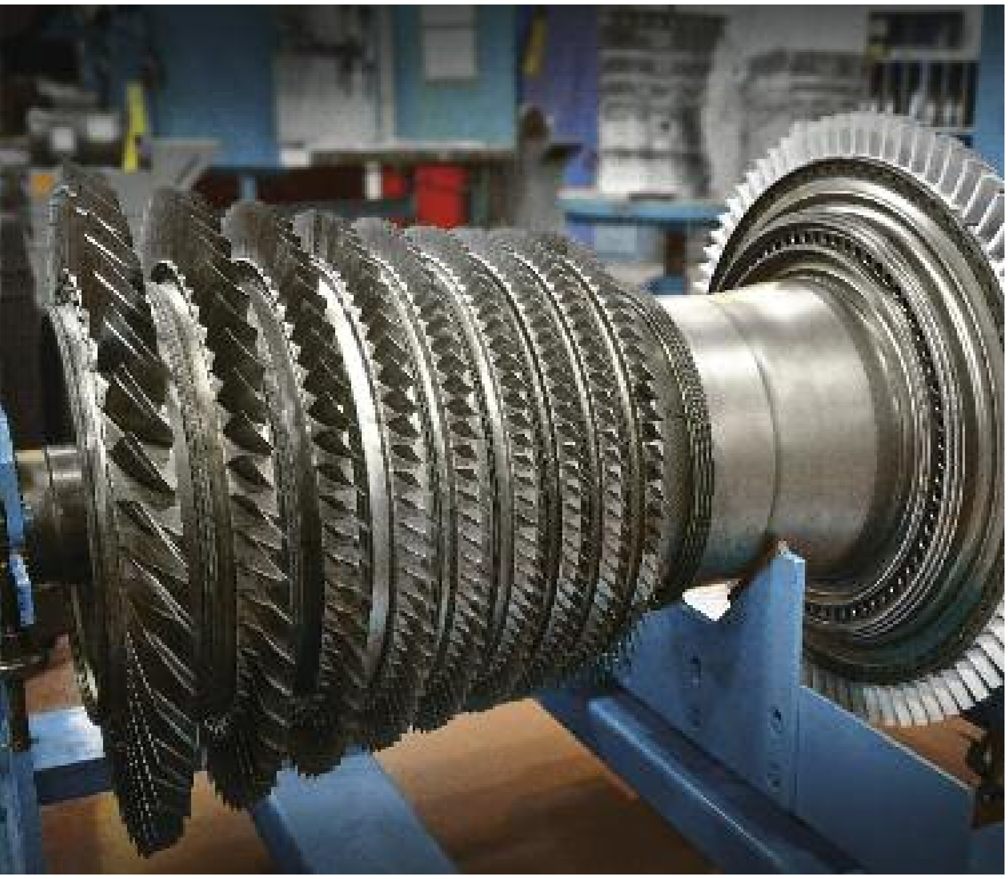
"This means that the -7B27 will have a starting EGTm of 40-45 degrees after the first shop visit, which is low," says Kleinhans.

The implications are that the -7B27 will be capable of second and subsequent removal intervals of just 5,000-7,000EFC.

The -7B26 would have a restored EGTm of 60-68 degrees. The second removal interval would therefore subsequently be limited to 11,000EFC by EGTm.

The -7B24 would have a restored margin of about 80 degrees, and so could remain on-wing for up to 16,000EFC.

The -7B22 would have a slightly higher restored margin of 85 degrees. With typical initial and stable EGTm



All shop visits will include a core workscope. Most engines regain 75-80% of their original EGT margins, although there are some shops that are capable of achieving 100% of original EGT margin at the first shop visits. Engines can remain on-wing for up to 20,000EFC, equal to about 10 years of operation.

erosion rates it would be capable of remaining on-wing for up to 20,000EFC. The -7B20 will be capable of a full removal interval of 20,000EFC.

Gareth Rudge, programme manager at Total Engine Support (TES), says that despite the general rule that restored margins are 70-80% of initial margins, some shops can achieve higher restored margins, even up to 100%. "There are even shops getting higher than the initial margins, because they are getting very good clearances and are accepting smaller tolerances. The implications of this are that operators are getting good second and subsequent removal intervals. The HPC is a big contributor to EGTm."

Removal causes

While loss of EGTm or performance and LLP expiry are the two major removal drivers, the CFM56-7B has had several problems with the deterioration of engine hardware. These issues can force removals prior to EGTm erosion and performance loss, or LLP expiry. Some of these were earlier problems with the engine, and solutions have been found while the engine has been in operation.

One issue was the disintegration of the outer cowl of the combustion chamber can. This was deteriorating after 10,000-16,000EFC on-wing, the exact time depending on the engine thrust rating and the EFH:EFC operating ratio.

The engine also had problems with the number three and four main bearings.

Bigger problems included cracking of HPT blades on earlier part numbers after 15,000-20,000EFC on-wing. Linked to early HPT blade issues were problems with damage to HPT nozzles. A soft time removal limit was set at 16,000-25,000EFC for the earlier part number HPT blades. There are currently 10 different HPT blade part numbers, and one of the improvements introduced by the Tech Insertion programme was an HPT blade free from these cracking problems.

"Soft removal intervals of 16,000-25,000EFC were established for the earlier blades, but it is possible to keep the engines on-wing for longer than these soft intervals, if the other HPT hardware condition is generally being confirmed as satisfactory with regular borescope inspections," says Rudge. "This practice is acceptable if the engine is a low-rated variant and running cooler. It is not worth taking the risk of running the blade too long because of the high cost of HPT blade failure.

"Even the first generation Tech Insertion blades exhibited signs that would lead to similar failure modes that were experienced by earlier part numbers. An SB was therefore issued to introduce a soft time limit, recommending removal of these blades prior to 25,000EFC," continues Rudge. "The second and third generation Tech Insertion blades have so far been satisfactory, as have the first generation blades on -7BE engines. Second generation -7BE HPT blades are due in 2013."

There has also been an issue with rotor-stator contact in the HPC. "HPC variable stators have come loose inside the HPC and have poor clearances as a result, as well as contact with the spool or even the HPC blades," explains Kleinhans. "This is due to the wear of bushings on the variable stator vanes."

Other problems in the hot section include issues with the fuel nozzles.

The LPT has also had some issues. The first is that there have been problems of distress and cracking of the LPT nozzles, connected with the possible need to replace the LPT case. There are rails on the inner wall of the case, and these hold the wear strip for the LPT blade shroud. The wear strips have had deterioration problems that can force an early shop visit for the LPT at the first removal. This leads to the need for a modification on the LPT nozzles if the LPT is opened.

"Earlier engines had problems with corrosion of LPT blades, and this forced unscheduled disassembly of LPT modules in the shop," says Rudge. "Now the shop manual limits for corrosion have been extended, so the LPT can achieve intervals of up to 25,000EFC before module disassembly is required."

Delta TechOps comment that it does not consider loss of performance and OAT to really be engine removal drivers. Instead, the prime driver after a long on-wing interval is the HPC rotor-stator contact, while HPT nozzle distress is the second main cause. This is mainly seen in the China region, however. A third main cause is stage 1 LPT nozzle distress, and HPT blades are actually the fourth main removal cause.

Shop-visit workscopes

Shop-visit workscopes and inputs will be closely determined by maximum possible removal intervals that are limited by LLP lives.

The core removal interval is mostly limited to 20,000EFC. "A full disassembly of the core will clearly be required when at or close to 20,000EFC on-wing so that LLPs can be replaced. Depending on post-repair time on-wing expectations, a core performance restoration can be carried out following a shorter interval, say up to 13,000EFC," says Rudge. "This will be used to restore EGTm and operating performance. The

The CFM56-7B does experience some problems with deterioration of hardware. One problem has been the deterioration of VSV bushings on the HPC outer case. These can be repaired without having to disassemble any of the engine's modules.

HPC, combustor and HPT will be disassembled to the level where clearances and seals can be re-established, and blade lengths and other dimensions also re-established. The main issue with a core engine shop visit is whether to repair or replace HPT blades. The main objective is to at least ensure alignment of remaining HPT blade life with the engine's LLP limiter. If there are 7,000-8,000EFC of remaining LLP lives, then re-installing repaired HPT blades will be sufficient. If the core is being overhauled, and a subsequent full on-wing run closer to 20,000EFC is being targeted, then HPT blades should be replaced with new or non time-restricted blades, due to the low availability of soft-time blades with sufficient remaining life.

"This issue was complicated with earlier engines that had the HPT blade part numbers with soft lives. The repair of these blades was affected by repair management programmes," explains Rudge. "These have recommended soft intervals or limits, over which certain blades cannot be repaired, and so have to be scrapped. It is unlikely that any HPT blade part number would be repaired if a long interval is being planned for. Some HPT blade part numbers, however, are capable of lasting as long as 25,000EFC."

Rudge explains that there is only a small difference between the final cost of a performance restoration and an overhaul. There is little difference in the cost of a performance shop visit after shorter or longer intervals. A significant contributor to the cost of a shop visit for the core modules is the HPT blades, with a complete set costing in the region of $850,000.

HPC blades last longer than HPT blades, but their durability depends on the operating environment.

Shop-visit inputs

The cost of shop-visit inputs comprises three main elements: labour man-hours (MH); materials and parts; and sub-contract repairs. There is a trade between the number of MH used and cost of parts, with the cost of sub-contract repairs.

Lighter core workscopes or a performance restoration will use about 3,000MH, while a core overhaul will use 3,600-4,000MH. At typical fully burdened labour rates of $75-100 per MH, this is equal to $225,000-400,000.

The cost of materials is the largest element. This can vary from $800,000-900,000 for a performance restoration, and can easily be $1.2 million for a large core workscope. Sub-contract repairs can typically be $250,000-350,000.

The scrap rate of blades and vanes is generally low for workscopes on the LPT. Corrosion and deterioration of the number four bearing are the main issues.

Stationary seals must also be repaired. An LPT workscope is usually a full disassembly, using 700-900MH in most cases. Cost of materials and parts can be more than $250,000, while sub-contract repairs can account for another $50,000-100,000.

The cost of materials in a fan/LPC workscope is heavily dependent on the number of fan blades that need to be replaced. Each one has a list price of $30,000-40,000. The replacement rate has fallen since repairs were introduced in 2009. Other repairs and replacements can take the cost of materials up to $200,000. The fan case has been scrapped on occasion.

The shop visit's final cost depends on the combination of workscopes for the different modules. Fan/LPC and LPT modules almost always have full disassembly and reassembly workscopes. The core can have a performance restoration, or a full overhaul.

The end cost for all permutations of workscope will vary from $1.6-1.85 million for a core performance restoration, to $3.3 million for a full overhaul.

A core performance restoration together with an LPC workscope will be $1.7-2.0 million, while together with an LPT it will be $1.8-2.1 million. A core performance restoration with both the fan/LPC and LPT will be $2.1-2.3 million.

A full core overhaul on its own will cost $1.9-2.45 million. Adding the fan/LPC will take the total to $2.6 million, while adding the LPT will cost $2.75 million.

Shop-visit patterns

Airlines managing their own engines can optimise possible removal intervals with LLP lives and shop-visit workscopes to achieve the lowest overall cost per EFC and per EFH. This is complicated by the fact that a large portion of engines are owned by operating lessors. With many aircraft and engines on relatively short lease terms, the ability to optimise engine removals and shop-visit workscopes is often compromised by short lease terms and lease return conditions.

There are several removal interval and shop-visit workscope patterns that airlines can plan for each variant.

The first issue is that most variants are capable of relatively long removal intervals. With LLPs at full target lives of 20,000EFC for the HPC modules,

High quality work on the -7B's HPC is essential to regaining EGT margin.

25,000EFC for the LPT module, and 30,000EFC for the fan/booster module, operators will be forced to compromise between replacing some LLPs early to achieve the longest possible removal interval, and accepting shorter intervals and frequent shop visits to allow the full or near full utilisation of LLP lives.

Each possible interval and shop-visit pattern will have different intervals, and should be considered up to a total accumulated time of 40,000EFC, equal to 20-24 years of operation.

Shop-visit patterns should be considered separately for base engines and Tech Insertion, /3 engines.

While there are several permutations of shop-visit patterns for each variant, the lowest reserve per EFC will be for the removal interval and shop-visit pattern that has the smallest number of workscopes and lowest total shop-visit cost over the protracted interval of 40,000EFC.

The higher end of shop-visit costs for each type and level of workscope, and reserves for LLPs are calculated at constant prices, without taking into consideration inflation and list price rises. That is, going forward in the future, or using lower costs for shop visits performed and LLPs installed historically.

The LPT and fan/LPC should only need a single full disassembly workscope in this interval. The lowest-cost shop visit will, therefore, only have a single LPT and a single fan/LPC workscope in the 40,000EFC interval, and the smallest number of core workscopes.

A core performance restoration will always be needed as a minimum at every shop visit, even if intervals have been as short as 5,000EFC. This will be the case, for example, if the LPT module was left at the first shop interval after 20,000EFC on-wing, and only the core was worked on. The second interval would be limited to 5,000EFC by the LPT's LLPs.

Such a shop-visit workscope pattern would result in a high cost per EFC over the 40,000EFC limit. A lower cost per EFC is achieved by compromising the utilisation of LPT LLP lives by performing a workscope on the LPT together with the core after 20,000EFC.

Base -7B engines

A large portion of base engines, built up to 2008, will have reached their first shop visit. These will have had some limitations to their first shop visits, either due to LLP lives, soft times for HPT blades or a combination of both. Most engines will now have had their initial core module airfoils replaced, and so will have few restrictions on subsequent removal intervals.

-7B20 & -7B22

The -7B20 and -7B22 were both capable of first removal intervals of 20,000EFC, due to EGTm and LLP lives in the core modules of both variants.

The lowest overall shop visit permutation for both variants is a full overhaul of all modules after an interval of close to 20,000EFC. This would be followed by another interval of 20,000EFC and a full engine overhaul.

This prevents any second and subsequent intervals being compromised by fan/LPC and LPT LLP lives, which would result in a larger number of shop visit intervals.

The cost for each shop visit will therefore be up to about $3.3 million. Such a pattern does put LLP reserves at $126 per EFC, since fan/LPC and LPT parts will be scrapped early. The overall cost per EFC is lowest with this pattern, however, at $291 per EFC over the 40,000EFC interval *(see table, page 52)*.

Airlines operating in a hot environment and/or operating on relatively short EFH:EFC ratios, using a low take-off thrust de-rate, or operating in a hot environment may more frequently achieve shorter intervals of 15,000-18,000EFC.

Following first removal intervals of 16,000-18,000EFC, the second interval would therefore be limited to 7,000-9,000EFC, by the LLPs in the LPT, and a total time of 25,000EFC if only the HP modules had been worked on.

There are several shop visit workscope patterns to follow when the first run has been limited to 17,000EFC. The pattern with the lowest overall cost per EFC is where the core modules and the LPT go through an overhaul. Here the LPT is left to the second shop visit after another 8,000EFC, and at a total time of 25,000EFC. A core performance restoration and full overhaul on the LPT would be required at this stage, at a cost of about $2.1 million.

Interestingly, the third removal would be limited to just 5,000EFC, where a core performance restoration and a fan/LPC overhaul would be performed at a cost of $2.0 million. The fourth interval would be limited to just 7,000EFC by the lives of core module LLPs that were installed at the first shop visit. The core modules would need a full overhaul at this stage if the engine were to continue in operation, at a shop-visit cost of about $2.45 million.

The overall reserve for this shop-visit pattern is $311 per EFC *(see table, page 52)*, over a total time of 37,000EFC.

-7B24

The -7B24 variant accounts for 641 aircraft in operation, making it the third most numerous variant. The two largest are 196 737-700s and 429 -800s. The -7B24 powers 170 -700s and 139 -800s.

The -7B24 has been compromised by the three different lives of the three major groups of LLPs. The initial EGTm of 100-105 degrees centigrade will theoretically allow a first removal interval of up to 19,000-20,000EFC. Actual intervals of 16,000-17,000EFC were experienced for earlier-build engines with particular LLP part numbers with shorter life limits.

A restored EGTm would average 75 degrees, so the engine could theoretically remain on-wing for up to 16,000EFC until EGTm is fully eroded.

The first of two lowest-cost options for a shop-visit pattern includes the LPT in the first workscope and replaces its LLPs. This would allow a second interval of 13,000-14,000EFC, when fan/booster LLPs would expire at a total time of 30,000EFC, equal to 14-18 years of operation. The second shop visit would then require replacement of core and fan/booster LLPs. A third interval of up to 11,000EFC, which would be limited by the lives of core LLPs installed at the first shop visit. This pattern would cost $308 per EFC over a total interval of 41,000EFC *(see table, page 52).*

The second main option is to perform just a core overhaul at the first shop visit. The second shop visit would include the LPT, so the second removal interval would be limited to just 8,000-9,000EFC, and be forced by the expiry of LLPs in the LPT. The LPT and fan/booster would be included in the workscope to replace LLPs. The core module LLP lives would allow a third removal interval of up to 11,000EFC, taking total engine life to 36,000EFC.

This shop visit pattern would have an overall cost of $306 per EFC over a total interval of 36,000EFC *(see table, page 52).*

-7B26

The -7B26 powers 902 aircraft, most of which are 737-800s. The big fleets of -7B26s on the 737-800s are operated by American, Delta, Qantas, Ryanair, Turkish and United. A small number are operated on -900s by Alaska and a few other carriers.

The -7B26 is the first higher-rated variant where removal interval is clearly forced by EGTm expiry. It should be capable of first removal intervals of 12,000-14,000EFC, equal to 6.5-8.5 years of typical operations. This is close to the life limits of some core module LLPs in some of the earlier-built engines.

The oldest -7B26 engines would have had their first planned removals and shop visits in 2004-2006. A restored EGTm of 60-64 degrees would mean that a second removal interval of 10,000-11,000EFC would theoretically be possible.

The remaining LLP lives at the first removal would therefore be a maximum of 6,000-8,000EFC for the core module LLPs, 12,000-13,000EFC for the LPT, and 16,000-18,000EFC for the fan/booster at the first shop visit.

The stub lives of some core module LLPs would actually be less than 6,000EFC, and in some cases zero; while the stub life of some parts in the LPT would be 5,500-7,500EFC for a part with a full life of 19,500EFC.

This means that a full core overhaul and replacement of LLPs would be necessary. This would cost $2.45 million.

The lowest shop-visit pattern from this point would be for the LPT and fan/LPC modules to limit the second shop visit to 11,000EFC. These two modules would have full workscopes, while the core would have a performance restoration. This would cost $2.3 million *(see table, page 52).*

The third interval would be limited to 7,000EFC by the core LLPs. EGTm would therefore allow a fourth interval of 10,000EFC, where a core performance restoration would be carried out. The overall cost of this shop visit pattern would be $353 per EFC, after a total time of 41,000EFC *(see table, page 52).*

-7B27

The -7B27 powers 291 aircraft, almost all of which are 737-800s. Alaska Airlines, American and GOL operate the largest fleets. There are also several operators that operate in hot environments, such as Air India Express and flydubai.

The -7B27's lower EGTm means it can achieve lower removal intervals, most of which will be forced by EGTm

NON-TECH INSERTION CFM56-7B REMOVAL INTERVAL, SHOP VISIT WORKSCOPE & LLP REPLACEMENT PATTERN

Removal	Interval EFC	Accumulated EFC	Workscope content	Shop visit Cost-$	LLP replacement	LLP cost $	Sub-total $/EFC	Sub-total $/EFH	Unsched visits $/EFH	QEC $/EFH	Total $/EFH
-7B20											
1st	20,000	20,000	All modules	3,300	All modules	2,521					
2nd	20,000	40,000	All modules	3,300	All modules	2,521	291	153	25	15	193
-7B22											
1st	20,000	20,000	All modules	3,300	All modules	2,521					
2nd	20,000	40,000	All modules	3,300	All modules	2,521	291	153	25	15	193
1st	17,000	17,000	Core O/Haul	2,450	Core	1,303					
2nd	8,000	25,000	Light core & LPT	2,100	LPT	706					
3rd	5,000	30,000	Light core & Fan LPC	2,000	Fan/LPC	511					
4th	7,000	37,000	Core O/Haul	2,450	Core	0	311	164	25	15	204
-7B24											
1st	16,000	16,000	Core O/Haul & LPT	2,750	Core & LPT	2,010					
2nd	14,000	30,000	Light core & Fan/LPC	2,000	Core & Fan/LPC	1,815					
3rd	11,000	41,000	Core O/Haul & LPT	2,750	Core & LPT	1,304	308	162	25	15	202
1st	16,000	16,000	Core O/Haul	2,450	Core	1,304					
2nd	9,000	25,000	Light Core, LPT & Fan/LPC	2,300	LPT & Fan/LPC	1,217					
3rd	11,000	36,000	Core O/Haul	2,450	Core	1,304	306	161	25	15	201
-7B26											
1st	13,000	13,000	Core O/Haul	2,450	Core	1,304					
2nd	11,000	24,000	Light core, LPT & Fan/LPC	2,300	LPT & Fan/LPC	1,215					
3rd	7,000	31,000	Core O/Haul	2,450	Core	1,304					
4th	10,000	41,000	Light core	1,850		0	353	186	25	15	226
-7B27											
1st	11,000	11,000	Light core	1,850		0					
2nd	8,000	19,000	Core O/Haul & LPT	2,750	Core & LPT	2,010					
3rd	8,000	27,000	Light core & Fan/LPC	2,000	Fan/LPC	511					
4th	8,000	35,000	Core O/Haul	2,450	Core	1,304					
5th	8,000	43,000	Light core & LPT	2,100	LPT	706	389	205	25	15	245

Planned shop visit engine maintenance reserves based on 1.9EFH per EFC.

erosion.

The first removal interval will be 10,000-12,000EFC. Early-build -7B27 base engines may have had a few LLPs with restricted lives, close to these intervals.

The restored EGTm would be 45-50 degrees, and on the basis of EGTm erosion rates would allow a second removal interval of 8,000EFC *(see table, this page)*.

On this basis it would have been acceptable to put the core engine through a restoration shop visit, but leave the LLPs in the core modules.

This would limit the second removal interval to 8,000EFC, after which a full core overhaul would be needed to replace the core LLPs, and also an LPT overhaul. This would be at a total time of 15,500-19,000EFC, or up to the life limit of the LLP with the shortest life.

The EGTm would limit subsequent intervals to 8,000EFC. This would conveniently coincide with fan/LPC LLP lives expiry. The third shop visit would therefore be a core performance restoration and a fan/LPC overhaul, with a shop visit cost of $2.0 million.

With intervals limited to 8,000EFC, the fourth shop visit would be a core overhaul, and the fifth shop visit a core performance restoration and an LPT overhaul. This takes total time to about 43,000EFC, and total overall reserve is $389 per EFC *(see table, this page)*.

Tech Insertion engines

Tech Insertion, or /3, engines will all have unrestricted LLP lives and be capable of longer first removal intervals than the earlier-built base engines.

-7B20/3 & -7B22/3

The lowest-cost shop-visit patterns for the -7B20/3 and -7B22/3 variants will be the same as the base -7B20 and -7B22 engines. This is because first removal intervals will be up to 20,000EFC.

The overall reserve will thus be $292 per EFC over a total time of 40,000EFC for engines that had removal intervals of 20,000EFC *(see table, page 54)*.

-7B22/3 engines that had first removal intervals limited to 17,000EFC would have the lowest cost per EFC when following the same pattern as the -7B22 base engine: a core overhaul at the first shop visit, and a core performance restoration and LPT workscope after another 8,000EFC at the second shop visit. This would be followed by third and fourth removal intervals of 5,000EFC and 7,000EFC that would take total time to 37,000EFC. Total overall cost would be $311 per EFC *(see table, page 54).*

-7B24/3

There are two options to follow for -7B24/3 engines, and these both have longer removal intervals than the -7B24 base engine. The -7B24/3 is capable of having first and subsequent removal intervals of 20,000EFC. As a result the -7B24/3 can achieve a lower overall cost per EFC *(see table, page 54).*

The first option is to follow the simple shop-visit pattern of two intervals of 20,000EFC each, with a full overhaul after each one. This will provide a reserve of $291 per EFC *(see table, page 54).*

The second option is to limit the total of the first and second interval to the 25,000EFC limit of LPT LLP lives. The first interval of 18,000EFC would be followed by a core overhaul. The second shop visit would therefore be a core performance restoration and a full LPT workscope, as well as a fan/LPC workscope. The shop visit cost for this input would be about $2.3 million.

The third interval would be limited by core module LLPs to 13,000EFC, and be followed by a core overhaul.

The overall cost per EFC for these three shop visits would be $290, over a total interval of 38,000EFC *(see table, page 54).*

-7B26/3

The -7B26/3 Tech Insertion engines would have a higher EGTm than the -7B26, so the Tech Insertion engines are capable of first removal intervals of 13,000-15,000EFC. This compromises the options for shop-visit patterns.

The restored EGTm will allow a second removal interval of 11,000-12,000EFC, close to the remaining lives of LLPs in the LPT. The operator therefore has two main options.

The lowest-cost shop-visit pattern for the -7B26/3 to follow is basically the same as the -7B26 base engine. The shop-visit pattern, however, does not compromise individual removal intervals, and so allows a longer total overall interval of 45,000EFC to be achieved *(see table, page 54).*

The first interval of 14,000EFC is followed by a core overhaul. The second interval is limited to 11,000EFC, and a core performance restoration plus full workscopes on both low pressure modules is performed. The third and fourth intervals of 9,000EFC and 11,000EFC are followed by the same workscopes as the first and second shop visits.

This generates an overall total cost of $332 per EFC over the total interval of 45,000EFC *(see table, page 54).*

-7B27/3

The -7B27/3 powers 179 aircraft, 171 of which are -800s. Large numbers are operated by Alaska Airlines, GOL, flydubai and Thomson Airways.

The -7B27/3 is the same relative to the base -7B27, as the -7B26/3 is relative to the base -7B26. That is, the -7B27/3 can achieve slightly longer removal intervals. This ability is compromised by LLP lives, however.

The implications of this are that the shop-visit pattern with the lowest cost per EFC for the -7B27/3 is the same as the -7B27. The total overall interval for the five shop visits is also virtually the same, at 43,500EFC. The overall cost over the total interval is thus $382 per EFC *(see table, page 54).*

Summary of reserves

The reserves for the main shop-visit inputs and LLPs expressed in $ per EFC must be converted to equivalent rates in $ per EFH. The fleetwide average EFH:EFC ratio is 1.9EFH, so $ reserves are $153-

TECH INSERTION CFM56-7B REMOVAL INTERVAL, SHOP VISIT WORKSCOPE & LLP REPLACEMENT PATTERN

Removal	Interval EFC	Accumulated EFC	Workscope content	Shop visit Cost-$	LLP replacement	LLP cost $	Sub-total $/EFC	Sub-total $/EFH	Unsched visits $/EFH	QEC $/EFH	Total $/EFH
-7B20/3											
1st	20,000	20,000	All modules	3,300	All modules	2,521					
2nd	20,000	40,000	All modules	3,300	All modules	2,521	291	153	25	15	193
-7B22/3											
1st	20,000	20,000	All modules	3,300	All modules	2,521					
2nd	20,000	40,000	All modules	3,300	All modules	2,521	291	153	25	15	193
1st	17,000	17,000	Core O/Haul	2,450	Core	1,303					
2nd	8,000	25,000	Light core & LPT	2,100	LPT	706					
3rd	5,000	30,000	Light core & Fan/LPC	2,000	Fan/LPC	511					
4th	7,000	37,000	Core O/Haul	2,450	Core	0	311	164	25	15	204
-7B24/3											
1st	18,000	18,000	Core O/Haul	2,450	Core	1,304					
2nd	7,000	25,000	Light core, LPT & Fan/LPC	2,300	LPT & Fan/LPC	1,215					
3rd	13,000	38,000	Core O/Haul	2,450	Core	1,304	290	153	25	15	193
1st	20,000	20,000	All modules	3,300	All modules	2,521					
2nd	20,000	40,000	All modules	3,300	All modules	2,521	291	153	25	15	193
-7B26/3											
1st	14,000	14,000	Core O/Haul	2,450	Core	1,304					
2nd	11,000	25,000	Light core, LPT & Fan/LPC	2,300	LPT & Fan/LPC	1,218					
3rd	9,000	34,000	Core O/Haul	2,450	Core	1,304					
4th	11,000	45,000	Light core & LPT	2,100	LPT	707	332	175	25	15	215
-7B27/3											
1st	11,500	11,500	Light core	1,850		0					
2nd	8,000	19,500	Core O/Haul	2,750	Core & LPT	2,010					
3rd	8,000	27,500	Light core & Fan/LPC	2,000	Fan/LPC	511					
4th	8,000	35,500	Core O/Haul	2,450		0					
5th	8,000	43,500	Light core & LPT	2,100	Core	1,304	382	201	25	15	241

Planned shop visit engine maintenance reserves based on 1.9EFH per EFC.

205 per EFH *(see tables, pages 52 & 54)*.

These two main cost elements have to be added to by the cost of unscheduled visits and a budget for reserves for quick engine change (QEC) components and accessory parts. The reserves for these will be $25 and $15 per EFH.

Total reserves for base engines are $193-245 per EFH for the five different variants (*see table, page 52*).

Total reserves for base -7B20 and -7B22 engines are thus $193 and $204 per EFH, depending on which shop visit pattern is followed *(see table, page 52)*.

Total reserves are marginally higher for the -7B24 at $201-202 per EFH; both shop visit patterns resulting in almost equal overall costs per EFH.

Overall cost per EFH for the -7B26 is $226, rising to $245 per EFH for the -7B27.

Total reserves for the Tech Insertion engines are $193-241 per EFH, and so only marginally lower than the base engines *(see table, this page)*.

Overall reserves are the same for the -7B20/3 and -7B22/3 engines compared to the base engines of the same variants.

This is because the Tech Insertion engines are not able to achieve removal intervals any longer compared to their base engine counterparts.

The -7B24/3 has a reserve about $10 per EFH lower than the base -7B24 engine *(see table, this page)*. This is because the -7B24/3's shop visit pattern is more optimised over a similar interval to the -7B24.

The higher rated -7B26/3 is able to achieve overall longer intervals than the base -7B26, while the two have overall similar total shop visit costs. The -726/3 consequently achieves an overall cost of $215 per EFC, $9 per EFC lower than the base engine *(see table, this page)*.

The 7B27/3 is unable to achieve much of an advantage over the base -7B27 in terms of removal intervals. The -7B27/3 has only a marginally lower cost per EFH at $241 *(see table, this page)*. AC