Boeing set a 15% maintenance cost reduction target for the 737NG over the previous family. The CFM56-7 has contributed to this with high EGT margins and potential for impressive on-wing reliability. If expected on-wing times are met, the CFM56-7 will have competitive maintenance costs.

CFM56-7 maintenance: A preliminary analysis

When Boeing launched the 737NG it set a target of a 15% lower maintenance cost compared to the 737-300/-400/-500 series. CFMI took an equal share of the task, by aiming to provide an engine which would have a 15% lower maintenance cost than the CFM56-3B/C series. The oldest CFM56-7s have been in operation for four years. Few engines have had their first removal, so it will be several years before a pattern of removal intervals and shop visit costs has been established. Leading operators, however, and engine shops have made some preliminary analysis that indicates the likely maintenance reserves required by the CFM56-7.

CFM56-7 in operation

The 737NG was designed to be capable of trans-continental operations in the US, and also extended range twin-engine operations (Etops) missions. The aircraft is therefore used in a wider variety of missions than the 737 classic family. Consequently, average CFM56-7 flight cycle (EFC) times vary widely.

At one extreme Delta Shuttle operates the 737NG on flights averaging 50 minutes from Boston and Washington. At the other extreme airlines like Aloha fly the 737NG on sectors of three or four hours.

The 737NG is also operated in different environments. Southwest, American and Delta operate from airports which experience high ambient daytime temperatures for several months of the year. European airlines operate in cooler environments, with carriers enjoying the benefits this brings.

Management of the CFM56-7's maintenance depends on its operation and operating environment. Management for removals and shop visits takes into consideration possible on-wing times and shop visit costs, as well as life limited parts (LLPS) and their replacement lives. The CFM56-7 has LLPs with lives of 13,000-30,000EFCs. One objective is to standardise their lives to 20,000EFCs in the high pressure (HP) spool and to 25,000/30,000EFCs in the low pressure (LP) spool. The CFM56-7 is generally regarded as capable of long on-wing intervals, equal to two-thirds of the life of some LLPs. The remaining life of LLPs after one on-wing interval may compromise subsequent on-wing times. This means operators will either be forced to remove LLPs, or accept short subsequent on-wing runs. This compromise between on-wing times and LLP lives will be made easier once LLPs with short lives in the HP and LP systems have had their lives extended closer to 20,000EFCs and 25,000/30,000EFCs. The 1-2 compressor spool in the HP system, for example, has a life of 13,800EFCs, but this should be extended to nearer to 20,000EFCs.

CFM56-7 family

There are six CFM56-7 variants, with thrust ratings between 19,500lbs and 27,300lbs. There are three engine variants for each 737NG model. The engine variants and their application are summarised *(see table, this page)*. There are also two sub-variants, one with a single annular combustor and the other with a dual annular combustor to reduce NOx emissions.

The CFM56-7 family has a large exhaust gas temperature (EGT) margin compared to other engines, although it is similar to the CFM56-5A/B series powering the A320 family. The large EGT margin on most CFM56-7 variants *(see table, this page)*, and its rate of reduction on most applications, means on-wing intervals of most engines will not be limited by EGT margin erosion. "The EGT margins on new CFM56-7s are huge for their low thrust ratings," comments David Beale, project leader CFM56 at MTU Maintenance.

On-wing performance

As with several other engine types, the rate of EGT margin erosion on the CFM56-7 is influenced more by EFCs than engine flight hours (EFHs).

CFM56-7 FAMILY CHARACTERISTICS AND APPLICATIONS

Engine variant	-7B18	-7B20	-7B22	-7B24	-7B26	-7B27
Thrust rating (lbs)	19,500	20,600	22,700	24,200	26,300	27,300
Application	737-600	737-600 737-700	737-600 737-700	737-700 737-800 737-900	737-800 737-900	737-800 737-900
Test cell EGT margin (degrees centigrade)	129	135	108	104	77	59
Installed EGT margin (degrees centigrade)	117	123	96	92	65	47

Average CFM56-7 flight cycle times vary, with operations ranging between 50 minutes and three hours. Operating environments also vary, from high ambient temperatures of desert regions to cool climates of north Europe. Even engines in hot environments are expected to have first on-wing runs limited by LLPs, rather than EGT margin erosion.

"The EGT margin on the -B24 and -B26 engines is high enough for them not to affect on-wing intervals," says Jacques Renvier, chief of customer operations at Snecma Services. "The EGT margins on most variants are high enough to allow long on-wing intervals that reveal other removal causes. In fact, 70% of removals will probably be forced by the need to replace LLPs and the other 30% due to mechanical failures. I estimate that EGT margin erosion is about four degrees centigrade per 1,000EFCs, compared to about five degrees for the -3 series. The test bed EGT margin is reduced by 10-12 degrees centigrade when the engine is installed. The rate of erosion means the highest thrust variant, the -B27, can achieve an on-wing time of about 12,000EFCs."

"Even in hot environments the CFM56-7 will have removals caused by the need to replace LLPs. While first run EGT margin erosion is four or five degrees per 1,000EFCs on lower thrust rated engines, it is nearer 7 degrees centigrade per 1,000EFCs on high rated variants," says Beale.

Typical 737NG operations for many airlines are a flight cycle (FC) time of 1.4 flight hours (FH), but the average is 2.0FH. Most airlines will achieve in the region of 2,500FH per year, equal to about 1,250FC.

The rate of EGT margin erosion means the highest rated engines could achieve on-wing times of about 12,000EFCs (10 years of operation), while the lowest rated variants up to more than 17,000EFCs (13.5 years). "While some airlines use the 737NG on similar operations to the 737 classics, others are using the aircraft on flight times averaging about 3FH," says Beale. "Even Southwest now operates some flights which are longer than its typical one hour length. The 737NG has also opened new routes for some airlines, and Aloha is an example," says Beale. "The -3 and -7 series have similar rates of EGT margin deterioration and deterioration curve, so operators and engine shops are anticipating how the -7 will behave. The -7 has a higher margin, so this should mean it will achieve longer on-wing times, which will contribute to lower maintenance costs."

While operators and shops will compare the -3 and -7 series, a large number of -3s were produced over more than 10 years. The initial engines had poor on-wing reliability, but this improved with the later production engines. "Some of our low thrust rated -3B1s, operating at a FC time of about 1.1FH, had first on-wing runs right up to LLPs limits of 20,000EFCs in some cases," says Markus Kleinhans, propulsion systems engineering for the CFM56-3/-7 at Lufthansa Technik. "It may be hard for the -7 series to achieve on-wing times much longer than the later produced -3 series. Although we do not operate the 737NG, our customers have FC times varying between 0.8FH and 3.0FH. We manage about 200 CFM56-7 engines."

Several factors determine on-wing times, including power de-rate, average EFC time, operating environment and ambient temperature. Kleinhans explains that these can all be used to predict on-wing reliability and removal interval, as well as EGT margin erosion rates. "EGT margin reduces by 8-10 degrees centigrade per 1,000EFCs for the first 2,000EFCs, but then reduces to 3-4 degrees per 1,000EFCs after."

On-wing times

Delta is one of the largest and earliest 737NG operators, with about 70 aircraft already in operation of a global fleet of about 1,020 aircraft. "We have engines rated at 26,000lbs for our -800s, and I estimate the installed EGT margin of new engines was about 77 degrees centigrade," says Craig Winter, manager of propulsion engineering at Delta TechOps. "We started operation in 1998 and are still taking delivery of aircraft. We have two operations. The first is the mainline operation, which has an average FC time of 2.0FH. Our aircraft average about 1,500FC and 3,000FH per year. The shuttle fleet's operation on the east coast averages about 50 minutes. In our experience the EGT margin deteriorates a little faster than General Electric (GE) predicted. While GE expects the LLPs to be the main limiter of on-wing times, we anticipate EGT margin erosion will be the main driver of first engine removals, and it will certainly be the main cause of subsequent removals. This is because the first LLP limit is 13,000EFCs, and while some engines will achieve this, others will run out of EGT margin before." At Delta's thrust rating, the predicted rate of EGT margin, after the first 2,000EFH on-wing, is three degrees per 1,000EFH. This will allow an on-wing time of about 15,000EFH. Higher rates of erosion for the first 2,000EFHs will reduce this closer to the 12,000-13,000EFH level for Delta's mainline fleet.

"We actually expect first on-wing runs to be about 12,000-13,000EFH, that is about 6,500EFCs (just over four years)," says Winter. "This will then allow the HP LLPs to stay in the engine for two or three runs. The aim is to extend the lives of other LLPs to 20,000EFCs. If this is done we can keep these parts in the engine for a third run, or possibly get longer first runs. The reason for our expected short on-wing run compared to some operators is that we have problems at high altitude airports with high ambient temperatures, including our Salt Lake City hub."

Renvier explains the wide range of 737NG operations is reflected in the predictions of on-wing times. "We estimate mature shop visit rates, for all causes, to be about 10,000EFH (about

CURRENT & PROJECTED LIFE LIMITS OF LLPS FOR THE CFM56-718, -7B20, -7B22, -7B24, -7B26 AND -7B27

Low pressure section

Part	Current limit (EFC)	Projected limit (EFC)
Fan disk	16,000	30,000
Booster spool	23,600	30,000
Fan shaft	30,000	30,000
LPT 1 disk	25,000	25,000
LPT 2 disk	25,000	25,000
LPT 3 disk	25,000	25,000
LPT 4 disk	25,000	25,000
LPT shaft	19,500	25,000
LPT rotor support	25,000	25,000
LPT turbine stator	20,400	30,000

High pressure section

Part	Current limit (EFC)	Projected limit (EFC)
HPC front shaft	20,000	20,000
HPC 1-2 spool	13,000	20,000
HPC 3 disk	20,000	20,000
HPC 4-9 spool	20,000	20,000
HPC CDP seal	18,600	20,000
HPT front shaft	17,300	20,000
HPT front air seal	15,900	20,000
HPT disk	14,700	20,000
HPT rear shaft	17,300	20,000

POSSIBLE EFC REMOVAL INTERVALS & LLP REPLACEMENT PATTERN

Engine variant	Low thrust	Low thrust	High thrust	High thrust
1st run	17,000 Repl parts up to 25K	14,000 Repl parts up to 20K Limits 2nd to 11K	14,000 Repl part up to 20K Limits 2nd to 11K	11,000 Limits 2nd to 9K
2nd run	13,000	11,000	11,000	9,000
Total	30,000 Repl 30K parts	25,000 Repl 30K parts	25,000 Repl 30K parts	25,000 Repl 25K parts Leave 30K parts

four years for an average operator) for the highest thrust rated engines, and in the region of 13,000-15,000EFH/ 10,000EFC (about five to six years) for lower rated engines," continues Renvier. "This is for an average FC time of 1.4FH. Removal intervals would be about 10-15% longer if the average cycle time was 2.0FH. I think high rated engines will achieve about 15,000EFH (11,000EFC/ six years) on-wing before their first removal, while engines rated at about 24,000lbs should be able to stay on-wing until their LLP limit. That is, about 25,000EFH (17,500EFC/seven years) is possible."

Beale at MTU agrees with Renvier's anticipated on-wing times for low rated engines, but this will only be possible if CFMI extends the lives of LLPs in the HP system from 13,000EFC to closer to 20,000EFC. "High rated engines will get removed due to parts wear and hardware problems, but should achieve 15,000-20,000EFH for typical FC times," comments Beale.

Kleinhans has calculated predicted first on-wing intervals on the basis of EGT margins of new production engines. "Although it is hard to say exactly, I think the lower rated engines from the -7B18 to the -7B24 should achieve 20,000EFCs, the -7B26 about 16,000EFCs and the -7B27 about 12,000EFCs. If CFMI does not extend LLPs in time operators will get early removals. It takes about three months to get an extension. Similar extensions were made in the -3 series and about 95% of the LLPs achieved projected limits."

Engine management

Operators have to consider on-wing intervals in relation to LLP lives to optimise maintenance costs. A full set of LLPs has a list price of $1.7 million, including static parts. Their fixed lives in terms of EFCs and the relatively short average EFC times of the engine in operation means LLPs will account for a large portion of total maintenance cost per EFH and EFC. Airlines should therefore aim to scrap LLPs with the shortest possible 'stub' lives. Airlines, however, have to consider maintenance costs of mature engines over three or four shop visits. This raises the issue of what EFC intervals are expected for its second and third on-wing runs.

While EGT margin is less of an issue for first run engines, restored EGT margin will be lower after the first shop visit. Renvier predicts restored EGT margin will be about 70% of the original level after the first shop visit. Margins will thus range from about 85 degrees for the lower rated variants to about 40 degrees for the -B27. Beale adds that second and subsequent on-wing runs should have slightly higher rates of EGT margin deterioration than the first.

"Engines may get a 20 degree reduction in restored EGT margin after the first shop visit," says Kleinhans. "While the -B27 would have a margin of 40-45 degrees, the -B18 would have about 95 degrees. I expect the second run to be about 80% of the first". Third runs may in the region of 60-70% of the first.

"We are concerned about HPT durability for second and third run engines," explains Winter. "I expect to get two on-wing runs for the shortest life LLPs, three runs for parts with lives of 20,000EFC and possibly four runs for parts with 30,000EFC lives."

Projected LLP lives are 30,000EFC in the fan and booster section, 25,000EFC in the low pressure turbine (LPT) section, and 20,000EFC in the HP spool. These are higher than current life limits for some parts, but there are aims to extend these before the current limits are reached.

The same LLP can be used for each variant. There are, however, several sub-variants of each variant, for example, the -B27, -B27/B1, -7B27/B3 and -7B27/2. The same part number can be used for each of these sub-variants, and in most cases has the same or similar life limit. There are also several different part numbers for the same part. In all cases, except the LPT stator, the different part numbers have the same EFC life limit. The LPT stator has a life limit range of 11,600-25,000EFC for the -7B18-27 series. These are different for the -7B18-27/B1/B3/2 engines.

The current and projected LLP life

While the CFM56-7's shop visit costs will probably be higher than the CFM56-3's because of the cost of parts, the CFM56-7 overall costs are likely to be lower because of the long on-wing times it is expected to achieve.

limits for the -7B18-27 series are shown *(see table, page 24)*. This shows that in the high pressure spool there are three parts with lives limited to 13,000-15,900 EFCs, equal to eight or nine years of operation. These will be reached in about 2005/06 for the first aircraft that entered service. Their extension to 20,000EFC should be completed by the end of 2003, meaning most engines' on-wing intervals will not be limited by these LLPs.

There are four parts in the low pressure spool with limits of 16,000-23,600EFCs, equal to 11-16 years of operation. These will be reached in about 2008-2013 for the first aircraft that started service. Their extension to life limits of 25,000/30,000EFC should be completed in 2003/2004, meaning their current lives will not limit possible on-wing intervals.

Low rated engines

Lower rated -7 variants are expected to have first on-wing runs almost equal to the limits of HP LLPs, in the region of 17,000-18,000EFCs. This is equal to about 11-12 years of operation.

Second runs are expected to be in the region of 11,000-13,500EFC, and third runs 8,500-11,000EFC. Total on-wing time at the second removal would be 28,000-30,000EFC (18-20 years of operation).

Parts with lives up to 25,000EFC should be replaced at the first shop visit. This would prevent 20,000/25,000EFC parts limiting the second run to 3,000EFC or 8,000EFC with their short remaining lives. Parts with lives of 30,000EFC could be left in the engine, allowing a second run of 13,000EFC.

These 30,000EFC parts would be replaced at the second shop visit, with almost zero 'stub' life, at about 20 years.

A third run of 10,000EFC would take total time to about 40,000EFC (27 years), where the youngest parts installed at the first shop visit would be replaced. Parts installed at the second visit are unlikely to require replacement in the engine's remaining operational life.

Engines which achieved a shorter first on-wing run would provide the operator with a dilemma. For example, a run of 14,000EFC would leave some parts with remaining lives of 6,000/11,000EFC in the engine. Many of these would have to be removed and possibly scrapped, thereby increasing cost. The operator could leave the parts with 11,000EFC remaining in the engine, limiting the second run to this interval, and a total time of 25,000EFC for the two runs, equal to about 17 years of operation. Parts with 30,000EFC lives would have to be scrapped at this second shop visit, so as not to limit the third on-wing run to 5,000EFC.

A third run of 9,000EFC would take total time to 34,000EFC, about 22 years of service. Parts installed at the first visit would have to be replaced here. Again, longest life parts installed at the second shop visit are unlikely to have to be replaced in the engine's remaining operational lifetime.

High rated engines

Beale at MTU predicts that high-rated engines will achieve first runs of 10,000-14,000EFC, and Kleinhans similarly expects the -B26 to achieve about 15,000EFC, thus up to 12 years of operation for engines achieving 1,250EFC per year.

Beale forecasts second runs of 7,000-11,000EFC, while Kleinhans thinks these engines should accumulate 9,000-12,500EFC. Total time to the second removal may therefore be 17,000-25,000EFC (13-20 years).

A long first run of 14,000EFC would mean parts with lives of up to 20,000EFC would have to be scrapped, to prevent limiting the second run to 6,000EFC. Parts with lives of 25,000EFC would be left in, limiting the second run to a maximum of 11,000EFC. All remaining original LLPs would have to be scrapped at the second shop visit to prevent parts with lives of 30,000EFC limiting the third on-wing run to 5,000EFC. A third run of 9,000EFC would take total time to 34,000EFC, about 22 years. Here shorter life parts installed at the first shop visit would need to be replaced. Longer life parts installed at the second visit may not require replacement in the remainder of the engine's operational life.

A removal after a shorter first run of 11,000EFC allows parts with lives up to 20,000EFC to be left in at this stage, limiting the second run to 9,000EFC, which is close to the expected on-wing time. The second shop visit would occur at a total time of 20,000EFC, equal to about 13 years of operation.

Parts with 25,000EFC would have to be scrapped at the second visit, since they would limit the third run to 5,000EFC.

Only parts with lives of 30,000EFC would be left in the engine at the second shop visit and replaced at the third, limiting the third run to 10,000EFC. These parts would use virtually all their lives. A third run of about 7,000EFC would take total time to about 27,000EFC and 18 years of operation. Shorter life parts replaced at the second shop visit would be replaced again at the fourth. It is possible that longer life parts, installed at the third shop visit would not need to be replaced in the engine's operational life.

When shorter on-wing runs are expected, as in the case of Delta, LLPs with the shortest lives of 13,000-15,000EFC could be removed at the second shop visit, parts with lives of 17,000-18,000EFC removed at the third shop visit, and others replaced at the fourth removal. Winter explains that Delta even plans to put used LLPs into the engines, since some parts scrapped by

The lowest rated engines operated in the coolest environments will achieve on-wing times up to limits of LLPs. This means many engines may not have their first removal until more than 10 years of operation.

other airlines may have remaining lives similar to the on-wing runs Delta expects. This will play a part in optimising maintenance costs per EFH.

Shop visit management

Airlines and shops expect the CFM56-7, like most engines, to conform to a pattern of shop visit workscopes. The actual pattern will depend on the thrust rating, since higher powered variants will experience higher rates of deterioration on-wing.

"The first shop visit is likely to be a performance restoration of the core, plus some LLP replacement. This will involve the HPC, combustor and HPT," says Beale. "The LPT and fan will have on-condition maintenance and probably just an inspection at the first removal. The CFM56-7 workscope planning guide (WPG) has on-wing thresholds for inspection, repair, performance restoration and overhaul for each module in a similar way to the CF6-80C2. These soft time thresholds have not yet been established. The major factors that affect these thresholds are the relation between the on-wing time and the cost of repairing or replacing parts. There is no doubt, however, of the -7's ability to stay on-wing longer than the -3."

Lower rated engines are expected to have their first removals driven by LLP expiry, while removal of higher rated engines are expected to driven by parts deterioration. "Higher thrust engines might be expected to have alternating performance restoration and overhaul shop visit workscopes," says Kleinhans. "Lower rated engines are more likely to require core overhauls at every shop visit and repairs of the LP sections every time. The need for an overhaul will depend on the need to replace LLPs. That is, LLP replacement in a module will force disassembly to piece-part level, thus resulting in an overhaul. The workscope required in each module to get an acceptable second on-wing run will be determined on-condition."

Winter explains Delta will initially have heavy maintenance on its engines to obtain information on part repairability, but will later perform performance restorations. The actual workscope, however, will depend on engine removal causes. "We expect to be able to maintain engine performance with repaired rather than replaced parts, and are looking to develop new repair technology."

The three inputs of man-hours (MH), materials and sub-contract repairs will depend on the in-house repair capability of the shop, the engine's condition at removal and previous shop visit workscope. Beale estimates MH inputs will be in the region of 2,500 for a performance restoration and 3,200 for an overhaul.

Materials, excluding LLPs, are expected to incur $400,000-500,000 for a performance restoration, but will climb to $600,000 as the engine matures. Materials are likely to start at $600,000 for an overhaul at the second removal.

Sub-contract repairs will be about $200,000 for a performance restoration and $300,000 for an overhaul.

A labour rate of $70 per MH therefore results in a total cost of $775,000-875,000 for earlier performance restorations and $1,125,000 for an overhaul, not including LLPs.

Lower rated engines may have similar shop visit costs at each removal, while higher rated variants are more likely to have alternating shop visit costs.

A low thrust rated engine may accumulate 30,000EFC up to its first two removals. This corresponds to about 42,000EFH, if the average FC time is 1.4FH. There will be a corresponding cost of $1,975,000 for the two shop visits, not including LLPs. All LLPs will have been replaced by the second shop visit, incurring an additional cost of $1.7 million. These two costs, totalling about $3.7 million, will be equal to $90 per EFH. The costs per EFH will be largely dependent on average FC time, so that aircraft operating longer average FC times will benefit. While this is a low maintenance reserve, maintenance costs will rise as the engine matures and on-wing times decrease. Third and subsequent on-wing intervals are expected to be about 14,000EFH and 10,000EFC for low rated engines. Shop visit costs will also climb to about $1.0 million for smaller workscopes and to the region of $1.3 million for larger shop visits. This will increase to a maintenance reserve in the region of $85 per EFH for the costs of the third and fourth shop visits spread over the third and fourth on-wing intervals, not including LLPs. LLPs will add a further cost of about $60 per EFH, taking total cost to the region of $145 per EFH.

A high rated engine, achieving shorter on-wing times, will incur costs of about $950,000 for lighter workscopes and $1.2 million for heavier shop visits, not including LLPs. These will be for the first two shop visits after a total time of 29,000-30,000EFC, or 40,000EFH, equivalent to about eight years of operation and equal to a reserve of about $55 per EFH. Added to this will be the cost of a full set of LLPs. This will add another $45 per EFH, taking total cost to about $100 per EFH.

As the engine matures, on-wing intervals for high rated engines are expected to be 10,000EFH/7,000EFC. Shop visit costs will rise in parallel to an average of about $1.2 million, raising maintenance reserve to about $120 per EFH. LLPs will add about $60 per EFH, taking the total to about $180 per EFH from after the second removal. The third removal, however, will come at a total time of about 50,000EFH, which is equal to about 12 years of operation.

This mature rate reflects the maintenance reserve of about $190 that airlines currently typically pay engine lessors for the CFM56-7.