The CFM56-3 is a mature engine and operates in large numbers. There are four different thrust ratings with a wide range of EGT margins and shop visit intervals as a result. These have to be considered against LLP lives to achieve the lowest possible costs per engine flight hour.

CFM56-3B1/B2/C1 maintenance cost analysis

The CFM56-3 is one of the most numerous engine types in the civil aircraft fleet. The first engine entered service in late 1984 and the last was manufactured in 2002, although after this spare engines could be purchased with up to a 24 month lead time. Given that civil aircraft can operate for up to an age of 30 years, the CFM56-3 could still be in operation in 2030. The CFM56-3 is the sole powerplant for the 737-300/-400/-500, of which almost 2,000 were built, putting more than 4,400 CFM56-3s on the market when spare units are considered. The CFM56-3's maintenance costs were first analysed in 1999 *(see CFM56-3 & -5A/B maintenance costs, Aircraft Commerce, November/December 1999, page 26)*. Now that the engine has reached maturity, and may soon enter operation with freight carriers on converted 737-300s, an updated analysis of its maintenance costs is required.

CFM56-3 in operation

There are three major CFM56-3 variants. The first to enter service was the -3B1 and rated at 18,500lbs and 20,000lbs. This engine powers the lower gross weight version of the intermediate-sized 737-300 and the smaller 737-500. The -300 is the most dominant of the family, with 1,100 having been built. About 400 -500s were constructed.

The -3B2 is rated at 22,000lbs thrust, but can be de-rated to the two lower ratings. The -3B2 powers the lower gross weight variant of the largest -400 model, and also the higher gross weight variant of the -300. The de-rated -3B2 would also be used to power the lower gross weight -300 and the -500.

The -3C1 is rated at 23,500lbs, and entered service in September 1988. This powers the higher gross weight variant of the -400, but is also de-rated for use on the -300 and -500. The -3C1 is also the most numerous of CFM56-3s built, and superseded the -3B2 and -3B1.

To date the CFM56-3 series has accumulated 130 million engine flight hours (EFH) of operational experience, and about 10 million EFH over the past 12 months. This indicates the fleet of about 2,000 aircraft generates about 2,500 flight hours (FH) per year each. The overall ratio of EFH to engine flight cycles (EFC) is about 1.4:1.0, or 84 minutes flight time per average flight.

Operations vary widely. While the global average EFC time is 1.4EFH, many European airlines use the 737 on shuttle routes and have average cycle times of 1.0-1.2 EFH, generating 2,000-2,500EFH per year. European charter airlines achieve average cycles of 2.0EFH or more and utilisations up to 3,500EFH. US carriers are more representative of the global average, although many 737s are used on shuttle routes in the north-eastern US where average EFC times are close to 1.0EFH.

CFM56-3 variants

The CFM56-3's four thrust ratings means it also has four exhaust gas temperature (EGT) margins. These deteriorate with operation, and force removals for a shop visit when reduced to near zero. Their initial levels thus have a bearing on timing of engine removal and maintenance management. EGT margins are highest for new engines.

A new -3B1, or engines rated at 18,500lbs, has a test cell EGT margin of about 140 degrees centigrade, although the installed margin will be about five degrees less.

The -3B2, or engine rated at 20,000lbs, has an installed EGT margin of about 110 degrees centigrade.

The EGT margin of higher rated engines is lower, at about 70 degrees for the 22,000lbs rating and 50 degrees for the 23,500lbs rating.

Because the CFM56-3 is used in short-haul operations, the principal factors in the engine's maintenance management are EGT margin deterioration, EFH:EFC ratio and lives of life limited parts (LLPs).

The engine has three groups of LLPs with lives of about 20,000EFC, 25,000EFC and 30,000EFC. The lives of the first group can thus be used in a relatively short period. Moreover, because the engine is operated on short cycles and EGT margin deterioration is related to accumulated EFCs on-wing, EGT margin reduces at a high rate relative to EFH on-wing when compared to an engine operating long average cycle times.

This implies that both EGT margin deterioration and LLP life expiry will account for a high percentage of engine removals, and therefore influence maintenance management. The issue is complicated by LLP lives varying with thrust rating: lower rated engines have the longest lives, and the highest rated engines have the shortest lives. Since engines can be used at different ratings, engine management personnel are required to calculate the lives allowed for LLPs by using tables which take into consideration the number of cycles accumulated at each thrust rating.

The lives of LLPs for each thrust rating are shown *(see table, page 28)*. There are several different part numbers for each LLP which also have different lives. The longest life for each part is shown, but engines will have LLPs with shorter lives installed. The Stage 2 low pressure turbine (LPT) disk in the -3C1 engine, for example, can have a life of 13,900 EFCs while other part numbers have a life of 25,000 EFCs.

LIFE LIMITS IN EFCs FOR CFM56-3 LLPs

LLP	List price $	Life-EFC -3C1	Life-EFC -3B2	Life-EFC -3B1
Fan disk	78,250	30,000	30,000	30,000
Booster spool	113,290	30,000	30,000	30,000
Fan shaft	70,850	30,000	30,000	30,000
Total	**262,390**			
HPC front shaft	48,720	20,000	20,000	20,000
HPC stage 1-2 spool	77,210	20,000	20,000	20,000
HPC stage 3 disk	24,120	20,000	20,000	20,000
HPC stage 4-9 spool	173,650	15,800	20,000	20,000
HPC CDP seal	34,760	15,000	18,000	20,000
HPT front air seal	64,690	15,100	15,800	20,000
HPT front shaft	60,880	17,000	17,300	20,000
HPT disk	116,140	16,600	18,500	20,000
HPT rear shaft	47,680	15,800	20,000	25,000
Total	**647,850**			
Stage 1 LPT disk	53,970	25,000	25,000	25,000
Stage 2 LPT disk	61,830	25,000	25,000	25,000
Stage 3 LPT disk	62,420	25,000	25,000	25,000
Stage 4 LPT disk	53,970	25,000	25,000	25,000
LPT shaft	100,450	30,000	30,000	30,000
LPT stub shaft	35,080	20,000	25,000	25,000
Conical support	41,880	25,000	25,000	25,000
Total	**409,600**			

EGT margin deterioration

The rate of EGT margin deterioration is generally higher for high rated engines. "All engines also suffer a high initial rate of EGT margin deterioration in the first 1,000EFCs due to 'running in' of rotor/stator clearances ," says Nick Hankins, engine programme manager at Total Engine Support. "The later built CFM56-3s have a better hardware standard than the earlier built engines and so have a lower rate of EGT margin deterioration. For example, earlier build engines utilised X40 material for the high pressure turbine (HPT) nozzles of which the nozzle areas tended to open during operation, causing EGT margin to erode. A new material, DSR142, released in 1990, made the nozzles more stable and so the EGT margin deterioration was not so rapid. As earlier build engines have gone through shop visits their older hardware has been replaced with younger material, and so their reliability and EGT margin deterioration rate have improved."

Most engines lose about 10 degrees of EGT margin during the first 1,000EFC on-wing, but the amount lost varies with thrust rating. This would take margins down to about 40 degrees for those rated at 23,500lbs, 60 degrees for those rated at 22,000lbs, 100 degrees for ones rated at 20,000lbs and about 130 degrees for ones at 18,500lbs. "The large differences in margin between high- and low-rated engines means that operators de-rate engines wherever possible," explains Hankins "This has the result of making gains in EGT margin and potential on-wing time."

Rate of EGT margin deterioration reduces to a lower rate after the initial loss following the first 1,000-2,000EFCs on-wing. The actual rate will depend on a variety of operational factors, in particular take-off weight of aircraft, engine thrust rating, EFH:EFC ratio and pilot de-rate at take-off.

"Rates of deterioration for the -3C1 are about 4.4 degrees per 1,000EFC after the initial 1,000EFC during the first run," says Graham Crawford, general manager at Pratt & Whitney Norway Engine Centre. "Therefore after the initial loss, the -3C1 or 23,500lbs engine with about 40 degrees of margin remaining can be expected to have another 9,000EFC on-wing before all EGT margin is used. Some operators do get as long as 20,000EFC on-wing, however. The rate of deterioration also depends on the engine's hardware standard."

David Beale, project leader CFM56 at MTU Maintenance estimates EGT margin loss will be in the region of four degrees per 1,000EFC for low rated engines, and as high as six or seven degrees per 1,000EFC for high rated powerplants. A 23,500lbs engine may therefore only achieve about 8,500EFCs before removal due to complete EGT margin erosion.

Crawford uses the effect of operating environment on the rate of EGT margin deterioration to make his point. Pratt & Whitney Norway manages Braathens' CFM56-3s, which are operated in a cool environment. "A 23,500lbs engine may lose about 4.4 degrees per 1,000EFC, a 22,000lbs engine about 3.0 degrees, a 20,000lbs engine in the region of 2.2 degrees and an 18,500lbs engine about 2.0 degrees per 1,000EFC."

After losing about 10 degrees in the first 1,000EFC, a 22,000lbs engine will have about 60 degrees margin left and so last for about another 11,000EFC, taking total interval to 11,500-12,000EFC.

Low rates of EGT margin loss for lower rated engines imply that EGT margin will not be a deciding factor in their removal. "The EGT margin loss for a 23,500lbs engine after 6,000EFC on-wing is 15-20 degrees more than an engine rated at 18,500EFC. The rate of deterioration also depends on pilot de-rate, based on aircraft weight, runway length and temperature, as well as warm-up and maintenance practices like water-wash. The variance in pilot de-rate is 0-20%, and typically 10-15%," explains Francis Nocchi, CFM56-3/-7 product director long-term contracts at Snecma Services. "A good level of pilot de-rate requires good pilot training and engineering management, and can extend on-wing life. A 10% pilot de-rate is like a 22,000lbs engine operating like a 20,000lbs engine, with the consequent benefit of improving life by about 1,000EFC."

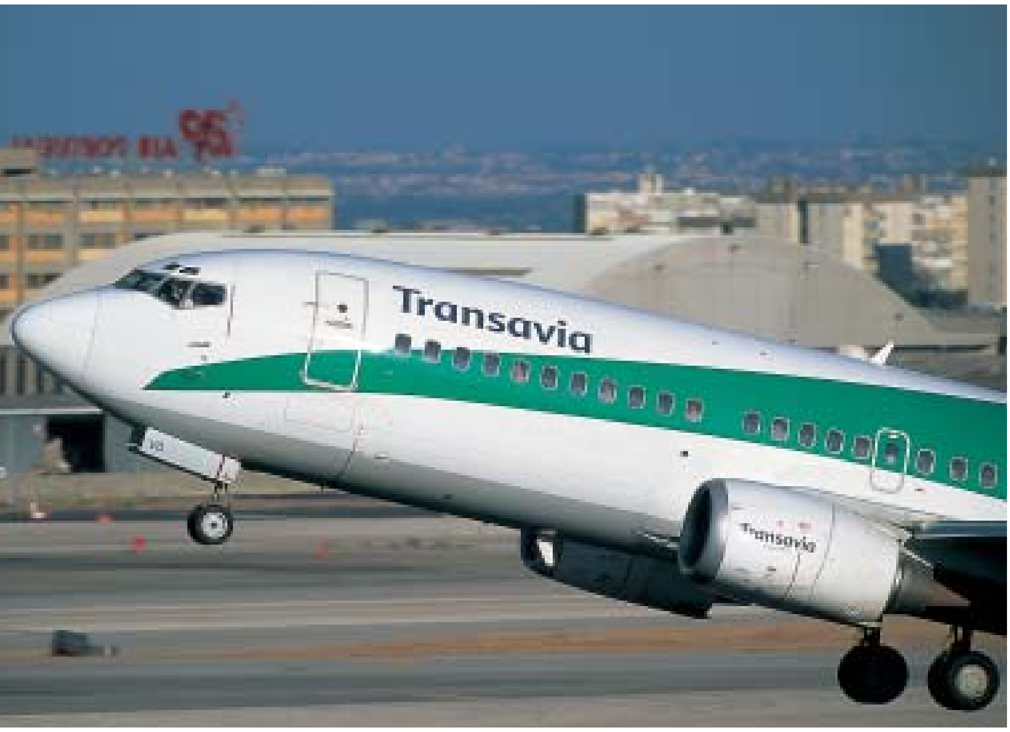
Lower thrust rated first run variants can have a large enough EGT margin for potential on-wing interval to last for 20,000EFC. A 20,000lbs engine, for example, will still have about 100 degrees remaining after the first 1,000-2,000EFC on-wing. At a deterioration rate of about 3 degrees per 1,000EFC it could therefore last for another 20,000EFC before using all its margin. LLP lives of 20,000EFC in the core section will, however, limit its first on-wing run, with some EGT margin still remaining at first removal.

The same applies to 18,500lbs engines, which will have an even larger amount of EGT margin remaining at removal.

1st on-wing intervals

Most CFM56-3s are now past their first on-wing interval and shop visit, although some of the last built -3C1s delivered in the late 1990s have still yet to be removed for the first time. Lufthansa, for example, operates a fleet of 737-300s/-500s that were delivered between 1986 and 1995. These are powered with -3B1s, -3B2s and -3C1s all rated at 20,000lbs, and are used on European and German domestic routes at an average EFC time of 1.0EFH.

"We still have some first run engines,"



The CFM56-3 series operates on average EFH:EFC ratios of 1.4:1, meaning LLP management is an integral part of engine maintenance management. The different lives of LLPs in the CFM56-3's core, LPT and fan/booster sections mean a balance has to be struck between removal intervals, shop visit workscopes and LLP replacement.

says Markus Kleinhans, propulsion systems engineering CFM56-3/-7B at Lufthansa Technik. "The rest of the fleet is mature. We see an initial EGT margin loss of about 10 degrees in the first 2,000EFC, which is then followed by a loss of about three degrees per 1,000EFC. The older built -3B1s had production test cell margins of 100 degrees, while the younger build engines had margins of about 120 degrees. Because of these high initial margins many first run engines have achieved intervals of 18,000-20,000EFC. This is why we have some first run engines still on-wing. The main removal causes for the first removal are thus LLP life expiry and EGT margin loss and which sometimes coincide. LLP expiry has been the main cause for removals, while some engines have used all EGT margin. Hardware and technical problems have been remote. Earlier build engines had technical problems with the HPT nozzle guide vane and other parts like C-clips, but these have been overcome with newer material."

Beale confirms that, generally, lower rated engines are capable of first run intervals that can be almost as long as LLP lives. "First run removals are mainly due to engine performance and LLP expiry. Engines at 18,500lbs can often go all the way to 20,000EFC, while 20,000lbs engines average about 17,000EFC, with EGT margin deterioration causing removals prior to LLP expiry. Higher rated engines have shorter runs due to EGT and performance erosion. Engines at 22,000lbs typically come off at about 11,500EFC, and 23,500lbs engines at about 8,500EFC," says Beale.

Crawford reports similar performance. "Because some removals are due to technical issues and unscheduled causes, the average for lower rated engines is 12,000-16,000EFC," explains Crawford. "Low thrust engines are mainly removed due to LLP limitation, because EGT margin is high. Higher rated engines typically get about 9,000EFC at first removal due to EGT margin loss."

Restored EGT margin

Following the first shop visit EGT margin is not fully regained, but is normally restored to 70-75% of its original level in most cases. "The actual restored margin depends on the shop visit workscope performed and the shop itself," explains Hankins. "This will be accomplished if the shop visit involves a performance restoration, but will be lower if just the hot section is worked on."

"The EGT margins following the first shop visit will be 30-35 degrees for a 23,500lbs engine," says Crawford. A margin of 45-50 degrees can be expected for a 22,000lbs engine, and about 85 degrees for 20,000lbs and 18,500lbs engines.

"EGT margin deterioration rate after the first shop visit will be similar to the first run," explains Nocchi. "The time on-wing for the second interval could therefore be about 75% of the first." A high rated engine might then be expected to get a second run of 6,000-7,000EFC. This would take total time at the second visit to 14,000-17,000EFC. A shorter run would allow a third run before core LLPs were replaced at the third shop visit, while a longer run of say 17,000EFC would require their replacement at the second."

Engines rated at 22,000lbs would have enough restored EGT margin to have a second on-wing run of about 9,000EFC. This would take total time to the second run up to 20,000EFC, which would coincide with the lives of core LLPs. These would have to be replaced at this stage. If total time to the second removal had been 18,000EFC or less, then the LPT LLPs could be left if a subsequent third run of about 7,000EFC was expected. If total time at the second visit was more than 18,500EFC then LPT LLPs would have remaining lives of 7,000EFC or less. If the expected subsequent third on-wing interval was longer than 7,000EFC it would thus require replacement of LPT LLPs at the second shop visit to prevent the third run from being limited. Since LLPs are expensive, operators have to strike a balance between maximising the use of LLP lives and maximising on-wing life. LPT LLPs, for example, have a list price of more than $400,000 *(see table, page 28)*. Optimisation can be achieved, however, by swapping LLPs.

"Engines rated at 20,000lbs and 18,500lbs typically have a second run of 12,000-15,000EFC," says Hankins. This would only be possible if the 20,000EFC LLPs in the engine core had been replaced at the first shop visit. Replacement of the LPT LLPs with lives of 25,000EFC would also be necessary at the first to avoid limiting the second run.

Kleinhans explains that Lufthansa Technik achieves a first interval of about 19,000EFC for its -3s rated at 20,000lbs and replaces core and LPT LLPs at the first shop visit. "The second interval has been 7,000-8,000EFC, although we expect this to improve to about 9,000-10,000EFC, but it will be limited to this by fan and booster LLPs. This will take total time to about 28,000EFC at the second visit, at which point we replace will fan and booster LLPs. Economical inputs will further lead to intervals of about 10,000EFC in order to optimise LLP usage."

Mature engines

Restored EGT margin after the second shop visit will be similar to that following the first. "While it will be 70-75% of the original after the first, it will

POSSIBLE MANAGEMENT, SHOP VISIT PATTERN & LLP REPLACEMENT TIMING OF CFM56-3 SERIES ENGINES

Removal	Interval EFC	Accumulated EFC	Workscope interval-EFC	Cost-$	$/EFC	LLP replacement	LLP cost $	LLP $/EFC	Total $/EFC	Total $/EFH
23,500lbs engine										
1st	8,500	8,500	Core	800,000	94	-	-	71	165	118
2nd	6,500	15,000	Heavy core	900,000	138	Core	650,000	71	208	148
3rd	6,500	21,500	Core + LPT	950,000	146	LPT	410,000	78	224	160
4th	6,500	28,000	Core + Fan	950,000	146	Fan	265,000	80	226	161
22,000lbs engine										
1st	11,000	11,000	Core	850,000	77	-	-	63	140	100
2nd	9,000	20,000	Core + LPT	1,000,000	111	Core + LPT	1,060,000	63	174	124
3rd	8,500	28,500	Core + Fan	1,050,000	124	Fan	265,000	66	190	136
4th	8,500	37,000	Core	900,000	106	Core	650,000	67	173	124
20,000lbs & 18,500lbs engines										
1st	18,500	18,500	Core +LPT	950,000	51	Core + LPT	1,060,000	66	117	84
2nd	11,500	30,000	Core + Fan	1,000,000	87	Fan	265,000	69	156	111
3rd	11,000	41,000	Core + LPT	1,000,000	91	Core + LPT	1,060,000	69	160	114
4th	11,000	52,000	Core	850,000	77	-	-	60	170	121

be slightly lower at about 65% of the original after the second and then stabilise," explains Hankins. This will allow third and subsequent on-wing intervals to be slightly less than the second. "Although we do not operate the CFM56-3 any longer ourselves, we still control maintenance for several fleets of mature engines," says Antonio Ferreira, engine maintenance customer programme manager CFM56 at TAP Maintenance & Engineering. "Mature EGT margins after a shop visit are 35-37 degrees for a 23,500lbs engine and 40-24 degrees for a 22,000lbs engine. The actual level depends on the shop visit. Another five degrees can be gained if the fan and booster section are worked on. The -B1 engines are rare, with most being -B2s and -3C1s. The -3B1s may have a mature EGT margin of 85 degrees after each shop visit. The younger build -3C1s are better than older engines because the hardware standard has been updated over the years. This means we are now able to get the same performance from older and younger engines.

"About eight degrees of EGT margin is lost in the first 500 EFC, and then declines at 3-6 degrees per 1,000EFC," continues Ferreira. "This means -B1s or 20,000lbs and 18,500lbs engines can have on-wing intervals of up to 17,000EFC, -3B2 or 22,000lbs engines intervals of about 8,000-10,00EFC and -3C1 or 23,500lbs engines of 7,000-8,000EFC."

Engine management

Engine management has to be considered in relation to on-wing intervals and LLP replacement timing for different rated engines. As previously described, the replacement of LLPs will have to be considered to avoid limiting on-wing intervals by leaving LLPs in the engine with lives shorter than possible intervals allowed by restored EGT margin.

Two considerations have to be made, first in respect of first run and young engines, and second in respect of mature engines. In both cases removal intervals have to be considered against optimising LLP replacement. This can be made easier by engine shops taking out LLPs with remaining lives that would limit a subsequent on-wing run, selling them on the aftermarket or swapping them with LLPs with longer remaining lives that would then allow a longer interval. This is not always possible, and this analysis looks at circumstances where intervals have to be optimised for the best LLP utilisation.

23,500lbs engine

As described, engines rated at 23,500lbs have first runs of about 8,500EFC and second runs of 5,000-7,000EFC, taking total time to 13,500-15,500EFC. Since the third and mature interval is expected to be 4,000-7,000EFC, core LLPs would be replaced at the second shop visit *(see table, this page)*. Total time at the third shop visit would be 20,000-23,000EFC, which would be optimum for replacing LPT LLPs. A similar interval for the fourth run would take total time to 28,000-30,000 and would provide an appropriate opportunity for replacing fan and booster LLPs.

Once mature, shop visit intervals are expected to average about 7,000EFC. Core LLPs could either be replaced every second or third shop visit, either every 14,000EFC or 20,000EFC, and each engine would have to be treated individually. The LPT LLPs could be replaced every third visit, or every 21,000-22,000. In terms of LLP amortisation, the most economic scenario is where a third shop visit is performed at 20,000EFC and both core and LPT LLPs are replaced *(see table, this page)*.

Fan and booster LLPs would be replaced every fourth shop visit, at about 27,000EFC.

22,000lbs engine

The first run for 22,000lbs engines will average 12,000EFC, with the engine being capable of a subsequent 9,000EFC for the second. Total time to the second removal will thus be limited to 20,000EFC, at which point core LLPs would be fully utilised and replaced. Since the third run could be 8,000-

Shop visit workscopes vary in content from core and performance restorations to full overhauls of all three major modules. Depending on thrust rating and removal interval, the LPT module only need to be worked on every second or third shop visits and the fan/booster module every third or fourth shop visit.

10,000EFC, it would also be prudent to replace LPT LLPs at this point *(see table, this page)*. Total time to the third removal would thus be 28,000-30,000EFC, at which point fan and booster LLPs could be replaced.

Mature average removal interval would be 8,000-10,000EFC. Core LLPs would thus be replaced every second shop visit at about every 16,000EFC, while fan, booster and LPT LLPs would be replaced every third shop visit about every 24,000-25,000EFC *(see table, page 32)*.

20,000lbs & 18,500lbs engines

These engines can be expected to have a first interval of 17,000-20,000EFC, and second run of 12,000-18,000EFC. It would thus be prudent to replace all LLPs at the first shop visit, unless a shorter first run meant fan and booster LLPs could be kept in until the second removal, limiting total time at this stage to 30,000EFC *(see table, page 32)*.

Mature engines will have average intervals of 10,000-14,000EFC. Shorter intervals would mean core and LPT LLPs would be replaced every second shop visit and fan and booster LLPs every third visit. Longer intervals would mean core LLPs every visit, but LPT, fan and booster LLPs every second visit *(see table, page 32)*.

These expected shop visit intervals are a guide, but operators in different environments will achieve different intervals. Delta, for example, operates 17 737-300s at Salt Lake City on routes averaging 1.6EFH, and another nine aircraft on the east coast in a shuttle operation with cycles averaging 0.7EFH. All are powered by -3B1 engines rated at 20,000lbs. "The combined fleet loses 6-7 degrees per 1,000EFC due to hot operations at Salt Lake City and short cycle shuttle operations," explains Teri Chiong senior propulsion engineer at Delta TechOps. "The aircraft were acquired through leases and most engines are second run. Most removals (85%) are due to EGT margin and LLP limitation, and the remainder unscheduled due to technical problems. Our mature on-wing removals interval is about 9,000EFH and we build engines in the shop for a minimum of 6,000EFC. We can only go down to an EGT margin of 44 degrees for our Salt Lake City operation, and engines come out of the shop with a margin in the region of 77 degrees. This 44 degrees margin has to be left for hot operations, and means we only get about 35 degrees of margin to use and so only get a short on-wing life of 6,000-7,000EFC. We have a disk management programme to allow for these intervals and do a core and performance restoration every shop visit, LPT every second or third visit, and fan and booster section every third visit."

1st shop visit workscopes

First shop visit workscopes will depend on time accumulated on-wing and expected next interval, as well as LLP replacement requirement.

"Engines rated at 23,500lbs will have been removed mainly due to performance deterioration," explains Crawford. "These engines will have had about 8,500EFC on-wing and so require a performance and core restoration, which will involve work on the HPC, combustion section and HPT. The LPT, booster and fan sections can be left."

Hankins explains that an engine can be basically split into performance modules and non-performance modules. "The performance modules include the HPC, combustor and HPT, while the non-performance modules are the fan, booster, and LPT," says Hankins. "The idea at the first workscope is to balance the second interval with the remaining LLP lives. The cost of disassembling, inspecting, repairing and re-assembling the LPT, for example, is about $200,000. It is therefore better to leave the LPT if the EGT margin will allow an interval that closely matches the remaining LLP lives. The first run of a 23,500lbs engine means all LLPs can be left, so the core LLPs will have 10,000-11,500EFC left and LPT LLPs will have 15,000-16,500EFC left."

Although nearly all performance-related removals at the first visit will be EGT and LLP related, Beale explains that the problem lies with intermediate and unscheduled workscopes. Some smaller shop visits can be performed that allow engines to be re-installed and so avoid a major workscope after a short interval. These are being developed by some shops.

Engines rated at 22,000lbs, having accumulated 12,000EFC on-wing will have a similar workscope to 23,500lbs engines, and will have 8,000EFC remaining for their core LLPs.

Low thrust rated engines, which will have achieved 17,000-20,000EFC on-wing will need to have core and possibly LPT LLPs replaced since they would have 5,000-8,000EFC remaining and this could limit and otherwise longer run. Some shops may avoid work on the LPT if there is a little as 6,000EFC left of the LLPs. Again a core and performance restoration will be required, but the need to replace LPT LLPs will also require work on the LPT. Because the engines may still have some EGT margin remaining at removal a refurbishment of just the hot section may be sufficient, rather than a full core refurbishment.

2nd shop visit workscope

At this stage a 23,500lbs engine will have a total time of 15,000EFC, when core LLPs would have to be replaced, but all others left in. The engine would thus require a further core and performance

Savings in shop visit workscope costs and overall costs per EFH can be made through careful engine management, the use of hi-tech repairs that reduce the number of parts replaced and using small repair workscopes that avoid the requirement for a full shop visit.

restoration, but a heavier visit than the first so that LLPs could be replaced.

The fan and booster sections would be left until the third shop visit.

A 22,000lbs engine will have used all its core LLP lives, and will also need to have LPT LLPs replaced. The engine would thus have a core restoration and workscope on the LPT. The fan and booster could be left until the third shop visit, depending upon the actual hard cycles remaining in the LLPs of the LPT and fan.

Low thrust rated engines will probably be removed at a total time close to 30,000EFC, and so have fan and booster LLPs replaced. A core and performance restoration would also be required, as well as a full workscope on the fan and booster. The LPT, having been worked on at the first shop visit, could be left until the third shop visit. If the engine had had a relatively short first run of about 16,000EFC, the LPT would be left until the second shop visit.

Mature shop visit workscopes

Once mature, all engines would require a performance and core restoration every shop visit. The LPT and fan and booster sections could be worked on in accordance with LLP replacement timing, as previously described.

Shop visit inputs

There are three main types of shop visit workscopes that engines could require during the course of their operation. The type required will depend on remaining LLP lives and time on-wing.

The simplest is the core and performance restoration. Beale estimates this will use about 1,500 man-hours (MH) of routine labour, $400,000-500,000 for materials and $200,000-300,000 in repairs. At a labour rate of $70 per MH the total cost would work out at $700,000-950,000, excluding any LLPs. "The industry is entering a phase where the cost of materials may actually start dropping due to increasing availability of PMA parts and third party hi-tech repairs, plus the recent appearance of increasing amounts of surplus use-unserviceable material on the market.

Nocchi's estimate of the cost of a performance restoration is similar at $800,000-900,000.

The two types of possible intermediate workscopes are: a core and performance restoration combined with either a LPT workscope or with a fan and booster workscope. Nocchi highlights that different actions implemented by Snecma Services like fleet management, workscoping optimisation and increasing repair solutions drive down costs by more than 15%.

A workscope on either the fan and booster or on the LPT will add about $20,000 to the cost of a core and performance restoration. The total for either would be about $0.90-1.1 million.

The largest possible shop visit would be a full overhaul workscope, where all major modules are worked on. Beale estimates this would require about 2,200MH routine work, $650,000-800,000 in materials and $250,000-330,000 in repairs. The total for this would be $1.0-1.4 million.

These costs, and the costs of LLPs, have to be considered in relation to time on-wing for early removals and for mature removal intervals *(see table page 32)*.

The possible pattern of shop visits and workscopes for engines rated at 23,500lbs up to their third removal is summarised *(see table, page 32)*. This shows engine shop visit costs per EFC rising from an initial low of $94/EFC to $146/EFC at the third removal due to a reduction in interval and requirement to increase workscope due to the LPT module. Taking average EFC to be 1.4EFH, this is equal to an initial rate of $67/EFH and rising to $104/EFH.

Over the same period LLPs are also replaced, with initial amortisation rates at about $71/EFC and rising to $78/EFC at the third shop visit due to the timing of the replacement of different LLPs. This equates to $51/EFH and $56/EFH. This takes total costs to $118/EFH in the initial period and $160/EFH by the third shop visit *(see table, page 32)*.

A mature engine will have a steady rate of about $146/EFC for shop visit workscope costs, equal to $104/EFH. LLP amortisation rate by this stage will be equal to about $80/EFC, or $57/EFH. Total costs will thus be in the region of $161/EFH.

An engine rated at 22,000lbs will have an initial shop visit cost of $77/EFC, equal to $55/EFH. LLP amortisation at this stage is equal to $63/EFC, or $45/EFH, taking total costs to $100/EFH *(see table, page 32)*.

By the third shop visit, costs have increased to $124/EFC or $89/EFH, and LLP amortisation has reached $66/EFC or $47/EFH, taking total costs to $136/EFH *(see table, page 32)*.

A mature engine will have shop visit costs of about $110-128/EFC or $92/EFH and LLP amortisation costs of $67/EFC or 48/EFH; with total costs at $125-140/EFH *(see table, page 32)*.

A low thrust rated engine will have initial shop visit costs of $51/EFC or $36/EFH. LLP amortisation will be equal to $66/EFC or $47/EFH, with total costs at $84/EFH *(see table, page 32)*.

By the third shop visit costs will have reached $91/EFC or $65/EFH, while LLP amortisation will have reached about $69/EFC or $49/EFH and a total cost of $114/EFH *(see table, page 32)*.

A mature engine will have shop visit costs in the region of $80-110/EFC or $57-72/EFH and LLP amortisation of about $60/EFC, taking total costs to about $100-120/EFH *(see table, page 32)*. AC