The JT9D, PW4000, CF6-50C2 & CF6-80C2 series are the most numerous widebody engines and power the same and similar aircraft types. Maintenance costs analyses for each type have been updated and reserves compared between the four families.

Maintenance cost analysis: JT9D, PW4000 & CF6-50/80

The JT9D, PW4000-94, CF6-50 and CF6-80C2 are the most populous group of engines, with similar thrust ratings, powering widebodies. Their maintenance costs have a large influence on total operating costs of a large number of widebodies.

The maintenance costs of these engines have already been analysed. This analysis updates previous examinations of maintenance costs and compares the four engine families.

Engines in operation

The JT9D has several variants; the -7A, -7F, -7J, -7Q, -70A and -7R4 series. Few older variants operate, and most are on 747Fs. The only variant operated in significant numbers are the 53,000lbs & 54,000lbs rated -7Q and -7R4G2 on high gross weight on passenger and freighter 747-200s and 747-300s. The -7R4 also powers a small number of A300-600s, A310s and 767-200s.

Typical operations are average flight lengths of 5-6 flight hours (FH) with 747-200Fs/-300Fs and 6-8EFH for passenger configured 747s.

The CF6-50 was a dominant widebody engine for a sustained period. It powered the 206 DC-10-30s built and about 200 747-200s. The number of these in active service is falling. A large volume of DC-10-30s have been parked. The total number of DC-10-30s that will be converted to freighter is unlikely to exceed about 80 units, and so the number of active aircraft will decrease. A large number of CF6-50-powered 747-200s were converted to freighters, but this activity has now stopped. Like the DC-10-30, the number of active CF6-50-powered 747-200s will diminish.

The CF6-50 also powers the A300B2/4. The majority of good quality aircraft have already been converted to freighter, and few others are likely to remain in service. The A300B2/4 therefore accounts for a minority of CF6-50s, although their maintenance costs influence the aircraft's continued viability.

The PW4000-94 (94-inch fan variant) continues to increase in numbers, and about 1,900 are in operation. The PW4000-94 has one of the widest applications of any engine type. It has thrust ratings between 52,000lbs and 62,000lbs. There are few 52,000lbs and 58,000lbs engines in operation, and the three other thrust ratings account for the majority in service.

The CF6-80A/80C2 has the same width of application and thrust ratings as the PW4000-94. The CF6-80A/C2 series has been more successful than the PW4000-94, with about 2,800 engines in operation.

The range of thrust ratings and applications means there is a wide variation in levels of de-rate, average engine flight cycle (EFC) time and operating environments. These factors all affect on-wing longevity and engine deterioration, and therefore, maintenance costs.

Engine management

Engine operation and maintenance can be managed to minimise maintenance costs and amortised rates per FH. "On-wing times that are possible due to engine performance should be matched with limits allowed by airworthiness directives (ADs), life limited parts (LLPs) and the shop visit (SV) workscopes to achieve the lowest cost per engine flight hour (EFH)," says Lutz Winkler, manager engineering GE engines at MTU Maintenance.

Higher SV workscopes mean that a higher percentage of parts is replaced and more man-hours (MH) are consumed to disassemble and assemble the engine for more detailed work. Higher or larger workscopes can be used to build engines for longer on-wing times. These can be limited or compromised by ADs and LLPs. Similarly, LLPs should not be left in engines if their lives are shorter than the anticipated life following the shop visit. Most JT9D, PW4000, CF6-50 and CF6-80 engines operating medium- or long-haul sectors with an average EFC time of 5.0EFH or more normally achieve removal intervals in the range of 2,500-3,000EFC. LLPs with remaining lives shorter than this should be removed at the shop visit to prevent compromising the on-wing interval. These expected intervals are the basis for 'stub life' policy for LLP removal followed by most operators.

Other ADs affect the on-wing times of some engines to different extents, by the need for regular inspections at intervals in the order of 2,000-3,000EFC. This means engines with this limit imposed should have workscopes tailored to provide an EGT margin and performance level that allows a similar on-wing interval. Higher workscopes will only incur large SV costs with no economic benefit.

EGT margin & deterioration

This raises the issue of what factors affect on-wing intervals and what intervals can be expected. The main factor affecting on-wing times is exhaust gas temperature (EGT) margin. This depends on engine variant and thrust rating, and previous shop visit workscope. EGT margin is also affected by outside air temperature. Engines operating in a hot environment will have a reduced margin compared to those in a cool one.

EGT margin erosion then depends again on thrust rating, de-rate in operation and average EFC time. Longer cycles and higher de-rate, and lower thrust rating all reduce EGT margin erosion and prolong on-wing life.

There are two specification levels of the PW4000: the Phase I and Phase III levels. The Phase III modification package

United's 747-400s operate average cycles of almost 8 flight hours. Aircraft only generate about 700 flight cycles per year, and the highest engines have only accumulated about 6,600 flight cycles since new. This compares to LLP lives of 20,000 flight cycles in its engines, which are unlikely to ever be replaced.

improved the fan blades, high pressure compressor (HPC) casing and high pressure turbine (HPT) airfoils, to reduce fuel burn and increase EGT margin. EGT margins of Phase III engines after a shop visit are 35-45 degrees centigrade, depending on variant and thrust rating. Margins of 30-35 degrees are typical for repaired PW4060/62 engines.

United illustrates the variation of EGT margin with thrust rating. Its PW4052s have an EGT margin of 47 degrees, its PW4056s an EGT margin of 48 degrees and its PW4060s an EGT margin of 31 degrees.

EGT margin erosion rates are in the order of 1.5 degrees centigrade per 1,000EFH, although much affected by EFCs on-wing. EGT margin thus allows potential on-wing times to exceed 20,000EFH. Many operators comment that EGT margin erosion is not a main cause of PW4000 removals. The rate of engine condition deterioration is also slow, thus allowing long on-wing times.

Andree Christianhemmers, propulsion systems engineering CF6-50, at Lufthansa Technik says EGT margin erosion on Condor's PW4000s is about 2 degrees per 1,000EFH. This indicates on-wing intervals of up to 18,000EFH are possible.

The CF6-50 has an EGT margin of 25-30 degrees centigrade. KLM still operates it on its 747-200s and -300s, and records a deterioration rate of about three degrees per 1,000EFH. Lufthansa, which still uses the CF6-50 on the 747-200 and -200F, has a margin of about 30 degrees and erosion rate of 2.5 degrees per 1,000EFH. This implies a possible on-wing interval of up to 12,000EFH. "We operate the -200s at an average EFC of 8.0EFH and -200Fs at 5.5EFH per EFC," says Christianhemmers.

Finnair manages CF6-50 maintenance for third party customers. "The DC-10-30's of Air Liberte have EFCs of 6-7EFH and a standard day EGT margin of 25-30 degrees," says Janne Tarvainen, CF6 engineering manager at Finnair. "EGT margin erodes at about 2-4 degrees per 1,000EFH, which would allow an on-wing time of about 10,000EFH. The A300B4 is different and EFCs are 2-3 EFH."

The CF6-80A/C2 series tends to have similar EGT margins to the PW4000 series, but a higher rate of deterioration, which leads to a greater limitation to on-wing times. Lufthansa is a large operator of the CF6-80C2A2/3/5, which power the A310-300 and A300-600. The -80C2A2 is rated at 54,000lbs and so has one of the highest EGT margins. "The -80C2A2 has an EGT margin about 49 degrees after a shop visit. It operates average EFC times of 1EFH and has a de-rate of 19%," says Burkhard Culeman, propulsion systems engineering CF6-80C2 at Lufthansa Technik. "EGT margin erosion is about 10 degrees for the first 2,000EFH and 6 degrees per 1,000EFH thereafter. This implies a possible on-wing time of up to 8,500EFH. The -80C2A3/5 powering our A300-600s and -600Rs are rated at 59,000lbs and have a lower EGT margin of about 37 degrees. Engine de-rate is is about 19%, while erosion rate is 12 degrees for the first 2,000EFH and about three degrees per 1,000EFH thereafter. This should allow an on-wing time of up to 10,000EFH."

The -80C2 is used in larger numbers on the 767, MD-11 and 747-400. Despite having a thrust rating of 61,500lbs, higher than the -80C2A3/5, the -B1F has a higher EGT margin of 48 degrees on the 747-400. "EGT erosion rate is about five degrees for the first 2,000EFH, and then about one degree per 1,000EFH thereafter. This almost implies an unlimited on-wing time," says Culeman.

KLM also operates the -B1F on the 747-400 and has a margin of about 50 degrees and erosion rate of 2-3 degrees per 1,000EFH. This would allow up to 25,000EFH on-wing.

KLM also operates the -D1F on the MD-11, the highest rating of 61,500lbs for the MD-11. This variant has a lower EGT margin of 30 degrees and erosion rate of 2-3 degrees per 1,000EFH. This implies the engine is only capable of an on-wing time of up to 12,000EFH.

Finnair also operates the -D1F and has an EGT margin of about 27 degrees. "A full authority digital engine control (FADEC) modifier can get an extra five degrees of margin and a hot day margin will add another 3-4 degrees. This can then take margin up to about 36 degrees, allowing a longer possible on-wing interval," says Tarvainen. "EGT margin erodes at 2-4 degrees per 1,000EFH, so an interval of about 12,000EFH is possible."

KLM also operates the -B6F on the 767-300ER, which has an EGT margin of 40 degrees. Erosion rate is similar to the -B1F and so possible on-wing time is up to about 16,000EFH. This is shorter than the on-wing intervals allowed by the PW4000 on the same aircraft.

On-wing intervals

Later variants of the JT9D have proved to be durable and to achieve longer average on-wing intervals than the CF6-50. SAA still operates the JT9D-7F, modified to a -7J standard, on its two 747SPs. The engines have operated average EFCs of 6.4EFH and achieve average intervals between all shop visits of about 8,000EFH.

SAA operates the JT9D-7R4G2 on its 747-200s and -300s. This JT9D variant has earned a reputation for achieving long intervals. SAA operates average EFCs of about 8EFH, and Joe Van Der Merwe, manager of powerplant engineering at South African Airways explains the airline has limited the hardware in the cold section of the engine to 21,000EFH between shop visits.

The JT9D series follows an approximate shop visit programme of alternating hot section inspections and and overhaul. "Typical time on-wing for

The CF6-80C2D1F powering the MD-11 is rated at 61,500lbs and has the highest rating of all CF6-80C2 series engines. It has an EGT margin in the region of 30 degrees centigrade and deterioration rate of about 2.5 degrees per 1,000EFH. This limits possible on-wing time to about 12,000EFH.

the first run to the hot section inspection for a -7R4G2 is about 10,000EFH, although it can be as much as 13,000EFH," says Der Merwe. "The second interval is thus limited to 8,000-11,000EFH by the limit of 21,000EFH for the cold section parts."

Snecma Services recommends its customers limit the -7R4G2's high pressure compressor shop visit interval to 20,000EFH, since longer intervals will lead to the possibility of stalls. Some airlines are even hard-timing their HPCs, and so effectively the overhaul interval.

SAA also operates the JT9D-7R4E on two 767-200ERs. Although these aircraft operate average cycle lengths of about 5EFH, half the time of the 747-200s, the engines are expected to achieve average intervals of 12,000EFH.

The -7R4G2 on the 747-200/-300 can get intervals of about 10,000EFH when operated on cycles averaging 8EFH. Engines operating shorter cycles, usually freight operations, will get intervals in the region of 9,000EFH. The -7Q series, now mainly operated on freighters, will achieve an overhaul interval of about 15,000EFH, so an average interval between shop visits of 7,500EFH.

The Phase III modified PW4000 has a reputation for being capable of long on-wing intervals. Delta Airlines operates the PW4060 on the 767-300s and MD-11s at average EFC times of 6EFH and 7EFH. The airline has set a goal of 18,000EFH between scheduled shop visits. About half the removals are due to high time on-wing and high accumulated time of the second stage high pressure turbine (HPT) blades. The engine is, however, subject to other removal causes, and unscheduled removals bring Delta's average interval down to 10,000EFH on both the airline's 767-300s and MD-11s.

The 767s operated by Condor have an average FC time of 6.5FH and achieve an average on-wing interval of 14,000EFH. "Most PW4000 removals for a shop visit are due to high time on-wing, that is 14,000-20,000EFH," says Culeman at Lufthansa.

The main AD affecting the PW4000-94 is AD 2001-09-07, which has been superseded by AD 2001-15-12. The AD requires an engine stall test in test cell every 2,300 cycles. An average EFC time of 6.5EFH thus results in an interval limited to 15,000EFH. It only affects certain serial numbers and these have modifications available for the HPC and HPT airfoils.

The CF6-50's possible on-wing interval is now limited by its relatively small EGT margin and high rate of deterioration. Tarvainen explains Finnair schedules 8,000-10,000EFH between removals on the DC-10-30. "A good interval for the A300B4 is 7,000EFH, since this is more than 2,000EFC. About two-thirds of CF6-50 removals are scheduled, and the engine has few specific problems that affect its on-wing interval," says Tarvainen. "Average actual interval for the -50 on the DC-10-30 is 7,500-8,000EFH (1,150EFC)."

KLM operates average EFC times of 6EFH for -50s used on its 747-200s/-300s. Main removal causes are EGT margin erosion and HPT blade damage. Average interval for all removals is about 7,000EFH (1,170EFC).

Lufthansa achieves an average interval for all removal causes of 10,000EFH (1,250EFC) for its passenger 747-200s, which have an average EFC time of 8EFH, and 8,500EFH (1,550EFC) for its freighters, which have an average EFC time of 5.5EFH. "Main removal drivers are EGT erosion and LLP expiry. We also have problems with HP rotor vibration and various problems in the HPC," says Christianhemmers.

The CF6-80C2 has been subject to technical problems which have resulted in on-wing intervals being reduced. One major issue has been AD 2000-16-12. This was preceded by AD 99-24-15 and relates to the 3-9 HPC spool. The AD requires regular inspections for cracking which influences the removal schedule. The inspection limits of affected engines are 2,000-3,500EFC, depending on the spool fitted. New spools are available which are not subject to inspections.

"The AD means engines operating short average cycles are more heavily affected, since EFC is limited," explains Culeman. "We have tried to re-install affected 3-9 spools on engines operating long flight cycles, and we also have a programme to replace all affected spools. There is a second major AD which requires inspection of the HPT disks. Depending on part number, the inspection interval is 3,500-5,000EFC."

The average time the CF6-80C2A2/3 achieves on-wing for all removal causes is 5,000EFH. "This is the interval for engines operating on a 1EFH average EFC time," explains Culeman. The other extreme is illustrated by the CF6-80C2B1F which achieves on-wing intervals of 14,400EFH for all removal causes. "We do not have any removals due to EGT margin erosion, but do have a limited number due to LLP expiry. A large number are due to AD 2000-16-12 in both the short- and long-haul fleets. This is because the new AD note was issued in late 2000 and triggered a lot of removals in 2001," explains Culeman. "We also have several unscheduled causes such as findings due to borescope inspections, findings in the HPC such as bushing wear, 3-5 stage blade dovetail cracks and 2nd stage HPT nozzle guide vane (NGV) problems. The HPT is one of the main removal drivers."

KLM, another major CF6-80C2B1F operator, has an average interval between all shop visits of 12,500EFH on its 747-400s. These operate about 1EFH shorter cycles than Lufthansa's fleet.

On-wing times for the CF6-80C2 on the 767-300 are lower for KLM, at about 7,000EFH. The airline operates these engines on medium-range routes, however, and not those of similar length to the 747-400. Delta operates the CF6-

80C2 on the 767-300 and has an average EFC time of 5.7EFH. Average time between all removals is in the region of 13,200EFH. This compares to the 10,000EFH it achieves for the PW4000 on its other 767-300 fleet operating virtually the same average EFC time of 6EFH. About half of the CF6-80C2's removals are scheduled.

The -80C2D1F powering the MD-11 is one of the highest rated variants. In KLM's operation it achieves about 10,000EFH between all removals, which compares to a maximum limit of 12,000EFH that would probably be permitted by EGT margin.

Tarvainen at Finnair comments that the mature -80C2D1F can get 14,000-21,000EFH on-wing on the basis of EGT margin and performance retention. "This is reduced to about 10,500EFH for all removal causes. The 3-9 spool AD can be one limiting factor, but there are also special problems which bring down the interval. These are second stage NGVs and first stage blades in the HPT," says Tarvainen. "We are happy if we get 12,000-14,000EFH, because it is time to do a performance restoration at this stage. The main removal causes are performance deterioration. Overall, the -80C2 would be a better engine if it did not have its reliability problems."

Winkler says the -80C2's high EGT margin should allow a long planned removal interval, and so there are other factors that force removals. "These include some small issues like vibration and high oil consumption."

An interesting contrast to the JT9D, PW4000-94, CF6-50 and CF6-80, is the RB211-524H powering the 747-400. SAA operates a fleet of RB211 powered 747-400s, and has been modifying some of its engines with the HPT module of the Trent 700 engine to upgrade to the RB211-524H2-T. "This modification has given us a large EGT margin of more than 60 degrees," says Der Merwe. "The EGT margin erosion rate is also low, at less than one degree per 1,000EFH. We expect the engines to achieve a mature average interval in the region of 20,000EFH."

Workscopes

As already described, the JT9D generally conforms to a pattern of alternating hot section inspections and full overhauls. Part replacement and sub-contract levels are generally high.

MH for an HSI are in the region of 4,500, and this increases to about 5,500 for an overhaul. Cost of materials is $700,000-800,000 and sub-contract repairs are $400,000 for an HSI. A labour rate of $70/MH takes the cost of an HSI to about $1.4 million.

Materials and sub-contract repairs are in the region of $1.5 million and $500,000 for an overhaul, taking total cost to about $2.5 million, excluding LLPs. The total shop visit costs for an overhaul cycle are therefore in the region of $4.0 million.

In most cases the PW4000's shop visits are managed in an approximate pattern of alternating workscopes. The HP system usually requires a major workscope every shop visit, because of the HPC. The HPT will also only do one on-wing run before requiring an overhaul. This results in a disassembly of the system. The LP system can often only require a major workscope every second shop visit, in particular the LPT, if it has had Phase III modifications. It will therefore only require a lighter workscope on previous shop visits.

This means every second shop visit is the heavier and consumes more MH and has a higher parts scrap rate than the previous workscope. As the engine ages scrap rate of parts increases, so raising shop visit inputs and costs.

Shop visit inputs for the PW4000-94 are 4,500MH for a lighter shop visit, $855,000 for materials and $285,000 for

JT9D, PW4000-94, CF6-50C2 & CF6-80C2 SERIES APPLICATIONS, PERFORMANCE AND MAINTENANCE RESERVES

Engine	JT9D-7Q	JT9D-7R4G2	JT9D-7R4G2	PW4156/58	PW4060	PW4460/62	PW4056
Aircraft application	747-200F	747-200F	747-200	A300-600/ A310-300	767-300	MD-11	747-400
Thrust	53,000	54,000	54,000	56,000/58,000	60,000	60,000	56,000
EFH:EFC ratio	5.0	6.0	8.0	3.0	6.5	7.0	8.0
S-V interval: EFH	8,000	9,000	10,000	10,000	12,000	12,000	14,000
S-V interval: EFC	1,600	1,500	1,250	3,300	1,850	1,700	1,750
S-V cost $	1,950,000	1,950,000	1,950,000	1,850	1,675,000	1,675,000	1,750,000
S-V reserve $/EFH	260	217	195	185	140	140	125
LLP lives EFC	15,000	15,000	15,000	20,000	15,000	15,000	20,000
Stub life EFC	2,000	2,000	2,000	3,300	2,000	2,000	2,000
Used life EFC	13,00	13,000	12,500	16,700	13,000	12,000	17,500
Used life EFH	67,500	81,000	100,000	50,000	84,000	84,000	140,000
List price LLP $ million	2.10	2.10	2.10	2.44	2.44	2.44	2.44
LLP reserve $/EFH	31	26	21	49	29	29	17
Total reserve $/EFH	**291**	**243**	**216**	**234**	**170**	**170**	**142**

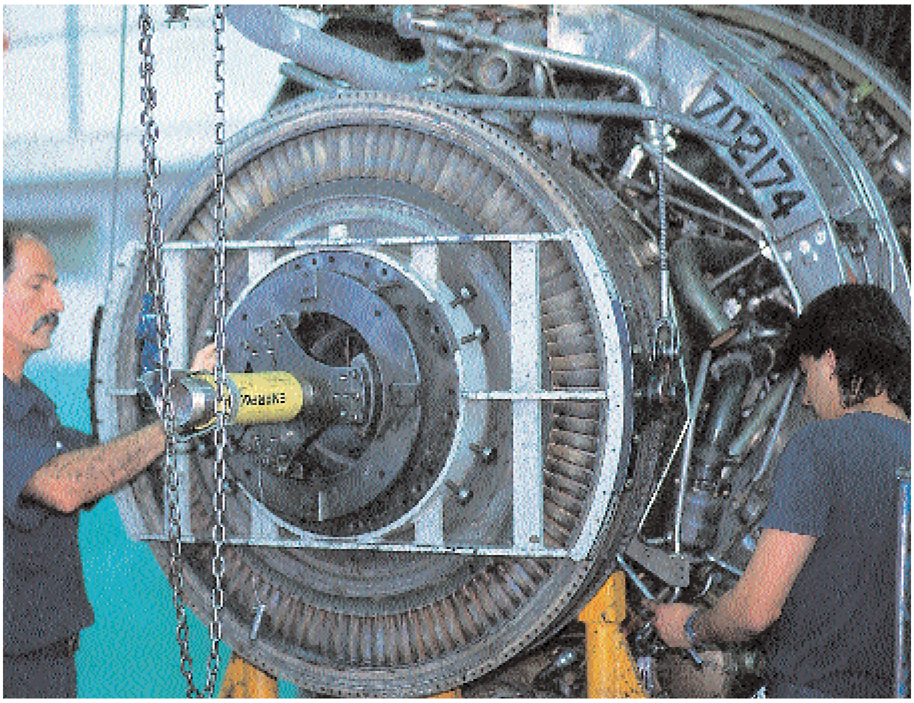
Engine	CF6-50	CF6-50	CF6-50	CF6-80C2 A2/3	CF6-80C2 B6F	CF6-80C2 D1F	CF6-80C2 B1F
Aircraft application	A300B4F	DC-10-30	747-200F	A300-600/ A310-300	767-300ER	MD-11	747-400
Thrust	52,500	52,500	52,500	53,500/59,000	60,800	61,500	57,900
EFH:EFC ratio	2.0	5.0	6.0	1.0/3.0	6.5	7.0	7.5
S-V interval: EFH	5,000	7,500	9,000	5,000/7,500	12,000	10,500	13,000
S-V interval: EFC	2,500	1,250	1,800	5,000/2,500	1,850	1,500	1,700
S-V cost $	1,750,000	1,750,000	1,750,000	1,900,000	1,800,000	1,600,000	1,700,000
S-V reserve $/EFH	350	200	183	380/240	133	152	131
LLP lives EFC	12,000-30,000	12,000-30,000	12,000-30,000	15,000/20,000	15,000/20,000	15,000/20,000	15,000/20,000
Stub life EFC	2,500	1,400	1,400	2,500/5,000	2,000	2,000	2,000
Used life EFC	9,500-27,500	10,000-28,000	10,000-28,000	10,000/17,500	13,000/18,000	13,000/18,000	13,000/18,000
Used life EFH	14,000-55,000	42,000-154,000	50,000-182,000	10,000/52,500	84,000/120,000	84,000/126,000	91,000/130,000
List price LLP $ million	2.10	2.10	2.10	2.70	2.70	2.70	2.70
LLP reserve $/EFH	70	21	24	200/57	25	24	23
Total reserve $/EFH	**420**	**224**	**204**	**585/300**	**158**	**177**	**154**

sub-contract repairs. At a labour rate of $70 per MH, this equals an average shop visit cost of $1.45 million. Higher workscopes will consume in the region of 5,000MH, use about $1.0 million of components and sub-contract repairs will rise to $500,000-700,000. This puts the cost of heavier workscopes in the region of $1.8-2.0 million, and the average shop visit at about $1.7 million.

The CF6-50 and -80C2 series follow a similar workscope pattern to the PW4000. The actual workscopes used by each shop follow GE's workscope planning guide (WPG). The CF6 family has four modules, and the WPG determines a workscope for each module. The WPG has an on-wing interval threshold since new or last overhaul for a light repair, performance restoration and overhaul for each module. Other information, such as trend monitoring data, ADs and LLP replacement requirements, is added to make a final workscope definition. LLP replacement in a module will increase workscope to overhaul because of the full disassembly required.

Generally, CF6 workscopes follow an approximate alternating pattern similar to the PW4000's. KLM says most workscopes involve performance restoration and full overhaul on the HPC and HPT, while all other sections of the engine have the minimum possible workscope.

Lufthansa Technik follows an approximate alternating pattern with its CF6-50s and -80C2s. "If engines have achieved an average or longer time on-wing we overhaul the HP system. On the same basis, we plan to overhaul the LP system (fan, LPC and LPT) every second shop visit," says Culeman. "We then try to do a lighter workscope every other



Despite efforts to increase on-wing times, a major factor in engine reserves is the rate of parts replacement. High pressure turbine blades can be repaired at 35-40% of the cost of new blades. A set of first stage high pressure turbine blades can cost about $350,000 for engines in the JT9D, PW4000 and CF6-50/-80 class.

shop visit. A lighter workscope is a module level inspection and a repair as necessary. Initial inspections, however, determine if a greater workscope is required."

Tarvainen says that Finnair likes to keep things simple and likes to get a performance restoration on every shop visit. "The LPT module can be repaired every second shop visit. Unfortunately, ADs on the -50C2 and problems on the -80C2 have forced disassembly so modifications can be made. Even though modules are split and they have different thresholds, they have to be inspected and this can raise the workscope of each one."

Besides basic thresholds and restoration requirements, Winkler reiterates that the installed EGT margins, AD inspection intervals and LLPs should all match up. "Although there is an approximate shop visit pattern the CF6 conforms to, the actual workscope and management of the engine depends on the operating environment. Every workscope therefore has to be customised," explains Winkler.

Workscope inputs for the CF6-50C2 vary, but are estimated at 5,350MH for a heavy workscope. Cost of materials and sub-contract repairs will be about $800,000 and $800,000. A labour rate of $70 per MH takes total SV cost to about $1.975 million, excluding LLPs. Costs for an average workscope are about $1.65 million. "Material costs for the -50C2 are hard to estimate in the current climate, because of the large amount of old material available on the market," explains Tarvainen.

Culeman explains that while the -50C2 and -80C2 engines consume similar amounts for MH for routine work (disassembly, inspection, assembly and test) the -80C2 requires less repairs and so uses less overall MH. MH consumption for the -80C2 is 4,000-5,000, depending on workscope. Average costs for materials and sub-contract repairs are $0.95-1.0 million and $200,000-350,000, depending on in-house capability. This puts the cost of lighter workscopes at $1.4-1.65 million and heavier shop visits at $1.5-1.7 million, excluding LLPs.

Tarvainen says material costs are as high as $1.0 million in some cases, but expects these to come down as the engine's problems are resolved. "First stage HPT blades were really bad, and there have been high category modifications of the NGVs, second stage HPT blades and 3-5 stage HPC blades. These costs should come down as the scrap rate of these parts was 100% every shop visit in some cases, but have since improved," explains Tarvainen.

LLPs

The maintenance reserve for LLPs depends on the life and cost of each part, the EFH:EFC ratio, the average on-wing time and stub life policy of the operator.

These engines operate mainly long cycles, with shop visit intervals of 1,500-3,000EFC and LLPs with lives in the region of 15,000-30,000. This means that some parts can remain in the engine for up to 18 shop visit intervals. Given that each interval is 6,000-12,000EFH for long-haul aircraft, it is possible to avoid replacing some LLPs. Others will be replaced after 20 years or more in the engine and generate low costs per EFH.

Engines operating short cycles will have longer EFC intervals between shop visits, and may have to be replaced after just two or three shop visits so as not to limit the third interval because of remaining life. Some airlines swap LLPs from engines operated on short cycles to engines on long cycles to extend useful life. "We take LLPs from the -80C2A2/A3 engines at the third shop visit, after about 15,000EFCs and put them in the -80C2B1F operated on the 747-400 to get another two intervals, which uses up almost all remaining life," explains Culeman. Airlines which are not able to do this are forced to scrap LLPs with long remaining stub life so as not to limit on-wing intervals.

This analysis assumes airlines are not able to swap LLPs and will remove parts with several thousand EFCs remaining to prevent limiting on-wing life. LLPs will therefore be removed with as many as 3,500EFCs left. LLP reserves for a range of applications and typical EFH:EFC ratios are based on life used and list price of $2.1 million for the JT9D, $2.44 million for the PW4000-94, $2.1 million for the CF6-60 and $2.7 million for the CF6-80C2 *(see table, page 29)*.

Summary

The total reserves per EFH for shop visit costs and LLP replacement are summarised *(see table, page 29)* for a range of aircraft applications for each of the four engine types studied.

Beyond removal causes, reserves are governed by the main factors of EFH:EFC ratio, shop visit interval, shop visit cost and LLP replacement interval. Engines of similar thrust rating, technology and generation operating similar aircraft types have similar reserves. The JT9D-7R4G2 and CF6-50C2 on the 747-200F operating an EFCs of 6.0EFH have reserves of $243 and $204, despite having similar on-wing times. The JT9D has both higher shop visit costs and shorter LLP lives.

The CF6-80C2 and PW4000 are closer in maintenance reserves on similar applications *(see table, page 29)*.

The main factor is shop visit costs, which is mainly determined by cost of materials and sub-contract repairs. Lower reserves can therefore be achieved by engine management which can predict or determine workscopes. A higher rate of repaired parts and life extension of parts will also reduce reserves. These are two new developments on which operators and engine repair shops are now concentrating their efforts. AC