There are more than 2,300 CF6-80C2 engines are still in operation, powering more than 870 widebodies. Many of these engines are more than 15 years old, and in the last few years of their operational life. Others are still relatively young. Their maintenance management & costs are examined.

CF6-80C2 maintenance management & budgeting

The CF6-80C2 family of engines is rated at between 52,460lbs and 60,690lbs of static thrust. The family powers two main Airbus, two main Boeing, and one McDonnell Douglas widebody families. The first engines entered service in the mid-1980s, and the CF6-80C2 is still being manufactured for the last 767-300ERs to be built by Boeing. The CF6-80C2 was the most successful widebody powerplant for 1980s vintage widebodies. Many aircraft have already been retired or parked, while others are due to be retired over the next five to 10 years. Many other engines are still relatively young. This raises the issue of how to manage these engines from a maintenance and engineering (M&E) standpoint.

CF6-80C2 family

The CF6-80C2 is a two-shaft turbofan, derived from the CF6-50 series. The -80C2 has a 93-inch diameter fan. The configuration of its core engine is four low pressure compressor (LPC) stages, 14 high pressure compressor (HPC) stages, two high pressure turbine (HPT) stages, and five low pressure turbine stages.

The engine's configuration is the same for all the variants in the family. There are three main sub-families. Engines with an -A suffix power Airbus A300-600 and A310 family widebodies, engines with a -B suffix power 767 and 747-400 family widebodies, and engines with a -D suffix power the MD-11 *(see table, page 36)*.

Overall there are six -A variants, 11 -B variants, and a single -D variant. All 18 variants have the same basic engine configuration, and common hardware. Parts and part numbers, however, have been upgraded and improved over the family's 30-year production and service history.

The single digit in the suffix of the variant's name indicates the order in which the variant was introduced. The first variants were the -80C2A1, powering the first A300-600s in service; and the -80C2B1, powering a small number of 747-200s and -300s in the mid-1980s.

The last variants to be introduced were the -80C2A8 and the -80C2B7F, which power the A310-300 and the 767-300ER respectively. These entered service in 1994. The -B8F, which powers the 767-400ER, entered service in 1999.

There are several main differences between sub-families and variants, however. The first is the thrust and fuel control systems used on the engines. Earlier-built engines use power management controls (PMC), which provide an analogue system for changing the engine throttle setting. The minority of engines were built with PMC controls. PMC engines are used by Airbus and Boeing aircraft, and have -A and -B suffixes.

Later-build engines were fitted with full authority digital engine control (FADEC) units. The first FADEC engines entered service in 1989. Most CF6-80C2s are FADEC engines, and provide more precise engine power and throttle settings. FADEC engines have -AF, -BF and -DF suffixes; the F denoting the presence of a FADEC unit.

Thrust ratings

"With the PMC unit, it is possible to change a variant from one thrust rating to another, although the operator has to pay a fee to General Electric (GE) for an increase in thrust rating," explains Doug Elder, engineering manager at CTS Engines. "Higher or lower thrust ratings are possible for PMC engines because they all have the same internal configuration."

FADEC engines also make it possible for airlines and operators to change an engine's thrust rating, although a fee again has to be paid to GE for a higher thrust rating. "The common build and turbomachinery hardware standard across all FADEC-equipped variants means an engine's thrust rating is changed through the use of a plug in the FADEC unit," says Elder.

While it is possible to change thrust ratings between different PMC engines, and between different FADEC engines, it is not possible to interchange between a PMC variant and a FADEC variant.

The second main difference between sub-families is the quick engine change (QEC) kits and accessories mounted on the outside of -A, -B and -D engines. "It is relatively easy to swap an -A engine between one A300-600 or A310 variant and another, and change thrust ratings, for example, but it is not as easy to swap an -A engine on to a Boeing aircraft or to the MD-11," explains Elder.

Michel Nollet, powerplant & testcell engineer at KLM E&M Powerplant Engineering, explains that it is possible to convert PMC -A engines to -B engines and vice versa, as well as convert an -AF to a -D1F engine and vice versa. "Service bulletin (SB) SB72-1470 was recently released to rebuild -D1F engines from an MD-11, which may have been retired, to a -B6F engine for use on a 767-300ER," says Nollet. "This new SB makes it possible to switch engines between each FADEC configuration, but airlines are not actually switching between Airbus, Boeing and MDC applications. Changing thrust ratings is done regularly. Changing between ratings to a twin-engined application may make it necessary to check if the engine is also extended range twin-engine operations (ETOPS) compliant."

The -A engines include five PMC-controlled variants that are rated between

CF6-80C2 SERIES VARIANTS, THRUST RATING & APPLICATIONS

Engine variant	Thrust rating (lbs)	Aircraft application	Mature EGT margin - degrees C
CF6-80C2A1	57,860	A300-600	35-50
CF6-80C2A2	52,460	A310-200/-300	38, up to 90
CF6-80C2A3	58,950	A300-600	25-45
CF6-80C2A5	60,100	A300-600R	25-45
CF6-80C2A5F	60,100	A300-600F	25-45
CF6-80C2A8	57,860	A310-300	35-50
CF6-80C2B1	55,980	747-200/-300	35-60
CF6-80C2B1F	57,160	747-400	35-50
CF6-80C2B2	51,950	767-200ER/-300ER	up to 90
CF6-80C2B2F	52,010	767-200ER/-300ER	up to 90
CF6-80C2B4	57,180	767-200ER	25-45
CF6-80C2B4F	57,280	767-300ER	25-45
CF6-80C2B6	60,030	767-300ER	25-45
CF6-80C2B5F	60,030	747-400	25-45
CF6-80C2B6F	60,030	767-300ER	25-45
CF6-80C2B7F	60,030	767-300ER	25-45
CF6-80C2B8F	60,030	767-400ER	25-45
CF6-80C2D1F	60,690	MD-11/MD-11F	25-35

52,460lbs and 60,100lbs, and power the A300-600, A310-200 and A310-300 *(see table, page 36)*. The -80C2A5F is the sole FADEC-controlled variant, and is rated at 60,100lbs and powers the A300-600. These aircraft are almost all factory-built freighter variants. There are 82 active A300-600s in operation, including 59 freighters. Of these, 30 are PMC-controlled. There are also 38 A310-300s in active service, and all are powered by PMC-controlled engines.

The -B engines include four PMC-controlled variants that are rated between 51,950lbs and 60,030lbs *(see table, this page)*. The higher-rated engines -80B2B6 engines power 80 767-300ERs, while the -80C2B4 engines power 18 of the same variant. Another 300 767-300ERs are powered by mainly -80C2B6F and -B7F engines rated at 60,030lbs thrust. There are also 37 767-400ERs powered by the -80C2B8F rated at 60,030lbs.

"It is possible to change thrust ratings between FADEC-controlled -B engines for different Boeing aircraft types using SB72-0389," says Nollet. "This SB can be used if the internal hardware is capable of the highest thrust ratings. All -B FADEC engines were built with common turbine components, and so should be capable of the highest thrust ratings.

There are 220 active 747-400s in passenger and freighter configuration. Almost all are powered by -80C2B1F engines.

There are 85 active MD-11s in service powered by -80C2D1F engines. Almost all of these are freighter-configured, and passenger-configured aircraft are due to cease operations by the end of 2014.

Of the 874 CF6-80C2-powered aircraft in active service, 705 have FADEC-controlled engines.

CF6-80C2 in operation

The CF6-80C2 engines powering the five main widebody types operate at a wide range of engine flight hour (EFH) to engine flight cycle (EFC) ratios, and annual rates of utilisation.

The A300-600R fleet is split between 23 passenger-configured aircraft and 59 freighters. The passenger-configured fleet is operated by three main carriers, and the aircraft are mainly powered by -80C2A3 and A5 engines. Many aircraft are now operated at low rates of utilisation, although Kuwait Airways still utilises its fleet at about 3,500FH per year and at 3FH per FC. The majority of the passenger fleet is more than 20 years old.

The freighter fleet is dominated by FedEx, which operates its aircraft at about 1,200FH per year and at an average FC time of about 1.85FH. Air Hong Kong and MNG Airlines operate their fleets at 2.50-2.90FH per FC, and at 1,200-1,600FH per year.

The A310-300 fleet is one of the fastest declining fleets. The remaining passenger fleet is 22-27 years old, and is operated by eight main airlines. These all generally use the A310-300 as a medium-haul aircraft at FC times of 2.1-4.2FH. Annual rates of utilisation are 1,700-4,000FH.

The 767 fleet is the largest fleet of CF6-80C2-powered aircraft, comprising 40 767-300s, 306 767-300ERs, 103 767-300 freighters, and 37 767-400ERs.

The 767-300 fleet is old at 15-24 years, with the first 767-300 variants in service. It is dominated by aircraft operated by All Nippon Airways (ANA), Asiana, and Japan Airlines (JAL). ANA and JAL aircraft are operated at short FC times of 1.1-1.3FH, and at 2,400FH per year.

Most of the 767-300ER fleet is used for long-haul operations. Aircraft and engines are operated at an average cycle time of 5.4FH, and aircraft have average utilisations of about 3,700FH per year.

The freighter fleet is dominated by factory-built freighters, and United Parcel Service (UPS) operates 59 aircraft on medium-distance operations that average about 3.3FH. Most other airlines operate their aircraft in a similar way, although a few operate them on longer missions.

The CF6-powered 747-400 fleet, which is dominated by the -B1F variant, has declined over the past eight years, with about 60 fewer aircraft in active service compared to 2006. The main operators include Air France, KLM, Lufthansa, Qantas, Thai, Transaero and Virgin Atlantic. Aircraft are mainly operated on typical long-haul missions of 6-8FH, although some airlines use their aircraft on ultra-long-haul_operations of 10-11FH. Most airlines achieve an average of 4,500-5,000FH per year with their aircraft.

The Combi fleet is dominated by KLM, which operates the aircraft similarly to passenger-configured variants.

The 747-400 freighter fleet now dominates the -400s, and is powered by -B1F and -B5F-equipped aircraft. Most are factory-built freighters, while 29 are converted aircraft. Freighters are operated on shorter missions of mainly 5-6FH, but the aircraft have similar annual utilisations to the passenger fleet.

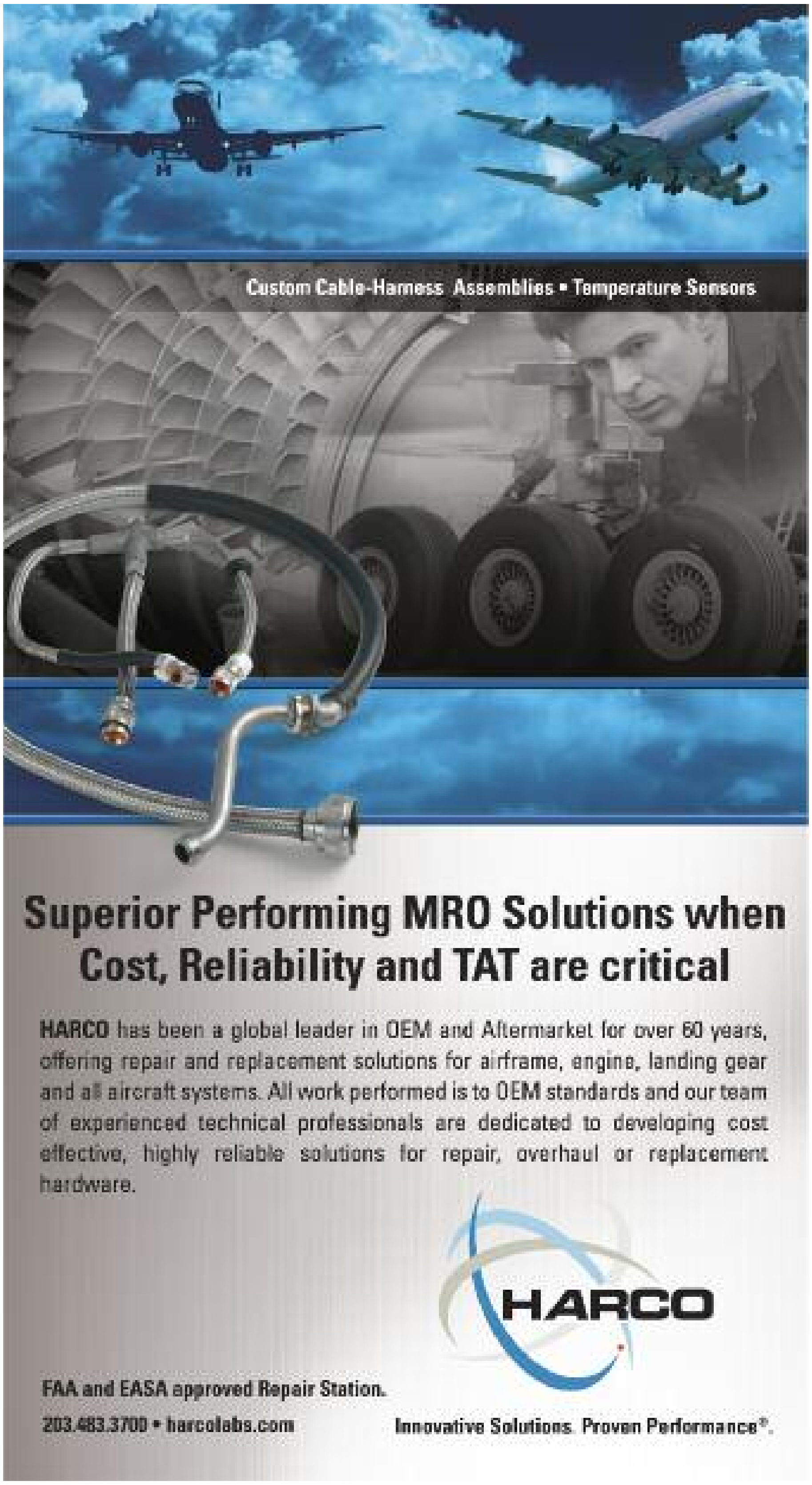
The MD-11 fleet is dominated by FedEx (42 aircraft), Lufthansa Cargo (15) and UPS (11). Operations are similar among all eight operators, with FC times averaging about 5.3FH. Few aircraft are utilised in excess of 3,500FH per year.

LLP configuration

A main factor influencing engine management is the configuration of life-limited parts (LLPs).

The CF6-80C2 is configured of four main modules: the fan and LPC, the HPC, the HPT, and the LPT.

The fan and LPC module have four LLPs. These are the fan disk, the stage 2-5 spool, the forward shaft and the fan mid-shaft. These four parts have target and certified lives of 20,000 engine flight cycles (EFC). This is the case with all -A engines and -B engines, except the -A5F



and -B5F/-B7F which have a life of 15,000EFC for the 2-5 booster spool part number (P/N) 1782M80P01. The same part in the -D1F also has a life of 15,000EFC.

These four parts have a 2014 list price of about $1.7 million.

The HPC module has six or seven LLPs, depending on configuration. These are the stage 1 disk, the stage 2 disk, the 3-9 stage spool, the 10-14 stage spool, and the CDP seal.

These six parts also have target lives of up to 20,000EFC. The stage 2 disk P/N 9380M27P08 and the HPC CDP seal P/N 1347M31P01 in the -A5F, -B5F/-B7F and -D1F both have certified lives of 15,000EFC, however.

These six parts have a list price of about $1.7 million.

The HPT module has four parts. The two HPT stages each have a disk, while these is also a space impeller and a rotating stage seal. These four parts experience the most stress, due to high temperatures in the HPT section, and have a shorter target life of 15,000EFC. The -A5F, -B5F/-B7F and -D1F have the life of HPT stage 1 disk P/N 1531M84G12 limited to 10,720EFC.

There is also a P/N for the HPT stage 2 disk in the -B5F/-B7F variants that has a life limited to 9,000EFC.

The four parts in this module have a 2014 list price of about $1.1 million.

The LPT module has six parts. These are a disk for each of the LPT stages, and the LPT shaft.

These parts all have target certification lives of 20,000EFC. The third LPT stage disk has some part numbers with a life limit of 17,400EFC. The other five parts all have life limits at the target life of 20,000EFC.

These parts have a 2014 list price of about $1.54 million.

A shipset of LLPs for all four modules for the complete engine have a 2014 list price of $6.1 million, compared to a shipset list price of $3.4 million in 2006 *(see CF6-80C2 owner's & operator's guide, Aircraft Commerce, October/November 2006, page 9)*. The price increase over this eight-year period is equal to a compounded annual increase of 7.5%.

Martin Matthews, programme manager at AerFin, says the 2015 list price for a full shipset of LLPs will be about $6.34 million.

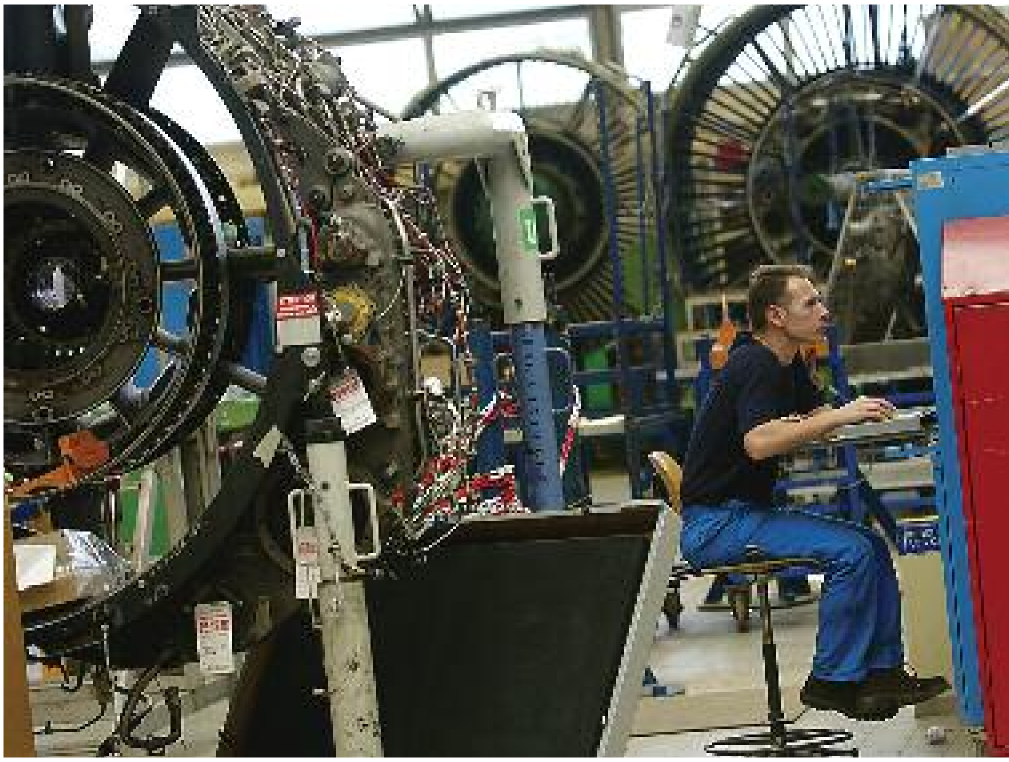
Engine management

The management of engines' maintenance depends on their age and expected remaining number of years in service. "Engines on young and medium aged aircraft will be managed so that all modules are passed through shop visits, on-condition parts and LLPs replaced as required, and removal intervals all optimised so as to achieve the lowest possible cost per EFH and EFC," says Elder. "Older engines, however, are now being managed with a view to phasing them out, in particular with the MD-11 and A300-600. One technique to minimise expenditure on engine maintenance is to avoid replacing certain LLPs. This may mean sacrificing removal interval and time on-wing, but this is cheaper overall for older engines."

Some airlines lease engines to postpone shop visits. This is economic because of the high availability of certain variants, such as the -B1F, caused by the large number of 747-400s that have been phased out in recent years. Some airlines are also able to save costs by swapping engines between variants, although this can incur costs.

Airlines can avoid putting particular engine modules through shop visits by acquiring time-continued modules from

The list price of a shipset of LLPs for the CF6-80C2 is approaching $6.34 million. The rate of utilisation of engines used on long-haul operations means the replacement of most parts can be avoided, however. There is also a supply of serviceable material on the aftermarket following the retirement of a large number of engines.



retired engines. "Airlines and engine shops can also use serviceable material to minimise costs," comments Matthews.

Engine management can be flexible so as to match maintenance performed with the desired or remaining service life of an engine. This is easier for an airline with a large fleet and its own in-house engine shop, or an independent maintenance, repair & overhaul (MRO) organisation managing an airline's fleet, to achieve. "We can evolve engine management according to its remaining service life," says Mike Moore, vice president of engine and component maintenance at Delta TechOps. "Engine management is also affected by lease return conditions for those engines that are leased. Cost per EFH is controlled through setting minimum build standards, and these can be matched with the engine's expected remaining life. Serviceable material can also be used wherever possible to achieve this and also reduce overall material expenditure. With lots of surplus engines and materials on the market there are plenty of opportunities for airlines to support their fleets with low-cost time-continued material. Delta Tech Ops can help airlines manage this process.

"Airlines can use certain engine management techniques to lower costs," adds Moore. "These include: adjusting minimum build standards for appropriate removal intervals; leasing 'green time' or time-continued engines instead of putting their own engines through shop visits; utilising used material and parts on the used market; and buying used engines from retired aircraft, and parting them out for parts and materials."

The long-term management of engines that includes the maintenance, and accruing maintenance reserves of all major modules and LLPs is still relevant for a large number of engines, however. The late entry into service of the 787 and A350 has meant that large numbers of 767-300ERs have remained in service longer than anticipated. Moreover, large numbers of 747-400s, 767-300ERs and 767-400ERs are still relatively young, and will continue to operate for 15 years or more. There is also strong demand for MD-11Fs, so some aircraft will continue to operate for the medium-term.

Engine removals

In the earlier years of operation, the loss of exhaust gas temperature (EGT) margin and operating performance was a main driver of removals for planned maintenance on the CF6-80C2. The CF6-80C2 has been manufactured in three main production blocks, referred to as Block 1, Block 2 and Block 3 engines.

Block 1 and 2 engines were the first two batches, and initially had relatively low EGT margins. These were improved, however, as operational experience with the engine was gained, and new improved materials and parts were introduced.

Block 3 engines generally have higher build standards and EGT margins.

As would be expected, initial EGT margins are higher than post shop visit EGT margins. The level of initial EGT margin regained, however, varies with workscope and subsequent engine operation and management.

EGT margins are clearly the highest for the lowest rated variants, and are lower for higher rated variants.

As GE has gradually introduced improved materials and parts for the CF6-80C2 since it entered service, EGT margin loss has become less of a removal driver. Deterioration of engine hardware and airfoils was a secondary removal driver, and is now the prime removal driver for some variants and operations.

EGT margin

Most engines have been through at least one shop visit. The EGT margin of engines post shop visit is thus the most important issue for engine performance.

"The initial rates of EGT margin erosion and loss are highest in the first 1,000-2,000EFC after a shop visit," explains Joana Palmeiro, powerplant engineering & engine maintenance at TAP Maintenance & Engineering. "EGT margin erosion reaches mature levels after this initial loss and then remains steady."

Matthews estimates that mature or post shop visit EGT margins for the lowest rated -80C2B2 and B2F variants rated at 51,950-52,010lbs for the 767-200ER and -300ER are up to as much as 90 degrees centigrade *(see table, page 36)*.

The similarly rated -80C2A2 for the A310-300, however, has a lower margin of 38 degrees centigrade *(see table, page 36)*.

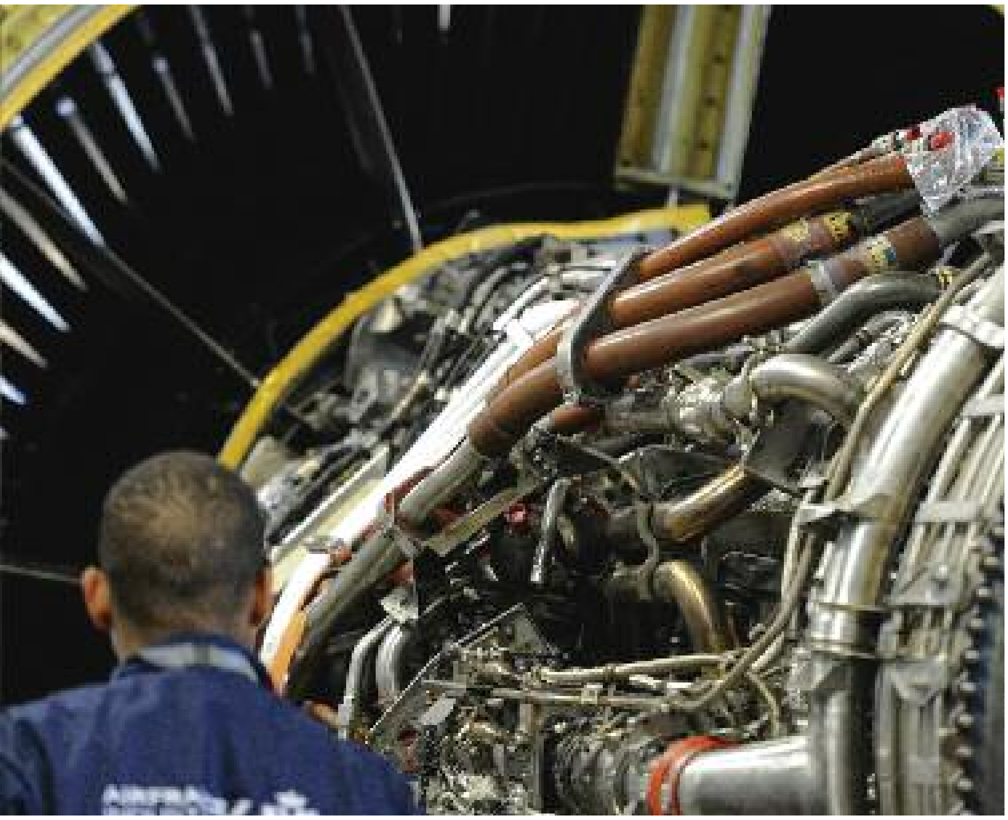
All other higher-rated variants have similar mature EGT margins. The -80C2B1F powering the 747-400 has margins of 35-50 degrees centigrade, while the A3/A5/B4/B6 variants powering the A300-600, A310-300 and 767-300ER have installed margins of 25-45 degrees.

Matthews estimates the EGT margin for the -80C2D1F powering the MD-11 is 25-35 degrees *(see table, page 36)*.

As a general guide, Nollet says that low-thrust variants have an EGT margin of 45-55 degrees, while the higher rated variants have margins of 30-40 degrees.

"All CF6-80C2 engines are in fact shunted," says Elder. "This means the pilot cannot tell what the actual EGT margin is on the flightdeck display, because this actually shows the turbine gas temperature (TGT). The shunt difference is the difference between the original design EGT and the actual used EGT. The FADEC variants, for example, have a 60 degrees shunt.

"The low thrust engines like the -B1F



A large portion of CF6-80C2 removals are not due to EGT margin erosion. Deterioration of engine turbomachinery now accounts for a large portion of engine removals. Main issues are problems with the HPC, first blade HPT deterioration, and problems with HPC variable stator vanes.

and -B4F have mature post shop visit EGT margins of 60 degrees centigrade," continues Elder. "The higher -B6F has a margin of 35-40 degrees, while the -D1F has a margin of 35 degrees.

"The quest for the best possible EGT margin is not always the best policy. This is because a high EGT margin is lost very quickly in an engine that has tight clearances," explains Elder. "In this case the engine can have a high initial rate of EGT margin loss. An engine that has looser clearances after a shop visit can have a higher margin as a result."

Initial rates of EGT margin loss are high during the first 2,000EFC on-wing after a shop visit. The loss can be 15-20 degrees during this period. "About 13 degrees are lost during the first 1,000EFC, and another seven during the second 1,000EFC up to a total on-wing time of 2,000EFC when about 20 degrees will have been lost," says Nollet.

Rates of EGT margin erosion after this initial 2,000EFC will be lower, at 2-3 degrees per 1,000EFH.

The implications are that a lower-rated engine with an initial margin of 50 degrees will be able to remain on-wing for 10,000-15,000EFH after the first 2,000EFC on-wing. If the engine operates at an average EFC time of 2.0EFH, then a total removal interval of 14,000-19,000EFH will be possible. An engine, such as a -B1F, may be able to achieve a removal interval of closer to 25,000EFH.

Higher-rated engines will have 10-20 degrees of margin remaining after the first 2,000EFC on-wing. This will include -A5F engines powering the A300-600, -B6F engines powering the 767-300ER, and -D1F engines powering the MD-11.

Engines powering the A300-600, and operating at 2.0EFH per EFC, may be able to remain on-wing for a further 4,000-5,000EFH; and so have a total removal interval of 9,000-11,000EFH in most cases.

Engines powering the 767-300ER, and operating at 5.5-6.0EFH per EFC should be able to achieve an interval of 14,000EFH to 24,000EFH.

"Most engines are built with enough EGT margin and performance to have a planned removal interval of 3,000-3,500EFC," says Elder. "Engines can be removed for hardware deterioration, and the interval ultimately depends on the time since the last heavy shop visit."

The technique of waterwashing is now extensively used to clean the airfoils and regain lost EGT margin. Elder explains that waterwashing only helps if there is dirt on the airfoils, and this depends on where the aircraft operates. Another effect of engine turbomachinery being contaminated is the residues of glycol and urea on the runways and taxiways as a result of de-icing.

"It is an essential part of engine life cycle management," says Moore at Delta TechOps. "Waterwashing can add 10 degrees centigrade of EGT margin back to the engine. The added margin also reduces specific fuel consumption (sfc) and results in a reduced rate of hardware and airfoil deterioration."

Matthias Binner, senior manager of powerplant engineering at MTU Maintenance, explains that almost all airlines use waterwashing to regain EGT margin on a regular basis. "The EGT margin gain is based on the condition of the HPC airfoils and stators prior to the waterwash. An increase of five degrees is more common, but rises of 10, or even 25 degrees, are possible," explains Binner. Waterwashing is seen as a cost-effective way of prolonging removal interval.

Removal causes

Besides the loss of EGT margin and engine performance, engine hardware and airfoil deterioration is the main factor forcing removals for shop visits.

"Engines undergo borescopes on a regular basis, and these often reveal findings and problems," says Elder. "Examples are deterioration of the HPC, combustion chamber, and the HPT. The HPT used to have a lot of problems, but the borescope inspection limits are now relatively liberal. The HPC is often a major issue, since even minor damage to a blade can cause stress that can lead to it coming loose and causing a lot of downstream damage. Some HPC repairs can be made, however, with a topcase repair that avoids a full shop visit."

The earlier HPT blade part numbers had problems with oxidation and fast deterioration. "First stage HPT blade deterioration, wear of the HPC and foreign object damage events are major removal causes," explains Matthews. "Others include high oil consumption, compressor rear frame (CRF) oil supply tube leaks, and hot section airfoil deterioration."

Nollet adds that LPT blades and nozzles have also caused problems. "Environmental pollution has a large impact on the mechanical condition of hardware, although sand and short EFH:EFC ratios have a bigger impact," says Nollet.

Older issues with hardware deterioration included the variable stator vanes (VSV) in the HPC.

The CF6-80C2 has also had some major airworthiness directives (ADs) that in the past have limited removal intervals by forcing inspections or modifications.

A recent AD is AD2014-21-01, which requires fuel manifolds to be replaced.

"AD 2000-07-13 affected the -A5F, -B5F and -B7F," says Matthews. "This required the removal of the HPT disk part number (P/N) 1531M84G10 and G12 before accumulating 10,720EFC

The removal intervals of CF6-80c2 family variants are generally between 2,500EFC and 4,500EFC. The main factors determining the number of EFC are the engine's thrust rating and its operational EFH:EFC ratio.

since new." This life limit may compromise the engine's optimal engine removal and shop visit pattern. Most engines affected by this AD have now had new P/Ns of the relevant LLP replaced.

A second AD was 2009-14-08, which affected the -B5F. This affected the HPC 11-14 spool P/N 1703M74G03, by reducing the part's life to 19,500EFC. This is unlikely to have a major impact, however, since the target life for this part is 20,000EFC.

A major AD was triggered by incorrect number three bearing packing, and incorrect sized cooling holes. AD 2012-03-12 capped the life of several LLPs to 5,500EFC if the engine had been manufactured with the incorrect bearing. These LLPs were all P/Ns relating to the 10-14 HPC spool, all P/Ns relating to the 11-14 HPC spool, P/N 9373M53P05 relating to the third LPT disk, and P/N 9373M54P03 relating to the fourth LPT disk. The AD therefore compromised an operator's scope to optimise the removal intervals and achieve the lowest possible maintenance reserves per EFH.

"AD 2008-21-11 requires the rework of the LPT case," says Binner.

The CF6-80C2 was also affected by a series of older ADs.

AD 2002-25-08 required an eddy current inspection of the part, and limited the life of the HPC 3-9 spool to 12,500EFC.

AD 2004-04-07 was superseded by AD 2006-16-06, which required dovetail slots to be reworked on the first stage HPT disk at a limit of 10,000EFC or 10,400EFC.

AD 2004-07-13 reduced the life limit of the stage 1 HPT disks on -1A5F, -B5F, -B7F ans -D1F engines.

AD 2004-27-07 required a particular part number for the stage 2 nozzle guide vane in the HPT to be replaced, to avoid repeat borescope inspections every 1,600EFC.

Removal intervals

The remaining CF6-80C2-powered fleet is now based around five or six airframe-engine variant combinations, each of which operates at a typical FH:FC and EFH:EFC ratio.

The passenger A300-600 fleet is powered by -A3 and -A5 engines, and operates at 3FH:FC. The freighter fleet is powered by -A5F engines, and operates at 2FH:FC.

The A310-300 fleet is powered by -A2 and -A8 engines, and operates at a range of 2-4FH:FC.

The 767-300ER fleet is powered mainly by -B6, -B6F and -B7F engines, and operates at 5-6FH:FC. The 767-300ER freighter fleet is powered mainly by -B6F and -B7F engines, and operates at an average of 3.5FH:FC.

The 747-400 fleet is mainly powered by -B1F engines, and a smaller number by -B5F engines. The aircraft operate at 7-8FH:FC.

The MD-11F fleet is powered by the -D1F variant, and operates at 5.5FH:FC.

The removal intervals for young engines powering a small number of 747-400Fs and 767-300ERs will be long for engines on their first removal. The removal intervals for all other engines will be mature, however.

Matthews estimates that the average interval for -A3 and -A5 engines on the A300-600 will be 2,500EFC, equal to 5,000EFH for engines on freighter aircraft, and 7,500EFH for engines on passenger-configured aircraft operating longer cycles.

The interval can be longer, and with an initial EGT margin of up to 45 degrees centigrade, could have a removal interval of up to 5,000EFC. This would be up to 10,000-15,000EFH for aircraft operating at 2-3EFH per EFC. Intervals will be shorter in a hot environment, however. Many A300-600s are operated in high ambient temperatures.

Removal intervals for -A2 and -A8 engines powering the A310-300 will contrast, with these two being low- and high-rated variants. The -A8 should achieve similar intervals as the -A3 and -A5 powering the A300-600. The -A8 will also have short intervals when operating in a hot environment. The lower-rated -A2 is capable of achieving longer intervals of up to 5,000EFC on more occasions.

Matthews, however, puts the average interval for -B6F and -B7F engines higher at 4,200EFC, equal to 25,000EFH.

There is variation between the variants, however. Binner at MTU Maintenance says that mature intervals for PMC -B6 engines average about 1,700EFC, which will be equal to about 10,500EFH. "The intervals for the -B6F will longer at about 2,500EFC, and so equal to 14,000-15,000EFH."

The -B6, -B6F and -B7F fleet is one of the largest, and there are more data relating to removal intervals for these variants. The Delta fleet, for example, which operates at an average of 6.2FH per FC, has mature intervals of 30,000EFH and 4,800EFC between heavy shop visits. This is an unusually long interval. Rather than carry out a pattern of alternating performance restoration and overhaul shop visits on the HPC and HPT modules, between relatively short removal intervals, Delta TechOps performs overhauls at every shop visit after longer than average removal intervals.

Intervals are in a similar range for -B1Fs powering 747-400s. "In good environmental conditions, and with engines that have had a recent change of hardware and airfoils, mature intervals are averaging 2,600-2,800EFC," says

The shop visit pattern of engines usually follows thresholds outlined in the workscope planning guide. The HPT has an overhaul threshold of 2,500EFC, and so would require an overhaul every shop visit. The HPC and fan/LPC have a longer overhaul threshold of 6,500EFC, while the LPT has an overhaul threshold as long as 7,500EFC.

Nollet. This is equal to 18,000-18,500EFH for engines operating at 7EFH per EFC.

Binner says that longer intervals are possible, and an average of up to 3,500EFC can be achieved. This is equal to 22,000-24,000EFH. Elder says that it is possible to build the -B1F in a shop visit to achieve an interval of 3,200-3,500EFC.

Intervals are shorter for the -D1F, as would be expected since it is the highest-rated variant. Binner says intervals should be 2,000EFC; equal to 11,000EFH. Nollet, however, says that in good environmental conditions an average interval of 2,400EFC can be expected, equal to 13,000EFH. Elder agrees, saying that the -D1F can have a build specification in the engine shop for the engine to achieve a removal interval of 2,500EFC, equal to about 13,500EFH.

Shop visit pattern

The CF6-80C2 workscope planning guide (WPG) has on-wing EFC thresholds for different levels and standards of shop visit workscopes for each engine module. These can be a guide to determining each variant's shop visit management.

"The CF6-80C2 generally follows a pattern of alternating performance restorations and overhauls," says Elder. "The performance restoration involves work on the HPC, the combustion chamber, and the HPT. These modules are worked on at every shop visit. The full workscope or overhaul also involves the LPC and the LPT. These are usually worked on at every second shop visit."

The HPC and HPT have different performance restoration and overhaul thresholds. The different performance restoration thresholds cause some difficulty in workscope planning. "A performance restoration can be performed after an interval of 2,500-3,000EFC," says Elder. "The problem is that going much beyond the WPG threshold of 2,500EFC for the HPC results in a high scrappage rate of airfoils and parts in the HPT, and the workscope comes closer to an overhaul. The problem is that in all cases 10-15% of airfoils get scrapped at initial inspection, while there will be another percentage of parts that fail the repair procedure, and yet another that will fail the post-repair inspections."

Different operators and engine shops use different thresholds for each module, and have different shop visit patterns.

"According to our WPG, the HPT and nozzle guide vane have an overhaul threshold of every 2,500EFC, and the combustor has an overhaul threshold of 1,800EFC," says Nollet. "That is why almost all of our HPTs and hot sections have an overhaul at every shop visit. Our engines have an average time on-wing of 2,500EFC."

"The performance restoration threshold for the HPC is up to 3,250EFC in the WPG," continues Nollet. "The overhaul threshold for the HPC is 6,500EFC. The HPC therefore usually has a performance restoration at the first and second shop visits, and an overhaul at the third shop visit. These are at 2,500-2,600EFC, 5,000-5,200EFC, and at 7,500-7,800EFC. A longer removal interval or total time at the second shop visit will see the HPC having an overhaul."

KLM Maintenance & Engineering use similar thresholds for the low-pressure spool modules. "We have no performance threshold on the LPT, and we have an overhaul every third shop visit after about 7,500EFC," says Nollet. "If the removal is longer, say after about an average of 3,000EFC, then we have an overhaul at the second shop visit."

The thresholds for the fan/LPC are the same as the for the HPC. That is, the threshold for a performance restoration is 3,250EFC and the threshold for an overhaul is 6,500EFC. "For an average removal interval of 2,600EFC, we have a minimum workscope at the first removal, a performance restoration at the second removal and shop visit, and an overhaul at the third removal," says Nollett. "Longer removal intervals will result in an overhaul at the second shop visit, after 6,000-6,500EFC."

Delta Tech Ops plans for a different shop visit pattern, and does not follow a system of alternating performance restorations and overhauls. "We perform overhauls on the core modules at each shop visit, and this is after a long interval of 4,000EFC," says Moore. "This when operating at a ratio of 6.0-8.0EFH per EFC, and so is equal to 30,000-34,000EFH. We have higher thresholds for an overhaul of about 12,000EFC for the fan/LPC and LPT," continues Moore. "The fan/LPC and LPT can therefore be worked on once every third shop visit."

Shop visit inputs

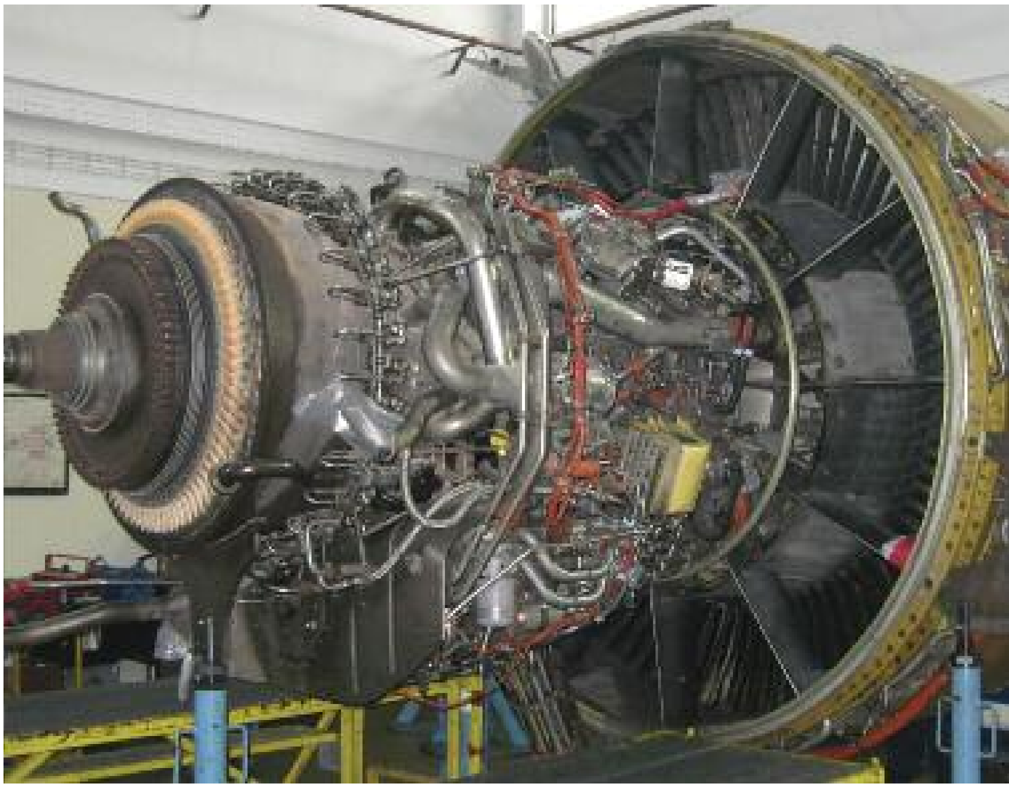
Shop visit costs can be considered for the three main module groups of the engine. The first is the high pressure (HP) section; the HPC, combustor and the HPT. The other two are the fan/LPC and the LPT.

"The cost inputs have been mitigated in recent years due to the availability of used serviceable material from time-continued engines. This offsets the rise in the price of new parts," says Elder.

An HP performance restoration, or lighter workscope where the HPC has a performance restoration and the HPT has an overhaul, will have a material cost of $1.0-1.5 million, excluding LLPs. This assumes that some time-continued materials and parts could be acquired on the aftermarket. If not, it is estimated that the cost of materials and parts would be 60% higher. That is, $1.6-2.4 million.

Sub-contract repairs will be

Following the retirement of a relatively large number of engines, it is now possible to acquire a substantial portion of parts and materials used in shop visit workscopes as serviceable material from time-continued engines. This can save several hundreds of thousands of dollars in the cost of a single shop visit.



$450,000-500,000, and the workscope will use 3,500-4,500 man-hours (MH). Using a labour cost of $75 per MH, this would generate a total cost for the input of $1.71-2.34 million in the case where some of the materials and parts used were serviceable from time-continued engines.

Matthews comments that this can be $2.3-2.5 million where there is less serviceable material available on the aftermarket.

If it was not possible to acquire any serviceable material then the cost of the shop visit would be higher at $2.3-3.1 million.

A heavier core of HP shop visit input, where the HPC, combustor and HPT are overhauled can cost up to $2.7 million.

The LPT may again benefit from the availability of used and serviceable material on the aftermarket. Materials and parts may cost $150,000-200,000, excluding LLPs, if serviceable material can be found, or $250,000-330,000 if it cannot.

Sub-contract repairs will cost $75,000-150,000, and the workscope will use 700-900MH. Using a standard labour rate, the input will cost $280,000-425,000, depending on the depth of workscope and whether it is a restoration or an overhaul. The shop visit will be higher, however, if less or no serviceable material can be acquired.

The fan/LPC will have similar inputs, although this module can cost $50,000-100,000 less than the LPT.

These approximate shop visit costs, that do not include LLPs, can be considered in relation to seven airframe-engine combinations: the -A3/A5 engines operating on the A300-600 at 3.0EFH per EFC; -A5F engines powering the A300-600F at 2.0EFH per EFC; -A2/A8 engines powering the A310-300 at an average of 3.0EFH per EFC; -B6F/-B7F engines on the 767-300ER operating at an average of 5.5EFH per EFC; the same engines powering the 767-300ERF and operating at 3.5EFH per EFC; -B1F engines powering the 747-400 and operating at 7.5EFH per EFC; and -D1F engines powering the MD-11/MD-11F operating at 5.5EFH per EFC *(see table, page 46)*.

These aircraft and engine combinations, their average EFH:EFC ratios, their average expected removal intervals, their shop visit workscopes and shop visit cost inputs, and the resulting maintenance reserves per EFC and per EFH are summarised *(see table, page 46)*.

Using the thresholds described for minimum workscopes, performance restorations, restorations, and overhauls as described, the shop visit pattern for each of the three main workscopes for each airframe-engine variant combination are summarised *(see table, page 46)*. The -A2/-A8 powering the A310-300 achieve the longest intervals because of their low thrust ratings, while the -A3/-A5 powering the A300-600 have a relatively long EFC interval, but this translates to a relatively short EFH interval. At the other extreme, the -B1F can achieve an average interval of 3,000EFC with some operators, and because it operates at the longest EFC time of all CF6-80C2 applications, it has a long EFH interval of 22,500EFH *(see table, page 46)*. Similarly, the -B6F/-B7F engines have relatively long intervals of 19,000EFH.

The shop visit input costs have been calculated over three removal intervals so as to indicate the likely average reserves, since not all modules would experience full workscopes or overhauls over a cycle of one or two removals *(see table, page 46)*. The shop visit costs used assume that some of the parts and materials used were serviceable from time-continued engines.

Maintenance reserves for shop visits, that do not include any allowance for LLPs, are an approximate guide. That is, shop visit inputs could be lower or higher than indicated, depending on the availability of used serviceable material in the aftermarket.

Reserves per EFC are highest for the -D1F powering the MD-11 at $1,147. This is equal to $208 per EFH, given the relatively long EFC time of 5.5EFH *(see table, page 46)*.

The -A5F, powering the A300-600F, has the highest reserve of $430 per EFH, mainly due to its relatively short removal interval. All aircraft operating short and medium average EFC times have relatively high maintenance reserves per EFH. The A300-600 in passenger services has a reserve of $273 per EFH when operating medium-haul mission at 3.0EFH *(see table, page 46)*, but these would be higher for an aircraft being used on shorter missions similar to the freighter variant.

The lower-rated -A2/-A8 have reserves of $251 per EFH when operating in similar way to the A300-600, and the -B6F/-B7F powering the 767-300 freighter have reserves of $283 per EFH on medium-haul missions.

The -B6F/-B7F and -B1F powering the 767-300ER and 747-400 on long-haul operations have the lowest reserves per EFH of $156 and $132 *(see table, page 46)*.

There is also the issue of reserves for LLPs. The four main groups of LLPs would have reserves of $320 per EFC if all parts had certified lives equal to target lives, and each part was able to fully utilise its certified life limit.

Most aircraft of all types, and operating in all roles, accumulate 600-1,200EFC per year, and the LLPs with lives of 20,000EFC expire after a maximum of 16-33 years. Parts with certified lives of 15,000EFC will fully utilise their life limits between over 12-25 years.

CF6-80C2 REMOVAL INTERVALS, SHOP VISIT WORKSCOPES & MAINTENANCE RESERVES

Engine variant	-A3/-A5	-A5F	-A2/-A8	-B6F/-B7F	-B6F/-B7F	-B1F	-D1F
Aircraft type	A300-600	A300-600F	A310-300	767-300ER	767-300ERF	747-400	MD-11/MD-11F
FH:FC ratio	3.0	2.0	2.0-4.0	5.5	3.5	7.5	5.5
1st removal							
Interval-EFC	4,000	3,500	4,500	3,500	3,000	3,000	2,500
Interval-EFH	12,000	7,000	14,000	19,250	10,500	22,500	13,750
S-V workscope							
HPC/HPT	Full OH	Perf/OH	Full OH	Perf/OH	Perf/OH	Perf/OH	Perf/OH
LPT	None	None	Min	None	None	None	None
Fan/LPC	Restore	Restore	Full OH	Restore	Restore	Restore	Min
S-V costs-$							
HPC/HPT	2,700	2,500	2,700	2,500	2,400	2,400	2,300
LPT	0	0	150	0	0	0	0
Fan/LPC	275	275	375	275	275	275	150
2nd removal							
Interval-EFC	4,000	3,500	4,500	3,500	3,000	3,000	2,500
Interval-EFH	12,000	7,000	14,000	19,250	10,500	22,500	13,750
S-V workscope							
HPC/HPT	Full OH	Full OH	Full OH	Full OH	Full OH	Full OH	Perf/OH
LPT	Full OH	Full OH	Full OH	Full OH	Full OH	Full OH	None
Fan/LPC	Full OH	Full OH	Full OH	Full OH	Full OH	Full OH	Restore
S-V costs-$							
HPC/HPT	2,700	2,700	2,700	2,700	2,700	2,700	2,400
LPT	400	400	400	400	400	400	0
Fan/LPC	375	375	375	375	375	375	275
3rd removal							
Interval-EFC	4,000	3,500	4,500	3,500	3,000	3,000	2,500
Interval-EFH	12,000	7,000	14,000	19,250	10,500	22,500	13,750
S-V workscope							
HPC/HPT	Full OH	Perf/OH	Full OH	Perf/OH	Perf/OH	Perf/OH	Full OH
LPT	Full OH	None	Min	None	None	None	Full OH
Fan/LPC	Restore	Restore	Full OH	Restore	Restore	Restore	Full OH
S-V costs-$							
HPC/HPT	2,700	2,500	2,700	2,500	2,500	2,500	2,700
LPT	400	0	400	0	0	0	400
Fan/LPC	275	275	375	275	275	275	375
Reserve-$/EFC	819	860	754	860	992	992	1,147
Reserve-$/EFH	273	430	251	156	283	132	208

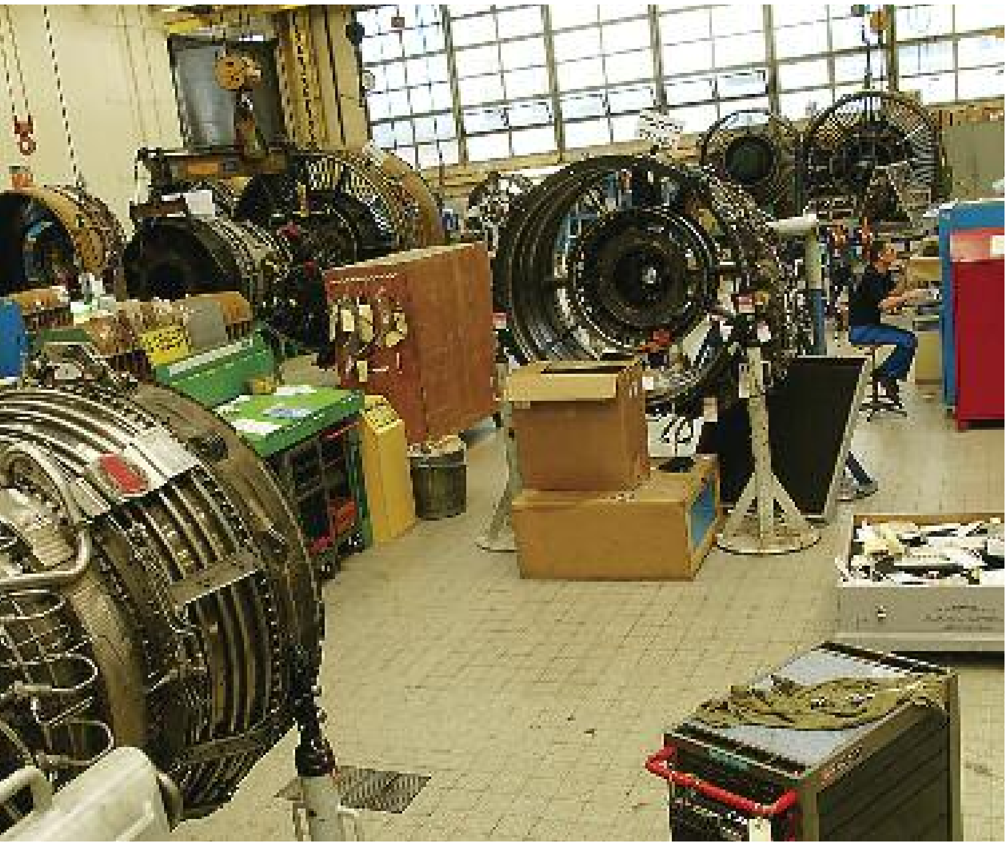
There are a large number of engines powering medium- and long-haul aircraft therefore where LLPs in the fan/LPC, HPC and LPT modules only come due at close to or at the time of the aircraft's retirement. In this case LLPs may never need to be replaced.

That is, all 747-400s in operation have accumulated a total time of fewer than 18,000EFC, most 767-300ERs have accumulated fewer than 20,000EFC, and the MD-11 with the highest total time has accumulated 14,000EFC.

"There are some cases where findings on individual LLPs during shop visits raise a requirement to replace them," says Matthews. "Besides these situations, an airline may only ever need to acquire LLPs from time-continued used engines now that large numbers have been retired." Airlines may have been able to avoid paying reserves for LLPs in these three modules, however.

The case is different for LLPs in the HPT module, which will have had to be replaced during the aircraft's economic operating life. Some operators will have acquired cheaper time-continued parts from older, already retired, engines.

The case is different on engines powering mainly the A300-600 and A310 operated at shorter average cycle times. These have accumulated more than 20,000FC, so a higher annual rate of FC accumulation means that all LLPs will have had to be replaced at some point during the aircraft's operational life. Some airlines may have saved costs by acquiring some of the parts as time-continued material from used and retired engines. Many engines, however, will have had to be fitted with all-new parts.



With many engines being older than 15 years and having passed through at least three shop visits, and due to be retired or phased out over the next five to eight years, it makes sense for them to be transferred to a time and material contract. This gives operators the freedom to use management practices that can avoid certain maintenance actions and minimise overall costs.

Low-cost management

Some of the engine fleet is maintained through power-by-the-hour (PBH), total care or similar-style maintenance and technical support contracts. Airlines enter into these contracts at the start of an engine's operational life, either with an original equipment manufacturer (OEM)-related engine shop or an independent shop. A few larger aircraft-affiliated maintenance shops also offer such contracts.

Such contracts are often entered into for a period of operation equal to two or three removal intervals. Binner says that contracts are often equal to a term that is equal to the expected engine's operational horizon, normally for 10-15 years.

These contracts will include the payment of reserves to accrue to replace LLPs when they expire, and to accrue funds so that the cost of shop visits is covered when they come due. This is necessary to keep the engine in a condition for long-term operation, and to optimise all maintenance costs and reserves.

It may be necessary to continue this for leased engines, but it is not a definite requirement for owned engines. As owned engines mature and approach retirement, maintenance costs can be saved in several ways. This can be by not replacing LLPs in some of the engine's modules, by using material taken from time-continued modules and whole engines, and by using time-continued modules or even whole engines instead of putting them through whole shop visits.

These techniques are now all generally possible because of the large number of CF6-80C2s that have become available over the past five or six years as large numbers of aircraft have been retired and parked. "The supply of time-continued engines, modules and used serviceable material can change fairly quickly," says Binner. "It is driven by the number of parked and retired aircraft and engines during a particular period, and the market demand for the particular engine variant at the time. The number of parked engines, however, does not necessarily equate to serviceable engines. It can suddenly become difficult to locate an engine in the required configuration, maintenance condition, the right number of EFH and EFC since its last shop visit, and with the right number of EFC left on its LLP lives."

The techniques of not replacing LLPs, for example, can be used because the long life limits of most parts, such as 20,000EFC for those on three of the CF6-80C2's four modules, mean that many aircraft operating long-haul missions may only need to replace LLPs once, or they may last the aircraft's entire operational life. That is, LLPs with a life of 20,000EFC will expire after more than 30 years in the case of the 747-400, 767-300ER, 767-400ER and MD-11 if these aircraft have always operated long-haul operations and only accumulated about 600FC per year. This raises the issue of whether an operator can negotiate in a fixed-rate-per-hour contract not to pay any reserves for LLPs for an engine they own, or have reserves paid for LLPs refunded if the parts are not replaced.

It is not possible to use the potential cost-saving techniques for engines under a PBH or total care contract, however. Airlines will therefore seek to terminate these contracts when the engine is about 15 years old, or due for retirement or is to be phased out. The best option in this case is to change to a time and material contract with a maintenance provide. In this situation the operator is free to manage engines with respect to removal intervals, shop visit workscope definition, and deciding whether or not to put certain modules through a shop visit, or swap them with time-continued modules as a lower cost alternative.

There are now an increasing number of specialist technical support contracts being provided by various suppliers for mature engines. MTU Maintenance, for example, has recently launched MTUplus Mature Engine Solutions, targeted at airlines' needs for ageing and mature engines. "There are two halves of the Mature Engine Solutions product," explains Binner. "These are Instant Power, and Smart Repair. Instant Power provides lease and exchange engines, while Smart Repair provides services for maintenance and salvation.

"Instant Power solutions involve either short-term leasing of engines, or the exchange of an engine for one with an equivalent configuration and remaining life adapted to the customers' needs. Smart Repair strongly relies on used serviceable and time-continued material, which has been gained from customer-owned engines or MTU's inventory. A feature of Mature Engine Solutions is a brand of fixed-price contracts, which can be referred to as 'instant power' guarantees. These types of contract may not even involve any MRO work, and can be paid for on an EFH or EFC basis. It is basically a 'fly-by-hour' contract tailored to mature engines. The operator transfers the engine availability risk to MTU Maintenance, which then decides whether to put the engine or modules through a shop visit, or provide exchange modules or an engine instead." AC