CF6-80C2 maintenance analysis & budget

The CF6-80C2 engine series has reached maturity. Removal intervals are well established and most of the engine's reliability issues have been addressed. Maintenance costs for its different applications are analysed.

There are about 3,000 CF6-80C2 series engines in operation, in a variety of styles. Engines range in age from zero to 20 years old, and the large number in existence means that the CF6-80C2 will be an important type for at least another 20 years.

The engines are rated from 53,500lbs to 62,000lbs thrust, with the majority of the fleet rated at 58,0000lbs thrust or more. Most engines are also operated on long average cycle times exceeding 6.0 engine flight hours (EFH). Many lower rated engines are operated on short- and medium-haul missions of 1.0-3.0EFH, while others can be operated on ultra-long-haul missions with average times of up to 10 or 12 EFH. Aircraft and fleets can also be operated in a variety of environmental and operational conditions.

The many thrust ratings available, the variety of possible operations and the range of environmental conditions mean that there will be a wide variation in maintenance costs and reserves. The main factors affecting maintenance reserves are thrust rating, average cycle time, take-off thrust de-rate and outside air temperature (OAT).

CF6-80C2 in operation

Of the 3,000 CF6-80C2s in civil operation, there are 13 main variants, powering five main aircraft types. An example is the 767 family, which includes several variants of the -200, -300 and -400 series. These aircraft have a wide range of maximum take-off weight (MTOW) and engine thrust requirements.

Only about 250 aircraft use engines with thrust ratings lower than 58,000lbs. These include the A300-600, A310 and some lower-weight variants of the 767-200/-200ER. These aircraft are mainly operated on short- and medium-haul operations, although some 767-200ERs are used as long-haul aircraft.

These 250 aircraft include about 80 A310-200s/-300s that are equipped with -80C2A2 engines rated at 53,500lbs thrust. Turkish Hava Yollari (THY) operates a fleet of six aircraft on medium-haul operations from its base at Istanbul. "Our engines have power management controls (PMC), as do all -80C2A2s, and have a special feature of a flat-rating temperature of 44 degrees centigrade. This allows the aircraft to operate at full take-off engine thrust at the high temperatures that are likely to be experienced in any global operation," explains Mujdat Uludag, engine shop manager at Turkish Technic. "We operate our A310s on medium-haul routes to India, the Middle East and Europe at an EFC time of 2.8EFH."

More than 1,000 aircraft equipped with CF6-80C2s have engines rated at 58,000lbs thrust or more. These include A300-600s with -80C2A1/A3/A5/A8 engines that in most cases operate on average EFC times of 1.0-1.5EFH. These include fleets operated by Lufthansa, Thai International and China Eastern. Other carriers have -80C2A5-powered aircraft which operate on medium-haul operations.

Aircraft with high thrust-rated engines also include about 30 A310-300s with -80C2A8 engines. These are operated by Air Transat, Pakistan International Airlines and Kuwait Airways.

Most high thrust-rated engines are utilised on 747-400s and 767s. There are more than 280 747-400s equipped with -80C2B1Fs, and about 400 767-300ER/-400ERs powered by -80C2B4/B6/B7/B8s.

Most operators have extensive intercontinental route networks and operate the 747-400 on flight cycles that average 7-8FH in most cases. Air New Zealand and Qantas operate their aircraft on ultra-long-distance routes, and each has average cycle times of up to 10-12FH.

The CF6-80C2 powers more 767s than any other aircraft. The -80C2B6 and -B6F each power about 100 767-300ERs. The PMC -80C2B6 engines are older than those with full authority digital engine control (FADEC), which power most of the younger 767s in service and the aircraft still being manufactured. Another 120 767-300ERs also have the -80C2B7F engine, and 30 767-400ERs have the -80C2B8F.

Most 767-300ER/-400ERs operators use the aircraft as a long-haul workhorse, but it is also used on medium-haul operations by KLM and others. The average cycle times of most engines are in the 5-7EFH range.

The -80C2 also powers about 110 MD-11s, with most operators using the aircraft on 5-7 hour cycles. "The average cycle time of our MD-11 fleet is about seven and half hours, which is equal to a trip length of about 3,500nm. The longer routes to China and Japan are about nine hours," explains Tuomo Karhumaki, vice president of the powerplant department at Finnair Technical Services. "This means that the aircraft often operate below maximum take-off weight (MTOW). The highest OAT we experience at our Helsinki home base is 25-30 degrees centigrade in the middle of summer, and this comes down to 0-5 degrees centigrade in the winter. The aircraft often leave the outstations in Asia in the mid-morning, so they do not often experience the highest temperatures there."

EGT margin

Exhaust gas temperature (EGT) margin can be a prime removal driver of many engine types in many different types of operation although it is not so important for most -80C2s. By now, most CF6-80C2 engines have been through their first shop visit and have reached maturity *(see CF6-80C2 specifications, page 10)*. The consequence of this is that most block 3 engines do not have their original EGT margin, but will have recovered about 80-85% of this level. Earlier-built block 1 and 2 engines had lower initial EGT margins, but the improved materials developed since their introduction mean that they have been able to recover an EGT margin close to their original level.

EGT margins of mature engines are generally higher for lower-rated engines compared to engines with high thrust ratings.

"The CF6-80C2A2 on the A310 is flat rated at 44 degrees centigrade," explains Uludag. "The EGT margin of a mature engine following a shop visit is 38 degrees centigrade, and our operation averaging 2.8EFH per engine flight cycle (EFC) means that we rarely have removals due to complete EGT margin erosion. We are able to get a margin close to the original because we have developed best practices in the shop, including getting the best tip and seal clearances, and surface finishes on the blades and vanes."

Most of the different -80C2 variants used to power the 767 and A300-600 range from 58,000lbs to 60,800lbs thrust, so they have high EGT margins compared to those used on the A310. Higher-rated engines generally have mature EGT margins of 25-45 degrees centigrade.

"The -80B2/B2F on the 767 are the only variants with a low rating, and the -B2F can have an EGT margin of more than 90 degrees," explains Paul Lueck, propulsion systems engineer at Lufthansa Technik. "This compares to the highest-rated -B6F which has an EGT margin of about 43 degrees following a shop visit. This will be higher than the -B6 PMC engine.

"The EGT margin of our -B1F engines following a shop visit is about 60 degrees centigrade," says Lueck. Most -B1Fs have an EGT margin of 35-50 degrees following a shop visit.

The highest-rated engines are the -80C2D1F engines powering the MD-11, rated at 61,960lbs thrust. Finnair's average post-shop visit margin is about 30 degrees centigrade, and varies by plus or minus five degrees.

VARIATION OF AVAILABLE EGT MARGIN WITH OAT FOR CF6-80C2 SERIES ENGINES

CF6-80C2
Standard EGT margin = 30 degrees

OAT deg C	10	15	20	25	30	35	40	44
Available EGT margin	109	93	77	61	45	29	13	0
OAT	10	15	20	25	30	35	40	41
Available EGT margin	99	83	67	51	35	19	3	0
OAT	10	15	20	25	30	35		
Available EGT margin	79	63	47	31	15	0		
OAT	10	15	20	25	30	33		
Available EGT margin	74	58	42	26	10	0		

EGT margin recovery

The EGT margin recovered after a shop visit is affected by the quality of the workscope performed in the shop.

"Tight blade tip clearances can get another 5-10 degrees of EGT margin in the test cell," explains Frank Herr, customer programme manager CF6 projects at MTU Maintenance Hannover GmbH. "If the blade tip clearance is too tight, however, you can get a high rate of initial EGT margin loss. Also, the individual operational environments will affect the need to customise engine maintenance, so it is hard to find the optimum blade tip clearance."

Lueck explains that the most effective clearances in restoring EGT margin are the high pressure compressor (HPC) and high pressure turbine (HPT). "Knife edge seals rub against honeycomb layers, and clearances in these seals are also important to get good EGT margin recovery," explains Lueck. "Tight clearances in each seal can improve EGT margin by 3-5 degrees. For example, reducing the compressor discharge pressure (CDP) seal clearance by 0.25mm can improve EGT margin by 4.7 degrees. This means that it is worth overhauling the honeycomb layers at every shop visit."

Available EGT margin

EGT margins for most variants are expressed for flat rating temperatures of 30 degrees centigrade, although some engine variants have higher flat rating or 'corner point' temperatures. The EGT margin actually available for particular operating conditions will be dependent on the OAT.

When operating at maximum thrust, the EGT decreases by 3.2 degrees for every one degree drop in OAT below the corner point temperature. The EGT margin will therefore increase at the same rate. Engine thrust is maintained at maximum thrust, and the EGT is allowed to vary with OAT when OAT is lower than the corner point temperature. For OATs above the flat rating temperature, the EGT is held constant by reducing thrust.

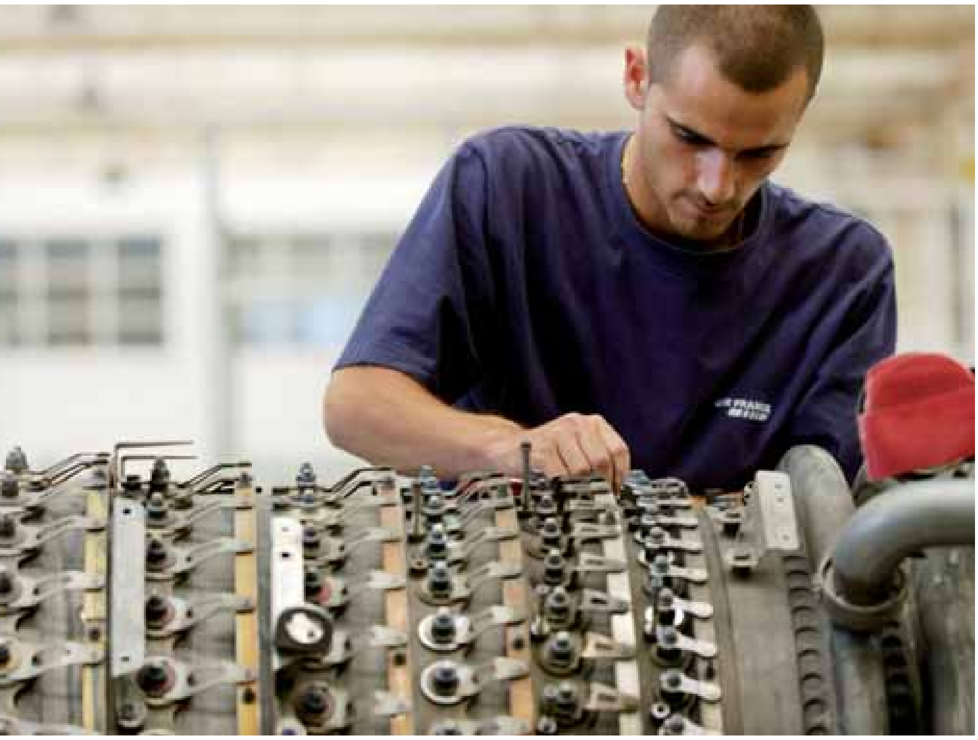
Operations in many parts of the world experience OATs lower than the corner point temperatures of 30-35 degrees centigrade, so their available EGT margins are higher than the standard EGT margins. An engine with an EGT margin of 35 degrees at the flat rating temperature of 30 degrees, for example, will have an additional 32 degrees of EGT margin at an OAT of 20 degrees. This will give it an available EGT margin of 67 degrees *(see table, this page)*. This will naturally prolong on-wing life, but only if the engine is able to operate at OATs similar to, or lower than this, for all operations.

The effects on engines of operating in environments where the temperature is higher than the flat rating temperature must also be considered. An engine with a standard EGT margin of 35 degrees centigrade can theoretically be allowed to maintain constant power for OATs higher than the flat rating temperature, until the EGT redline is reached, where the engine will then have zero EGT margin. The OAT at which the redline is reached is the sea level OAT limit (SLOATL).

For example, an engine with a standard EGT margin of 35 degrees will have a zero EGT margin when the OAT is 11 degrees centigrade higher than the flat rating temperature, at the SLOATL of 41 degrees.

In actual operations, however, the aircraft's manuals are used to keep the engine's EGT, and therefore EGT margin, constant for all OATs higher than the corner point temperature. The EGT margin is therefore the same at the corner point temperature as it is at 35 degrees, 40 degrees and 45 degrees. The manual informs the crew of the N1 speed or power setting permitted for the engine at a particular OAT. N1 speed is reduced as OAT increases. Maximum power is permitted at the corner point temperature, but thrust steadily reduces as OAT increases.

An engine's hardware deteriorates with frequency of use. Its EGT increases and its EGT margin and SLOATL reduce as a result. The SLOATL will gradually get closer to the corner point temperature as deterioration progresses. When the SLOATL is equal to the corner point temperature, the EGT margin is zero. The engine will still have some EGT margin at



The CF6-80C2 is generally removed for shop visits due to hardware deterioration rather than EGT margin erosion. Hardware problems include those associated with HPT blades and VSV bushings. Some airlines have seen removal intervals steadily improve as hardware deterioration problems are overcome.

OATs lower than the corner point temperature, however. SLOATL is useful, because it indicates the maximum OAT at which maximum thrust can be used for a deteriorated engine. SLOATL therefore also gives an indication of how deteriorated the engine's condition is.

The available EGT margin at different OATs has to be considered. More consideration must be given to aircraft operating in the hottest climates, where OATs can reach 40-45 degrees centigrade. Engines powering the 747-400, 767-300ER/-400ER and MD-11 that operate at high take-off weights require the most consideration.

Airlines need to be able to operate with engines that can use maximum, or near to maximum, take-off thrust. This becomes more difficult for deteriorated engines operating in OATs above the corner point temperature. The higher the OAT, the larger the reduction from maximum power by limiting N1 speed.

The effect of engine deterioration on available EGT margin for different OATs can be illustrated *(see table, page 19)*. As described, an engine with an EGT margin of 35 degrees at the flat rating temperature of 30 degrees has an available EGT margin of 67 degrees for an OAT of 20 degrees centigrade, and a zero EGT margin at an OAT of 41 degrees.

A deteriorated engine with its standard EGT margin reduced to 10 degrees, will have a zero EGT margin at 33.1 degrees. This is lower than the midday temperatures in many parts of the Asia Pacific and Middle East. This practical problem therefore forces many airlines to remove engines that have plenty of standard EGT margin remaining.

The consequence of this is that many operators will adopt shop visit techniques to maximise EGT margin so as to maintain operational flexibility, as well as use techniques such as water washing to prolong good on-wing lives.

Take-off de-rate

De-rating the engine during take-off to less than maximum thrust increases available EGT margin, thereby prolonging on-wing life. Take-off de-rate also reduces the rate of engine deterioration, as illustrated by General Electric's (GE's) severity curve, which graphically illustrates the severity of an engine's operation in relation to take-off de-rate and EFH:EFC ratio, since engine deterioration is affected by both.

Engines operating short average cycle times are more affected than those operating long ones. The first 5% of de-rate from 100% thrust to 95% thrust has more of an effect in terms of reducing severity than subsequent 5% de-rates. At maximum power, the severity factor for engines operating at EFC times of 1.0EFH will be about 1.65, the severity factor for engines operating at 1.5EFH will be about 1.35, the severity factor for engines operating at 3.0EFH will be about 0.9, and the severity factor for engines operating at 6.0EFH will be about 0.78.

These severity values reduce when 5% de-rate is used, and engines operating at shorter EFC times experience a larger drop in severity. Engines operating at 1.0EFH, for example, see a drop in severity from 1.65 to about 1.4, while engines operating at 6.0EFH see a drop in severity from 0.78 to 0.65.

Engines operating on short cycle times benefit the most from take-off de-rate. Moreover, engines used on long average cycle times have low rates of severity, even at maximum thrust and zero de-rate. An engine operating at 1.0EFH per EFC would need to have a de-rate of about 30% to have the same severity as an engine operating at 6.0EFH per EFC with zero take-off de-rate.

EGT margin deterioration

The rate of EGT margin deterioration is indicated by the severity curve, but thrust rating also has an impact. EGT margin deteriorates at its highest rate in the first 2,000-3,000 EFH following a shop visit. There are various shop visit techniques to minimise rates of EGT margin erosion, which include water washing to recover some of the lost EGT margin.

Initial rates of EGT margin loss are higher for engines used on short-haul operations than for those utilised on longer cycles.

"Engines used on short cycles of just 1.0EFH per EFC will lose about seven degrees centigrade per 1,000EFH in the first 2,000EFH/EFC, and so lose about 15 degrees," says Nicola Henderson, engineer at Total Engine Support (TES). "EGT margin erosion will then reduce to a steady rate of 4 degrees per 1,000EFH/EFC."

A high-rated engine with an initial margin of 35-40 degrees will thus only be able to achieve a total time of about 5,000EFH/EFC before full EGT margin loss. An engine with an EGT margin of just 30 degrees may only be able to have an on-wing interval of 3,000-3,500EFC before all EGT margin is eroded. The maximum EGT margin possible is important for engines operated on short average cycle times.

Rates of EGT margin erosion will be moderately lower for engines operated on longer EFC times of 1.5-3.0EFH. This will be in the region of 8.0 degrees per 1,000EFH, but it will reduce. Lufthansa's short-haul operation with A300-600s, for example, has an initial rate of EGT margin loss of 8.0 degrees per 1,000EFH, but this reduces to 3.0 degrees per 1,000EFH after the first 2,000EFH or so.

"We do not monitor EGT margin

erosion that closely, but after the initial high rate it reduces to 2.5-3.0 degrees per 1,000EFH. This is equal to 8.0 degrees per 1,000EFC," says Uludag. "Our post-shop visit EGT margin of 38-40 degrees centigrade allows for an on-wing interval of up to 5,000EFC."

Engines operated on long-haul operations see initial rates of EGT margin loss of 3.5-5.0 degrees per 1,000EFH for the first 2,000EFH, and so lose 7-10 degrees. These rates then decline to 2.0-3.0 degrees per 1,000EFH.

The -80C2D1F powering the MD-11 has the highest rating, and so may experience relatively high initial rates of EGT margin erosion. "After the initial period of high EGT margin loss, the rate of margin loss reaches 1.5-2.0 degrees centigrade per 1,000EFH," says Karhumaki.

This implies that an engine with an EGT margin of 35 degrees will lose 7-10 degrees in the first 2,000EFH, leaving it with an EGT margin of 25-28 degrees. The following rate of margin loss will allow it to remain on wing for a further 9,000-14,000EFH. This would therefore allow a total interval of 11,000-16,000EFH.

The high temperatures experienced at some airports that take available EGT margin down to almost zero have to be considered. "We use the water washing technique to restore some of the lost EGT margin, because w0e have found that water washing can add up to 25 degrees of EGT margin," explains Karhumaki. "The rate of EGT margin erosion can also be reduced if tight clearances are achieved with the compressor and turbine. The surface finish of HPC blades is also an important factor. FADEC controls also allow better control of the turbine blade tip clearances, and therefore generally reduce EGT margin erosion rate. If we did not use water washing we would only achieve about 15,000EFH on wing before all EGT margin was lost. We actually get 15,000-17,000EFH on wing with about 5 degrees of EGT margin left. This allows us to operate without limitations at hot airports, and also has the benefit of reducing our shop visit costs and maintaining fuel burn performance."

Engines like Lufthansa's -80C2B1Fs, which have an EGT margin of about 60 degrees, will still have an EGT margin of 50 degrees after the first 2,000EFH. "The rate of EGT margin erosion may only be about 1.5 degrees per 1,000EFH, so the engine could remain on-wing for up to another 30,000EFH. Intervals are, however, limited by there being no available EGT margin in conditions of high OAT, and by life limits of LLPs with the shortest lives or other mechanical reasons," explains Lueck.

The -80C2B6F's EGT margin of 50-55 degrees allows a removal interval of up to 15,000-16,000EFH.

Removal causes

While the EGT margins on most -80C2 variants are not high, the EGT margin erosion rates allow long potential intervals for engines operated on long-haul missions. These result in hardware deterioration, which becomes a major removal driver.

First-run removal intervals are high for engines operated on long-haul operations. "The average first-run interval for our -B1Fs was about 28,000EFH," says Lueck. At an average EFC time of 8.0, this is equal to 3,500EFC. Engines used on short-haul flights will accumulate 4,000-5,000EFC on-wing for the first interval, depending on cycle time and style of operation. These intervals must be considered against the LLPs with the shortest lives, which in some cases can be 9,000EFC and 15,000EFC. LLPs can become removal drivers in the second or third intervals.

"The main removal drivers we have found are the deterioration of the variable stator vane (VSV) system, burning and breaking of the HPT blades, and airworthiness directives (ADs) requiring reworking on the first stage HPT disk," says Lueck. "EGT margin erosion is not a main driver, although we have to be careful that the engine still has enough EGT margin to operate on the longest routes from airports that have high OATs."

Herr adds that most -80C2s used on long-haul operations do not have intervals driven by EGT margin loss. "Engines like the -B6F with a relatively low EGT margin will have removals driven by both mechanical problems and full performance loss," says Herr. "The highest-rated -D1F engines have removals due to both full EGT margin loss and mechanical problems, as do the high-rated -B6F engines. The -B1F engines have removals mostly driven by mechanical deterioration. The PMC-controlled -B6 engines with lower EGT margin are mainly removed due to performance loss.

"In the past, stage 1 HPT blade burning and cracking was a main removal driver for all -80C2 variants until the late 1990s," continues Herr. "The new HPT stage 1 blade is much improved and is no longer a main removal driver."

In addition to EGT margin loss and mechanical problems, the CF6-80C2 has had some major ADs issued against it. The first of these is AD 2004-04-07, which concerns damage on the dovetail slots for HPT blades on the first stage HPT disk. "The AD required removals for re-working of the dovetail slots following an incident involving an uncontained failure. The AD has since been revised to AD 2006-16-06, following an incident on an -80A installed on an American Airlines 767 during a ground test run," explains Uludag. "This AD requires an inspection every 3,000EFC, and has a limit of 10,000-14,000EFC for re-working the dovetail slots. The actual EFC limit depends on the number of accumulated cycles and the engine's previous inspection history."

The second major AD that affects the -80C2 series is AD 2002-25-08, which concerns the HPC 3-9 stage spool LLP. "The AD requires an inspection every 2,000-3,500EFC, which forces an early removal in many cases and a deep workscope. The AD also reduced the life limit of the concerned part numbers from 15,000EFC to 12,500EFC," explains Uludag. "This problem can be circumvented by replacing the 3-9 spool with a new part number that is not affected by the AD."

A third major AD concerning the -80C2 series is AD 2004-22-07, which relates to an inspection on an old version of the stage 2 HPT nozzle guide vanes via a borescope inspection. The initial inspection threshold is 1,600FC. These values may differ, depending on the engine variant.

The terminating action for these last two ADs is the incorporation of the latest part numbers of the respective parts. The 3-9 HPC spool has a cost of $250,000, and a new nozzle guide vane costs $290,000.

Life limited parts

The LLPs in the CF6-80C2 series can be split into four groups related to the engine's four main modules. These are the fan and booster, the HPC module, and the HPT and LPT modules. These are described in detail *(see CF6-80C2 specifications, page 10).*

The target lives for all LLPs are 20,000EFC, although many are limited to less than this. There are several part numbers for each LLP. The early part numbers for some LLPs have relatively short lives, some of which are also affected by AD notes either restricting their lives or requiring inspections and re-working. In some instances, the lives of later part numbers are closer to the target lives.

The life limits also vary according to thrust rating. The most recent part numbers for the majority of LLPs have lives of 15,000EFC and near to 20,000EFC. Two parts, the second stage HPT disk and the rotating stage seal, have lives of just 9,000EFC for some engine ratings, and will therefore force removals.

Removal intervals

Removal intervals should be considered as planned removal intervals. These are intervals that can be expected with the available EGT margin or probable time on wing before degradation of the engine's various systems starts to take effect. Planned removal intervals do not include unscheduled removals, which are a consequence of foreign object damage (FOD), or small failures that require repairs or shop visits.

FADEC engines have longer planned intervals than PMC engines.

-80C2A3/A5

There are relatively few aircraft operated on short cycle times of 1.0-1.5EFH, and the A300-600 accounts for the majority of these. A small portion of the 767 fleet is also operated like this, mainly by Japan Airlines (JAL) and All Nippon Airways (ANA) on domestic Japanese routes. Lufthansa operates the A300-600 on German domestic and intra-European routes at an average cycle time close to 1.0EFH. "The -80C2A3/A5 on the A300-600 can be expected to achieve up to 5,000EFC on short cycles with the high levels of de-rate on short cycle times," says Lueck. "Engines that are operated on cycles of 2.0EFH can get to 4,500EFC, and as the cycle time increases to 3.0EFH the severity reduces dramatically and the intervals change to 4,000EFC and 12,000EFH."

Herr says that there is a shorter interval in EFC for longer cycle times. "An engine operated at 4.0EFH per EFC will achieve 2,500EFC on-wing between planned removals, equal to 10,000EFH," explains Herr.

-80C2A2

Similar average removal times are illustrated for engines powering the A310-300.

"Our -80C2A2 engines, which are PMC-controlled and operated on cycles averaging 2.8EFH, can remain on-wing for up to 5,000EFC," says Uludag. "The EGT margin of 40 degrees centigrade allows our engines to achieve up to 5,000EFC on-wing, which is equal to 14,000EFH. The first removal interval was long, about 18,000EFH. The 5,000EFC interval is possible if there are no AD or LLP limitations, or unscheduled removals due to FOD or other failures."

The -80C2A2 is rated at 53,500lbs thrust, one of the lower ratings for the -80C2 series, and powers most A310-300s.

The -80C2B2, with PMC controls, is similarly rated at 52,500lbs thrust and powers low gross-weight versions of the 767-200/-300. It powers a minority of 767s in operation, mainly older -200s. Intervals of 3,000-4,000EFC can be expected for engines operated at average cycle times of 2.0-3.0EFC.

-80C2B4/B6/B7/B8

The -80C2B4 PMC engine powers a small number of 767-300s. Engines operating at an average EFC time of 2.6EFH can achieve 2,600EFC on-wing, equal to 9,000EFH.

The majority of 767s, however, are high gross-weight extended-range aircraft that are powered by the PMC-controlled -80C2B6 and FADEC-controlled -80C2B6F and -80C2B7F engines.

"The PMC -B6 engines operating at an average cycle time of 6.0EFH can only be expected to remain on wing for 1,700EFC," says Herr. "This is equal to 10,000EFH, and compares to 2,500EFC and 15,000EFH for -B6F FADEC engines operated at the same average EFC time. This will change to 3,600EFC and 14,500EFH for engines operated at an average cycle time of 4.0EFH, and to 2,350EFC and 16,500EFH for engines operated at longer cycles of 7.0-8.0EFH." By comparison, PMC engines operated at long average cycle times on the 767 can only achieve about 1,700EFC, equal to 12,000-13,500EFH.

-80C2B1F

The -B1F engines rated at 58,000lbs power the majority of 747-400s and display similar on-wing performance. Herr says that there is a large difference

SHOP VISIT MANAGEMENT OF MATURE CF6-80C2 SERIES ENGINES

-80C2A3/A5 engine for A300-600

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	5,000	5,000	5,000	5,000
Accumulated interval-EFC	5,000	10,000	15,000	20,000
EFH:EFC	1.0	1.0	1.0	1.0
Interval-EFH	5,000	5,000	5,000	5,000
Accumulated interval-EFH	5,000	10,000	15,000	20,000
Shop visit workscope				
HPT	Overhaul	Overhaul	Overhaul	Overhaul
HPC	Overhaul	Overhaul	Overhaul	Overhaul
LPT	Minimum	Overhaul	Minimum	Minimum
Fan/booster	Minimum	Overhaul	Minimum	Minimum
LLP replacement:	2 items at 9,000EFC		15,000EFC parts	20,000EFC parts

-80C2A3/A5 engine for A300-600

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	4,500	4,500	4,500	4,500
Accumulated interval-EFC	4,500	9,000	13,500	18,000
EFH:EFC	2.0	2.0	2.0	2.0
Interval-EFH	9,000	9,000	9,000	9,000
Accumulated interval-EFH	9,000	18,000	27,000	36,000
Shop visit workscope				
HPT	Overhaul	Overhaul	Overhaul	Overhaul
HPC	Heavy restore	Overhaul	Heavy restore	Overhaul
LPT	Minimum	Overhaul	Minimum	Overhaul
Fan/booster	Minimum	Overhaul	Minimum	Overhaul
LLP replacement:	2 items		15,000EFC parts	20,000EFC parts

-80C2A2 engine for A310-300

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	5,000	5,000	5,000	5,000
Accumulated interval-EFC	5,000	10,000	15,000	20,000
EFH:EFC	3.0	3.0	3.0	3.0
Interval-EFH	15,000	15,000	15,000	15,000
Accumulated interval-EFH	15,000	30,000	45,000	60,000
Shop visit workscope				
HPT	Overhaul	Overhaul	Overhaul	Overhaul
HPC	Heavy restore	Heavy restore	Heavy restore	Heavy restore
LPT	Minimum	Overhaul	Minimum	Overhaul
Fan/booster	Minimum	Overhaul	Minimum	Overhaul
LLP replacement:			15,000EFC parts	20,000EFC parts

-80C2B6/B7 engine for 767-200ER/-300ER

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	2,500	2,500	2,500	2,500
Accumulated interval-EFC	2,500	5,000	7,500	10,000
EFH:EFC	6.0	6.0	6.0	6.0
Interval-EFH	15,000	15,000	15,000	15,000
Accumulated interval-EFH	15,000	30,000	45,000	60,000
Shop visit workscope	Heavy restore	Overhaul	Heavy restore	Overhaul
HPT	Restore	Restore	Overhaul	Restore
HPC		Restoration or overhaul		Restoration or overhaul
LPT		Restoration or overhaul		Restoration or overhaul
LLP replacement:	Replace parts at 6th & 8th shop visits			

between earlier-built and block 3 engines. "The fan, LPT and HP systems on block 3 engines have higher thresholds for performance restorations and overhauls than block 1 and 2 engines," explains Herr. "Today's -B1F engines can remain on-wing for up to 40,000EFH, especially those engines operated on long cycles, such as those operated by Qantas or Air New Zealand."

Lufthansa Technik achieves some of the longest intervals for the -B1F. "The youngest engines on aircraft delivered in the past four or five years have had first removal intervals of up to 30,000EFH, and average intervals of 28,000EFH," says Lueck. "Our average cycle time is 8.0EFH, and engines on their second and third runs have achieved 17,000EFH, equal to 2,100EFC. The third run is slightly shorter than the second, but the intervals depend on the maintenance condition of the different modules. This interval of 17,000EFH is not EGT margin-limited, although there will be little EGT margin left after this interval at the high ambient temperatures experienced at airports like Singapore or Hong Kong. This therefore forces a removal.

"The LPT should last 34,000EFH, and so will have to be done every second shop visit. This means the average interval would be limited to 17,000EFH," continues Lueck.

-80C2D1F

The -D1F engines powering the MD-11 are the highest rated, at 62,000lbs thrust, and as described, are mainly removed due to EGT margin erosion. "We can keep our engines on wing for up to 15,000-17,000EFH, or 2,200-2,500EFC, and have about 5 degrees centigrade of EGT left with the use of water washing about every 1,000EFH," says Karhumaki.

Similar intervals are observed by Lufthansa Technik. "We can expect about 2,300EFC for a passenger aircraft operated at 7.0EFH, equal to 16,000EFH. A freighter flying at shorter cycles of 5.5EFH will achieve about 2,200EFC or 12,500EFH," says Lueck.

Unscheduled removals

Unscheduled removals can have several causes, and have the effect of interrupting scheduled removal intervals and reducing the potential planned maintenance intervals of which the engine is capable.

The -B1F engine powering the 747-400, for example, is capable of intervals of 17,000EFH. The engine could conveniently conform to a shop visit pattern of alternating performance restorations and overhauls. These projected intervals will be reduced by some of the unscheduled removals, which will then reduce the average interval between all removals, and have the effect of increasing maintenance reserves per EFH.

There are several categories of unscheduled removals. These are first split between engine- and non-engine related events. Non-engine events are birdstrikes and ingestion of FOD. If serious, these will pass through the engine core and result in a heavy shop visit.

Engine-related events can be divided between light and heavy events. Light events include problems such as oil leaks, small internal repairs or fan blade repairs. While these force removals, they do not interfere with the pattern of scheduled removals, but are simply added to additional light shop visits.

Heavy engine-related events force removals and heavy shop visits. These can include bearing failures, which incur some of the most expensive shop visits.

Non-engine issues of FOD damage or birdstrikes and heavy engine-related unscheduled events have an impact on scheduled removal intervals and the pattern of shop visits. Unscheduled events occur at random, which inevitably makes engine management difficult.

Unscheduled events occur about once every 30,000EFH. An engine with an average planned removal interval of 15,000EFH could therefore be expected to have one unscheduled removal for every two scheduled removals. Similarly, an engine with a shorter planned interval of 10,000EFH will have an unscheduled removal for about every three planned removals.

Light unscheduled shop visits have costs of $200,000-400,000, while a heavy engine-related visit and FOD or birdstrike incident can incur a cost of anything from $1.0 million up to $3.0 million. Major failures, such as bearing failures will have some of the highest costs. Taking an average of $1.0 million for an unscheduled event will result in a reserve of $35 per EFH, which will have to be added to maintenance reserves for planned removals, so that operators have a conservative budget for all maintenance costs.

Shop visit pattern

There are on-wing EFC thresholds for different workscope levels for the engine's different modules.

The shop visit workscope will also be affected by the age and repair status of blades and vanes in the engine. "The level of take-off de-rate is one factor affecting the percentage of parts that are scrapped and have to be replaced, and the percentage of parts that can be repaired," explains Henderson. "Parts in the HPT and LPT suffer the most from high temperatures which lead to oxidation and sulphidation. Older and high-thrust engines tend to have higher scrap rates. Blades and vanes in younger engines can last up to two shop visits (three runs on-wing).

"The threshold for a performance restoration in the HPT is 2,000EFC, and 4,000EFC for an overhaul," continues Henderson.

An engine that has achieved 3,000EFC on-wing will therefore have a heavy performance restoration workscope with a high scrap rate. The thresholds for the HPC are 2,000EFC for a performance restoration and 6,000EFC for an overhaul. Depending on the removal intervals, the HPC may be able to have an overhaul every third shop visit. The LPC and fan/booster modules have thresholds of 6,000EFC for an overhaul. If they are removed after intervals shorter than this, they can simply be inspected and undergo no work if their condition allows.

These thresholds must be considered for the different variants, their applications and removal intervals.

SHOP VISIT MANAGEMENT OF MATURE CF6-80C2 SERIES ENGINES

-80C2B1F engine for 747-400

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	2,400	2,400	2,400	2,400
Accumulated interval-EFC	2,400	4,800	7,200	9,600
EFH:EFC	7.0	7.0	7.0	7.0
Interval-EFH	17,000	17,000	17,000	17,000
Accumulated interval-EFH	17,000	34,000	51,000	68,000
Shop visit workscope				
HPT	Restoration	Overhaul	Restoration	Overhaul
HPC	Restoration	Restoration	Overhaul	Restoration
LPT	Minimum	Minimum	Overhaul	Minimum
Fan/booster	Minimum	Minimum	Overhaul	Minimum
LLP replacement:	Replace parts at 6th & 8th shop visits			

-80C2D1F engine for MD-11

Shop visit	First	Second	Third	Fourth
Removal interval-EFC	2,200	2,200	2,200	2,200
Accumulated interval-EFC	2,200	4,400	6,600	8,800
EFH:EFC	7.0	7.0	7.0	7.0
Interval-EFH	15,400	15,400	15,400	15,400
Accumulated interval-EFH	15,400	31,000	46,000	62,000
Shop visit workscope				
HPT	Restoration	Overhaul	Restoration	Overhaul
HPC	Restoration	Restoration	Overhaul	Restoration
LPT	Minimum	Minimum	Overhaul	Minimum
Fan/booster	Minimum	Minimum	Overhaul	Minimum
LLP replacement:	Replace parts at 6th & 8th shop visits			

Engines used on long-haul applications generally have shop visit patterns of alternating performance restorations and overhauls. Engines used on short cycles can have intervals of up to 5,000EFC, and therefore have heavier workscopes. "The HPT would normally alternate between a performance restoration and an overhaul when used on long-haul missions, but would require a heavier workscope of an overhaul every removal when used as a short-haul engine of 1.0 or 2.0EFH," explains Lueck. "The HPC would require heavier restorations or an overhaul every second shop visit. The LPT and fan/booster sections, however, may still not require any work at the first removal after an overhaul. They would be checked for condition, and an overhaul would only be carried out if their condition warranted it. The LPT and fan/booster sections are more likely to follow a pattern of alternating minimum workscope and overhaul."

The workscope patterns for the modules for different applications and average EFC times are summarised *(see tables, pages 26 & this page)*.

Shop visits inputs

The varying removal intervals for different engine variants, applications and types of operation relative to the threshold intervals for performance restorations and overhauls mean that the shop visit workscopes and their size of inputs will vary accordingly. The 2,000EFC and 4,000EFC thresholds for HPT performance restorations and overhauls, for example, mean that engines removed after 2,500-3,000EFC will require a heavier, different HPT workscope to those removed after 1,700EFC. A longer removal interval and heavier workscope will usually result in a higher level of parts replacement and a lower level of parts repair and sub-contract repairs.

The HPT can thus require an average performance restoration, a heavy performance restoration or an overhaul, depending on its removal interval and the previous workscope.

Similarly, the HPC can require an average or heavy performance restoration, a light overhaul or normal overhaul.

Work on these two core modules is required every shop visit, but the workscope will vary with time on wing in relation to the thresholds described. A light core performance restoration will require $1.0 million in parts and materials, $250,000 in sub-contract repairs and 4,000 man-hours (MH) in total labour. Labour charged at $70 per MH will take the labour portion to $280,000. The total cost will be $1.6 million.

A heavy core performance restoration will use up to $1.3 million in parts and materials, $300,000 in sub-contract repairs and up to 4,500MH in labour. This will take the total cost to $2.0 million. An average core performance restoration will cost $1.8 million in most engine shops.

A light core overhaul will use $1.25 million for parts and materials, $250,000 for sub-contract repairs and 4,250MH in labour, making a total cost of $1.8 million.

A heavy core overhaul will use $1.55 million in parts and materials, $300,000 in sub-contract repairs and up to 5,000MH in labour, thereby incurring a total of $2.3 million. An average core overhaul will have a cost of $2.1 million, about $300,000 more than the average core performance restoration.

The LPT and fan/booster sections can usually remain on-wing for 5,000-6,000EFC, which can be up to three shop visits. This can pose a problem for long EFC intervals on engines operated on short average cycle times of up to 4,000EFC. Lueck explains that at this removal interval, LPT and fan/booster sections can often still require minimal work, usually little more than a visual inspection, and remain on wing for another 4,000-4,500EFC before requiring a full overhaul at the second removal following a total time of up to 10,000EFC.

A minimal workscope on the two modules will cost a total of $100,000.

A light LPT overhaul will use about $120,000 in parts and materials, $30,000 in sub-contract repairs and 700MH in labour, taking the total cost to $200,000. A heavier workscope will use $190,000 for parts and materials, $40,000 in sub-contract repairs and 1,100MH, taking the total cost to $300,000.

A light fan/booster overhaul will have similar components to a light overhaul for the LPT. A heavier overhaul on the fan/booster section will vary little from a light workscope and take total cost to $250,000.

Light workscopes on the two modules will incur a cost of $450,000, while heavier workscopes will incur a cost of $500,000.

Total shop visit costs

These workscope costs can be applied to the different workscopes for each engine variant and application described *(see tables, pages 26 & this page)*.

The -A3/A5 engine, for example, operating on a 1.0EFH cycle time will have a core shop visit cost of $2.2 million and an LPT and fan/booster cost of $100,000, taking the total cost to $2.3 million for the first shop visit in sequence.

CF6-80C2 ENGINE SERIES MAINTENANCE RESERVES

Engine variant	-80C2A3/A5	-80C2A3/A5	-80C2A3/A5	-80C2A3/A5
EFC time-EFH	1.0	2.0	3.0	4.0
Average removal interval-EFC	5,000	4,500	4,000	3,500
Average removal interval-EFH	5,000	9,000	12,000	14,000
Shop visit reserve-$/EFC	500	505	544	636
LLP reserve-$/EFC	180	200	190	202
Total reserve-$/EFC	680	705	734	838
Total reserve-$/EFH	680	353	245	210

Engine variant	-80C2A2	-80C2B6/B7	-80C2B1F	-80C2D1F
EFC time-EFH	3.0	6.0	7.0	7.0
Average removal interval-EFC	5,000	2,500	2,400	2,200
Average removal interval-EFH	15,000	15,000	16,800	15,400
Shop visit reserve-$/EFC	480	890	930	1,068
LLP reserve-$/EFC	180	230	190	194
Total reserve-$/EFC	660	1,120	1,120	1,262
Total reserve-$/EFH	220	187	160	180

The second shop visit will be heavier for the LPT and fan/booster sections, incurring a total of $500,000. The total for the engine will be $2.7 million, with an average of $2.5 million for the two visits. The average will reduce to about $2.3 million for the engine operated on an average cycle time of 2.0EFH.

A light full engine overhaul will cost $2.2-2.3 million, while a heavy overhaul will cost up to $2.8 million.

"An overhaul which includes an upgrade of hardware from block 1 or 2 to block standard can cost $3.0 million or more, although this only occurs once for an engine" says Herr.

The approximate shop visit costs for the different variants and applications are summarised *(see table, this page)*. These shop visit costs are then expressed in $ per EFC, as an average reserve for their shop visit workscope pattern. Average reserves vary from $500 to $1,050 per EFC.

The LLPs can be replaced at intervals close to their full life. The four parts that have 15,000EFC lives, for example, can be replaced at the third shop visit for an -A3/A5 engine operating at 1.0EFH per cycle with little or no stub life remaining. These parts have a list price of $620,000.

The other 16 parts with life limits of 20,000EFC can be replaced at the fourth shop visit. These LLPs have a list price of $2.76 million.

A few variants have two LLPs with lives of only 9,000EFC, and these have to be replaced at the appropriate intervals.

Most LLPs can be replaced close to utilisation of their full lives, thereby incurring low reserves for LLP amortisation. The reserves for replacement of all LLPs can be calculated, and vary from $180 to $230 per EFC, depending on engine variant and removal interval and replacement timing.

The full reserves for each variant and application can therefore be determined. These are then expressed as a reserve per EFH, taking the average cycle time into consideration *(see table, this page)*.

The -A3/A5 engines used at a cycle time of 1.0EFH have the highest reserve of $680 per EFC, and $680 per EFH. The reserve for engines operated at an average cycle time of 2.0EFH is $355 per EFH *(see table, this page)*.

The benefit of longer average cycle times is seen with the -A2 engine powering the A310-300, operating at 3.0EFH per cycle with a reserve of $220 per EFH.

Similarly, the -B6/B7 operated on the 767-200ER/-300ER at 6.0EFH per cycle has a reserve of $186 per EFH *(see table, this page)*, while the -B1F powering the 747-400 has a reserve of $160 per EFH. The -D1F powering the MD-11 at the same 7.0EFH cycle time as the 747-400 will incur higher shop visit costs because of its higher thrust rating, so it will have a higher reserve of $180 per EFH *(see table, this page)*.

Reducing shop visit costs

The cost of shop visit materials and parts can be reduced by the utilisation of parts manufacturer approved (PMA) parts. The list prices of PMA parts are lower than the same parts offered by the original equipment manufacturer (OEM), but the parts are still approved for use in the engine.

HEICO Aerospace manufactures several types of parts for the CF6-80C2, including various consumables, vane arms, turbine ducts and shrouds, compressor ducts and shrouds and HPC blades. Rob Baumann, president of HEICO parts group, explains that compressor vanes tend to be repaired at a high rate. There is also a low demand for LPT blades, which are also repaired at a high rate and not replaced.

PMA HPT blades are provided by Belac, which is a joint venture between Chromalloy and several airlines.

"The best efficiency and cost gains are achieved by utilising PMA parts for HPC and HPT blades," says Baumann. "We offer several hundred PMA parts for the -80C2, and our customers save an average of $100,000 per engine shop visit by using HEICO parts. This comes from consumable and repairable parts. Our parts cost 50-75% of the price of OEM parts, and can lead to sizeable cost savings. One of our customers once saved $330,000 by using HEICO and Belac parts. Some of our customers save up to $15 million a year by using HEICO parts. HEICO has built up partnerships with various customers, which means that not all of our parts are available to all customers. This is because our customers share in the development of some of our products. "

Summary

The reserves clearly illustrate the effect that long cycle operations have on reducing costs per EFH. Once an average EFC time of more than 4.0EFH is reached, the CF6-80C2 provides acceptable maintenance costs, although these can be expected to increase as the list price of LLPs, blades and vanes increases each year. The reserves shown are for mature engines and contrast well with narrowbody engines operated on cycles of 60-90 minutes. Reserves are high for CF6-80C2s operated on short cycles, a cost burden of short-haul operations.

LLPs in engines operated on medium and long cycle times will probably only have to be replaced once during an engine's operational lifetime and may be after the aircraft has been sold by its original operator. This is one way of saving on maintenance reserves, although leaving LLPs with short remaining lives will reduce their re-sale value. AC