OWNER'S & OPERATOR'S GUIDE: CF6-80C2 SERIES

CF6-80C2 series specifications

The CF6-80C2 is a ubiquitous engine, with more than 3,200 units in operation and powering five widebody aircraft families.

The General Electric (GE) CF6-80C2 series is one of the most popular widebody engines in operation. The first engines were delivered in 1986 and there are still outstanding orders for 747-400s with CF6-80C2 engines. A main factor in its popularity is that it has 13 main variants and it powers five main widebody types. There are more than 1,200 aircraft and in excess of 3,200 installed engines in operation. The large number in service and the young age of the aircraft it powers, mean that the CF6-80C2 will continue to operate for at least another 20 years.

Configuration

The CF6-80A and -80C2 are derived from the CF6-50, developed to power the DC-10 and later the A300B2/B4 and 747-200 in the 1970s.

The CF6-50 and -80 are two-shaft engines. The -50 has an 86.4-inch fan diameter, a three-stage low pressure compressor (LPC), 14-stage high pressure compressor (HPC), two-stage high pressure turbine (HPT) and four-stage low pressure turbine (LPT). Eight variants were rated at 51,000lbs-54,000lbs thrust for the DC-10-30 and 747-200. The fan diameter and configuration gave it a bypass ratio of 4.21-4.31, depending on thrust.

The CF6-80A was a simple derivative of the -50 series, with the same fan diameter and engine configuration and lower thrust ratings. The -80/-80A1 are rated at 48,000lbs thrust, and the -80A2/-A3 at 50,000lbs thrust. All power the 767-200 and A310-200. The first -80As entered service in 1981.

The -80C2 series differs from the -80A only in that the -80C2 has a large fan diameter of 93 inches. This larger fan is turned through the use of a five-stage LPT, which is one more stage than the -50/-80A engines have.

The CF5-80C2 family has 13 main variants *(see table, page 12)*. These variants use a two- or three-character suffix to describe the engine's application. The first character of the suffix is the letter A, B or D, to denote the use of the engine on Airbus, Boeing or McDonnell Douglas (MDC) aircraft. The -80C2 is utilised on the A300-600 and A310, the 767 family and 747-400, and the MD-11.

The second character is a digit denoting the engine number in the series. The use of a third character will be an F, which indicates that the engine has full authority digital engine controls (FADEC). Engines without the F suffix use power management controls (PMC). Some variants offer both PMC and FADEC controls, while some offer one or the other option.

"FADEC controls allow the engine's fan N1 speed to be corrected to the actual thrust rating, so that it is possible to calibrate the correct N1 to get the correct thrust," explains Frank Herr, customer programme manager CF6 projects at MTU Maintenance. "The PMC is a less accurate control, so they generally have lower EGT margins and are removed earlier due to EGT margin erosion. The -B6F, for example, gets 30-40% more on-wing time than the -B6 due to higher EGT margin."

Family members

There are five A variants of the CF6-80C2: the -A1, -A2, -A3, -A5 and -A8. Only the -A5 is offered with both PMC and FADEC controls, while all the others have only PMC controls.

The -80C2A1 is rated at 59,000lbs thrust, flat rated to 86 degrees Fahrenheit (30 degrees centigrade), and powers the A310-200 *(see table, page 12)*. The flat rating temperature of 30 degrees centigrade is the 'corner point' temperature. That is, the engine can be maintained at maximum thrust up to an outside air temperature (OAT) equal to the corner point temperature. Exhaust gas temperature (EGT) is then held constant by the pilots adjusting the N1 power setting by following guidelines in the manual. The N1 setting is related to the OAT, so N1, and therefore engine power, reduce as OAT increases.

The -80C2A2 is rated at 53,500lbs thrust, flat rated at 111 degrees Fahrenheit (44 degrees centigrade), and powers the A310-200/-300. This high corner point temperature allows the engine to offer maximum thrust up to a high OAT of 44 degrees, making it appropriate for operations in hot environments.

The -80C2A3 is rated at 60,200lbs thrust and is flat rated up to 86 degrees Fahrenheit (30 degrees centigrade), and powers the A300-600 *(see table, page 12)*.

The-80C2A5 and -A5F are both rated at 61,300lbs thrust and are flat rated up to 86 degrees Fahrenheit. They power the A300-600 *(see table, page 12)*.

Most A300-600s are powered with -A3 or -A5 engines. The earlier-built aircraft were equipped with -A3 engines, while later builds were certified only with the higher-rated -A5 engines, which have higher rates of engine deterioration when operated at maximum thrust compared to the lower-rated -A3s. The -A5s, however, have more reserve power.

The -80C2A8 is rated at 59,000lbs thrust and flat rated up to 95 degrees Fahrenheit (35 degrees centigrade). It powers the A300-600 and A310-300, and provides operators with the ability to operate at maximum thrust at higher OATs than most other -80C2A series engines.

The -A2, -A3 and -A5 are the most numerous of the -80C2A series. They power 241 aircraft, 163 of which have engines with high thrust ratings. The -A1 and -A8 power just 31 aircraft.

There are seven variants of the CF6-80C2B series: the -B1, -B2, -B4, -B5, -B6, -B7 and -B8. All have FADEC controls, while the -B5, -B7 and -B8 do not offer the option of PMC controls.

The CF6-80C2B1 is rated at 56,700lbs thrust and flat rated to 86 degrees. It was used to power the last 747-200/-300s built in the mid-1980s.

The -80C2B1F is rated at 58,090lbs thrust, and flat rated at 90 degrees Fahrenheit (32.2 degrees centigrade). It was the first CF6-80C2 variant to power the 747-400. Most 747-400s with CF6-80C2 engines utilise this variant.

The -80C2B2 is rated at 52,500lbs thrust, flat rated at 90 degrees Fahrenheit, and powers the 767-200ER/-300ER. The -80B2F is rated slightly higher at 52,700lbs thrust, and powers the same aircraft.

The -B4, -B6, -B7 and -B8 all power the 767-200ER and -300ER, while the -B7 also powers the 767-400ER. The -B4 is rated at 57,900lbs thrust and the -B4F is rated at a slightly higher thrust of 58,100lbs thrust. The remaining engines are all rated at 60,800lbs thrust and flat rated at 86 degrees Fahrenheit *(see table, page 12)*.

The -B5F is rated at 60,800lbs thrust, flat rated at 86 degrees Fahrenheit and is the other engine option on the 747-400, although only a small number of aircraft have this engine.

CF6-80C2 SERIES THRUST RATING & PERFORMANCE DATA

Engine variant	Thrust rating (lbs)	Bypass ratio	Flat rate temperature Degrees C	EGT margin post shop visit Degrees C	Application
CF6-80C2A1	59,000	5.15	30	35-50	A300-600
CF6-80C2A2	53,500	5.31	44	40	A310-200/-300
CF6-80C2A3	60,200	5.09	30	35-50	A300-600
CF6-80C2A5	61,300	5.03	30	35-50	A300-600
CF6-80C2A5F	61,300	5.03	30	35-50	A300-600
CF6-80C2A8	59,000	5.15	35	35-45	A300-600 A310-300
CF6-80C2B1	56,700	5.19	30	35-60	747-200/-300
CF6-80C2B1F	58,090	5.15	32.2	35-50	747-400
CF6-80C2B2	52,500	5.31	32.2	45-60	767-200ER/-300ER
CF6-80C2B2F	52,700	5.30	32.2	45-60	767-200ER/-300ER
CF6-80C2B4	57,900	5.15	32.2	30-50	767-200ER/-300ER
CF6-80C2B4F	58,100	5.14	32.2	35-50	767-200ER/-300ER
CF6-80C2B5F	60,800	5.06	30	35-50	747-400
CF6-80C2B6	60,800	5.06	30	35-50	767-200ER/-300ER
CF6-80C2B6F	60,800	5.05	30	35-50	767-200ER/-300ER
CF6-80C2B7F	60,800	5.05	30	35-50	767-200ER/-300ER/-400ER
CF6-80C2B8F	60,800	5.05	30	35-50	767-200ER/-300ER
CF6-80C2D1F	61,960	5.03	30	30-35	MD-11

The -B1F, -B6/-B6F, -B7F and -B8F are the most numerous variants of the B series, powering 280 747-400s and 350 767s. All are rated at 58,000lbs or 60,800lbs thrust, and so have relatively high thrust ratings.

The CF6-80C2D1F is the only -80C2 variant available on the MD-11, and is rated at 61,960lbs thrust and flat rated at 86 degrees Fahrenheit. This is the highest thrust rating of all -80C2 variants, and powers more than 115 in operation.

All variants have the same basic hardware, with the exception of the difference between PMC and FADEC controls. This means a PMC engine can be changed from one variant to another, as can a FADEC engine. "There is an extensive list of service bulletins (SBs) to change between variants," says Henderson. "There may also be a hardware change required if the engine is being converted to operate at a higher thrust, and a change of rating plug on the electronic engine control (EEC).

In operation

The CF6-80C2 is used across a range of operations, with average engine flight cycle (EFC) times varying from one hour to nine or 10 hours. A few operators, such as Air New Zealand and Qantas, use the CF6-80C2 on their 747-400s and operate the aircraft on ultra-long-haul sectors of 10-13 hours.

The engine powers more than 1,200 aircraft, almost 1,000 of which utilise engines with thrust ratings of 58,000lbs or higher. The remainder use engines with the lower thrust ratings.

The first CF6-80C2s were delivered in 1981. In excess of 3,500 have been built over the last 25 years, with the engine accumulating more than 120 million engine flight hours (EFH) of operational experience. As a consequence GE has been able to identify weaknesses that have enabled it to improve the engine build standard progressively over the production period.

"The build standard of recently manufactured engines is superior to engines built in the early and mid-1980s and 1990s," explains Herr. "The engines can broadly be divided into block 1, block 2 and block 3 engines, with block 1 engines being the first built. Currently produced engines are block 3, and have only FADEC controls. Block 1 and 2 engines are no longer built, and have PMC controls. A -B1F engine built today, for example, can have an EGT margin of 75 degrees centigrade compared to 35 degrees centigrade for a block 1 -B1F built 10 years ago.

"The improvements over the production period come from improved blades and vanes, better life limited parts (LLPs), superior seals and incorporation of many SBs," says Herr. "These have led to higher EGT margins of new engines, lower rates of EGT margin deterioration, and improved EGT margin recovery rates following a shop visit. It is now possible for a block 1 engine to have a higher EGT margin following a shop visit than it originally had when first delivered, as a result of the various improvements made over the production period."

EGT margin

The EGT margin of new engines is mainly irrelevant, since most have passed their first shop visit. The restored EGT margin following a shop visit is more relevant to most operators.

"The rate of original EGT margin recovery will depend on the build standard of the engine, the workscope of previous shop visits, and the number of shop visits the engine has been through," says Herr. "First-run block 3 engines can usually recover 85% of their original EGT margin, which is more than the original margins on older block 1 and 2 engines. It is actually possible for a block 1 engine to recover more than 100% of its original EGT margin by incorporating blades, vanes, seals and cases that have since been developed. Later generation blades, for example, have added 8-10 degrees centigrade to EGT margins. These improved materials have also improved specific fuel consumption."

Nicola Henderson, engineer at Total Engineer Support (TES), explains that lower-thrust-rated variants, with thrust of up to 58,000lbs, will generally have EGT margins of 45-60 degrees centigrade following a shop visit, while engines with higher thrust ratings will have margins of 25-35 degrees centigrade following a shop visit.

The actual EGT margins of different operators will depend on their type of operation and maintenance policy. Finnair operates seven MD-11s on long-haul operations with an average flight cycle (FC) time of about seven hours with relatively high loads, and has an EGT margin of 30-35 degrees centigrade at the flat rate temperature of 30 degrees following a shop visit. "This compares with an EGT margin of about 45 degrees for a new engine," says Tuomo Karhumaki, vice president of the powerplant department at Finnair Technical Services.

The MD-11 has the highest rated variants of the CF6-80C2, and the next lowest are engines rated at 60,800lbs for the different members of the 767 family.

The -B1F powers almost all 747-400s, and is rated at 58,000lbs thrust. It can be expected to have higher EGT margins. Lufthansa Technik has an average post-shop visit EGT margin of about 60 degrees centigrade, which is a high rate of recovery of the original margin. "The EGT margin of new engines is about 64 degrees centigrade," says Paul Lueck, propulsion systems engineering at Lufthansa Technik.

EGT margins are measured at an OAT equal to the flat rating temperature. In the case of most variants this is 30 degrees, but it is higher at 32.2, 35 or 44 degrees with some of the -80C2 family members.

The EGT margin is the difference between the redline temperature of 960 degrees centigrade and the actual EGT produced by the engine.

Thrust is held at a constant rating up to the flat rating temperature, so EGT rises as a higher OAT is experienced. EGT is allowed to rise until the OAT equals the flat rating or 'corner point' temperature. The engine's EGT is then held constant for OATs higher than the corner point temperature via adjustments to throttle settings that result in reductions in thrust as OAT rises. The difference between the engine's EGT and the red line EGT, the EGT margin, is therefore held constant when OAT is higher than the corner point temperature.

Less than maximum thrust is therefore provided when the OAT is higher than the flat rating temperature. This can limit the performance of aircraft when operating in high OATs.

Airlines will have more than the standard EGT margin available in most operating conditions, firstly because thrust de-rate at take-off is often used. A de-rate of a few per cent will reduce the EGT by several degrees, thereby increasing the EGT margin by an equal number of degrees.

The second factor in making more EGT margin available is that most aircraft experience OATs lower than the flat rating temperatures of 30-44 degrees centigrade. Up to the flat rating temperature, the engine's EGT varies at a rate of 3.2 degrees centigrade per degree centigrade variation in OAT. For example, an engine with an EGT margin of 30 degrees at the flat rating OAT of 30 degrees, will actually have an additional 32 degrees of EGT margin when the OAT drops by 10 degrees to 20 degrees centigrade. This would increase the EGT margin to 62 degrees, before any further benefits of take-off de-rate were considered.

EGT will rise as the engine hardware condition deteriorates with utilisation and operation. While the engine's EGT will still be held constant at OATs higher than the flat rating temperature, the difference with the redline EGT will gradually fall as the engine deteriorates. The engine will have zero EGT margin when its EGT at the flat rating OAT is the same as the redline EGT. Engines will still have a large amount of EGT margin available when operating at lower OATs.

Rates of EGT margin loss are significant for engines operated on short average cycle times. Loss of performance is therefore a main removal driver for engines operated on average cycle times of 1-2FH. Rates of EGT margin erosion are lower for engines operated on medium and long average cycle times, and EGT margin loss is not a main removal driver for many CF6-80C2s in operation. This is particularly the case for engines operated in moderate OATs.

CF6-80C2 LIFE LIMITED PART EFC LIMITS

Part name	Life limit A1/A2/A3/A5	Life limit A5F	Life limit B1/B2/B4/B6/B8	Life limit B5/B7	Life limit D1F
Fan disk 1	20,000	15,000	20,000	20,000	20,000
Stg 2-5 spool	20,000	15,000	20,000	15,000	15,000
Forward shaft	20,000	19,600	20,000	20,000	20,000
Fan mid shaft	20,000	20,000	20,000	20,000	20,000
HPC Stage 1 disk	20,000	20,000	20,000	20,000	20,000
HPC Stage 2 disk	20,000	15,000	20,000	15,000	15,000
Stage 3-9 spool	20,000	20,000	20,000	20,000	20,000
HPC Stage 10 disk	20,000	15,000	20,000	15,000	15,000
Stage 11-14 spool	20,000	20,000	20,000	20,000	20,000
Stage 10-14 spool	20,000	20,000	20,000	20,000	20,000
CDP seal			20,000	15,000	15,000
HPT Stage 1 disk	15,000	13,200	15,000	13,200	13,200
HPT Stage 2 disk	15,000	9,000	15,000	9,000	9,000
Spacer impeller	15,000	15,000	15,000	15,000	15,000
Rotating stage seal	15,000	9,000	15,000	9,000	9,000
LPT Stage 1 disk	20,000	20,000	20,000	20,000	20,000
LPT Stage 2 disk	20,000	20,000	20,000	20,000	20,000
LPT Stage 3 disk	20,000	17,400	20,000	17,400	17,400
LPT Stage 4 disk	20,000	20,000	20,000	20,000	20,000
LPT Stage 5 disk	20,000	20,000	20,000	20,000	20,000
LPT Shaft	20,000	20,000	20,000	20,000	20,000

Life limited parts

The CF6-80C2 has 20 or 21 LLPs, depending on engine configuration, which are used in four modules.

The first module is the fan and booster section. "This has four LLPs, which include the fan mid-shaft, fan forward shaft, fan rotor stage 1 disk, and fan rotor stage 2-5 disk," explains Henderson. The list price for the four LLPs is $950,000. GE has a system for stating target lives for LLPs when an engine first enters service, and the target life for LLPs in this module of the CF6-80C2 is 20,000EFC. Several part numbers are available for each LLP, and most have lives of 20,000EFC in this module.

The HPC module has five or six LLPs, depending on configuration. Four are the stage 1 disk, stage 2 disk, stage 3-9 spool, and compressor discharge pressure (CDP) seal. In engines with five LLPs, the fifth LLP is the stage 10-14 spool, while engines with six LLPs have a stage 10 disk and stage 11-14 spool.

Most part numbers have lives of 15,000EFC, although some have lives of 20,000EFC and others have lives limited to less than 15,000EFC. The list price for a set of HPC LLPs is $950,000.

The HPT module has four LLPs: the stage 1 and 2 disks, the spacer impeller and the rotating stage seal. The target life of these parts is 15,000EFC, and many part numbers are certified with this limit. There are, however, several part numbers with lives limited to less than this. In many cases lives are limited to 9,000EFC or 13,000EFC. The list price for these four LLPs is $620,000.

The LPT has six LLPs: the stage 1, 2, 3, 4 and 5 disks, and the LP shaft. Most part numbers have lives of 20,000EFC, but some are restricted to between 15,000 and 20,000EFC. These six parts have a list price of $865,000. AC

CF6-80C2 modification programmes

The build standard of the CF6-80C2 series has improved during its 20 years of production, and has required few modifications or upgrades. There are some upgrades that are appropriate for airlines operating in harsh environments and suffering poor on-wing reliability.

There are two main upgrade programmes for the CF6-80C2 series: the high pressure turbine (HPT) upgrade, and the new Tech CF6 programme.

HPT upgrade

The HPT upgrade follows early problems with the stage 1 HPT blades. These had poor durability and consequently resulted in poor on-wing and maintenance intervals.

The HPT upgrade modification revolves around the installation of a new HPT blade. The original stage 1 HPT blade suffered from burning, cracking and severe deterioration, and consequently was a main removal driver *(see CF6-80C2 maintenance analysis & budget, page 18)*. The CF6-80C2 is not generally removed due to exhaust gas temperature (EGT) margin erosion, but more due to technical deterioration. The original stage 1 HPT blade was a major example of the CF6-80C2 being prone to deterioration.

The HPT upgrade programme used advanced materials and technology in the HPT to address engine durability and reliability. This is through the use of an improved stage 1 HPT blade, as well as improved HPT nozzles and shrouds.

The ultimate objective of the HPT upgrade programme is to improve the HPT hardware durability. This would have the benefit of increasing removal intervals for shop visits, as well as increasing the percentage of HPT blades that could be repaired rather than replaced. Both airlines and engine shops comment that upgraded engines no longer have HPT distress and deterioration as a main removal driver, and other durability and technical issues now affect the engine's on-wing intervals.

The list price of this kit is $1.7 million, which is expensive for most airlines to consider. The upgrade does not have to be completed in one shop visit, however, and can be completed over a series when material has to be replaced with new parts. Even with a purchase discount, the cost of the modification can only be justified where a large improvement in performance results.

Tech CF6 programme

Like the Tech CFM56 programme launched by CFMI to improve the CFM56, Tech CF6 involves several modifications and upgrades to improve the CF6 series.

Tech CF6 will be available in early 2007, and will consist of three main parts: the high pressure compressor (HPC) durability kit; the HPT durability kit; and the combustor durability kit.

The HPC durability kit stems from various technical and durability problems that operators have encountered over the years. Variable stator vane (VSV) bushings in particular have experienced durability and poor wear problems. The HPC blades themselves were also poor, and leakage and poor HPC performance are the main factor in EGT margin erosion. VSV bushing wear is a main driver in unmodified engines. Block 1 and 2 engines generally suffered from technical reliability and durability problems. Later-build Block 3 engines had improved hardware, and block 1 and 2 engines have been upgraded with block 3 material over the years.

The HPC durability kit is designed to improve the HPC reliability through improved VSV bushings, more durable HPC blades, and HPC blades that are resistant to foreign object damage (FOD).

The HPC blades have been improved by adding a more resistant coating material. The overall benefits are improved HPC durability, less leakage and improved specific fuel consumption retention as a result.

The HPT durability kit offers improved cooling of stage 1 HPT blades through an advanced cooling hole design in the blades, improved stage 2 blade coatings, advanced stage 1 and 2 nozzles for improved durability, and next

The HPT upgrade and Tech CF6 programmes are intended to improve engine performance. Their high cost means they can only be justified for engines that are operating in harsh environments and that suffer short maintenance intervals and high shop visit costs.

generation HPT shroud material to improve leakages.

This programme improves HPT blade and vane durability, again to lessen the general effects of engine deterioration. Like the HPT upgrade programme, the HPT durability kit is intended to reduce HPT blade scrap levels, and overall reduce related maintenance costs.

The combustor durability kit is an advanced multi-hole design on the combustor can inner and outer liner. The modification also includes a temperature-resistant combustor liner material. Both of these designs are intended to improve on-wing life, thereby reducing repair costs.

The Tech CF6 programme has a cost of $400,000 for the HPC module, $300,000 for the combustor liner and $1.9 million for the HPT module. This totals about $2.6 million. Auvinash Narayen, engine programme manager at Total Engine Support, comments that this modification is only likely to be attractive to airlines operating in harsh environments that result in short on-wing intervals and high shop-visit costs. He explains that the cost of the modification will only make economic sense to those engines operating in extreme conditions, and where the modification can offer an an improvement in performance.

Major AD notes

Three major airworthiness directive (AD) notes affect the CF6-80C2. The first of these is AD 2002-25-08, which relates to inspections on the HPC stage 3-9 spool life limited part (LLP). The spool requires an inspection every 2,000EFC, which can force the early removal of engines. Most CF6-80C2s are used as long-haul engines and have removal intervals of 2,000-3,500EFC. Some engines used on the 767 series can remain on wing for longer than this, but the AD allows a partial disassembly of the engine. Narayen explains that a probe is then inserted into the HPC so that the inspection can be made. If the HPC passes, the engine can be reassembled and put back on-wing. Engines used on the 767, A300-600 and A310 on short cycle times of 1.0-3.0 engine flight hours (EFH) tend to be capable of removal intervals of up to 5,000 engine flight cycles (EFC). These would clearly be disrupted by the need to inspect the spool. The simplest way for operators to terminate this AD is for them to replace the affected part with a new LLP, at a cost of $250,000.

The second major AD is 2004-22-07. This relates to an inspection on the old version of the stage 2 nozzle guide vanes. This can be done with a borescope inspection. The initial inspection threshold is at 1,600EFC, which could disrupt planned removal intervals and force early shop visits. Replacement is only required when the vanes fail the condition standard. This AD can be terminated by replacing the affected part numbers with the latest part number for the stage 2 nozzle guide vanes, at a cost of $290,000.

The third major AD is 2006-16-06, which supersedes AD 2004-04-17. It relates to the re-working of dovetail slots for HPT blades following an uncontained failure in an -80A engine.

The AD requires an inspection every 3,000EFC. This is not a problem for most engines, since it will not force removals earlier than planned, except for those operating at the shortest cycle times and achieving up to 5,000EFC on-wing. There is also a limit of 10,000-14,000EFC for re-working the dovetail slots. The actual limit depends on several factors, including the number of accumulated cycles and inspection history, but it will not affect removal intervals. Most operators will re-work the slots during a shop visit. AC

CF6-80C2 fuel burn performance

The CF6-80C2 powers a large number of widebody aircraft types and variants. The fuel burn performance of the most popular types is examined.

The CF6-80C2 has several applications, which include the A300-600, A310, 767 family, 747-400 and MD-11 *(see CF6-80C2 series specifications, page 10)*. While there are up to 13 different variants of the -80C2, there are a few that dominate the fleet. Moreover, the fleet is dominated by several airframe-engine variant combinations: the A300-600 with -80C2A5, the A310 with the -80C2A2; the 767-200ER with the -80C2B6F; the 767-300ER with the -80C2B6F and -B7F; the 747-400 with the -80C2B1F; and the MD-11 with the -80C2D1F. The fuel burn performance of these airframe-engine combinations has been analysed on sample routes.

Aircraft analysed

There are several weight and fuel capacity specifications of each aircraft type with different variants of the CF6-80C2, but the weight and fuel capacity specifications of the aircraft analysed are summarised *(see table, page 17)*.

The A300-600 with the -A5 engine has been analysed with a maximum take-off weight (MTOW) of 375,900lbs and a fuel capacity of 16,124 USG. It has been analysed with a 260-seat configuration.

The A310-300 model analysed has an MTOW of 361,600lbs, a fuel capacity of 18,030USG and -80C2A2 engines *(see table, page 17)*. This is the highest gross weight and fuel capacity version of the A310-300. The aircraft has been analysed with 230 seats, which is typical of a European-style, two-class configuration.

The 767-200 and -300 models analysed are aircraft with MTOWs of 351,000lbs and 350,000lbs. Both have fuel capacities of 16,700USG, and are powered by the -B2F engine. The -200 has been analysed with 230 seats, and the -300 with 260 seats. This is typical for a two-class configuration.

The 767-200ER has an MTOW of 351,000lbs, a fuel capacity of 21,140USG and -80C2B6F engines. The aircraft has been analysed with 180 seats, typical of a tri-class configuration.

The 767-300ER has an MTOW of 412,000lbs, the highest gross weight version of the -300ER, and a fuel capacity of 21,140USG, and is equipped with -80C2B6F engines. It has been analysed with 215 and 260 seats, typical of tri- and two-class configurations.

The 747-400 has the highest MTOW available of 870,000lbs, a fuel capacity of 57,065USG, and is equipped with -B1F engines *(see table, page 17)*. It has been examined with a 390-seat configuration.

The passenger variant of the MD-11 has an MTOW of 630,500lbs, the highest available for the aircraft, a fuel capacity of 38,615USG, standard -D1F engines, and an interior layout of 298 seats.

Routes analysed

All airframe-engine combinations have been analysed on routes with lengths typical for their gross weight and range capability. The performance of each aircraft has been examined with a payload of a full complement of passengers. All routes used do not limit the aircraft's payload-carrying performance below its maximum capacity. Its performance has been examined in both directions on a route, to reveal the effect of head- and tailwinds, and its impact on fuel burn performance.

The low-weight and short-range aircraft, the A300-600R, 767-200 and 767-300, have been analysed on the intra-European route of Rome-Athens, which has a tracked distance of 600nm and a flight time of 90 minutes for most types. This route length is similar to many US and Japanese domestic city-pairs where many of these aircraft operate.

The A310-300 and 767-300ER with 260 seats have been analysed on Larnaca-Paris. This is typical of a medium-haul route, with a tracked distance of 1,650nm and flight time of close to four hours.

The 767-300ER and MD-11 with 215 seats have been examined on Copenhagen-Tokyo Narita, a typical long-haul route of about 5,000nm, with a flight time of nearly 11 hours.

The 747-400's performance has been examined on Auckland-Los Angeles, which has a tracked distance of about 5,700nm and flight time of 12-13 hours.

The performance of all aircraft has been examined using 85% annual winds for the month of June, a 20-minute taxi time for each leg and the long-range cruise speed for each aircraft type.

The standard weight for each passenger has been taken as 220lbs.

Aircraft fuel burns

As described, the aircraft have been analysed in groups, with two or three

The CF6-80C2B4, -B6, -B7 and -B8 variants power more than 400 767 family aircraft. The majority of these are the 767-300ER with B6, B6F and B7F engines.

FUEL BURN PERFORMANCE OF CF6-80C2 SERIES

City-pair variant	Aircraft	Engine model	MTOW lbs	Fuel capacity USG	Fuel burn USG	Flight time mins	Passenger payload	ESAD nm	Fuel per seat	Wind speed
Rome-Athens	A300-600R	CF6-80C2A5	375,900	16,124	2,400	87	260	601	9.23	+15
Rome-Athens	767-200	CF6-80C2B2F	351,000	16,700	2,012	92	230	601	8.75	+15
Rome-Athens	767-300	CF6-802C2B2F	350,000	16,700	2,197	91	260	601	8.45	+15
Athens-Rome	A300-600R	CF6-80C2A5	375,900	16,124	2,746	100	260	713	10.56	-57
Athens-Rome	767-200	CF6-80C2B2F	351,000	16,700	2,295	106	230	713	9.98	-57
Athens-Rome	767-300	CF6-80C2B2F	350,000	16,700	2,489	105	260	714	9.57	-57
Paris-Larnaca	A310-300	CF6-80C2A2	361,600	18,030	5,000	218	230	1,613	21.74	+9
Paris-Larnaca	767-300ER	CF6-80C2B6F	412,000	21,140	5,401	224	260	1,612	20.77	+9
Larnaca-Paris	A310-300	CF6-80C2A2	361,600	18,030	5,794	251	230	1,860	25.19	-56
Larnaca-Paris	767-300ER	CF6-80C2B6F	412,000	24,140	6,212	255	260	1,862	23.89	-56
Copenhagen-Tokyo	767-200ER	CF6-80C2B6F	351,500	20,400	14,950	675	180	5,101	83.06	-6
Copenhagen-Tokyo	767-300ER	CF6-80C2B6F	412,000	24,140	17,551	675	215	5,101	81.63	-6
Copenhagen-Tokyo	MD-11	CF6-80C2D1F	630,500	38,615	26,974	646	298	5,098	90.52	-6
Tokyo-Copenhagen	767-200ER	CF6-80C2B6F	351,500	20,400	15,598	688	180	5,214	86.66	-31
Tokyo-Copenhagen	767-300ER	CF6-80C2B6F	412,000	24,140	17,983	688	215	5,214	83.64	-31
Tokyo-Copenhagen	MD-11	CF6-80C2D1F	630,500	38,615	27,480	657	298	5,197	92.22	-31
Auckland-Los Angeles	747-400	CF6-80C2B1F	870,000	57,065	37,648	695	390	5,606	96.53	10
Los Angeles-Auckland	747-400	CF6-80C2B1F	870,000	57,065	43,612	764	390	6,189	111.83	-36

Source: Navtech

airframe-engine combinations being analysed on a specific city-pair that would be typical of airline deployment.

The A300-600R, 767-200 and 767-300 have been examined on Rome Fiumicino-Athens. Travelling eastwards to Athens, aircraft experience a 15-knot tailwind. The tracked distance is 623nm, and the tailwind reduces this to an equivalent still air distance (ESAD) of 601nm *(see table, this page)*. The 767-200/-300 have a flight time of 92 minutes, while the A300-600R is a little faster at 87 minutes. On this sector both 767 models burn similar amounts of fuel per passenger, with the -200 using just 0.30USG more. The A300-600R's fuel burn is 9.23USG per passenger.

In the westerly direction to Rome, a headwind of 57 knots increases the tracked distance by about 100nm to 713nm *(see table, this page)*, which increases the fuel required. The fuel burned per passenger is again similar for both 767 models: about 10USG in both cases. The A300-600R, by comparison, burns 10.56USG per passenger.

The A310-300 and 767-300ER are examined on Larnaca-Paris CDG, which is a medium-haul route of similar length to that on which many aircraft in this category are operated. In the easterly direction to Larnaca, the aircraft benefit from a small tailwind of nine knots *(see table, this page)*. This reduces the tracked distance of 1,645nm to an ESAD of 1,612nm. The A310-300's flight time is 218 minutes, while the 767-300ER is a little slower with 224 minutes. The 767-300ER is the larger of the two aircraft and so gains from this scale effect with a slight fuel burn advantage per passenger of about 1USG.

In the westerly direction the aircraft face a headwind of 46 knots, which increases the tracked distance by about 200nm to 1,860nm *(see table, this page)*. There is a small difference in flight times between the two, with the 767-300ER completing the flight in about four and a quarter hours. Again, the 767-300ER has the lower fuel burn per seat, being about 1.3USG less than the A310-300.

The 767-200ER, 767-300ER and MD-11 are examined on Copenhagen Kastrup-Tokyo Narita, a long-haul route within their full payload-range capability that allows all three to comfortably carry a full passenger load. This is a trans-Siberian routing, so the aircraft face a headwind when operating in both directions. However, this is small at just six knots when travelling east to Tokyo, increasing the tracked distance of 5,034nm to about 5,100nm. On this long sector the 767's relatively low cruise speed gives it a 30-minute longer flight time than the MD-11.

Despite having 83 more seats than the 767-300ER, the MD-11 has a poorer fuel burn performance per passenger because of the inefficiency of its three-engined design. The MD-11 has a fuel burn rate per seat of about nine USG more than the 767-300ER, equal to a higher cost of about $20 at current fuel prices.

In the westerly direction, the tailwind rises to 31 knots, increasing the tracked distance by about 350nm to 5,200nm. The MD-11 has a flight time of 11 hours, while that of the slower 767-300ER is 31 minutes longer at 11 hours and 28 minutes *(see table, this page)*.

Again, the MD-11 has a higher fuel burn per passenger of about nine USG over the route than the 767-300ER.

The 747-400 is examined on an ultra-long-haul route: Auckland-Los Angeles International. Flying to Los Angeles the aircraft has a small tailwind that reduces the ESAD to 100nm less than the tracked distance of 5,722nm. The headwind in the opposite direction increases the tracked distance by 460nm to an ESAD of 6,189nm, about 1,000nm longer than the ESAD of the Tokyo-Copenhagen route. Although the 747-400 is able to carry a full passenger load on Auckland-Los Angeles, its fuel burn performance is worse than the 767-300ER in terms of per available seat-mile, and is similar to the MD-11. This is due to the 747's four-engined design, which is heavier per seat than the twin-engined aircraft. AC

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

CF6-80C2 values & aftermarket activity

Despite the CF6-80C2 being a ubiquitous engine, supply of spare units is short and this stabilises values and lease rates.

The CF6-80C2 is a prime example of an engine with little liquidity in the used market. There is strong demand for all the aircraft types it powers, with few airframes or engines staying on the market for more than a few months. This low liquidity has kept the supply of available CF6-80C2s tight, and the values of used engines strong and at a high percentage of new engine list prices. Few engines are available on short-term leases, and most that are available in engine lessors' portfolios are leased on long-term contracts.

New engines

The -80C2 has been in production since the mid 1980s, and has sold in large numbers. The largest fleets are the -B1Fs powering 280 747-400s and -B4/B6/B7/B8 variants powering 400 aircraft of the 767 family. A smaller number power the A300-600, A310 and MD-11. Only the 747-400 and 767 can be ordered new from Boeing, and with the 787 available, orders for 767s have virtually stopped. Most orders for 747-400s are for the freighter variant, and these are also in small numbers. The launch of the 747-8I is likely to herald the end of production for the CF6-80C2.

As a result of few engines now being built, General Electric (GE) steeply increased the list price of new engines in 2004 and 2005. "The list price of new engines depends on the thrust rating, but it went up from $7.5 million to $11 million in two jumps over an 18-month period," says Tom MacAleavey, senior vice president at Willis Lease Finance Corporation (WLFC). "This is mainly due to the sharp increase in the list price of life limited parts (LLPs) in the engine. The list price for a full stack has gone up to about $3.4 million. The list price for a -B7F, for example, is now $11.4 million. The LLPs are one way for GE to profit from aftermarket activity. Given the age of most engines, the lives of LLPs and the fact that many are used on long-haul operations, many LLPs are coming due for replacement.

"The limited supply of engines in the market and the high price of new engines keeps the value of used engines buoyant," continues MacAleavey. "The engine is also popular, with none being parked, even during the downturn of 2002 and 2003."

The value of used engines is determined by their maintenance status. Jon Sharp, president and chief executive of Engine Lease Finance (ELF), explains that an engine overhaul will cost up to $2.3 million and the list price of a full LLP stack is $3.4 million. A completely run-out engine will require about $5.7 million to recover its maintenance condition. "The market value of a -B6/B7 engine with half-life maintenance condition is $6.5 million, while Airbus engines will be worth a little less because of the smaller number of A300s and A310s in the market," says Sharp. "There is no feasible replacement for the 747-400 yet, so this makes the market for -B1F engines very secure. The same applies to all variants used on the 767. These aircraft are long-term assets used by major airlines, and they are not sold or traded on a frequent basis. Spare engines are consequently also retained, and there are very few available in the market. The value of an engine with full maintenance life and new LLPs will therefore be high."

MacAleavey puts the value of a freshly overhauled engine (zero-timed) at about $7.5 million, but it can be up to $8 million or more if it is in a very good condition where its LLPs are near to full life. "The carcass of a completely run-out engine will be worth $2.5-3.0 million, so the total of $5.5-5.7 million added to this will take the value of a zero-timed engine to about $8 million," explains MacAleavey.

Few or no CF6-80C2s are available for short-term leases, which is explained by Sharp's point that these assets are invested in on a long-term basis. "Engine lease rates are basically a lease factor of the engine's value," explains Sharp. "These factors are less than 1% per month, at 0.65-0.80% per month. A new or young engine with a market value of $10 million will therefore have a lease rate of $65,000-80,000 per month." These are similar rates quoted by MacAleavey. "Rates for most engines in a good maintenance condition are $75,000-80,000 per month, if you can get one. The independent lessors have modest fleets and the situation of the tight supply of engines has not changed since 1998. Most engines are held by GE Engine Leasing." AC

The -80C2B1F powering the 747-400 is the most numerous variant of the CF6-80C2 series. The aircraft and engines are long-term assets invested by major airlines, and there is little liquidity in the -80C2 market generally as a consequence.