Regional aircraft typically seat between 70 and 100 passengers, and fly sectors of up to two hours. Engines, as such, will undergo high flight cycles in relation to the flight hours performed by the operator. This will have a knock-on effect on the maintenance requirements of the engines. The various demands are explored here.

Regional aircraft engine maintenance

Regional aircraft are generally powered by two turboprop or turbofan engines, and have 50 to 120 seats. Smaller turboprops are more expensive to operate on a per seat-mile basis. The market has, therefore, expanded to incorporate larger, more economic jets, such as the CRJ 900 or the Embraer E-175, and E-190/-195. The main manufacturers are ATR, Bombardier and Embraer.

There are three main original equipment manufacturers (OEMs) that build engines popular for regional airframes: Pratt & Whitney Canada (P&WC), General Electric (GE) and Rolls-Royce (RR). The engines explored in this article include the P&WC PW120 and PW150 series, which power a range of turboprop ATR, Dash 8 and Q400 family aircraft. Models and variants included within these types are the PW120A, PW121, PW123C, PW123D, PW123B, PW124, PW127E, PW127M, and the PW150A. These engines are prevalent within the regional turboprop aircraft categories. The aircraft powered by these engines include the Embraer EMB120, the ATR 42-300/-320/-400/-500 and ATR 72-500; and the Bombardier Q100, Q200, Q300 and 400.

The General Electric (GE) CF34 engine family powers a large number of regional aircraft. The variants explored in this feature for the CF34 family are the -3B, -8C5, -8CE, and -10E variants. The aircraft powered by these engines include the CRJ 100/200/700/900 and CRJ1000, and the E-170/-175.

Considerations

A main element to consider when examining engine maintenance costs are for hot section repairs and performance restoration. That is, the high pressure turbine (HPT), high pressure compressor (HPC), and combustion chamber. There are also low pressure (LP) sections, gearbox, propellers and life limited parts (LLPs). While some of these are monitored on-condition, a portion are hard-timed and, therefore, relatively easy to predict costs for and so maintenance can be scheduled accordingly. Each of these elements is explored as appropriate.

Key parameters are monitored when maintaining engine modules on-condition. Turbomachinery, for example, is maintained on an on-condition basis. EGT margin is a measurement considered as a key indicator of engine performance and deterioration, and is an important element in on-condition maintenance.

EGT and indicated turbine temperature (ITT) are key parameters when assessing engine performance. Deterioration in either parameter, beyond a certain point, implies that the engine requires removal and a performance restoration. EGT is the temperature recorded by sensors at the engine exhaust. The margin between actual EGT and the redline temperature is, therefore, a measure of an engine's efficiency and remaining ability to produce its designed thrust. The higher the EGT the greater wear and deterioration of turbine components and blade-tip clearances, and the more the negative effect on engine performance. Red line limits for EGT will be outlined by the OEM, and monitored in operation by airlines. Once EGT margin has deteriorated to just a few degrees, the rate of deterioration to turbine parts and components will increase. It is important to minimise the rate at which EGT increases.

EGT is often monitored by operators by plotting it graphically. Thrust is measured against outside air temperature (OAT), with fluctuations of actual EGTs of in-service engines compared against this relationship. EGT is at its highest during take-off. Once the EGT margin becomes too narrow because of accumulated hardware deterioration, a shop visit (SV) is required, since maximum thrust cannot be used in all operations. The OAT at which thrust cannot be kept constant, and has to be reduced by throttle de-rate, is known as the corner-point temperature, displayed on the engine thrust versus EGT graph.

Throughout this analysis, there are some estimates given to LLP stack prices. These are based on historical OEM escalations, and refer to the price of the complete set of LLPs rather than individual parts. OEMs, however, have complete oversight on the performance of each part and component via health monitoring data transmitted by the aircraft communications and addressing system (ACARS) channel, and more recently the emergence of big data. They are able to closely monitor reliability and true potential of each LLP. This means that manufacturers are now able to escalate individual parts in accordance with their true performances. Variations can subsequently be expected, where only stack list prices are given.

Turboprop engines

PW120 & PW150

The PW118, PW120, PW125, PW127 and PW150 models make up the PW100 and PW150 families, with more than 8,000 built. The PW118 to PW127 models are comprised of two-spool, two-stage compressors; single-stage LPTs and HPTs, and two-stage power turbines. The PW120/121 are fitments for the Dash 8-100 and early models of the ATR 42. The

A variety of factors removal intervals for the PW100 and PW150 series. Average removal interval depends on environment and operation. A hot section inspection or performance restoration that is carried out about halfway between an overhaul. The condition of the engines is monitored via borescope inspections and trend monitoring.

PW125 powers the Fokker 50, while the PW127/127M is the engine of choice for the ATR 42-600 and the ATR 72-600.

The PW118A is rated at 1,893 shaft horsepower (eshp), while the PW120 and PW120A gives out between 1,787eshp and 1,892eshp, for instance.

The PW121 and PW121A are rated at 1,992eshp and 2,044eshp respectively. The PW 127, including its PW127F and PW127M variants, give out a maximum continuous rating of 2,617eshp.

The PW150 is overall a larger engine, made up of a two-spool, four-stage compressor, and full authority digital engine control (FADEC) in addition to the single-stage LPT and HPT. The PW150A's thrust rating is 5,071eshp.

Propellers

In addition to the main body of the engine, a key component is the propellers. This system is comprised of the propeller, hub and actuator.

Illinois-based Aircraft Propeller Service (APS) provides a full range of MRO services on propellers for a variety of aircraft, including the ATR 42/72, Dash 8, Saab 340 and the Embraer EMB120 families. As such, it performs about 250 propeller SVs annually on PW120 variants, including PW120A (Q100), PW121 (ATR 42-300/320 and Q100), PW123C (Q300), PW123D (Q200), PW123B (Q300), PW127E (ATR 42-400/500), and the PW127M (ATR 42-400/500 and ATR 72-210/500).

"It is important to consider that operators are probably unable to synchronise propeller and engine maintenance," comments Dennis Santare, vice president of sales and marketing at APS. "Propeller and engine maintenance is, therefore, often treated as two separate requirements for the system."

The propellers used with the PW100 families include the Hamilton Sundstrand (HS) 14SF-5, the HS 14SF-23, HS 14RF-9 and the Hamilton Standard 568F-1.

Generally, the elements maintained in the propeller system include the hub, actuator, propeller blades, oil transfer tube, slip ring, adjusting nut and bulkhead. "The component maintenance manuals (CMMs) provide the main source of maintenance requirements for all propellers," explains Santare. "Additionally, our license with UTC Aerospace Systems (formerly Goodrich and Hamilton Sundstrand), the manufacturer of propellers on the PW100 series engines, allows us to have access to proprietary repair information in addition to the CMM.

"The propeller systems are hard-timed, rather than maintained on an on-condition basis," continues Santare. "For example, the UTC propellers on the PW100 engines generally have hard times at 10,500 engine flight hours (EFH) or seven calendar years. Given industry usage, in reality the time between overhaul (TBO) is more like five years.

"Overhauls (OVHs) following the first removal interval to SV are normally lighter than SVs following the second, third, and fourth runs," adds Santare. "OVH costs can vary widely at between $150,000 and as much as twice that amount, depending on factors that include operator habits."

During the average SV, APS receives a shipped assembly of main time-limited elements of the propeller's system. These are the blades, hub and actuator. "The actuator controls the pitch of the blades, that are affixed to the actuator via blade pins," describes Santare. "The actuator then sits inside the hub, which is essentially an empty chamber."

Blades

Blade repairs represent the biggest cost of most propeller maintenance, with costs of up to $25,000 or more per blade. The leading edge of each blade, which is commonly made of nickel, may sustain nicks due to foreign object damage (FOD), which will need to be repaired.

Also, the de-icing boot may become delaminated or encounter electrical problems. These are significant issues that can lead to substantial repair costs if they arise," says Santare. He explains that there is an electric current that runs along the de-ice boot via a cable to heat the system in icy weather. If this cable gets damaged or even cut, the de-ice system can malfunction or stop working. Another requirement for the de-icing system is regular recoating of the boots, using an OEM-produced protective film.

Overall, APS estimates that a light SV to inspect and repair the blades, hub and actuator can be between 10 and 15 days, whereas a heavier shop visit needing repairs and OVHs may take more than 25 days to perform.

While older HS propeller models reflect these common traits, new propellers seen on later ATR 72s have different materials that affect maintenance requirements. "The HS 568-F propeller is scimitar-shaped, and while the older prop model has an aluminium spar, the new spar is composite and made of Kevlar," says Santare. "Corrosion has been seen in the composite material and, therefore, requires a new type of repair method for the HS 568-F. OVH requirements for the new propeller also mean that new blades undergo detailed inspections of critical blade areas."

A common site for corrosion is on the blade shank where it interfaces with the hub. "With the older model HS propellers, tolerances from the OEM gave enough allowance to treat the shank area in many cases, rather than replace the entire blade," explains Santare. "With the new blades seen on the 568-F props, however, tolerances are so tight that, if corrosion is spotted, the blade must be replaced which is why it is important for operators to adhere to OEM-recommended practices to prevent corrosion. APS issues guidance and training in order to prevent scraps."

A service information letter (SIL) has been released by the OEM to counter shank corrosion for the HS 568-F model. "Operators are now advised to use a rubber cap, developed by the OEM," says Santare. "This cap is designed to cover the shank overnight, and whenever blades are not used for extended periods of time, preventing unnecessary exposure to corrosive weather or climates."

Hubs

Hubs receive a lot of attention during SVs because of forces that interact with it throughout operation. A great deal of stress, strain, and wear can produce conditions that require repair at SVs.

"Because of wear and tear in the arm bores, where the blade shanks interact, there is a requirement for MROs to re-metal the arm bore of the hubs on the first SV for 568-F propellers. This means that the cost is high on the first hub SV to mitigate unforeseen costs due to wear and tear later on," explains Santare. "This process can take in excess of 30 days. Fortunately, costs are often offset if the blades have been well-maintained, and APS can be creative with exchange assets to mitigate the effect on visit length."

Optimising prop maintenance

Operators can manage propeller maintenance to a considerable extent. "Some operators do not allow pilots to reverse-rotate propellers," says Santare. "Reverse-rotation is sometimes used as a braking method, particularly for short runways. The technique can cause wear on the system, and drive up SV costs."

Operators are advised to change the actuator oil at least every 12 months. This is often incorporated by operators as a line maintenance task. Changing oil regularly reduces wear on the actuator. If not done, metal could contaminate the oil over time by friction, resulting in high-value actuator parts being scrapped.

Health monitoring

The majority of components and modules on the PW110 and PW150 engine and CF34 are maintained on-condition. Various parameters are monitored while engines are in operation to determine condition and maintenance status, and establish a SV workscope that can optimise utilisation requirements. Condition is monitored via borescopes, trend monitoring data and life limited part (LLP) replacement of rotating components. The longest time on-wing (TOW) drives the next SV event for operators based on unscheduled removals not limited to performance deterioration, metal contamination, smell, smoke or high oil consumption.

"The various health and performance parameters monitored on all engines include indicated turbine temperature (ITT) margin, fuel flow, compressor pressure ratio, vibrations and oil pressure," explains Mark Johnson, chief executive officer at Lufthansa Technik AERO Alzey (LTAA). ITT refers to the combustion gas temperature near the inter turbine, calculated via information recorded by sensors on the exhaust duct and other parameters during a test run.

"The main drivers for ITT margin deterioration include environment, starting altitude and take-off duration," continues Johnson.

PW120/PW150 shop visits

A variety of factors will affect removal intervals for the PW100 series. "Typically, the pattern is a hot section inspection (HSI) or performance restoration about halfway between an engine OVH," explains Johnson.

Airlines monitor PW127 and PW150A engines via engine conditioning, trend monitoring and scheduled borescope inspections. SVs for the PW127 and PW150A engines follow the HSI and OVH patterns described.

A lower-rated engine is expected to achieve average longer on-wing life between removals and SVs. Given that there are elements to the PW120 and PW127 that are hard-timed, namely life limited parts (LLP), or referred to as low cycle fatigue (LCF) parts in P&WC turboprop engines, an ideal solution is to establish a pattern of removal intervals and SVs in which LLP replacement coincides with an OVH, both of which require complete engine disassembly.

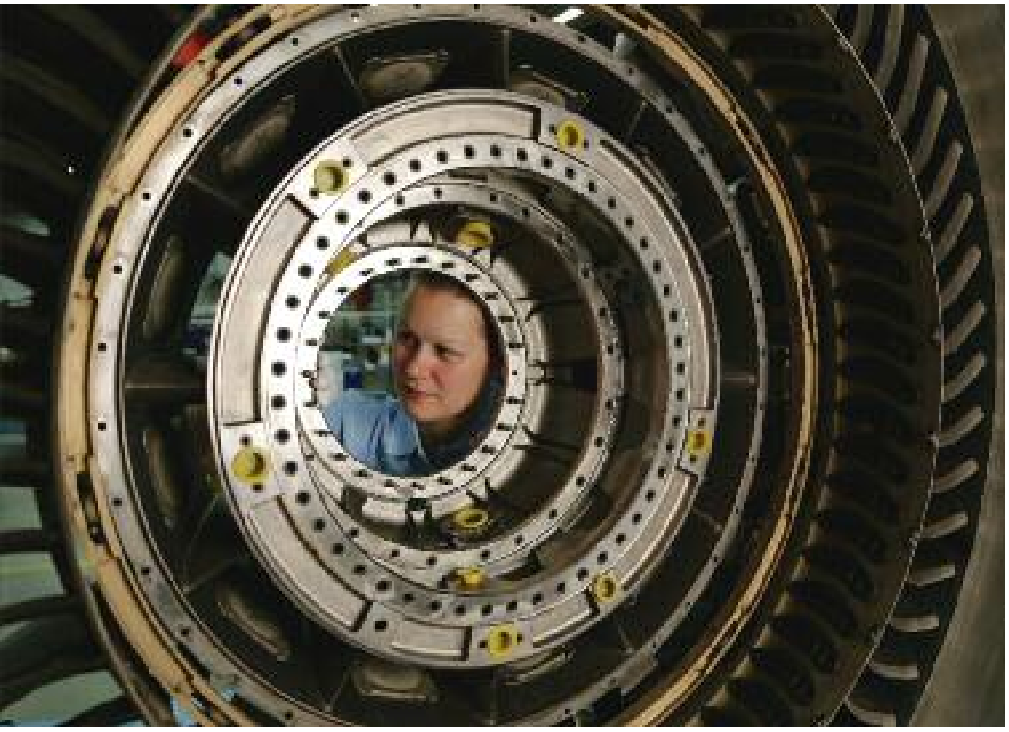
HSIs, OVHs and LLP replacement can be synchronised for an average operator. The HSI of the PW100's turbine module is costly, particularly if turbine blades have to be replaced. (A shipset of HPT blades costs about $150,000).

"PW120/121 engines have nine LCF parts," explains Paul Baker, senior vice president of international operations at NTE Aviation. "Four of these are located in the HPT section. The HPT stack of LLPs includes the HP disk, front and rear covers, and interstage airseal. Remaining LLPs include LP and HP impellers and PT1 and PT2 disks." All the LCFs except covers have a life limit of 15,000 engine flight cycles (EFC). The covers have a longer life of 30,000EFC. While the PW120's removal and SV interval may coincide with the necessary replacement of these LLPs, this is not always possible due to EGT margin deterioration. EGT margin will erode and decline over a shorter interval than the LCF lives.

A performance restoration or HSI workscope is often required after a removal prior to OVH following deterioration of this EGT margin because it is expected that the first parts of the engine to deteriorate due to wear and tear, and causing loss of performance, will be components and parts found in areas that undergo extreme temperatures and pressures. These conditions lead to frequent metal expansions and contractions, eventually causing cracks and potential weaknesses.

PW120/150 removal pattern

Engines operating in cold climates may remain on-wing for as long as



OEM manuals and maintenance planning guides that form the basis of a maintenance workscope for engines. These are combined with customer requirements, soft times for modules and accessories, LLP limits and service bulletin (SB) requirements.

13,000EFC before removal is required. Conversely, engines operating in hot or tropical environments, coupled with a short EFH:EFC ratio, may witness as many as two intermediate HSIs prior to OVH and LLP replacement at the third SV, which is forced by LLP expiry.

"For the PW100 variants, operating in a very convenient environment, the HSI is estimated to occur about every 7,500EFC, whereas the engine overhaul is expected about every 15,000EFC. For the PW 150, the intervals are slightly longer, with an HSI at about 10,000EFC, followed by an OVH between 15,000 and 20,000 cycles," says Johnson.

In Europe, LTAA sees slightly shorter intervals between HSI and OVH SVs that can be due to a short EFH:EFC ratio. For example, operators with average missions shorter than one hour will experience different removal intervals and SV patterns than operators whose average sector length is between 90 minutes and two hours in the same environment.

"For the PW100, we typically see from customers a SV at 4,000-6,000EFH for the HSI, and between 8,000-12,000EFH for the OVH," says Johnson. "As an approximate guide, depending on the workscope and findings, the HSI for the PW120/121 can take up to 450 man-hours (MH), and can cost $350,000 and upwards for parts and repair work." An aircraft operating in a hostile environment may experience cracks in engine seals and cases. All of these are expensive to replace, and will drive up the cost of the performance restoration.

"If an operator is maintaining hard-timed engines, we see HSI removal intervals of 4,000-5,000EFH for the PW120/121 and the PW127 series," says Baker. "Because the majority of operators maintains engines in accordance with the P&WC on-condition programme, the intervals have now increased on average.

"Downtime for the SV for the average HSI ranges between four to six weeks," says Baker. "Costs can vary between $400,000 and $700,000, with the higher numbers relating to the PW127 series."

"The PW127F/M's hard-time intervals for its HSI and OVHs are 3,500EFH and 7,000EFH," says Bill Polyi, president and chief executive officer at Magellan Aviation Group. "For the other PW100 types it is generally 4,000EFH and 8,000EFH. Cost of a HSI after the first run start at about $225,000-300,000, but will increase depending on rate of blade and stator scrappage."

Because most operators perform maintenance on-condition, PW127F/M engines typically see 5,500EFH-6,500EFH between HSIs, and 11,000EFH-13,000EFH between OVHs. These are typical figures for aircraft operating in normal environments, as opposed to island hopping, hot and high, or desert operations that can significantly lower mean time between removal (MTBRs). Conversely, cold and clean environments can increase MTBRs.

"An engine OVH for the PW120/121 can require about 1,000MH, and cost up to $1,200,000, including LLP replacements and repairs for the average OVH SV," says Johnson.

"OVH costs, not including LLPs, can start at about $700,000 for a PW120/121, and at $900,000 for a PW127," adds Baker. Polyi adds, however, that overhaul costs can start as low as $500,000 for low-time engines. LLPs will be in addition.

The workscope required and resulting SV costs thus depends on removal interval and SV pattern. A longer interval will increase SV costs. The cost for a heavy HSI and performance restoration on the PW121 and PW127M will thus reach up to $550,000, while a larger scope OVH can exceed $1.0 million.

LTAA maintains that costs for a SV can be divided into three main elements: about 60% may go towards material or parts repair and replacement, while sub-contracted repair work can account for about 30%. Lastly, labour accounts for as little as 10% of the overall cost.

Gearbox OVH for the a PW120/121 and PW127 costs about $100,000.

The PW150's LLP lives of 20,000EFC make the removal interval and SV pattern challenging; it may be harder to achieve a simple pattern of a HSI/performance restoration at up to 10,000EFC, followed by an OVH at close to 20,000EFC. The engine is more likely to follow an approximate pattern of two HSI inputs followed by an OVH with intervals for each removal of 5,500-7,000EFC.

A light HSI costs over $470,000 for the PW150, but this can be expected to climb to as high as $800,000 for an engine that has achieved a long interval in the region of 10,000EFC.

A light overhaul for the PW150, where the engine requires a workscope heavier than an HSI/performance restoration, but has not yet reached the interval for full disassembly for LLP. is estimated to cost about $600,000. The OVH that involves full disassembly when LLP replacement is due, may cost up to in $900,000, or even $1.0 million.

LLP costs PW120 & PW150

The list price of LLPs in the PW120 is about $470,000, with an annual list price escalation rate of about 5%. If the annual price increase rate is maintained, the list price for a LLP shipset looks set to be in the region of $700,000 by 2025.

This price is based on the full set having a warrantable life of 30,000EFC. In reality, some of the LLPs require replacement prior to reaching that limit. The HPT LLPs, for example, require replacement at about 15,000EFC. The OEM then provides the operator with a value credit for the unused 15,000EFC life limit. This means customers are able to amortise half the cost of a stack of LLPs over the OVH and LLP replacement interval. A full stack of LLPs for the

CF34-3B1 LLP LIFE LIMITS & LIST PRICES

LLP name	Part number	List price 2017	OEM life limits EFC
Fan Module			
Fan front shaft	6078T51P02	$76,710	25,000
Fan drive shaft	6036T78P02	$103,700	25,000
Fan disc	6078T57G05	$174,800	25,000
Compressor Module			
Forward shaft	5037T01P04	$39,000	30,000
Stage 1 disk	5087T84P03	$126,900	25,000
Stage 2 disk	6036T91P02	$29,690	25,000
Spool stage 3-8	6078T56P05	$111,400	25,000
Stage 9 disk	6087T01P03	$44,060	25,000
Spool stage 10-14	5087T46P02	$96,460	25,000
Rear shaft	6087T03P03	$84,440	25,000
Discharge seal	4019T38P01	$8,515	30,000
Combustor/HPT Module			
Rotor shaft	5079T62P02	$87,970	30,000
Balance piston seal	5079T63P02	$32,080	18,000
Stage 1 fwd cooling plate	5079T65P06	$17,290	30,000
Stage 1 disc	5079T52P09	$98,670	18,000
Stage 1 aft cooling plate	5123T02P01	$37,440	18,000
Outer torque coupling	5079T64P05	$43,730	30,000
Stage 2 fwd cooling plate	5079T55P04	$15,620	30,000
Stage 2 disc	5079T73P02	$100,400	18,000
Stage 2 aft cooling plate	5079T56P02	$15,520	30,000
Low Pressure Turbine Module			
LPT shaft	6030T72P02	$58,200	25,000
Stage 3 disc	6078T91P02	$78,590	25,000
Stage 3/4 seal	5023T59P02	$11,940	25,000
Stage 4 disc	6078T02P04	$91,180	25,000
Stage 4/5 seal	5023T67P01	$11,650	25,000
Turbine drive cone	5023T40P03	$43,100	25,000
Stage 5 disc	6078T92P02	$86,580	25,000
Stage 5/6 seal	5023T64P02	$10,730	25,000
Stage 6 disc	6078T89P03	$61,140	25,000
Total		**$1,797,505**	

PW120/121 can incur a current net cost of $250,000-$300,000 that operators can amortise over the replacement interval.

"Midcycle LLPs, if acquired, are cheaper," say Baker. "The two impellers can typically be purchased for about $50,000 for both, while the HP stack is usually about $35,000. Lastly, the PT1 disc market cost is about $15,000-$20,000, and the PT2 disc is between $10,000 and $12,000 on average."

Used, serviceable LLPs are not hard to find for the PW120 series. "LP and HP impellers are hard to come by for the PW127, which drives up the cost," adds Baker. "There are also few remaining MROs in Europe that have contracted deals or programmes for the PW120/121, making it difficult to market spares for the engine, with most being sold to an MRO provider in North America."

According to Magellan Aviation Group, the Pratt & Whitney Canada (PWC) list price on an LLP stack for the PW127 series is about $900,000. Significant discounts are given by designated overhaul facilities.

The PW150 is basically a scaled-up PW127. The PW150 has an additional LLP, meaning a full set of 11 LLPs. While the majority of the LLPs have a life limit of 20,000EFC, the HP impeller is limited to 15,000EFC and two HPT disks have a set limit of 25,000EFC. The HP impeller is the most costly LLP. List price for the PW150 stack is $1,000,000.

ADs/SBs

One AD released in 2013 required a detailed inspection of the first stage PT Blades in all PW100 series engines.

"This AD introduced a soft time limit on the PT blades, which required X-ray inspection," says Baker. "It caused a lot of disruption, because once this AD was released, it highlighted the fact that first stage PT blades installed in earlier SVs had not been specifically tracked by operators, lessors or MROs. It was difficult, therefore, to establish and prove how many EFH these parts had accumulated, and consequently led to the replacement of many blade sets."

Another AD that had significant impact concerned the PW150, and required NDT inspection of the No. 4 Keywasher.

"This AD has had a substantial impact on shop visits for the PW150A, when it was released last year," explains David Rushe, sales and marketing manager at Magellan Aviation Group. "It required all PW150A engines to be removed and taken in for inspection.

"Demand for the PW150A is outweighing supply," adds Rushe. "This is inflating engine trading values, since there is currently a hunger for on-wing PW150A engines that are just not available." He explains that PW150A engines are being traded for as high as $2.5 million due to this need for availability, and that lessors and traders are having to look to the OEM for new engines to satisfy market requirements.

The CF34 family

The engines explored in the CF34 family include the CF34-3B, which powers the CRJ100/CRJ200; the CF34-8C that equips the CRJ700, 900 and 1000; the CF34-8E for the E-170/-175; and last the CF34-10E that powers the E-190/-195.

The CF34-3/-8C family architecture comprises two-shaft turbofan engines. There are several variants rated between 8,700-14,500lbs. The CF34-3A1/-3B1 have a intake fan with a diameter of 49.0 inches. Unlike most two-shaft turbofan engines, their core engine configuration do not have any low pressure compressor (LPC) stages. The engine has a 14-stage HPC, a dual-stage HPT, and a four- stage LPT. The two engines have analogue main fuel control (MFC) systems.

The CF34-8C1 and -8C5 series first entered service in 1999 and 2001 with the CRJ-700. The -8C5 has two other variants which power the CRJ-900 and -1000.

The -8C1 and -8C5 series have a different configuration to the -3A/-3B engines. The -8C1 and -8C5 have a wider intake fan diameter of 46.2 inches, and a larger core to generate higher take-off thrusts of 12,670-14,510lbs thrust. The core engine has a 10-stage HPC, a dual-stage HPT, and a four-stage LPT. All -8C variants are controlled with a full authority digital engine control (FADEC) system.

In addition, the CF34-10E has been the sole engine to power the E-190/-195 since its entry into service 2005. Its architecture is widely acknowledged to be derived from the CFM56 engine series, and as such is different to the CF34-3 and -8 variants. It has the widest intake fan diameter of the family at 53.0 inches, with maximum take-off thrusts of up to 20,360lbs. The CF34-10E's modules consist of three LP stages and nine HP stages in the compressor, four LP stages and a single HP stage in the turbine.

Based on the CF34-10E engine, the CF34-10A engine powers the Commercial Aircraft Corporation of China (COMAC) ARJ21 regional jet, the first regional jet to be designed and built in China. The first aircraft was delivered to Chengdu Airlines in late 2015 for more than 350 ARJ21 regional jets on order.

Condition monitoring

Again, much of the structure behind maintenance for the CF34 family is centred around on-condition maintenance.

Airlines generally use both trend monitoring, and scheduled borescope inspections to determine shop visit patterns for CF34-8E and CF34-10E engines. This has established a shop visit pattern that alternates between repairing parts as required, and a formal performance restoration, for the operator.

MTU Maintenance Berlin-Brandenburg has been a GE authorised CF34 service provider since 2001. As an OEM network partner, it is also licensed to perform first-run warranty repairs. "The main data source used to monitor performance is the ITT margin," outlines Thomas Needham, head of programmes and sales, MTU Maintenance Berlin-Brandenburg. "There are, however, various additional engine performance parameters that are taken into consideration, for example when utilising our MTU^{Plus} Engine Trend Monitoring service. Other factors are EGT, EGT margin, fuel flow, rotor RPMs, oil consumption, and vibrations."

Due to the average EFH:EFC operating ratio for the CF34, accumulated EFH and EFC both contribute to EGT margin deterioration. "Utilisation is about 1.0EFH per EFC for CF34-3 engines operated in Europe. Given a normal or average aircraft utilisation of about 2,500EFC a year, the EGT deterioration is about one degree Celsius per 1,000 EFC,"continues Needham.

General Electric (GE) further explains that the CF34 is monitored by a number of different factors. While EGT/ITT margin is a main performance factor, the engine's performance is also based on other analytics that GE has been developing that look at conditions that may drive an engine to be unserviceable.

Borescope inspection intervals are a key source of input, although GE's efforts have been toward driving for less inspection and towards more analytics to proactively identify performance shifts. In essence, the industry is experiencing a greater drive towards 'preventative maintenance'. This is a result of the increasing use of big data analytics.

"Being a regional aircraft powerplant means the engine is operated at short flight ratios, and the world EFH:EFC ratio average is about 1.45:1. This means that regional operating styles and environments have a direct, immediate and consistent influence on performance," highlights Graeme Crickett, senior vice president and head of technical at Sumisho Aero Engine Lease B.V.

LTAA performs almost 100 shop visits a year for the CF34 family. "About 90% of the CF34's maintenance is monitored on-condition," explains Johnson. "This affects how operators can structure their SVs and engine removals."

According to GE, the only hard-time limit on the CF34 is the life limit on LLPs, which are all at 25,000EFC. The remainder of the fleet is monitored through performance, analytics, and conditions that arise during borescope. Overhaul timing and LLP expiry are

CF34-8E5 LLP LIFE LIMITS & LIST PRICES

LLP name	Part number	List price 2017	OEM life limits EFC
Fan Module			
Fan drive shaft	4118T61P01	$169,900	25,000
Fan disc	4114T16G02	$319,200	25,000
Compressor Module			
Stage 1/2 Blisk	4129T60P02	$271,400	20,000
Fwd shaft	4128T91G05	$84,500	25,000
Stage 3 blisk	4129T59P02	$94,090	25,000
Aft shaft	4129T50G04	$393,300	25,000
Vortex spoiler	4129T40P01	$17,110	25,000
CDP seal	4129T28P05	$49,650	25,000
Combustor HPT Module			
Inner balance piston	4124T93P03	$54,940	25,000
Outer balance piston	4124T92P02	$75,670	25,000
Fwd cooling plate	4125T30P02	$16,420	25,000
Stage 1 disk	4125T22P04	$229,500	20,000
Torque coupling	4125T37P02	$85,570	21,000
Stage 2 disk	4125T23P04	$153,900	20,500
Stage 2 Aft cooling plate	4124T95P03	$16,260	25,000
Low pressure turbine module			
Stage 3 disc	4118T63P02	$87,110	25,000
Stage 3/4 seal	4117T16P01	$22,260	25,000
Stage 4 disc	4117T13P05	$110,200	25,000
Stage 4/5 seal	4117T17P01	$22,260	25,000
Stage 5 disc	4117T14P02	$110,200	25,000
Stage 5/6 seal	4117T18P01	$22,260	25,000
Stage 6 disc	4117T15P02	$106,400	25,000
Rear shaft	4118T62P01	$173,800	25,000
Combustor	4180T27G04	$504,200	41,100
Total		**$2,685,990**	

therefore designed to coincide for the CF34-8C, the -8E, and the -10E in the case of most operators.

This depends on operating habits, however, and the influence of the engine's thrust rating on performance.

Therefore, key factors that affect the CF34's removal intervals include the environment an engine is operated in, the de-rate the operator uses to use for take-off, and the FH:FC ratio.

CF34 shop visit patterns

There are several sources of documentation, and various considerations to take into account when establishing the most suitable maintenance framework for an operator.

"OEMs provide engine manuals, component maintenance manuals, powerplant manuals and maintenance planning guides for each engine type," explains Needham. "We use the engine manuals as a basis for work carried out, because the engine, modules and piece parts are all covered within. When MTU Maintenance introduces a new engine into its portfolio, however, we create an 'MTU Shop Handling Guide' that incorporates this literature from the OEM with our technical knowledge from maintaining the engine type.

"Essentially, this combined with the customer requirements finds its way into a customised maintenance specification guide that usually contains soft times for modules and accessories, build-life (for example, minimum remaining EFC for LLPs), service bulletin (SB) requirements and further technical information. This becomes the basis for any work we do on the engine, and is used when working with our customers to define the workscope according to their needs," says Needham.

Shop visits & removals

"The CF34-3B1 engine was built with a 25,000EFC LLP stack, with the exception of some HPT parts limited at 18,000EFC and 30,000EFC," says Polyi.

"This makes the engine repair very difficult to manage in its later years, because the engine operates well for the first 18,000EFC with a HSI performed somewhere in the middle (9,000EFC-12,000EFC), depending on operator environment. Its overhaul (not including the LPT) is then between 18,000EFC and 22,000EFC. At this point, you have three options," continues Polyi. "One, build an engine for a subsequent short time interval of about 7,000EFC. Two, you replace the entire LLP stack and build an engine for another 18,000EFC, and third, one can sell off the engine or aircraft."

The first shop visit option averages a cost of about $1,000,000 for the HSI and the replacement of the shipset of LLPs. The second option, an overhaul, can cost between $1,700,000 and $2,000,000, including a full stack of LLPs. If customers go for the third option, they face the cost of acquiring a new aircraft.

"Shop visits for performance restoration are running at six engines/month (30% of all removals) for the CF34-10E fleet. The expectation is that the fleet will start to roll through for first restorations relatively soon," explains Crickett. "MRO shop capacity is a little tight, and any significant wave of shop events can easily place a burden for labour and experience because most MROs which cater for the -10E also do the other CF34 variants."

GE explains that the typical removal interval for the CF34 varies by engine model, thrust, and operating environment. The CF34-10E5, however, has the longest average TOW of about 16,000EFC when operating in a standard environment.

Typically, the CF34 engine has a performance shop visit on first removal, which involves a workscope in the HPT and HPC modules of the engine, restoring performance and EGT margin. As the engine comes in for LLP replacement at the second shop visit, all modules become exposed and the shop visit becomes a heavy visit, or an overhaul. There are occasionally light workscopes to fix specific issues, but these events often do not constitute a full shop visit.

The hot section and borescope inspection may find a condition on engines with longer removal intervals that is deemed unserviceable, and so could drive a shop visit. The shop visit workscope typically follows the pattern as defined above.

"We divide shop visits into two categories," says Needham. "Category one covers LLP exchange, which is hard-timed and cannot be delayed. This would be a heavy shop visit, where full disassembly is required. LLP refurbishment takes place according to the cycles flown.

"LLP life limits for modern engines have been extended in such a way that some engines may only need LLP replacement at a second or third shop visit," continues Needham. "The second category covers on-condition shop visits that make the engine serviceable again, either as performance restoration visits or as an unscheduled event for instance in the case of foreign object damage (FOD). For CF34 engines, nearly all shop visits (99%) are performed on-condition."

Accumulated EFC is commonly seen as the main driver for shop visits on the CF34. There are other factors, however. "Sumisho finds that the biggest SV cost driver (outside harsh environments) is typically the modification state of the particular engine being shopped," says Crickett.

"GE has released a number of high cost SBs that can have a significant impact over the shop visit," adds Crickett. "These costs are upwards of $240,000 and can exceed $880,000 depending on the SB.

"Costs such as these can easily project the final invoice to about $2.5 million, but there are some OEM concessions or fleet support programmes available which can make in-roads into the costs of parts," continues Crickett.

"Modifications, more than the ADs, have driven specific engines into a different shop visit scheduling," adds Needham. "Generally, 10% of maintenance events are related to new SILs, ADs or SBs that come into force," specifies Johnson at LTAA.

"In terms of removal, the first CF34-3 LLP replacement shop visit is at 18,000EFC," says Needham. For the CF34-8 the LLP replacement shop visit is at the 24,200EFC limiter, while on the CF34-10E the LLP replacement shop visit is at the 24,600EFC limiter.

If performance is alright and no damage, such as FOD, occurs, then engines may last on-wing for the full LLP limit. But usually, engines require a performance-related shop visit halfway to the first LLP visit.

"The CF34-3 often comes into the shop for mid-life shop visits (after about 10,000EFC) to have a performance restoration, which corresponds to an HPT repair. This is normally inspected at about half the HPT's LLP life limit. Complete overhaul usually only takes place for engines that have reached their LLP life limit," summarises Needham. During a hot section repair, the HPT blades and HPT shrouds will be replaced or repaired and the clearance between rotor and stator will be optimised through rotor stator grinding. In the case of complete engine overhauls, the engine will be disassembled to piece part level, and all parts will be inspected to overhaul limit.

"Because the CF34-8C5/-8E5 engine was built as a 25,000EFC engine, with all LLPs limited to 25,000EFC except the HPT 1 and 2 disks at 24,200EFC and 24,100EFC, these engines are much easier to repair, manage and overhaul compared to the CF34-3B1," adds Polyi. Magellan estimates the average HSI for the CF34-8 to cost about $800,000, while the overhaul, not including LLPs, costs about $1.4 million. A full set of LLPs has a 2017 list price of $2.7 million. "Many operators, however, get discounts on new LLPs or time-continued LLPs, to reduce these shop visit costs," says Polyi.

A typical HSI shop visit may consist of compressor repair, and HPT refurbishment, whereas overhaul consists of complete module refurbishment, and will require incoming inspection, workscoping, disassembly, cleaning, inspection, repair, assembly, and testing throughout each engine module.

In terms of labour consumption, an HSI may require about 1,500MH, and an engine overhaul between 1,200MH and 2,000MH depending on the variant.

On the CF34-10E, a big restoration costs about $2.5 million, while the overhaul including modification packages is in the region of $3.8 million, according to Crickett. 70% of these costs can be attributed to material or parts repairs and replacement costs.

Early model CF34-10Es had some findings that led to several maintenance programme modifications to the variant. "The early line number engines suffered from oil consumption issues, and GE has addressed these in subsequent builds and

CF34-10E5 LLP LIFE LIMITS & LIST PRICES

LLP name	Part number	List price 2017	OEM life limits EFC
Low pressure compressor module			
Fan disc	2050M52P04	$141,900	25,000
Booster spool	B1316-02110	$217,400	25,000
Fan shaft	45P2303	$117,300	
Fan drive shaft	2226M21P05	$175,100	
High pressure compressor module			
Fwd shaft	2028M39P01	$89,850	25,000
Stage 1-2 disc	2028M40G01	$128,300	25,000
Stage 3 disc	2028M41P01	$40,120	25,000
Spool stage 4-9	2028M42G03	$289,200	25,000
Compressor discharge seal	2028M43P03	$54,250	25,000
High pressure turbine module			
Rotor front shaft	186M47P02	$103,400	25,000
Front rotating air seal	2448M30P02	$231,000	25,000
Rotating disc	1865M51P03	$237,800	25,000
Rear shaft	1865M55P02	$76,380	25,000
Low pressure turbine module			
Stage 1 disc	2226M14P02	$87,650	25,000
Stage 2 disc	2226M15P04	$101,900	25,000
Stage 3 disc	2226M16P05	$118,900	25,000
Stage 4 disc	2226M17P01	$88,780	25,000
Static parts			
Combustion Assy	2070M47G05	$653,800	24,600
TRF	2228M11G01	$387,600	32,400
Total		**$2,299,230**	

configuration releases," explains Crickett. "A number of SBs have been released, so these developments can be retrofitted to earlier engines where required.

"GE released improvements to address the -10E's fuel consumption, noise levels, and reliability during the initial production. These improvements have carried been continued through the current production run, so there can be wide variations in configurations now operating," continues Crickett.

"First removal is generally planned or expected after 11,500-13,500EFC (-10E7) for the first performance restoration, and the second shop visit closer to the LLP limits of 25,000EFCs," continues Crickett. "Other variants have expectations of: The -10E6 at 14,000–16,000EFC, the -10E5A1, and the -10E6A1 at 13,000-15,000EFC.

"The reported high-time engine sits at 29,000EFH, 22,000EFC at present, which is pretty impressive," says Crickett. "The fleet in general sits at average removal intervals between 8,000EFC and 14,000EFC since new. Only engines operated in a harsh environment have more than one restoration visit completed, these account for about 5% of the total fleet.

"Aircraft operating under harsh environments can result in removals as short as about 6,000EFC. These are mostly due to hot-end distress. The additional cost impact on such shops can drive the final cost of a performance restoration to more than $3.0 million. This is because of the large modifications," continues Crickett.

GE, however, has developed a range of special modifications that are specific to aircraft operating in these climates. These are outlined in SB72-197 for the combustor, and SB72-198 concerning the HPT blades.

GE suggests that typical budgetary targets for first SVs be in the vicinity of $1.6-1.8 million, depending on the operator's thrust settings and de-rate. While this may well be correct for later-build -10E engines, it is not the case for the earlier-build examples which regularly exceed $2.0 million on the first SV.

"Typically, GE also suggests the same engines for overhaul could well be in the range of $1.7-2.0 million, plus LLP costs," further outlines Crickett.

"GE also has a commitment to further improve the issue of high oil consumption, which results in fleet removals on an operator elective basis. Some operators are electing to incorporate some other enhancement SBs for reliability and/or performance issues when the engine is in the shop. Typically, the result is a final invoice in excess of $700,000 for the modification work," adds Crickett.

"Timing on-condition shop visits to achieve maximum value and minimised costs is a balancing act, and more of an economic issue than a technical one," says Needham. "On the one hand, airlines do not usually remove an engine earlier than scheduled, since this incurs extra costs, especially if parts are replaced that have remaining green time. That is, are not fully worn out.

"On the other hand, if performance is deteriorating quickly, it is important to take the engine off-wing before more serious (and cost-intensive) damage is done," continues Needham. "This is where engine trend monitoring can be helpful. Through monitoring and expert analysis, we can recommend the optimal point for an engine removal, and time it accordingly as part of our fleet management service. On-site and on-wing services, such as repairs, inspections, component or module replacement can also be beneficial here.

"Furthermore, it is always worth looking at the number of remaining EFCs of the LLPs during a visit (particularly when unscheduled), it could make sense to replace them early, to avoid an additional shop visit later," adds Needham. "In such cases, these serviceable used parts can be re-used in other engines in the airline's fleet (for instance as part of our mature engines programme), or remarketed by the maintenance provider."

Life limited parts

Taking into account LLP shipset list escalations, *Aircraft Commerce* gauges the 2017 list price for the CF34-8C5/-8E rotating parts at about $2.68 million *(see table, page 66)*, and $3.19 million when static parts are included. As disclosed earlier, price estimates throughout this article are used on a constant-dollar basis, plus an assumption that the price of each LLP is escalated by the OEM at the same rate. There might, therefore, be slight variances to this price.

The 2016 list price for a full stack of LLPs for the CF34-10E is in the region of $2.299 million for rotating parts *(see table, this page)*, and $3.34 million when static parts are included.

"There is some thought in the industry that the -10E model will not operate very far past the LLP stack life expiry," says Crickett. "There are E-190s younger than 10 years being disassembled into parts, and the engines being disseminated into the leasing market." AC