There are still 800 active 757-200s. The majority are still flown by their original operators, although many aircraft are 25-28 years old. With large fleet retirements likely over the next five to 10 years, the options airlines have for minimising engine maintenance costs are explored.

The maintenance and management of old PW2000 & RB211-535 engines

The fleet of active 757-200s comprises almost 800 units, split between 460 Rolls-Royce (RR) RB211-powered aircraft, 336 equipped with Pratt & Whitney (PW) PW2000 engines, and 110 parked aircraft. All were built in 1983-2005, making them eight to 30 years old.

The number of 757-200s still in active service is relatively high, and the type remains popular, despite the age of some aircraft. Many of the aircraft remain with original operators. While 135 757-200s have been converted to freighters, and more are due to be converted for FedEx, many are still in passenger configuration. More than 530 active aircraft are operated by just six US carriers.

The PW2000 and RB211-535 engines powering these aircraft account for a high percentage of total aircraft maintenance costs. Operators can manage these engines so that maintenance costs are reduced, while keeping the aircraft and engines airworthy during their last years of operation.

RB211-535 series

The RB211-535 is the smallest series of the RB211 family. There are four variants: the -535C, rated at 37,400lbs thrust; the -535E4, rated at 40,100lbs thrust; the -535E4-B, rated at 43,100lbs thrust; and the -535E4-C, rated at 44,800lbs thrust.

There are currently just 34 aircraft equipped with -535C engines. The -535C was quickly superseded in 1984 by the -535E4 and -535E4-B, which power 426 active 757-200s. The -535E4-C powers only a small number of 757-300s.

The RB211-535 has the three-shaft configuration of all RR RB211 and Trent engines. The engine is configured with a 74.1-inch diameter intake fan, an intermediate pressure compressor (IPC), a high pressure compressor (HPC), a high pressure turbine (HPT), an intermediate pressure turbine (IPT), and a low pressure turbine (LPT).

The fan provides a bypass ratio of 4.3:1. The three-shaft design makes the engine relatively short and stiff. The IPC and HPC both have six stages, the HPT and IPT both have a single stage, and the LPT has three stages. The core engine, therefore, has a total of 17 stages.

The -535C was the last RB211 variant to use fan blades with a mid-span shroud that connects all blades to form a ring. The -535C has 33 fan blades.

The -535E4 introduced the use of wide chord, shroudless fan blades. The -535E4, -535E4-B and -535E4-C have 22 fan blades. The use of wide chord fan blades incurs less drag, so it leads to a lower specific fuel consumption (sfc) over the -535C. There are also annulus fillers between fan blades. Fan blades and fillers are classed as life limited parts (LLPs) in the RB211-535 series.

There are 460 active RB211-powered 757-200s. This includes 34 -535C-powered -200SF converted freighters that are operated by DHL and European Air Transport. These are some of the oldest 757-200s in operation.

There are 262 -535E4-powered active aircraft. Of these, 138 are passenger-configured, including 20 operated by US Airways. There are a large number of other fleets. There are also 124 freighters. The cargo-configured aircraft comprise 43 factory-built -200PFs, 40 of which are operated by UPS, and 81 conversions; 17 -200PCFs operated by a variety of small cargo carriers; and 64 -200SFs that are mainly operated by FedEx.

There are 164 active -535E4-B-powered aircraft of which only one is a freighter aircraft. The 163 passenger aircraft include 98 operated by American Airlines, 41 by United Airlines (ex-Continental Airlines).

RB211-535 LLPs

The short length and relatively small number of stages in the core engine has the benefit of a relatively small number of LLPs. The disks and shafts of the core engine and fan hub are classed as Group A LLPs, while the fan blades and blade fillers are referred to as Group B LLPs. It is only recommended, however, that fan blades and fillers are treated like LLPs, so their lives are not mandatory.

There are standard lives for Group A parts, but the actual lives depend on whether the engine is operating at profile A or B. "For an -E4 engine operating at profile A, the limits in the HPC 1-2 disc are 18,000EFC, and the limits in the LPT stage 1 disk are 27,650EFC," says Julian Lopez Lorite, RB211 production support manager at Iberia Maintenance & Engineering. "For an engine operating at profile B, the HPC disc 1-2 has a life limit of 12,600EFC, and the LPT 1 disc has a life limit of 27,650EFC."

The two shaft parts in the IPC have standard lives of 26,000EFC. The HPT has just a disk, with a standard life of 15,000EFC.

The IPT has a disc and a shaft, both with lives of 26,500EFC. The LPT has three discs and a shaft, with lives of 16,000-27,650EFC.

The lives of the Group A parts are, therefore, 12,600-27,650EFC.

The Group B fan blades have recommended standard lives of 23,000EFC for the -535E4-B variant. The annulus fillers have recommended

Of the 336 active PW2000-powered 757-200s, 273 are utilised by three US carriers. Delta Airlines has the largest fleet of 145 aircraft.

standard lives of 10,000EFC.

"A full shipset of LLPs, for both Group A and Group B parts, has a list price of $4.05 million," says Lopez Lorite. "This is split between $2.67 million for the Group A parts, and about $1.38 million for the fan section parts."

Standard RB211 management

Most RB211-535 engines will have been managed under programmes offered by RR because there are two independent shops. The majority of maintenance and management programmes offered by RR are power-by-the-hour (PBH) contracts, also referred to as TotalCare.

"Most of the -535 fleet is maintained through RR or joint venture shops," says Auvinash Narayen, vice president for sales and marketing at AerFin Limited.

RR contracts for airlines that have operated the engines since new tend to include the shop-visit maintenance, plus a whole suite of ancillary engineering management and support services. "This includes on-wing care during operation, technical records, and engineering management," says Andrew Gainsbury, team leader-airlines, at Total Engine Support (TES). "Contracts for engines operated in the first part of their lives have tended to be relatively long - 10 or 12 years. The contract will include a management plan for each engine, with removal intervals to each shop-visit, the resulting workscopes, and plans for LLP replacement. The shop-visit workscopes are a high standard, with parts being replaced and repaired so that the engine achieves a long removal interval."

The only independent shops are those operated by Ameco Beijing and Iberia. "Contracts with these tend to be short, just a few years for shop-visit maintenance," says Gainsbury. "The airline organises all other services, and performs its own engineering management."

Airlines using these shops have more flexibility to define shop-visit workscopes. They will still use soft times between the different levels in the engine shop manual, and will have more freedom to decide what to contract the shop to do, what to organise themselves, and therefore have more freedom to use engine management techniques to minimise reserves and achieve savings.

Long-term engine management will attempt to match possible removal intervals with shop-visit workscopes, and the timing of LLP replacement. If this is optimised then the lowest cost per EFH and EFC will be achieved.

Engine shop-visit workscopes will, therefore, have a relatively high content. This will, for example, include a high percentage of new parts. All LLPs will be managed and replaced to prevent the engine's operational life and maintenance costs being compromised. This will incur full reserves for engine shop-visits and the replacement of all LLPs.

RB211-535 performance

The RB211-535 has proven to be a durable engine. Performance in most engine types is related to exhaust gas temperature (EGT) margin and its rate of erosion. EGT margin is not used in the RB211-535; turbine gas temperature (TGT) margin is used instead. TGT is measured in the LPT stages.

The RB211-535 has a TGT margin of 30-35 degrees post-shop-visit. TGT margin erosion rates are 6.0 degrees in the first 2,000EFH on-wing, and then 2.0 degrees per 1,000EFH thereafter. The engine should, therefore, be capable of intervals averaging of 14,000EFH before complete loss of performance.

Rates of TGT margin erosion are also 8.0 degrees in the first 1,000EFC on-wing, and then 3.0 degrees per 1,000EFC thereafter. An average interval of 8,000EFC is therefore possible, when based on performance. 757-200s in passenger operations have flight hour (FH) to flight cycle (FC) ratios of 2.6-3.4:1. The removal interval between shop-visits could, therefore, be 20,000-24,000EFH. Engines operating at 2.0EFH per EFC can achieve removal intervals of up to 16,000EFH or 8,000EFC.

Lopez Lorite comments that -E4 engines tend not to be removed because of TGT margin loss, but -E4-B engines sometimes are. The main removal drivers in the past have been deterioration of hot section components and parts. HPT blades last up to 6,000-8,000EFC, although they can often achieve 5,000-7,000EFC. If they are repaired during a shop-visit after 4,000EFC on-wing they can last another 2,000EFC.

Another issue is deterioration of nozzle guide vanes (NGVs), which can also be repaired. Combustion cans also deteriorate, but can be repaired several times, which is not the case with airfoils.

Shop-visit management

There are four levels of shop-visit workscope for the RB211-535. Level 1 is a serviceability shop-visit. It usually relates to a single module, and often consists of no more than an external visual inspection. Lopez Lorite gives a borescope inspection and a preliminary test in the test bench as an example of a Level 1 shop-visit, with a corresponding cost of about $22,000.

A Level 2 shop-visit is a visual check and partial repair on a workscope. This is used when there is specific damage on a module. It does not include any work that restores performance of the engine. "This could be a workscope to repair the damage or part of the damage found to the combustion chamber, HPT blades or just a compressor blade. The repair costs $100,000-200,000," says Lopez Lorite.

Level 1 and 2 workscopes are, therefore, only light repairs, and these repairs do not involve disassembly or

The majority of 757-200s are powered by RB211-535E4 and -535E4-B engines. American Airlines has an active fleet of 98 -E4-B-equipped aircraft.

reassembly of the engine, or any improvement in engine performance.

A Level 3 workscope involves work on all engine modules, and so requires disassembly and reassembly. The workscope is also used to restore engine performance, or zero-life the module. Once disassembled into modules, the Level 3 shop-visit further requires the disassembly of each module, and the repair or replacement of parts that have suffered thermal deterioration.

A Level 4 workscope is a full overhaul, requiring complete disassembly of the engine into all separate modules, and then the disassembly of each module into piece parts. A Level 4 shop visit may be required on a module to make LLP replacement possible.

All parts have a complete inspection, including the checking of dimensions and shop manual condition limits. Parts can be repaired or replaced.

The cost of Level 3 and Level 4 shop-visits is $3.5-4.0 million. "These are typical shop-visit costs when new parts are used," says Narayen.

Lopez Lorite, however, estimates that Level 3 and 4 shop-visit workscopes could cost less, at $3.0 million and $3.2-3.3 million respectively.

"The recommended soft time intervals for the Level 3 and Level 4 shop-visit workscopes are determined by the RR engine maintenance programme," says Narayen. "The interval will depend on EFH:EFC ratio, annual utilisation, operating environment, and other characteristics of operation. The soft times will, therefore, vary for each operator, and the engine maintenance programme has a decision tree to assist in the workscope decision process. While they are soft times, and so only recommended intervals or interval thresholds between one level of shop-visit and another, airlines and engine shops generally stick to these.

"The implications of the soft times are that extensive shop-visits can be difficult to avoid," continues Narayen. "This is because the manual requires further disassembly and inspection once a module has exceeded its soft time or is exposed, so it is usually hard to avoid a Level 3 or Level 4 workscope. This in turn increases the engine's shop-visit cost. This contrasts with other types, such as the CFM56-3, which are mainly on-condition engines, with no generic soft times for different levels of shop-visit in the workscope planning guide. Operators, therefore, have more freedom in how they manage their engines, and more potential to avoid expensive shop-visit inputs."

For long-term maintenance management, the RB211-535 will be operated on the basis of typical shop-visit intervals of 12,000-20,000EFH, equal to 5,500-7,000EFC, depending on EFH:EFC ratio. Each interval will be followed by a Level 3 or 4 shop-visit. Total accumulated time after two intervals will, therefore, be 11,000-14,000EFC, compared to LLP lives of 14,000-27,000EFC. Most LLPs will, therefore, need to be replaced at the second or fourth shop-visits.

Engines will typically follow a shop-visit pattern of alternating Level 3 and Level 4 workscopes. Engines can in fact be managed with consistent Level 3 workscopes until LLPs need replacement, when a Level 4 workscope is used.

Low-cost engine management

Airlines can reduce the amount of maintenance, and so reserves paid by the operator, in the latter years of an engine's operational life by omitting some reserves, or performing cheaper maintenance, especially when the engine is likely to be retired in a few years.

Most airlines have long-term maintenance and support contracts with RR for their engines. Airlines are required to pay big penalties if they terminate the long-term contracts early, but once they expire, airlines can contract with RR to maintain RB211-535s on a time-and-material basis only.

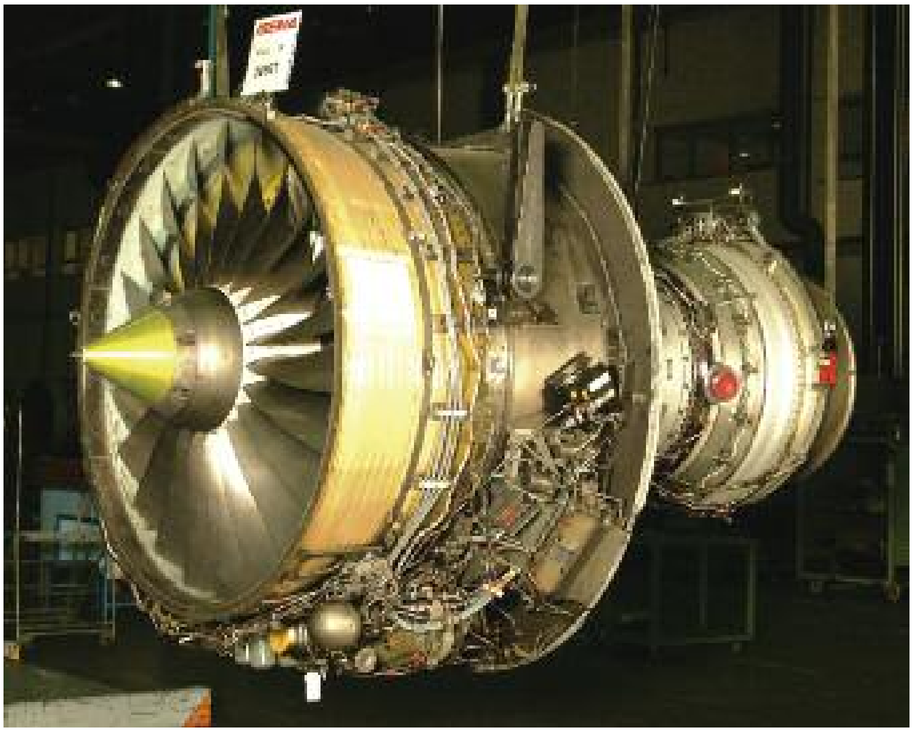
"An example is American Airlines, which did not renew its TotalCare contract with RR after it expired," says Gainsbury. "RR has become a lot more creative in terms of what they offer airlines, including their time-and-material contracts."

Airlines can go to Ameco Beijing or Iberia instead. These shops will provide just shop-visit maintenance to airlines, and airlines are free to manage engines.

The first possibility to reduce reserves is to lower, minimise or omit LLP reserves, which account for a high percentage of all reserves for the engine. It is only necessary to pay reserves to replace a full set of LLPs if it is known or anticipated that the current shipset, or a portion of a shipset, will have to be replaced to allow the engine to continue in operation. If the remaining lives of the installed LLPs, however, are at least as much as the engine's anticipated remaining operational life, then paying reserves for their replacement is not necessary, so large savings can be achieved.

Lopez Lorite explains that many operators are trying to build engines for one or two on-wing lives, and are looking for LLPs with enough remaining life for the equivalent time on-wing. He explains that there are many LLPs available in the market, and the majority of Iberia Maintenance & Engineering's customers are looking for time-continued units.

The reserves that RB211-535 operators pay to RR under various types of engine management contracts generally include costs for shop-visit inputs, but not for LLPs. Operators will still pay LLP reserves, however, for leased engines to lessors. The operators will then reclaim



The only two independent shops with RB211-535 capability are operated by Iberia Maintenance & Engineering in Madrid, and Ameco Beijing in Beijing. These offer flexible maintenance contracts, that include time and material. They have also been active in buying used material and parts.

the reserves from the lessors after the full cost has been paid to RR for new parts.

The cost of replacing LLPs is often excluded from a TotalCare agreement. "In the case of owned engines, operators still pay a PBH rate or time-and-material for shop visits on a regular basis. They buy new LLPs if and when they are required," continues Narayen. This gives operators the ability to avoid accruing reserves for the future replacement of installed LLPs, if they plan to retire the engine before or at the LLPs' expiry.

A second option is to have a time-and-material contract with a supplier which will allow the use of serviceable used and time-continued parts to reduce shop-visit cost. It also allows the operator more flexibility in workscope and build life, especially if the engine type is due to be phased out in the near future.

"This more liberal style of engine management is only possible if engines are owned by the operator," says Narayen. "It is difficult or even impossible, however, if the engines are leased. Lessors require their engines to be maintained in accordance with the RR maintenance programme. There is no discrimination to the fleet and to the build life in order to protect the value of the engine, and so enhance its remarketability to other operators."

Quite a large number of RB211-535s have been parted out, with the retirement of 11 aircraft by American over the past two years. "We look to buy LLPs with at least 6,000-7,000EFC remaining," says Gainsbury. "Many LLPs are being bought by Ameco Beijing and Iberia Maintenance & Engineering. Moreover, RR has bought several engines from US Airways, so it has a supply of parts. Some of these have been sold to TES."

In the case of owned engines, airlines have some flexibility to put them through lighter shop-visits when they are in the last years of their operational life. "An engine can typically remain on-wing for four to five years. The engine may also be under a 10- or 12-year PBH contract, so the operator is paying separately for LLPs,"says Narayen. "At the second shop visit after eight to 10 years, the airline will not normally have the flexibility, under a PBH contract to perform a lighter workscope. If it was technically possible to do so, it would reduce the LLP build life of the engine. A lighter workscope will mean that at the end of the contract, the engine will most likely have close to zero on-wing life remaining. Although the operator has realised savings at the second shop-visit, on LLP replacement, the engine may then need an extensive shop-visit, outside the PBH contract, if the operator later changes its fleet strategy, and decides to keep operating the engine instead of retiring it. If the shop-visit workscopes have been kept light, the engine will have a very low residual value and be less marketable. This of course is only a desirable route to take if there is not a likely market for continued operation the engines or the aircraft combination."

Trying to perform lighter shop-visits as a strategy to reduce maintenance costs, however, is not easy with the RB211-535. "There is always an increase in the TGT margin measured in the test cell, but this always increases when the engine is installed on the aircraft," says Gainsbury. "The risk with a light shop-visit is that the engine may only have a negative TGT margin in the test cell, in which case the engine shop cannot release the engine for service. This means that an airline is always forced to pay over the odds for a larger shop-visit just to get a positive TGT margin in the test cell. You also often find that the workscope has to be escalated to get the performance back. Examples are improving clearances in the HPC or repairing turbine seal segments."

A third way of achieving savings with most engine types is by swapping used modules with time-continued ones. "This is physically possible," says Gainsbury. "It does not actually work, however, since a test cell run is always required afterwards, and there is a strong possibility of getting a negative test cell margin. This means it is probably better to do a full shop-visit."

A fourth cost-reduction technique to use, as fleets get retired, is to switch engines between aircraft. Fully-used engines can be retired, and time-continued ones put in their place until the aircraft is retired. This can be done if there is no or limited used market, and an operator is phasing out its fleet.

A fifth option is for an airline to swap a zero-timed engine with a time-continued one that is owned by someone else. It may be cheaper overall for an airline to buy a time-continued engine than put it through a shop-visit.

"We will swap a time-continued engine, with say 7,000EFC remaining, for a zero-timed one owned by an airline," says Gainsbury. "The airline will pay us the difference in value between the two, and we will tear down the zero-timed engine for parts and accessories."

Gainsbury notes that there is still high demand for used engines in the aftermarket, so there are few used engines and modules available. A large number of aircraft have been acquired by FedEx for freighter conversion, and there are still 300 passenger-configured aircraft with -535E4 and -535E4-B engines in operation. Large 757-200 fleets are still operated by major US carriers, and substantial fleets by other airlines. Demand for time-continued engines from airlines and lessors is still high, so airlines can justify maintaining engines to a high level, even if they are retiring relatively soon.

"The used market can quickly become limited, however, since demand for freighter conversions will dwindle at some point, and the retirement of a large passenger fleet will flood the market," continues Narayen. "Spending on high levels of shop-visit maintenance and LLP replacement may not be the best option. It is actually very difficult for engine owners to forecast the most cost-effective option for their fleet and operation. Engine maintenance and LLP status can be influenced by used engine market conditions, engine ownership, lease-end obligations, and market demand for the engine/aircraft combination."

"Despite these influencing parameters, few airlines have the ability to micromanage their engine fleets to reduce operating cost, facilitate phase-out and retirement," comments Narayen.

RB211-535 economics

Level 3 and Level 4 shop-visits cost $3.0-4.0 million. "These costs can be reduced by utilising used parts, although only by $100,000-200,000. It could be more, depending on the availability of used material on the market and its pedigree," notes Narayen.

There is little scope for reducing the cost of shop-visit maintenance. This suggests that the engine should continue in operation for as long as possible after a shop-visit. Once the engine is in a time-and-material contract during the last years of its life it is possible to pay zero reserves for shop-visit maintenance, if it is known that the engine will be retired and scrapped, or if used engines can be acquired on the used market at low values. This will be the case once large numbers of aircraft are retired. Cost of replacing LLPs can be avoided if is expected that the engine will be retired and phased out.

It will be economic to acquire used engines when their supply on the used market increases. "Currently, the value of RB211-5354s fresh from a Level 3 or Level 4 shop-visit is $3.0-3.5 million," says Narayen. "This is typical for an airline looking to buy engines to replace other engines. This option would avoid repairing an engine. This trading value is less than the cost of putting engines through shop-visits and replacing some or all of the LLPs. By comparison, run-out, or zero-timed, engines are trading at $800,000-1.6 million, depending on the LLP life remaining."

PW2000 family

The PW2000 family was developed specifically for the 757 family. There are three variants: the PW2037, rated at 38,250lbs; the PW2040, at 41,700lbs; and the PW2043, at 43,000lbs. The PW2037 and PW2040 power the 757-200, while the PW2043 powers the 757-300. The PW2037 entered service in 1984, and the PW2040 in 1991.

The PW2000 has a standard two-shaft configuration. The engine has an intake fan with a 78.5-inch diameter. This gives the engine a bypass ratio of 6.0:1; higher than the RB211-535 series.

The PW2000 has a relatively large core, with 23 core stages, compared to the RB211-535's 17 stages.

In 1988, PW introduced a performance improvement package (PIP) and a reduced temperature configuration (RTC) for the PW2000. Both were material and parts upgrade packages, and the RTC included a compressor exit temperature (CET) kit. The improvement modifications also included a second-generation full authority digital engine control (FADEC), intended to increase time on-wing by raising EGT margin.

The RTC was introduced in 1994 for all engines manufactured from this date. It was also available as an option to modify older PW2000s to a higher standard of EGT margin, and improve specific fuel consumption by about 1%.

The release of the RTC package means that the PW2000-powered fleet is sub-divided into four groups: aircraft powered by PW2037, PW2037RTC, PW2040, and PW2040RTC engines. Engines without the RTC configuration or modification have a lower EGT margin and a higher rate of EGT margin erosion than those with it. Non-RTC engines tend to have a high percentage of engines removed due to EGT margin erosion and performance loss, as well as shorter removal intervals.

There are 336 PW2000-powered active aircraft, split between 227 aircraft equipped with PW2037 engines, and 109 equipped with PW2040 engines.

273 of these aircraft are operated by three US carriers: Delta, United and UPS. Delta has the largest number, with 145 active aircraft, while United has 89.

Another 63 are operated in smaller fleets by Ethiopian Airlines, FedEx, Shanghai Airlines, UTair, Uzbekistan Airways and a few other carriers.

The PW2037-powered fleet comprises

FedEx is the only major carrier actively buying a large number of RB211-535s, since it has now converted more than 90 757-200s. This demand is keeping RB211-535 trading values high at $3.0-3.5 million. Engine values will fall once FedEx has acquired its fleet and more passenger-configured aircraft have been retired.

213 passenger-configured aircraft, including 145 operated by Delta, 44 by United, and 14 freighters.

The PW2040 fleet comprises: 67 passenger-configured aircraft, including 45 operated by United, and 42 freighters, including 36 operated by UPS.

PW2000 LLPs

The PW2000 has a relatively long core engine and 23 stages, so it has a large number of LLPs.

The earlier-build engines have 30 LLPs, while later-build models have 25. Some of the discs parts in the older engines were combined into single units.

Unlike many PW engine types, the PW2000 does not have uniform LLP lives. "The HPT disks have lives of 15,000EFC, most of the other LLPs have lives of 20,000EFC, and two parts have lives of 30,000EFC. These last two are a hub and a drive shaft," says Narayen.

The list price of a full shipset is $4.9-5.0 million: $1.1 million for parts with lives of 15,000EFC, and $3.9 million for the parts with lives of 20,000EFC and 30,000EFC. "Managing LLPs in terms of replacing them after utilising their full lives is made difficult by the two HPT disks having lives of 15,000EFC and the other parts having lives of 20,000EFC," says Narayen. "This means that parts may get scrapped with a lot of stub life remaining."

Standard PW2000 management

Unlike the RB211-535, there were more engine shops for PW2000 operators to choose from. The number was still relatively small, however, compared to other types like the JT8D or CFM56-3.

Major PW2000 engine shops include Delta Tech Ops, Atlanta, Georgia; and MTU Maintenance, Hannover, Germany. PW still operates several shops.

Some of the alternative shops had limited parts repair capability, however. Many shops, such as Delta Tech Ops, disassemble engines into modules and modules to piece-part level, and then re-assemble to complete engines.

Specialist parts repair shops include Airfoil Technologies International (ATI) and PW's shop, both in Singapore. ATI was acquired by General Electric in 2009. Other parts repair shops for the PW2000 include Chromalloy, which provides a comprehensive parts repair programme for United Airlines' PW2000 fleet.

Most of the PW2037-powered fleet operates at an average cycle time of 2.5-2.7 FH. Long-range PW2037-powered and PW2040-powered aircraft have longer average FC times of 3.0FH. Most airlines operate their aircraft at annual rates of utilisation of 2,800-3,200FH and 1,000-1,300FC. Engine removal intervals for passenger-configured aircraft have to be considered in four broad categories.

Non-RTC engines

The first two are non-RTC-modified engines. These have EGT margins of 28-35 degrees centigrade. EGT margin erosion rates are 8-9 degrees in the first 2,000EFH on-wing, and then decline at a steady rate of 3.5 degrees per 1,000EFH. EGT margin erosion is the main removal cause for non-RTC engines.

The PW2037 engines have typical removal intervals of 11,000EFH, equal to 4,250EFC. This suggests that the HPT LLPs with lives of 15,000EFC should be replaced at the fourth shop-visit, with the full life virtually used, after 11-14 years of operation. The remaining parts would be replaced at the fifth shop-visit after a total accumulated time of 19,000EFC, at 14-17 years of age.

Higher-rated PW2040 engines have intervals of 9,000EFH. With these aircraft operating longer average cycle times, this is equal to about 3,000EFC.

The HPT LLPs could thus be replaced at the fifth shop-visit, and the remaining parts at the sixth shop-visit, equal to 15 and 18 years.

RTC engines

The next two categories are RTC-modified PW2037 and PW2040. These have EGT margins that are up to 20 degrees higher than the non-RTC engines. Delta says the CET kit and RTC production engines have EGT margins about twice those of non-RTC engines.

These RTC-modified engines achieve longer average planned removals. These engines are also removed for loss of EGT margin, but the longer achievable intervals mean that more engines are removed due to mechanical deterioration and even LLP life expiry.

The lower-rated PW2037 runs for about 18,000EFH, and 6,000-7,000EFC. This would force a workscope to replace HPT LLPs at the second shop-visit, after a total time of 12,000-14,000EFC. This is equal to nine to 13 years of operation.

The remaining parts with lives of 20,000EFC would be replaced at a third removal after a total time on-wing of 18,000-20,000EFC. LLPs would thus utilise most of their lives.

The RTC-modified PW2040 has planned intervals of 15,000EFH. With operations averaging 3.0EFH per EFC, this is equal to 5,000EFC.

HPT parts could thus be replaced at the third shop-visit, and remaining parts would be replaced at the fourth, after 13 and 17 years of operation. Both would have utilised virtually all of their lives.

The implications are that most engines' HPT LLPs will come due for their second replacement at 22-26 years. The relatively small number of parts involved, and the low cost of replacing them, means that most operators will have considered it worth the expense of buying a third set. Installing these could make it possible for the engines to operate for another five or six years.

Large savings can be made in PW2000 maintenance costs by avoiding the replacement of LLPs with lives of 20,000EFC and 30,000EFC after they expire for the second time. An increased number of used engines is coming available on the market, making it possible to make savings through acquiring time-continued modules and engines.

The first set of LLPs in the remainder of the engine, with lives of 20,000EFC, will expire after 14-18 years, so the second set will expire and come due for replacement after 28-34 years, coinciding with the maximum working life or likely retirement age of most aircraft. The high cost of replacing them would probably represent a retirement watershed.

Shop-visit pattern

In most cases, PW2000s go through an alternating shop-visit pattern of hot-section heavy maintenance, and a full overhaul. The hot-section heavy maintenance workscopes include work on the HPC, HPT, NGV, combustor, and the LPC. An overhaul includes all modules, so will have the fan and LPT in addition to those worked on in the lighter visit.

"Like the RB211-535, the PW2000 has a decision tree in the engine shop manual to decide or determine the required level of shop-visit," says Narayen. "Removal interval has a big influence on the level of shop-visit used. As with the RB211-535, it is hard to avoid accruing engine restoration costs."

The cost of a hot-section heavy maintenance workscope is estimated to be $2.3-2.8 million, and $3.0-3.5 million for a full overhaul, compared to higher shop-visit costs for the RB211-535.

On the basis of current LLP list prices, non-RTC engines will have reserves of $1,100-1,300 per EFC. RTC-modified engines, which achieve longer removal intervals, will have reserves of $800-950 per EFC.

Low-cost management

An airline's main option to reduce maintenance reserves during the last few years of operation is to omit payment of reserves for LLPs. Delta comments that the PW2000 is not set up all that well for strict LLP management, because the HPT parts are at 15,000EFC, and the remainder at 20,000EFC.

The replacement of most LLPs, with lives of 20,000EFC and 30,000EFC, would come due for the second time after 28-34 years. Their first replacement would have been at 14-17 years of age.

This timing creates a dilemma for the operator, which must decide whether to buy most of a shipset of these parts when they are due for replacement for the second time. This will cost $3.9 million at current list prices.

If the operator decides not to replace these parts for the second time, then it will be forced to scrap the engine when the second set of LLPs expires, at an age of 28-34 years. If the parts are not replaced when they expire, the engine will have a near-zero value.

This is likely to be the correct decision for most engines, because there is unlikely to be a market for operable but old engines in most cases. Deciding not to buy replacement LLPs, however, will only be possible if the operator owns the engine. If this policy is followed, then a large saving of $205 per EFC for the replacement of 20,000EFC and 30,000EFC parts will be realised. This will be from the shop-visit after these parts were replaced for the first time, at 14-17 years, until the engine is retired.

A further potential to make savings in the last few years of operation is to minimise the shop-visit workscopes between the HPT LLPs being replaced for the second time, and the 20,000EFC LLPs expiring.

Removal intervals, and the approximate shop-visit workscope pattern, means that LLPs with lives of 20,000EFC will be due for their second replacement after 10,000EFC and another two or three shop-visits after the second replacement of the HPT LLPs.

If LLPs with lives of 20,000EFC are not replaced when they come due for replacement the second time, the operator can minimise the engine's first shop-visit workscope following the second replacement of LLPs in the HPT, and avoid the cost of the second or third shop-visit altogether. This strategy could save accruing reserves of $3.0 million for the final shop-visit cost in the last few years of the engine's operation.

There is also the option to use time-continued parts and modules in shop-visits to lower maintenance costs. Another option is buy used modules or even whole engines with the HPT's LLPs at lives of 15,000EFC, or the rest of the parts with lives of 20,000EFC as they come due for replacement.

Delta Airlines has taken advantage of the fact that retirements by some operators, including itself, have created a surplus of used LLP material. This allows operators to fulfil a good portion of their needs for LLPs at less than catalogue or list price, especially for older engines that have not had the RTC and CET modifications. They consequently have shorter removal intervals, and are less likely to have fully utilised their LLP lives.

Delta has found that one way of making full use of remaining LLP lives, is to use creative shop-visit techniques, such as building engines with LLPs that have stub lives and generally swapping modules. The most important issue is to try to match LLP lives as closely as possible. Swapping modules, however, may be a false economy. Some operators have found that EGT margin can deteriorate very quickly in these cases.

There are still many PW2000-powered aircraft in operation. Supply of used engines and modules will rise, and their trading values fall, as larger numbers of aircraft start to be retired. The retirement of Delta's and United's fleets will have the largest impact.