PW2000 & RB211-535 maintenance analysis & budget

The majority of PW2000s & RB211-535s 757s operate at 3.0EFH per EFC. Their operation and maintenance costs are analysed here.

The RB211-535 and PW2000 engines power a total of 1,010 757-200s and -300s. The PW2000 suffered from an image of poor reliability during its first few years of operation, as a result of which it lost market share to the RB211. The RB211-535 series won orders for the majority of aircraft and customers, and now powers about 580 aircraft. The PW2000 powers 430 aircraft, 305 of which are in large fleets operated by Delta Airlines, Northwest and United Airlines.

The first 757s entered service in 1982, and the last were built in 2004. Most engines have therefore passed their first shop visit and are mature in maintenance terms. About 880 of the 757s are configured as passenger aircraft and have flight cycle (FC) times varying from 2.0 to 4.0 flight hours (FH). Another 130 aircraft are freighter variants, the majority being factory freighters. The average FC length across the 757 passenger fleet is about 2.7FH, so the PW2000's and RB211-535's maintenance costs are therefore examined in operations with this average FC.

Engines in operation

About 90% of 757s in operation are in passenger configuration. The largest number of 757s is used by US majors. This group totals 530 of the 880 passenger aircraft. American Airlines, Continental Airlines and USAirways operate 225 RB211-535-powered aircraft, while Delta Airlines, Northwest, and United Airlines operate 305 PW2000-powered aircraft.

Northwest operates a fleet of 71 PW2000-powered 757-200s and -300s. The airline's -200s are powered by the PW2037, and were first delivered in 1985. The carrier's -300s started operations in 2002 and are equipped with PW2040s. The two sub-fleets average about 3,300FH and 1,200FC per year, with an average FC time of 2.75FH.

Most of these aircraft are operated on domestic routes by their airlines, with the 757 often being used on the longer and heavier routes. An increasing number of 757s are operated on international routes by some US majors. Delta, for example, has reorganised its operation by reducing its domestic capacity, and shifting some of its 757s and other aircraft to Central and South American routes. This has affected the average FC time of these aircraft, which has now increased to about 3.0FH.

Delta has the largest 757 fleet in operation, with 137 PW2037-powered 757-200s. Some of its aircraft have extended range capability and are used on international routes for up to 11FH per day. The larger group of aircraft used on domestic flights operates at 2.83FH per FC.

European carriers account for the second largest group of passenger-configured 757s. About 190 aircraft are operated in Europe and the CIS. Large fleets of 757s are operated in Western Europe by British Airways, Condor, Finnair, First Choice, Iberia, Icelandair, Jet2.com, Monarch Airlines, Thomas Cook and Thomsonfly.

Iberia has operated the RB211-535E4-powered 757-200 for more than 10 years in its European network. The aircraft have been operating at a utilisation of 2,600FH and 1,800FC per year, a ratio of about 1.5FH per FC.

Finnair operates seven 757-200s, equipped with PW2040 engines, as charter aircraft with a high-density seating configuration. These aircraft have some of the longest average FC times in the 757 fleet. "The aircraft are relatively young, with the first one delivered in 1997," says Janne Pallonen, manager PW2000 engineering at Finnair Technical Services. "We operate the aircraft to Brazil and Mexico in the winter months, and to Mediterranean destinations in the summer. The average FC time across the year's operation is about 4.5FH."

The third largest group of 757s is in China, with Air China, China Southern, Shanghai Airlines and Xiamen Airlines operating more than 50 aircraft.

The overall 757 passenger fleet achieves annual utilisations of 3,100FH and 1,100FC per year, with FC time averaging 2.9FH.

The freighter fleet of 190 aircraft is a mix of factory-built and converted freighters. The converted freighters operated by European Air Transport and DHL are used for express package operations, as are virtually all the factory-built aircraft that are operated by United

The majority of 757 operations are medium haul, with many close to an average EFC time of 3.0EFH.

The PW2000 fleet is divided between engines that do not have the RTC modification and those with the RTC modification. The RTC modification reduces engine temperature to improve on-wing life.

Parcel Service. These aircraft generally have low rates of utilisation and average FC times of 1.0-1.5FH. The converted freighters are dominated by those modified by Precision Conversions, and are operated by Varig Log, Icelandair, Blue Dart Aviation and Cargojet. These have higher rates of utilisation, and longer FC times of 2.6-3.0FH.

EGT margin

Exhaust gas temperature (EGT) margin can be a major factor forcing removals for shop visits. EGT margin and its erosion is most important for engines operated on short engine flight cycle (EFC) times, since it is often the main cause of removals. EGT margin accounts for fewer removals as EFC time increases. Mechanical deterioration of engine hardware becomes more of an important engine removal driver as EFC time increases. Since most 757s are operated on medium-haul operations, EGT margin is not a prime removal cause for engine shop visits in the case of most engine variants.

RB211-535

The RB211-535E4 generally has sufficient EGT margin and EGT margin retention for EGT margin loss not to be a main removal driver. "The RB211-535's test cell EGT margin following a full refurbishment is 18-30 degrees centigrade, but averages about 22 degrees," explains Julian Lopez Lorite, RB211 production support manager at Iberia Maintenance & Engineering. "The reason for this variation is because the values vary, depending on whether the engines have a Phase II and Phase V combustor that meet CAEP II and CAEP IV NOx emissions standards. EGT margin on-wing is 8-9 degrees higher than test cell EGT margin. The on-wing EGT margin following a shop visit will therefore be 26-39 degrees, and average about 30 degrees."

Andrew Gainsbury, programme manager at Total Engine Support, comments that the RB211-535's typical turbine gas temperature (TGT) margin on the test cell following a level 3 shop visit is 20-25 degrees centigrade. The on-wing margin is 8-10 degrees higher at 28-35 degrees. The TGT is measured in the stages of the low pressure turbine (LPT), and is a similar measurement to the EGT that is used on other engine types.

PW2000

The PW2000 comes with, and without, the reduced temperature configuration (RTC) modification, which was introduced on the production line in 1994. The RTC modification supercharged the low pressure compressor (LPC) to increase airflow, and the combustion exit temperature (CET) modification kit could also be used to modify the low-speed rotor system of earlier-built engines to achieve the same effect. The CET kit was designed to increase core flow and turbine cooling, and to reduce EGT, thereby increasing EGT margin by up to 25 degrees centigrade.

The CET kit could be installed on engines built prior to 1994 during a shop visit. Most PW2000s have now been modified.

Engines with the RTC modification have a higher EGT margin than those without it. EGT margin erosion therefore accounts for a higher percentage of removals for shop visit maintenance in non-RTC-modified engines than those that have the RTC modification. EGT margin also depends on thrust rating, with lower-rated PW2037 engines having a higher EGT margin than PW2040 engines.

Non-RTC-modified engines have an EGT margin of 28-35 degrees centigrade, while RTC engines have a higher margin of 45-50 degrees centigrade.

"An old-standard, non-RTC-modified PW2037 has an EGT margin of about 35 degrees centigrade," says Thomas von Kaweczynski, PW2000 customer program manager at MTU Maintenance. "The higher-rated PW2040 with the RTC modification will have an EGT margin in the region of 28 degrees centigrade."

The EGT margins of RTC-modified engines are up to 20 degrees higher than those of non-modified engines. "The mature RTC engines in our fleet have a test cell EGT margin of 50-60 degrees, and the on-wing margin is similar," says Pallonen. "The RTC modification affects turbine cooling, which is where most of the benefit comes from."

Von Kaweczynski reports similar EGT margins. "A PW2037 engine with the CET upgrade kit or the new production engine, with the RTC modification, will have an EGT margin of about 55 degrees centigrade. A PW2040 engine will have a margin averaging 45 degrees, about 18 degrees more than the non-modified engines."

Delta, however, says that the restored EGT margins of its CET-modified engines are 35-40 degrees.

EGT margin erosion

TGT and EGT margin erosion is naturally the highest during the first 1,000-2,000EFC on-wing following a shop visit, and then reduces to a more stable level. The rate of TGT and EGT margin erosion, and the initial TGT or EGT margin will combine to influence whether or not TGT and EGT margin erosion is a main factor in driving engine removals.

RB211-535

"The initial rates of TGT margin loss on the RB211-535 depend on several factors. These include take-off de-rate, average FC time, and outside air temperature," explains Lopez Lorite. "At an average FC time of 2.0-3.0FH, the

The RB211-535E4 is rarely removed due to loss of TGT margin. The engine has demonstrated its ability to achieve long on-wing intervals.

initial rate of TGT margin erosion is 3.0 degrees per 1,000EFH in the first 2,000EFH on-wing, and then it slows to 2.0 degrees per 1,000EFH. An engine with a margin of 30 degrees will therefore be capable of remaining on-wing for 14,000EFH."

Gainsbury quotes similar rates of TGT margin loss. "The engine loses about eight degrees in the first 1,000EFC, and then the rate steadies to about three degrees per 1,000EFC thereafter."

The engine could therefore remain on-wing for 8,000-9,000EFC, which would be equal to 24,000-27,000EFH. TGT margin erosion is rarely a driver of removals for shop visits for the RB211-535, however. Gainsbury explains that the RB211-535, like other RR engine types, tends to undergo a reducing rate of TGT margin loss, and so it experiences the deterioration of hot-section components before TGT margin is completely lost.

PW2000

"The initial rate of EGT margin erosion for the PW2000 may be 4.0-4.5 degrees per 1,000EFH during the first 2,000EFH on-wing," explains von Kaweczynski. "The rate of EGT margin then reduces slightly to an average of 3.5 degrees per 1,000EFH when operating an average EFC time of 3.0EFH, although the actual rate is dependent on the operator."

EGT margin is naturally higher in the higher-rated PW2040 at 8.0 degrees per 1,000EFC, and 6.0 degrees per 1,000EFC in the PW2037.

This rate of erosion will allow a non-RTC-modified PW2040, with the lowest EGT margin, to remain on-wing for about 9,000EFH or 3,000EFC. The lower-rated non-RTC-modified PW2037 will be able to remain on-wing for about 2,000EFH longer, at 11,000EFH or 3,700EFC.

The RTC-modified engines clearly benefit from their higher EGT margins. The lower-rated RTC-modified PW2040 will be able to remain on-wing for 14,000-15,000EFH, or up to 5,000EFC. The lower-rated RTC-modified PW2037, which has the highest EGT margins, will be able to achieve a removal interval of 17,000-18,000EFH or about 6,000EFC.

Northwest, for example, which operates the PW2037 and PW2040, has EGT margins of 50 degrees following heavy engine maintenance, and experiences EGT margin erosion rates of 3.0 degrees per 1,000EFH.

Life limited parts

The removal intervals that are possible with TGT and EGT margins, the probable removal intervals of engines when actual removal causes are considered, shop visit workscopes at each removal, and the pattern of shop visits must all be considered in relation to the lives and list prices of life limited parts (LLPs).

A high proportion of maintenance reserves for the RB211-535 and PW2000 operated on the 757 will be accounted for by LLP reserves when the aircraft is operated at EFC times of 2.0-3.0EFH. The lowest reserves will be achieved when LLPs are removed with the shortest possible remaining lives or 'stub lives', and when LLPs are removed and replaced during a heavy shop visit when the engine already requires full disassembly. Higher maintenance reserves are the result when LLP life expiry coincides with a shop visit that would otherwise be relatively light were it not for the need to replace LLPs, or when LLP life expiry occurs between planned shop visits and so forces an early removal.

RB211-535

LLPs in the RB211-535 are grouped into Group A LLPs and Group B LLPs. Gainsbury explains that Group A LLPs are the same as those found in other engine types, for example disks, shafts and hubs. Rolls-Royce, however, only recommends that Group B LLPs be treated like LLPs, and limited lives are therefore not actually mandatory, although most operators still choose to use limited lives.

The RB211-535 has six main turbomachinery modules, which have 14 Group A LLPs. These are the fan or LPC, intermediate pressure compressor (IPC), high pressure compressor (HPC), high pressure turbine (HPT), intermediate pressure turbine (IPT) and LPT.

The two parts in the fan module for the -E4B engine have lives of 17,200 and 22,600EFC, and a list price of $310,000. One part has a life of 14,230EFC in the higher-rated -E4C engine.

The two parts in the IPC have a list price of $408,000, and lives a little over 26,000EFC in the -E4B and -E4C variants.

The three parts in the HPC have a list price of $487,000. Lives are 12,600-25,000EFC for the -E4B and -E4C engines.

The HPT disc has a list price of $340,000, and a life of 15,000EFC in the -E4B and 10,000EFC in the -E4C variants.

There are two parts in the IPT, with list prices of $244,000. These have lives of 26,500EFC.

There are four parts in the LPT, with a list price of $311,000. These have lives of 16,000-27,650EFC in the -E4B variant. Lives in the -E4C are the same, except for one turbine disc that has a life of 23,200EFC.

Besides the fan and LPC, the parts with the shortest lives are found in the HPC, HPT, and the LPT.

In addition to these 14 Group A LLPS, there are also 44 Group B LLPs. These comprise 22 fan blades and 22 fillers between fan blades on the fan disk.

The main cause of removals for the non-RTC modified PW2000 engines is loss of EGT margin. PW2000 engines which have the RTC modification are also removed because of EGT margin, but do achieve longer removal intervals.

The fan blades each have a list price of $45,000 and have a life limit of 23,000EFC in the -E4B variant, and a life limit of 17,600EFC in the -E4C variant. The list price for the total shipset is $983,000.

The 22 fillers in the LPC have lives of 10,000EFC in the -E4B and -E4C variants. This will force a removal and a relatively heavy shop visit at 10,000EFC, since a high level of engine disassembly will be required to replace these parts.

These 44 fan blades and fillers can easily be accessed by removing the spinner. The blades can then be removed for inspection and repair, without the need to disassemble any engine module, as is the case with Group A LLPs. While the fan blades have lives of 17,600EFC or 23,000EFC, this is equivalent to 50,000-75,000EFH over a 16-25 year period. Dents or bending of the airfoil shape and erosion to leading edges will be experienced during this period, so these blades and fillers will be periodically removed for inspection and repair. Airfoil Technologies International, for example, is a specialist provider of repairs for engine blades, and is capable of repairing fan, IPC and HPC blades.

Overall, the full shipset of LLPs in the RB211-535 series engine has a 2008 list price of $3.15 million, up from a 2005 list price of $2.65 million. This indicates that the list prices have increased at a rate of 6% per year.

PW2000

There are different configurations for the LLPs. "The older engines had a configuration of 30 LLPs," explains von Kaweczynski. "Later configurations have only 25 LLPs. The reduction in LLPs is achieved by combining several parts. One example is where the HPT stage 1 disk and an airseal have been combined to form one part. Another example is where the stage 16 and stage 17 disks and the rear shaft have been combined as one part and are now a drum. The compressor discharge pressure (CDP) seal also forms part of this drum, so four parts have been combined to make one."

The most recent configurations on the PW2000 are for 25 LLPs in the complete shipset. Unlike those in most PW engines, the LLPs in the PW2000 do not have uniform lives.

The majority of parts have lives of 20,000EFC. These are parts in the LPC, HPC and LPT modules.

The HPT, however, has six parts with lives of 15,000EFC.

The LPT hub, HPC drive shaft and LPC drive shaft all have lives of 30,000EFC.

The complete shipset of LLPs has a 2008 list price of $3.6 million. This compares to a 2005 list price of $2.5 million, indicating that the list price has increased at a rate of 10% per year.

The reserves for LLP replacement must take into account the likely timing for replacement, and the stub life of parts at removal.

Removal causes & intervals

The loss of TGT and EGT margin, and therefore engine performance, is the main cause of removals for engines operated on short EFC times. TGT and EGT margin and performance loss become less of an issue for engines with high TGT or EGT margins and those operated on medium or long EFC times, in which case mechanical deterioration and LLP expiry become more of a removal cause.

RB211-535

The RB211-535 is generally not forced off-wing for shop visits by loss of TGT margin and performance. "The loss of TGT margin is almost never a removal cause for shop visit maintenance," says Gainsbury. "The main removal cause for the RB211-535 is the thermal deterioration of the hot-section components, in particular the HOT blades, nozzle guide vanes (NGVs), and combustion chambers.

"HPT blade distress and deterioration is the biggest removal cause, and Rolls-Royce's engine maintenance programme (EMP) recommends that these are replaced every shop visit," continues Gainsbury. "The HPT blades can actually last 6,000-8,000EFC and be repaired after an interval of about 4,000EFC. They are then likely to force a removal after another 2,000-3,000EFC. Replacing them at each shop visit means that their lives are limited to 5,000-7,000EFC. The cost of replacing a shipset of HPT blades is about $600,000.

"The NGVs also get tired after a similar interval and their replacement is also recommended. A full shipset costs $500,000-600,000," continues Gainsbury. "It may be possible to repair NGVs, but they deteriorate faster afterwards and would force an earlier subsequent removal."

Combustion cans also wear out after 5,000-7,000EFC on-wing, but different parts of these can be replaced at different shop visits. They are therefore in a continual state of repair.

"The typical life between level 3 and level 4 shop visits, those that are used to restore engine performance, is 15,000-20,000EFH, and 5,500-7,000EFC," says Gainsbury.

Lopez Lorite at Iberia also comments that the deterioration of HPT blades and combustion chamber distress are main removal drivers. "An engine operating at an EFC time of 2.0EFH can remain on-wing for about 16,000EFH," says Lopez Lorite. "This will increase to about 18,500-20,000EFH for engines operated at 3.0EFH per EFC.

Condor, for example, operates at 3.0EFH per EFC and has a mature planned interval of about 18,000EFH and 6,000EFC.

The Rolls-Royce engine maintenance plan requires level 3 or level 4 workscopes on all engine modules at scheduled shop visits. This puts the cost of shop visit inputs at a high level relative to other engine types.

PW2000

As described, the EGT margins of the PW2000 series vary, while non-RTC-modified engines have margins 15-20 degrees less than the enhanced variants.

Loss of performance is a main removal driver for non-RTC-modified engines. As described, the non-RTC-modified PW2040 is likely to remain on-wing for about 9,000EFH, while the PW2037 could possibly remain on-wing for longer, up to 11,000EFH. Northwest, for example, has an average interval between shop visits and minor repairs of about 8,000EFH. Von Kaweczynski says that non-RTC-modified engines will achieve 10,000-12,000EFH between shop visits. "Main removal causes are loss of performance and EGT margin."

RTC-modified engines tend to have fewer removals forced due to loss of EGT margin, although some are still due to loss of performance. As described, their 15-20-degree higher EGT margins can be expected to allow removals of 14,000-15,000EFH.

"RTC-modified engines are still removed mainly because of EGT margin erosion, but they have longer shop visit intervals of 15,000-18,000EFH," says von Kaweczynski. Pratt & Whitney's record for RTC-modified engines is an average interval of 16,500EFH.

Delta, which has a typical operation of about 2.9EFH per EFC, has a mature planned removal interval of 18,000EFH and 6,000EFC on its domestic fleet. Its international fleet operates at longer cycles of about 4.9FH per FC, and the planned interval is 20,000EFH and 4,000EFC.

Finnair, which operates at one of the longest EFC times of all 757 operators, reports that loss of EGT margin and performance is rarely an issue with its PW2040 RTC-modified engines. "Besides our long average EFC times, we also have the advantage of operating in a cold environment," says Pallonen. "The main removal causes are mechanical deterioration, and we try to keep maintenance costs optimal by not leaving the engine on-wing for too long. If the engine is left on-wing for too long, then the turbine deteriorates and the compressor suffers. If the turbine blades exceed the overhaul limit they have to be replaced rather than repaired, which obviously pushes up the shop visit cost. With our long average EFC time we can keep the engine on-wing for a long time, so the physical state of the engine determines when we remove the engine for shop visit maintenance.

"The first runs were naturally the best. For these we had a target of about 20,000EFH, and then a target of about 15,000EFH for mature engines," continues Pallonen. "We actually got longer intervals, and managed to achieve first runs of 22,000-23,000EFH. The second runs have been about 15,000EFH and 4,000EFC."

Shop visit workscopes

RB211-535

There are four levels of workscope for the RB211-535. A level 1 shop workscope is only a serviceability shop visit, and is only used on a module when it is not being stripped. It usually consists of no more than an external visual inspection. "A level 1 workscope is a package of work for completing serviceability tasks or troubleshooting," explains Lopez Lorite.

A level 2 workscope is a check and partial repair shop visit on a particular module. It involves stripping and disassembling a module, but is only used when there is some specific damage. It does not involve performance restoration work. "A level 2 workscope is a 'check and rectify' shop visit," says Lopez Lorite. "It is a package of work that restores the engine to a serviceable condition for its remaining residual life. The tasks are listed in Rolls-Royce's EMP 'module check and rectify' section."

Level 3 and 4 workscopes involve rework on all engine modules. The workscope results in restoration of engine performance, so these two workscopes incur the highest shop visit costs.

"A level 3 workscope is a refurbishment shop visit. Unlike a level 2 workscope, it involves the disassembly of modules. It is used for a complete performance restoration, and the repair of parts that have suffered thermal deterioration," explains Gainsbury. "This allows the module to be zero-lifed. It is normal to carry out a level 3 workscope on all modules at the same time, which results in the best on-wing life."

"The level 3 workscope is a refurbishment shop visit," says Lopez Lorite. "It is a package of work that at the minimum completes the module 41 (HPC, HPT and combustion chambers) refurbishment and the IP mini-module 51 (IPT, LPT and LPT case) refurbishment in accordance with the appropriate EMP section."

"A level 4 workscope is a full overhaul. It involves a complete disassembly of each module to piece-part level and carrying out a full inspection of all parts," continues Gainsbury. "It may be necessary to have a level 4 workscope on a module that requires full LLP replacement.

Most PW2000s follow a simple alternating pattern of performance restorations and overhauls. This makes shop visit inputs cheaper than the RB211-535E4's, but the PW2000 achieves shorter removal intervals.

"For a normal pattern of shop visits, operators are recommended to follow a pattern of alternating level 3 and level 4 workscopes," continues Gainsbury. "A level 3 workscope gives the necessary performance restoration. Provided that no LLPs have to be replaced, all operators can have level 3 workscopes at every shop visit. Operators need to only have level 3 workscopes on the LPT, IPC and IPT modules at every other removal.

A level 4 workscope involves more in-depth work, and usually a higher rate of parts replacement. There are a few issues with the IPC that affect the size of the workscope. "The original standard of the IPC is known as a list 1 standard," explains Gainsbury. "This was later replaced with a list 2 IPC, which was thought to be an improved version. However, this actually suffered from cracking, so it had to be de-bladed for an inspection to be made to detect the cracking problem. This means the blades also have to be inspected. The list 1 IPC was then reintroduced as a result of the difficulties with the list 2 IPC."

Lopez explains that unlike other engine types, the recommendation for the RB211-535 is that there is at least a level 3 workscope on each main module at every shop visit. "The general recommendation is that a level 3 workscope shop visit is followed by a level 4 shop visit, and then the engine follows a pattern of alternating shop visits. I think it is possible for the engine to have two level 3 workscopes and then a level 4 workscope. The requirement for a workscope on each module nevertheless makes the shop visit costs of the engines relatively high," explains Lopez.

Gainsbury estimates that level 3 workscopes cost in the region of $3.0 million. About $400,000 of this is accounted for by sub-contract repairs, another $800,000 is for labour, and $1.8 million is for parts and materials, but not including LLPs.

Gainsbury puts the cost of a level 4 workscope at about $3.5 million.

Lopez makes a similar estimate for a level 3 workscope, with a total cost of $2.8-3.0 million. A level 4 workscope requires more labour and may have more findings and a need to replace more parts because of the high level of disassembly. The total cost will be $3.3-3.4 million. The relatively small increase of $0.4-0.5 million is because all modules have workscopes in both levels of shop visit.

PW2000

Most PW engines usually follow a simple pattern of alternating shop visit workscopes. These are usually a hot-section inspection or performance restoration followed by a complete overhaul. "We like to try to follow a pattern of a hot-section heavy maintenance (HSHM) and then have an overhaul every second removal," says Pallonen. "The HSHM at least includes work on the HPC, HPT, combustor and nozzle guide vanes between the exit of the combustors and the first stage of HPT blades. We may also add work on the LPC in the workscope. This will include partial disassembly of the module, and leave the blades installed. There will be a visual inspection and clearances will be restored. There are also abradable rubber seals in the LPC casings, and replacing these restores performance.

"An overhaul of engine heavy maintenance (EHM) involves the full disassembly of all modules," continues Pallonen. "The fan and LPT modules are therefore added to the workscope, and the engine has a full teardown."

The lighter core or performance restoration shop visit will consume about 3,500MH, $400,000 in sub-contract repairs, and $1,0-1.6 million in parts and materials. At a typical labour rate of $70-80 per MH, this will take the total cost to $1.7-2.3 million.

Heavier overhauls will use 5,000-5,500MH, about $500,000 in sub-contract repairs, and $1.6-2.1 million. The total cost of this workscope will be $2.5-3.0 million when labour is charged at $70-80 per MH.

Unscheduled shop visits

Unscheduled shop visits fall into engine-related and non-engine-related events.

Engine-related events involve the failure of engine hardware, and are divided between light and heavy events. Light events are issues such as oil leaks, hospital visits for damage to the HPC, and other minor incidents that do not require full engine disassembly.

These occur at a rate of about once every three to four scheduled shop visits, and incur shop visit costs of up to $500,000. These do not interrupt the schedule of planned shop visits, and so a budget of $8 per EFH should be made for the RB211-535, and $6-9 per EFH for the PW2000 to cover for these events.

Heavy events are major failures such as bearing failure, and these result in heavy shop visits that usually require a full workscope on every module.

Non-engine-related events are items such as birdstrikes and foreign object damage (FOD). These also often result in a heavy shop visit and full disassembly.

Heavy engine-related and non-engine-related events should be considered as one category because of the high shop visit cost they incur, which can be up to $3.0 million. These occur at a rate of once every four to five planned shop visits. One of these events therefore replaces one of the four or five planned shop visits. Since these events always usually result in a heavy shop visit, and will therefore replace a performance restoration on about half the occasions they occur, the cost of half of one of these visits should be amortised over the

RB211-535E4 & PW2000 REMOVAL INTERVALS, SHOP VISIT INPUTS & MAINTENANCE RESERVES

Engine type	RB211-535E4	PW2000 non-RTC	PW2037 RTC	PW2040 RTC
1st removal-EFH	17,000-19,000	10,000-12,000	15,000-16,000	14,000
1st shop visit-$	3,000,000	1,700,000	2,200,000	2,200,000
2nd removal-EFH	17,000-19,000	10,000-12,000	15,000-16,000	14,000
2nd shop visit-$	3,500,000	2,500,000	2,800,000	2,800,000
Shop visit reserve-$/EFH	171-180	200	167-173	178-189
LLP reserve-$/EFC	185	200	200	189
Total reserve-$/EFH	263-272	292-295	259-268	259-268

Planned shop visit engine maintenance reserves based on 3.0EFH per EFC.

interval of four or five planned visits. This is equal to $22 per FH for the RB211-535, and $19 per FH for the PW2000.

The total allowance for unscheduled shop visits should therefore be $30 per EFH for the RB211-535E4, and $25-28 per EFH for the PW2000.

Maintenance reserves

The maintenance reserves for the two main engine types are summarised *(see table, this page)*. This includes non-RTC-modified and RTC-modified PW2000 engines. These are for engines operating at 3.0EFH per EFC.

The RB211-535E4 will have intervals of 17,000-19,000EFH between successive shop visits. This is equal to 5,700-6,300EFC. It is assumed that the engine follows a shop visit pattern of alternating level 3 and level 4 workscopes. These have shop visit costs of about $3.0 million and $3.5 million. The reserve for these two will therefore be equal to $171-180 per EFH *(see table, this page)*.

The RB211-535E4's LLPs have lives of 14,000-27,650EFC, and will therefore be replaced every second, third or fourth shop visit at intervals averaging 12,000EFC, 18,000EFC and 24,000EFC. On this basis the reserve for these parts will be $122 per EFC. The additional reserve for the fan blades and fillers will be a further $63 per EFC. These can be removed from the fan disc without the need for a full disassembly. The total reserve for LLPs will therefore be $185 per EFC.

The total reserves for the shop visit maintenance, unscheduled maintenance and LLPs for the RB211-535E4 operated at the EFC time of 3.0EFH will therefore be $263-272 per EFH *(see table, this page)*.

The non-RTC-modified PW2000 engines have shorter intervals of 10,000-12,000EFH between shop visits. This is equal to 3,300-4,000EFC. Most engines follow a pattern of a core and performance restoration workscope followed by an overhaul, over a total interval of 22,000-24,000EFH. This is equal to 7,300-8,000EFC. The first shop visit will be $1.9-2.0 million, and the overhaul $2.5-2.8 million. The total cost of $4.4-4.8 million for the two visits amortised over the interval will be about $200 per EFH *(see table, this page)*.

Replacement of LLPs in the non-RTC-modified engines fits well with the typical intervals of 3,300-4,000EFC, and the interval of the second shop visit, the overhaul with a higher level of disassembly, about once every 7,500-8,000EFC. This would allow the small number of LLPs lifed at 15,000EFC to be replaced at every fourth shop visit after full utilisation of their lives. The majority of parts would be replaced every sixth shop visit, again at or near to their full life of 20,000EFC. The small number of parts with lives of 30,000EFC would be replaced every eighth shop visit. Overall, this would result in a reserve of $200 per EFC.

The total reserve for shop visit maintenance, unscheduled shop visits and LLPs for the non-RTC-modified PW2000 engines at the EFC time of 3.0EFH will therefore be $292-295 per EFH *(see table, this page)*.

The RTC-modified engines will follow the same type of removal and shop pattern, but with longer intervals. In the case of the PW2037 this could be removed at an average of 16,000EFH. This is equal to about 5,300EFC. If the engines are operated at 3.0EFH per EFC, then the intervals will be limited to 15,000EFH and 5,000EFC because of LLP life limits.

The cost for the two successive shop visits will be $5.0-5.2 million, and reserves will therefore be $167-173 per EFH.

LLPs in this engine will have to be managed differently. Parts with lives of 15,000EFH will either have to be replaced at the second shop visit, or the total interval of the third shop visit will be limited to 15,000EFC. Parts with lives of 20,000EFC will have to be replaced at the fourth shop visit, and parts with lives of 30,000EFC replaced every sixth shop visit. Again, LLP lives will be almost or completely utilised, and reserves will be $200 per EFC.

The total reserve for shop visit maintenance, unscheduled shop visits and LLPs for the RTC-modified PW2037 at the EFC time of 3.0EFH will therefore be $259-268 per EFH *(see table, this page)*.

The higher-rated PW2040 engines will be removed at an average of 14,000EFH, at this ratio of 3.0EFH, and equal to 4,700EFC. The reserve for these engines will therefore be $178-189 per EFH *(see table, this page)*.

The three groups of LLPs with lives of 15,000EFC, 20,000EFC and 30,000EFC will still be replaced at the third, fourth and sixth shop visits, but lives will not be fully utilised because of the shorter average removal interval of about 4,700EFC. These replacement intervals will be about 14,000EFC, 19,000EFC and 28,000EFC. Reserves will be $189 per EFC.

The total reserve for shop visit maintenance, unscheduled shop visits and LLPs for the RTC-modified PW2040 at the EFC time of 3.0EFH will therefore be $259-268 per EFH *(see table, this page)*.

Summary

The total reserves for the main engine types are summarised *(see table, this page)*. While the RB211-535E4 clearly has longer removal intervals, its higher shop visit costs offset this advantage in the case of some PW2000 variants. The RB211-535E4's reserves are $233-242 per EFH, and these are lower than those for the two main groups of the PW2000.

The non-RTC-modified PW2000s have the problem of relatively short intervals, which result in total reserves of $260 per EFH.

The RTC-modified PW2037 gains from longer intervals, and despite the resultant slightly high shop visit costs, has reserves of $227-233 per EFH. The higher-rated RTC-modified PW2040 has shorter intervals and does not achieve the same degree of LLP life utilisation. Reserves are $241-252 per EFH. AC