The PW4000-94 engine has proven itself to be highly durable and has few causes for shop visit removals. Apart from short-cycle operations, the PW4000-94 regularly achieves 15,000EFH between scheduled removals, has long life LLPs and low maintenance reserves as a result.

PW4000-94 on-wing durability makes for economic reserves

There are about 1,550 PW4000-94-in (PW4000-94) fan engines installed on about 550 widebody aircraft. These are divided between six basic widebody aircraft types. The PW4000-94 achieves long on-wing times for most of these types and stable maintenance costs per engine flight hour (EFH). An analysis of how the PW4000-94 is managed in operation and its costs per EFH is undertaken here.

PW4000-94 in service

The PW4000-94 has five thrust ratings of 52,000lbs (52Klbs), 56Klbs, 58Klbs, 60Klbs and 62Klbs. The engine has the same configuration, including the 94-in wide fan, but rated at five different thrust ratings for each application.

Nomenclature for the PW4000 is based on the second digit, indicating to which airframe manufacturer the application applies. Digit 0 is for Boeing, 1 for Airbus and 4 for McDonnell Douglas (MDC) aircraft. The last two digits denote the number of thousands of pounds of its thrust rating. The PW4152, therefore, is rated at 52Klbs, and is on an Airbus.

The application and number of aircraft in service using PW4000s are:

Engine	Application	No.
PW4152	A310-300	45
PW4052	767-200ER	3
PW4156	A310-300	11
PW4056	747-400	184
PW4158	A300-600R	90
PW4060	767-300ER	140
PW4460	MD-11	52
PW 4062	767-300ER	4
PW4462	MD-11	25

The PW4000-94 can broadly be divided into two groups on the basis of its style of operation. The majority of engines are operated on long average flight cycle (FC) times. That is, an average of five hours of more. These long cycles reduce engine wear and so increase on-wing life. These are operated on the 767, 747-400 and the MD-11.

The second smaller are engines operated on the A300-600 and A310 on shorter average FC times.

The PW4000 has two basic configurations. Phase III was introduced because of higher than expected fuel burn. The modification improves fuel burn performance and on-wing times.

"The physical changes to the engine are new fan blades, new design high pressure compressor (HPC) casing, improved high pressure turbine (HPT) airfoils and seals and upgraded low pressure turbine (LPT) materials," explains Lars Edström, PW4000 engineer at Volvo Aero Engine Services (VAES). "The objective of Phase III was to improve fuel burn by 1.8% on the 747 and by 2.8% on Airbus and MDC aircraft. Phase III included a wider nacelle for Airbus and MDC engines".

Engine management

The PW4000-94 is simple engine to manage in terms of scheduling shop visits. The most common cause of scheduled removals is the erosion of exhaust gas temperature (EGT) margin. This is not the case with the PW4000.

"EGT margin erosion is not really a problem on the PW4000-94," says Edstrom. "Engines tend to be removed for shop visits because of other reasons. It did have a lot of other teething problems to begin with and most have been solved. One remaining difficulty is a surge problem in the HPC, especially with high rated variants. It also tends to occur with engines that have accumulated a high on-wing time and can lead to a compressor stall".

EGT margins vary between Phase III modified and non-modified powerplants. "The Phase III engines have brush seals, while the non-modified ones have knife-edge seals. The brush seals retain better performance. Phase III engines therefore have better EGT margins," says Stephan Leunig, product manager PW4000**,** at SR Technics. "For example, the Phase III MD-11 engines have an EGT margin of about 40 degrees centigrade at 60Klbs and 29 degrees at 62Klbs, while non-modified engines at 60Klbs thrust have a margin in the region of 26 degrees, 14 less than Phase III ones".

Although EGT margin erosion is not yet a removal driver for the PW4000, Leunig says the rate of erosion is 8–12 degrees per 1,000 engine flight cycles (EFC) depending on operational severity. "A 30 degree margin would then give an engine a 3,000–4,000EFC on-wing life. Engines operating average FC times of four EFH will then be able to achieve on-wing times of 12,000–14,000EFH," says Leunig. This increases to 15,000EFH for most other engines.

Airlines operating the PW4056 on the 747-400 often have average cycles of 10 flight hours. LLP replacement is avoided, since they will only come due for replacement after about 35-40 years.

Removal intervals

Leunig explains that the scheduled on-wing EFH times or removal intervals is predictable relative to EFH : EFC ratio. "EFH on-wing increases with longer average EFC times. The rate of increase in removal interval reduces and time on-wing levels once average EFC time has gone beyond about five or six flight hours," explains Leunig. "The time on-wing also depends on engine de-rate and thrust rating. At zero de-rate, a EFC of 5.0EFH results in an on-wing time of about 15,000EFH, while a 10% de-rate will increase this to over 16,000EFH. This compares to about 10,000EFH for an engine operating a 3.0EFH cycle. Engines in both cases are achieving about 3,000EFC on-wing. Very long missions, such as trans-Pacific 747-400 operations with average EFC times exceeding 10FH, still achieve average on-wing times in the region of 18,000EFH, or about 2,000EFC. This levelling of on-wing EFH times is explained by the reduced impact on the hot section of the high stress take-off power cycle on long-range flights".

Airlines operating in a hot environment have to limit thrust. On-wing times are less because EGT margin is smaller to begin with. The main removal drivers are degradation to 1st (T1) and 2nd (T2) stage HPT blades and HPC stability and stall problems. "SAS regularly achieves 16,000–20,000EFH times for 767 engines that have been overhauled," says Edstrom. "The engines have normally been removed after about 16,000EFH because of the risk of HPC surge and T1 distress. The HPT has the capability to last 20,000EFH plus, while the LPT has 30,000EFH plus capacity".

Edstrom advises that operators can expect on-wing times of 2,500–3,500EFC. Many 767 fleets operate average 6.0FH per FC and so 15,000–18,000EFH on-wing times. "A300s operate cycles of only 1.5FH, and so get about 5,500EFH between removals," says Edstrom.

Many engine shops attempt to achieve the optimum on-wing time, so that the point of removal coincides with the lowest cost per EFH. "The optimum time for the PW4000 is only a concern with the HPT,"explains Leunig. "Excessive on-wing times leads to a high scrap rate of blades, which increases cost per EFH. We target removals to replace HPT blades at the point of optimum cost, which is about 3,500–4,500EFC. The actual optimum point depends on the EFH : EFC ratio. In all other modules the cost per EFH generally reduces with on-wing time".

Leunig says that the PW4460 operating a 5.0EFH cycle will have an on-wing time of about 16,000EFH. The same engine on the 767 operating a 3.0EFH will get about 10,000EFH, while 16,000EFH will be normal for a high EFC of 6.0EFH on the same aircraft.

Phase I engines (unmodified) tend to to achieve shorter times because they are hotter in the turbine area. "The Phase III kit makes the engine cooler and is installed during a shop visit," says Dave Coulson, engine manager at Kellstrom. "The conversion kit can probably be acquired for about $900,000 and provides fuel burn and maintenance benefits. On-wing times are longer and there is a lower part scrap rate". The majority of PW4000-94s are Phase III modified.

Delta Airlines operates 70 PW4060s in its 767-300 fleet and another 45 PW4460s on its MD-11 aircraft. Most engines are Phase III modified. "The PW4060s operate an average EFC of 6.35EFH and the PW4460s, 8.24EFH," says Steve Rush, PW4000 workscope engineer at Delta. The airline achieves impressive on-wing times with both engines, the PW4060 18,000–20,000EFH and the PW4460 slightly longer with 18,000–21,000EFH because of the longer average cycle time.

As with VAES and SR Technics, Rush explains that EGT margin erosion is not the main removal driver here. "The main cause is HPC stability, as well as the need to refurbish and restore stability to the N2 spool".

Several carriers, including Singapore Airlines, United, Northwest and Korean Air, operate PW4000-powered 747-400s. Many operations, particularly those of Northwest and United, operate trans-Pacific networks and so fly average cycles up to 10.0EFH.

United operates more than 250 PW4000s on its 747-400s and 767s. The 747's PW4056 engines are operated mainly across the Pacific and have EFC times of 7.4FH. Its PW4060s are used on the 767-300s, which operate the trans-Atlantic network and have EFC times of 4.9FH. Most of United's experience is with Phase I engines. New engines have first on-wing times of 15,0000–25,000EFH, while previously overhauled powerplants get 14,000–20,000EFH. The higher thrust engines have on-wing times in the lower ranges. United also highlights HPC stability problems as the main removal cause, with hardly any being removed for EGT margin erosion.

Northwest, which also has PW4056s for its 747-400s, operates average cycles of 8.2EFH and gets about 18,100EFH between removals. This is expected to rise once hardware has been modified.

To summarise, engines operating short flights on the A300-600 will achieve in the region of 5,500EFH between removals. Most other aircraft types operate longer average cycles. The A310-300 and some 767 operations have EFCs in the region of 3.0–4.0EFH and get 10,000–12,000EFH on-wing, or about 3,300EFC.

On-wing times of 14,000–16,000EFH can be expected for aircraft operating cycles of 5.0EFH. Most aircraft have average EFCs of 5.0–8.0EFH. On-wing times for engines operating 6.0EFH gradually rise to 16,000–20,000EFH for average cycles of 7.0–10.0EFH.

Scheduled shop visit intervals of 15,000-17,000 flight hours and LLP replacement intervals of 75,000-100,000 flight hours means engines on the 767-300 operating 5-7 flight hour cycles will have reserves in the range of $131-154 per FH.

Unscheduled removals

Besides scheduled removals for |major causes, operators will experience problems caused by small items. These require repairs or small shop visits.

"We try to build engines during shop visits to a standard so that a minimum of unscheduled removals occur. That is, a poor build standard or low cost shop visit will incur limiting problems on-wing thereafter," says Leunig. "Generally cheaper fixes will force a higher number of unscheduled removals and repair while the rest of the engine has no problems. We aim for most of the removals and shop visits to be scheduled, using the on-condition concept."

Brush at Delta explains how lighter visits can occur before scheduled removals are due. "If we have to remove engines with less than 14,000EFH since the last shop visit it will get a workscope to address the cause of removal," says Rush. "If it occurs close to 14,000EFH then additional work can be done to improve its long-term stability and increase on-wing run. If the on-wing time is more than 14,000EFH a major shop visit is performed".

Unscheduled removals reduce overall average on-wing time of all removals.

Shop visit workscopes

Workscopes for scheduled removals are similar. The first removal is lighter than the second, but the difference in labour and material content is less than in other types.

The PW4000 conforms to this alternating pattern in all types of operation. "There is no such thing as a light workscope, such as a hot section inspection," explains Edstrom. "Work is usually required in the HPC, but not always necessary in the LPT. The LPT sometimes only requires a visual inspection. If it has Phase III modifications it can do two on-wing runs before requiring overhaul, otherwise it will only do one run. The HPT, however, will always only do one run before requiring overhaul work. This means every second shop visit is slightly heavier than the first, because of the need to do work on the LPT. This results in a fairly constant shop visit pattern."

As an engine ages the workscopes get larger because of higher scrap and repair rates. That is, the third shop visit will be heavier than the first and likewise the fourth heavier than the second.

"The first major shop visit basically requires overhaul on the HPC, overhaul of the HPT and a reduced workscope or inspection on the rest of the modules. The second visit will require overhaul on all major modules," says Leunig. The on-wing times between removals will also gradually reduce. They will also be longer than average after the heavier shop visit and shorter after the lighter workscope.

An engine achieving 16,000EFH between removals (the average on-wing interval between scheduled removals) will then achieve about 32,000EFH for every major shop visit workscope cycle. "Unscheduled removals are about 35-45% of all removals," says Leunig. The consequences of those are to reduce the average removal interval.

Shop visit inputs

The inputs for shop visits mainly constitute routine labour for disassembly, inspection and re-assembly, repair of parts and new material. Inputs are also similar for engines with different thrust ratings.

"New parts and material costs are low for this engine because replacement rates are low," claims Edstrom. "High-tech repairs are high. Manhour (MH) inputs for a lighter shop visit are in the region of 4,000–4,500, and rise to 5,000 for a heavier shop visit".

Labour inputs are similar for SR Technics, which has experience with MD-11 engines. "We use 4,200–5,000MH in the first and second shop visits," says Leunig. "About 2,200-2,500 are used for the routine portion and the remainder for repairs. The portion used for repair will increase as the engine ages, because new repairs are steadily being developed. The difference in inputs is usually between repair MH and materials".

Labour rates have tended to remain stable over the past decade with competition focusing on the maintenance market. A typical rate in western Europe or in the US is $50–60/MH. Labour inputs at each shop visit are therefore $200,000–$300,000. Materials incur $700,000–850,000, while repairs about a further $700,000. A lighter shop visit will therefore have a total cost of $1.7 million and a heavier visit, $2.0 million.

"The average on-wing intervals are increasing as engines age, because of improved modification status," says Leunig. "Although labour rates have remained stable, the price of spare parts is increasing. The combination of these two factors helps to stabilise the cost per EFH for a mature engine.

On the basis that most engines can on average achieve 30,000–32,000EFH every full shop visit cycle and will have two shop visits at a total cost of $3.7–4.0 million, cost per EFH for scheduled shop visits will be $116–125 per EFH. This excludes a consideration for unscheduled shop visits and life limited parts (LLPs).

Life limited parts

The PW4000's LLPs further simplify the engine's management. LLP lives are either 15,000EFC throughout the engine for powerplants rated at 58,000lbs or more, or 20,000EFC for those rated at 56,000lbs or less.

SUMMARY OF PW4000 SHOP VISITS AND SCHEDULED MAINTENANCE COSTS

Aircraft application	A300-600R	A310-300/ 767-200	MD-11/ 767-300	747-400
Engine	PW4158	PW4052/56	PW4060/62	PW4056
Average EFC (EFH)	1.5	3.0	5.0–7.0	8.0–10.0
Shop visit interval (EFH/EFC)	5,500/ 3,670	10,000/ 3,300	15,000–17,000/ 2,400–3,000	18,000–20,000/ 1,800–2,250
Shop visit cycle interval (EFH-2 removals)	11,000	20,000	30,000–34,000	36,000–40,000
1st shop visit cost $	1,700,00	1,700,000	1,700,000	1,700,000
2nd shop visit cost $	2,000,000	2,000,000	2,000,000	2,000,000
LLP lives (EFC)	15,000	20,000	15,000	20,000
LLP replacement interval-EFH	22,000	60,000	75,000–100,000	160,000–180,000
LLP costs $/EFH	105	38	23–31	13–14
Total costs $/EFH	440	223	131–154	117

The varying EFC times for different operations means the EFH intervals between LLP replacement varies with application.

The A300-600s operating FCs of 1.5FH will have LLPs of 15,000EFC in their PW4158s. Engine removal intervals of 5,500EFH/3,700EFC mean LLPs will be replaced every fourth shop visit or about every 22,000EFH.

A310s and 767s operating 3.0FH EFCs, which get about 10,000EFH/ 3,300EFCs between removals, will have LLPs of 20,000EFCs. LLP replacement will then occur every six shop visits, or about every 60,000EFH.

Higher thrust rated PW4060/62s, with LLPs lives of 15,000EFC, operated on the 767 and MD-11, typically operate EFCs of 5.0–7.0FH. Removal intervals are constantly in the 15,000EFH range. Shorter cycle, 5.0EFH engines will have LLPs replaced every fifth shop visit and so every 75,000EFH. Longer cycles of 6.0EFH will get a longer LLP interval of 90,000EFH. This will rise to about 100,000EFH for engines on a 7.0EFH cycle time.

The longest cycles of 8.0–10.0EFH are normally operated by the 747-400 using PW40456s. With shop visit intervals of 18,000–20,000EFH, LLPs will only need to be replaced every nine or 10 shop visits. This is equal to 160,000–200,000EFH.

A full set of LLPs costs about $2.3 million, but is cheaper than those in the JT9D. The total EFH between LLP replacement will then determine cost per EFH.

PW4158s on the A300-600 will have LLP costs of about $105/EFH. PW4052/56s on the 767 and A310 will have a lower LLP rate of $38/EFH.

Engines with median EFC times, operating on the 767-300s and MD-11s, will have LLP costs of $23–31/EFH.

PW4056s operating the longest cycles will have LLP rates down to $14/EFH.

Maintenance costs

Although shop visit costs vary according to average EFC time, total cost for a two shop visit cycle is in the region of $3.7 million. As the engine ages this likely to rise to over $4.0 million. The reason is that more parts will require replacing and new parts will become more expensive.

When intervals, shop visit costs and LLP reserves are all considered, the cost per EFH for scheduled maintenance can be estimated *(see table, this page)*.

Engines on the A300-600 operating the shortest cycles will have rates as high as $440/EFH. This reduces as average EFC time increases. A310s and 767s operating longer cycles of 3.0FH will have rates in the region of $225/EFH.

The PW4000 comes into its own when cycles of 5.0FH or longer are flown. Longer on-wing times between removals means maintenance costs for scheduled visits as well as LLP reserves fall to the $130–155/EFH level for engines operating 5.0–7.0FH cycles.

Ultra long-range routes unsurprisingly have the lowest costs. The extremely long intervals between removals and long LLP replacement intervals (up to 40 years is theoretically possible for some 747-400 operators!) reduces costs down to the $117/EFH level. "Reserves for the PW4000 rarely need to be higher than $170/EFH," says Edstrom.

Unscheduled shop visits

The consequence of unscheduled removals is that repair workscopes are either required in addition to the scheduled shop visits, or scheduled visits have to be performed earlier than planned, raising the total cost per EFH.

"It is difficult to say what an unscheduled shop visit cost is," says Leunig. "It varies widely from $0.3 million to $1.2 million, depending on the removal cause. If the reason is serious then a major shop visit workscope might be required, although the pre-defined running time has not been achieved".

Rush explains that Delta's system for dealing with this is to use the 14,000EFH point as a pivot for deciding how to manage the engine. Anything earlier than 14,000EFH and a repair will be made. At or above 14,000EFH a shop visit workscope or overhaul will be performed.

Early workscopes would then be light and would have a cost in the lower range, while later removals would have heavier shop visits and higher costs.

The unpredictability of unscheduled visits makes it hard to estimate their effect on overall engine maintenance reserves. Considering that about one-third of all shop visits are unscheduled, a light visit will be performed on each engine every scheduled shop visit cycle of two removals; occurring every 32,000EFH. The cost of $0.3–0.7 million over 32,000EFH will then add $9–22/EFH.

Heavier unscheduled visits would replace a scheduled visit and the cost of $0.7–1.2 million would be combined with the other scheduled shop visit. The engine would then complete its shop visit cycle in less than 32,000EFH and so have higher maintenance reserves than those budgeted for scheduled removals. AC