PW4000-100/-112 maintenance analysis & budget

The variants of the PW4000-100 and -112 have overcome initial durability problems and have predictable removal intervals.

The PW4000-100 and PW4000-112 power 156 A330s and 165 777s. These fleets have relatively few operators. In the case of the A330, there are 12 major fleets powered by PW4000-100 engines. There are only nine major 777 operators that are equipped with PW4000-112 engines. The maintenance costs of these engines depend on how they are operated, the intervals achieved between removals for shop visits, the workscopes of subsequent engine shop visits, and the management of life limited parts (LLPs).

PW4000-100 in service

The A330 fleet is divided into A330-200s and -300s. The A330-200 fleet is operated in greater numbers, and by more airlines. All aircraft are equipped with the PW4168A, and large fleets are operated by Delta Airlines, Kingfisher Airlines, Air Berlin, Swiss Airlines, TAM, TAP Air Portugal and Vietnam Airlines. There are also several operators with smaller fleets of two or three aircraft.

Most of these fleets are operated on average flight cycle (FC) times of more than 5.0 flight hours (FH). In many cases, the aircraft are long-haul workhorses. Delta, LTU, Swiss, TAM and TAP all use the aircraft for transatlantic services.

Airlines with the longest average FC times are Kingfisher (8.60FH), Air Berlin (7.7FH), TAM (7.24FH) and TAP (7.51FH).

Malaysia Airlines and Vietnam Airlines both use the A330-200 on shorter average FC times, for regional services in the Asia Pacific at average FC times of 3.50-3.70FH.

The A330-300 fleet is mainly powered by PW4168 and PW4168A engines. Only a small number of aircraft, operated by Thai International, have PW4164 engines.

The largest A330-300 fleets with PW4168 engines are operated by Korean Air, Air Berlin and Malaysia Airlines.

The later PW4168A powers more aircraft, operated by Asiana Airlines, Delta, Korean Air, and USAirways.

Operation of A330-300s is more varied than the longer-range A330-200. Asia Pacific operators use the aircraft for high-density regional services. Asiana, Korean Air, Malaysia Airlines and Thai International all have average FC times of 2.80-3.25FH.

Air Caraibes, Delta and USAirways use the aircraft for long-haul operations at FC times of 7.30-7.80FH.

PW4000-112 in service

Like the A330, the PW4000-powered 777 fleet should be considered in terms of -200s and -300s. The -200 fleet is dominant, however, with only three operators of -300s.

The 777-200 can be divided into three main groups: aircraft powered with PW4074/77 engines; aircraft powered with PW4084 engines; and aircraft powered with PW4090 engines.

The PW4074/77 power the lighter models of the 777-200 that are operated by All Nippon Airways, Japan Airlines (JAL) and Air China. ANA and JAL operate their aircraft on Japanese domestic services, so they have average FC times of only 1.10-1.45FH. Air China uses the aircraft for similar purposes on trunk routes in China, with a longer average FC time of 2.30FH. United, which was the launch customer for the 777, also has a large fleet of PW4077-powered aircraft, which are used on US domestic and some transatlantic services. Average FC time is therefore 6.42FH.

The PW4084 powers higher gross weight 777-200s and -200ERs. These are operated by United and Vietnam Airlines, both of which use the aircraft for long-haul operations, and so have FC times of 4-5FH.

The PW4090 fleet is the largest, with nine different carriers, including Air China, Air India, ANA, Asiana, Egyptair, Korean Air and United. With the exception of Air China's, these fleets are all 777-200ERs with maximum take-off weights (MTOWs)of 625,000-648,000lbs. The aircraft are used for long-haul operations with FC times of 5.0-8.5FH.

The 777-300 fleet is operated by ANA, JAL and Korean Air. ANA and JAL use the aircraft for high-density, domestic operations and achieve the same average FC times as with their PW4074-powered 777-200s. Korean Air uses the aircraft for regional operations with a range of route lengths, so the average FC time is consequently 3.55FH.

Engine management

Optimum maintenance costs will be achieved with the best engine management. A key factor will be maximising the use of LLP lives. All Pratt & Whitney (PW) engines make this part of engine management relatively easy, because their LLPs have uniform lives. Maximum utilisation of LLP lives will be achieved if engine removal coincides closely with a planned removal interval. Moreover, engine maintenance costs will be minimised over the long term if the shop visit that occurs when LLPs expire is planned to be a heavy one. If LLPs expire when the next planned shop visit is only likely to be a performance restoration, rather than a full engine disassembly, the shop visit workscope will be unnecessarily heavy and expensive.

The PW4000-100 is relatively simple even though there are two main thrust variants of the PW4164 and PW4168, and both have LLP shipsets that have uniform lives of 15,000EFC *(see table, page 14)*. The shipset of LLPs comprises 25 parts and has a 2010 list price of $5.97 million. If fully amortised over their full life limit, these LLPs would have a reserve of $398 per EFC.

The PW4000-112 has a shipset of 33 LLPs, and is divided between the lower-rated PW4074 and PW4077 engines, and the higher-rated PW4084, PW4090 and PW4098 engines. LLPs in the lower-rated PW4074 and PW4077 engines have uniform lives of 20,000EFC, while LLPs in the three higher-rated engines have lives of 15,000EFC. The complete shipset of parts has a 2010 list price of $9.26 million. If the full life limit is utilised, the PW4074/77's LLP reserve would be $465 per EFC, while the PW4084/90/98's LLP reserve would be $617 per EFC.

It should be noted that the list price of LLPs increases each year by 6-8%, so reserves should be adjusted accordingly. This is not necessary for airlines whose engines are maintained under fleet hour agreements.

PW4000-100 on-wing

When removal intervals are most closely related to the engine's initial exhaust gas temperature (EGT) margin and EGT margin erosion rates, the intervals tend to be in terms of EFC for

PW4000-100 & -112 MODULE CAPABILITIES

Facility	Fan	Low Pressure Compressor	High Pressure Compressor	High Pressure Turbine	Low Pressure Turbine
Air Nippon Airways	M/R/O	S	M/R/O	M/R/O	S
Eagle Services Asia (-100 only, -112 planned)	M/R/O	M/R/O	M/R/O	M/R/O	M/R/O
GE Engine Services -Malaysia	M/R/O	M/R/O	M/R/O	M/R/O	M/R/O
P&W Cheshire Engine Center	M/R/O	M/R/O	M/R/O	M/R/O	M/R/O
SR Technics (-100 only)	M/R/O	M/R/O	M/R/O	M/R/O	M/R/O

In-house Shop visit levels
M - Minimum
R - Refurbishment
O - Overhaul
S - Module sent away

engines operated at short average EFCs, and in terms of EFH intervals when operated on medium or long average EFCs. The removal intervals of the PW4168A, powering the A330-200, will therefore be determined in EFH, since all aircraft are operated on medium and long flight cycles.

The EGT margin of new PW4164 engines was about 63 degrees centigrade. Unsurprisingly, the EGT margin of the higher rated PW4168 was 50 degrees centigrade when new. The new PW4170 will have a high thrust rating of 70,000lbs, and a higher EGT margin of 55 degrees centigrade. The PW4168A-1D is a de-rated PW4170, and will have an EGT margin of 65 degrees centigrade.

The A330-200 has been in service since 1998, and the oldest aircraft have accumulated 40,000-50,000FH. The engines powering these aircraft are therefore mature, having passed through their first and second shop visits. Like all other PW engines, the PW4164 and PW4168 follow an alternating shop visit pattern of performance restoration followed by a full overhaul. Only a minority of aircraft have accumulated more than 15,000EFC, so the LLPs on their engines will have been replaced.

Some operators, such as Swiss which had early engines, had their first removal intervals limited by an airworthiness directive (AD) to 10,000EFH and 1,770EFC. TAP also operates some of the older A330-200s, whose engines had early problems with the carbon seals in the front bearing compartment, degradation of the high pressure turbine (HPT) in the case of second stage vanes, and high oil consumption. Some of these issues have been dealt with, and later-built engines have experienced longer first removal intervals.

Delta Airlines, Air Berlin and TAM all have relatively young fleets, and all operate on EFC times of 7.0EFH. These three carriers have all had first removal intervals of 18,000-24,000EFH. At an average EFC time of 6.0-7.0EFC, this is equal to 3,000-3,500EFC.

Engines operated on shorter EFC times of 3.0EFH have demonstrated shorter first removal intervals of 12,000-15,000EFH, equal to 4,000-5,000EFC.

First shop-visit workscopes have tended to be performance restorations or core engine restorations, with the HPT and combustor modules worked on, and in some cases the high pressure compressor (HPC) also worked on if the first removal interval was long.

Restored EGT margin is expected to be 19-25 degrees centigrade after the first shop visit. Average EGT margin erosion rates are 1.5-2.0 degrees per 1,000EFC, so the engine could theoretically remain on-wing for a further 12,000EFC.

The engine also experiences other degradation that shortens the potential removal interval.

Second removal intervals for most carriers operating at EFC times of 5.0-7.5EFH, have been 15,000-18,000EFH in most cases; equal to 2,000-2,500EFC. When operating at 3.0EFH per EFC, second removal intervals are likely to be 10,000-12,000EFH and 3,500-4,000EFC.

At this stage engines operated on average EFC times of 3.0EFH will have accumulated a total time of 7,500-9,000EFC; equal to 22,000-27,000EFH. Engines that have been operated on longer EFC times of 6.0-7.5EFH will have accumulated 33,000-42,000EFH and 5,000-6,000EFC.

After the second removal, engines are likely to have a heavy workscope or full overhaul, which will involve all core engine modules and the fan.

Following the second shop visit and an overhaul, the engine will be in a mature maintenance condition. Intervals will therefore be shorter than the first and second removal intervals, at 10,000EFH and 3,300EFC for engines operated at an EFC time of 3.0EFH, and 15,000EFH and 1,800-2,500EFC for engines operated at an EFC time of 6.0-8.0EFH. Even mature engines are expected to follow an alternating shop visit pattern of performance restorations and full overhauls.

The total accumulated EFC at the second removal means that most engines operated on EFC times of 3.0EFH can expect to have another two shop visits before reaching LLP expiry at a total time of 15,000EFC. This conveniently occurs when the engine reaches its second overhaul. In fact, LLP expiry is likely to force the removal for the second heavy shop visit.

Engines operated on EFC times of 6.0-7.5EFH are likely to reach LLP expiry at the fifth or sixth shop visit, again with LLP expiry forcing engine removal. Depending on the total time accumulated at the second shop visit, average removal intervals for these engines would be optimal at 2,300-2,500EFC; equal to 14,000-17,500EFH.

PW4000-112 on-wing

The oldest PW4000-112s in service power some of the first 777s to enter operation, which started operations in 1995. These are PW4074s and PW4077s operated by ANA, JAL and United. The ANA and JAL aircraft operate at high frequencies, having accumulated up to 22,000EFC. The United aircraft are operated on transatlantic services, and have therefore accumulated up to 58,000EFH.

The youngest aircraft with PW4000-112 engines are PW4090s that power Asiana's 777-200ERs.

In most cases, the PW4000-112s follow the usual alternating shop visit pattern of a performance restoration followed by a heavy shop visit or full overhaul. Managing engines around LLP lives and expiry means trying to time LLP expiry with the second shop visit in the cycle. In the case of PW4074/77 engines operated on short cycle times that have LLPs with lives of 20,000EFC and typical removal intervals of 9,000-10,500EFC, LLP expiry and replacement will take place at the second shop visit. Annual rates of utilisation are 1,700-1,900EFC, so LLPs will be replaced after 10-12 years of operation.

EHT margins for most -112 series variants are lower than they were for new -100 series engines. The PW4074 had a new EGT margin of 55 degrees centigrade, while the PW4090 has a new engine EGT margin of 50 degrees centigrade. The de-rated PW4077D and PW4084D variants have higher EGT margins of about 75 degrees centigrade.

Removal intervals are 2,000EFC for higher-rated engines with LLP lives of 15,000EFC, and that operate at longer EFC times of 6.0-7.5EFH. This means LLPs will be replaced between the sixth and eighth shop visit in most cases.

The initial EGT margin for the

The highest rated PW4090 engines powering high gross weight 777-200s on long-haul missions have mature removal intervals of 14,000-17,000EFH. LLP replacement will only come due after about 20 years of operation.

PW4000-112 was 45 degrees centigrade, as recorded by Egyptair Maintenance & Engineering for its PW4090s powering its five 777-200ERs.

After an initial period of relatively high rates of EGT margin erosion, the stabilised rate of EGT margin deterioration averages 3.8 degrees centigrade per 1,000EFH in the case of Egyptair, although these aircraft are operated in a hot and sandy environment. Taking into account the initial period after a shop visit or introduction into service, the overall average rate is 4.5-5.0 degrees centigrade per 1,000EFH.

Typical first removal intervals vary with average EFC length and engine thrust. PW4074/77 engines operating at 1.2-2.0EFH per EFC will have first removal intervals of 15,000EFH; equal to 7,500-12,500EFC. Removals for these engines will have been forced mainly by EGT margin erosion, but the early-build PW4000-112s had to deal with several issues of HPT distress and problems with the early HPT blades.

Islam Alnady, powerplant and performance engineer at Egyptair Maintenance & Engineering, explains that HPT distress of burn-through, sulphidation, and cracks caused early removals prior to full EGT margin erosion. After incorporating new HPT blades, HPT distress and EGT margin erosion coincided. Several replacement blade numbers have been released since the engine entered service.

Higher-rated PW4084/90/98 engines operating on medium flight cycle times will have slightly longer first removal intervals, although the operating environment influences this greatly. Egyptair's PW4090 engines operate at average EFC times of 4.70EFH in a hot and sandy environment, and have experienced average EGT margin erosion rates of 4.5 degrees per 1,000EFH. Its first removal intervals were at 10,000EFH and 2,200EFC, due mainly to HPT distress. These have since increased following use of improved HPT blades. "After removal the engines had a first shop-visit workscope of an HPT overhaul and performance restoration. After this length of removal interval the engine will either require work on just the HPT, or the HPT and LPC," explains Alnady.

Engines operating on longer average EFC times and in more moderate climates have generally achieved longer first removal intervals. Engines operating at 3.0EFH per EFC will get intervals of 16,000-18,000EFH, while those on longer EFC times of 6.0-7.5EFH will have first removal intervals of 17,000-20,000EFH; equal to 2,300-3,300EFC. In the best cases, engines can get intervals of up to 24,000EFH.

First shop-visit workscopes for engines that have achieved longer average first removal intervals will involve all high pressure core modules.

Restored EGT margin following the first shop visit will be 30-35 degrees centigrade, with shorter second removal intervals as a result.

PW4074/77 engines will have second and subsequent removal intervals of 10,000-12,500EFH; equal to 5,000-10,000EFC. At this stage engines will have accumulated 12,500-20,000EFC, with the 20,000EFC total time forcing a removal due to LLP expiry.

Second removal intervals for higher-rated engines operating at longer EFC times will be 14,000-17,000EFH; equal to 1,900-2,800EFC. Engines will thus have a total time of 30,000-37,000EFH and 4,200-6,100EFC at this stage.

Following this total time on-wing, most engines would need a full overhaul for all modules to be disassembled. Mature intervals thereafter would be similar to second removal intervals. LLP life limits would be reached after another four or five removals and shop visits. This would be equal to more than 20 years' operation for higher-rated engines accumulating 500-700EFC per year.

Egyptair's experience has been a second removal interval of 9,000EFH and 2,000EFC. "The engine again had to be removed due to HPT distress and EGT margin loss," says Alnady. "The shop visit that followed was an overhaul of the HPT and LPC, but not for the whole engine. A full overhaul for the engine is not required until the third shop visit. At this stage total time will be about 28,000EFH and 6,000EFC."

Maintenance reserves

PW4000-100

Maintenance reserves should be considered for the PW4168 operating at EFC times of 3.0EFH and 6.0-7.0EFH, for the PW4074/77 operating at 1.5EFH per EFC, and for the PW4084/90/98 operating at 6.0-8.0EFH.

The PW4168 operating at 3.0EFH per EFC will have its first removal and shop visit after an interval of 13,500EFH and 4,500EFC. This engine operating at this EFH:EFC ratio may have a shop-visit pattern where the full overhaul does not occur until the third shop visit. In this case the first and second shop visits would be relatively light. The first shop visit would certainly involve work on the combustor and HPT modules. The typical cost would be $2.5 million.

Where the following shop visit would be a full overhaul, the cost will be about $4.0 million. At this stage the engine will have accumulated a total time of 24,500EFH and 8,200EFC. Reserves for these two shop visits would be $265 per EFH *(see table, page 14)*.

In addition, the reserve for LLPs will be determined by the mature interval of

PW4000-100 & PW4000-112 ENGINE MAINTENANCE RESERVES

Engine type	PW4168	PW4168
EFH:EFC ratio	3.0	6.0-7.0
First removal interval-FH/FC	13,500/4,500	18,000-21,000/2,500-3,000
Shop visit cost-$	2,500,000	2,700,000
Second removal interval-FH/FC	11,000/3,700	15,000-18,000/2,100-3,000
Shop visit cost-$	4,000,000	4,500,000
Shop visit reserve-$/EFH	265	190-218
LLP reserve-$/EFC	412	406-430
Total reserve-$/EFH	**403**	**240-285**

Engine type	PW4074/77	PW4090/98
EFH:EFC ratio	1.5	6.0-8.0
First removal interval-FH/FC	15,000/10,000	17,000-20,000/2,300-3,300
Shop visit cost-$	4.0	4.5
Second removal interval-FH/FC	12,000/8,000	14,000-17,000/1,900-2,800
Shop visit cost-$	5.0	5.5-6.0
Shop visit reserve-$/EFH	333	265-300
LLP reserve-$/EFC	514	661
Total reserve-$/EFH	**675**	**350-395**

following removals. These would be in the region of 3,300EFC, so LLP expiry would be most likely to coincide with the fourth removal. This would be convenient, since it would be equal to a total time of 14,500EFC. Reserves for a full shipset of LLPs with a list price of $5.97 million would therefore be $412 per EFC *(see table, this page)*.

The two reserves together at this EFC time of 3.0EFH are equal to $403 per EFH *(see table, this page)*. Reserves will rise after this, however, due to mature removal intervals reducing to 10,000EFH and shop visit costs increasing.

The PW4168 operating at longer cycle times of 6.0-7.5EFH will have higher shop-visit costs, but lower overall reserves because of longer removal intervals.

First removals at 18,000-21,000EFH will be followed by the first shop visit, involving a performance restoration and high workscope on the core engine, incurring a cost of $2.7 million.

The second removal will be after a further 15,000-18,000EFH, and the following workscope will be a full overhaul. The cost for this second shop visit will be $4.5 million. Total time at this stage will be 33,000-39,000EFH and 4,900-5,500EFC, so reserves for the two shop visits will be $190-215 per EFH *(see table, this page)*.

LLPs have to be considered together with shop visit costs. Mature intervals after the second shop visit are likely to be 1,800-2,300EFC, so LLPs are likely to be replaced after a further four or five removals at a total time of 14,000-14,800EFC, giving LLP reserves of $406-430 per EFC. When combined with reserves for the first two shop visits, total reserves will be $240-285 per EFH *(see table, this page)*.

These reserves will also rise after the second shop visit because mature removal intervals are shorter than first and second removal intervals.

PW4000-112

The PW4074/77 operating at 1.5-2.0EFH will have short intervals. Moreover, the total accumulated time at the second removal and shop visit will be 18,000EFC, which will force a complete overhaul due to the need to replace all LLPs. The EFH:EFC ratio of 1.5 will also mean the engine experiences a high rate of wear and deterioration. Shop-visit costs for the first and second shop visits will be $4.0 million and $5.0 million. The reserve for these two amortised over the total time of 27,000EFH will be about $333 per EFH *(see table, this page)*.

LLP reserves will be $514 per EFC, due to the parts having to be replaced after 18,000EFC *(see table, this page)*. Total reserves will be $675 per EFH.

Maintenance reserves will increase thereafter, due to mature removal intervals of 8,000EFC and 12,000EFH. LLPs will have to be replaced after 16,000EFC, and shop visit costs will also increase.

The PW4084/90/98 operating at 7.0-8.0EFH per EFC will have longer intervals as described, with total accumulated time at the second removal reaching 33,000-39,000EFH and 4,600-4,900EFC. The second shop visit will clearly be a full overhaul given the total time accumulated. First shop visits for these engines have been $4.2-4.5 million, while full overhauls at the second shop visit have been $5.5-6.0 million, with the cost of the two workscopes totalling $9.5-10.5 million. Reserves for these two shop visits have therefore been $265-300 per EFH *(see table, this page)*.

Reserves for LLPs must be combined. Total time of 4,600-5,000EFC at the second removal, and mature intervals of 2,000EFC mean LLPs will be replaced after a further four or five shop visits and a total time of 14,000EFC. LLP reserves will thus be $661 per EFC, taking total reserves for the first two shop visits to 350-$395 per EFH *(see table, this page)*.

As with all other cases, reserves will rise after the second shop visit due to shorter mature removal intervals and higher shop-visit costs.

In all cases, further reserves should also be added for two reasons: these removal intervals are planned or scheduled, and average intervals can be reduced by the effect of unscheduled removals; and a further $20 per EFH should be added for quick engine change (QEC) kit and accessory components.

A major cost consideration is LLPs, which clearly make up a high percentage of total reserves. Their list prices increase each year by 6-8%. While airlines operating short and medium cycles will have to keep a reserve to replace LLPs, aircraft operated purely on long-haul services averaging 6.0-8.FH per FC will not need new LLPs until they are 18-20 years old, so they may be able to avoid LLP replacement and the associated cost. This will be irrelevant, however, if engines are maintained on a fleet-hour agreement with the original manufacturer. AC