PW4000-94 maintenance analysis & budget

The PW4000-94 has overcome its earlier performance and HPC stall & surge problems and is now delivering stable maintenance costs.

There are 2,160 Pratt & Whitney (PW) PW4000-94 engines in operation on about 710 aircraft, comprising 747-400s, 767s, MD-11s, A300-600s and A310-300s *(see PW4000-94 specifications, page 10)*. Their operations vary from flight cycle (FC) times of 1.0 flight hours (FH) to an average of 9.0FH. The PW4000-94 engine series has five thrust ratings varying from 52,000lbs to 62,000lbs *(see PW4000-94 specifications, page 10)*.

PW4000-94 in service

The lowest-rated variants are the PW4052 for the 767-200ER and the PW4152 for the A310-300. These engines generally power the lower gross weight versions of these aircraft, while the higher-rated PW4056 and PW4156 are more common and power a larger number of 767-200ERs and A310-300s.

These aircraft are operated mainly on medium- and long-haul routes. FC times are 4.0-8.0FH for the 767-200ER, so the PW4056 engines have engine flight cycle (EFC) times of 4.0-8.0 engine flight hours (EFH). The PW4156s on the A310-300 operate mainly medium-haul routes, with EFC times of 2.0-4.0EFH. There are 14 767-200ERs and 62 A310-300s in service with these lower-rated engines.

Examples of A310-300 operators are Air India, Pakistan International Airlines and TAROM. Operators of 767-200ERs include Air China, El Al, Aeromexico and Avianca.

The PW4056 rated at 56,000lbs is also used to power 220 747-400s. The largest operators include Air China, Air India, China Airlines, Korean Air, El Al, Northwest Airlines, Singapore Airlines and United Airlines. These aircraft operate the longest cycles of all PW4000-94-powered aircraft, averaging EFC times of 7.0-9.0EFH. The 747-400 is used by some airlines on ultra-long-haul sectors, however, and EFC times can reach 11.0-13.0EFH in many cases.

A smaller number of 747-400s are also powered by the PW4062 rated at 62,000lbs thrust. These are generally higher gross weight aircraft that are used on the longer sectors. There are, however, only two active aircraft in the fleet with PW4062 engines.

The higher-rated variants include the PW4158, which is rated at 58,000lbs and powers 150 A300-600Rs. These aircraft are used both as package freighters on short cycles of 1.0-2.0FH and in the passenger role on short- and medium-haul cycles of up to 3.0FH. Short-haul operators include FedEx, United Parcel Service (UPS) and Japan Airlines. Korean Air, Thai Airways and China Southern Airlines also use it on regional services.

The 767-300ER and MD-11 are powered by the highest rated variants: the PW4060/4460 and PW4062/4462 rated at 60,000lbs and 62,000lbs thrust. The PW4000-94 powers 190 767-300ERs, most of which are powered by the PW4060. The 767-300ER is used extensively on medium- and long-haul operations, and EFC times are mainly 4.0-9.0EFH.

One example of a 767-300ER operator is Delta Airlines, which has a fleet of 35 aircraft. These are used exclusively on its international services, which have an average FC time of 7.8FH.

There are 80 MD-11s in operation with PW4460/62 engines, and these operate similar EFC times to the PW4060/62s powering the 767-300ER.

The largest operators of PW4000-powered MD-11s include World Airways, VARIG, Martinair, China Cargo Airlines, FedEx and UPS.

The general trend, therefore, is that higher-rated engines are used on longer EFC times than the lower-rated engines. The exception is PW4158 engines powering some of the A300-600R fleet.

Maintenance factors

EFC time is a major factor that affects the rate of exhaust gas temperature (EGT) margin erosion, time on-wing between removals, and ultimately maintenance cost for most engine types. Time on-wing is also affected by the EGT margin measured at standard outside air temperature (OAT), and the available EGT margin at the actual OAT at take-off. Most PW4000 operators have found, however, that the PW4000-94 is rarely removed because of full erosion of EGT margin.

Major issues affecting on-wing

The PW4000-94 has been through two major modification programmes; the Phase III programme to improve fuel burn & EGT margin and the ring case modification to cure the problem of HPC surges. The PW4000-94 has rarely been removed for maintenance due EGT margin loss, and with these modifications in place is capable of planned removal intervals of up to 20,000EFH.

PW4000-94 SERIES THRUST RATINGS & APPLICATIONS

Engine variant	Thrust rating lbs	Flat rated temperature deg C	Application	Mature EGT margin deg C
PW4052	52,200	33	767-200/-200ER	40-50
PW4056	56,750	33	767-300/-300ER 747-400	35-40
PW4060	60,000	33	767-300ER/-400ER 747-400	25-35
PW4062	62,000	30	767-300ER, 747-400	25-35
PW4152	52,000	42	A310-300	40-50
PW4156	56,000	33	A300-600, A310-300	35-40
PW4158	58,000	30	A300-600R	35-40
PW4460	60,000	30	MD-11	25-35
PW4462	62,000	30	MD-11	25-35

VARIATION OF AVAILABLE EGT MARGIN WITH OAT FOR PW4000-94 SERIES ENGINES

PW4056
EGT margin variation, with 33 deg C corner point temperature

OAT deg C	10	15	20	25	30	33	35	40	45
Available EGT margin	99.4	85.4	71.4	57.4	43.4	35.0	29.4	15.4	1.4
OAT deg C	10	15	20	25	30	33	35		
Available EGT margin	78.4	64.4	50.4	36.4	22.4	8.4	0.0		

PW4060/62
EGT margin variation, with 30 deg C corner point temperature

OAT deg C	10	15	20	25	30	35	39
Available EGT margin	81	67	53	39	25	11	0
OAT deg C	10	15	20	25	30	32	
Available EGT margin	61	47	33	19	5	0	

removal intervals are the engine's modification status in relation to specific airworthiness directives (ADs), and the engine's build and modification standard.

The major AD affecting the PW4000's removal intervals is AD 2003-19-15. This relates to the ring case modification, which was issued to cure the engine's problems with stalls and surges in the high pressure compressor (HPC). "The PW4000 suffered from HPC surges and stalls over a 10-year period, and numerous fixes were provided in an attempt to cure the problem," says David Garrison, director of engine and component maintenance at Delta Tech Ops. "The frequency of engine surges increased as the engine deteriorated in operation, and so resulted in removals for shop visits. The problem was fixed by AD 2003-19-15."

A second issue affecting the PW4000 has been an inspection required for the spacer between the sixth and seventh HPC stages. A service bulletin (SB) issued to cure this problem involves the addition of a blade to the fifth stage.

A third issue with the PW4000-94 has been internal sulphidation of the second high pressure turbine (HPT) blades, which led to external cracking of the blades and, ultimately, to engine removals. This only relates to Phase III engines. The problem was overcome by the use of a different blade coating material.

All PW4000-94s are equipped with a full authority digital engine control (FADEC) unit. Most of the original engines from the production line have been upgraded with a Phase III performance improvement kit, which was first introduced in 1992 *(see PW4000-94 modification programmes, page 13)*, with the aim of: reducing noise; improving specific fuel consumption and performance retention; lowering EGT; and increasing time on-wing between removals. The first 1,100 engines produced from 1987 did not have this Phase III kit as standard, but 950 of these have since been modified. The last 1,000 engines built included the Phase III modification kit as standard on the production line *(see PW4000-94 specifications, page 10)*. There are now 1,950 PW4000-94s with the Phase III performance improvement kit, and 150-200 unmodified earlier-built engines.

EGT margin

Few PW4000-94s in operation are young enough to still be on their first removal interval. Most have had their first shop visit, and have reached maturity in maintenance terms. EGT margins of engines after a shop visit are not as high as new production ones. As described, the loss of EGT margin is not a main removal driver, however.

There are three different flat rating or corner point temperatures for the PW4000-94 family *(see first table, this page)*. These are relatively high at 30, 33 and 42 degrees centigrade. This is the OAT below which thrust is held constant. With thrust held constant, the EGT increases at a rate of 2.8 degrees centigrade per one degree rise in OAT up to this flat rate temperature. Thrust is then reduced to hold EGT constant for further increases in OAT that are higher than this corner point temperature. These OATs at which the EGT is flat-rated are relatively high for most operations.

There are three corner point temperatures for the PW4000-94 series. The lowest-rated PW4152 powering the A310-300 has a corner point temperature of 42 degrees *(see first table, this page)*.

The PW4050, PW4052, PW4056 and PW4060 for Boeing aircraft and the PW4156 powering the A310-300 have a flat rating temperature of 33 degrees.

The PW4158 powering the A300-600R, the PW4062 powering the 767-300ER and 747-400, and the two engines powering the MD-11 all have a corner point temperature of 30 degrees *(see first* *table, page 20)*.

While EGT is held constant at higher OATs, it is not at its maximum level or red line limit of 644 degrees centigrade for engines rated at 52,000lbs thrust, and 654 degrees centigrade for higher-rated engines. The EGT margin is measured at the flat rating temperature, and is the difference between the actual and red line EGT. The engine's EGT gradually increases as its hardware deteriorates with operation and use, and so EGT margin erodes.

Initial EGT margins for new Phase III standard engines are 60-70 degrees for engines rated at 52,000lbs and 56,000lbs thrust, 53-55 degrees for engines rated at 60,000lbs thrust, and about 45 degrees for engines rated at 62,000lbs thrust.

Mature EGT margins are highest for the lowest-rated variants. "The lower thrust variants, rated at 52,000lbs thrust, have EGT margins of 40-50 degrees centigrade following a shop visit," says Christian Nicca, manager of PW4000 engine overhaul engineering at SR Technics. "The higher thrust models rated at 62,000lbs thrust have margins of 25 degrees centigrade."

Engines rated at 56,000lbs and 58,000lbs have EGT margins of 35-40 degrees, but these can rise to 50 degrees.

The actual EGT margin will depend on the previous shop visit workscope and the engine's modification states. "Higher-rated PW4060/62 engines can have an EGT margin of 35 degrees centigrade if they have undergone the Phase III and ring case modifications," says Paul Lueck, propulsion systems engineering at Lufthansa Technik. "EGT margins of engines that have not had the Phase III modification will be 15 degrees lower. PW4056 and PW4158 engines with the Phase III modification have EGT margins of 50 degrees after a shop visit."

Available EGT margin

As described, the engine's EGT is held constant above the flat rating or corner point temperature, and EGT reduces and EGT margin increases for OATs lower than this. The available EGT margin in particular operating conditions therefore not only depends on the condition of the engine's turbomachinery, but also on the OAT at take-off.

Most operations take off at OATs lower than the corner point temperature. A PW4056 engine, for example, may have an EGT margin of 35-40 degrees for OATs of 33 and higher. The engine will therefore have an additional 36.4 degrees of EGT margin for an OAT of 20 degrees, giving it an available EGT margin of 71-76 degrees *(see second table, page 20)*. Even as the standard EGT margin reduces to zero, the engine will still have an EGT margin of 36 degrees at an OAT of 20 degrees centigrade.

Engines operating in temperate climates and conditions clearly have a lot of EGT margin, even when hardware has deteriorated. Engines operating in hot temperatures also have to be taken into consideration.

While engines are flat-rated or their thrusts are reduced to keep EGT constant above the corner point temperature, an engine can still maintain constant power above this temperature. EGT therefore continues to rise at the constant rate of 2.8 degrees per degree of OAT in this scenario, reaching the red line limit of 644 or 654 degrees centigrade, at the engine's maximum thrust, at an OAT higher than the corner point temperature. The OAT at which the EGT reaches the engine's red line limit is called the sea level OAT limit (SLOATL).

A PW4056 engine with an EGT margin of 40 degrees at its corner point of 33 degrees, would reach zero EGT margin at a SLOATL of 47 degrees. The implications of this are that an aircraft can still use maximum thrust when operating at high temperatures.

AJW support

A J Walter Aviation holds the largest stock of aviation spares for commercial jet aircraft worldwide

- Inventory of 500,000 line items
- Exchange, loan, AJW FIX, sale and PBH support
- Guaranteed availability
- Unbeatable rotable and consumable support
- Structured lease packages for Airbus & Boeing spare parts: A310, A320, A330, A340, 737, 757, 767, 777

Fully staffed AOG service available
24 hours a day, 7 days a week
+44 (0)7831 583205
aog@ajw-aviation.com

Visit us at Asian Aerospace 2007
September 3rd - 6th, Stand 5J21 - Hong Kong

Specialists in the supply and repair of commercial aircraft spare parts

75 YEARS IN AVIATION

Since EGT rises as the engine's hardware deteriorates, EGT margin and the SLOATL fall to limit the aircraft's performance at high temperatures. If EGT margin is eroded down to 20 degrees, the SLOATL will fall to 40 degrees.

Even when the EGT margin is reduced to zero at the corner point temperature, the engine will still have an EGT margin of 36 degrees centigrade at an OAT of 20 degrees. SLOATL will be reduced to 33 degrees.

A PW4060 or PW4062 engine with an EGT margin of 25 degrees at its corner point temperature will have an available EGT margin of 53 degrees for an OAT of 20 degrees *(see second table, page 20)*. SLOATL will then be 39 degrees. An erosion in EGT margin to 5 degrees will reduce SLOATL to 31-32 degrees. This reduction would be likely to prevent the aircraft operating with maximum engine thrust after EGT margin has been reduced to this level. The engine will still have an available EGT margin of 33 degrees at an OAT of 20 degrees.

Reduction in EGT margin therefore has its most limiting effect on aircraft that are powered by the highest-rated PW4000-94 variants flat-rated at 30 degrees centigrade.

EGT margin erosion

Rates of EGT margin erosion depend on the application, thrust rating, rate of take-off de-rate and EFH:EFC ratio. The relative rates at which EGT margin erodes for different ratings and different operations can be analysed with a severity curve. The highest severity will come from a short EFC time and a zero de-rate for the highest-rated variants.

Take-off de-rate has its largest effect for the first 5%. That is, the severity factor will be reduced from 2.2 to 1.9 for a PW4060 engine when a 5% de-rate is applied at an EFC time of 1.0EFH. A further use of de-rate to 10% achieves a reduction in severity to 1.7 for the same EFC time. Smaller reductions in severity are achieved for engines used on medium and long EFC times.

The main factor affecting severity is EFC time. A PW4060 engine will have a severity of 1.9 for a 5% de-rate when operated at 1.0EFH. The severity factor falls to 1.35 at 2.0EFH, 1.2 at 3.0EFH, 1.0 at 5.0EFH and 0.9 and 7.0EFH.

Thrust rating is the other major factor. The PW4060 is the second highest rating, so it has high severity factors compared to other variants, except the PW4062. The lower ratings of other variants are effectively equal to higher take-off de-rates. A 5% de-rate on the PW4056, for example, has a similar effect to an 11% de-rate on the PW4060. This would reduce the severity factor from 1.1 to 1.0 at an EFC time of 4.0EFH.

A 5% de-rate of the PW4062, however, is similar to only a 2% de-rate on the PW4060.

EGT margin erosion rates are generally high for the first 1,000-2,000EFH on-wing after a shop visit. "The initial rates of EGT margin loss are 5-8 degrees centigrade per 1,000EFH," says Nicca. "Generally, the removal intervals of engines used on long-haul operations are EFH-limited, while the intervals of engines used on short-haul operations are EFC limited.

Keith Lindstrom, PW4000-94 program manager at Pratt & Whitney, comments that EGT margin erosion rates are more consistent with accumulated EFC on-wing rather than EFH time on-wing. "Rates per 1,000EFC are higher for aircraft operating on long average cycle times, and lower for engines on shorter cycle times. Initial rates are 10-15 degrees for the first 1,000EFC on-wing," says Lindstrom. "Rates then reduce to 2-5 degrees per 1,000EFC thereafter."

This rate of loss brings initial EGT margins down to 11-17 degrees for PW4060/62 engines used on long-haul operations, to 25-30 degrees for PW4056 engines used on medium- and long-haul operations, to 35-40 degrees for PW4052/4152 engines used on medium-haul operations, and to 25-30 degrees for PW4158 engines used on medium-haul operations after the first 1,000EFC on-wing.

These mature rates of EGT margin loss potentially allow PW4060/62 engines to remain on-wing for up to 25,000-30,000EFH when used on long-haul missions.

Lower-rated PW4056 engines also used on long-haul missions have a potential on-wing interval of more than 30,000EFH.

The same PW4056 engines used on medium-haul operations have a potential on-wing life of up to 35,000EFH.

The lowest-rated PW4052 engines have a potential on-wing life of more than 40,000EFH.

Even the PW4158 operated on short-haul EFC times of 1.0-1.5EFH can remain on-wing for up to 20,000EFH.

These long potential removal intervals show that in most cases and applications the PW4000-94 has enough EGT margin for performance loss not to be a main removal cause. The exceptions are operations in high temperature environments where available EGT margin becomes limiting and high OATs prevent a high level of take-off de-rate. This results in relatively high severity, so loss of EGT margin becomes a factor in engine removal for maintenance. "Some EGT margin can be preserved and regained, however, by using water washing. This technique can regain about 6 degrees of EGT margin," says Nicca.

Removal causes

The EGT margins of most PW4000-94 operations are not a limiting factor in removal intervals, and the engine has experienced other major removal drivers. Most engines are used for medium- and long-haul operations of 4.0-8.0EFH per EFC. Most aircraft achieve utilisations of 3,500-4,500FH per year, and so engines accumulate 550-900EFC per year. An interval of 20,000-25,000EFH that is possible with the EGT margin of long-haul engines is equal to 2,800-3,200EFC. Life limited parts (LLPs) in contrast, mostly have lives of 15,000EFC or 20,000EFC, so LLP life expiry will only be a removal driver for some engines at their fifth to seventh removals.

Most of the PW4000-94's removals have been due to hardware deterioration, and problems with HPC stalls and surges.

One of the first issues to be addressed on the PW4000-94 is sulphidation of stage 2 HPT blades. "Sulphidation begins internally on the blades, and eventually leads to external cracking and deterioration. When this external cracking is detected on the blades with borescope inspections, the engine has to be removed," explains Christian Revilla, manager of propulsion engineering at Delta Tech Ops. "Two types of material have been used for the stage 2 HPT blades: PWA1480 and PWA1484. PW has since withdrawn PWA1484, since this was the material that led to the sulphidation problems, so only blades with PWA1480 are now available."

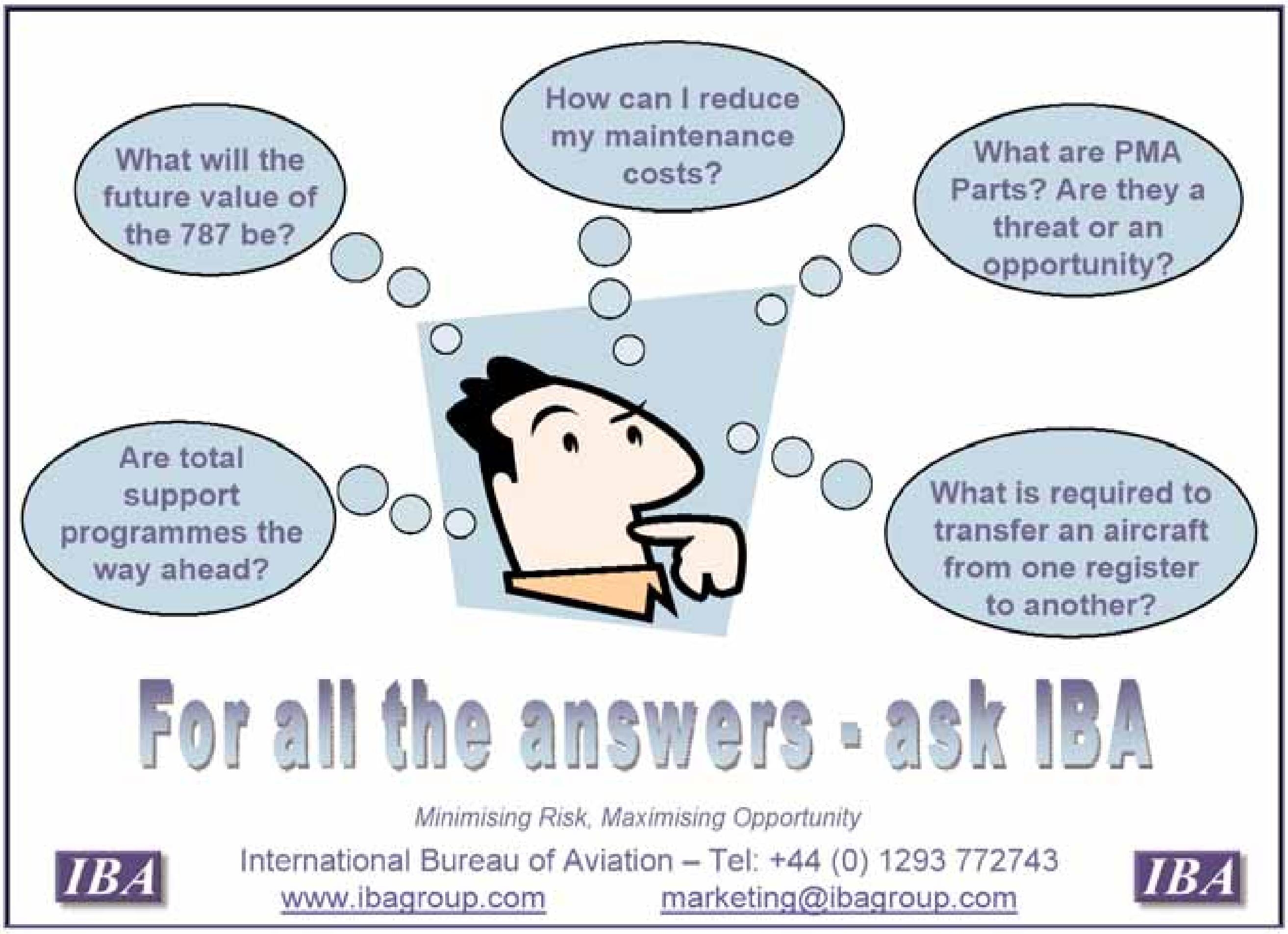
Lufthansa Technik manages PW4062 engines for Condor, whose engines experienced the same sulphidation problems. "The problems with these blades limited removal intervals to 2,300-2,500EFC for long-haul engines, equal to 17,500EFH. The actual interval depends on the EFC time," says Matthias Albrecht, director PW4000 engine services at Lufthansa Technik. "The removal intervals have been managed according to the customised fleet management programme. There are two SBs. The first, SB72-723, refers to a new coating on the old blades. The second, SB72-716, exchanges the blades for a new one. Both SBs fix the hard-time problem. Most Condor engines have been modified with the new coating or have the new blade fitted. Some engines are achieving 22,000EFH on-wing between removals."

A second major cause of removals has been the much publicised surge and compressor stall problems the engine suffered over a 10-year period. "There were various fixes and several ADs to cure the problem of compressor stalls that the PW4000 was experiencing. Test 21 was required to see if the engines were prone to stalling, which involves running the engine at full power, cutting it back to idle and re-engaging full thrust," says Albrecht. "Stalling became more frequent as the engine's condition deteriorated, and so engines had to be removed. The problem has now been cured with AD 2003-19-15."

This is the ring-case modification, which is a re-design of the latter part of the inner HPC case, just in front of the combustor. The old design had instability problems because of thermal expansion of the case, which resulted in larger HPC blade tip clearances, leading ultimately led to compressor stalls. The ring case modification provides a single HPC case ring for each stage from stages 8-15. This results in better HPC blade tip clearance.

The AD had threshold dates for compliance, dependent on the number of engines on the aircraft. For A300-600s, A310s and 767s, half an operator's fleet had to be modified by 31st May 2006, and the other half by 30th June 2009.

In the case of the MD-11, two-thirds of an operator's engines had to be



PW4000-94 LIFE LIMITED PARTS-EFC LIMITS

Life limited part	Unit cost $	EFC limit PW4052/56	EFC limit PW4058/60/62
Low pressure compressor (LPC)			
Hub, front compressor	250,000	20,000	15,000
Disk drum rotor	334,000	20,000	15,000
LPC/LPT coupling			
Turbine shaft (LPC/LPT)	99,000	30,000	30,000
High pressure compressor			
Hub, HPC front	67,000	20,000	15,000
Disk, stage 5	52,000	20,000	15,000
Disk, drum rotor (stage 6-12)	516,000	20,000	15,000
Disk, drum rotor (stage 13-15)	450,000	20,000	15,000
Shaft, HPC drive	134,000	20,000	15,000
Airseal, diffuser	43,000	20,000	15,000
High pressure turbine			
Hub, turbine front	161,000	20,000	15,000
Hub, turbine intermediate rear (stage 2)	147,000	20,000	15,000
Airseal HPT stage 1 - outer rotating	99,000	20,000	15,000
Plate, HPT stage 2	44,000	20,000	15,000
Airseal HPT stage 1 - inner rotating	38,000	20,000	15,000
Airseal, HPT stage 2	100,000	20,000	15,000
Low Pressure turbine			
Disk, LPT stage 3	110,000	20,000	15,000
Disk, LPT stage 4	230,000	20,000	15,000
Hub, rear turbine stage 5	152,000	20,000	15,000
Disk, LPT stage 6	128,000	20,000	15,000
Airseal, LPT stage 3	84,000	20,000	15,000
Airseal, LPT stage 4	57,000	20,000	15,000
Airseal, LPT stage 5	67,000	20,000	15,000
Front comp drive turbine	119,000	30,000	30,000
Airseal, LPT stage 3	68,000	20,000	15,000
Total	**3,551,000**		

modified by the end of August 2006.

At least one engine on the 747-400 had to be modified by 31st January 2007. All engines must be modified by 30th June 2009.

The date for full compliance on all aircraft is 2009. PW says that by the end of February 2007 1,400 engines had been modified, leaving the AD to be completed on 750. PW has delivered about 1,900 ring case modification kits to date.

HPC stalls and the ring case modification have been a main removal driver for most engines, and have had a limiting effect on removal intervals.

A third issue affecting the PW4000-94 has been deterioration of the stage 2 turbine nozzle guide vane (NGV2). This part has experienced some heat-related distress that has led to fatigue, resulting in SB72-780. This requires a borescope inspection, which can be terminated for RCC-modified engines by SB72-788, incorporating a new vane.

Once the stage 2 HPT blade and ring case modifications have been addressed, operators and engine shops expect the engine to have longer removal intervals. Removals would then be forced by the deterioration of other hardware. "One example is oil leaks from the second and third bearings," says Revilla. "Other hardware issues relate to items such as combustion-chamber cracking and deterioration, and hot-section distress.

Wayne Pedranti, programme manager at Total Engine Support (TES), says that 25% of engine removals relate to AD 2003-19-15 and 15% to stage 2 HPT blade and vane problems. A further 25%, however, are due to time expiry and the need for an overhaul.

Life limited parts

The PW4000 has 24 LLPs in its four main modules. Pedranti points out that with Phase III engines the number of LLPs has been reduced by some parts being combined as one.

The fan and low pressure compressor (LPC) has just two LLPs, and the HPC and the HPT each have six, and the low pressure turbine (LPT) has nine.

LLP lives are uniform throughout the engine, except the stub shaft and the LPT shaft, which have lives of 30,000EFC. The remaining LLPs have lives of either 20,000EFC or 15,000EFC, depending on thrust rating and application. The LLPs on the PW4052 and PW4056 have lives of 20,000EFC, while LLPS on all other applications and ratings have lives of 15,000EFC *(See table, this page)*.

The list price for the two LLPs in the fan/LPC module is $584,000. The list price for the six HPC LLPs is $1.26 million, while the six parts in the HPT have a list price of $589,000. The nine parts in the LPT, including the LPT shaft, have a list price of $1.01 million.

The uniform lives of the parts simplify engine removal and shop visit management, so that all parts can be replaced at the same time. It is also possible to use a high percentage of the available life of the parts and so achieve a low LLP reserve rate per EFC. The total list price of the complete LLP set is $3.6 million. Full use of LLP lives results in LLP reserves of $240 per EFC for higher-rated engines with LLPs of 15,000EFC, and $180 per EFC for lower-rated engines with LLPs of 20,000EFC. Actual replacement lives and reserves will depend on removal intervals and shop visit workscopes and patterns, however.

Removal intervals

As discussed, removal intervals are rarely driven by loss of EGT margin. The main removal drivers are HPC surges and stalls, and deterioration of stage 2 HPT blades. With these problems now solved, intervals are expected to increase.

"We think it is possible for engines used on long-haul operations on the 767 and 747 to have intervals as long as 22,000EFH, provided there are no interruptions caused by unscheduled removals," says Albrecht. "PW4000-94s used in long-haul applications could certainly have planned intervals longer than 18,000EFH. We modified Condor's PW4062 fleet over the past three years with the new stage 2 HPT blade, so it is too early to get an accurate picture of the engine's exact removal intervals."

Delta's experience of improving on-

The PW4000-94 benefits from stable operating performance, good EGT margin retention and uniform LLP lives. These all combine to deliver competitive maintenance reserves.

wing durability following the solution of HPC stall and stage 2 HPT blade deterioration problems is similar to Lufthansa Technik's. "We established a soft time of 18,000EFH as a removal interval for engines not upgraded with the ring case modification, since this was the interval that was possible by the HPC," explains Revilla. "The engine's removals were managed around the ring case modification AD. Modified engines are expected to achieve 25,000EFH between removals. Once the ring case and stage 2 HPT blade issues are dealt with, the engine can remain on-wing longer so that other issues relating to hardware deterioration start revealing themselves. An example is oil leaks, which may start to arise after intervals longer than 18,000EFH. The current mean time between removals (MTBR) of both planned and unplanned shop visits is 20,000EFH now that the main problems have been solved, compared with 10,000-15,000EFH that the engine was achieving in its earlier years of operation."

More than 500 PW4000-powered aircraft are used on long-haul operations, including 205 767s, 220 747-400s and 80 MD-11s. Another 210 A300-600Rs and A310-300s operate mainly in short- and medium-haul modes. "Engines used on long-haul operations generally tend to have planned removal intervals of 16,000-18,000EFH, and intervals are EFH-related," explains Nicca. "Engines used on medium-haul operations of EFC times of 3.0-4.0EFH have planned removal intervals of 15,000EFH. Engines used on short-haul operations have intervals of 3,000-3,500EFC, equal to 3,500-7,000EFH. Intervals in this case are EFC-related. While the PW4000-94's removals are generally not driven by loss of EGT margin, engines operating in hot and sandy environments do have 30% shorter EFH intervals compared to engines operating in temperate climates."

Shop visit pattern

Like all PW engines, the PW4000-94 conforms to a simple shop visit and workscope pattern, generally alternating between a core restoration or overhaul, and a full overhaul of all engine modules. This simplifies engine management, since the full disassembly of the engine at an overhaul provides a convenient opportunity for the LLPs to be replaced.

"All PW4000 variants have the same workscope philosophy. The engine core, which comprises the HPC, diffuser combustor, turbine nozzle and HPT, gets heavy maintenance every shop visit," says Pedranti. "The remaining modules get the heavy maintenance every second shop visit, except for HPCs that have been upgraded with the ring case modification. These have a core restoration at the first shop visit and a full overhaul at the second, because the modification increases the life of the HPC module."

While this alternating pattern of visits is usual for most engines, Nissa warns that problems with HPT durability can interfere with it. "SR Technics developed a technique to perform early HPT repairs, by removing the engine at 70-80% of the planned removal interval if findings are made during the borescope inspections," says Nissa. "The engine can be split into modules, and a repair performed on just the HPT while all other modules are left. The aim is to keep the engine flying for another 4,000EFH. The engine can then be reinstalled so that it can achieve its potential removal interval of 16,000-18,000EFH."

While the ideal is for engines to have a simple alternating pattern of core restorations and overhauls, they do suffer unscheduled removals, due to items such as oil leaks, bearing failures and foreign object damage. These account for 10-15% of all removals and shop visits, and their random nature means the MTBR and average interval for all removals will be less than the planned intervals.

Engines used on long-haul missions with the 747-400 and 767-300ER have planned removal intervals of 18,000EFH, but the MTBR for all removals will be 15,000EFH. Engines on medium-haul operations with planned removal intervals of 15,000EFH will have an MTBR of 12,000-13,000EFH.

PW4158 engines used on short-haul missions with the A300-600R can have MTBRs of 3,500EFC, equal to 6,000EFH.

Shop visit inputs

The engine generally follows an alternating pattern of a core restoration or overhaul, followed by a full overhaul. The labour inputs and costs of materials and sub-contract repairs are considered for these two workscopes.

A heavy core restoration will use 2,700 man-hours (MH) for routine items and a total of 5,800MH for the full workscope. At a standard labour rate of $70 per MH this is equal to $410,000. The cost of materials for the visit will be $1.0 million, or as high as $1.5 million if, for example, the HPT hardware has been through several repair cycles. The cost of sub-contract repairs will be $400,000. This takes the total cost of the shop visit to $1.8 million, and up to $2.3 million for a full core restoration.

A full overhaul has incrementally higher inputs. Routine labour is 3,200MH and total labour for the shop visit is 6,700MH. At a standard labour rate of $70 per MH, the cost is $470,000.

The cost of materials for the visit is at least $1.2 million, about $200,000 higher than the core restoration. A higher material cost of $1.6 million is more likely for a heavier visit. Pedranti says that material cost can reach $3.0 million where the HPT hardware has experienced

PW4000-94 ENGINE SERIES MAINTENANCE RESERVES

Engine variant	PW4158	PW4052/56	PW4056	PW4060/62
Application	A300-600R	767-200ER/ A310-300	767-200ER/ 747-400	767-300ER/ MD-11
EFC time-EFH	1.5	3.0	8.0	7.0
Average removal interval-EFC	3,100	4,250	1,900	2,100
Average removal interval-EFH	4,700	12,750	15,300	16,000
Shop visit reserve-$/EFH	409	150	125	125-130
LLP reserve-$/EFC	231	121	188	240
Total reserve-$/EFH	563	190	149	160-170

a lot of repairs. The cost of sub-contract repairs is $450,000-600,000.

These three elements take the total cost of the shop visit to $2.1-2.7 million for most overhauls, but in excess of $3.0 million for the worst cases.

The total cost of the two most likely shop visits in an engine's management cycle will therefore be $4.1-5.0 million.

Workscopes are sometimes required on just the LPT and fan/LPC. A visit for the LPT will use 600MH, equal to $45,000 plus $70,000-160,000 for materials, and $125,000-140,000 for sub-contract repairs. This takes the total cost to $250,000-350,000.

A visit for the fan/LPC module will use 300MH in labour, $30,000 for materials and $55,000 for sub-contract repairs. This takes the total cost of the workscope to $110,000.

Total shop visit costs

Assuming the engine is able to conform to the simple shop visit pattern of alternating core workscopes and overhauls, the engine's maintenance reserves can be estimated.

In the case of PW4056 engines used on the longest missions with 747-400s, a planned interval of 18,000EFH can be expected for engines that have not had the ring case modification. Taking unscheduled removals into consideration, an average interval of 15,000EFH between all removals is likely, equal to 1,500-1,900EFC at EFC times of 8.0-10.0EFH. Under this scenario LLPs with lives of 20,000EFC will be replaced every 10-12 shop visits after an interval of 19,000EFC.

The maintenance reserves for the two shop visits will be $125 per EFH. With reserves for LLPs added in, total reserves would be $180-190 per EFC, equal to $18-24 per EFH, taking total reserves to $145-150 per EFH *(see table, this page)*.

Planned intervals for PW4056 engines that have been upgraded with the ring case modification can be expected to be 20,000-25,000EFH. The average removal interval for all removal causes would therefore be 17,000-21,000EFH. Total reserves would be $10 per EFH lower.

In the case of PW4060/62 engines used on long-haul missions with the 767-300ER and MD-11, planned removal intervals of 18,000-20,000EFH can be expected for unmodified engines. The average interval for all removal causes would be 15,000-17,000EFH, equal to 2,100EFC. LLPs would be replaced every sixth or seventh shop visit. The engines would incur similar shop visit costs to the PW4056 engines used on the 747-400, while LLP reserves would be higher at $240 per EFC because of their shorter life of 15,000EFC. Total reserves would be $160-170 per EFH *(see table, this page)*.

In the case of PW4052/56 and PW4152/56 engines used on the 767-200ER and A310-300F, planned removals of 15,000EFH would result in an average removal interval for all causes of 12,500EFH. Reserves for shop visits would be $150 per EFH, and for LLPs, replaced every seventh shop visit, reserves would be $121 per EFC, equal to $40 per EFH. This would take total reserves to $190 per EFH *(see table, this page)*.

PW4158 engines used on short-haul operations of 1.5EFH per EFC for the A300-600 would have planned intervals of 5,500EFH. Once all removal causes and removals are considered, the average interval for all removals would be 4,700-5,000EFH. Reserves for shop visits would be $409 per EFH. LLP reserves of $231 per EFC would be equal to $155 per EFH, and take total reserves to $563 per EFH *(see table, this page)*.

Reducing shop visit costs

The cost of materials is the largest portion of the total shop visit cost. This explains the increasing trend for airlines to use parts manufacturer approved (PMA) parts in their engines: the list price of PMA parts is lower than that of the same parts supplied by the original equipment manufacturer (OEM).

There are several PMA parts providers for the PW4000-94, including HEICO Aerospace. Most of the parts that HEICO supplies for the PW4000-94 are non-turbomachinery parts, including fuel pump gears, bearings, expendables and airseals. "We also manufacture turbine spacers, and are adding other PMAs to our list of what we provide for the PW4000-94. There are 3,000 different part numbers in each engine type, and we have up to 550 part numbers for different engine types," says Rob Baumann, president of HEICO parts group. "We estimate that using the PMAs we provide for the PW4000-94 can save up to $120,000 on the cost of a heavy shop visit." Given the average intervals that most engines achieve, this shop visit cost reduction is equal to $6-8 per EFH.

"We do not have a large number of turbomachinery parts on the PW4000-94 as we do on the CFM56, for example," continues Baumann, "and what we offer is mainly driven by our customers. These include United Airlines, Lufthansa Technik and SR Technics. Not only do we see increased use of PMAs by airlines, but we are now also seeing a rise in their use by engine lessors, particularly with expendable parts. Some are agreeing to the use of PMAs in their lease contracts."

Summary

The reserves show that the PW4000-94 is economic on a variety of mission lengths and applications *(see table, this page)*. Reasons include its uniform LLP lives, and the fact that, like all other PW engines, the PW4000-94 conforms to a simple shop visit pattern of alternating core workscopes and engine overhauls. This simplifies engine management and allows a high proportion of LLP lives to be used. Also, the PW4000-94 is rarely removed due to performance and EGT margin loss. While HPC surges and loss of surge margin have been a major removal cause, the RCC modification will rectify this, increasing removal intervals and resulting in savings of $10 per EFH.

The reserves *(see table, this page)* for engines used on long-haul missions include an allowance for LLP replacement. If engines are operated only on long-haul missions of 8.0EFH or more for their entire lives, which is likely for a large number, then the original set of LLPs can last for the aircraft's entire working life. LLP reserves may therefore not be required in practice, meaning that airlines can save $20-30 per EFH in total reserves in some cases. AC

To download 100s of articles like this, visit: www.aircraft-commerce.com