OWNER'S & OPERATOR'S GUIDE: PW4000-94

PW4000-94 specifications

The PW4000-94 powers more than 700 1980s-generation widebodies. It's thrust ratings vary from 52,000lbs to 62,000lbs.

The Pratt & Whitney (PW) PW4000-94 series powerplant, with a 94 inch-fan diameter, is the first of three family series. With certified thrusts of 52,000-62,000 pounds, it powers the A310-300, A300-600, 747-400, 767-200/300 and MD-11 aircraft. For twin-engine aircraft, the PW4000 is approved for 180-minute extended-range twin-engine operations (ETOPs). The two subsequent and more powerful series developed for the A330 and 777 aircraft have 100- and 112-inch diameter fans.

There are 10 main application/thrust variants of the PW4000-94 series: the PW4052, PW4056, PW4060, PW4062, PW4152, PW4156, PW4158, PW4460, and PW4462. The characteristics of all these variants are summarised *(see table, this page)*.

The system for the PW4000-94's nomenclature uses the second digit to indicate the airframe manufacturer application for which the engine variant is used, and the last two digits to indicate the thrust at which the engine is rated. For the second digit, a 0 indicates that the engine is used on a Boeing aircraft, a 1 denotes Airbus, and a 4 McDonnell Douglas. If the last two digits are 52, this indicates a rating of 52,000lbs thrust. The use of 56, 58, 60 and 62 therefore indicates thrust ratings of 56,000lbs, 58,000lbs, 60,000lbs and 62,000lbs. For example, the PW4156A is rated at 56,000lbs thrust and powers an Airbus aircraft, in this case the A310-300. It also has an improved take-off rating 'boost' option for hot-and-high operations.

The PW4000-94 was launched in 1982 and received its FAR Part 33 certification in 1986. The first PW4000-94, a PW4152, was installed on an Airbus A310 delivered to Pan Am in 1987. Subsequently, the family was certified on the following aircraft: A300-600 (PW4158), 767-200/-300 (PW4052, PW4056, PW4060 and PW4062), 747-400 (PW4056 and PW4062A), and the MD-11 (PW4460 and PW4462).

Apart from take-off thrust ratings, the main differences between the engine variants are associated engine mountings, nacelles, quick-engine-change (QEC) and full authority digital engine control (FADEC) configurations. Although PW has originated service bulletins (SBs) so that the engine can be converted from one aircraft application to another, such exercises are rare in practice, even for engine sale or lease situations.

By September 2007, these versions of the PW4000 had accumulated in excess of 89 million engine flight hours (EFH) and 18.4 million engine flight cycles (EFC).

While there is no modular interchangeability between the PW4000-94 and its two larger siblings, there is some parts commonality with the 100-inch version at the line-replaceable-unit (LRU) level. Some internal components are also interchangeable. Likewise, there is also some commonality of engine shop tooling with the 100-inch version, with 67% of the tools being identical.

The engine incorporates single-crystal superalloy turbine blade materials and has FADEC as standard. For a further reduction in emissions, especially NOx, Technology for Advanced Low NOx (TALON) combustor technology (derived from the 112-inch fan model) became available as an option in the late 1990s. TALON uses segmented, replaceable liner panels for improved maintainability, and air blast fuel nozzles for better fuel atomisation and mixing. The PW4000-94 engines are flat rated at 30°C, 33°C or 42°C. The bypass ratio ranges from 4.8 to 5.1, the overall pressure ratio from 27.5 to 32.3, and the fan pressure ratio from 1.65 to 1.80.

Today, there are 2,169 PW4000-94s in the world fleet, powering about 717 aircraft. Around half of all these engines power 225 747-400s. The next largest engine fleet grouping is for 205 767-200/-300s. Meanwhile, the PW4000-94 also powers about 147 A300-600s, and 48 A310-300s. About 75 MD-11s are also equipped with the PW4460/62.

The PW4000-94 can broadly be divided into two groups on the basis of its style of operation. Most engines are operated on long average EFC times, of five hours or more per cycle, which is typical of 767, 747-400 and MD-11 applications. These long cycles minimise engine wear and maximise on-wing life. In contrast, the engines operated on the A300-600 and A310 have shorter average EFC times.

PW4000-94 SERIES THRUST RATING & SPECIFICATION DATA

Engine model	Take-off thrust lbs	Flat rate temp deg C	EGT red line deg C	Aircraft application
PW4052	52,200	33	644	767-200/-200ER/-300
PW4056	56,750	33	654	767-200/-300
PW4056	56,750	33	654	747-400
PW4060	60,000	33	654	767-300/-300ER
PW4060A	61,570	33	654	767-300/-300ER
PW4152	52,000	42	644	A310-300
PW4156	56,000	30	654	A300-600/A310-300
PW4156A	56,000	33	654	A310-300
PW4158	58,000	30	654	A300-600
PW4460	60,000	30	654	MD-11
PW4062	62,000	30	654	767-200/-300
PW4062A	62,000	30	654	747-400
PW4462	62,000	30	654	MD-11

LLP lives

All PW4000-94s have the same core architecture and stage configuration. Each therefore has a fan, four-stage booster or low pressure compressor (LPC), an 11-stage high pressure compressor (HPC) , a two-stage high pressure turbine (HPT), and four-stage low pressure turbine (LPT). For the 94-inch engine, most life limited parts (LLP) have lives that are mostly fixed at either 20,000 engine flight cycles (EFCs) or 15,000 EFCs. Engines rated at 50,000lbs, 52,000lbs and 56,000lbs thrust have

The majority of PW4000-94s are used to power long-haul aircraft, including about 220 747-400s. Having been modified, the PW4000-94 is capable of removal intervals exceeding 18,000EFH.

LLPs with lives of 20,000EFC, and engines with higher ratings have lives of 20,000EFC.

For operations where the EFH:EFC ratio is about 5:1, LLP-associated engine removals will not usually be a problem.

There are two parts with lives of 30,000 EFC: the LPT shaft and the LPT coupling. Since most engines accumulate only 600-700EFC per year, it is unlikely that these two parts will have to be replaced. Moreover, the LLPs with lives of 20,000EFC will have to be replaced only after 30 years in some cases.

According to Wayne Pedranti, engineering group program manager at UK-based Total Engine Support (TES), a complete set of LLPs has a current list price of $3.5 million.

Given that EFH times per cycle vary for different operations, the accumulated EFH intervals between LLP replacement therefore vary with application. For example, A310s and 767s powered by PW4152,s PW4156s and PW4056s have LLPs with lives of 20,000EFCs. These aircraft typically operate at 3.0FH per FC and the engines can achieve 16,000-18,000EFHs and 5,000-6,000EFCs between removals. In this case, LLP replacement will occur every three to four shop visits, or every 50,000-55,000EFH.

The higher thrust engines (such as PW4158s on A300-600s) which contain LLPs lifed at 15,000EFC, and which operate FH:FC ratio of 1.5, will incur LLP replacement at every fourth shop visit, equating to every 22,500EFH (assuming shop visits typically occur every 6,000EFHs or 3,700-4,000EFCs).

The highest thrust-rated PW4060/62s, operated on the 767 and MD-11, also have LLPs with lives of 15,000EFC. These aircraft typically operate with FC times of 5-9FH. Moreover, average engine shop visit intervals are typically every 15,000EFH. While the shorter-cycle (5.0EFH) engines will have LLPs replaced every fifth shop visit (equating to 75,000EFH), with the longer cycles of 9.0EFH, the same engine model will achieve a longer cumulative LLP on-wing life of up to 135,000EFH. LLPs will only need to be replaced every nine or 10 shop visits.

"Pratt & Whitney has designed LLPs to have the same lives so that operators do not have to manage removals around the expiry of individual LLPs," explains Pedranti. "It was meant to ensure that everything synchronises such that the first time the engine comes in, you just 'go into' the core, and the second time the engine comes in, there is a heavier workscope and this provides an opportunity to change LLPs. While this is what was designed to happen, the reality is that it does not."

EGT margin & flat rating

To guarantee how a new engine will perform, there are two different flat rating concepts used by engine manufacturers. One concept is to rate the engine to a constant compressor speed. The other concept is to flat rate the engine to a constant exhaust gas temperature (EGT). PW uses the latter of the two. The flat rate temperature is the outside air temperature (OAT) above which the EGT is held constant, or 'flat rated', by reducing thrust. Moreover, as long as the OAT is below the corner point, then the thrust is constant. The EGT rises as OAT increases, and the EGT rises at a constant rate of 2.8 degrees centigrade per one degree centigrade increase in OAT when thrust is held constant at the maximum rating.

In the case of the PW4000-94 family, all family engines have the same gas path design. Higher thrust ratings are achieved by a higher throttle setting and by adding more fuel and higher rotational speeds. In essence, a PW4462 has to work much harder to maintain 60,000lbs thrust than a PW4152 does at 52,000lbs thrust. This is reflected by the higher rated variants having lower flat-rated temperatures *(see table, page 10)*. Also illustrated are the respective maximum permissible EGT redline operating temperatures for the various models within the PW4000-94 family.

It should be noted that because the PW4152 works less and has a greater EGT margin, it can maintain constant thrust up to an OAT of 42°C, whereas a PW4460 can only maintain constant thrust to a temperature of 30°C as it is operating much closer to its EGT margin.

EGT margin is the difference between the constant actual flat-rated EGT and the red-line temperature limit. As a result, even though this PW4152 has a flat rate of 42°C, its absolute EGT is lower than that of the PW4462 at its respective 30°C flat rate temperature. While this is true for a new engine, the constant EGT at flat rate becomes hotter as the engine deteriorates through accumulated flight cycles. In general therefore, and given that the different thrust-rated PW4000-94 share a common gas path, new engines with higher thrust typically have higher EGT than that of a lower thrust version. Therefore, the higher thrust engine would have the shorter on wing life.

When early models of the PW4000-94 were released, there was no international standard on the flat-rate temperature. These early engines had therefore been assigned flat-rate temperatures that were dependent on the engine design in relation to operational thrust expectations. These varied from 33°C to 42°C. Later models of the engine were subject from the outset to an international standard which assigned the flat-rate on a 'standard day' of ISA+15 (30°C) rating for take-off. However, the maximum continuous figures are still dependent on the design of the engine, hence the wide variation, and are set by the interactions between the compressors and turbines. AC

PW4000-94 modification & upgrade programmes

The PW4000-94 has had several major upgrade & modification programmes. These are the Phase III programme, the more recent 'ring case' modification, and the withdrawal of a new HPT blade alloy. These improvements have led to a higher level of on-wing performance & reliability.

There have been several major modification and upgrade programmes and airworthiness directives (ADs) for the 94-inch fan Pratt & Whitney (PW) PW4000-94 engine series. The most significant of these has been an AD from the Federal Aviation Administration (FAA), addressing the take-off surge condition in the engine's high pressure compressor (HPC). Another prominent upgrade to the engine has been the Phase III modification.

Phase III programme

The PW4000-94 has two basic configurations: the earlier built Phase I engines, of which 1,100 were produced; and the Phase III modification and upgrade package, which was introduced in 1992 to address higher-than-expected fuel burn, and improve durability and on-wing times. This was aimed particularly at certain MD-11 operations that were having difficulty meeting range and performance targets, although it was subsequently adopted across the wider PW4000-94 fleet.

The physical changes to the engine comprise: new fan blades and fan rub strip; a new design HPC; casing, improved high pressure turbine (HPT) airfoils; gas path seals; a low loss burner, and upgraded low pressure turbine (LPT) materials and airfoils. The objective of this phase III standard was to improve fuel burn by 1.8% on the 747, and 2.8% on the Airbus and MDC applications. Phase III engines also have about 15 degrees higher EGT margins than Phase I engines. About 950 engines were converted to Phase III standard.

This standard also included a wider nacelle for engines powering Airbus and MDC aircraft. Exhaust gas temperature (EGT) margins vary between Phase I and Phase III engines. Phase III engines have brush seals, while the former have knife-edge seals. As an example, the Phase III powerplants of MD-11s have EGT margins about 40°C at 60,000lbs thrust and 29°C at 62,000lbs thrust. In contrast, non-modified engines at 60,000lbs thrust have an EGT margin of around 26°C, which is 14°C less than for the Phase III standard.

"There are still quite a few Phase I engines in operation," says Wayne Pedranti, engineering group program manager at UK-based Total Engine Support (TES). "It is a very costly modification to go from a Phase I to a Phase III. Most operators decided that it was not economically feasible to do so, preferring instead to intermix Phase I and Phase III engines on an airframe. But with that said, about 950 engines were converted."

"Internally, a Phase III standard PW4056 looks exactly like a Phase III PW4060," observes Pedranti. "The only difference involves the data-entry plug electronic engine control settings. To go from one model to another you have to show that your engine can meet the new thrust level. However, there are service bulletins (SBs) to be implemented for some older PW4056s, since these engines may otherwise have internal problems. Moreover, I believe that some operators are required to pay PW for the right to go to the higher thrust level. In fact, many operators use 'multi-thrust' ratings, testing all their engines at the highest PW4060 rating before deciding on which aircraft they will fly. They will fit the corresponding entry plug onto the electronic engine control (EEC) accordingly, to be able to run at that thrust level."

For the 747-400, Boeing offers a Phase III modification with noise reduction inlet. When combined with

The Phase III programme was initially introduced in 1992 to address performance shortfalls of some MD-11 operations. The Phase III modification was subsequently used on the whole PW4000-94 fleet. The main features of the modification were improved fuel burn performance and increased EGT margin. About 950 of 1,100 Phase I engines have been modified.

Part of the Phase III modification programme was the introduction of a new HPT stage 2 blade alloy. This was used to withstand the higher temperatures that Phase III engines run at. The unforseen problems with the new alloy, however, was internal sulphidation and external cracking. This blade material has been withdrawn and the original blade alloy is now used.

FB2C fan blades, the improved noise-reduction liner technology brings noise levels down by 5-8 EPNdB over the original PW4000 delivery configuration. Lead time for hardware is about two months.

2nd-stage HPT blade

The PW4000-94 has also suffered from well-publicised problems with some of the original second-stage (T2) HPT blades that were used in the engine. Two types of blade material were originally used in Phase III engines: PWA1480 and PWA1484. The material PWA1484 caused internal sulphidation of the blades, which then led to external cracks. The engine would have to be removed for a shop visit once these cracks were detected in a borescope inspection.

"PWA1484A is the new alloy for the T2 HPT blades that was used on Phase III engines. This has led to internal sulphidation and stress-corrosion-cracking, especially at the higher temperatures that the Phase III engines are supposed to be able to run at," explains Predranti. "Pratt & Whitney has now released SB72-716 to revert the T2 blade back to the original blade material, PWA1480, because this was used in the Phase I engines which did not have any internal sulphidation problems," says Pedranti. "SB 72-716 re-introduced the PWA1480 material (from which the Phase I blades were made) into the Phase III blade. This SB also modified the Phase I blade by adding a small scarf cut on the root and a new material on the blade tip. This was further enhanced by SB 72-763, which introduced a platinum-aluminide coating on the root. It is also desirable to look for engines that have the second-stage HPT nozzle guide vanes with the improved cooling, which were introduced by SB 72-780."

Pedranti advises that prospective operators of an engine will need to check whether the new SB 72-716, affecting the new second stage (T2) HPT blades, has been applied.

Ring case modification

The FAA's involvement stemmed from a large number of HPC surges at take-off suffered by the PW4000-94 during the 1990s. PW issued more than 100 SBs addressing this and other problems. Many were based on improvements designed for the larger and later variants of the engine.

In 1999, after double surge events on at least two aircraft, the FAA mandated a programme of inspections. PW also redesigned the HPC stator vanes with cutback trailing edges on the vanes at stages eight, 10, 12 and 13 to redistribute the airflow and increase the surge margin. Modified engines continued to experience surges, however, and in late 2000 the FAA prohibited further stator vane modifications and imposed a limit of one modified engine per airframe.

PW subsequently developed a new HPC case design for the engine. This was certified in November 2002 after 200 flight hours of tests on an ex-Air China 747SP acquired specifically to test engines that had failed in service. Based on the equivalent component designed for the PW4000-112, the new 'ring case' design comprises a series of one-piece rings that replace the original HPC case. The original comprised two to four segments around the circumference of the engine's HPC. This is known as the segmented compressor case (SCC), and refers to unmodified engines.

The problem had been the difference in the coefficients of expansion exhibited by the rotating stages and the casing. This resulted in an increased clearance between blade tips and casing shortly after the selection of take-off thrust. The new ring case more closely matches the expansion rate of the disc and provides more rigorous blade tip clearance control.

The new one-piece stator rings require the replacement and modification of both static and rotating HPC hardware. As well as reducing surge risk, the new ring case configuration (RCC) of modified engines improves engine reliability and operability, and should improve the HPC overhaul interval for increased time on-wing and lower operating cost. Additional predicted benefits are a 0.3% improvement in specific fuel consumption and a 3.2 degrees Centigrade improvement in EGT.

The installation of the new cases was mandated in FAA AD 2003-19-15. Pedranti points out that the instructions for performing the RCC modification can be found in the following SBs: 72-755 for Boeing-configured engines; 72-756 for Airbus-configured engines; and 72-757 for McDonnell-Douglas-configured engines. The main reason for this differentiation is to accommodate some external differences which are specific to each engine type. To this end, the applicable SBs must be undertaken at the same time as, or after, the listed RCC

The PW4000-94 series suffered problems with HPC stalls and surges for about 10 years. This was due to wide blade tip-casing clearances in the HPC's latter stages. This has been cured by the 'ring case' modification. With this in place, many operators expect the engine to be capable of removal intervals of 20,000EFH or longer.

modification. Incorporation of the appropriate RCC modification SB therefore constitutes the terminating action for the FAA AD 2003-19-15.

One provision of this AD is compliance date thresholds or deadlines for the number of SCC engines allowed on each aircraft type.

Since June 2006, SCC engines on the 767 must have the HPC inner-case rear hook modified in accordance with SB PW4ENG 72-714 or SB PW4ENG 72-749. Furthermore, only one SCC engine has been allowed on each aircraft.

The inner-case rear hook modification and single-SCC engine limit have applied to the A300, A310 and MD-11 since September 2006, and to the 747-400 since February 2007. After June 2009 only RCC engines will be allowed on all types.

AD 2003-19-15 has also revised the fleet management programme originally imposed by AD 99-17-16. AD 2003-19-15 identifies nine distinct engine configurations and specifies a variety of inspections and tests that engines must undergo prior to their RCC modification.

To reduce the likelihood of surges occurring to unmodified engines, operators were required to carry out a stability test on the HPC at 2,800 EFC after overhaul. In what is known as the 'fuel spike test' or 'Test 21', the engine has to be tested at take-off power in a test cell with the fuel supply cut, re-engaged and then surged back to take-off power. Failing this test forces a removal, in which case the engine is split at the HPC and the modification has to be performed.

Another element to this 'belt-and-braces' approach is to stagger engines on an aircraft, so that there are never two high-time engines on the same aircraft, especially on extended twin-engine operations (ETOPs) A300/A310s and 767s. This is to reduce the chances of a dual-engine surge.

Lufthansa Technik, which is the biggest independent engine overhauler dealing with the PW4000, carried out its first ring case modification in 2004. Robin Schmitz, product and engineering team manager for the engine at Lufthansa Technik, says that by the end of September 2006 the completion rate for the ring case modification on the engine had reached 77%. The active population was 2,169 from a total of 2,477 engines delivered, which means that there were still 477 engines remaining to be modified.

Schmitz expects that all the active engines will be converted by the cut-off date. The estimated cost of the work, including labour, transportation and the test run, is $650,000, and the PW material kit for the ring case costs $300,000.

The modification involves a complete overhaul of the HPC module, with the case being exchanged and the front case modified. The blades of stages 8 to 12 have their tips coated, there is a modification to the turbine vane and blade cooling air valves, and there are two wiring harness modifications and new full authority digital engine control (FADEC) software. Boeing engines also require new quick engine change brackets and tubes.

Schmitz says that the turnaround time for the ring case implementation is 48 calendar days. The work is normally carried out in combination with an overhaul of the complete engine, for which the target time is 60 days.

According to operators, the modified compressor is good for about 30,000EFH or 6,000EFC.

PW says that incorporation of the ring case modification in the PW4000-94 fleet has eliminated the potential for surges. The OEM adds that the confirmed surge rate for the engine has been decreasing steadily since the ring case configuration was released, and over the past year the 12-month rolling rate has reached 0.000 per 1,000EFH. In addition, the PW4000-94's shop visit rate has fallen to 0.076, the lowest in its history.

Other issues

There are several other issues affecting the PW4000-94.

One is an inspection for the spacer between the sixth and seventh HPC stages, as a result of vibrations on these stages. An SB has been issued to deal with this vibration, and it involves the addition of a blade to the fifth stage.

Another modification is an FAA-approved SB issued by Boeing, which provides the data needed to revise PW4056-rated engines to a PW4060 rating, with thrust bump to PW4060C. The SB provides the instructions necessary to revise the thrust management computer and engine indicating and crew alerting system (EICAS) pin selectable wiring.

In other upgrades and modifications, Schmitz says there are some reliability issues with the engine. One is the problem of oil leaking from the bearing, and LHT recommends the implementation of an SB to improve the seals of the forward bearing compartment and the number three bearing compartment.

Another is the HPT stage 2, where Lufthansa Technik recommends the new blade configuration and the new T2 stator vanes for the turbine. The oil leakages and turbine issues have been the principal factors limiting time on-wing.

Cracks are the main problem with the T2 vanes, and Lufthansa Technik has developed a weld repair that means they can still be repaired even if the cracks are beyond the limits specified in the engine manual. AC

PW4000-94 fuel burn performance

The PW4000-94 powers many 1980s-generation widebodies. The fuel burn performance of the major aircraft types is analysed.

The PW4000-94 series powers a large number of widebody aircraft types and variants. The fuel burn performance of the most popular types is analysed. This engine family has various applications which include the A300-600, A310, 767 family, 747-400 and MD-11 *(see PW4000-94 specifications, page 10)*.

The applications analysed here include: the 767-200, 767-300 and 747-400 all powered by the PW4056; the 767-300ER with the PW4060; the A300-600R with the PW4158; the A310-300 with the PW4156A; and the MD-11 with the PW4460. The fuel burn performance of these airframe-engine combinations has been analysed on sample routes.

Aircraft analysed

There are several weight and fuel capacity specifications of each aircraft type with different variants of the PW4000-94, and these are summarised for the aircraft analysed *(see table, page 17)*.

The A300-600R with the PW4056 engine has been analysed with a maximum take-off weight (MTOW) of 378,533lbs and a fuel capacity of 16,124 US Gallons (USG). It has been analysed with a 266-seat configuration.

The A310-300 model analysed has an MTOW of 361,558lbs, a fuel capacity of 18,030USG and PW4156 engines *(see table, page 17)*. This is the highest gross weight and fuel capacity version of the A310-300. The aircraft has been analysed with 220 seats, which is typical of a European-style, two-class configuration.

The 767-200 and -300 models analysed have MTOWs of 351,000lbs and 350,000lbs respectively. Both have fuel capacities of 16,700USG, and are powered by the PW4056 engine. The -200 has been analysed with 230 seats, and the -300 with 260 seats. This is typical for a two-class configuration.

The 767-200ER aircraft was not included in this study, since there is only a small number in service powered with PW4000-94 engines.

The 767-300ER has an MTOW of 412,000lbs, the highest gross weight version of the -300ER, and a fuel capacity of 24,140USG, and is equipped with PW4060 engines. It has been analysed with 215 seats for long-haul operations and 230 seats for medium-haul operations. The 747-400 has the highest MTOW available of 870,000lbs, a fuel capacity of 57,065USG, and is equipped with PW4056 engines *(see table, page 17)*. It has been examined with a 390-seat configuration. The passenger variant of the MD-11 has an MTOW of 630,500lbs, the highest available for the aircraft, a fuel capacity of 38,615USG, PW4460 engines, and an interior layout of 298 seats.

Routes analysed

All airframe-engine combinations have been analysed on routes with lengths typical for their gross weight and range capability. The performance of each aircraft has been examined with a payload of a full complement of passengers. All routes used do not limit the aircraft's payload-carrying performance below its maximum passenger capacity. Aircraft performance has been examined in both directions on a route to reveal the effect of headwinds and tailwinds on fuel burn performance and flight time.

It should be noted that the tracked distances as listed *(see table, page 17)* vary between different aircraft on a given route, and also according to the direction flown. This is because two sources for the aircraft flight plan data were used: Airbus computed the flight plans for the A300-600 and A310, while plans for all the other aircraft were provided by Jeppesen. Furthermore, for the latter, the multiple waypoints and climb segments used in each flight plan would have influenced the actual tracked ground distance covered, as well as the winds encountered en route. Moreover, the waypoints used by Jeppesen could not match those provided by Airbus.

The low-weight and short-range aircraft, the A300-600R, 767-200 and 767-300, have been analysed on the intra-European route of Rome, Fiumicino (FCO) - Athens (ATH) whose stage length is similar to many US and Japanese domestic city-pairs where many of these aircraft operate. The route has an approximate tracked distance of 600nm and a flight time of 100 minutes for most types when flying at optimum long-range cruise. The alternate airport for Rome is Naples, and for Athens it is Crete.

The A310-300 and 767-300ER with 220 and 230 seats respectively have been analysed on Larnaca (LCA) - Paris (CDG), and Paris-Larnaca. The alternate airport for Larnaca is Paphos, and for Paris it is Brussels. This is typical of a medium-haul route, with a tracked distance of 1,700nm and flight time close to four hours, depending on the waypoints chosen for each calculation.

The 767-300ER configured with 215 seats and the 295-seat MD-11 have been examined on Copenhagen (CPH) - Tokyo, Narita (NRT). This is a typical long-haul route of 5,100nm, with a flight time of over 10 hours.

The 747-400's performance has been examined on Auckland (AKL) - Los Angeles (LAX), which has a tracked distance of 5,800nm and flight time of 12-13 hours, depending on the direction of travel.

The performance of all aircraft has been examined using 85% reliability winds for the month of July, a 15-minute taxi time (10 minutes out and five minutes in), and the optimum long-range cruise for each type. The standard weight for each passenger is given as 220lbs.

Aircraft fuel burns

As described, the aircraft have been split into groups, with two or three airframe-engine combinations being analysed on a specific city-pair that would be typical of airline deployment. The A300-600R, 767-200 and 767-300 have been examined on FCO-ATH. Travelling eastwards to Athens, aircraft experience an 18-21 knot tailwind. The tracked distance is either 616nm or 701nm (depending on whether the flight plans are supplied by Jeppesen or Airbus). With the tailwind, the resultant equivalent still air distance (ESAD) is between 590nm and 685nm *(see table, page 17)*. The 767-200/-300 both have a block time of 104 minutes, while the A300-600R missions take 103 minutes block time. On this sector, both 767 models burn similar amounts of fuel per passenger-mile. It should be noted that using the ESAD in this calculation of fuel burn per passenger-mile enables a like-for-like comparison between the aircraft in terms of quantifying the fuel required to transport a given payload over a given distance. Using tracked distance instead would skew the result because of the

FUEL BURN PERFORMANCE OF PW4000-94-POWERED PASSENGER AIRCRAFT

City-pair	Aircraft variant	Engine type	Seats	Payload lbs	MTOW lbs	Actual TOW lbs	Fuel burn USG	Flight time mins	ESAD nm	USG per pax-nm
FCO-ATH	767-200	PW4056	230	50,600	351,000	254,809	2,348	104	608	0.0150
FCO-ATH	767-300	PW4056	260	57,200	350,000	284,483	2,550	104	685	0.0143
FCO-ATH	A300-600R	PW4158	266	58,520	378,533	289,902	2,586	103	590	0.0165
ATH-FCO	767-200	PW4056	230	50,600	351,000	254,422	2,492	111	732	0.0148
ATH-FCO	767-300	PW4056	260	57,200	350,000	283,983	2,690	110	730	0.0142
ATH-FCO	A300-600R	PW4158	266	58,250	378,533	290,617	2,996	120	717	0.0157
CDG-LCA	767-300ER	PW4060	230	50,600	412,000	295,361	5,539	228	1,652	0.0146
CDG-LCA	A310-300	PW4156A	220	48,400	361,558	275,670	5,338	241	1,647	0.0147
LCA-CDG	767-300ER	PW4060	230	50,600	412,000	303,344	6,346	256	1,872	0.0147
LCA-CDG	A310-300	PW4156A	220	48,400	361,558	283,662	6,210	272	1,895	0.0149
CPH-NRT	767-300ER	PW4060	215	47,300	412,000	379,948	17,586	652	4,931	0.0166
CPH-NRT	MD-11	PW4460	298	65,560	630,500	52,267	24,866	630	4,925	0.0169
NRT-CPH	767-300ER	PW4060	215	47,300	412,000	381,279	18,332	675	5,140	0.0166
NRT-CPH	MD-11	PW4460	298	65,560	630,500	545,219	25,837	653	5,123	0.0169
AKL-LAX	747-400	PW4056	390	85,800	870,000	759,233	38,531	702	5,735	0.0172
LAX-AKL	747-400	PW4056	390	85,800	870,000	801,084	42,936	750	6,164	0.0179

variations in the figures, thereby making a meaningful comparison impossible.

On this basis, the 767-200 uses 0.015USG per passenger-mile (ESAD); the 767-300ER uses 0.0143USG; and the A300-600R uses the most fuel per passenger mile with 0.0165USG. In the westerly direction to Rome, a headwind of 52-66 knots increases the ESAD to 717-732nm *(see table, this page)*, which increases the fuel required. The fuel burned per passenger-mile (ESAD) is again similar for both 767 models: 0.0148USG for the 767-200; and 0.0142USG for the 767-300. The A300-600R, by comparison, burns 0.0157USG per passenger-mile.

Meanwhile, the A310-300 and 767-300ER are both examined on LCA-CDG, which is a medium-haul route of similar length to that on which many aircraft in this category are operated. In the easterly direction to Larnaca, the aircraft benefit from a small tailwind of 11-12 knots *(see table, this page)*. This results in an ESAD of 1,650nm, which compares to the tracked distance of 1,690nm. The A310-300's block time is 241 minutes, while the 767-300ER is a little faster with 228 minutes. The fuel burns per passenger-mile of the 767-300ER and A310-300 are very close indeed: 0.0146USG for the 767-300ER; and 0.0147USG for the A310-300.

In the westerly direction to Paris, the aircraft face a headwind of 40-51 knots, which increases the ESAD to 1,900nm *(see table, this page)*. This compares to a tracked distance of 100nm shorter. There is a small difference in flight times between the two, with the 767-300ER completing the missions in 256 minutes and the A310-300 in 277 minutes. Again, the 767-300ER has a slightly lower fuel burn per seat-mile, of 0.0147USG, compared to the A310-300's 0.0149USG.

The 767-300ER and MD-11 are examined on CPH-NRT, which is a long-haul route within their full payload-range capability that allows both types to comfortably carry a full passenger load. This is a trans-Siberian routing, so the aircraft face a headwind when operating in both directions. However, this is small at just three knots when travelling east to Tokyo, resulting in an ESAD of about 4,930nm. The actual tracked distance is therefore very similar at 4,902nm. On this long sector the 767's lower long-range-cruise speed gives it a 22-minute longer block time than the MD-11.

Despite having 83 more seats than the 767-300ER, the MD-11 has a higher fuel consumption per passenger-mile because of its much higher structural weight coupled with its lower lift-to-drag ratio. The MD-11 therefore has a fuel burn per seat-mile (ESAD) of 0.0169USG compared to 0.0166USG for the smaller 767-300ER.

In the westerly direction to Copenhagen, the tailwind rises to 27 knots, resulting in an ESAD of 5,130nm. This compares with the actual tracked distance of 4,852nm, giving a difference of 278nm.

The MD-11 has a flight time of almost 11 hours, while that of the slower 767-300ER is 22 minutes longer at 11 hours and 15 minutes *(see table, this page)*. Again, the MD-11 has a higher fuel burn per passenger-mile of 0.0169USG, compared to 0.0166USG for the smaller 767-300ER.

The 747-400 is examined on an ultra-long-haul route: AKL-LAX. Flying to Los Angeles the aircraft has a small tailwind of eight knots which results in an ESAD of 5,735nm compared with the actual tracked distance of 5,820nm, giving a 85nm difference.

The 13-knot headwind in the opposite direction results in an ESAD of 6,164nm compared with the actual tracked distance of 6,003nm, a difference of 161nm. Although the 747-400 is able to carry a full passenger load on Auckland-Los Angeles, its fuel burn performance per passenger-mile is worse than that of all the other aircraft analysed in this study. This is partly due to the 747-400 having a high overall lift-to-drag ratio, and partly due to its lower-than-optimum passenger load (the 747-400 can easily accommodate about 415 passengers in two classes, in contrast to the 390 here). AC

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.

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

PW4000-94 technical support providers

There are about 2,200 PW4000-94s in service with more than 700 aircraft. A global survey of six major levels of support identifies the major providers.

This survey summarises the major aftermarket and technical support service providers for the Pratt & Whitney (PW) PW4000 94-inch turbofan series.

It is grouped into six sections covering the categories of technical support offered by each of the providers:

1. Line maintenance and in-service operational support *(see table, page this page)*;
2. Engine management *(see table, page 30)*;
3. Engine provisioning *(see table, page 30);*
4. Engine components *(see table, page 30)*;
5. Shop visit maintenance *(see table, page 31);*
6. Specialist repairs *(see table, page 31)*.

Those companies that are listed in most or all of the six sections can loosely be called one-stop-shop service providers for the PW4000 94-inch family. This means that they provide most, if not all, the technical support services that a third-party customer would require. The survey tables show that the providers capable of offering a complete range of services for the PW4000-94 include: Delta TechOps; Lufthansa Technik; SR Technics; and, of course, the original equipment manufacturer (OEM), Pratt & Whitney Engine Services (PWES). Notably, United Parcel Services (UPS) and FedEx are among the OEM's largest engine overhaul customers. FedEx sends its A300/A310 and MD-11 engines to PWES's Cheshire Engine Center, while UPS sends similar powerplants to PWES's Eagle Services Asia. Martinair is another big outsourcing customer, sending its engines to both Eagle Services Asia and SR Technics.

Market share analysis

In terms of the major portion of PW4000-94 engine overhauls, the largest provider of full overhauls is the OEM itself. According to ACAS, which records actual maintenance contracts, PWES performs about half of all PW4000-94 engine shop visits. In the US, PWES's Engine Center, based in Cheshire, CT, accounts for 21% of total PW4000-94 worldwide engine shop visits, while its Eagle Services Asia venture with SIA Engineering Company (SIAEC) in Singapore performs 20%. ACAS also lists Pratt & Whitney as carrying out 6.2% of total worldwide engine shop visits for the PW4000-94.

The next biggest slice of the pie, 14.2%, is undertaken by airlines' own in-house overhaul facilities. One of these, United Services, offers third-party full-engine overhaul services to customers, accounting for 9.7% of the world total. The remainder include: Delta TechOps (5.4%), of which World Airways is a big customer; Lufthansa Technik (4.7%); Ameco Beijing (3.8%), a venture with Lufthansa Technik, primarily servicing Air China's fleet - together LHT and Ameco account for 8.5% of the worldwide PW4000-95 maintenance, repair and overhaul (MRO) market; SR Technics (3.6%); GE Engine Services (2.9%); Mitsubishi Heavy Industries (1.2%); Biman Bangladesh Airlines (0.6%); SAS Technical Services (0.4%); and Air India (0.29%).

Aftermarket perspectives

According to Robin Salisbury at PW, the PW4000-94 fleet is now experiencing 'unprecedented levels of reliability and on-wing durability', which PW 'expects to continue going forward'. This will reduce operators' maintenance costs, and ensure that overhaul shop capacity with existing suppliers will be more than adequate.

"PWES intends to continue to seek MRO volume as more operators outsource overhaul capability," notes Salisbury. "We are working with our customers to expand the scope of our offerings in engine health monitoring, defined-cost arrangements (flight-hour-based cost of maintenance), fleet management, and line maintenance services such as 'EcoPower', which is an environmentally neutral engine wash system that increases an engine's on-wing time by restoring exhaust gas temperature (EGT) margin, and improving fuel burn and CO2 emissions."

PWES, working with its 'global service partners', provides a full suite of engine overhaul, parts repair and replacement solutions, line maintenance and lease engines to support all models of the PW4000. These engines are overhauled at the company's two centres in Cheshire, CT, USA and in Singapore, which are supported by a worldwide network of 18 part-repair facilities. PWES also repairs composite material components, particularly for nacelle inlets and thrust reversers with exchange material available to support operators' needs.

In February 2006, FedEx chose PWES to provide an off-wing Fleet Management Program (FMP) as part of a 20-year

PW4000-94 LINE MAINTENANCE & IN-SERVICE OPERATIONAL SUPPORT

	On-wing maintenance	Line maintenance	Hospital repair/ Quick turn repairs	On-wing support	AOG/field services	Borescope inspection
Air India	Yes	Yes	Yes	Yes	Yes	Yes
AMECO Beijing	Yes	Yes	Yes	Yes	Yes	Yes
Delta TechOps	Yes	Yes	Yes	Yes	Yes	Yes
Egyptair E&M	Yes	Yes	Yes	Yes	Yes	Yes
Korean Air	Yes	Yes	Yes	Yes	Yes	Yes
Lufthansa Technik	Yes	Yes	Yes	Yes	Yes	Yes
Pratt & Whitney Engine Services	Yes	Yes	Yes	Yes	Yes	Yes
SIA Engineering (SIAEC)	Yes	Yes	Yes	Yes	Yes	Yes
SR Technics	Yes	Yes	Yes	Yes	Yes	Yes
United Services	Yes	Yes	Yes	Yes	Yes	Yes
VEM	Yes	Yes	Yes	Yes	Yes	Yes

PW4000-94 ENGINE MANAGEMENT

	Maintenance management & check planning	ADs/SBs management	Documentation management	Health/ condition monitoring
Air India	Yes	Yes	Yes	Yes
AMECO Beijing	Yes	Yes	Yes	Yes
Chromalloy	Yes	Yes	Yes	Yes
Delta TechOps	Yes	Yes	Yes	Yes
Egyptair E&M	Yes	Yes	Yes	Yes
GA Telesis	Yes	Yes	Yes	Yes
IASG	Yes	Yes	Yes	Yes
Korean Air Maintenance	Yes	Yes	Yes	Yes
Lufthansa Technik	Yes	Yes	Yes	Yes
Pratt & Whitney	Yes	Yes	Yes	Yes
SIA Engineering (SIAEC)	Yes	Yes	Yes	Yes
SR Technics	Yes	Yes	Yes	Yes
Total Engine Support UK	Yes	Yes	Yes	Yes
United Services	Yes	Yes	Yes	Yes
Varig VEM	Yes	Yes	Yes	Yes

PW4000-94 ENGINE PROVISIONING

	Short-term leasing	Medium- & long-term leasing	Engine pooling	Sale & leasebacks
Chromalloy	Yes	Yes	~	~
Delta TechOps	Yes	Yes	Yes	~
Engine Lease Finance Corp (ELFC)	Yes	Yes	~	Yes
Lufthansa Technik	Yes	Yes	Yes	Yes
Pratt & Whitney	Yes	Yes	~	Yes
SR Technics	Yes	Yes	Yes	Yes
Willis Lease	Yes	Yes	Yes	Yes

PW4000-94 ENGINE COMPONENTS

	QEC repair	QEC build-up & engine dressing	LRU repair	LRU pooling & logistics
Delta TechOps	Yes	Yes	Yes	Yes
GKN Aerospace	Yes	~	~	~
Korean Air Maintenance	Yes	Yes	Yes	Yes
Lufthansa Technik	Yes	Yes	Yes	Yes
TCI International	Yes	~	Yes	Yes
Pratt & Whitney	Yes	Yes	Yes	Yes
SR Technics	Yes	Yes	Yes	Yes

exclusive contract for the operator's fleet of PW4000-94 engines. The agreement includes the overhaul and repair of 135 PW4000 engines operating on FedEx's fleet of MD-11s, A300-600s and A310s, with the option to include any PW4000-94-equipped aircraft added to its fleet throughout the lifetime of the contract. The engines will be maintained within PWES's global service partners' restoration and repair network. PWES will manage the performance of FedEx's PW4000 fleet using its advanced diagnostics and engine management (ADEM) system, which is a web-based, automated tool.

Europe is host to some significant providers of PW4000-94 aftermarket services. Of these, SR Technics (SRT) has refurbished more than 1,650 PW4000-94s at its engine overhaul facility in Zurich. A notable recent contract was with Air Macau, which signed a five-year contract in 2006 with SR Technics for engine maintenance and support for the PW4158 engines on the airline's A300-600 aircraft. Other PW4000-94 MRO customers include: Martinair Holland (MD-11F, 747-400F and 767-300); Aeromexico (767-200 & -300); Belair (767-300); Tarom (A310-300); Transmile Air Services (MD-11F); and XL Airways (767-300).

The company offers what it calls 'integrated engine solutions' (IES), which include field team availability, engineering support, and removal planning throughout the engine's lifecycle. SRT provides PW4000 engine services to more than 60 different airlines or leasing companies, including non-exclusive contracts.

According to Vivienne Burch, marketing spokesperson at SRT, the competition for the MRO work on the PW4000 engine is strong. This depends largely on technical support providers; having sufficient shop capacity and access to available parts coming from the aftermarket. Moreover, on the PW4000-94 in particular, Burch reports that SRT is seeing increasing business from non-exclusive contracts. SRT is also actively following-up the re-entry of aircraft such as the 747-400.

"This situation has arisen because of delays on both the Airbus A380 and the 787," notes Burch. "The result of these delays is that leasing companies and other parties are offering older 747-400s (and other types) as an alternative until the new generation of large aircraft enters service. This therefore provides SRT with the opportunity for many shop visits and ring case modifications for PW4000 engines."

Burch observes that the PW4000-94, which is still in production, will be in operation for 'quite some time'. This is because many aircraft, including the A300, 767, MD-11, and 747-400 will be converted to freighters, which are expected to reach an age of 30 years.

On the provider side of the market, Burch believes that the OEM will aggressively try to increase its market share by offering spare engines and low shop visit rates. "The risk for airlines is that PWES will gain market domination and increase its prices to recover the losses made during its quest for market share," she notes. "A general consolidation in the PW4000 overhaul market is also expected. Volvo has already left, and other providers might change their capabilities when the aircraft leave the fleet of their main customer."

Another big player, Lufthansa Technik, performs most of its PW4000-94 overhauls in Hamburg, but also has capabilities at its joint venture partner Ameco Beijing. Together they account for more than 8% of the PW4000-94 overhaul market. Customers include: Aerolineas Argentinas, Air Madagascar, Cathay Pacific Airways, China Southern,

PW4000-94 SHOP VISIT MAINTENANCE

	Hot-section inspection	Module change	Module overhaul	Full overhaul	No of annual shop visits	Mods & upgrades	Disassembly/ build-up	On-site test cell	Specialist processes (HVOF/plasma)
Air India	Yes	Yes	Yes	Yes	n/s	Yes	Yes	Yes	Yes
AMECO Beijing	Yes	Yes	Yes	Yes	n/s	Yes	Yes	Yes	~
Delta TechOps	Yes	Yes	Yes	Yes	>65	Yes	Yes	Yes	Yes
Egyptair E&M	Yes	Yes	Yes	Yes	n/s	Yes	Yes	~	~
Lufthansa Technik	Yes	Yes	Yes	Yes	40-50	Yes	Yes	Yes	Yes
Korean Air Maintenance	Yes	Yes	Yes	Yes	n/s	Yes	Yes	Yes	Yes
Pratt & Whitney	Yes	Yes	Yes	Yes	>250	Yes	Yes	Yes	Yes
SIA Engineering (SIAEC)	Yes	Yes	Yes	Yes	n/s	Yes	Yes	Yes	Yes
SR Technics	Yes	Yes	Yes	Yes	>120	Yes	Yes	Yes	Yes
United Services	Yes	Yes	Yes	Yes	n/s	Yes	Yes	Yes	Yes

PW4000-94 SPECIALIST REPAIRS

	Fan blade repair	Vanes & stator repair	Compressor blade repair	Turbine blade repair	Combustor repair	Casing repair	Seals repair	On-site DER authority	PMA parts approved
Asian Compressor Technology services	~	Yes	~	~	~	~	Yes	~	~
Asian Surface Technologies/ Praxair	Yes	~	~	~	~	~	~	~	~
Barnes Aerospace Windsor Airmotive	~	~	~	~	~	Yes	Yes	Yes	~
Chromalloy	~	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Delta TechOps	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
GKN Aerospace	Yes	~	~	~	~	Yes	~	~	~
Lufthansa Technik	Yes	Yes	Yes	~	Yes	Yes	Yes	Yes	Yes
Pratt & Whitney Engine Services	Yes	Yes	Yes	~	Yes	Yes	Yes	Yes	Yes
PWA International	~	~	~	~	~	Yes	~	~	~
SR Technics	~	Yes	Yes	Yes	Yes	Yes	Yes	Yes	~

Condor Flugdienst, Corsairfly, Czech Airlines, LAN Airlines, and Lauda Air.

Klaus Mueller, marketing research manager at LHT, notes: "Of course the engine is ageing, and many shop visits are in their second or third life. Consequently, the age of the PW4000 will play a role in the cost per event, which is increasing. The ring case modification is a market driver, but airlines and operators are tending to include that modification programme in a regular shop visit."

Mueller observes that in 2007, the total number of shop visits (for the worldwide market) on the PW4000 increased sharply. "The global average of 300 shop visits for the past two years has risen to 550," he notes. "Many engines from the mid-to-late 1990s are coming into their third lives, so I expect the average number of shop visits for the next four or five years to stabilise at 500 engines per year."

Specialist repairs

GKN Aerospace Engine Products has full repair and overhaul capability for the 94-inch fan PW4000 engine on both the Phase I and Phase III fan blades, as well as the exhaust sleeve. Its fan blade business is located in El Cajon, CA, while its PW4000 exhaust sleeve repairs are undertaken at its facility in Santa Ana. According to Steve Pearl, marketing spokesperson at GKN's Chem-Tronics division, the company has several approved OEM repairs available, as well as extended designated engineering representative (DER) repairs.

Another PW4000-94 component repair and modification specialist is Barnes Aerospace/Windsor Airmotive Division, which offers alternative DER repairs on many PW4000 engine components. Its facilities in Connecticut, Ohio and Singapore perform P&W-approved repairs and modifications on a variety of parts, including: casings and frames; rotating parts such as disks, drums and low pressure turbine (LPT) rotating air seals; honeycomb seal repair; high pressure solid turbine shroud; and other major turbine engine components. Windsor Airmotive also provides DER repairs on PW4000-94s, and other engine types.

William Gonet, vice president of sales and marketing at Barnes Aerospace, believes that the overhaul market remains strong for the PW4000-94 engine for the foreseeable future. "Windsor Airmotive will continue to invest in new processes and equipment to meet the needs of the PW4000-94 overhaul market, along with the other large commercial turbine engines. One of our key strengths is our ability to work effectively with the OEMs to provide them with valuable repair solutions."

Another specialist provider, Asian Compressor Technology Services (ACT), Taiwan, repairs and overhauls high pressure compressor (HPC) stators and variable vane inner shrouds (VVIS) on the PW4000-94 . Its customers for these repairs include China Airlines and SIA, as well as other regional carriers. ACT was ISO14000 certified in 2003.