747-400 maintenance analysis & budget

The 747-400 clearly has lower maintenance costs than its older -200 and -300 series counterparts. Combined with lower fuel burn, the 747-400 will displace the older Classic models.

The 747-400 is the most successful series of the 747 model, having won 694 of the 1,500 total orders for the aircraft family. The 747's size means that it has always been operated by a small number of the largest airline, the majority of which are flag carriers. The first -400s went into operation in early 1989 with Northwest Airlines, with 660 having now been delivered, and about 35 still on order. The last orders for the -400 series have now been placed, selling in small numbers because the market is now focusing on the new -8 series.

The 747-400 replaced most 747-100s, -200s and -300s in mainline passenger operation. The 747-400 has no direct competitors, although the 777-300/-300ER are the closest in seat capacity and range capability. The 747-400 freighter also has a unique payload capacity, and is, like the passenger variant, in a class of its own. These factors could see 747-400s remaining in operation until they are 25-30 years old, which means that the majority of these aircraft are less than halfway through their lives, with about 500 having been delivered since 1992.

The 747-400's full maintenance costs are analysed here, including: line and ramp maintenance; base check maintenance; engine repair and overhaul; heavy component maintenance; and rotable repair and management.

747-400 in operation

Of the 700 -400 series that have been ordered, 465 are passenger variants and another 61 are configured as Combis. Another 166 aircraft are freighters, which is a high percentage of the fleet compared to other types *(see 747-400 fleet analysis, page 7)*. The 747-400's popularity as a freighter is explained by its payload-range performance, which allows it to carry a near full payload across the Pacific, albeit with a technical stop at a midway refuelling point like Anchorage, Alaska.

The 747-400's size makes it a high-risk aircraft to operate. Like the -100 and -200 'Classic' series before it, the -400 is operated by airlines that are regularly able to fill its large capacity. This requires both a large operating base and a well developed route network with routes and traffic rights to a large number of major airports. The -400's largest operators are British Airways (BA) (57 aircraft), Cathay Pacific (23), China Airlines (15), Japan Airlines (40), Korean Air (25), Singapore Airlines (SIA) (23) and United Airlines (30). Other operators include Air China, Air France, Air India, EVA Air, KLM, All Nippon Airways, Lufthansa, Northwest, Thai International and Qantas.

The -400 is clearly a long-haul workhorse, and accumulates up to 5,000 flight hours (FH) per year in most operations. It is used to operate on some of the world's longest and busiest routes, such as London-Singapore and -Hong Kong, Sydney-Singapore, Auckland-Los Angeles. The average flight cycle (FC) time in passenger operations is 7.5FH. The longer-range -400ER is exclusively used on ultra-long-distance routes, and has longer average FC times of 11.5FH.

The 747-400 is also a major freighter. Virtually all orders for 747-400s in recent years have been for freighter variants. There are 131 aircraft in operation, with the fleet split between 109 -400Fs and 22 -400ERFs. The largest fleets are operated by China Airlines (20), Cargolux (14), Atlas Air (15), Korean Air (10) and SIA (18). The largest number of -400ERFs in operation are a fleet of eight with Korean Air, and smaller fleets of two or three aircraft operated by KLM and Jade Cargo of China. All 35 outstanding orders for the 747-400 are for -400F and -400ERF models.

Freighter aircraft operate shorter average routes than passenger aircraft, because the range performance of the freighter models is shorter than that of passenger aircraft. The majority of -400Fs and -400ERFs have been acquired to operate routes serving markets in the Asia Pacific and China. Aircraft often require technical stops to refuel when carrying full payloads, so their average FC time is 6.0FH as a result. Freighter aircraft accumulate 4,800FH per year.

The 747-400 has clearly not yet entered the arena of used aircraft, although a small number of the oldest examples have been converted to freighter and have been returned to service in the cargo divisions of their original operators.

A large number of 747-400s are expected to be converted to freighter as aircraft now come due for retirement

The 747-400 is used as a long-haul workhorse, with aircraft achieving annual rates of utilisation of 4,500-5,000FH per at average FC times of 8.0-11.0FH.

The 747-400's MPD has an A check interval of 600FH, C check interval of 7,500FH and 18 months, and D check interval of 72 months. Some operators have managed to extend A check intervals to 850FH and C check intervals to 24 months.

from passenger service. Few aircraft are likely to be operated by secondary passenger airlines, however, because of the difficulty in filling them profitably.

The 747-400's full maintenance costs are examined here for a passenger aircraft completing 5,000FH and 625FC per year, at an average FC time of 8.0FH, and for a freighter completing 4,500FH and 750FC per year, at an average FC time of 6.0FH.

Maintenance programme

The 747-400 has a maintenance steering group 3 (MSG3) programme, which is similar to the programme for the 747-200's/-300, from which it is derived.

The 747-400's line and ramp maintenance programme has pre-flight checks prior to the first flight of each working day, a transit check prior to all other flights of the day, a daily check up to every 48 hours and a weekly check with a maximum interval of eight days.

Daily checks will often be performed at the operator's homebase, and airlines are often allowed an interval of up to 48 hours. Daily checks sometimes have to be performed at outstations by sub-contractors.

The basic A check interval in the original maintenance planning document (MPD) was 500FH, but it has been revised to 600FH. The 500FH interval is still used by some operators, but it will be extended to 600FH for several carriers. Some of the more experienced operators are trying to escalate the A check interval to a higher number of FH. "The 747-8 is expected to have an MPD interval of 800FH at service entry, so we are trying to extend it for the -400s," says Wilfred van Duuren, director of widebody base maintenance at KLM Engineering & Maintenance. "Our own MPD interval has already been extended to 850FH and 150FC, whichever is reached first. The 150FC limit is for engine-related items, including engine borescopes. Our customers also benefit from this extended interval, which includes a major Chinese freight operator and two important European 747-400 operators. KLM Engineering & Maintenance manages the engineering for these airlines, so they have the same check intervals as us."

Besides the 1A items, there are five groups of A check task multiples, the highest of which are the 6A items with an interval of 3,600FH. The other tasks are 2A, 3A, 4A and 6A tasks with intervals of their respective multiple of 600FH.

The full A check cycle is therefore theoretically reached when all these multiples are in phase, which will not be until the 12th check in succession, the A12 check. This will have a full interval of 7,200FH. The actual amount of this interval that an operator is able to utilise will be influenced by their ability to schedule and plan maintenance in accordance with the aircraft's operation. A typical rate of A check utilisation is 75-80%. Airlines will therefore be performing checks every 400-500FH.

The 747-400's base maintenance programme comprises two independent cycles of C and D checks. The 747-400's basic C check interval for 1C tasks is 7,500FH and 18 months, although this has been extended from a shorter interval in an earlier revision of the MPD. These two intervals mean that an aircraft can operate for 5,000FH per year and reach both limits at the same time. This is similar to the annual rate of utilisation achieved by most operators.

Freight aircraft operating at lower levels of utilisation will not be able to fully utilise the 7,500FH limit in the 18-month interval.

Most operators' C check intervals are the same as, or close to, the MPD interval. United Airlines, for example, has an interval of 18 months with no FH limit.

"Our C check intervals are longer than the MPD intervals," says van Duuren. "The C check interval is 24 months for aircraft up to 14 years of age under our programme, and is reduced to 18 months for aircraft older than 14 years. Operational constraints mean that we are not quite able to fully utilise these intervals. We are trying to escalate the interval to 24 months for aircraft older than 14 years. The other main benefit is that our C check intervals do not have an FH limit."

The 747-400's MPD comprises another three groups of C check tasks: the 2C, 3C and 4C items with respective intervals that are multiples of the base 1C interval. There are relatively few 3C items, while the 4C is a large group of tasks. These tasks have an interval of 30,000FH and 72 months, equal to six years.

The 747-400's D check MPD interval has similarly been extended with operational experience accumulated by the aircraft. The original MPD interval of 25,000FH and 60 months has been extended to 72 months. This interval is used by United and Ameco Beijing. The D check interval is therefore equal to the 4C interval, so the two are performed together, although the C and D check tasks run as two independent groups of inspections.

KLM's D check interval is longer than the MPD interval. "The interval for the first D check in our programme is 96 months," says van Duuren. "This is equal to four times the basic C check interval for aircraft of this age. All subsequent D checks have an interval of 72 months."

Line, ramp & A check inputs

A passenger aircraft, operating at 5,000FH and 625FC per year, will complete about 350 pre-flight checks annually, and another 275 transit checks

The 747-400 completes a base check about once every five years. This is long compared to younger generation aircraft. The 747-8 is expected to have a D check interval of eight years.

for the remaining number of FCs completed over the course of the year. It will also undergo about 325 daily checks and 50 weekly checks every year.

A freighter aircraft operating at 4,500FH and 700FC per year will have the same number of pre-flight, daily and weekly checks per year, but about 400 transit checks.

Budgets for inputs for these checks will be three man-hours (MH) and $20 of materials for a pre-flight check, 1.5MH and $10 of materials for transit checks, 25MH and $80 of materials for daily checks, and 30MH and $100 of materials for weekly checks.

Passenger aircraft will use 11,000MH and $41,000 in materials and consumables a year. Labour for line and ramp maintenance charged at $70 per MH will take the total annual cost to $820,000, equal to $165 per MH *(see tables, page 24).*

Freighter aircraft will use 11,500MH and $42,000 in materials and consumables, taking the cost for line and ramp checks to $190 per FH *(see tables, page 24).*

Inputs for A checks vary with the tasks included, since lighter checks include the 1A and 3A tasks, while heavier checks also include the 2A, 4A and 6A tasks. These make the A4, A6, A8 and A12 checks the largest. "The average labour requirement for A checks is 550MH," says van Duuren. "This is the total package that includes routine inspections, rectifications, modifications and interior work. The A check has a downtime of 24 hours and requires 90-100 mechanics. About $17,000-18,000 should be budgeted for materials and consumables for passenger aircraft, but $43,000-44,000 for Combis which have the freight loading system."

An aircraft will therefore consume 6,500MH every A check cycle, with an average interval of 450FH and $175,000 of materials and consumables. The cycle will be completed about once every 5,400FH. Labour charged at the rate of $70 per FH will take the total cost for the inputs to $680,000, equal to a cost of $125 per FH *(see tables, page 24).*

Base check contents

Inspections

The full C and D check workpackages on the 747-400 comprise several elements. The first of these is naturally the routine inspections and job cards, as previously described. The earlier 747 'Classic' models, the -100, -200 and -300 series, had separate ageing aircraft inspections added to their initial maintenance programmes, comprising four elements: the corrosion prevention and control programme (CPCP); the supplemental structural inspection document (SSID); the repair assessment programme; and the widespread fatigue damage programme. The SSID can often be confused with the significant structural inspection (SSI) items, which form part of the original maintenance programme.

The 747-400's MSG3 maintenance programme has incorporated these ageing aircraft inspections into the MPD, thereby simplifying maintenance.

These routine inspections result in non-routine rectifications. Operators will also use the C and D checks to clear all outstanding defects that have arisen during operation and that have not been cleared during the lighter A checks.

Base checks will also include out-of-phase (OOP) items, such as the inspection and removal, for repair and overhaul, of hard-timed rotable components like batteries and safety equipment.

Engineering orders

Another major element of base checks is inspections relating to service bulletins (SBs) and airworthiness directives (ADs), and associated terminating actions. The 747-400 is fortunate not to be affected by the major ADs that applied to the 'Classic' series, in particular the Section 41 inspection and modification programme. Cracks in the forward fuselage Section 41 on the 747 Classics were discovered in the mid-1980s, as a result of which an AD was issued to force inspections and terminating action. This only affected 747s up to line number 685, and all -400 models are exempt.

A second major modification, which did affect a small number of -400 series aircraft, concerned engine pylons. In-flight separation of engines from three aircraft resulted in AD 95-13-05 being issued in 1995. This affected 747s up to line number 1,046, and so included 321 -400 series aircraft.

The modification required the use of stainless steel engine mounting bolts and the fitting of new engine mountings in the engine pylon. The deadline for completing this modification was 1998, so all affected aircraft have been modified.

The 747-400 is affected by a few moderate ADs and SBs. "The first of these is the AD relating to the dual side brace modification which affects the mounting on the pylons. The AD number is 2005-19-09," says van Duuren.

The AD requires inspections of the dual side braces and mid-spar fittings that attach the engine pylon to the wing. These items are repaired and modified as mandated by the AD. "Carrying this out on each aircraft takes 800MH and $13,000 in materials, and is included in the D check," explains Robert Henry, manager of line maintenance and event & capacity planning at United Services. "The AD also requires the purchase of three sets of special project tooling at a cost of $570,000.

"There is another AD that requires the removal of the heat exchanger from

Base check contents will include routine inspections, non-routine rectifications, EOs, out-of-phase tasks and clearing deferred defects. D checks can often also include refurbishment of the interior and stripping and repainting.

inside the fuel tank, and modifications to prevent electrical arcing in the event of a lightning strike," continues Henry. "This takes 180MH per aircraft to complete."

A third major AD to complete on the 747-400 involves a modification to thrust reverser locks to prevent in-flight deployment. Van Duuren estimates that carrying this out requires about 870MH, and it is performed during a D check.

A fourth major upgrade affecting the 747-400 is a modification to the fuel harness, and is performed during a D check. "This is still only an SB at the moment," explains van Duuren, "and requires 400MH and a kit of $70,000 to complete."

An example of an SB with a smaller impact that can be included in 747-400 base checks is the replacement of the trim air diffuser duct (TADD). "This is because ducts and joints deteriorate over time due to high air temperatures. This SB requires about 65MH and $26,000 of materials per aircraft to complete," says Henry. "Another SB is the replacement of the electrical equipment centre drip shield, which requires the removal of associated electrical equipment to gain access to, and replace, cracked and damaged drip shields. This SB requires 100MH and $4,000 in materials to complete per aircraft."

Van Duuren explains that the list of SBs and ADs worked on during base checks will be unique to each check, since airlines will plan them into checks as they are issued and according to which SBs they want. The MH used for SBs and ADs during base checks therefore vary between checks, but an amount of MH has to be budgeted.

Rotable components

C and D checks will also include the removal of some rotable components for repair and overhaul. These will be scheduled during these base checks either because they are large items that require the downtime of base checks to remove them, or because they involve deep access to the aircraft.

Removed items will have to be reinstalled once repaired if they are closed-loop components, or have repaired components installed in their place if they are open-loop components.

Examples of large items are the landing gear, which requires 1,000MH for removal and installation of a shipset. Other examples are thrust reversers and the auxiliary power unit (APU).

Examples of smaller components are batteries, evacuation slides and oxygen bottles.

Interior work

Interior work is another major element of C and D check workpackages. The list of interior items is extensive on a passenger aircraft, and includes: seats; carpets; curtains; sidewall and ceiling panels; the bulkhead; toilets; galleys; overhead bins; passenger service units; in-flight entertainment (IFE) equipment; lighting; and air conditioning ducts. The interior was traditionally repaired and cleaned on an on-condition basis during A and C checks, and refurbished during D checks. "The extended maintenance intervals, especially of heavy checks, has led to some airlines adopting a more on-condition approach to interior refurbishment and maintenance," says van Duuren.

"The interior of the 747 is usually refurbished every D check," says van Duuren, "although the timing for refurbishment is determined by the downtime allowed by the check as well as the condition of the cabin."

United performs a complete interior refurbishment at the D check, since this provides about five weeks of downtime plus the access provided by deep inspections that require removal of galleys, toilets and panels. "We use the A and C checks to maintain the interior for functionality and appearance as part of a find-and-fix programme," says Henry. "The D check involves the refurbishment and replacement of most interior items. About 85% of the interior items are refurbished, while 15% have to be replaced."

Other operators choose to refurbish the interior in portions at different base checks. "We remove major interior items in conjunction with the CPCP inspections," explains Shaul Peri, maintenance specification manager, at El Al Engineering. "This means that we remove and overhaul different items when CPCP inspections dictate their removal, so we refurbish parts of the interior at each C check. The seats are overhauled every 5-6 years."

Interior cleaning and refurbishment account for a large percentage of the total MH used during C and D checks in passenger aircraft. Freighter aircraft use fewer MH for interior work. While all passenger-related items are absent, freighter aircraft do have cargo loading systems which suffer punishment from loading and off-loading pallets and containers. Freighters therefore require some MH for interior-related items.

Stripping & repainting

Stripping and repainting are another item that is treated on an on-condition basis by many airlines, although completion of a strip and repaint on a 747-400 takes 12-16 days. This is done under the D check that is performed every five to six years. Some airlines schedule this at either end of a D check, while others strip and repaint their aircraft at longer intervals of seven years.

Lufthansa Technik strips and repaints its 747-400s every six to eight years, and estimates that this requires 2,600-3,000MH and $70,000 for the paint.

The MH and material cost inputs a 747-400 uses in a complete base check cycle is 40-45% less than that required by the 747-200/-300 in a full base check cycle.

Base check inputs

The 747-400 certainly has lower total inputs for labour and materials and consumables over its base check cycle than the 747-200/-300.

The labour input for the first three C checks, the D check that includes the fourth C check, complete interior refurbishment, and stripping and repainting, totals 80,000-85,000MH. This labour input is used for mature passenger-configured aircraft in their second or third base check cycle, which will have an interval of about 26,000FH when probable utilisations of check intervals are considered.

This compares to a total labour input of 135,000-170,000MH for the three C checks, D check, interior refurbishment, and stripping and repainting used for a 747-200/-300 in its fourth or fifth base check cycle with an interval of 20,000FH *(see 747-200/-300 maintenance analysis & budget, Aircraft Commerce, June/July 2005, page 13).*

The actual contents of base checks vary, and some operators choose to schedule the majority of engineering orders and interior work in the D check, thereby resulting in relatively small C checks. Others have larger C check workscopes and smaller D checks.

Henry estimates that C checks consume an average of 10,000MH and another $175,000-225,000 in materials and consumables. Checks vary in size and content, however, and the lighter C1 and C3 checks can consume in the region of 9,000MH, while heavier C2 checks will use 5,000MH.

The following D check will use 48,000-50,000MH. The associated cost of materials and consumables for this check will be $600,000-750,000. The additional task of stripping and painting, which is done about once every base check cycle, will use 3,000MH. The cost of paint and other materials used is $75,000-100,000.

This system of organising base maintenance results in relatively large C checks, with some of the cabin refurbishment tasks being scheduled in these checks. Operators may also choose to include some major modifications in these checks, which will result in relatively light D checks.

The inputs for these base checks will take the total labour consumed to 84,000-86,000MH, and total materials and consumables to $1.2-1.4 million. A labour cost of $50 per MH will take the total cost for this base check cycle to $5.4-5.7 million. This is equal to a reserve of $208-220 per FH *(see table, page 24).*

An alternative way to organise base check workscopes is to schedule all major tasks in the D check, and have just routine inspections, non-routine rectifications, some cabin cleaning and a relatively small package of SBs and ADs in the C checks. This will leave all major items for the D check, making it relatively large. A cabin refurbishment programme can be added to a C check if necessary. "We feel it is better to use the D check, because there are several items which result in a long check downtime, and so should be done in the D check," says Andreas Drosdowski, leader of maintenance planning services and Lufthansa Technik. "These items include refurbishment of the interior, major modifications, installation of new IFE equipment, and overhaul of major rotables like the flap carriages. We feel that it is best to put all these items in the D check. There are also some findings arising from inspections in the C check that can be deferred to the D check. The result of following this philosophy is that the C checks are relatively small and the D checks large.

"The C checks use about 2,500MH for routine inspections and an average of 1,500MH are required for non-routine rectifications, resulting in a sub-total of about 4,000MH," continues Drosdowski. "Another 1,000MH are used for cabin cleaning and some light refurbishment. Unless there is a major modification to be performed, 300-500MH will be used for engineering orders (EOs). This results in a total of 4,000-5,000MH. While there are some differences in the size of different C checks due to different inspection packages, the total MH used for the checks only varies by 5-10%. The cost of associated materials and consumables is in the region of $85,000.

"The D check uses about 22,000MH for routine inspections. This is about the same for the D1, D2 and D3 checks," continues Drosdowski. "The labour required for non-routine has increased from about 22,000MH for D1 checks to 28,000MH for D3 checks, resulting in a sub-total of about 50,000MH for routine and non-routine labour. The amount of non-routine labour has increased with aircraft age because of structural damage and corrosion found in the galley lift and stairs connecting the main and upper passenger decks. A further 5,000MH will be used for interior refurbishment, which accounts for virtually all the interior and cabin refurbishment made over the base check cycle. Another 3,500-5,000MH will be used for EOs and modifications, and 800-1,000MH can be used for changing heavy components such as landing gears. This reaches a total of about 60,000MH for a D3 check, and compares to 54,000-55,000MH for a D1 check. Another 3,000MH can be added to the check total if stripping and painting are included at this time. These are productive MH. Another 5,000MH can be used for management issues that include check planning, task card preparation, controlling, administration and material management. A third-party

Freighter aircraft use only about 3,000MH fewer MH for a D check than a passenger aircraft. While a freighter will use about 5,000MH less because it has no interior to refurbish, it will use about 2,000MH to repair its cargo loading system.

maintenance provider can either charge for the additional management MH, or include them as an element of the labour rate charged for the productive MH.

"The associated cost of materials and consumables for a check of this size will be about $1.25 million," continues Drosdowski.

Using the *Aircraft Commerce* standard labour rate of $50 per MH for base maintenance checks, the 63,000 productive MH for a D3 check, including stripping and painting, on a passenger-configured aircraft will take the total cost to about $4.4 million. It is generally observed that there is only about a 5% variation in the number of MH used for the same check on different aircraft in the fleet.

The total labour for the third or fourth base check cycle for a passenger aircraft is therefore expected to be 77,000-80,000MH. The total cost, including materials and consumables, is $5.3-5.5 million, which is equal to a reserve of $205-212 per FH *(see table, page 24)*.

There are also large numbers of 747-400 freighters in operation, so base check inputs also have to be considered for these aircraft. "While all 5,000MH used for the interior refurbishment during the D check will not be used for a freighter, there will be a further 2,000MH used for defects on the cargo loading system, so there will only be a net reduction of about 3,000MH compared to the D check for a passenger aircraft," says Drosdowski. "A D3 or D4 check on a 747-400 freighter will therefore use about 60,000 productive MH." The cost of materials will be lighter for a freighter, because of the absence of interior items, so this will be in the region of $0.8 million, thereby taking the total cost to about $3.8 million.

The total inputs for the full base check cycle for a mature freighter will therefore be about 72,000MH and $1.1 million in materials and consumables, taking the total cost to $4.7 million. At an annual utilisation of 4,500FH, freighters would be able to complete a base check cycle in about 25,000FH, so reserves would therefore be about $190 per FH *(see table, page 24)*. Many freighter operators, however, achieve higher rates of utilisation in excess of 5,500FH per year, so they would have longer intervals and lower reserves over the full base check cycle.

Rotable components

The majority of rotable components on the 747-400 are maintained on an on-condition basis, or are condition monitored. Few components are maintained on a hard-time basis.

Northeast Aero is a rotable repair shop in New York state. "We specialise in repairing several hundred rotable part numbers for several aircraft types, including the 747-400. These fall into the categories of pneumatics, hydraulics, fluid and air driven components, and electromechanical components," says Vic Calabrese, vice president of operations and quality control at Northeast Aero Inc. "Our core business is components like air cycle machines, and associated components like valves and actuators. An example of a pneumatic component is the leading edge flap drive on the 747-400. Most of these components are now maintained on an on-condition basis, which is done as an attempt to drive down maintenance costs. The repair and management of these components can therefore be included as part of an all-inclusive rotable support packages that are offered to airlines from specialist rotable suppliers. One such company that is a customer of ours is AAR. We also deal directly with airlines. Our airline 747-400 customers include UPS, Air France, China Airlines and EVA Air."

Andre Fischer, section manager of product sales aircraft component services at Lufthansa Technik, estimates that there are 800-1,000 rotable part numbers installed on the 747-400, with the actual number depending on the configuration and modification status of the aircraft. The total number of rotable components installed is 2,500-2,700, with the actual number again dependent on the aircraft's configuration. Only 30-50 of these rotables are hard-timed, and these include safety items such as oxygen bottles and escape slides. The cost of maintaining these components is included in base check costs.

Besides items such as wheels and brakes, most rotables are maintained on-condition, so they are removed after failure. These items can be supplied, maintained and managed in an all-inclusive support package for an operator. "We can provide a customer with a Total Component Support (TCS) package, where we are responsible for monitoring the reliability of components, managing the exchange of failed parts with serviceable units, managing all paperwork and documentation, and managing repairs and other items such as transport and storage," says Fischer.

The costs of this type of service comprise three elements. The operator will be supplied with an inventory of homebase stock, which are items that they will require at their homebase. These can be leased. The list price for this inventory of stock is $6-8 million for a fleet of five aircraft, and $9-11 million for a fleet of ten. Freighter aircraft will require smaller inventories than passenger aircraft because of the difference in cabin- and passenger-related items.

Monthly lease rates for these components are 1.2%,which is equal to about $29 per FH for a fleet of 10 passenger aircraft operating at 5,000FH per year. The rate for five freighters operating at 4,500FH per year is about $39 per FH.

The remaining parts can be accessed

747-400 HEAVY COMPONENT MAINTENANCE COSTS

Number of main & nose wheels	16 + 2
Tyre retread interval-FC	250/325
Tyre retread cost-$	550/450
Number of retreads	4
New main & nose tyres-$	2,000/1,100
$/FC retread & replace tyres	**58**
Wheel inspection interval-FC	250/325
Main & nose wheel inspection cost-$	2,500
$/FC wheel inspection	**175**
Number of brakes	16
Brake repair interval-FC	2,000
Brake repair cost-$	70,000
$/FC brake repair cost	**560**
Landing gear interval-FC	5,500-6,000
Landing gear exchange & repair fee-$	700,000
$/FC landing gear overhaul	**120-130**
Thrust reverser repair interval-FC	5,000
Exchange & repair fee-$/unit	300,000
$/FC thrust reverser overhaul	**200**
APU hours shop visit interval	9,000
APU hours per aircraft FC	2.5
APU shop visit cost-$	450,000
$/FC APU shop visit	**125**
Total-$/FC	**1,235**
Total-$/FH passenger aircraft @ 7.5FH per FC	**165**
Total-$/FH freighter aircraft @ 6.0FH per FC	**205**

by the operator from the supplier through a pooling agreement, whereby a pool of parts is held by the supplier for all its customers whenever they are required. Fischer estimates that the pool access fee will be about $55 per FH for an operator with a fleet of 10 passenger aircraft, but higher at about $65 per FH for a freight airline operating at lower rates of utilisation.

The third element will be a fee for managing and repairing all parts from the homebase stock and pool stock. This will be $200 per FH for passenger aircraft, but $220 per FH for freighters operating at lower rates of utilisation.

The total costs for passenger aircraft operating as described will be $284 per FH, and the costs for freighters will be $324 per FH *(see tables, page 24)*.

Heavy components

Heavy components comprise four types of items: wheels, tyres and brakes; the thrust reverser; the landing gear and APU.

The 747 has 16 main wheels and two nose wheels. The 16 main wheels are equipped with carbon brakes as standard. Wheels are removed when tyre treads or brake disc thickness have worn down to a minimum accepted level. This means that removals are entirely on an on-condition basis, and intervals vary according to the heaviness of landings and harshness of braking by pilots. Wheels are most often removed for tyre tread wear. Tyres are then remoulded, and wheel rims undergo inspection with non-destructive testing (NDT) at the same time. Intervals that can be used for budgeting purposes are 250FC for main wheels and 325FC for nose wheels. Tyres are remoulded an average of four times before being replaced after the fifth removal. Tyre remoulds cost about $550 for main tyres, and $450 for nose tyres. New main tyres cost about $2,000, while nose tyres cost about $1,100. The total cost for the complete cycle of remoulding and replacing the shipset of tyres is about $75,000, and a reserve of $58 per FC is allowed for the cycle interval *(see table, this page)*.

Wheel inspections have an average cost of $2,500, and a resulting cost per FC of $165 *(see table, this page)*.

Average repair intervals for the carbon brakes are 2,000FC, and average repair costs for a unit are about $70,000, equalling a reserve of $560 per FC for the shipset of 16 brakes. The total cost for tyres, wheels and brakes is about $795 per FC *(see table, this page)*.

The landing gear intervals for the 747-400 are 10 calendar years and 6,000FC, whichever is reached first. An interval of 5,500-6,000FC is possible for aircraft operating at 625FC and 750FC per year. Exchange and overhaul fees for a shipset are in the region of $700,000, so they are equal to a reserve of $120-130 per FC *(see table, this page)*.

Thrust reversers are maintained on-condition, and the use of composite materials in the units on modern aircraft means that intervals can be longer than those for older aircraft. Reversers on the CF6-80C2 and PW4000 can remain on-wing for 5,000-6,000 landings (FC). An average shop visit cost of $300,000 per unit results in a reserve of $50 per FC, which is equal to $200 per FC for the whole aircraft *(see table, this page)*.

The PW901A is the exclusive APU on the 747-400. APUs are typically used for two to three hours per flight. They are sometimes switched on for the entire turnaround between flights, but more usually they are on after landing and again before departure.

Like engines, the APU is maintained on an on-condition basis. "The mean time between APU shop visits is about 9,500 APU hours," says Frank Schwaben, engineering product line PWC engines at Lufthansa Aero. "The maintenance guide to the PW901A has a maintenance 'soft' time of 10,000 hours, and can be used for planning. New APUs can meet this 10,000 hours, and several will exceed it. Mature PW901As can have an average closer to 5,000 hours. The only control the pilots have on the APU is the start button, as there is no throttle or other controls, and it is fully automatic. Mechanics only fix an APU when it fails to start, and if they cannot start it after troubleshooting it is removed for a shop visit. While it is possible to track temperature margins, no airlines actually do this."

Engines that reach a soft time on wing close to about 10,000 APU hours should have a complete disassembly and a full refurbishment. This workscope will typically cost about $450,000. A removal after about 9,000 APU hours will equal a reserve of $125 per FC for APUs operating at 2.5 APU hours per FC *(see table, this page)*.

The total cost per FC for these four groups of components is $1,235 per FC. This equals $165 per FH for aircraft operating at an FC time of 7.5FH, and $205 per FH for aircraft operating at an FC time of 6.0FH *(see tables, page 24)*.

Engine maintenance

The three engine types powering the 747-400 fleet are the General Electric (GE) CF6-80C2B1F, Pratt & Whitney (PW) PW4000-94 and Rolls-Royce (RR) RB211-524G/H. The CF6-80C2 is the most dominant engine type on the 747-400, having been specified for 305 aircraft. The PW4000-94 has been specified for 216 aircraft, and the RB211 is used by only six operators.

The PW4000-94 and CF6-80C2B1F have similar fuel burn performance and a similar effect on the operating empty weight (OEW) of the aircraft. Their maintenance costs are also close. The RB211-524 gives the aircraft a higher OEW, thereby resulting in a smaller payload. The aircraft also has a higher fuel burn with these engines *(see 747-400 fuel burn performance, page 12)*.

In terms of maintenance costs, operators focus on removal intervals between shop visits, shop visit input costs, life limited part (LLP) lives and costs, and maintenance and aftermarket support. The engine type installed also has an effect on the aircraft's residual value. RR is known to control the maintenance and aftermarket support of RB211-524 engines, so operators of RB211-powered aircraft have no other choices for engine overhaul and technical support. RB211 engines have the reputation, however, of achieving longer removal intervals between shop visits than the CF6-80C2 and PW4000-94.

The maintenance costs of all three engine types have been analysed here for two operations: a passenger aircraft operating at an average FC time of 7.5FH; and a freight aircraft operating at an average FC time of 6.0FH.

CF6-80C2B1F

The CF6-80C2B1F, rated at 58,000lbs thrust, has a mature exhaust gas temperature (EGT) margin of 35-55 degrees centigrade. There are three main production blocks of CF6-80C2 engines. The older block 1 and block 2 engines generally have a poorer build and material standard than the younger block 3 engines. Block 1 and 2 engines therefore have lower EGT margins of 35-40 degrees, while the block 3 engines have higher margins of 45-55 degrees.

The engines lose up to 10 degrees of EGT margin in the first 2,000 engine flight hours (EFH). The deterioration rate subsequently falls to 2.5-3.0 degrees per 1,000EFH. The CF6-80C2B1F has registered first removal intervals of up to 28,000EFH, but mature intervals for engines operating at an average EFC time of 7.5EFH are about 15,000EFH. This is equal to about 2,000EFC. EGT margin erosion is not a main removal driver, however, and mechanical deterioration of parts such as the variable stator vanes and cracking of the high pressure turbine blades (HPT) is the main cause.

Engines operating at an average EFC time of 6.0EFH achieve an average removal interval of 13,500EFH.

The two core modules generally follow a pattern of a heavy restoration that alternates with an overhaul, while the low pressure turbine (LPT) and fan/booster module usually only require a performance restoration or an overhaul every second shop visit.

A heavy core restoration uses about $1.3 million in materials, $300,000 in sub-contract repairs and 4,500MH in labour. Charged at a labour rate of $70 per MH, the total shop visit cost for this level of workscope is in the region of $1.95 million. A core overhaul will use more materials and require about 500MH more labour. Overall it will have a higher cost of about $2.1 million.

An LPT overhaul every second shop visit will use an average of $150,000 in materials, $40,000 in sub-contract repairs and 900MH in labour. The total cost for this module will therefore be about $255,000. A fan/booster overhaul will use about $125,000 in materials, $30,000 for sub-contract repairs and 650MH in labour, taking the total cost of the shop visit to about $200,000. A heavy second shop visit with a core, LPT and

DIRECT MAINTENANCE COSTS FOR PASSENGER-CONFIGURED 747-400

Maintenance Item	Cycle cost $	Cycle interval	Cost per FC-$	Cost per FH-$
Line & ramp checks	820,000	1 year		165
A check	630,000	5,400FH		125
Base checks	5,300,000-5,700,000	26,000FH		205-220
Heavy components:			1,235	165
LRU component support				284
Total airframe & component maintenance				**934**
Engine maintenance:				
4 X PW4000: 4 X $210 per EFH				840
4 X CF6-80C2: 4 X $191 per EFH				764
4 X RB211-524G/H: 4 X $215 per EFH				860
Total direct maintenance costs:				
4 X PW4000				**1,784**
4X CF6-80C2				**1,708**
4 X RB211-524G/H				**1,804**

Annual utilisation:
5,000FH
625FC
FH:FC ratio of 7.5:1.0

DIRECT MAINTENANCE COSTS FOR FREIGHTER-CONFIGURED 747-400

Maintenance Item	Cycle cost $	Cycle interval	Cost per FC-$	Cost per FH-$
Line & ramp checks	820,000	1 year		190
A check	630,000	5,400FH		125
Base checks	4,700,000	25,000FH		190
Heavy components:			1,235	205
LRU component support				325
Total airframe & component maintenance				**1,035**
Engine maintenance:				
4 X PW4000: 4 X $231 per EFH				924
4 X CF6-80C2: 4 X $214 per EFH				856
4 X RB211-524G/H: 4 X $235 per EFH				940
Total direct maintenance costs:				
4 X PW4000				**1,959**
4X CF6-80C2				**1,891**
4 X RB211-524G/H				**1,975**

Annual utilisation:
4,500FH
750 FC
FH:FC ratio of 6.0:1.0

fan/booster overhaul will therefore incur a total shop visit cost of $2.55 million.

These two levels of shop visit cost will result in a reserve of $150 per EFH for engines operated at an average time of 7.5EFH per EFC, and $167 per EFH for engines operated at an average EFC time of 6.0EFH.

A minority of the CF6-80C2's life limited parts (LLPs) have lives of 15,000EFC, while the majority have lives of 20,000EFC. The total list price for a full shipset is about $3.4 million. The average removal interval of 2,200-2,400EFC means that LLPs will be replaced every sixth to eighth shop visit, thereby resulting in a reserve of about $190 per EFC. This is equal to $26 per EFH for engines operated at 7.5EFH, and $32 per EFH for engines operated at 6.0EFH.

The third main element of engine maintenance costs is related to the quick engine change (QEC) kit. This has a reserve rate of about $15 per EFH.

These three elements total about $191 per EFH for engines operated at an EFC time of 7.5EFH, and $214 per EFH for engines operated at an EFC of 6.0EFH *(see tables, this page).*

PW4000-94

The PW4000-94 achieves similar performance and removal intervals to the CF6-80C2B1F, but the PW4000-94 has been affected by a few ADs in recent years.

The PW4056 is the most numerous PW4000 variant on the 747-400. "Mature engines have an EGT margin of 42-45 degrees centigrade following a shop visit, and the engines have a stabilised EGT margin degradation rate of about 1.0 degree per 1,000EFH after initial losses," says Wayne Pedranti, programme manager at Total Engine Support. "EGT margin loss only accounts for a minority of engine removals, while the majority of removals are due to mechanical deterioration. Examples are the burning of the second stage nozzle guide vane (NGV), and sulphidation of the first-stage HPT blades.

"The major AD that has affected the PW4000 in recent years is the 'ring case' modification, or RCC. The deadline for completing this on all engines is 2009. The AD states that out of four engines on the 747-400, one already has to be modified," continues Pedranti. "The rules for unmodified engines are that a stability test has to be done on the high pressure compressor (HPC) at 2,800EFC since overhaul. The engine has to be tested at take-off power in a test cell with the fuel supply cut, re-engaged and then surged 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 done. About half of the PW4000-94 fleet has been modified. The modification kit costs about $300,000 per engine, and this can be incorporated in a shop visit."

Mature engines often achieve 18,000EFH or more between planned removals when operating at average EFC times of 7.5EFH, but when unscheduled removals are taken into consideration the average works out to be about 15,000EFH. This is equal to about 2,000EFC. The PW4000 has already been

The 747-400 will displace the 747-200 in the freight sector. The -400 series not only has superior payload-range performance, but also has about $1,000 per FH lower maintenance costs and $300-300 per FH lower fuel cost.

through a modification programme known as Phase III, and engines with this upgrade have 12-15 degrees higher EGT margin, so they can last longer on wing, and also have better specific fuel consumption. Pratt & Whitney is also designing a second stage NGV to improve on-wing life.

"The PW4000 conforms to the usual pattern of alternating shop visits, with the first being a performance restoration, which is followed by an overhaul," says Pedranti. "The performance restoration requires work on the HPC, the diffuser case and combustor, the HPT, and the turbine nozzle. This will use 3,500-4,000MH of labour, about $1.1 million in materials and parts, and up to $0.8 million in sub-contract repairs. The PW4000 has a high percentage of parts that are repairable. A standard labour rate of $70 per MH will take the total cost of the shop visit input to about $2.1 million.

A full overhaul will use 4,500-5,000MH, about $1.7 million in materials and parts, and about $1.0 million in sub-contract repairs. This will have a total cost in the region of $3.0 million.

The total for the two shop visits can be amortised over 30,000EFH for two removals for engines operated at an average EFC time of 7.5EFH. Reserves will be equal to $170 per EFH. Engines operating at shorter cycle times of 6.0EFH will achieve about 13,500EFH between removals, and so have reserves of $185 per EFH.

All LLPs in the engine have lives of 20,000EFC, which simplifies engine management, although there are two parts that have lives of 30,000EFC: the LPT shaft and the LPT coupling. Given that engines accumulate only 600-700EFC per year, it is unlikely that these two parts will require replacement. Moreover, the LLPs with lives of 20,000EFC will have to be replaced after about 30 years. A full set of LLPs has a current list price of $3.3 million. Amortised over a used life of 18,000EFC, this results in a reserve of $183 per EFC. This is equal to $25 per EFH for engines operating at 7.5EFH per EFC, and $31 per EFH for engines operating at 6.0EFH.

The third element of engine maintenance is the reserve for the QEC kit, which is about $15 per EFH.

The total reserves for engines operating at 7.5EFH are therefore $210 per EFH, and $231 per EFH for engines operating at 6.0EFH *(see tables, page 24).*

RB211-524H

The RB211-524H and -524H-T engines are renowned for their durability and long removal intervals between shop visits. While the CF6-80C2B1F and PW4000-94 have average removal intervals of about 15,000EFH when operating on the 747-400 at cycle times of about 7.5EFH, the RB211-524H/-524H-T have average removal intervals of about 19,000EFH.

Although these longer intervals are welcomed by operators, the cost of shop visit inputs for the RB211-524H/-524H-T are also notoriously high, and the long intervals are not enough to offset the additional expense. The reserves for shop visits are in the region of $178 per EFH, making them about $13-18 per EFH higher than the CF6-80C2B1F and PW4000.

Reserves for LLPs are $24 per EFH, and a further $13 per EFH is required for the QEC kit. These three elements total $215 per EFH *(see tables, page 24).*

Maintenance cost summary

The direct maintenance costs for passenger-and freighter-configured 747-400s are summarised *(see tables, page 24).* These costs are $950-1,100 per FH lower than for 747-200/-300s operating at a lower rate of utilisation of about 3,500FH per year *(see 747-200/-300 maintenance analysis & budget, Aircraft Commerce, June/July 2005, page 13).*

While the repair and overhaul costs of the 747-400's heavy components, and the costs relating to its rotable components are higher than those for the 747-200/-300, the 747-400 clearly benefits from lower airframe and engine maintenance.

The 747-400 uses about half the inputs for line and ramp checks that the 747-200/-300 do. This is one example of the lower maintenance costs of younger aircraft. The 747-400 also uses less labour and fewer materials for the A checks. The largest difference between the two types is reserves for base checks. This is due to both higher labour and material inputs for the C and D checks and shorter check intervals of the 747-200/-300. This gives the 747-400 an advantage of $300-330 per FH.

The 747-400 also has a smaller cost advantage over its older counterparts with its engine-related maintenance costs. These are $300-400 per FH lower for the -400's four engines. The 747-400 also gains from its lower fuel burn, consuming 150-200 fewer US Gallons per FH on long-distance missions. Considering current fuel prices of $2.05 per USG, this adds a further $300-400 per FH to the -400's cost advantage. These two points illustrate how the 747-400 is now likely to displace the 747-200/-300 in a freight role once enough passenger-configured -400s are retired to make their conversion economic.

Although the 747-400 benefits from a two-man flightcrew, airlines are required to carry supernumerary crew on many operations, which eliminates the cost advantage that a smaller crew would have given it over the -200/-300. AC