The engines powering the A330 & 777 have now been in operation for up to 15 years. A summary view of their operational performance, removal intervals, shop visit input costs, LLP reserves, and maintenance reserves is made here.

Big engine in-service performance & maintenance

The engines powering the A330 and 777 families are the highest-rated powerplants. The General Electric (GE) CF6-80E1 series, Pratt & Whitney (PW) PW4000-100 and Rolls-Royce (RR) A330 engines have been in service since 1993, although some later variants did not enter service until 1999 or 2006. The first variants of the GE90, PW4000-112 and Trent 800 powering the 777 entered service in 1997. The highest-rated versions of the GE90 are the most recent engines to start operations, in 2004. Now that most engine models have been operated long enough to be mature in maintenance terms, their in-service performance and maintenance costs are reviewed here.

Engine description

The main factors affecting the performance, on-wing life and maintenance costs of engines are their configurations, thrust ratings, the number and lives of life limited parts (LLPs), and initial exhaust gas temperature (EGT) margins. These characteristics of the engine variants powering the A330 and 777 families are examined.

A330 engines

CF6-80E1

The CF6-80E1 series is the last and largest member of the CF6 family. These are two-shaft engines. The CF6-80E1 has a 96.2-inch diameter fan, while the -80C2 has a 93-inch diameter fan.

There are three variants of the -80E1: the -80E10-A2 rated at 65,800lbs thrust; the -80E10-A3 rated at 69,800lbs thrust; and the -80E1-A4 rated at 68,100lbs thrust *(see table, page 42)*. These thrust ratings are for a flat rating of 30 degrees centigrade. The initial EGT margins are 35-45 degrees centigrade.

Like the -80C2, the -80E1 has four low pressure compressor (LPC) stages, 14 high pressure compressor (HPC) stages, a two-stage high pressure turbine (HPT), and a five-stage low pressure turbine (LPT).

The CF6-80E1's LLPs have lives of 20,000 engine flight cycles (EFC) in the low pressure models, and 8,400-20,000EFC in the high pressure modules. The parts in the fan and LPC, and some parts in the HPC and the LPT have lives of 20,000EFC. Other parts in the HPC and LPT have lives of 15,000EFC and 17,800EFC. The two HPT stage disks have lives of 8,400EFC and 10,800EFC.

The 2008 list price for a shipset of LLPs is $5.55 million.

The CF6-80E1 series powers 107 A330-200s and 52 -300s.

PW4000-100

The PW4000-100 is the second generation of the PW4000. The -100 suffix of the engine series powering the A330-200 and -300 is used to denote the engine's 100-inch fan diameter. There are two main variants: the PW4164 rated at 64,500lbs thrust; and the PW4168 rated at 68,600lbs thrust *(see table, page 42)*. These engines are flat-rated at 30 degrees centigrade.

Initial EGT margins are 35 degrees centigrade. Air Berlin, which took over the LTU fleet of A330-300s, operates the PW4168. Northwest operates 11 A330-200s and 21 A330-300s with PW4168s, and started with average initial EGT margins of 40 degrees centigrade.

The PW4000-100 is a standard two-shaft engine with a five-stage LPC, 11-stage HPC, two-stage HPT and five-stage LPT. The engine has a 100-inch fan diameter and achieves a bypass ratio of 5.1:1.

The PW4000-100 has a stack of 25 LLPs which have uniform lives of 15,000EFC. This has a 2008 list price of $4.88 million.

The PW4064/68 power 64 A330-200s and 83 A330-300s. Initial EGT margins of new engines are about 35 degrees centigrade.

Trent 700

The Trent 700 was the first model of the Trent family. The Trent was derived from the RB211, with the two engines having the same basic architecture and configuration. These have a three-shaft design. The tip speed of fan blades is limited to less than supersonic. As fan diameters have been steadily increased to achieve higher bypass ratios in an effort to improve fuel efficiency, the rotational speed of fans in revolutions per minute (RPMs) has been reduced by the constraints of fan-blade tip speed. The fan and LPC stages in a two-shaft engine are mounted on the same shaft. The RPMs of the LPC are therefore limited by the fan's RPMs. This requires a relatively high number of LPC and HPC stages to achieve the required compression ratio.

RR developed the three-shaft concept to overcome this issue. The fan and first compressor module in the core engine are driven by different shafts so that they can turn at different RPMs. This results in an intermediate pressure compressor (IPC) which can turn faster than the LPC in a two-shaft engine. The fan, IPC and HPC are mounted on different shafts, so the three are each turned by a turbine: the

CF6-80E1, PW4000-100 & TRENT 700 SPECIFICATION DETAILS

Engine type	CF6-80E1-A2	CF6-80E1-A3	CF6-80E1-A4
Fan diameter-inches	93	93	93
No LPC stages	4	4	4
No HPC stages	14	14	14
No HPT stages	2	2	2
No LPT stages	5	5	5
Thrust rating-lbs	65,800	69,800	68,100
Flat rating temp-degrees C	30	30	30
Bypass ratio	5.1:1	5.1:1	5.0:1

Engine type		PW4164	PW4168
Fan diameter-inches		64,500	68,600
No LPC stages		5	5
No HPC stages		11	11
No HPT stages		2	2
No LPT stages		5	5
Thrust rating-lbs		64,500	68,600
Flat rating temp-degrees C		30	30
Bypass ratio		5.1:1	5.1:1

Engine type	Trent 768	Trent 772	Trent 772B
Fan diameter-inches	97.4	97.4	97.4
No IPC stages	8	8	8
No HPC stages	6	6	6
No HPT stages	1	1	1
No IPT stages	1	1	1
No LPT stages	4	4	4
Thrust rating-lbs	67,500	71,100	71,100
Flat rating temp-degrees C	30	30	37
Bypass ratio	5.0:1	5.0:1	5.0

LPT turns the fan; the intermediate pressure turbine (IPT) powers the IPC; and the HPT powers the HPC. The drawback of this three-shaft configuration is the complexity of its construction, although the Trent engines are shorter than the PW and GE engines being considered here. The Trent 700 is 154 inches long, compared to the CF6-80E1 which is 173.5 inches, for example. This short design generally gives the engine more durability, and the RB211 and Trent family engines tend to have better EGT margin retention and longer removal intervals than their closest competitors.

The Trent 700 has a fan diameter of 97.4 inches. The basic configuration is an eight-stage IPC, six-stage HPC, single-stage HPT, single-stage IPT, and four-stage LPT.

The Trent 768 is rated at 67,500lbs thrust, and the Trent 772 at 71,100lbs thrust *(see table, this page)*. Both are flat-rated at 30 degrees centigrade. The Trent 772B is a special variant for high temperature operations, also rated at 71,100lbs thrust and is flat-rated at 38 degrees centigrade. All three variants have a bypass ratio of 5:1.

The engines have an initial EGT margin of 40-50 degrees centigrade.

The current shipset of LLPs for the Trent 700 comprises 13 main parts, although one of these is a set of 26 fan blades, which are life limited. The fan disk and fan shaft are also in this module. The IPC has a drum and shaft, and the HPC has a drum for all six stages. The HPT has a single disk, the IPT has a disk and a shaft, and the LPT has four disks and a shaft.

Earlier-build standard LLP shipsets have lives varying from 4,200EFC to 15,000EFC. The HPT shaft, for example, has a life of 4,200EFC. The next shortest lives are the HPC rotor at 6,000EFC, and the HPT disk at 9,000EFC. Other parts in the engine have lives of 12,000-13,000EFC, while the LPT has parts with the longest lives of 15,000EFC. The list price for the stack of parts is $3.3 million.

The latest-build standard of 13 LLPs has a uniform life of 15,000EFC, but also a higher list price of $4.50 million.

The Trent 700 series power 119 A330-200s and 97 A330-300s.

777 engines

GE90

The GE90 was developed as a result of the CF6 reaching its limit of development with the -80E1. The engine was designed to provide thrust ratings from 76,000lbs up to 115,000lbs for aircraft in the 777 family.

The standard GE90 has a two-shaft configuration, with a 123-inch fan diameter. The basic design criteria were for it to have high bypass and pressure ratios to achieve superior fuel burn to previous generation turbofans. The engine's configuration is a three-stage LPC, 10-stage HPC, two-stage HPT and six-stage LPT.

The suffix of each variant denotes the thrust rating of the engine in thousands of lbs. The variants in the standard GE90 family are: the GE90-76B rated at 76,000lbs thrust; the GE90-77B rated at 77,000lbs thrust; the GE90-85B rated at 84,700lbs thrust; the GE90-90B rated at 90,000lbs thrust; and the GE90-94B rated at 93,700lbs thrust *(see table, page 44)*. These five variants are all rated at 30 degrees centigrade and have a bypass ratio of 8.1:1.

The LLP shipsets for these GE90 variants have 26 parts. Lives vary from 3,500EFC to 30,000EFC. One part in the HPT has a life of 3,500EFC, another 9,500EFC and others 15,000EFC. This LLP will limit the removal interval of the GE90. Other parts in the engine, such as the HPC, have lives of 9,800EFC, 10,000EFC and 11,000EFC. Engine removals and shop-visit workscopes have to be managed around these intervals. The list price for a full shipset of LLPs is $8.07 million.

These five variants of the GE90 power the variants of the 777-200 with maximum take-off weights (MTOWs) ranging from 506,000lbs to 656,000lbs. There are 164 777-200s in operation equipped with these variants of the standard GE90.

Following the development of the 777-200ER with an MTOW of 656,000lbs and the 777-300 with an MTOW of 660,000lbs, Boeing wanted to develop ultra-long-range variants: the 777-200LR with an MTOW of 750,000lbs and range of 8,865nm; and the 777-300ER with an MTOW of

GE90, PW4000-112 & TRENT 800 SPECIFICATION DETAILS

Engine type	GE90-76B	GE90-77B	GE90-85B	GE90-90B	GE90-94B
Fan diameter-inches	123	123	123	123	123
No LPC stages	3	3	3	3	3
No HPC stages	10	10	10	10	10
No HPT stages	2	2	2	2	2
No LPT stages	6	6	6	6	6
Thrust rating-lbs	76,000	77,000	84,700	90,000	93,700
Flat rating temp-degrees C	30	30	30	30	30
Bypass ratio	8.1:1	8.7:1	8.7:1	8.7:1	8.7:1

Engine type	PW4074	PW4077	PW4084	PW4090	PW4098
Fan diameter-inches	112	112	112	112	112
No LPC stages	6	6	6	6	6
No HPC stages	11	11	11	11	11
No HPT stages	2	2	2	2	2
No LPT stages	7	7	7	7	7
Thrust rating-lbs	74,000	77,000	84,600	90,000	98,000
Flat rating temp-degrees C	30	30	30	30	30
Bypass ratio	6.4:1	6.4:1	6.4:1	6.4:1	6.4:1

Engine type	Trent 875	Trent 877	Trent 884	Trent 892/892B	Trent 895
Fan diameter-inches	110	110	110	110	110
No IPC stages	8	8	8	8	8
No HPC stages	6	6	6	6	6
No HPT stages	1	1	1	1	1
No IPT stages	1	1	1	1	1
No LPT stages	5	5	5	5	5
Thrust rating-lbs	74,600	77,200	84,950	91,600	95,000
Flat rating temp-degrees C	30	30	30	30	25
Bypass ratio					

GE90-110B/-115B SPECIFICATION DETAILS

Engine type	GE90-110B	GE90-115B
Fan diameter-inches	128.2	128.2
No LPC stages	3	3
No HPC stages	9	9
No HPT stages	2	2
No LPT stages	6	6
Thrust rating-lbs	110,000	115,300
Flat rating temp-degrees C	33	30
Bypass ratio		

750,000lbs and range of 7,200nm.

GE90 was given the exclusive contract to develop an engine for these two aircraft. There are two larger variants of the GE90 with a fan diameter of 128.2 inches: the GE90-110B1 rated at 110,000lbs thrust for the 777-200LR, flat-rated at 33 degrees centigrade, and with a bypass ratio of 7.2:1; and the GE90-115B rated at 115,300lbs thrust for the 777-300ER, flat-rated at 30 degrees centigrade, and with a bypass ratio of 7.2:1. Delta Airlines has been operating its two GE90-110B1-powered 777-200LRs since early 2008. The initial EGT margins on these engines were about 45 degrees centigrade.

These variants have a similar configuration to the standard GE90 family, with the difference that the higher-rated engines have one less HPC stage and a wider fan diameter.

The GE90-110/-115 have 26 LLPs. The latest shipset of parts have the same lives as the standard GE90 variants. The list price of these parts is $8.07 million.

PW4000-112

The PW4000-112 is the largest variant of the PW4000 family. Its -112 suffix denotes that the engine has a 112-inch fan diameter. There are five main variants of the PW4000-112: the PW4074 rated at 74,000lbs thrust; the PW4077 rated at 77,000lbs thrust; the PW4084 rated at 84,600lbs thrust; the PW4090 rated at 90,000lbs thrust; and

Northwest, which operates its PW4168s at 7.0EFH per EFC, says it is aiming for first and second removal intervals of 24,000EFH.

the PW4098 rated at 98,000lbs thrust *(see first table, page 44)*. These engines have a bypass ratio of 6.4:1 and are flat-rated at 30 degrees centigrade.

The PW4000-112's configuration is a two-shaft design with a six-stage LPC, 11-stage HPC, two-stage HPT, and seven-stage LPT.

The PW4000-112 has 26 LLPs. The lower-rated PW4074 and PW4077 have uniform LLP lives of 20,000EFC, except for three parts in the LP system which have lives of 40,000EFC. A shipset of LLPs has a list price of about $7.0 million.

The LLPs in the PW4084/90/98 have the same LLPs, but with shorter uniform lives of 15,000EFC. The list price for a shipset is $7.52 million.

Trent 800

The Trent 800 has a fan diameter of 110 inches, and the same core engine configuration as the Trent 700 except that the Trent 800 has one additional LPT stage. There are six variants of the Trent 800, the first five of which are: the Trent 875 rated at 74,600lbs thrust; the Trent 877 rated at 77,200lbs thrust; the Trent 884 rated at 84,950lbs thrust; the Trent 892 rated at 91,600lbs thrust; and the Trent 892B rated at 91,600lbs thrust. These five variants are flat-rated at 30 degrees centigrade. The sixth variant is the Trent 895, which is rated at 95,000lbs thrust, and flat-rated at 25 degrees centigrade.

The Trent 884 and 892 have LLPs with lives of 15,000EFC, while the Trent 895's LLPs have lives of 10,000EFC. A shipset has a list price of about $6 million.

The Trent 800 powers 179 777-200s and 40 777-300s.

Delta has a fleet of eight Trent 892B-powered 777-200ER, which have been in operation since 1999, and had initial EGT margins of 50 degrees centigrade.

Engines in operation

The style and nature of the engines' operation are a major influence on their removal intervals for shop visits and maintenance costs.

Most operators utilise their A330s and 777s on medium or long cycle times. The removal cause for maintenance of most engines used on short-haul operations is erosion of EGT margin and loss of performance. The main removal cause for engines used on medium and long average EFC times is mechanical deterioration. The large engines powering the A330 and 777 have generally demonstrated good EGT margin retention and have been removed mainly for hardware deterioration. EGT margin erosion can nevertheless become more of a problem as engines pass their first removal and shop visit, and reach maintenance maturity with lower EGT margin following each shop visit.

The A330-200 is used as a long-haul workhorse by most of its operators. Flight hour (FH) to flight cycle (FC) ratios are 6-8FH per FC in most cases. Some operators use it for medium-haul operations at 2.5-5.0FH per FC.

CF6-80E1

The CF6-80E1 powers 107 A330-200s and 52 -300s. Major CF6-80E1-powered A330-200 operators include Aer Lingus, Air France, EVA Air, JetAirways, JetStar Airways, KLM, Qatar Airways, Qantas, and Turkish Airlines. Many of these carriers accumulate 4,500FH per year with their aircraft.

Qantas, Air France and Jet Airways use the aircraft at an FH:FC ratio of 7:1, while other carriers use the A330 for medium-haul services at FH:FC ratios of 2.5-5.0:1.

First removal intervals for the CF6-80E1 have been 15,000-17,000EFH for earlier-built engines, although some engines operated on the longest EFC times are achieving longer intervals in excess of 20,000EFH.

KLM, for example, has operated the A330-200 since 2004 at an average FC time of 6.25FH and at a take-off de-rate of 10%. Main removal causes for these engines are related to HPC damage, high oil consumption, and bearing vibration. First removal intervals have averaged 16,500EFH and 2,600EFC. These have been followed by a performance restoration, which is typical of most engines at their first removal.

Engines operated on shorter EFC times of 5.0EFH can be expected to have average first removal intervals of about 15,000EFH and 3,000EFC.

KLM says that the first shop visit will restore EGT margin to a lower-than-original level of about 25 degrees. On this basis the engine should be capable of remaining on-wing for 12,000-15,000EFH for the second interval.

Engines on shorter cycles of 5.0EFH can be expected to have second intervals of 12,500EFH.

At the second removal, after a total time of 27,000-35,000EFH for engines operated at 5.0-7.0EFH per EFC, the engine will require a complete overhaul and workscope on all modules. This total time will be equal to 5,000-7,000EFC.

Medium-haul engines used at 3.0EFH per EFC will have the shortest intervals. EVA Air of Taiwan operates its A330-300s at about 2.9FH per FC. First intervals have been 5,500-6,000EFC, equal to 15,750-17,150EFH.

Second intervals for engines on shorter cycles of 3.0EFH can be expected to achieve intervals of 12,000-13,000EFH and 4,000-4,400EFC.

The total time at this stage for engines

Like many other engine types, most of the large engines powering the A330 & 777 families are able to conform to a shop visit workscope pattern of alternating performance restorations and overhauls.

operated on medium-haul services will be 27,000-28,000EFH, or 9,000-10,000EFC.

Third and mature removal intervals from this point are expected to be 11,000EFH and 3,700EFC for engines operating at 3.0EFH per EFC, and 14,500EFH and 1,800EFC for an EFC time of 8.0EFH. Engines will generally be expected to follow a pattern of alternating performance restoration and overhaul shop visits.

These total times must be considered in relation to the engine's LLPs. Most parts have lives of 15,000EFC or 20,000EFC. These will have to be replaced at the second or third shop visit for engines operated at 3.0EFH. Replacement would be due at the sixth to eighth shop visit for engines operated at 8.0EFH, although it may be necessary or advisable to replace the parts with lives of 8,400EFC and 10,800EFC at the third or even the second shop visit.

PW4000-100

The PW4168 powers 64 A330-200s and 75 A330-300s. The PW4164 powers another eight A330-300s. Like the CF6-powered A330-200s, the PW4000-powered aircraft are most used on long-haul operations at average FC times of 6.0-8.0FH. Major operators include Air Berlin (which operates the old LTU fleet), Northwest Airlines, Swiss, TAM, and TAP Air Portugal.

Swiss operates at an average FC time of 5.0FH, Air Berlin at 6.0FH, and Northwest Airlines at 7.0FH.

Major operators of PW4168-powered A330-300s include Asiana, Korean Air, Malaysia Airlines, and Thai International. These operators all use the aircraft on medium-haul services of about 3.0FH per FC, as the A330-300 is a popular aircraft for operations in the Asia Pacific region. Northwest and USAirways use the A330-300 for transatlantic services, and have average FC times of 6.5-7.5FH.

The PW4168 has generally achieved longer first removal intervals than the CF6-80E1. The range of EFC times among A330 operators is similar to the CF6-80E1. Swiss uses the engine at an average EFC time of 5.0EFH, but had its first removal intervals limited to 10,000EFH by an airworthiness directive (AD). Air Berlin, which operates at 6.0EFH per EFC, has first intervals of 18,000EFH and 3,000EFC. Northwest says that its engines lose EGT margin at a rate of about 2.0 degrees centigrade per 1,000EFH on its operation of 7.0EFH per EFC, and is aiming for first removal intervals of up to 24,000EFH. TAM, another long-haul operator, has averaged 22,000EFH for its first removal interval.

First shop-visit workscopes involve a performance restoration in most cases, although Northwest says that it expects a heavy maintenance workscope to be required after an interval of 24,000EFH.

EGT margin following the first shop visit is expected to be 19-25 degrees centigrade. At average EGT margin erosion rates of 1.5-2.0 degrees per 1,000EFC, the engine could remain on-wing for its second interval of 12,000-18,000EFH.

SR Technics, which manages Swiss's engines, averaged a second interval of 16,000EFH. Air Berlin has a similar second interval of 15,000EFH, despite operating at a longer EFC time of 6.0EFH. Most operators will put their engines through an overhaul at this stage. This will be at a total time of 31,000-33,000EFH and 6,000-6,500EFC.

Engines are then expected to follow an alternating pattern of performance restoration and overhaul shop visits. Air Berlin, for example, expects a mature interval of 14,000-15,000EFH and 2,300-2,500EFC. Total time at the third shop visit will therefore be 8,000-9,000EFC.

Mature intervals are expected to be about 10,000EFH and 3,300EFC for an average EFC time of 3.0EFH, and to rise to 13,500-15,000EFH and 1,700-1,900EFC for an EFC time of 8.0EFH.

These mature intervals have to be considered in relation to LLPs, which have lives of 15,000EFC. These can be replaced at the third shop visit for engines at 3.0EFH. LLPs in engines at 6.0-8.0EFH would be replaced at the fourth or fifth of six intervals, when accumulated time has reached 10,000-15,000EFC.

Northwest expects another long interval of about 24,000EFH, given that it will put the engine through a heavy shop visit at the first removal. It then expects mature intervals to be about 20,000EFH.

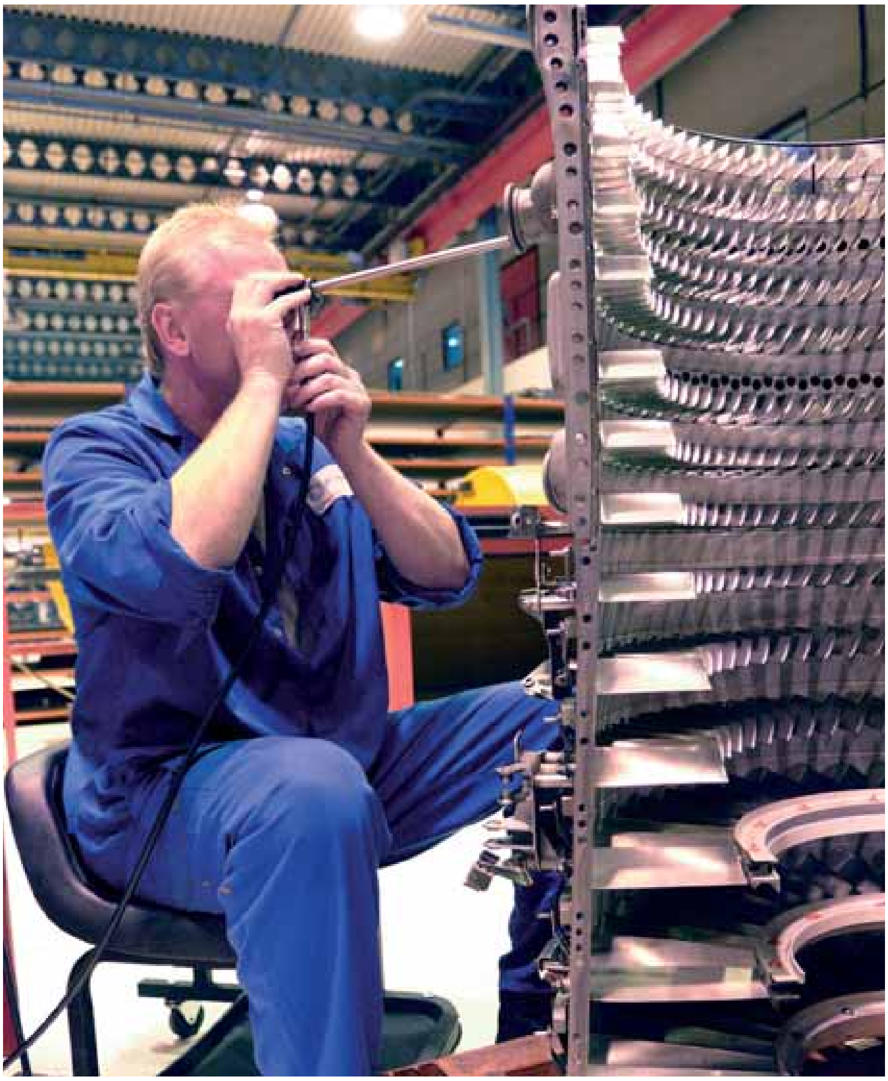
Trent 700

The Trent 772 powers 119 A330-200s and 97 A330-300s. The Trent-772-powered A330-200s are used on a mixture of medium- and long-haul routes. Air China, China Eastern, China Southern, Egyptair, Emirates, Gulf Air, MEA and Sri Lankan all use the aircraft on medium-haul services with FC times of 2.5-5.0FH.

British Midland, Jet Airways, and Thomas Cook use the aircraft on longer services of 6-7FH per FC.

Most Trent-772-powered A330-300s are with Asia Pacific carriers that include Cathay Pacific, China Eastern, China Southern, Dragonair and Garuda. FC times are 2.5-3.5FH. Other operators include Air Canada, Lufthansa and SAS, which operate the aircraft in a long-haul mode at FC times of 5.5-7.5FH.

The Trent 700 generally achieves longer intervals than its GE and PW counterparts. EGT margin erosion is slow and is rarely a removal cause for the first shop visit.



The combined first and second removal intervals of the large engines, unless operated on short-haul missions, are equal to 8-10 years of operation.

First removal intervals have been 16,000-23,000EFH and 2,300-4,000EFC, but several operators have been able to achieve longer intervals. Emirates, which operates its A330-200s on medium-haul services at about 3.5FH per FC, says that the engines lose EGT margin at a rate of 10 degrees per 1,000EFC, and so could theoretically remain on-wing for 5,000EFC. The first removal intervals, however, are determined by the engines reaching their first LLP life limit of the HPT shaft at 4,200EFC. This is equal to about 15,000EFH.

British Midland uses the Trent 772B-powered A330-200 for long-haul operations at about 7.1FH per FC. First removal intervals have been determined by this LLP limit in most of its engines. This is equal to 30,000EFH.

The Trent 772 also has another LLP that could severely limit the second removal interval: the HPC rotor with a life of 6,000EFC. This is removed at the first shop visit to avoid limiting the second interval to just 1,800EFC. The LLP with the third longest life is the HPT disk at 9,000EFC. This can be left in the engine, limiting the second removal interval to 4,800EFC.

Dick Chambers, powerplant development manager at British Midland, says that he does not expect the engines to get to this full limit at the second removal. Second intervals are about 80% of first intervals, which suggests that engines operating at 3.0EFH could get about 12,000EFH and 3,400EFC, while those operating at 7.0EFH could achieve 22,000-24,000EFH and 3,100-3,300EFC.

The total accumulated time at the second removal would therefore be about 27,000EFH and 7,600EFC for those engines operated at 3.0EFH. Engines operated at 7.1EFH would have accumulated a total time of 52,000-54,000EFH and 7,300-7,600EFC.

These intervals have to be considered in relation to LLPs, with uniform lives of 15,000EFC.

Mature intervals are expected to be 10,000-12,000EFH and 3,300-4,000EFC for operations at 3.0EFH per EFC, and as high as 17,000-20,000EFH and 2,100-2,500EFC for operations at 8.0EFH per EFC.

LLPs with longer lives would probably be replaced at the third shop visit for those engines operating at 2.0-3.0EFH, and the fourth to sixth removal in the case of engines operating at 7.0-8.0EFH.

777 engines

The 777-200 and -300 are used primarily as long-haul aircraft by most of their operators. The exceptions are airlines in the Asia Pacific which use the aircraft on regional routes that have FC times of 2.5-4.0FH. Japan Airlines and All Nippon Airways (ANA) use the 777 for domestic operations at 1.0-1.3FH per FC.

Standard GE90

The standard GE90 powers 164 777-200s. China Southern and Saudia use the GE90-powered on medium-haul services at FC times of 2.5-4.0FH. Air France, Austrian, British Airways, Continental and KLM use the aircraft on long-haul services at FC times of 6.5-9.5FH.

The 128-inch fan powers 19 777-200LRs and 141 777-300ERs. The -200LRs are used on long-haul and ultra-long-haul operations with FC times of 11-13FH in cases such as Air India. The -300ERs have average FC times of 8-11FH. The largest operators include Air Canada, Air France, All Nippon Airways (ANA), Cathay Pacific, Emirates, Etihad Airways, EVA Air, Japan Airlines, Jet Airways, Pakistan International Airlines, and Singapore Airlines (SIA).

The standard GE90 powering the 777-200/-200ER is generally capable of achieving first removal intervals of 16,000-18,000EFH. This is equal to 2,700-3,000EFC when operating at an EFC time of 6.0EFH per EFC. This has to be considered in relation to the HPT interstage seal which has a life of 3,500EFC. The removal intervals for engines operated on long cycle times are unlikely to be affected. This part could restrict or limit the removal intervals of engines operated on short- or medium-cycle times.

The workscope at the first removal is generally expected to be a performance restoration. The HPT interstage seal will also need to be replaced at this stage, meaning that the HPT will have to be fully disassembled. Other LLPs can remain in the engine.

Following the first shop visit, the standard GE90 will have second removal intervals of 13,000-16,000EFH, equal to 2,200-2,700EFC when operating at 6.0EFH per EFC. At this stage the engine will have a full overhaul. Total time

The GE90 has been designed for long-haul missions of EFC times of 8.0-10.0EFH. Mature removal intervals are expected to be 17,000-20,000EFH.

reached will be 29,000-34,000EFH and 4,000-5,700EFC. This has to be considered in relation to LLPs, many of which have lives of 15,000EFC and 20,000EFC.

Mature intervals are 14,500EFH and 7,300EFC for operations at 2.0EFH per EFC. A few LLPs will then have to be removed at this stage to prevent limiting the third interval.

The third interval will be 16,500-17,500EFH and 4,000-4,400EFC for operations at 4.0EFH per EFC, and 18,500-20,000EFH and 2,300-2,500EFC for operations at 8.0EFH per EFC.

LLPs with lives of 15,000EFC will be reaching expiry by the fifth or sixth shop visit, while parts with lives of 20,000EFC will be reaching expiry by the seventh shop visit.

Some HPC, HPT and LPC parts have lives of 9,800-12,300EFC and these will have to be replaced at the third, fourth or fifth shop visits.

GE90-110/115

These engines have been intended for use on ultra-long-haul missions with EFC times of 10EFH or more. Delta began operations with the GE90-110B in early 2008 with two 777-200LRs, so its experience to date is limited. It operates the engines for an average of 13EFH per EFC.

The new engines have an initial EGT margin of 45 degrees centigrade and a predicted first removal interval of about 20,000EFH, equal to less than 2,000EFC. Some operators predict that intervals could be as long as 25,000EFH. The expected shop visit will be a heavy performance restoration.

Few or no engines have yet been removed for their first shop visit, so it is hard to predict the condition of engines and the restored EGT margin following the first shop visit. Second removal intervals are expected to be 14,000-17,500EFH, equal to 1,400-2,200EFC. The total time at this stage will be 35,000-42,000EFH and up to about 4,000EFC. Engines will require a full workscope or overhaul at this stage. The HPT interstage seal will also need to be replaced, but other LLPs could remain.

Mature intervals are expected to be about 17,000EFH and 2,100EFC when operated at 8.0EFH per EFC. About another 4,200EFC will have been accumulated at the next overhaul, at a total time of 7,500-8,000EFC. The HPT stage 1 disk may require replacement at this shop visit, but all other LLPs could remain in the engine.

The engine has 26 LLPs, 16 of which have lives of 3,500-15,000EFC. The other 10 have lives of 19,000-30,000EFC. Parts with lives of 9,800-11,300EFC will be replaced at the fifth to the seventh shop visits. Some parts with longer lives are unlikely to require replacement during the engine's working life, given the long EFC time of its operations.

PW4000-112

The PW4000-112 powers 143 777-200s and 18 777-300s. The 777-200s are equipped with the PW4074, PW4077, PW4084 and PW4090. A large number of operators are based in the Asia Pacific, and include Air China, ANA, Asiana, JAL and Korean Air. Many operators use the aircraft on medium-haul operations with FC times of 2.5-3.5FH, while JAL and ANA use many of their aircraft on domestic Japanese routes with FC times of 1.1-1.3FH. Other operators include United and Vietnam Airlines. United has a fleet of 52 777-200s powered by PW4077/84/90 engines, and operates the fleet on mainly long-haul operations at FC times of 6.5-9.3FH.

The PW4090/98-powered 777-300 fleet is small, with ANA, JAL and Korean Air the only operators. JAL and ANA operate their aircraft on Japanese domestic routes and have FC times of 1.2FH. Korean uses its aircraft on regional services at an average FC time of 3.5FH.

First and second removals for the PW4000-112 are up to 24,000EFH when operated on long EFCs of about 8.0EFH. Engines operated at shorter average lengths will have intervals of 16,000-18,000EFH and 8,000-9,000EFC for early removals. First shop-visit workscopes are typically performance restorations or hot-section inspections, and are followed by an overhaul.

Mature intervals are 13,000-16,500EFH and 4,000-6,500EFC for engines operated on short- and medium-haul cycles of 2.0-4.0EFH per EFC. Lower-rated engines on longer EFC times of 6.0-8.0EFH per EFC have mature intervals of 17,500-18,000EFH and 2,300-2,900EFC. Higher-rated PW4090/98 engines will have shorter mature intervals of 16,000-17,000EFH, equal to 2,600-2,800EFC.

Trent 800

The Trent 800 series powers 179 777-200s/-200ERs. These are used on a mix of medium- and long-haul operations. Cathay Pacific, Emirates, SIA and Thai International all use the aircraft on regional services at FC times of 2.5-4.0FH. Air New Zealand, American Airlines, British Airways, Delta Airlines, El Al and Malaysia Airlines all use the aircraft at FC times of 7.0-10.0FH. Delta has the longest average FC time of about 10FH.

There are 40 Trent 800-powered 777-300s, which are operated by Cathay Pacific, Emirates, SIA and Thai International. These are used on regional Asia Pacific services at FC times of 2.3-3.5FH, although Emirates operates its aircraft to Europe and has longer FC times of about 5.2FH.

The Trent 800 has generally shown good on-wing durability, and seems capable of achieving removal intervals that are longer than those of the standard GE90 and PW4000-112.

Delta's operation with the Trent 800 has an average EFC time of 10.0EFH. The airline has been operating the Trent 800-powered 777-200ER since March 1999 at an annual utilisation of 5,250FH.

Delta has already been through its round of first removals for its Trent 800s, and the average removal interval is about 30,000EFH and 3,000EFC. Main removal causes have been general deterioration, with metal chips on the magnetic detectors.

Most operators have achieved intervals of 22,000-24,000EFH for typical long-haul operations at EFC times of 6.0-8.0EFH.

Delta says that the restored EGT margin following the first shop visit was about 42 degrees centigrade, and that the engine is expected to achieve a second interval of about 23,000EFH and 2,300EFC. At this stage the engine will have accumulated a total time of 48,000-53,000EFH and 4,800-5,300EFC.

Following the second shop visit, Delta expects the engine to have a mature removal interval in the region of 20,000EFH and 2,000EFC. This must be considered in relation to LLPs, which have lives of 15,000EFC or 10,000EFC.

Second removal intervals are 12,000-17,000 for lower-rated versions when operated at EFC times of 2.0-4.0EFC. These are higher at 18,000-20,000EFH for all variants when operating at 6.0-8.0EFH per EFC.

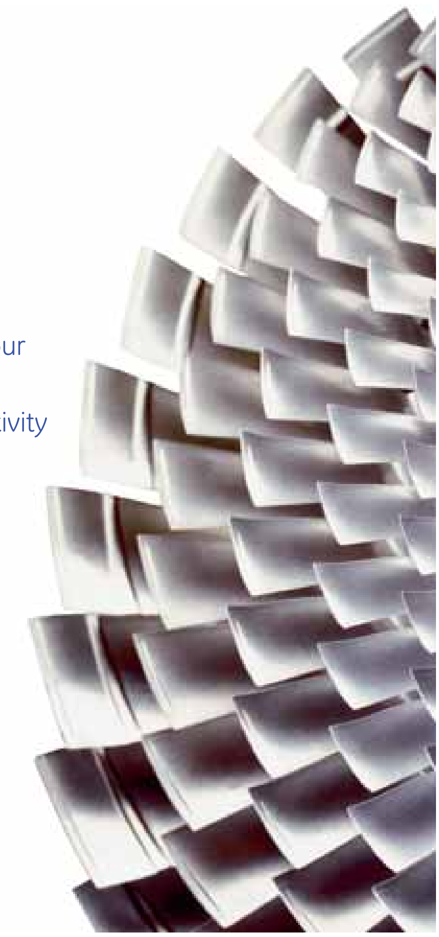
Maintenance reserves

Taking into account the removal intervals, shop-visit workscopes, LLP lives and typical shop-visit costs, maintenance reserves can be estimated. These are all for the first two removals. Even for engines with the shortest intervals and the shortest average EFC times, total time to the second removal is at least 18,000EFH, equal to about six years of operation. In some cases it is up to 50,000EFH or more than 10 years of operation.

CF6-80E1

CF6-80E1s operated at 3.0EFH per EFC will have a performance restoration at the first removal after the time on-wing described, followed by a heavy workscope or overhaul at the second shop visit. The performance restoration or hot-section inspection will incur a cost of about $2.3 million, while the heavier workscope will cost up to $3.5 million. The cost of these two shop visits amortised over the total interval of about 28,500EFH will equal a maintenance reserve of about $204 per EFH.

LLPs will be replaced at different intervals because of their varying stub lives, and average replacement time will be about 15,000EFC. The list price of $5.55 million results in a reserve of $370 per EFC. Total reserves for the engine over the first two shop visits will be $327 per EFH.



Engine type	CF6-80E1	CF6-80E1	CF6-80E1
EFH:EFC ratio	3.0	6.0	8.0
First & second removal interval-FH	28,500	30,500	32,500
First & second shop-visit cost-$	5,800,000	6,200,000	6,300,000
Shop-visit reserve-$/EFH	**204**	**203**	**194**
LLP shipset price-$	5,550,000	5,550,000	5,550,000
LLP replacement life-EFC	15,000	16,000	16,000
LLP reserve-$/EFC	**370**	**343**	**343**
Total Reserve-$/EFH	**318**	**260**	**237**
Engine type	**PW4168**	**PW4168**	**PW4168**
EFH:EFC ratio	3.0	6.0	8.0
First & second removal interval-FH	28,000	33,500	38,000
First & second shop-visit cost-$	6,150,000	6,800,000	7,000,00
Shop-visit reserve-$/EFH	**220**	**203**	**184**
LLP shipset price-$	4,880,000	4,880,000	4,880,000
LLP replacement life-EFC	13,000	14,000	14,000
LLP reserve-$/EFC	**375**	**350**	**350**
Total Reserve-$/EFH	**345**	**261**	**228**
Engine type	**Trent 772**	**Trent 772**	**Trent 772**
EFH:EFC ratio	3.0	6.0	8.0
First & second removal interval-FH	25,000	45,000	54,000
First & second shop-visit cost-$	8,800,000	9,500,000	9,750,000
Shop-visit reserve-$/EFH	**352**	**211**	**181**
LLP shipset price-$	3,300,000	3,300,000	3,300,000
LLP replacement life-EFC	10,000	10,000	10,000
LLP reserve-$/EFC	**330**	**330**	**330**
Total Reserve-$/EFH	**462**	**266**	**222**

Engines operated on longer cycles of 6.0-8.0EFH will follow the same basic shop-visit pattern, although shop-visit workscopes will incur higher costs. These will be $2.5-2.6 million at the first removal and $3.7-3.9 million for the second heavier workscope. Shop-visit reserves will be amortised over the longer interval of 30,000-32,000EFH, and will be $194-204 per EFH. Longer intervals may allow a longer average LLP replacement life, and so a lower reserve of $343 per EFC. Total reserve for the first two shop visits will be $267 per EFH for 8.0EFH per EFC, and $237 per EFH for 6.0EFH per EFC *(see table, this page)*.

PW4168

The PW4168s operated at 3.0EFH will have similar first and second intervals to the CF6-80E1, and reach a total time of about 28,000EFH and 9,300EFC. PW engines often follow a shop-visit pattern of a performance restoration followed by an overhaul. These will incur costs of about $2.3 million and $3.85 million. The shop-visit reserve for these two workscopes will be about $220 per EFH.

The uniform life of LLPs means that maximum utilisation of available life can be achieved, with parts likely to be replaced at about 13,000EFC. This would result in a reserve of $375 per EFC. Total reserves will be $345 per EFH *(see table, this page)*.

Engines operated at 6.0-8.0EFH will have a total interval of 33,500-38,000EFH at the second removal. Shop-visit workscopes will be similar to engines operated at 3.0EFH, although the replacement rate of parts will be higher and so workscope costs will be higher. These will be $2.6-2.7 million for the first visits, and $4.2-4.3 million for the overhaul. These two workscopes will have a reserve of $184-203 per EFH.

It may be possible to replace LLPs at a slightly longer interval of 13,500-14,000EFC, resulting in a reserve of $350 per EFC. Total reserves will be $261 per EFH for engines at 6.0EFH, and $228 per EFH for engines at 8.0EFH.

Trent 700

Unlike the CF6-80E1 and PW4168, the Trent 772's first removal interval is limited by the life of the HPT shaft. Engines operating at 3.0EFH are likely to have similar first and second intervals of 12,500EFH each, and so reach a total time of 25,000EFH.

Shop-visit workscopes are expensive compared to the CF6-80E1 and PW4168. Workscopes generally follow Rolls-Royce's engine maintenance programme. Most modules require a level 3 or level 4 workscope, and the cost of materials and parts replacement is high. The first shop visit will cost $4.0 million, and the second, heavier, visit will cost $4.8 million. The reserve for these first two visits will be about $352 per EFH.

LLPs have lives varying from 4,200EFC to 15,000EFC. Average replacement life will be about 10,000EFC, and LLP reserves for old shipset parts with a list price of about $3.3 million will be about $330 per EFC. Total reserves will be $462 per EFH *(see table, this page)*.

Engines on 6.0EFH and 8.0EFH are able to achieve proportionately higher intervals, while workscope costs are also higher because of longer accumulated time on-wing. First workscopes will incur a cost of $4.4-4.6 million, and second visits a cost of $5.1-5.3 million. These result in reserves of $180-210 per EFH.

LLP reserves of $330 per EFC take total reserves to $266 per EFH for engines at 6.0EFH and $222 per EFH for engines at 8.0EFH *(see table, this page)*.

GE90 standard

Virtually all GE90 standards are operated at missions of 6.0EFH or longer. Most engines will have a performance or core restoration at the first shop visit, costing $3.8-4.0 million. Heavier workscopes and overhauls at the second shop visit incur costs of $4.8-5.0 million. Amortised over the combined interval of 32,000-34,000EFH, they will have a shop- visit reserve of $270-275 per EFH.

Given the varying lives of LLPs, average LLP replacement life will be about 10,000EFC, resulting in a reserve of $807 per EFC. Total reserves will be $408 per EFH for engines at 6.0EFH, and $370 per EFH for engines at 8.0EFH.

GE90-110/115

The GE90-110/115 will benefit from being operated on longer missions and cycles than the GE90 standard. The GE90-110/115 will have higher shop-visit costs, but these will be offset by the longer intervals. Shop-visit reserves will be $252 per EFH for engines at 8.0EFH, and $229 per EFH for engines at 10.0EFH.

LLP reserves will be $807 per EFC, as in the case of the GE90 standard, and total reserves will be $353 per EFH for engines at 8.0EFH, and $309 for engines at 10.0EFH *(see table, this page).*

PW4000-112

The PW4000-112 achieves similar total reserves to the GE90, although the PW4000 has longer intervals which are offset by higher shop-visit costs.

The PW4074/77 variants have a total time of about 39,000EFH when operated at 8.0EFH. Engines generally have the usual shop-visit pattern of a performance or core restoration followed by an overhaul. These have costs of $3.8 million and $5.0 million, and reserves for the two over the total interval are about $224 per EFH.

The LLPs for these lower-rated variants can probably be replaced at about 18,000EFC. This results in a reserve of $389 per EFC, and total reserve will be $273 per EFH for engines at 8.0EFH *(see table, this page).*

The higher-rated PW4084/90/98 variants have a total time of about 35,000EFH by the second removal. These engines also have higher shop-visit costs of $3.9-4.0 million at the first shop visit, and in the region of $5.5 million for the second heavier workscope. Reserves for the two shop visits will be about $269 per EFH.

The shorter lives of LLPs for these variants means that they should probably be replaced at about 13,500EFC, resulting in reserves of $556 per EFC. Total reserves will be $338 per EFH *(see table, this page).*

Trent 800

Similarly to the PW4000-112, the Trent 800 will have longer removal intervals that are offset by higher shop-visit costs, with the result that reserves are competitive with the GE90 standard and PW4000-112.

The lower-rated Trent 884/892 can achieve a total time of 45,000EFH by the second shop visit. Like the Trent 700, shop-visit workscopes and costs are relatively heavy. The first will incur a cost of about $4.7 million, and the heavier second visit in the region of $5.5 million. This results in a reserve of $227 per EFH.

LLPs can be replaced at about 14,000EFC, resulting in reserves of about $429 per EFC. Total reserves are about $280 per EFH *(see table, this page).*

The higher-rated Trent 895 will have a shorter total time of 43,000EFH by the second shop visit, and have workscope costs of $4.8 million and $5.7 million that result in a reserve of $244 per EFH.

LLPs with shorter lives will be replaced at about 8,600EFC, thereby resulting in reserves of $698 per EFC. Total reserves are $331 per EFH *(see table, this page).*

Engine type	GE90	GE90	GE90-110/-115	GE90-110/-115
EFH:EFC ratio	6.0	8.0	8.0	10.0
First & second removal interval-FH	31,500	33,500	36,500	42,000
First & second shop-visit cost-$	8,600,000	9,000,000	9,200,000	9,600,000
Shop-visit reserve-$/EFH	**273**	**269**	**252**	**229**
LLP shipset price-$	8,074,000	8,074,000	8,074,000	8,074,000
LLP replacement life-EFC	10,000	10,000	10,000	10,000
LLP reserve-$/EFC	**807**	**807**	**807**	**807**
Total Reserve-$/EFH	**408**	**370**	**353**	**309**

Engine type	PW4077/77	PW4084/90/98
EFH:EFC ratio	8.0	8.0
First & second removal interval-FH	39,000	35,000
First & second shop-visit cost-$	8,750,000	9,400,000
Shop-visit reserve-$/EFH	**224**	**269**
LLP shipset price-$	7,000,000	7,500,000
LLP replacement life-EFC	18,000	13,500
LLP reserve-$/EFC	**389**	**556**
Total Reserve-$/EFH	**273**	**338**

Engine type	Trent 884/892	Trent 895
EFH:EFC ratio	8.0	8.0
First & second removal interval-FH	45,000	43,000
First & second shop-visit cost-$	10,200,000	10,500,000
Shop-visit reserve-$/EFH	**227**	**244**
LLP shipset price-$	6,000,000	6,000,000
LLP replacement life-EFC	14,000	8,600
LLP reserve-$/EFC	**429**	**698**
Total Reserve-$/EFH	**280**	**331**

Summary

While these removal intervals, shop-visit input costs, LLP lives and LLP list prices give an idea of what reserves will be with different EFC times, many operators have fixed-rates-per-hour programmes with the original equipment manufacturers (OEMs) of these engines.

These shop-visit removal rates, shop-visit input costs and calculated reserves do not include costs relating to unscheduled shop visits and reserves for repair of rotable components on quick engine change (QEC). These will clearly add to the total reserves for these engines.

Reserves are also likely to increase as engines age. The rates calculated and shown relate to first and second shop visits. These, however, are for the first seven to 10 years of operational life. Most aircraft will be with their primary operators for 15-20 years. One problem that inflates reserves for engines used exclusively on long-haul missions is LLP reserves. Aircraft in this case are only likely to accumulate 450-750EFC per year. The majority of LLPs in most engine types have lives of 15,000EFC or more and are therefore only likely to expire after 20-33 years of operation, which means that it is possible that LLPs need not be replaced in many cases. This could therefore present a possible saving for some operators, although many fixed-rate-per-hour programmes would preclude this. AC