OWNER'S & OPERATOR'S GUIDE: GE90 FAMILY

GE90 family specifications

The General Electric GE90 engine family comprises two main variants. The are the GE90 standard, with five thrust ratings; and the GE90 Growth, with two thrust ratings. Their development, configuration & bypass ratios, thrust ratings, and emissions standards are examined.

The General Electric (GE) GE90 engine family powers about 650 active 777-200s/-300s. There are also another 330 777s on firm order which will be powered by GE90s, so almost 1,000 aircraft will be equipped with GE90 engines. The main models are the engine with the 123-inch fan, known as the GE90 'base' or 'standard' engine; and the engine with the 128.2-inch fan diameter, known as the GE90 'growth' engine. Each has several thrust ratings.

Engine concept

Development of the GE90 started in the mid- and late 1980s, after the CF6 family reached the limit of its thrust growth potential. The highest thrust-rated variant of the CF6-80E1 is the -80E1A3, rated at 68,530lbs thrust. The engine has a 96.2-inch fan diameter and a bypass ratio of 5.1:1.

The GE90 was developed solely for the 777 family. The initial variants of the 777-200 required engines with take-off thrust ratings of 76,000lbs (-76B), 77,600lbs (-77B), 85,000lbs (-85B) and 90,000lbs (-90B) *(see table, page 5)*. Aircraft could have maximum take-off weights (MTOWs) of 506,000lbs, 515,000lbs and 535,000lbs, although only 535,000lbs was selected by airlines. Aircraft with MTOWs up to 535,000lbs had standard fuel capacities of 31,000US Gallons (USG).

The 777-200ER has a higher fuel capacity of 45,220USG, and higher corresponding MTOWs of 580,000lbs, 590,000lbs, 632,500lbs and 656,000lbs. The GE90 engine options for these were rated at 85,000lbs (-85B), 90,000lbs (-90B) and 93,700lbs (-94B) *(see table, page 5)*. The 93,700lbs (-94B) engine was also available for the 777-300, which had a stretched fuselage, a fuel capacity of 44,700USG and MTOWs of 580,000lbs to 660,000lbs. No airlines chose this airframe-engine combination.

There are therefore five thrust ratings for the GE90 standard. This engine was one of three options for 777 customers, the other two being the Rolls-Royce Trent 800 family and the Pratt & Whitney PW4000-112 family.

The GE90 standard is no longer manufactured. Of all the 777-200/-200ERs built, there remain 169 in active service with GE90 standard engines. There are just four aircraft with -76B engines, 28 with -85B engines, 73 with -90B engines, and 64 with -94B engines.

Later developments of the 777-200 and -300 were ultra-long-range variants called the -200LR and -300ER. These aircraft have MTOWs of 760,700-775,000lbs and fuel capacities of 47,890USG and 53,440USG, so they required higher take-off thrusts of 110,100lbs (-110B) and 115,000lbs (-115B). This makes them the highest rated civil airliner turbofan engines. The GE90 growth engine is the only option for the 777-200LR, -200F and -300ER.

The GE90 growth has been more successful than the GE90 standard. Relatively few 777-200LRs have been ordered, with just 54 in service and another four on firm order. Most of these 58 have the -110B engine, although 11 have the higher-rated -115B. There are 65 777-200Fs in service, and another 62 on firm order. All 127 aircraft have the -110B engine. There are 357 777-300ERs in service and another 262 on firm order, making a total of 619 aircraft. All have the -115B engine.

GE90 standard

The 777-200, -200ER and -300 are powered by the GE90 'base' or 'standard' engine, with a fan diameter of 123 inches

One particular technology developed for the GE90 was swept, wide-chord fan blades made with composite materials. These blades allow the wide-diameter fan to turn at a relatively high RPMs.

GENERAL ELECTRIC GE90 FAMILY SPECIFICATIONS TABLE

Engine Model	GE90-76B	GE90-77B	GE90-85B	GE90-90B	GE90-95B
Thrust rating-lbs	76,000	77,000	84,700	90,000	93,700
Fan diameter (inches)	123	123	123	123	123
Fan blades	22	22	22	22	22
Bypass ratio	8.7:1	8.7:1	8.7:1	8.7:1	8.7:1
Overall pressure ratio	35:1	36:1	38:1	40:1	41:1
Flat rate temp-deg C.	33	30	30	30	30
NOx CAEP VI margin	19%	19%	14%	15%	13%
Application	777-200	777-200	777-200/ 777-200ER	777-200/ 777-200ER	777-200ER/ 777-300
Engine configuration					
Fan stages	1	1	1	1	1
LPC stages	3	3	3	3	3
HPC stages	10	10	10	10	10
HPT stages	2	2	2	2	2
LPT stages	6	6	6	6	6

Engine Model	GE90-110B	GE90-115B
Thrust rating-lbs	110,100	115,300
Fan diameter (inches)	128.23	128.2
Fan blades	22	22
Bypass ratio	7.2:1	7.2:1
Overall pressure ratio	40:1	42:1
Flat rate temp-deg C.	33	30
NOx CAEP VI margin	8%	6%
Application	777-200LR/ 777-200F	777-200LR/ 777-300ER
Engine configuration		
Fan stages	1	1
LPC stages	4	4
HPC stages	9	9
HPT stages	2	2
LPT stages	6	6

and thrust ratings of 76,000lbs to 93,700lbs *(see table, page 5)*. Conceiving an engine that was capable of delivering this amount of thrust required the GE90 to have a higher overall pressure ratio than the CF6-80C2 and -80E1 families. The CF6-80E1 has an overall pressure ratio of 34.8:1.

The GE90's high pressure compressor (HPC) is one of its most important features. Its design and configuration is central to the GE90 'standard' achieving an overall pressure ratio of 35-41:1 *(see table, this page)*. The significance of a high overall pressure ratio is that the higher the overall pressure, the more efficient is the cycle of inducting air, compressing it, heating it and expelling it. Each engine design therefore aims to reach as high an overall pressure ratio as possible. The overall effect is for thrust to be generated more efficiently, so that a lower amount of fuel is used for the same thrust.

The GE90 standard's HPC is central to the engine's high pressure ratio. It has 10 stages, four fewer than the CF6-80E1. Despite its shorter length, the GE90's HPC design allows it to generate a high enough pressure ratio. This reduces the number of stages, and therefore the number of blades and vanes.

GE also developed the GE90's combustor to be shorter than the CF6's, so the GE90's core is overall shorter. This gives the engine stiffness, which reduces flexing so that there is less rub between the tips of blades and the inner walls of the engine casing. This improves durability.

A third factor contributing to the GE90's short core engine is the use of a three-stage low pressure compressor (LPC) or booster. This compares to a four-stage configuration for the CF6-80C2/-80E1 engine.

Similar to the CF6-80C2/-80E1, the GE90 standard uses a two-stage HPT, a feature necessary to extract enough power to turn the engine's large fan.

The GE90 standard's bypass ratio is 8.7:1. This compares to the CF6-80E1's bypass ratio of 5.1:1. The GE90 achieves this higher bypass ratio, and therefore lower specific fuel consumption (sfc) and noise emissions, through the use of a wider intake fan.

This larger fan requires a six-stage low pressure turbine (LPT) to turn it, compared to a five-stage LPT used for the CF6-80E1.

Specific technologies

Several new technologies were developed for the GE90 standard. The first of these was curved, wide-chord fan blades for the intake fan. The tip speed of fan blades is limited by aerodynamics, and the problem of generating a shock wave if the air speed at the tips of the blades exceeds the speed of sound. This shock wave limits a fan's efficiency, so the fan's rotational speed has to be limited. The wider the fan, the lower the rotational speed or revolutions per minute (RPM).

The GE90's wider fan compared to the CF6-80E1, for example, meant that it would have to turn at lower RPMs. This would compromise the engine's efficiency. More LPC and LPT stages, for example, would be required to turn a larger fan.

GE overcame these limitations by developing modern generation fan blades for the GE90. These had a three-dimensional (3-D) aerodynamic shape, and were wide-chord, snubberless blades.

The design was made possible by the use of various composite materials. Besides allowing the fan to turn at a relatively high RPM for its diameter, it also has fewer fan blades than the CF6-80C2's/-80E1's fan. That is, both main GE90 variants have 22 fan blades, compared to the CF6-80C2's 38 blades. The aerodynamic efficiency and light weight of the fan blades mean that the fan requires less energy to turn it than a fan of conventional design would.

Another bonus of the use of composite materials in the GE90's fan blades was that the intake fan is more resistant to foreign object damage.

A second major technology used in the GE90 was several generations of 3-D aerodynamic airfoils in the core engine. There are three main groups of GE90 variants.

The first group comprises the GE90 standard variants rated at 76,000lbs, 85,000lbs and 90,000lbs thrust. These engines had the same component configuration, and different thrust ratings

The GE90 Growth engine is the only engine powering the 777-200LR/-300ER. There are more than 480 aircraft in operation, and another 330 aircraft on firm order. These aircraft are in operation on long-haul and ultra long-haul routes.

are simply achieved through the use of the full authority digital engine control (FADEC). These used the first generation 3-D airfoils in the HPC.

The second group is the GE90 standard engine that employs second generation 3-D aerodynamic airfoils in the HPC to allow the engine to achieve a higher thrust rating of 93,700lbs. The main benefit of these airfoils is that they have the effect of lowering the core engine temperature, which increases the engine's removal interval, and reduces fuel burn compared to the previous GE90 standard engines.

Once this engine was put into production, second generation 3-D aerodynamic airfoils could also be used in lower-rated standard engines to improve their aerodynamic efficiency.

Following the introduction of the second generation 3-D aerodynamic airfoils, GE introduced a performance improvement program (PIP), whereby the second generation HPC airfoils can be installed in the earlier-built -76B, -85B and -90B engines. These engines can be kept at their original thrust ratings, but can also be uprated to a -94B engine if required. Some airlines have installed these parts, but kept the engines at a -85B rating.

The second group of GE90 variants is the higher rated -110B and -115B engines with a 128.2 inch diameter fan.

A third main technology was the development of a dual annular combustor (DAC). This utilises two rings of annular burners, rather than a standard single ring of burners. This has the effect of burning more fuel in a shorter combustor length, with the benefit of reducing fuel burn and NOx and CO2 emissions.

The engine's high bypass ratio and overall pressure ratio not only contributes to it having a low sfc, but also means it has lower noise emissions than earlier generation turbofans. The GE90-76B has a 13.2-14.6 EPNdB margin for Stage IV noise compliance.

The GE90 standard also has a high flat-rating temperature. This is the outside air temperature up to which the engine maintains maximum thrust. Above this temperature, thrust has to be reduced for the exhaust gas temperature (EGT) not to exceed the redline limit. The GE90-76B has a flat rate temperature of 33 degrees centigrade, while all other GE90 standard variants are flat-rated at 30 degrees. This will allow the engine to operate at maximum thrust in most environments.

GE90 growth

The GE90-110B and -115B are rated at 110,000lbs and 115,000lbs. The 777-300ER is powered solely by the -115B, and the -200F solely by the -110B. The majority of 777-200LRs are powered by the -110B, although a small number of aircraft are powered by the -115B.

Several major changes were made to the GE90 standard to acquire the required thrust ratings. The key factor was the utilisation of a larger intake fan with a diameter of 128.2 inches. The diameter of the core engine is the same as the GE90 standard's core engine. The difference to the -110B/-115B's core engine is that it has an additional LPC stage to increase core flow, which is required to turn the larger fan at the optimum speeds required. It also, however, has one less HPC stage. A consequence of the higher coreflow is that the GE90-110B/-115B have a lower bypass ratio of 7.2:1 *(see table, page 5)* compared to 8.7:1 for the GE90 standard. The -110B/-115B's fan uses the same fan blade technology and same number of fan blades as the GE90 standard engine. The -110B/-115B's larger fan diameter means it has a 12% higher airflow than the GE90 standard's fan. This is a contributing factor to the growth engine's higher thrust rating.

The GE90-110B/-115B have an overall pressure ratio of 40-42:1 *(see table, page 5)*.

While the -94B utilised second generation 3-D aerodynamic airfoils in the HPC, the -110B/-115B utilised a third generation of refined 3-D aerodynamic airfoils in the HPC. The -110B/-115B also use new materials and airfoils in the turbine, in particular 3-D aerodynamic HPT blades and vanes.

Another feature of the -110B/-115B is improved aerodynamic airfoils in the LPT. This allowed the GE90 growth engines to utilise the same six-stage LPT, although the base engine has a slightly more efficient LPT.

GE wanted to use the same bearings in the growth -110B and -115B variants. The problem this posed was that a larger fan requires more energy to turn it, and this can require a thicker shaft. The need to maintain bearing design and the same shaft width as the GE90 standard meant that the growth engine's shaft required more torque, and so had to be stronger. This was achieved through the use of a new alloy.

The GE90-110B/-115B have NOx emissions margins of 8% and 6% relative to CAEP VI requirements. The GE90-110B is flat rated at 33 degrees centigrade, and the -115B flat rated at 30 degrees centigrade *(see table, page 5)*. AC

GE90 Growth fuel burn performance

The GE90 Growth engine exclusively powers the 777-200LR and -300ER, which are mainly used for long-haul and ultra long-haul operations. The fuel burn and operating performance of the aircraft with these engines is examined on routes between 3,500nm and 9,200nm.

The GE90 family of engines was developed specifically for Boeing's 777 family. The most powerful variant is the GE90-115B, which is the only powerplant available for the 777-300ER. There is also an option to fit this to the 777-200LR, although this aircraft and the 777-200F are normally equipped with the de-rated GE90-110B1.

The fuel burn performance of the GE90-110BL-, GE90-115B- and GE90-115BL-powered 777-200LR and 777-300ER are analysed here. Six sample routes, or city-pairs, of increasing distance from 3,500nm to 9,200nm have been selected. The 777-200LR and -300ER have been examined on four routes from 3,500nm to 6,045nm, and the 777-200LR has been analysed on two ultra-long-haul routes of 7,000nm and 9,000nm.

Aircraft analysed

The specifications of the aircraft analysed here are summarised *(see table, this page)*. A manufacturer's standard three-class configuration has been used to determine the maximum passenger payload.

The 777-200LR used for the shorter distance routes including Frankfurt (FRA) - New York (JFK) is equipped with GE90-110Bs. It has a maximum take-off weight (MTOW) of 766,800lbs and a fuel capacity of 48,533 US Gallons (USG) *(see table, this page)*. The passenger capacity for this aircraft is 301 seats.

The 777-300ER used here is equipped with GE90-115Bs. It has an MTOW of 775,000lbs and a fuel capacity of 48,533 USG *(see table, this page)*. The passenger capacity for this aircraft is 365 seats.

The 777-200LR variant used for the ultra-long-distance sectors of Hong Kong (HKG) to Toronto (YYZ), and Singapore (SIN) to JFK, is equipped with GE90-115BLs engines. It has an MTOW of 766,800lbs and a fuel capacity of 53,440 USG *(see table, this page)*. The passenger payload is 301 seats. However, this is more than typical airline configurations when using the aircraft on ultra-long-haul routes, since airlines will want to configure their aircraft to provide a greater level of comfort for these services. The flight plans conducted for the analysis, however, indicate the available payload that the aircraft is capable of carrying in both directions on each route. The weight for the passenger payload is deducted from the available payload that the aircraft can carry on the route in order to leave the available freight payload that could be carried *(see table, page 10)*.

777-200LR & 777-300ER CONFIGURATIONS

Aircraft Engine variant	777-200LR GE90-110B1/B	777-300ER GE90-115B
Engine thrust - lbs	110,100	115,300
Long-range cruise speed	Mach 0.84	Mach 0.84
Seats-tri-class:	301	365
Weights:		
MTOW-lbs	766,800	775,000
MLW-lbs	492,000	554,000
MZFW-lbs	461,000	524,000
OEW-lbs	320,000	370,000
Fuel capacity - USG	48,533/53,440	48,533
Belly freight containers	32 LD-3s	44 LD-3s

Routes analysed

The routes chosen for the analysis include a selection of existing long-haul city-pairs. They will demonstrate the fuel burn performance of the aircraft in terms of the total USG used, and the rate of USG used per available seat-mile (ASM).

Three of the first four city-pairs analysed originate in FRA and operate to JFK, Chicago O'Hare (ORD) and Los Angeles (LAX) *(see table, page 10)*. The fourth operates between SIN and London Heathrow (LHR). These four routes have a tracked distance of 3,501nm to 6,157nm. On these routes the performance of the 777-200LR equipped with GE90-110B1s will be compared with the 777-300ER equipped with GE90-115Bs *(see table, page 10)*.

For the 777-200LR equipped with the GE90-115BL, four longer-distance missions have been considered. These are the operations in each direction on the YYZ-HKG routes, with tracked distances of 7,293nm and 6,955nm; and the SIN-JFK routes, with tracked distances of 8,615nm and 9,187nm *(see table, page 10)*. The two operations on the SIN-JFK route are on the edge of the 777-200LR's payload-range performance.

The tracked distance between two points, provided by the flight plan, has been used in the analysis. Due to air traffic control (ATC) following airways and transatlantic tracks, extended range twin engine operations (ETOPS) requirements and departure and arrival routeings, aircraft cover a longer tracked distance than the great circle distance between the origin and destination.

The equivalent still air distance (ESAD) is also shown. This takes into account the affect of en-route winds so that subsequently the ESAD will be longer than the tracked distance when there is a headwind, and shorter when

The 777-200LR is utilised on some of the world's longest routes, which have tracked distances exceeding 8,000nm.

there is a tailwind. The ESAD indicates the effective distance that the aircraft has flown, and this is the figure that should be considered against the aircraft's payload-range curve.

Other assumptions for these flight plans include average temperatures from the month of June, 85% reliability winds, the use of International Flight Rules and standard assumptions relating to fuel reserves, diversion fuel and contingency fuel. The total additional fuel carried for diverting to an alternative airfield, holding prior to landing at the destination, and reserve fuel ranges from 3,382USG to 5,683USG for the flightplans performed.

Long-range-cruise (LRC) speed has been used for each mission. The 777-200LR's and -300ER's LRC is Mach 0.84, but the actual Mach number used varies throughout the flight according to operating conditions.

LRC allows the aircraft to achieve the most efficient fuel burn rate per ASM. Optimum routes and flight levels have been used where possible in the flight plans. A total taxi time of 30 minutes per flight has been assumed, making block time equivalent to flight time plus 30 minutes. Total fuel burn is calculated as the sum of taxi fuel burn and fuel burn during flight.

The great circle distance on the FRA-JFK sector is 3,350nm, while the tracked distance is 3,501nm *(see table, page 10)*. A headwind of 29-30 knots (kts) means that the ESAD for this route ranges from 3,727nm when flown by the 777-200LR, to 3,733nm when operated by the 777-300ER. There is little difference in the block time for the two aircraft, with the 777-200LR taking eight hours and 17 minutes (08:17) and the 777-300ER taking two minutes longer *(see table, page 10)*. Variances in block times between aircraft are caused by differences in climb, cruise and descent speeds.

On the FRA-ORD route the great circle distance is 3,774nm, while the tracked distance is 3,964nm. Due to headwinds of 19kts the ESAD for both aircraft is 4,127nm *(see table, page 10)*. The difference in block time is again minimal with the 777-200LR taking 09:05, and the larger 777-300ER taking 09:03.

A great circle distance of 5,045nm compares to a tracked distance of 5,279nm on the FRA-LAX route. Headwinds of 17kts lead to an ESAD of 5,473nm for the 777-200LR and 5,471nm for the 777-300ER. The 777-200LR again has the longer block time, taking 11:54 compared to the 11:48 achieved by the 777-300ER.

On the SIN-LHR route the great circle distance is 5,879nm and the tracked distance is 6,045nm. With a 9kt headwind the ESAD for both aircraft is 6,157nm. The difference in block time is extremely small with the 777-200LR taking 13:03 and the 777-300ER taking 13:02.

Where the extra-long-haul routes flown by the 777-200LR are concerned, YYZ-HKG has a great circle distance of 6,787nm and a tracked distance of 7,099nm. A headwind of 13kts contributes to an ESAD of 7,293nm and a block time of 15:14.

In the opposite direction, HKG-YYZ, the great circle distance remains the same but the tracked distance increases to 7,156nm. In this direction the aircraft benefits from a tailwind of 14kts reducing the ESAD to 6,955nm and the block time to 14:29.

On the SIN-JFK route the great circle distance is 8,288nm and the tracked distance 8,826nm. A tailwind of 12kts leads to an ESAD of 8,615nm and a block time of 17:43.

The opposite direction, JFK-SIN, has the same great circle distance but a longer tracked distance of 9,375nm. A tailwind of 10kts contributes to an ESAD of 9,187nm and a block time of 19:01; being the longest mission analysed.

Fuel burn performance

Total fuel burn (block fuel) and fuel burn per ASM are shown for each aircraft and engine combination, for each route *(see table, page 10)*. The block fuel used is dependent on aircraft weights and route distance. The longer the route, the greater the amount of block fuel used. A more accurate comparison of performance, therefore, can be drawn from the fuel burn per ASM.

Across the four city-pairs on which they are compared, the 777-300ER uses a greater amount of block fuel than the 777-200LR, but the -300ER has a slightly lower fuel burn per ASM. A significant contributing factor to this is that the

FUEL BURN PERFORMANCE OF THE GE90-110B/-115B-POWERED 777-200LR & 777-300ER

Route	Aircraft type	Engine model	Available payload (lbs)	Passenger payload (seats)	Available freight payload (lbs)	Tracked distance (nm)	ESAD (nm)	Wind (kts)	Block time (hr:min)	Block fuel (USG)	Fuel burn USG per seat-mile
FRA-JFK	777-200LR	GE90-110B	141,000	301	74,780	3,501	3,727	-29	8:17	18,754	0.0178
	777-300ER	GE90-115B	204,000	365	123,700	3,501	3,733	-30	8:15	21,850	0.0171
FRA-ORD	777-200LR	GE90-110B	141,000	301	74,780	3,964	4,127	-19	9:05	20,928	0.0175
	777-300ER	GE90-115B	204,000	365	123,700	3,964	4,127	-19	9:03	24,372	0.0168
FRA-LAX	777-200LR	GE90-110B	137,924	301	71,704	5,279	5,473	-17	11:54	29,193	0.0184
	777-300ER	GE90-115B	193,927	365	113,627	5,279	5,471	-17	11:48	33,392	0.0173
SIN-LHR	777-200LR	GE90-110B	140,171	301	73,951	6,045	6,157	-9	13:03	33,516	0.0184
	777-300ER	GE90-115B	173,478	365	93,178	6,045	6,157	-9	13:02	37,019	0.0168
YYZ-HKG	777-200LR	GE90-115BL	131,743	301	65,523	7,099	7,293	-13	15:14	40,706	0.0190
HKG-YYZ	777-200LR	GE90-115BL	141,000	301	74,780	7,156	6,955	14	14:54	38,431	0.0178
SIN-JFK	777-200LR	GE90-115BL	102,146	301	35,926	8,826	8,615	12	18:08	46,524	0.0175
JFK-SIN	777-200LR	GE90-115BL	68,021	301	1,801	9,375	9,187	10	19:21	47,756	0.0169

Source: Navtech

larger aircraft has the capacity for 64 additional passengers. The larger 777-300ER also has a greater available freight payload across all four routes. This freight payload is calculated by subtracting the weight of the passengers from the total available payload. The total available payload is defined by the aircraft's performance limitations within the mission criteria.

On the FRA-JFK route the 777-300ER burns 0.0171 USG per ASM in comparison to a 0.0178 burn per ASM on the 777-200LR. The larger aircraft has the ability to carry an additional 48,920lbs of freight than the 777-200LR. This represents an additional 65% of freight payload.

On the FRA-ORD route the 777-300ER has a fuel burn per ASM of 0.0168 USG, in comparison to a burn rate of 0.0175 USG per ASM on the 777-200LR. The difference in available freight payload is identical to the FRA-JFK route. The larger aircraft is again able to carry an extra 48,920lbs or 65% more of freight payload.

The FRA-LAX route saw the 777-300ER use 0.0173 USG per ASM, compared to a 0.0184 USG burn per seat mile on the 777-200LR. The disparity in available freight payload was 41,923lbs in favour of the larger aircraft. This represents an additional 58% of freight payload.

On the SIN-LHR route the 777-300ER has a fuel burn per ASM of 0.0168 USG. This compares to a burn of 0.0184 USG per ASM on the 777-200LR, and represents the biggest disparity in performance between the two types on the routes analysed. The difference in available freight payload between the two aircraft is reduced to 19,227lbs in favour of the 777-300ER on this longest route. This represents 26% of additional freight payload, the smallest difference across the routes compared.

The 777-300ER's fuel burn per ASM ranged from a minimum of 0.0168 USG on the FRA-ORD and SIN-LHR routes to a maximum of 0.0173 USG on the FRA-LAX city pair. This compared with a minimum burn of 0.0175 USG per ASM by the 777-200LR and a maximum of 0.0184 on the FRA-LAX and SIN-LHR routes.

As route length increased, the difference in fuel burn per ASM grew in favour of the 777-300ER, due in part to its additional capacity. Despite consistently offering a greater potential, the -300ER's available freight payload reduced as route length increased.

On the ultra-long-haul routes the 777-200LR is analysed alone. On the YYZ-HKG route the aircraft burns 0.0190 USG per ASM and has an available freight payload of 65,523lbs. In the HKG-YYZ direction, with a slight increase in tracked distance, but with the benefit of a tailwind, the aircraft burned 0.0178 USG per ASM, with an increased available freight payload of 74,780lbs.

On the longest SIN-JFK sector the 777-200LR's burn per ASM improved again to 0.0175 USG, but there is a significant reduction in available freight payload with only 35,926lbs available.

In the opposite JFK-SIN direction, the longest of all tracked distances and ESADs analysed, the fuel burn per ASM improves to 0.0169 USG, but the available freight payload is minimal. It shrinks to a mere 1,801lbs. This is hardly surprising given that the aircraft is operating at the edge of its payload-range profile.

In general as the route length increased, the 777-200LR equipped with GE90-115BLs and a full passenger payload saw improved performance in terms of fuel burn per ASM. This would be expected, unless the aircraft was only able to carry a restricted number of passengers on the longer routes, in which case the burn per ASM would be higher. The available freight payload decreased to the extent that on the JFK-SIN route there was little in the way of potential commercial freight capacity. AC

GE90 family maintenance costs

Removal intervals, shop visit workscope patterns & costs, LLP lives and reserves provide a guide to maintenance reserves for the GE90 Standard and GE90 Growth engines at typical rates of operation & utilisation.

The GE90-powered fleet of 777s is the largest sub-fleet of 777s in operation. There are about 650 aircraft in service with GE90 engines, and a further 330 aircraft on firm order. The majority of aircraft are operated on long-haul services.

The fleet can be sub-divided between the smaller variants with the 123-inch fan, and those with the larger 128-inch fan. Most engines in the 123-inch-fan fleet are mature in age and maintenance terms. The oldest 128-inch fan engines are 10 years old, although the engines did not come into service in significant numbers until 2004. The oldest 128-inch fan engines will have been through at least two major shop visits. The majority of engines in the fleet will have either been through only one shop visit, or are still in their first removal interval.

The maintenance reserves of both main variants operated at different rates of utilisation and at different engine flight hour (EFH) to engine flight cycle (EFC) ratios are examined.

GE90 in operation

There are about 170 aircraft in active service with 123-inch-fan engines. These are eight to 17 years old; with most aircraft being delivered up to 2007, although the final two were delivered in 2010. The fleet can be sub-divided into four fleets of the -76B, -85B, -90B and -94B. These are rated at 76,000lbs to 93,700lbs thrust *(see GE90 Specifications, page 4)*. The -76B and -85B fleets are small, with just 32 aircraft in total. These power early-built 777-200s and -200ERs, and are operated mainly by British Airways (BA) and a smaller number by China Southern Airlines. The BA fleet is operated on medium-haul services to the Middle East and some East Coast destinations in the US. China Southern operates its aircraft on Chinese domestic services.

The higher-rated -90B and -94B fleets account for most of the 123-inch-fan fleet, with 137 aircraft in operation. The biggest operators are Air France, China Southern, Saudia, United Airlines (which are ex-Continental Airlines aircraft), Alitalia, Japan Airlines (JAL), KLM, Pakistan International (PIA) and Vietnam Airlines.

The -90B and -95B fleets are both operated at similar rates of utilisation and EFH:EFC ratios. A minority of the aircraft are operated on medium-haul operations with annual utilisations of 3,000-3,500 flight hours (FH). These are aircraft operated by Saudia, PIA and Vietnam Airlines.

Most aircraft, however, are operated on long-haul networks, and have annual utilisations of up to 5,500FH. EFH:EFC ratios are 8-11:1. Some airlines operate their aircraft on ultra-long-haul operations. These include Air France, Alitalia and United/Continental.

There are almost 480 active aircraft with 128-inch-fan engines. The oldest of these is 10 years, while there are more than 300 aircraft on firm order. The 128-inch-fan fleet can be sub-divided into three sub-fleets. There is the GE90-110B, rated at 110,000lbs thrust, which powers two of the sub-fleets. There are two sub-fleets of 54 777-200LRs and 65 777-200Fs in active service.

The third sub-fleet is the 777-300ER powered by the GE90-115B, rated at 115,000lbs thrust. This has almost 360 active aircraft, and has another 263 on firm order, and so is the largest sub-fleet of GE90-powered aircraft.

The 777-200LR is operated by Air Canada, Air India, Delta, Emirates, Ethiopian Airlines, PIA and Qatar Airways. This is a specialist ultra-long-haul aircraft, although Air India and Ethiopian Airlines operate their fleets on long-haul services of more typical flight lengths. All other operators utilise the 777-200LR on ultra-long-haul services. These have EFH:EFC ratios of 9-11FH, and annual utilisations of 4,500-5,500FH.

The 777-200F fleet includes main fleets operated by Aero Logic, China Cargo Airlines, China Southern, Emirates, FedEx, LAN Cargo, Qatar Airways, Southern Air and TNT Airways. As with all freight operations, the EFH:EFC ratios of the 777-200F are shorter than the -200LR, even though the aircraft has almost identical maximum take-off weights (MTOWs) and fuel capacities. Most aircraft are operated at flight cycle (FC) times of 4.5-6.5FH, and have annual utilisations in the region of 4,500FH.

The 777-300ER fleet also operates with a mix of average FC times. Most aircraft are utilised for long-haul missions, but fleets operated by Saudia, Emirates, EVA Air and Philippine Airlines are used on medium and shorter long-haul operations of 2.5-7.0FH.

Most other operators use their aircraft on long-haul missions of 7.0-13.5FH. Virgin Australia operates the longest FC times, with aircraft being deployed from Sydney to Los Angeles and Johannesburg. These aircraft achieve annual utilisations of 4,700FH and 350FC.

Turkish Airlines (THY) operates a fleet of 12 aircraft to destinations in North America, Sao Paulo, Hong Kong, Beijing and Singapore and generate about 5,300FH and 570FC per year. Singapore Airlines achieves some of the highest rates of utilisation at about 5,500FH and 650-700FC per year.

Maintenance management

While a portion of engines are managed under total care style programmes, the removal intervals and workscopes of engines generally have to be managed around the life limits of life limited parts (LLPs) and shop-visit workscopes.

The GE90 has four main modules. These are the fan and low pressure compressor (LPC), high pressure compressor (HPC), high pressure turbine (HPT) and combustor, and low pressure turbine (LPT). There are a total of 22 rotating LLPs in these four modules in the 123-inch-fan engine *(see table, page 12)*, and 23 rotating LLPs in the 128-inch-fan engine *(see table, page 12)*.

The target lives for these rotating LLPs are 20,000EFC in the fan LPC and HPC, and low pressure turbine in the 123-inch-fan engine. The rotating parts in the HPT have target lives of 15,000EFC.

The target life of all rotating parts is 15,000EFC in the 128-inch fan engine.

In addition to these, fan blades are also classified as LLPs, and these have lives of 30,000EFC in both main variants *(see table, page 12)*. Given the rates of utilisation of most aircraft and engines, these parts are unlikely to require replacing due to life limit expiry in their operational lifetime. They are, however, susceptible to foreign object damage

GE90 FAMILY LIFE LIMITED PARTS

Engine variant	GE90 Std		GE90-110B/-115B	
	Certified life EFC	Target life EFC	Certified life EFC	Target life EFC
Fan/LPC				
Fan blades	30,000	30,000	30,000	30,000
Fan rotor disk	20,000	20,000	15,000	15,000
Booster spool	20,000	20,000	15,000	15,000
Forward fan shaft	20,000	20,000	13,100	15,000
Mid fan shaft	10,000	20,000	9,400	15,000
HPC				
HPC forward shaft			15,000	15,000
Stage 1 disk	19,000-19,100	20,000	15,000	15,000
Stage 2-6 spool	11,000-15,000	20,000		
Stage 2-5 spool			8,800	15,000
Stage 6 disk			8,500	15,000
HPC impeller			15,000	15,000
Stage 7 disk	14,000-15,800	20,000		
HPC 7-9 spool			7,700	15,000
Stage 8-10 spool	9,800-16,700	20,000		
Tube supporter ring	20,000	20,000		
CDP seal	18,000-18,600	20,000	12,400	15,000
HPT				
Forward seal	15,000	15,000	9,000	15,000
Stage 1 disk	9,500	15,000	8,100	15,000
Interstage seal	3,500	15,000	11,400	15,000
Stage 2 disk	14,200	15,000	8,600	15,000
Aft seal	15,000	15,000	15,000	15,000
LPT				
Stage 1 disk	19,800	20,000	15,000	15,000
Stage 2 disk	12,300	20,000	13,800	15,000
Stage 3 disk	14,900	20,000	15,000	15,000
Stage 4 disk	14,600	20,000	8,700	15,000
Stage 5 disk	13,400	20,000	15,000	15,000
Stage 6 disk	20,000	20,000	10,800	15,000
Cone shaft	15,000	20,000	15,000	15,000
Cases				
HPC forward case			25,380	40,000
HPC extension case			7,430	40,000
HPT case	13,370	40,000	6,780	40,000
Combustion case			17,700	40,000
Turbine center frame			14,300	40,000
LPT case	19,800	40,000	24,800	40,000

(FOD) and other types of damage, and so may require replacing for these reasons.

A third group of parts are also classified as LLPs. The high pressure (HP) turbine case and the low pressure (LP) turbine case in the 123-inch engine have target lives of 40,000EFC. The actual certified lives of these parts are 13,370EFC and 17,900EFC *(see table, this page)*. The engines will therefore have to be managed around these life limits.

In the 128-inch-fan engine, the HPC forward case, the HPC extension case, the combustion case, the HPT case, the turbine centre frame, and the LPT case are all classified as LLPs. These six parts all have target life limits of 40,000EFC. The actual life limits of two of these parts with the shortest lives are 7,430EFC and 6,780EFC. The lives of the other four parts are 14,300EFC to 25,380EFC *(see table, this page)*.

The lives of the rotating LLPs have an impact on engine management. Not only do their target lives of 15,000EFC and 20,000EFC mean that they are likely to need replacement during the operational life of the aircraft, but many of the parts have actual certified lives that are shorter than these target limits. This means that they are likely to require replacement during the aircraft's operational lifetime, so the relatively short life of some rotating LLPs means that engine removals and shop-visit workscopes will have to be managed around the life limits of these parts.

The actual certified life limit of rotating LLPs for each part has varied since the engine's entry into service. This is first because there are several part numbers for each rotating part. Different part numbers are used on the production line during the manufacture of each engine variant, and a part number with a longer life limit will replace an earlier part number used in earlier-build engines. The removal of different engines of the same variant may therefore have to be managed differently because of their varying LLP life limits.

Another factor is that the life limit of particular part numbers has been increased by General Electric (GE) during their operational life due to operational experience. This may or may not come before the original life limit is reached.

Each variant had one or two rotating LLPs with short life limits. The GE90-76B, for example, had a life limit of just 3,500EFC for its HPT interstage seal in 2008. The same part in the -85B, -90B and -92B variants of the 123-inch-fan engine and the GE90-110B had the same life limit.

The life limit of this part has been increased to 15,000EFC in the 123-inch-fan engine, and to 11,400EFC in the 128-inch fan engine.

Other rotating LLPs in the 123-inch-fan engine had lives of 9,500-11,000EFC in 2008. These have been increased to 15,000-20,000EFC.

This highlights the problem of managing engine removal when LLPs with restricted lives force removals and are replaced with parts with longer lives.

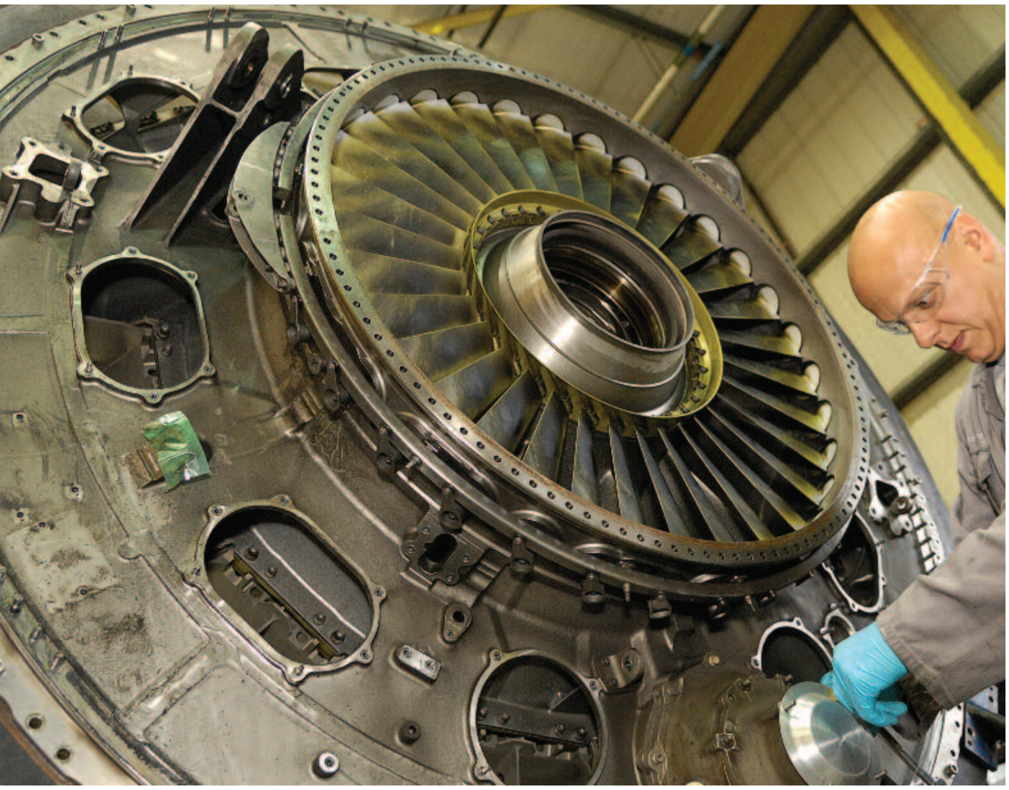
GE90-76B/-85B/-90B/-92B

As described, the majority of 777-200s are utilised by their operators on long-haul operations. The engines on most of these aircraft operate on average EFC times of 6.0-8.0EFH. These engines have achieved typical first planned removal intervals of 16,000-20,000EFH, equal to 2,000-2,700EFC. At typical rates of aircraft utilisation, this is equal to three-and-half to five years of operation.

These intervals would not have been limited by the 3,500EFC limit of the HPT interstage seal. This LLP would have to be removed at the first shop visit, however, to prevent limiting the second removal interval.

Engines at 2.8-4.5EFH

Engines operating at shorter EFC times of about 3.0EFH were capable of longer EFC intervals to the first shop visit, but these would have been limited to 3,500EFC if the interstage seal with a



While both main GE90 variants have LLPs that can limit planned removal intervals, engines can generally remain on-wing for extended periods, and without removal being forced by loss of EGT margin.

life of this limit had been installed on the engine. This is equal to 12,500-14,000EFH, depending on each EFH:EFC ratio.

The same engines, which are mainly the lower rated -76B and -85B, have demonstrated an ability to achieve second removal intervals of 4,500-5,500EFC; the longer interval being possible because of the absence of a LLP limiter. The engine would have been capable of first intervals of 5,000EFC or more. The total time at the second removal would be 8,000-9,000EFC. Removal would ultimately have been forced by a second LLP limit of 9,500EFC by the HPT first stage disk, and also at 9,800EFC by the HPC 8-10 spool.

Aircraft operating at 2.8-4.5EFH per EFC have reached maturity and removal intervals have settled to mature intervals that are close to the second removal intervals of 4,500-5,000EFC. This is equal to 16,000-20,000EFH. The actual interval will depend on the operating environment. Some Saudia aircraft operate in high ambient temperatures, so shorter intervals can therefore be expected.

The earlier-built GE90s had other limited LLPs with lives of 12,300EFC, 13,400EFC, 14,200EFC and 14,600EFC *(see table, page 12)*.

Paolo Lironi, executive director leasing at SGI Aviation explains that at maturity, the engine can broadly follow a shop-visit workscope pattern of a core refurbishment and minor work on the LPT, followed by a broader workscope that will include the fan and LP modules. The engine can therefore be expected to approximately follow an alternating shop visit pattern.

The pattern of workscopes can differ, however, depending on removal intervals. The first shop visit can be a full core workscope, while the second can include a light workscope on the LPT. The fan and LPC module may not be included until the third shop visit, and a full LPT workscope would not be included until the fourth shop visit.

Estimates for the first shop visit are $5.5-6.5 million, and $6.5-7.5 million for the second. The cost for the third shop visit is similar to the second shop visit. This would result in a total cost over the three shop visits of $18.5-21.5 million for a mature engine. Amortised over the total mature interval of 48,000-66,000EFH up to the third shop visit, this would result in reserves for shop visits of $325-285 per EFH *(see table, page 15)*.

This is the reserve for planned removals, but reserves for unscheduled or unplanned removals must also be budgeted for. "The rate of unscheduled removals for shop visits is 0.05 per 1,000EFH," says Lironi. This is equal to about 20,000EFH. The implication is that an unscheduled visit will come due at an interval about equal to scheduled removals.

Reserves for LLPs also have to be considered. This raises the issue of how much operators can be compensated for the restricted lives of LLPs with lives shorter than the target lives. That is, compensation could come in the form of a replacement part being supplied at a pro-rated price so that LLP reserves are the same as would be experienced for parts with unrestricted lives.

If compensation is possible, then LLP reserves could be close to the cost of a shipset of parts amortised over the full life limit. The LLPs have to be considered in three main groups. The 17 rotating parts with target lives of 20,000EFC have a list price of $4.6 million. The five rotating parts with target lives of 15,000EFC have a list price of $1.8 million. The 22 fan blades, which have a unit cost of $95,000, have a life limit of 30,000EFC. The fourth group is the two cases that have a list price of just over $1 million and have a target life of 40,000EFC. The four groups have a total list price of $9.5 million. When amortised over their full target lives they have a reserve of $445 per EFC. This is equal to $100-160 per EFH when amortised over the EFC times of 2.8-4.5EFH *(see table, page 15)*. Given that aircraft operating at these FH:FC ratios will accumulate about 1,000EFC per year, the fan blades and cases will need replacing within 10-14 years.

The total reserve for these two main elements is $425-545 per EFH *(see table, page 15)*.

Additional consideration has to be given here for the effect of unscheduled removals and shop visits. These can either add to the number of planned shop visits an additional cost that has to be amortised over the same interval, or reduce the total interval of three or four consecutive shop visits.

A further issue is the cost of repair and reserves for the engine quick engine change (QEC) kit. An allowance of $40-50 per EFH should be made for this.

Engines at 6.0EFH

The first planned removal intervals of engines operated at 6.0EFH per EFC are 2,700-3,000EFC. This is equal to 16,000-18,000ERH; so a longer EFH interval than engines operated on shorter EFC times. The life limit of the HPT interstage seal at 3,500EFC would clearly prevent a longer interval. The removal of this part would allow an unrestricted second removal interval, since the rotating LLP with the second shortest interval was 9,000EFC in earlier-built engines.

Engines operated at this moderate EFH:EFC ratio achieved second and subsequent removal intervals of 2,200-2,700EFC; which is equal to 13,000-

16,000EFH. Total interval to the second removal will therefore have been 29,000-34,000EFH, equal to six years of operation. While the second and third removal intervals would not have been affected by any LLP life limits, the fourth removal interval may have come close to being compromised by parts with lives of 9,500EFC. These parts, and others with life limits of up to 12,000EFC would have to be removed at the third shop visit to prevent limiting the fourth removal interval. Given that one of these parts was the fan mid-shaft, limited at 10,000EFC, and others are in the HP modules, most of the engine would require a full disassembly. Depending on condition and findings, the engine may require a full disassembly at the second shop visit. The parts with lives of up to 11,000-11,500EFC would then probably have had to be replaced at this stage to prevent forcing a full disassembly of the engine again prematurely at the third or fourth shop visit.

The majority of GE90 123-inch fan engines will have been through their first two planned shop visits. Only a small number of engines manufactured in 2007 and 2010 will have been through one planned shop visit.

Most engines will therefore be at maintenance maturity. The engines will conform to a fairly steady shop visit workscope pattern. This can be where the fan and LP modules can be worked on every second interval, although it may be possible to leave the fan to every third shop visit.

As with engines operated on short EFC times of 2.8-4.5EFH, shop-visit costs will be $5.5-6.5 million where just the core and possibly a light workscope on the LPT is performed. Larger workscopes that include the fan and LPC modules would cost $6.5-7.5 million. On the basis that the engine can be managed so that the fan and LPC module is worked on every third shop visit, total costs will be $20-22 million. The total interval for the three shop visits will be 40,000-48,000EFH. Reserves for these shop visit inputs will therefore be $455-500 per EFH *(see table, this page)*.

The second main element of maintenance reserves is for LLPs for all groups of LLPs. As described, this is a rate of $445 per EFC. This is equal to $74 per EFH when considered at the engine's EFC time of 6.0EFH.

Aircraft operating at this FH:FC ratio will not accumulate 30,000FC in their operational lifetime. If reserves for fan blades and cases are avoided, then reserves for LLPs will be reduced to $350 per EFC. This is equal to $58 per EFH when considered at the engine's EFC time of 6.0EFH.

The total for these two elements is $518-558 per EFH *(see table, this page)*.

GE90 STANDARD SHOP VISIT REMOVAL INTERVALS & MAINTENANCE RESERVES

EFH:EFC Ratio	2.8-4.5	6.0	8.0
1st removal interval			
EFC	3,500	2,700-3,000	2,300-2,800
EFH	12,250-14,000	16,000-18,000	18,500-22,400
LLP limiter:	3,500EFC-HPT module	3,500EFC	3,500EFC
Shop visit input:	$5.5-6.5 million	$6.0-6.5 million	$6.0-6.5 million
2nd removal interval			
EFC	4,500-5,500	2,200-2,700	2,000-2,300
EFH	16,000-22,000	13,000-16,000	16,000-19,000
LLP limiter	9,500EFC-HPT module	N/A	N/A
Shop visit input:	$6.5-7.5 million	$6.5-7.5 million	$6.5-7.5 million
3rd removal interval			
EFC	4,500-5,500	2,200-2,700	2,000-2,300
EFH	16,000-22,000	13,000-16,000	16,000-19,000
LLP limiter	Various: 12,300-14,600EFC	9,500EFC	N/A
Shop visit input:	$6.5-7.5 million	$6.5-7.5 million	$6.5-7.5 million
Total interval			
EFC	12,500-14,500	7,100-8,400	6,300-7,400
EFH	44,500-58,000	40,000-48,000	50,500-60,400
Total shop visit inputs:	18.5-21.5 million	$19.0-22.0 million	$20.0-22.0 million
Shop visit reserve:	$325-385/EFH	$460-500/EFH	$385-420
LLP reserve:			
$/EFC	$445	$445	$445
$/EFH	$100-160	$58	$44
Total shop visit & LLP reserve-$/EFH	%425-545	$518-558	$429-464

The main reason this is higher than engines operated at EFC lengths of 2.8-4.5EFH is because the first removal intervals were limited.

The cost of unscheduled removals and QEC should be considered in addition.

Engines at 8.0EFH

Engines operating at longer average EFC times of 8.0EFH should be able to achieve slightly longer EFH intervals. First intervals were 2,300-2,800EFC, equal to 18,500-22,400EFH. The HPT interstage seal with a life of 3,500EFC would prevent a longer interval.

Second and subsequent planned intervals for the -85B, -90B and -94B have been 2,000-2,300EFC, which is equal to 16,000-19,000EFH. The total accumulated time would therefore be 66,000-80,000EFH by the fourth removal and shop visit, without an interruption due to unscheduled removals. This is equal to 8,200-9,600EFC. The fourth shop visit would therefore be forced by LLPs with limited lives.

Given that the second or third shop visits would require work on most modules, a heavy visit and full disassembly would be required at either of these to prevent compromising the subsequent pattern of shop visit workscopes.

Most engines will be at mature intervals and maintenance status. They will follow the same or similar workscope pattern over three workscopes to engines operated at 6.0EFH per EFC. Engines operated at 8.0EFH per EFC will achieve slightly longer intervals, and will therefore have lower reserves for shop visits because the costs will be amortised over a total interval of 50,000-60,000EFH. Reserves will therefore be $385-420 per EFH *(see table, this page)*.

The second main element of rotating LLPs will be a reserve of $350 per EFC, equal to $44 per EFH *(see table, this page)*. Total reserve for the two main elements is $440-476 per EFH.

GE90-110B/-115B

The GE90-110B and -115B power ultra-long-range aircraft. The majority of engines operate on long average FC times of 7-11FH, although a minority operate on shorter FC times on medium-haul

GE90-110B/-115B SHOP VISIT REMOVAL INTERVALS & MAINTENANCE RESERVES

Engine	-115B (777-300)	-110B (777-200LR)
EFH:EFC ratio	8.5	10.0
1st removal interval		
EFC	2,900-3,100	2,800-3,000
EFH	25,000	28,000-30,000
LLP limiter:	3,500	N/A
Shop visit input:	$6.0-6.5 million	$6.5-7.0 million
2nd removal interval		
EFC	2,200	2,000
EFH	19,000	20,000
LLP limiter	N/A	N/A
Shop visit input:	$7.0-7.5 million	$7.5-8.0 million
3rd removal interval		
EFC	2,200	2,000
EFH	19,000	20,000
LLP limiter	N/A	6,780-HPT CASE
Shop visit input:	$8.0 million	$8.0 million
Total interval		
EFC	7,300-7,500	6,800-7,000
EFH	63,000	68,000-70,000
Total shop visit inputs:	$21.0-22.0 million	$22.0-23.0 million
Shop visit reserve:	$333-350/EFH	$325-330/EFH
LLP reserve:		
$/EFC	$432	$432
$/EFH	$51	$43
Total shop visit & LLP reserve-$/EFH	$483	$475

operations.

The GE90-110B/-115B have identical components, but are rated at two different thrust ratings. Like the GE90 Base engine, the 128-inch-fan engine does not generally have engines removed due to EGT margin loss. Most removals are driven by hardware deterioration.

THY had its first engines delivered in 2010. "Initial installed EGT margin is 35-49 degrees centigrade, and so an average of about 43 degrees," says Erkan Evcan, CF6 and GE90 engine programme manager at Turkish Technic. "The rate of EGT margin loss in the first 1,000EFC on-wing is about 12 degrees. This settles to about five degrees per 1,000EFC thereafter."

This amount of initial EGT margin is therefore enough for the engine to remain on-wing for up to about 5,500EFC. "We actually expect the first planned removal intervals to be about 3,500EFC. We operate at about 9EFH per EFC, so this is equal to more than 30,000EFH," says Evcan. "This is for the later-built engines that do not have any of the technical problems that the earlier-built engines had."

Early production 128-inch-fan engines have had a series of technical issues that have forced removals. "The three main issues that caused problems were the LPT stage 6 blades, the HPT blade shroud, and the leaf seal in the last stage of the HPC," says Uwe Zachau, senior manager performance & central engineering at MTU Maintenance. "All of these forced early removals, which meant that a lot of shop visits took place earlier than planned. This disrupted the shop-visit plan and pattern. We are expecting the first planned shop visits in 2013 for later-build engines that have had modifications to overcome these issues. These first planned visits will be core and performance restorations following long first-run removal intervals."

The problem of LPT stage 6 blades was that some separated and broke lose from the turbine disk on eight different occasions. These separations could lead to uncontained engine failures, so an airworthiness directive (AD) was issued. AD 2009-25-14 requires repetitive inspections if two particular LPT stage 6 blade part numbers are installed. These inspections are then terminated if new blades are installed.

The inspections are required prior to 3,000EFH or 400EFC being accumulated to detect wear of the shroud interlock. Repeat inspections are then required once every 1,000EFH or 125EFC, whichever comes first. Replacement of the two part numbers with new blades terminates the need for inspections.

A second major problem was the liberation of small parts from the seal teeth between stages 1 and 2 of the HPC. AD 2011-26-11 was issued and required eddy current inspection or other non-destructive testing (NDT) of the seal teeth.

There was also an issue with the HPT shroud, which required a change of HPT blades.

Zachau comments that in some cases these issues could be resolved through a minor quick turn repair, to fix the problem, and a full shop visit would not necessarily be required.

The problem of the pin coming loose that holds the leaf seal in place at the last stage of the HPC caused the seal to separate. This resulted in a leak of airflow into the HPC drum, which increased EGT and so reduced engine efficiency. General Electric recommends a borescope inspection at this point. "There have been four fixes for this leaf seal problem," says Zachau. "These have been detailed in service bulletins (SBs). SB numbers include 72-337/-338. Once the problem has been detected the affected parts need to be replaced or repaired. SB 72-424/-425 describes the repair process to introduce the new hardware."

SB 72-337 details performance trend monitoring and the inspection of the stage nine outlet guide vane (OGV) leaf seals. SB 72-988 details a rework to add a longer leaf seal pins to the stage 10 OGV assembly. Other SBs issued in relation to the leaf seal problem are SB 72-290, SB 72-354 AND SB 72-487.

"Premature removals of engines due to these technical issues have been very short: as little as 100EFC and up to 1,500EFC," continues Zachau. "There have so far been about 300 shop visits globally to deal with leaf seal problems. Some engines have had two shop visits to cope with the issue.

"If the problem happens after an interval of 1,500-1,800EFC then a performance restoration can be carried out, although normally this would not be expected until at least 2,000EFC had been accumulated," explains Zachau.

Evcan also highlights the issue of the rubbing of third and fourth stage HPC blades on the inner compressor wall. "This can fortunately be dealt with by using a quick turn repair, and does not require a full shop visit," says Evcan.

Once early-build engines had been cured of their initial reliability problems, mature removal intervals would settle down to 2,000-2,200EFC and 18,000-

The GE90 Standard and Growth variants should have reserves for shop visit inputs and LLPs in the region of $425-560 per EFH.

20,000EFH. Like the GE90 standard, the 128-inch-fan engines would conform to a similar shop-visit pattern. This would involve all HP modules at every shop visit, and work on the fan and LPC every second or third shop visit. Work in the LPT could be at alternate shop visits, with the second shop visit having a light LPT workscope, and the fourth having a full workscope. A full LPT workscope may have to be included at the fourth shop visit.

Younger engines, that have not experienced the reliability problems that the older engines experienced, are generally expected to be able to achieve a full planned first removal interval of about 2,800-3,000EFC. At EFC times of 8.5EFH and 10.0EFH, this is equal to 25,000EFH and 30,000EFH.

The subsequent second and third intervals are expected to be 2,000-2,200EFC and so 19,000-20,000EFH.

The total accumulated time over three shop visits is thus expected to be 63,000-70,000EFH and 6,800-7,500EFC *(see table, page 16)*.

The costs for the first shop visit will be $6.0-6.5 million. Taking into consideration experience of the GE90 standard, costs for the second and third shop visits are expected to be $7.0-7.5 million each. The third shop visit could rise closer to $8.0 million. The total cost of these three shop inputs is therefore $21.0-23.0 million.

A reserve of $333-350 per EFH for engines operated at 8.5EFH per EFC, and $325-330 per EFH for engines operated at 10.0EFH per EFC should therefore be budgeted for *(see table, page 16)*.

Consideration also has to be given to reserves for LLPs. There are three elements of rotating parts, fan blades, and cases.

A shipset of rotating LLPs has a list price of $6.5 million. These have target lives of 15,000EFC.

Assuming compensation for those parts with restricted lives is possible, or that these parts have their certified lives extended, reserves would be close to the list price amortised over the target life of 15,000EFC. This would be equal to $432 per EFC.

Each fan blade has a list price of $116,000 and a life limit of 30,000EFC. Reserves for a full shipset would therefore be $85 per EFC.

Although these parts have a fixed life, they are susceptible to foreign object damage or delamination, which can incur a high repair cost.

The third element is for engine cases. These have target lives of 40,000EFC, although the six parts have lives restricted to 6,780-25,380EFC. Again if compensation for parts with restricted lives is possible, then a reserve for these parts with a combined list price of $5 million would be $125 per EFC.

As with the 123-inch fan engines, the life limits of fans and cases are unlikely to be reached during the aircraft's operational life. Reserves for LLPs could therefore be limited to the rotating parts, with a reserve of $432 per EFC. This is equal to reserves of $43 per EFH for the -110B engine operated at 10.0EFH per EFC, and $51 per EFH for the -115B engine operated at 8.5EFH per EFC *(see table, page 16)*.

Total reserve for shop visits and rotating LLPs is thus $475 per EFH for the -110B engine operating at 10.0EFH per EFC, and $483 per EFH for the -115B engine operating at 8.5EFH *(see table, page 16)*.

Maintenance services

Many GE90 engines are maintained under General Electric's (GE) OnPoint services. These include shop visit maintenance, maintenance management, engine health monitoring (EHM) and range of other support products. Operators can sign contracts for OnPoint services for a particular period, and then decide whether to renew or seek alternative maintenance support providers.

The other providers of maintenance support for the GE90 include MTU Maintenance, Air France Industries KLM Engineering & Maintenance, Taexl in Xiamen, All Nippon Airways and Emirates. MTU maintenance is the only provider that is completely independent to GE.

Besides opting for time and material contracts with MTU Maintenance for the 128-inch fan engine, airlines can also subscribe to its EHM, shop visit planning and workscope definition, hi-tech parts repairs planning, and access to a pool spare engine.

"We offer time and material, never-to-exceed (NTE) cost maintenance, and power-by-the-hour (PBH) contracts," says Zachau. "The hi-tech parts repairs we will offer may become OEM-licensed, since many lessors prefer these to non-licensed."

MTU Maintenance also offers line maintenance aircraft-on-ground (AOG) support. AC