Engine performance is subject to a variety of factors, both on a fleet-wide and individual engine level. The technology on the new-generation engines is designed to maximise performance, while that early-service issues will influence a fleets' operational life. This can be via unscheduled shop visits or reduced dispatch reliability.

Widebody engine performance

The 787 Dreamliner and A350 represented milestones in aircraft development when they entered service. The 787 introduced new concepts in electrical design, and a shift away from hydraulic and pneumatic systems that promised greater efficiency and reliability. The A350 is built with more than 70% advanced materials, such as carbon composites and titanium and aluminium alloys (www.airbus.com). The engines that power these new aircraft families (the General Electric (GE) GEnx-1B, the Rolls-Royce (RR) Trent 1000 and the RR Trent XWB) are designed to complement and realise the potential of the new types.

While the GEnx-1B and the Trent 1000 power the 787 family, the Trent XWB is the sole engine option for the A350, which is also known as the A350-XWB family. The 787 comprises the 787-8 and 787-9 variants, which are in operation, and the 787-10 series which will shortly enter service. The A350-XWB meanwhile, comprises the in-service A350-900, and the -800 and -1000 which are yet to start operations.

The GEnx, Trent 1000 and XWB each boast design developments that set them aside from earlier engine families. Extended use of composite materials, additive layer manufacturing (ALM or 3D-printing), and bladed disks (blisks) have been incorporated to create weight savings, and realise greater performance and fuel savings for operators. Increasingly sophisticated cooling systems are incorporated, to minimise hot section deterioration and therefore prolong time on-wing (TOW). Fan blades are now designed to further reduce foreign object damage (FOD). In addition, each type has greater engine health monitoring (EHM) and prognostic capability.

While this new generation of engines is expected to increase TOW and engine reliability for operators, it is also generally expected that new engine families at entry into service (EIS) will encounter early-service issues. These can prompt performance enhancements or modification work across the fleet as it ramps up operational activity. Given the new technology present across these engine families, such issues are arguably even more likely.

Understandably, original equipment manufacturers (OEMs) are keen to observe any common EIS issues on a fleet-wide level, since the behaviour of engines in operation will as yet be unknown. Observations may not be immediate, and will typically arise after the first engines in service have started to accumulate higher engine flight hours (EFH) and engine flight cycles (EFC). Different utilisations, operating profiles and levels of atmospheric corrosion will affect engines differently, as will the thrust ratings they operate at and their individual configurations.

If fleet-wide defects are observed, this can lead to service bulletins (SBs) being issued by OEMs, often resulting in airworthiness directives (ADs) then being released by regulatory authorities. These can lead to further unscheduled removals. SBs can also be generated as a result of

The GEnx-1B has undergone two key performance-improvement packages: PIP I and PIP II. These offered modifications, aimed to improve the fuel burn and durability of early build engines in service. PIP II is currently the build standard configuration for -1B engines.

performance modifications and upgrades being designed by the OEM to mitigate against further issues. Full coverage, total care or power-by-the-hour (PBH) agreements (sometime referred to as flight-hour agreements or FHAs) will typically cover unscheduled removals, which makes them attractive to operators of new technology.

Due to the infancy of the engines being explored in this article, very little data is available from fleets in operation. Some performance data is accessible, but much of the information on shop visits (SVs), likely removal causes and mean time between removals (MTBRs) is only available from the OEMs. Given the high percentage of the fleet on FHAs and other full coverage agreements, data is further retained by the OEMs as these engines accumulate EFC.

Performance considerations

Key performance indicators have been established *(see GE90, GP7200, Trent 800 & Trent 900 performance & maintenance, April/May 2017, page 81).* Ultimately engine performance for maturing engines can be determined by the following parameters: MTBRs; fuel consumption and burn; engine flat rating temperature; exhaust gas temperature margin (EGTm); average EFH to EFC ratio; take-off de-rate; and ambient operating temperature.

Engine performance allows operators to establish exactly how efficiently the engine is working, in terms of how many EFH and EFC the engines are accumulating on-wing before they require removal and extensive maintenance in the form of a performance restoration or overhaul. This can also affect the maintenance reserves that these operators are paying to the OEM or lessor via a PBH maintenance contract. As was established in Issue 111 April/May 2017, EGTm loss is typically monitored against EFC, since it is a more accurate parameter than EFH. Factors such as high-pressure turbine (HPT) module performance will influence EGTm deterioration.

It can generally be assumed, unless stated otherwise, that scheduled removals for the subject engines follow a pattern of performance restoration followed by overhaul SVs. "Given the early stages of these engines' operational lives, it is not yet known what their workscopes will comprise," says Kane Ray, head analyst of commercial engines at IBA. "There has not been enough performance restoration activity to determine the workscope requirements on the GEnx-1B or Trent 1000, much less the XWB." Generally a performance restoration (referred to as a refurbishment on Trent engines) involves a hot-section inspection (HIS), overhaul of the combustor liners, HPT blade overhaul, and engine cleaning.

Life limited part (LLP) replacement has traditionally been factored in as the engines age, and can impact SV activity and TOW if early replacements are required. While limits tend to be gauged conservatively early after EIS, these can be expected to increase as engines mature. LLPs will therefore be explored throughout this article.

The 787 has entered its sixth year of commercial operations, while the A350 is in its third. Gauging the performance of immature engines, such as the GEnx, Trent 1000 and Trent XWB, is complex because there is not enough in-service fleet data available to determine accurate performance. Early data can be affected by findings on early-build engines that have not undergone performance upgrades, and unscheduled SVs.

"Early engine data should not be used to determine true-fleet averages," says Ray. "There are too many anomalies and early-service issues within a fledgling fleet to truly determine engine performance early in operation. Early-build engines also perform differently to those that have benefited from performance-enhancing programmes, which have begun to be incorporated into these engine fleets. Performance data can therefore become skewed."

It should be noted that all data provided in this article is based on estimation and industry opinion. It is not representative of the future and expected in-service performance of these fleets.

General Electric

GEnx family

Sumisho Aero Engine Lease B.V. is an engine lessor that was formed in 2013 as a joint venture (JV) between Sumitomo Corporations and MTU Aero Engines. Specialising in medium- to long-term leasing, Sumisho has GEnx-1B engines in its portfolio. The data it provides on the GEnx-1B is relevant to the GEnx-1B64, -1B70, -1B70/75, and -1B76A series that make up Sumisho's GEnx fleet. The lessees that use these engines have a mix of full and partial FHA contracts direct with GE, Graeme Crickett, senior vice president and head of technical at Sumisho Aero Engine Lease, explains. This means that the performance monitoring and maintenance management of these engines is mainly managed by the OEM.

Architecture

The GEnx family comprises the GEnx-1B and -2B series. The -2B was the first engine series to EIS in 2011 via the 747-8, while the -1B followed in 2012. The -1B is an option on the 787-8, -9, and -10 series. The -1B is therefore the main series in the GEnx family. The -1B variants deliver 64,000-78,000lbs of thrust, while the -2B's rating provides 67,000lbs. The -1B's thrust rating is denoted by the last two suffixes of the variant: the GEnx-1B64 has a thrust rating of 64,000lbs and powers the 787-8; and the -1B67 delivers 67,000lbs and also powers the -8, as does the -1B70 at 70,000lbs of thrust. Meanwhile, the GEnx-1B74/75 and -1B76A are options for the 787-9 and -10 series, and the GEnx-1B76's sole application is the 787-

GENX-1B LLPS LIMITS AND PRICING 2017 - CHAPTER 5 & ULTIMATE LIFE LIMITS *

PART	-1B64/P2 CH 5 LIFE	-1B64/P2 ULT LIFE	-1B70/75/P2 CH 5 LIFE	-1B70/75/P2 ULT LIFE	-1B76/P2 CH 5 LIFE	-1B76/P2 ULT LIFE	CLP 2017 $
DISK, FAN	20,000	20,000	15,000	15,000	15,000	15,000	413,500
SHAFT, FWD FAN	20,000	20,000	15,000	15,000	15,000	15,000	236,500
SPOOL, BOOSTER	20,000	20,000	15,000	15,000	15,000	15,000	455,200
SHAFT, ROTOR FWD	17,700	20,000	15,000	15,000	14,600	14,600	227,200
BLISK, STG 1	20,000	20,000	15,000	15,000	15,000	15,000	445,800
BLISK, STG 2	15,200	20,000	13,500	15,000	12,500	12,500	344,300
SPOOL, STG 3-4	12,700	20,000	10,900	15,000	9,800	15,000	443,900
BLISK, STG 5	13,300	20,000	12,200	15,000	11,600	15,000	319,000
SPOOL, BOOSTER 6-10	6,600	20,000	6,600	15,000	6,600	15,000	847,200
RING, TUBE SUPPORT	13,900	20,000	13,900	15,000	13,900	15,000	51,830
SEAL CDP	12,900	20,000	12,900	15,000	12,900	15,000	152,100
SEAL FWD	12,100	15,000	10,600	15,000	9,600	15,000	353,000
DISK, STG 1	11,800	15,000	10,700	15,000	9,400	15,000	745,800
SEAL, INTERCHANGE	15,000	15,000	15,000	15,000	13,800	15,000	383,100
DISK, STG 2	12,100	15,000	10,400	15,000	9,500	15,000	404,600
SEAL, AFT	13,000	15,000	12,800	15,000	12,200	15,000	167,100
SHAFT, FAN MID	20,000	20,000	14,900	15,000	12,500	15,000	371,700
SHAFT, CONE	17,000	20,000	14,600	15,000	14,200	15,000	191,500
DISK, STG 1	8,100	20,000	7,000	15,000	6,400	15,000	213,900
DISK, STG 2	18,900	20,000	15,000	15,000	15,000	15,000	335,500
DISK, STG 3	16,400	20,000	15,000	15,000	15,000	15,000	358,600
DISK, STG 4	8,600	20,000	8,600	15,000	9,500	15,000	272,600
DISK, STG 5	17,300	20,000	15,000	15,000	15,000	15,000	215,400
DISK, STG 6	19,500	25,000	15,000	15,000	15,000	15,000	229,300
DISK, STG 7	20,000	20,000	15,000	15,000	15,000	15,000	230,700
CASE, COMBUSTION	11,300	15,000	9,800	15,000	7,500	15,000	497,200
CASE, HPT	12,500	15,000	9,800	15,000	7,500	15,000	340,300
TOTAL							$8,409,330

* DOES NOT INCLUDE STATIC LLPS

10 when it enters commercial operations. The engine serial number (ESN) prefix is different for the -1B and -2B: for the -1B it is 956; and 959 for the -2B.

The -1B has a bypass ratio at take-off of 9.1-9.3:1.0 depending on the series installed. Built on the foundations of the GE90 engine family, the GEnx is designed to offer a 15% improvement in fuel consumption to its legacy GE counterpart, the CF6 family.

Both the -1B and -2B comprise a composite fan case and 18 composite fan blades. The fan diameter for the -1B is 111.1 inches, and 104.7 inches for the -2B. The GEnx's core modules comprise a 10-stage compressor, two-stage HPT and seven-stage low-pressure turbine (LPT).

According to Crickett the GEnx (as of July 2017) powers about 62% of the 787 in-service fleet, while the Trent 1000 is installed on the remaining 38%.

Performance upgrades

It has become common for engines in their early stages of operation to undergo configuration changes, or performance enhancements or modifications. These are designed and implemented by OEMs to counteract early service issues and further optimise the performance improvements promised by the new core architecture and design. These are commonly referred to as performance improvement packages (PIP). Some of these may be mandatory and implemented as a result of an SB or AD. Meanwhile, others may be specific to certain operational conditions such as hot-and-high performance, or operational locations where atmospheric corrosion is an issue.

The GEnx-1B has gone through a number of variant upgrades since its 2012 EIS, Crickett explains. Initial configurations of the GEnx-1B, were termed 'Block 4'. Crickett explains that these were swiftly upgraded by the PIP1 (Product Improvement Package) and then subsequently by the PIP2, which is the current build configuration. Older configurations are not supported by the OEM in parts manufacturing anymore, so upgrading is a matter of SV timing and workscope developments, he adds. FHAs in place may well cover some if not all of the upgrade expense, but this depends on the agreement held with the operator.

Some of the PIP packages implemented did not emerge until some time after EIS, and as such some ESNs are retrofitted with modifications. While some modifications have been introduced to achieve the lower fuel burn promised by the GEnx-1B and -2B, others have been mandated to mitigate against the build-up of ice on certain configurations of the -1B, or to maximise operation in hot-and-high environments.

Other ESNs will undergo further enhancements, depending on the operator's specific operating profile or thrust rating. Identifying the variants that have undergone PIP or configuration changes can therefore become complex.

Essentially, the GEnx-1B has four main configurations in its fleet: the GO3 Block 4 (original configuration); the GO4 initial PIP configuration (specific to 70k thrust variants); the P1G01 PIP1 configuration; and the P2G01 PIP2 configuration, which is the current-production build specification.

According to Crickett, the following is an approximation of ESNs and configurations:

- 956-103 to 956-130 (Original G03 Block 4 configuration);
- 956-140 to 956-158 (G04 (70k thrust), initial PIP configuration);
- 956-159 to 956-197, 956-203 to 956-271, and 956-310 to 956-312 (P1G01 PIP1 configuration)
- 956-198 to 956-202, 956-272 to 956-309, and 956-313 upwards

GENX-2B LLPS LIMITS AND PRICING 2017 - CHAPTER 5 & ULTIMATE LIFE LIMITS

PART	-2B67P CH 5 LIFE	ULT LIFE	CLP2017 $
DISK, FAN	15,000	15,000	413,500
SHAFT, FWD FAN	12,400	15,000	236,500
SPOOL, BOOSTER	15,000	15,000	455,200
SHAFT, ROTOR FWD	15,000	15,000	227,200
BLISK, STG 1	15,000	15,000	445,800
BLISK, STG 2	11,000	15,000	344,300
SPOOL, STG 3-4	7,900	15,000	443,900
BLISK, STG 5	9,500	15,000	319,000
SPOOL, BOOSTER 6-10	6,300	15,000	847,200
RING, TUBE SUPPORT	15,000	15,000	51,830
SEAL CDP	8,800	15,000	152,100
SEAL FWD	6,300	15,000	353,000
DISK, STG 1	8,200	15,000	745,800
SEAL, INTERCHANGE	10,400	15,000	383,100
DISK, STG 2	7,600	15,000	404,600
SEAL, AFT	12,200	15,000	167,100
SHAFT, FAN MID	5,000	15,000	371,650
SHAFT, CONE	15,000	15,000	179,700
DISK, STG 1	9,200	15,000	204,600
DISK, STG 2	13,300	15,000	308,400
DISK, STG 3	10,900	15,000	343,800
DISK, STG 4	7,800	15,000	280,700
DISK, STG 5	10,300	15,000	203,100
DISK, STG 6	15,000	15,000	154,900
CASE, COMBUSTION	11,000		543,500
CASE, HPT	10,900		340,000
TOTAL			$8,036,980

(P2G01 PIP2 configuration). As of Q3 2017, P2G01 PIP2 is into the second 1,000 ESN production with the 958- series.

"A few G05 engine variants were released as an interim model, but they were all converted to P1G01 prior to being sold commercially," adds Crickett. "PIP1 configuration was an initial desire to improve durability, and partially address fuel burn.

"Meanwhile the PIP2 configuration was released in May 2013," continues Crickett, "and consisted of virtually a full makeover of the PIP1 variant to further improve fuel burn and durability." The SBs that comprised this second PIP comprise SB72-0154 to SB72-0162 inclusive, SB72-0281 and SB79-0018.

"Further focus was required with the fan blade track clearance per SB72-0314 and 0317 respectively (which applied to PIPII variants initially, and was then rolled out across the fleet), requiring cutback at the 6 and 12 o'clock radius of the fan case because the fan case flexes during operations," adds Crickett.

In addition, there are intermix issues which need to be observed carefully with engine change and spare engine suppliers. 'Intermix' refers to the installation of two engines with different thrust settings on the same airframe, which requires the more powerful engine to be derated to match the lower-rated engine. "SB72-0154R1 should be followed for intermix requirements," advises Crickett.

GE has another partial upgrade in the pipeline due in 2018 for aircraft-installed engines and later for the HPT stage 2 blades. "This upgrade is mainly to improve TOW durability in hot and harsh environments, which has become a focus," continues Crickett. "This partial upgrade to the PIPII is called Phase 2, and is a continuation of Phase 1 (combustor and HPT stage 1 blades released in 2016). Phase 2 is due for release Q2 2018."

DVB's Overview of Commercial Aircraft 2017 explains that initial builds of the GEnx (and Trent 1000) engines missed fuel burn targets by 3-4%. By making incremental improvements to engine hardware and software, it states that engine performance was better able to match these targets. Indeed, the PIP II package for the -1B is expected to achieve or exceed original fuel burn targets.

There remains a number of early-production aircraft with GEnx-1B PIP I enhancements only. According to DVB, GE has indicated that all PIP I engines may be upgraded to PIP II in future SVs.

Utilisation

IBA states a typical EFH:EFC ratio of 6.5:1 for the GEnx-1B engine, while Crickett sees it as 6.5-10.0:1, depending on the type of utilisation. For example, European operators tend to perform about 4,200EFH and 650EFC per year (an EFH:EFC ratio of 6.5:1); and African carriers of the -1B achieve 4,800EFH and 720EFC per year (an EFH:EFC ratio of 6.7:1). Meanwhile, Sumisho's American group of airlines performs about 5,800EFH and 580EFC annually, or an EFH:EFC ratio of 10:1.

"The global GEnx-1B-powered aircraft have separated into two distinct fleets, where one has an EFH:EFC ratio above 6:1, and even upwards of 9.0:1," says Crickett. "Typically, this is the Extended-range Twin-engine Operational Performance Standards (ETOPS) operators in the Americas, the European Union (EU) and South Pacific (New Zealand, Australia) as the fleet replaces the 767-300ER.

"The other half of the fleet operates at a ratio of less than 6.0:1, mostly down in the 4.0-5.0:1 EFH:EFC range." continues Crickett. "This type of operator is more likely to be in Asia, where the dynamics of operations dictate a large widebody moving people on relatively short routes. For instance, India to Singapore, or Thailand to Indonesia."

The GEnx-2B powers the 747-8. Global FleetsAnalyser shows an average annual utilisation across its passenger-configured fleet of 4,600EFH and 500EFC, equivalent to an EFH:EFC ratio of 9.2:1.

Fleet profile

Latest figures show 25 main operators of the -1B engine, operating more than 700 engines on-wing across -8 and -9 aircraft. These carriers include: Japan Airlines (JAL) (68 engines installed); United (66); Qatar (60); Air Canada (58); American Airlines (58); Air India (46); Hainan (42); TUI Group (30); Etihad (30); Ethiopian (26); Aeromexico (28); Vietnam (22); Jetstar (22); China Southern (20); Saudia (18); Xiamen (18); KLM Airlines (16); Royal Jordanian (14); Kenya (14); Oman (12); Royal Air Maroc (10); Korean Airlines (6); Uzbekistan (4); Air France (4); and Azerbaijan (4).

Global FleetsAnalyser shows 36 passenger-configured 747-8s in service, divided among three operators: Air China (7 aircraft); Korean Air (10); and Lufthansa (19). The average age of this fleet is 3.5 years.

Performance

As previously described, many factors can affect the performance of engines in

TRENT 1000 PACK 'C' LLP LIMITS AND PRICING 2017 - CHAPTER 5 LIMITS

PART	CH 5 LIFE LIMIT	CLP 2017 $
LP Compressor Rotor Disc	12,000	341,282
LP Compressor Rotor Shaft	9,000	204,278
LP Turbine Rotor Shaft	9,000	242,842
LP Turbine Rotor Disc (Stg 1)	3,000	192,927
LP Turbine Rotor Disc (Stg 2)	3,000	269,271
LP Turbine Rotor Disc (Stg 3)	3,000	295,871
LP Turbine Rotor Disc (Stg 4)	3,000	358,855
LP Turbine Rotor Disc (Stg 5)	3,000	410,859
LP Turbine Rotor Disc (Stg 6)	3,000	275,096
IP Compressor Drum	6,000	1,263,541
IP Compressor Rear Stub Shaft	5,170	81,747
IP Turbine Rotor Shaft	6,000	124,700
IP Turbine Rotor Disc	4,100	498,794
HP Compressor Stg 1-3 Drum	3,000	393,786
HP Compressor Stg 4 Drum	3,000	130,056
HP Compressor stg 5-6 Drum & Cone	3,000	958,918
HP Turbine Rotor Disc	3,000	549,658
HP Turbine Disc Front Cover Plate FRT	3,000	208,378
IP Rotor Seal	6,000	75,884
Rotating Seal Arm	3,000	37,608
Total		$6,914,351

operation. Operators try to keep engines on-wing for as long as possible, so average MTBRs are a sensible indicator of engine, as well as dispatch, reliability, AOGs and the number of unscheduled removals that arise in service.

The previous engine performance article explored maturing engine maintenance *see GE90, GP7200, Trent 800 & Trent 900 performance & maintenance, April/May 2017, page 81)*. This identified EGTm loss as one of the key causes of engine removals and SVs, since this will require a performance restoration of the hot section to refresh performance.

According to IBA's Ray, the EGTm is 86 degrees when the GEnx-1B is first delivered. This is for -1B engines with a 64,000lb thrust rating; EGTm decreases with higher engine thrust. "Early data suggests that the EGTm deterioration of the -1B during the first 1,000 EFC is about 12 degrees, and the mature rate per 1,000EFC is a loss of about 3.0 degrees," he says.

Crickett explains that engines at this early stage of operation are not as subject to EGTm deterioration for performance-related removal, as they are for early EIS issues. "The GEnx-1B has similar EGTm retention and degradation to the GE90-115 series engine. Most GEnx engines will experience hot section deterioration and be removed for either HPT restoration and/or upgrade well before EGTm begins to be an issue," he says.

IBA provides indicative removal intervals for the first scheduled SV. "GE expects the first SV removal for performance restoration to occur at 22,000-27,000EFH for the -1B, and 24,000-28,000EFH for the -2B," says Ray. MTBRs for the GEnx cannot be established, however, due to the fact that the fleet has not yet reached this maturity.

The well-publicised, early-service issues that beset the 787 and its engines meant that many early removals occurred across the -1B fleet. The build-up of ice, originally in the engine core and then on the fan blades, has become a recurrent problem during service. Some configurations of the GEnx-1B have encountered different issues to others. The Federal Aviation Administration (FAA) mandated PIP-2 configured engines to undergo work to overcome the problems with build-up of ice, for example. The AD required grinding of the fan blades to achieve greater clearance spaces between the fan blades and casing.

"Most GEnx-1B engine removals are due to deterioration of the hot section hardware, with a significant number of engines in operation undergoing some form of upgrade from the OEM," adds Crickett.

"The GEnx-1B is still well into a new engine development programme, so the overall removal rates reflect the mechanical design and repair issues typical of modern engines, caused by high bypass ratios, hotter operations and harsh environments," Crickett continues. "These engines therefore undergo upgrades and/or modification workscopes."

According to Ray, some -1B engines have undergone formal SVs at 1,700EFC. "LLPs have needed replacing, so the workscope matches that of a SV, although this is likely to have been an anomaly," says Ray. "Some have also undergone modification and upgrade programmes, which is expected for new engine types."

Naturally, it is too early to predict SV costs for the GEnx or the Trent 1000 and XWB. The OEMs do supply customers with estimates, however. "GE estimates the first planned SV event to be at 3,000-4,000EFC and cost about $4.8 million for the first SV," says Crickett. "The second SV is anticipated to occur at about 90% of the first removal interval. Preliminary costs for the second SV stand at $6.8-7.0 million. The third SV event is predicted to cost the same, with roughly the same TOW beforehand as the second SV." Ray also anticipates that LLPs could start to need replacement by the second SV for the -1B, in addition to LPC and HPC restoration work.

According to Crickett, increased removal rates have identified another problem. "This is due to careless handling of the fan cowl when the GEnx-1B is removed," he says. "Significant damage is being reported on the carbon-fibre fan frame when moving the engine and/or installing/removing the fan cowl. GE is assessing this and developing special limits and repairs to address this problem."

"All things taken into account, engines on a full-coverage FHA with GE will not necessarily see the full account invoice," explains Crickett. "Those on a lighter-coverage FHA where the rate paid is topped up at the end of the SV event, may well have some concerns over the accrual rate their engineering departments have identified."

LLPs

The LLP lives and list prices for the GEnx–1B and -2B series are listed *(see table, pages 58 & 60)*. All GEnx engines have both static and rotating LLPs that are life-limited and rated in the Engine Manual, ref Chapter 5. These are therefore known as 'Chapter 5 limits'. GEnx-1B rotating LLPs cost $8.4 million (2017 CLP) and Static LLPs cost $840,000.

"Since the GEnx is still under development, progress on the ultimate life for many parts is still to be confirmed," explains Crickett. "Some of the early P/N LLPs will never make maximum life. Their production has been stopped and they will be replaced in newer engines by alternative P/Ns.

TRENT XWB-84 LLP LIMITS AND PRICING 2017 - CHAPTER 5 LIMITS

PART	CH 5 LIFE LIMIT	CLP 2017 $
Fan Disc	6,845	411,499
Fan Shaft	6,845	158,568
LPT Shaft	5,180	173,021
LPT1 Disc	6,500	245,770
LPT2 Disc	6,500	245,770
LPT3 Disc	6,500	245,770
LPT4 Disc	6,500	245,770
LPT5 Disc	6,500	245,770
LPT6 Disc	6,500	245,770
IP Compressor Drum	6,845	937,316
IP Stub Shaft	6,845	113,319
IPT Shaft	6,845	134,316
IPT Disc 1	2,700	474,450
IPT Disc 2	2,700	676,151
IPT Mini Disc	2,700	151,709
IPT Flying Seal	6,845	42,456
HPC 1-3 Discs	5,180	693,477
HPC Stg 4 Disc	2,700	151,494
HPC Stg 5-6 Rear Shaft Assembly	1,850	1,197,408
HPT Cover Plate	1,850	211,434
HPT Disc	1,850	592,582
Total		$7,593,820

"Early GEnx-1B engines, such as the G03/G04 series, have a design target for either 20,000EFC or 15,000EFC, depending on the applicable parts installed and their thrust ratings," continues Crickett. "For the P1 and P2 variant series, a Q2 2017 LLP life programme review has just been issued."

"GE claims the GEnx-1B engines have an advantage over the Trent 1000 current engine configuration with a 2.3% better fuel burn, although this should be qualified with the latest cutback of the GEnx Fan Track requirement," adds Crickett. The cut back of the Fan Track could reduce the efficiency of the engine and therefore impact fuel burn. "This cutback has some operators concerned over how this has happened with the composite fan case, which they believe may be too flexible. When compared to the Trent 1000, the GEnx is rated at similar thrusts, weight, size and rotor RPMs. The later Trent 1000 (72-G318) makes a reasonable jump of nearly 300kg dry weight increase."

Reliability data has been provided comparing the GE and RR engines powering the 787 as of early 2017. Broadly speaking, the GEnx has an in-flight shutdown (IFSD) rate, per 1,000EFH, of 0.0027, whereas the Trent 1000 has a rate of 0.0050 which equals one per 370,000EFH and one per 200,000EFH. Schedule reliability for the GEnx engine family was estimated at 99.96%, compared to the Trent 1000 at 99.97%. The aircraft turn back (ATB) rate per 100 departures for the GEnx and Trent 1000 was 0.001 and 0.011.

Rolls-Royce

Operational data on the Trent 1000 and XWB is notoriously difficult to determine; particularly because there remains a near-100% take-up rate of full coverage FHA and PBH contracts by operators of these fleets. This means that operators are closely aligned with the OEM. Data provided is therefore industry-derived, with much based on OEM estimation.

Trent 1000

Architecture

The Trent 1000 was the launch engine for the 787-8 at service entry in 2011. According to RR, 787s powered by the Trent 1000 are 20% more efficient than the 767 fleet the family replaces. RR also projects that the three-shaft design symbolic of the Trent family (it has an additional 'intermediate' pressure stage in the core) boasts a 3% fuel burn improvement over its competitors.

This fan and core configuration achieve a high bypass ratio of 10:1 to 11.0:1 for the eight variants, and an overall pressure ratio of 52:1. These two factors are important in achieving Boeing's target fuel burn performance.

The Trent 1000 uses several technological features to achieve the fuel burn and emissions performance required of the 787 *(see Owner's & Operator's Guide, Rolls-Royce Trent Family, August/September 2012, page 4)*. These include 20 wide-chord, low hub-tip ratio swept fan blades. This is possible through the use of a smaller diameter fan hub, which means a larger fan intake area is possible for the same fan diameter. This allows air to pass through more efficiently. The Trent 1000 has a six-stage LPT, needed to turn the larger intake fan, which has a diameter of 112 inches. A single stage intermediate pressure turbine (IPT) and HPT, six-stage HPC and eight-stage intermediate pressure compressor (IPC) comprise the remaining core architecture.

Fleet profile

Global FleetsAnalyser shows 575 787-8 and -9 aircraft in operation, and a further 688 787-8, -9 and -10 aircraft on order. More than 200 787-8s, -9s, and -10s on order will be powered by the Trent 1000, while another 183 orders still have engines unannounced.

Of those in service, 219 787s are powered by Trent 1000 engines. Six 787-8s are powered by Trent 1000-64s, and 74 -8s are powered by the 1000-67 variant. A further 20 787-8s have Trent 1000-70s installed, and 16 787-8s use the Trent 1000-70/-74 variant. Meanwhile, 89 787-9s are powered by the Trent 1000-74, and the -74/76 variant is used on 14 other 787-9s.

There are 16 operators with Trent-powered 787-8s and -9s in the fleet: All Nippon Airways (60 -8 and -9 aircraft); British Airways (24 -8s and -9s); LATAM Airlines Chile (24 -8s and -9s); Norwegian (17 -8s and -9s); Scoot 15 -8s and -9s; Virgin Atlantic Airways (14 -9s); Avianca (11 -8s); Air China (10 787-9s); Air New Zealand (nine -9s); LOT Polish Airlines (eight -8s); Air Europa (eight -8s); Ethiopian Airlines (six -8s); Thai Airways International (six -8s); Royal Brunei Airlines (four -8s); Air Austral (two -8s); and EL AL (one -9).

Ray at IBA estimates a general fleet utilisation for the Trent 1000 of 3,350EFH and 610EFC per year. This equates to an EFH:EFC ratio of 5.5:1. This average sector length is slightly shorter than the current GEnx figures suggest, which implied that 6.5EFH is the average sector length for GEnx-powered 787s. The Trent 1000, therefore, appears to operate slightly shorter sectors on average.

Performance

While the GEnx-1B has encountered icing issues in the early stages of its programme, the Trent 1000 has experienced two different technical problems in operation. “Atmospheric corrosion on the IPT blades and oil leak findings have been the main issue,” explains Ray. Up to 500 engines were affected by the IPT issue, which was widely publicised when ANA grounded four of its 787 fleet as a result of three engine failures in 2016.

“RR has estimated a removal interval of 20,000-25,500EFH for the first Trent 1000 refurbishment SV,” says Ray. “The oil leak and IPT blade issues have affected many engines, however, and led to a substantial amount of hospital visits before this can be reached. The downtime experienced during these SVs has been quite high, since RR has had to produce sufficient numbers of parts to meet the number of Trent engines in its MRO shops.” Indeed it was also reported in Q3 2017 that Thai Airways had to ground four of its six 787-8s due to parts shortages following the turbine blade findings.

SGI Aviation is based in the Netherlands, and provides technical consultancy to aircraft owners and operators worldwide. While it focuses mainly on smaller airframes and engines, it gains significant market intelligence via its asset management arm. Danilo Colombo, programme manager at SGI, anticipates that the main drivers for the first SV, apart from early-service issues, will be LLP replacement and engine refurbishment. “HPT blade failure has also forced some early removal,” he adds. An FAA AD issued in February 2017, which became effective in March 2017, requires initial and repetitive inspections of affected HPT blades (those with P/N FW63853 installed) for cracks.

Ray advises that RR try should try to keep mature MTBRs consistent. As such, the second SV is expected to occur at 18,000-23,000EFH after the first SV. This is estimated by IBA to cost $6.0-7.5 million per engine. A refurbishment is expected to be 10-20% less than an engine overhaul.

Since the RR Trent 1000 entered service in 2011, modification programmes have been introduced. The first programme after EIS was called ‘Package B’ and the second was ‘Package C’. According to RR, Package B was developed during the early stages of 787-8 operations to provide better fuel efficiency. This was achieved by relocating the IPC bleed offtake ports, and revising the six-stage LPT design. Package C focused on producing the higher thrust of 74,000lbs needed for the 787-9 aircraft ahead of its EIS.

LLPs

The LLP lives and list prices for the Trent 1000 are listed *(see table, page 62)*. The 2017 CLP for a stack of Package C LLPs is $6.91 million. The shipset comprises 20 parts of varying life limits. Current limits range from 3,000EFC to 12,000EFC, according to the data provided. 12 of the parts in the shipset have the lower limit of 3,000EFC currently applied. The utilisations provided in the ‘performance’ section for the Trent 1000 suggest that these LLPs require removal within five years of operation, if an operator is achieving 600EFC per year. These 12 LLPs account for more than $4.0 million of the shipset cost.

Trent XWB

The Trent XWB engine is the youngest engine discussed in this article. The sole powerplant for the A350 family, the XWB, entered service in January 2015 via the A350-900 series. The XWB fleet is therefore young and in the very early stages of commercial operation; just over 36 months. To date, 102 A350s have been delivered (Global FleetsAnalyser)

The Trent 1000 has experienced IPT blade corrosion and oil leaks while in-service. These have lead to a high volume of hospital visits, which have in-turn caused significant downtime for some operators.

suggesting that a little more than 200 XWBs are on wing. Fleets Analyser suggests that almost 750 A350s remain on order and pending delivery.

The database suggests cumulative data for the most active aircraft in the A350 fleet exceed 11,000FH and 1,700FC. This is for one of the earliest serial numbers (S/N), S/N 6, which is operated by the launch customer Qatar Airways. It is therefore likely to have been used for flights during the certification phase before official EIS. Discounting the first 10 S/N, the highest accumulated hours shown by FleetsAnalyser is closer to 7,800FH.

14 carriers operate the A350-900 via the XWB-84 series. It must be noted that the A350's in operation represent the earliest XWB engines installed. Further PIP programmes, modifications and fleet trends have yet to be experienced at this stage in the XWB's service.

Given the in-service infancy of the Trent XWB, operational data is limited for this engine series currently.

Architecture

As the -84 suffix suggests, the current in-service Trent XWB deliver 84,000lbs of thrust. The Trent-97, when it enters operations, will offer 97,000lbs. As described by RR, the Trent XWB comprises 22 fan blades and a 118-inch diameter fan case, an eight-stage IPC, and a six-stage HPC. It also has a single-stage HPT, dual-stage IPT and six LPT stages. The three-shaft turbofan is designed to provide a bypass ratio of 9.6:1 and an overall pressure ratio of 50:1.

Fleet profile

Global FleetsAnalyser provides an early indication of usage as operators incorporate the A350XWB into their fleets. Average annual utilisation across in-service -900s is 2,600EFH and 390EFC. This figure is likely to be skewed, however, due to the infancy of the aircraft from which this data is taken. Focusing on the five A350-900s that are over two years old, Annual utilisation rates are closer to 4,600EFH and 680EFC.

14 operators are currently operating the A350-900, including: Asiana Airlines (2); Cathay Pacific (18); China Airlines (7); Delta Airlines (2); Ethiopian Airlines (5); Finnair (10); French Blue (1); LATAM Airlines Brazil (3); Lufthansa (4); Qatar Airways (19); Singapore Airlines (16); Thai Airways International (5); and Vietnam Airlines (8).

SGI Aviation's Colombo suggests an EFH:EFC of 6.5:1 for the current XWB fleet. This is likely to change with operators taking further deliveries, and expanding route networks as the A350 further replaces 777-200ER and A340 fleets *(see Assessment of the 200- to 400-seat widebody market, Aircraft Commerce, June/July 2017, page 22).*

Performance

Little has been reported on early removals of the XWB-84. The engine does not appear to have yet encountered the EIS headaches of its Trent 1000 counterpart. It is expected that RR is undertaking early XWB SVs throughout its commercial run, to inspect hot sections and LLPs, and collate in-service data, and to prevent any observations arising from EHM and other data analysis then turning into defects, in addition to discounting anomalies that would cause a fleet-wide inspection.

"Some LLPs are also causing early removals for inspection and potential replacement," says Colombo. "The first formal SV is likely to be a refurbishment of the high- and intermediate-pressure systems, including IPT LLP changes."

"OEM figures suggest that the first scheduled SV should occur at 20,000-25,000EFH for the -84," adds Ray. "Assuming an operator is performing at an average EFH:EFC of 8:1 with engines at a 15% de-rate on take-off, we estimate the SV reserves to be $270-315/EFH."

It is expected that the first removal interval for the -97 will be longer than the -84's when the series enters service. The -97 has much of the core architecture present in the -84, albeit at a higher thrust.

Nevertheless, it is unlikely that scheduled SVs on the -84 will occur for a further two to three years of operation. Unscheduled removals may begin to happen more often as the XWB-84s global fleet increases, with different utilisation profiles and climatic operations.

It follows, therefore, that overhauls and other major SV workscopes for the Trent XWB are some years away. "The second SV workscope is likely to consist of LLP replacement and engine overhaul of the HP system, and IPTs in addition to a refurbishment of the LPC and LPTs," says Colombo. "LPT LLPs are also likely to require replacement."

IBA has early indications for the second SV removal of the -84 as 18,000-22,000EFH, and a cost estimation between $6.5 million and $7.5 million. "The first SV is likely to cost 15-20% less than the second," Ray adds.

While early into EIS, in-service issues for the A350 and Trent XWB have not appeared to occur at the same frequency or extent as the 787 and its engines. Frequent SVs are likely to be undertaken by RR to collate EHM and performance data.

Enhanced performance

Rolls-Royce announced a PIP for the XWB-84 in early 2016, known as an Enhanced Performance (EP) programme, about one year after the A350's EIS. Modified -84s are called XWB-84 EPs.

The EP programme is designed to provide a further one 1% fuel burn improvement over the original -84 series model, and is based on technology derived from the higher thrust-rated XWB-97 engine. Such technology includes improved secondary air system and interstage sealing; improved turbine cooling, and optimised -84 turbine tip clearance control system (www.rolls-royce.com). According to RR, the XWB-84 and XWB-84 EP are intermixable, so that an A350-900 can be powered by a combination of both these engine series.

The A350-84 EP is due to EIS in late 2019 via Singapore Airlines. While it is unclear whether the EP will be available as a retrofit, RR has indicated that the -84 EP will be made available as an option to customers with deliveries due after its EIS.

LLPs

The LLP lives and list prices for the complete stack of rotating and static LLPs for the XWB-84 is provided *(see table, page 64)*. The 2017 list price for the full shipset is $7.59 million and comprises 21 parts.

While EFC limits for these are expected to change in line with in-service maturity, the short limits of some LLPs is expected to lead to some SVs in the early stages for LLP inspection and replacement. The HPT disc, cover plate and stage 5-6 rear shaft assemblies, for example, each have life limits of 1,850EFC. This could lead to an LLP SV within three years for some of the higher-utilisation operators (600EFC+). The upper limits of the shipset currently reach 6,845EFC. This number is still low for LLPs, so these could be expected to increase well before the operating fleet begins to meet these parameters.

ADs and SBs

The FAA and European Aviation Safety Agency (EASA) have released ADs for the XWB-84, that have arisen from non-modification service bulletins (NMSBs) issued by RR since EIS. Examples include ADs that require inspection/replacement of LPC case support inboard pins, dowels and bolts (2016-0242), and the inspection of IPT stage 2 locking plates (2017-0088). The applicability of each of these ADs (that is, the ESNs to which these ADs relate) is set out by the NMSB related to the AD.

According to the FAA, AD 2016-0242 arose because it was established by RR that a batch of LPC case support pins and hollow dowels did not meet material specification, and would therefore need to be replaced. The AD became effective in December 2016, and required inspective and corrective action to be carried out either within 1,500EFC of first operation, or four months after the effective date.

AD 2017-0088 was created due to the possibility that some of the 16 locking plates installed in the IPT stage 2 assemblies might have cracked without being detected. Inspection of these locking plates for certain ESNs was therefore actioned, to be carried out either within 750EFC of first installation or within 100EFC of the effective date of the AD, which was May 2017.

Summary

The above information should be treated as a general overview of early-entry observations on these engines, rather than representative of true performance, since establishing the latter will take some time. "OEM-supplied data tends to be on the conservative side, and is sometimes more than a year out of date," says Crickett. "It takes a while for OEMs to collate SV data from around the world, which is carried out to gain true in-fleet intelligence via SVs and operator feedback."

It can be assumed that future engines being delivered will benefit from the modifications brought about by the PIP and EP programmes developed by the OEMs. Therefore, performance trends should only improve as each fleet matures. Build standards of the GEnx and Trent 1000 engines now delivered to customers are not the same as the build standard when the 787 entered service six years ago. There will eventually be a larger number of these engines in operation than their preceding engine models. The Trent TEN, for instance, is due to commence commercial operations later this year, having received EASA certification in August 2017. It will power the 787-8, -9, and -10 upon EIS.

The Trent 1000 TEN series benefits from XWB and the RR Advanced Performance engine programme technology, having been designed on the back of the early-service issues seen in early Trent 1000 engines. - *CLD* AC