There are four new engine programmes under development; two for narrowbody aircraft and two for widebodies. All four programmes have followed a path of optimising turbofan designs to achieve higher bypass ratios, while aiming to avoid increasing maintenance costs.

New engine programmes: optimised for fuel burn

Rising fuel prices and airlines' constant need to lower operating costs have stimulated the need for a generation of new jetliner engines: the CFM International LEAP-X, the Pratt & Whitney (PW) PW1000G, the General Electric (GE) GEnx, and the Rolls-Royce (RR) Trent 1000 and Trent XWB. These four engine families will power all new large regional jet (RJ), narrowbody and widebody airliners.

Engine development

Several generations of turbofan engines have focused on gradually increasing engine bypass ratio through the use of larger intake fans. Larger fans and higher bypass ratios increase propulsive efficiency, thereby reducing aircraft fuel burn and noise emissions. These generations of turbofans are based on two- and three-shaft/spool designs. However, manufacturers' ability to further increase bypass ratios with current configurations has been limited by several factors.

The four new engine families have adopted designs and technologies to overcome these limitations, and achieve higher bypass ratios and lower rates of fuel burn, while attempting not to compromise reliability and maintenance costs.

CFMI LEAP-X

The CFM56 has been developed to the point where the highest bypass ratio of all series and variants is 6:1. The development of the A320neo and Comac C919 required the aircraft to have fuel burns that are 15-20% lower than current A320 and 737NG models.

CFMI examined up to 18 different engine configurations before deciding to optimise the current two-shaft, conventional turbofan in order to achieve higher bypass ratios and reach the targeted fuel burn reduction.

The basis for this reduction is an engine core with a pressure ratio of 20:1. This high ratio also increases the combustion chamber inlet temperature. This compares to a ratio of 11:1 for the CFM56, which it achieves with a nine-stage high pressure compressor (HPC). The LEAP-X is able to generate almost twice the core pressure ratio with a 10-stage HPC. The LEAP-X has a three-stage low pressure compressor (LPC).

The LEAP-X's high pressure ratio drives a 78-inch diameter fan, which achieves a bypass ratio of between 10:1 and 12:1. These parameters compare to fan diameters of 68.3 and 61 inches, and bypass ratios of 5.5-6:1 and 5.1-5.4:1 for the CFM56-5B and -7B series.

The LEAP-X's high bypass ratio is not just due to a high core pressure ratio, however. The larger amount of energy required to turn a larger fan is also due to a higher combustion temperature. The combination of the two increases energy, which is extracted through a dual-stage high pressure turbine (HPT). All CFM56

The PW1000G's use of a gearbox allows the engine to achieve a high bypass ratio with a core engine that has fewer stages than current generation turbofans of similar thrust ratings, and five fewer stages than the CFMI LEAP-X.

variants have a single-stage HPT.

The higher temperature means that the engine is also able to use a smaller core compared to the CFM56-5B/-7B, so the LEAP-X's core uses a smaller volume of air. This is a third factor in achieving a high bypass ratio.

Another factor contributing to the engine's high bypass ratio and propulsive efficiency is its low-speed fan. The low speed of the fan's revolutions necessitates the use of two additional low pressure turbine (LPT) stages compared to the -5B's/-7B's four-stage LPT.

Overall, the LEAP-X's core has 21 stages: three LPC, 10 HPC, two HPT and six LPT stages. This compares to 21 core stages in the V2500-A5, 18 in the CFM56-5B, and 17 in the CFM56-7B.

The ultra-high bypass ratio of 12:1 is partly achieved through the use of a 78-inch-wide intake fan. This compares to a 68.3-inch fan on the CFM56-5B. The wider fan diameter is offset by the use of lightweight, wide-chord fan blades of composite material. The intake fan has 18 fan blades, compared to 24 blades on the -7B's fan and 36 blades on the -5B's fan.

The overall effect of the LEAP-X's high bypass ratio is to produce fuel burn that is about 15% lower than the A320 or 737NG powered by the CFM56-5B and -7B series. This high bypass ratio results in the LEAP-X's noise emissions having a 10-15% margin over Stage IV standards.

The high combustion temperature also results in a similar reduction in CO2 emissions compared to the current CFM56 variants.

The high combustion temperature would also result in higher NOx gaseous emissions, but this is overcome through the introduction of a twin-annular pre-swirl (TAPS) combustor.

However, the LEAP-X's design goal for achieving an ultra-high bypass ratio and lower fuel burn may compromise engine maintenance costs.

The first design factor relating to maintenance is the engine's configuration and number of stages. The LEAP-X has one more HPC stage, one more HPT stage, and two more LPT stages than the CFM56-5B and -7B. These additional stages increase the LEAP-X's length, and therefore its tendency to flex. This would cause blade-tip rub and hardware deterioration that would ultimately lead to shorter removal intervals. However, this has been mitigated by a rigid engine casing structure.

The main concern relating to maintenance costs is the higher combustion temperature, which would be expected to lead to a faster rate of deterioration of HPT blades, and so shorter removal intervals. While a higher combustion temperature will lead to higher propulsive efficiency, CFMI says it expects the temperature of the HPT blade material in the LEAP-X to be no higher than the temperature of the blades in the current CFM56 variants. This is due to the new coatings and cooling hole designs in the HPT blades that will be used in the LEAP-X.

Exhaust gas temperature (EGT) margin is also an issue. Because the combustion chamber temperature is higher, the EGT will also be higher and so the EGT margin is expected to be lower. Again, CFMI claims the improved cooling and HPT material means that it expects the LEAP-X to have a similar EGT margin to the CFM56-5B/-7B.

The engine's four additional stages, including an additional HPT stage, still increase the number of airfoils used by the engine compared to current CFM56 variants. This would be expected to have a proportionate increase in shop-visit material costs.

PW1000G

The alternative to the LEAP-X is PW's geared turbofan: the PW1000G. This is a family of new engines, based around a common design and engine architecture. There are four main variants of the

PW1000G, which will power: two large RJs, the Mitsubishi MRJ and Bombardier C Series; and two narrowbody families, the A320neo and Irkut MC-21 *(see table, page 24)*.

PW has opted for a geared fan configuration in order to achieve a high bypass ratio, and lower fuel burns and noise emissions compared to current turbofans of similar thrust ratings.

The use of a gearbox between the intake fan and the core engine means that the low pressure (LP) spool, and therefore the LPC and LPT, no longer has its revolutionary speed limited by the tips of the fan blades, as is the case with conventional turbofans. The PW1000G's LP spool is therefore free to turn at higher revolutionary speeds, and so achieve higher compression ratios than in conventional engines. This means that the PW1000G has one LPC and one LPT stage fewer than the CFM56-5B, for example. Moreover, the higher compression achieved by the LPC and LPT means that the PW1000G's HPC also has one less stage than the CFM56-5B.

The first implication of this design feature is that the PW1000G will have fewer airfoils and be lighter. Three of the larger PW1000G variants have 16 core stages *(see table, page 24)*. This compares to 17 core stages for the CFM56-7B, 18 for the CFM56-5B, and 21 for both the V2500-A5 and LEAP-X, all of which are engines with similar thrust ratings. The PW1000G's small number of core stages illustrates its ability to achieve a higher core pressure ratio with fewer stages. The advantages of this are a lighter, shorter engine that will flex less, and the use of fewer airfoils (up to 1,500 fewer core airfoils than other similar-sized turbofans).

The use of a gearbox allowing the LPT to turn at a higher revolutionary speed, also means the LPT can turn a larger fan compared with a conventional turbofan. The engine therefore has a high bypass ratio compared to conventional, current generation engines. The resulting bypass ratios of the four variants range from 9:1 to 12:1, compared to ratios of 5:1 to 6:1 for current turbofans of similar thrust ratings.

The four variants of the PW1000G use a scalable core, so it is not the same size in the four variants. Each one has a different diameter and different rates of airflow.

The smallest PW1215G/1217G, powering the MRJ70 and MRJ90, have an intake fan diameter of 56 inches and a bypass ratio of 9:1. This compares to a 53-inch intake fan and bypass ratio of 5:1 for the GE CF34-8E/-10E powering the Embraer E-Jets.

The PW1521G/1524G powering the Bombardier CS100 and CS300, rated at 21,000-23,000lbs thrust, have an intake fan diameter of 73 inches and a bypass ratio of 12:1.

The larger engines powering the A320neo and MC-21 families have a fan diameter of 81 inches and bypass ratio of 12:1, while rated at 24,000lbs to 33,000lbs. By comparison, the CFM56-5B and -5C have fan diameters of 68.3 and 72.3 inches, and bypass ratios of 5.5-6.0:1 and 6.5:1.

PW says that the use of a scalable core means the PW1000G could also be developed for use on widebodies, and provide up to 100,000lbs of thrust.

The PW1000G's design has several implications on its maintenance costs. The positive effects are its fewer core stages and LLPs, and smaller number of airfoils. The engine is also short in comparison, and it is also expected to have a higher EGT margin than competing engines. The negative effects of the engine's design are that it will have a higher combustion temperature than conventional engines, although the use of new HPT materials should offset this. The use of a dual HPT is likely to increase the cost of parts during shop visits. This, however, could be more than offset by the use of a smaller number of airfoils and LLPs in the engine.

PW1000G ENGINE FAMILY CHARACTERISTICS

Engine variant	PW1200G	PW1500G	PW1100G	PW1400G
Aircraft application	Mitsubishi MRJ	Bombardier C Series	Airbus A320neo	Irkut MC-21
Aircraft models	MRJ70, MRJ90	CS100, CS300	A319neo A320neo A321neo	MC-21-200 MC-21-300 MC-21-400
Engine models	PW1215G, PW1217G	PW1521G, PW1524G	PW1124G PW1127G PW1133G	
Thrust ratings-lbs	15,000, 17,000	21,000, 23,300	24,000, 27,000, 33,000	24,000 to 33,000
Fan diameter	56 inches	73 inches	81 inches	81 inches
Bypass ratio	9:1	12:1	12:1	12:1
LPC stages	2	3	3	3
HPC stages	8	8	8	8
HPT stages	2	2	2	2
LPT stages	3	3	3	3
Total core stages	15	16	16	16

The engine's resulting performance is expected to provide a 15% lower aircraft fuel burn for its applications compared to current generation aircraft such as the Embraer E-Jets and A320 family. The higher bypass ratio will also translate into lower noise emissions, and it will have a 20 EPNdB margin over stage IV limits.

The higher combustion temperature also means the PW1000G will have 20% lower CO_2 emissions, but this will also raise NOx emissions. To counter this effect, the engine will be fitted with an improved combustion chamber, and so actually have lower NOx emissions levels than current generation engines.

GEnx

GE's GEnx engine family is a two-spool conventional turbofan optimised to achieve higher bypass ratios and lower fuel burn than current widebody engines.

The two GEnx variants are the -1B rated at 64,000lbs to 75,000lbs thrust for the 787 family; and the -2B rated at 67,000lbs thrust for the 747-8.

The GEnx compares in thrust rating to the CF6-80C2 and -80E1, as well as the lower rated GE90 variants. While the GEnx has a similar number of core stages to its predecessors, the GEnx core has a higher core pressure ratio and higher combustion temperature, and so is able to turn a larger intake fan than the CF6-80C2/-80E, thereby achieving a higher bypass ratio. The GEnx uses new materials and cooling holes in its HPT blades to improve cooling, so as to avoid compromising HPT blade deterioration and EGT margin.

The GEnx-1B has a 111-inch diameter intake fan, and four ratings of 64,000lbs, 67,000lbs, 70,000lbs and 75,000lbs thrust for the 787 family. The highest rated variant is being certified as part of a performance improvement programme (PIP), that GE currently has under development.

The -1B series has a core engine consisting of four LPC, 10 HPC, two HPT, and seven LPT stages. The HPC pressure ratio is high at 22-23:1, and the engine's overall pressure ratio is 35-45:1, depending on the thrust rating, compared to 30:1 for the CF6-80C2. The GEnx's core is also smaller than that of the CF6-80C2.

The GEnx-1B's high pressure ratio allows the engine to use a 111-inch fan, which has just 18 wide-chord lightweight fan blades. This is half the number of fan blades in the CF6-80 series. The engine configuration translates into a bypass ratio of about 9.5:1, compared to about 5:1 for the CF6-80C2.

The first PIP, PIP1, being developed for the -1B will provide a new LPT that is expected to be certified in late 2011. The second PIP, PIP2, will introduce an upgrade for the HPC and HPT. The HPC will have almost new airfoils, while the HPT will have airfoils with improved aerodynamics. PIP2 is due to be certified in the second half of 2012, and so enter service in late 2012 or early 2013.

The overall benefits of the PIP for the -1B series are to increase EGT margin by about 45%, and reduce specific fuel consumption (sfc) by about 2.5%.

The -2B series is optimised for use on four-engined aircraft, and so has a smaller core with a three-stage LPC and six-stage LPT. Total stages in the core engine are 21 compared to the larger -1B series, and 25 in the CF6-80C2/-80E1 and 21 in the GE90.

The -2B's smaller core consequently results in a smaller intake fan with a diameter of 105 inches. The engine is rated at 67,000lbs and has a bypass ratio of 7.4:1. The engine uses the same number and type of fan blades as the -1B.

The benefits for the -2B series are an increase in EGT margin of about 45 degrees centigrade, and an improvement in sfc of about 1.6%. It is expected to enter service on the 747-8 in the fourth quarter of 2013.

Although the first engines introduced into service will be manufactured too early to have the PIP installed, they can have the PIP parts installed at their first shop visit.

The engine is thus optimised to achieve a higher bypass ratio in the same way that the LEAP-X has been optimised.

The resulting performance is that the -1B-powered 787 is expected to have about 15% lower fuel burn than the CF6-80C2-powered 767-300ER, while the -2B-powered 747-8 is expected to have about 13% lower fuel burn than the CF6-80C2-powered 747-400.

The effects of a higher combustion temperature will result in lower CO_2 emissions than current engines. The GEnx will utilise a TAPS combustor to counter higher combustion temperatures, and so have lower NOx emissions than current engines. This will give it a 50% margin over CAEP VI standards.

Like the LEAP-X, the GEnx's high compression ratio and combustion temperature, and use of a dual-stage HPT could negatively impact its maintenance costs. The CF6-80 and GE90, however, also use a dual-stage HPT. The GEnx will have active clearance control in the HPT to counter higher temperatures. The GEnx will also use blisks in the HPC module. It will also have a counter-rotating LPT, which GE claims will allow it to operate with one fewer LPT stage. The engine will therefore overall have fewer airfoils and LLPs than current

Like other new engines, the Trent 1000 and XWB have been optimised to deliver high bypass ratios and improved fuel efficiency through the use of high compression ratios. The Trent XWB's overall pressure ratio is 50:1; the highest of any commercial turbofan engine.

generation engines.

GE also claims the engine will have a higher EGT margin than the CF6-80 series. The engine rated at 67,000lbs thrust, for example, is expected to have an EGT margin of 44-90 degrees centigrade, depending on whether the PIP has been installed on the engine. At service entry the GEnx's EGT margin is expected to be about 44 degrees, but then increase to 90 degrees after the PIP has been installed. This compares to 35-60 degrees centigrade for mature CF6-80C2 engines. GE's estimates for removal intervals for the GEnx are in the region of 4,000EFC for the first removal, and 2,500EFC for the second removal. Since most engines are expected to operate on medium- and long-haul operations, first removal intervals should exceed 20,000EFH for engines that do not have the PIP installed.

Like the CFM56 family, GE's policy with respect to life limited parts (LLPs) is to start with conservative lives, but have target lives of 20,000EFC for parts in the core, and target lives of 25,000EFC for parts in the fan, LPC and LPT.

Trent 1000 & XWB

The Trent 1000 is the alternative engine option for the 787, and the Trent XWB is the sole engine choice for the A350 programme.

These two Trent family members are the most recent members of the Rolls-Royce RB211 and Trent family. The RB211 and Trent family are based on RR's well-known three-spool design. This allows the fan and first core compressor module, the intermediate pressure compressor (IPC), to be mounted on separate shafts. Like PW's use of the gearbox on the PW1000G, the use of different shafts for the fan and IPC allow the IPC to turn at a higher revolutionary speed. The IPC therefore achieves a higher compression ratio than the LPC in a two-spool engine. The benefit of this is that the engine requires fewer stages.

The development of the RB211 and succeeding Trent family since 1970 has seen bypass ratios increase from about 4.3:1 at its lowest levels to 8.6:1 for the Trent 900 powering the A380. The configuration of the 1000 and XWB variants has allowed their bypass ratios to reach about 10:1 and 9.3:1. Like the other engines described, this has been achieved through higher core engine pressure ratios and higher combustion temperatures.

Unlike other engines, the Trent 1000 and XWB have had to use more core stages to increase core engine pressure ratio. The Trent 1000 has been able to use a single-stage HPT, but has a six-stage LPT. There are six variants with thrust ratings of 64,000lbs to 74,000lbs thrust. This is similar to the higher end of the Trent 700 and lower end of the Trent 800. By comparison, the Trent 700 and 800 have fan diameters of 97 inches and 110 inches, and bypass ratios of 5:1 and 5.8-6.2:1. In contrast, the Trent 1000 has a fan diameter of 112 inches and a bypass ratio of 10:1. This illustrates the effect of the core engine's higher compression ratio. Its overall pressure ratio is 49:1.

The Trent XWB is the only RB211 and Trent family member to use a dual-stage IPT, and it also has a six-stage LPT. There are up to five variants. The three lowest rated variants are rated at 75,000lbs and 79,000lbs, and power the A350-800. The variant powering the A350-900 is rated at 84,000lbs thrust, while the highest rated variant at 97,000lbs thrust powers the A350-1000.

This is the same level of thrust ratings as the Trent 800. The Trent 800 has a 110-inch diameter fan and bypass ratio of about 8.6:1, while the Trent XWB has a 118-inch wide intake fan and a bypass ratio of 9.3:1. Like the Trent 1000, the higher core pressure ratio allows a larger fan and higher bypass ratio. The XWB's overall pressure ratio is 50:1; the highest of any turbofan engine.

These design characteristics deliver 15% lower sfc for the Trent 1000 compared to the Trent 700, and 16% lower sfc for the Trent XWB compared to the Trent 800. The higher bypass ratios also translate into noise emissions that give about a 20 EPNdB margin over Stage IV standards.

Several design features have been incorporated to achieve a reduction in maintenance costs, including the use of blisks in the IPC and HPC. The Trent 1000 is expected to have 15% fewer airfoils than the Trent 700, while the XWB will have 10% fewer airfoils. The 1000 and XWB will also have EGT margins of at least 40 degrees centigrade, and uniform LLP lives of 15,000-26,000EFC, depending on thrust rating.

Particular technological features used on the Trent 1000 are a low hub-tip ratio fan to reduce fan drag, and soluble core HPT blades to provide high temperature turbine capability. AC