New generations of aircraft and engines are always required to provide savings in fuel burn and maintenance costs. Continuing rises in oil & fuel prices enhance the need for new technologies. New engines being developed by the big three manufacturers are examined.

New offerings: the latest turbofan programme developments

While developments in engine technology are an on-going process for the industry's manufacturers, the relentless rise in oil and jet fuel prices over the past seven years makes advances more important than ever. Progress in engine technologies has a role in leading the development of new aircraft and pushing down aircraft operating costs. The latest engine development programmes are analysed here, and examined in terms of what they can be expected to offer the industry. These include Pratt & Whitney's (PW) geared turbofan (GTF), General Electric's (GE) GEnx family, and Rolls-Royce's (RR) Trent 1000 and Trent XWB engines.

Airlines push for improvements in fuel consumption, maintenance costs, and noise, CO2 and NOx emissions, but development of all engines has several physical constraints, which manufacturers must bear in mind when they consider their design objectives.

The turbofan design and configurations that have been used by PW, GE and RR over the past 40 years are nearing their optimum in some respects. For example, intake fan diameters and pressure ratios have been steadily increased to raise bypass ratios and improve propulsive efficiency and fuel burn, as well as to lower noise. Larger fan diameters increase engine size and engine weight, which at some level offsets gains in fuel burn efficiency. Wider intake diameters also lead to constraints with engine installation. Higher fuel burn efficiency also requires higher combustion temperatures, which lowers CO2 emissions, but also increases NOx emissions and leads to faster engine hardware deterioration and higher maintenance costs.

Trade-offs and compromises clearly have to be made between lowering fuel burn and improving maintenance costs, and also between lowering CO2 and noise emissions and reducing NOx levels. Engine manufacturers have been able to make improvements, however. Better materials for turbine blades, for example, allow higher temperatures and improvements in fuel burn, while maintaining or even improving rates of engine deterioration and maintenance costs. Another example is better designed combustion chambers that reduce NOx emissions for the same combustion temperatures, and so alter the trade-off between fuel burn and CO2 emissions.

The limit to which these trade-offs and compromises can continue to be made is diminishing with the current design configurations. Alternative configurations can be used, but each manufacturer's choice depends on their design objectives, which in turn depend on what they think will be the most important requirements that airlines will have of engines in the future. If engines are developed which satisfy the less important of airlines' requirements then a manufacturer's existence in the market will be compromised. In the late 1980s both GE and PW experimented with unducted, ultra-high-bypass (UHB) engines. These had two sets of contra-rotating fan blades at the rear, and achieved bypass ratios in excess of what engines were capable of at the time, and consequently reduced fuel burn. These engines were not followed commercially, however, because fuel prices were low and the complexity of the engines would have led to higher maintenance costs. The engines' size also led to installation limitations, which meant that they had to be mounted high up on the rear of the fuselage and could not be mounted under the wing.

PW GTF

PW's GTF is one engine development that is clearly aiming for a significant improvement in fuel burn. The manufacturer has been experimenting with, and developing, geared fan technology since the 1990s. PW's GTF has a similar configuration to a conventional two-shaft engine, with the exception of having a gearbox between the fan and low pressure compressor (LPC) or booster section.

In a conventional two-shaft engine, the fan and LPC are mounted on the same shaft and so turn at the same number of revolutions per minute (RPM). The need to limit the speed of the tip of the fan blades to less than supersonic speed limits the RPMs of this section. Moreover, the fan and LPC shaft runs through the length of the engine to the low pressure turbine (LPT). The LPT, which turns the fan and LPC, therefore has the same limit in RPMs. This constrains the power that the LPT can generate.

A gearbox between the fan and LPC allows the two to turn at independent speeds. While the RPM speed of the fan is

Pratt & Whitney's GTF will have a bypass ratio of up to 10:1. This is made possible because the gearbox allows the LPT shaft to turn three times faster than the fan. The LPT consequently generates more power than it would in a conventional engine, and so can turn a larger fan.

still constrained by the need to limit fan blade tip speed, the LPC and LPT are free to turn at higher speeds. Increases in fan diameters, and so bypass ratios, of conventional turbofans are constrained by the LPT's ability to turn the fan. The wider the diameter, the slower the RPMs have to be to keep the blade tip speed less than supersonic. The slower the RPMs of the LPT, the more its power to turn the fan and LPC is limited. A gearbox that allows the LPT to turn at a higher RPM means that it can turn a larger fan than it could otherwise turn in a conventional design.

"The GTF programme was initiated in late 2004, with the aim of providing an engine that could ultimately be used to power replacements for the 737 and A320 families, which are aircraft in the 120- to 220-seat category," explains Robert Saia, vice president of next generation product family at Pratt & Whitney. "The first GTF variant is expected to enter service in the 2013-2020 period, and will have a thrust rating of 13,000-30,000lbs. It will power the Mitsubishi regional jet (MRJ) and the Bombardier C Series. The 70- to 100-seat MRJ will be powered by engines rated at 13,000-17,000lbs thrust, and engines for the 110- and 130-seat C Series will be rated up to 24,000lbs thrust.

"A higher-thrust-range family could also be developed for aircraft in the 120- to 220-seat category. It is still possible that new 200-seat aircraft could have a widebody configuration, rather than a narrowbody configuration. There is actually no limitation to the GTF being developed for a 350-seat widebody aircraft," continues Saia.

The GTF has six main modules: the fan; the LPC; the high pressure compressor (HPC); the combustion chamber; the high pressure turbine (HPT); and the LPT. There is also the gearbox between the fan and LPC. "The gearbox means the LPC/LPT can turn three times faster than the fan. The LPT can therefore turn a larger fan," says Saia. "This results in a higher bypass ratio and greater propulsive efficiency and reduced noise emissions. The higher speeds that the LPC/LPT can turn at also mean that these two modules require five fewer stages than a conventional engine. This is equal to 1,500 fewer blades and stators, which are some of the most expensive parts in the engine. While this will translate into savings in maintenance costs, the fewer stages also mean that the engine is about 8% shorter and 10% lighter than a conventional turbofan of the same thrust rating. The shorter length means the engine will flex less and so have greater durability. This will increase removal intervals for maintenance, making another contribution to lower maintenance costs.

"The main benefit of the gearing system is that the LPT turns faster. LPTs are at their most efficient when turning at high speeds," continues Saia. "The challenge is to make the gearbox light and efficient. A lot of heat is generated, and so lubrication is very important. The gearbox has five planetary gears which are stationary, and the centre gear moves. Another challenge is that big fans are heavy, so lighter-weight materials are also required."

The engine powering the MRJ will have a two-stage HPT. A two-stage design extracts more power than a single-stage and so maximises fuel burn efficiency. Its disadvantage is that two stages of HPT blades increase maintenance costs. The engine also has an eight-stage HPC, two-stage LPC and a three-stage LPT. The aircraft will have a 53-inch fan diameter, just four inches wider than the CF34-3A/B series rated at 9,220lbs thrust. The GTF will have a bypass ratio of 8:1. This compares to the CF34-3's ratio of 6.2:1, despite the two having similar fan diameters.

The larger engine powering the C Series will have the same HPC, HPT and LPT configurations, but will have a three-stage LPC. The fan will have a 73-inch diameter, the same as the CFM56-5C series rated at 31,200lbs to 34,000lbs thrust. The GTF will have a bypass ratio of 10:1. This compares to the CFM56-5C's ratio of 6.4 to 6.6:1.

Like all PW engines, the GTF will have uniform lives of 25,000 engine flight cycles (EFC) for its life limited parts (LLPs) of disks and shafts. A full set of LLPs for an engine is expensive and accounts for a high portion of maintenance costs. Uniform lives simplify engine maintenance planning, which allows a high utilisation of LLP lives.

The GTF has a high pressure ratio, which increases the engine's thermal and propulsive efficiencies. A high pressure ratio also means that the engine will have higher core temperatures, and so better cooling is required. A higher bypass ratio, however, lowers the turbine temperature.

PW's objective with the GTF is to have about 12% lower fuel burn than the CFM56. Saia says that the Bombardier C Series is expected to have about 20% lower fuel burn than similar-sized 737 variants powered by the CFM56. The GTF would therefore save about 300 US Gallons of fuel on a 650-700nm mission.

While higher bypass ratios have generally led to higher combustion temperatures, and so compromised maintenance costs, the GTF will benefit from about 1,500 fewer blades and vanes and three or four fewer LLPs than a conventional turbofan of the same thrust rating. "This will make a contribution to lowering maintenance costs," says Saia. The target is to have 40% overall lower maintenance costs than current generation equivalent engines. The short engine design will also contribute to the engine having a higher exhaust gas temperature (EGT) margin, which will allow it to remain on-wing longer between shop visits.

CO_2 emissions are proportional to fuel burn, and so will be reduced by about 20%. Saia also claims that the GTF will have a similar combustion temperature to today's engines, but will have a better combustion chamber and so produce half the NOx emissions. Because of the engine's high bypass ratio, noise emissions will be half those of the CFM56 variants of similar thrust ratings, and the GTF will have a 20 EPNdB margin over Stage IV noise emission limits.

GEnx

GE's current development programme is the GEnx. This is being developed to replace the CF6-80C2 that evolved in the 1980s to power the A300-600/A310, 767 family, MD-11 and 747-400; and the CF6-80E1, which powers the A330-200/-300.

There are currently two main series of GEnx engines in development: the -1B, which will power variants of the the 787 family; and the -2B, which will power the 747-8.

The -1B has three variants. The -1B54 will be rated at 54,000lbs and power the 787-3; the -1B64 will be rated at 64,000lbs thrust and power the 787-8; and the -1B70 will be rated at 70,000lbs thrust and will power the 787-9.

The -2B67 will be rated at 67,000lbs thrust and power the 747-8.

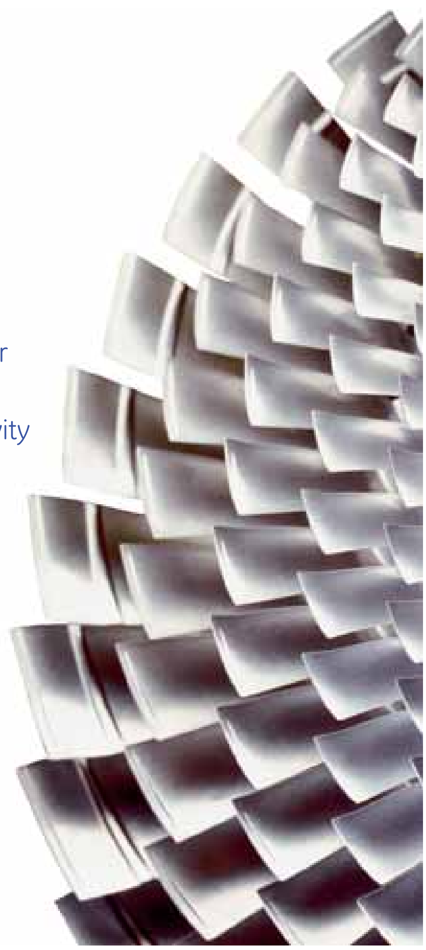
GE has chosen to optimise the two-shaft design, as it has done with more recent CF6 variants and the GE90, rather than follow a new engine configuration. The -1B and -2B will have the same core engine, but have different intake fans. Both engines are due to enter service in the second half of 2009.

The engine will be configured with five modules: a single-stage fan; a four-stage LPC; a 10-stage HPC; a combustion chamber; a two-stage HPT; and a seven-stage LPT. The two-stage HPT configuration is the same as its CF6-80C2/-80E1 predecessors. "The two-stage HPT extracts more power and so leads to fuel burn efficiency, but of course this has a negative effect on maintenance cost," explains Bill Brown, marketing manager of middle market engines at GE Aviation. "The GEnx's special features are a composite fan blade made from carbon fibre. This is a material that we've been using now for 18 years, which started with the experimental unducted fan (UDF) engine and then the GE90. Carbon fibre blades are extremely durable and so they are almost scrap-free. They are also lightweight, which allows fan diameter to be maximised for a given size of turbine.

"The HPC of the GEnx will feature 3-D aerodynamic blades in 10 stages, four fewer than the CF6-80C2/-80E1. This will generate a compression ratio of 23:1, which is a main feature in extracting the highest possible efficiency and fuel burn performance from a conventional two-shaft design," continues Brown. "Some of the HPC stages are blisks: a disk and blades cast from a single piece of metal. This contributes to fewer airfoils which saves in material-related maintenance costs. It also eliminates cracking in dovetails, which leads to the need to replace blades.

"The GEnx will also feature a twin annular premixing swirler (TAPS) combustor. This is designed to achieve a better mixing of fuel and air and achieve a leaner mixture, ultimately contributing to higher fuel burn efficiency," continues Brown. "The leaner mixture also reduces NOx emissions by up to 50% compared to current generation engines. There is a big environmental pressure coming to reduce NOx emissions."

The HPT will also feature 3-D aerodynamic blades and new cooling technologies, that include cooling holes at the blade tips. These will be required to offset the higher combustion temperatures that are used to improve



The GEnx is an enhanced conventional two-shaft turbofan that will have bypass ratio of up to 9:1 and an overall pressure ratio of 40:1.

fuel burn efficiency. Another feature is active clearance control. The HPT is one of the hottest parts of the engine, which causes expansion and so leakage of air around the blade tips that ultimately reduces efficiency. Active clearance control pumps cooling air around the HPT casing to reduce its diameter, and so minimise leakage of air around the blade tips.

The new feature in the LPT is that it counter-rotates with the HPT. This eliminates the need to change the direction of the air leaving the HPT nozzle, and provides an efficiency gain. The LPT also uses a Titanium-Aluminium alloy in the blades that makes them lighter and more durable, contributing to lower maintenance costs. The weight saving allows the engine to have seven stages for the same weight as six stages in a conventional turbofan. Seven stages allow more power to be extracted and give the ability to turn a larger fan.

The -1B series will have a fan diameter of 111 inches and bypass ratio of 9:1. This compares to a 120-inch fan diameter and bypass ratio of 8.7:1 for the GE90. The GEnx therefore achieves a similar bypass ratio with a smaller core engine to the GE90. The -2B series will have a fan diameter of 104.7 inches and bypass ratio of 7.4 to 8.0:1.

Both GEnx variants will have a high pressure ratio of 40:1, the design objective clearly being to improve fuel burn performance. "The design objectives with the GEnx were to achieve 15% lower specific fuel consumption (sfc) than similar-rated CF6-80C2 variants, and about 20% lower fuel burn than similar-sized aircraft in operation with the CF6-80C2. The target for the 787 is to have about 20% lower fuel burn than variants of the 767, while the target for the 747-8 is to have about 13% lower fuel burn than the 747-400.

"Meanwhile, we expect similar maintenance cost performance to the CF6-80C2," continues Brown. "Shop visit costs will be higher than the CF6-80C2 and -80E1 because of the GEnx's higher material costs. The GEnx should achieve 20% longer removal intervals between shop visits, however, to offset these higher shop visit costs. Longer intervals will be achieved through the engine's higher EGT margin, which is more than 100 degrees centigrade for the base engine rated at 64,000lbs thrust and about 50 degrees centigrade for the highest thrust variants. EGT margin erosion should also be six to eight degrees centigrade per 1,000EFC. This compares to eight to nine degrees for the GE90, and about 10 degrees for the CF6-80C2.

"In addition, the GEnx will have lower CO_2 emissions on account of its lower fuel burn, but it will also have 60% lower NOx emissions because of the TAPS combustor. The margin over CAEP IV standards is expected to be about 60%," continues Brown. "The engine will also have a large margin on Stage IV emissions standards, and the 787 will have half the noise footprint of the 767.

RR Trent 1000 & XWB

Like GE, RR has taken the strategy of enhancing the configuration of its current engines, rather than opting for a new configuration. RR's RB211 and Trent engines have a three-spool configuration versus the two-shaft design of PW's and GE's current engines.

The additional shaft on RR's design turns the first compressor section in the core engine, rather than it being mounted on the same shaft as the fan. While fan shaft RPMs are limited by blade tip speed constraints, in the compressor section, the intermediate pressure compressor (IPC) replaces the LPC in a two-shaft engine that is free to turn at a higher speed and so generate more compression. This allows fewer IPC and HPC stages than a similarly rated two-shaft engine such as the RB211-524G/H, which has 13 IPC and HPC stages. The PW4000-94 has 15 LPC and HPC stages, and the CF6-80C2 has 18 LPC and HPC stages. This is not only intended to make the engine shorter and so more durable because it flexes less, but also provides the engine with higher thrust growth capability.

RR has developed various technologies for its RB211/Trent family to maximise its efficiency. Its latest developments are the Trent 1000, which is being developed for the 787, and the Trent XWB, which is being developed for the A350XWB.

The Trent 1000 has three variants rated at 53,000lbs, 64,000lbs and 74,000lbs thrust for the 787-3, -8 and -9 models. The Trent 1000 will enter service in late 2009.

The Trent XWB has three variants rated at 74,000lbs, 83,000lbs and 92,000lbs for the A350-800, -900 and -1000. The Trent XWB will enter service in 2013.

Both basic models have eight modules. The fan section is considered as

The Trent 1000 and XWB are the latest variants in the long-running RB211/Trent family. The Trent 1000 will have a bypass ratio of 10:1 and a pressure ratio of 50:1; the highest of all jetliner turbofans.

three modules: the fan disk and shaft; the fan blades; and the fan case. There is also the IPC, HPT system, intermediate pressure turbine (IPT), LPT, and external gearbox. The IPC has eight stages, while the HPC has six stages, making a total of 14. This is the same as the GEnx-1B, and one more stage than the GEnx-2B. The Trent 1000 also has a single-stage HPT, single-stage IPT and six-stage LPT. The Trent XWB's turbine configuration is the same, except for a two-stage IPT. This is the first time an RB211/Trent variant has had such a feature.

The Trent 1000 is configured with a 112-inch diameter fan, a bypass ratio of 10:1 and a pressure ratio of 49:1. The engine's fan is just two inches wider than the Trent 800's, which has higher thrust ratings of 75,000lbs to 95,000lbs thrust. Moreover, the Trent 800 family's bypass ratio is just 5.8 to 6.2:1.

The Trent XWB has a 118-inch fan diameter, two inches more than the Trent 900 which is rated at 70,000lbs to 76,500lbs thrust. The Trent XWB family also has a bypass ratio of 9.3:1, which compares to the Trent 900's ratio of 8.5 to 8.7:1. The Trent XWB also has a pressure ratio of 50:1, one of the highest ratios of all jetliner turbofans.

The two new Trent models have clearly been designed with the intention of improving fuel burn efficiency. These high bypass and pressure ratios are achieved by large fans, which in turn are possible because of a larger number of turbine stages. Andrew Booth, marketing manager at Rolls-Royce explains that the Trent XWB, powering the A350 which will replace the A330, is expected to have about 15.5% better sfc than the Trent 700 powering the A330.

The Trent 1000 is expected to have 15.5% lower sfc compared to the RB211-524G/H powering the 767 and 747-400. This is mainly achieved through higher pressure and bypass ratios. One special feature of the Trent 1000 and XWB is the use of blisks throughout the IPC and HPC, as well as a contra-rotating turbine.

These high bypass ratios are also expected to provide the additional benefit of lower noise emissions. These are expected to be about 18EPNdB lower than Stage IV standards. This compares to a margin of about 3EPNdB of current generation Trent family engines.

Other areas where the basic design has been optimised is through the use of wide-chord, swept fan blades. This makes the fan more efficient than on current generation engines. The Trent 1000 will have 20 fan blades, and the Trent XWB will have 22 blades, compared to the Trent 700's 26 blades. The Trent 1000 and XWB models are also expected to have NOx emissions that are 35-40% within CAEP IV standards.

Other features have been introduced to improve maintenance cost performance. The Trent XWB will have 10% fewer IP and HP airfoils and the Trent 1000 15% fewer airfoils compared to the Trent 700.

"The two models are designed to have an EGT margin of at least 40 degrees centigrade," says Booth. "The lower rated engines will have higher EGT margins. EGT margin erosion rates are expected to be similar to current generation RB11 and Trent engines. As with all our other types, the majority of engines will be maintained under our total care packages, so we have an interest in optimising maintenance costs. An example is that the Trent 1000 and XWB will have uniform LLPs lives. These will vary between 15,000EFC and 26,000EFC, depending on thrust rating."

Summary

Clearly conventional turbofans designs can be further optimised to extract more efficiency. PW's GTF project is the first indication that new jet engine configurations will be seen in the following generation of jetliner powerplants. Continued pressure of high fuel prices will be sure to accelerate their development. CFM International, for example, has several design configurations it can follow, and will select the one most appropriate for the prevailing economic conditions. AC