Mid-Size Marvels

The Narrowbody Engines of Tomorrow

Chris Kjelgaard reports on the far-reaching technological developments that will be introduced in the huge mid-size commercial turbofan market for the next generation of narrowbody jet airliners

Because airframe manufacturers launch new commercial aircraft into production only rarely, engine makers have to take a long view of the market. Their job is greatly complicated by the fact that manufacturer studies of aircraft definition and the characteristics of the engines to power them change frequently, depending on market conditions and the general state of materials, systems and aerodynamics technology.

Consequently, each of the big three commercial turbofan manufacturers employs a development strategy that is constantly looking a minimum of six years ahead – typically, the time it takes to develop, test and certify a new engine – and beyond to at least ten years.

This strategy results in what Robert Nuttall, Rolls-Royce's Vice President of Strategic Marketing, calls a "moving conveyor belt" of new technologies. Rolls-Royce's conveyor belt for technological development includes programmes with such esoteric acronyms as EFE (Environmentally Friendly Engine), an advanced three-shaft demonstrator; E3E, a high pressure compressor (HPC) development programme run by Rolls-Royce Deutschland that has created what "we believe is the most efficient compressor in the world, running", according to Nuttall; and Silence(R), a programme looking at engine noise treatments of nacelles and exhaust nozzles.

Each of the major engine manufacturers is involved in many such programmes, often with development partners in

The PurePower PW1000G demonstrator engine fitted to the company's own Boeing 747 test bed aircraft. *Pratt & Whitney*

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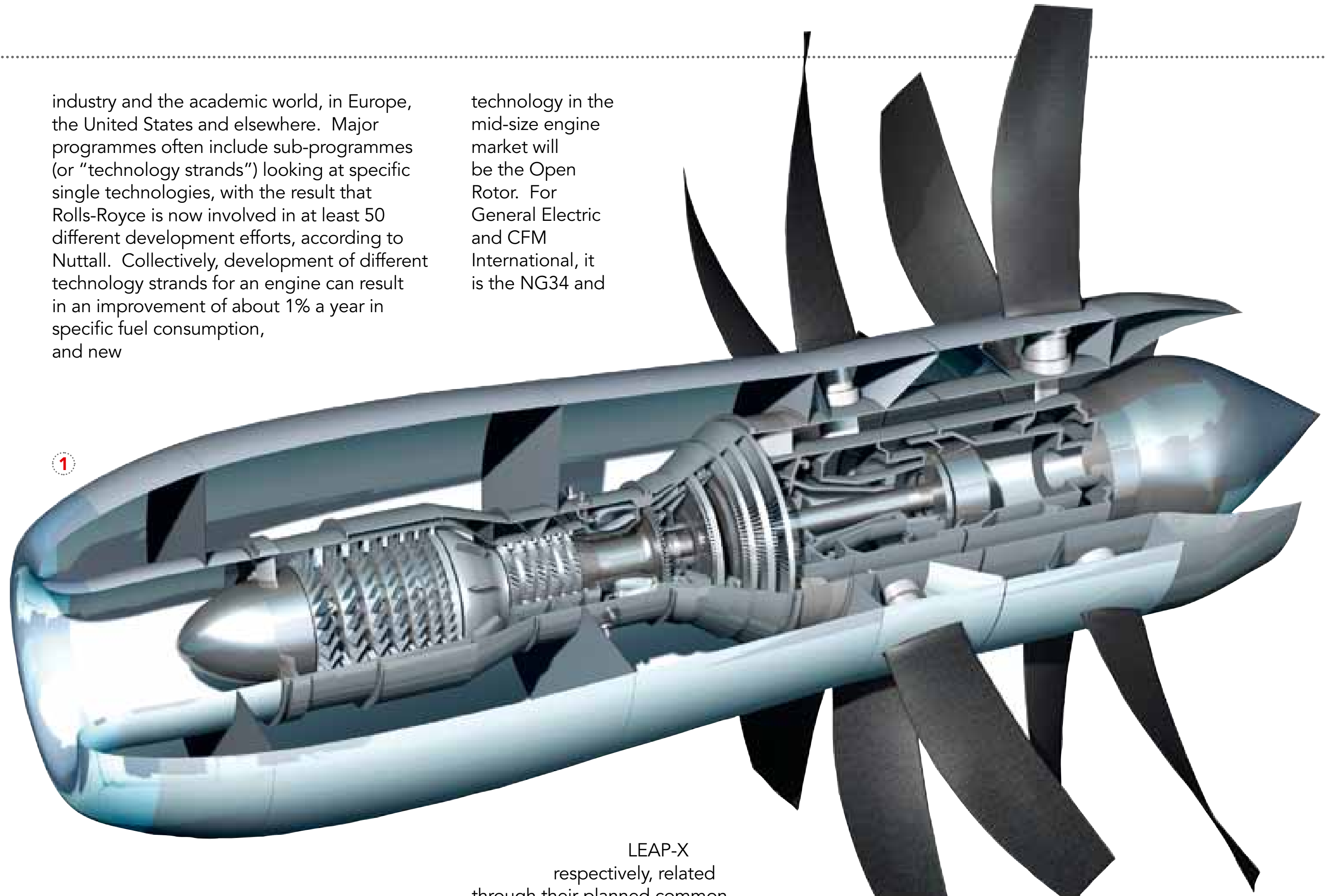

industry and the academic world, in Europe, the United States and elsewhere. Major programmes often include sub-programmes (or "technology strands") looking at specific single technologies, with the result that Rolls-Royce is now involved in at least 50 different development efforts, according to Nuttall. Collectively, development of different technology strands for an engine can result in an improvement of about 1% a year in specific fuel consumption, and new technologies are often incorporated into a manufacturer's existing product lines.

But sometimes a much greater degree of improvement is needed – particularly when manufacturers get closer to defining their next-generation commercial jets, or (as today) when external factors such as the growing need for environmental friendliness become important. Then the engine-makers must find radical new answers to keep their customers – the airlines and the general public – happy.

For Rolls-Royce, the next game-changing technology in the mid-size engine market will be the Open Rotor. For General Electric and CFM International, it is the NG34 and LEAP-X respectively, related through their planned common use of GE's eCore technology. (GE also says it would adopt Open Rotor configurations for these engines if the technology proves itself sufficiently.) For Pratt & Whitney, it is the Geared Turbofan, the first competitor from the starting block. Below we look at each.

Rolls-Royce's Option 15-50 and the Open Rotor

Rolls-Royce's long-term strategy for the 100-to-150-seater market has evolved into its Option 15-50 technology development programme. This begins with a two- or three-stage turbofan engine, developed either at Dahlewitz near Berlin, R-R's centre of excellence for two-shaft designs, or Rolls-Royce Derby, which specialises in three-shaft designs – that would be available five to six years from now.

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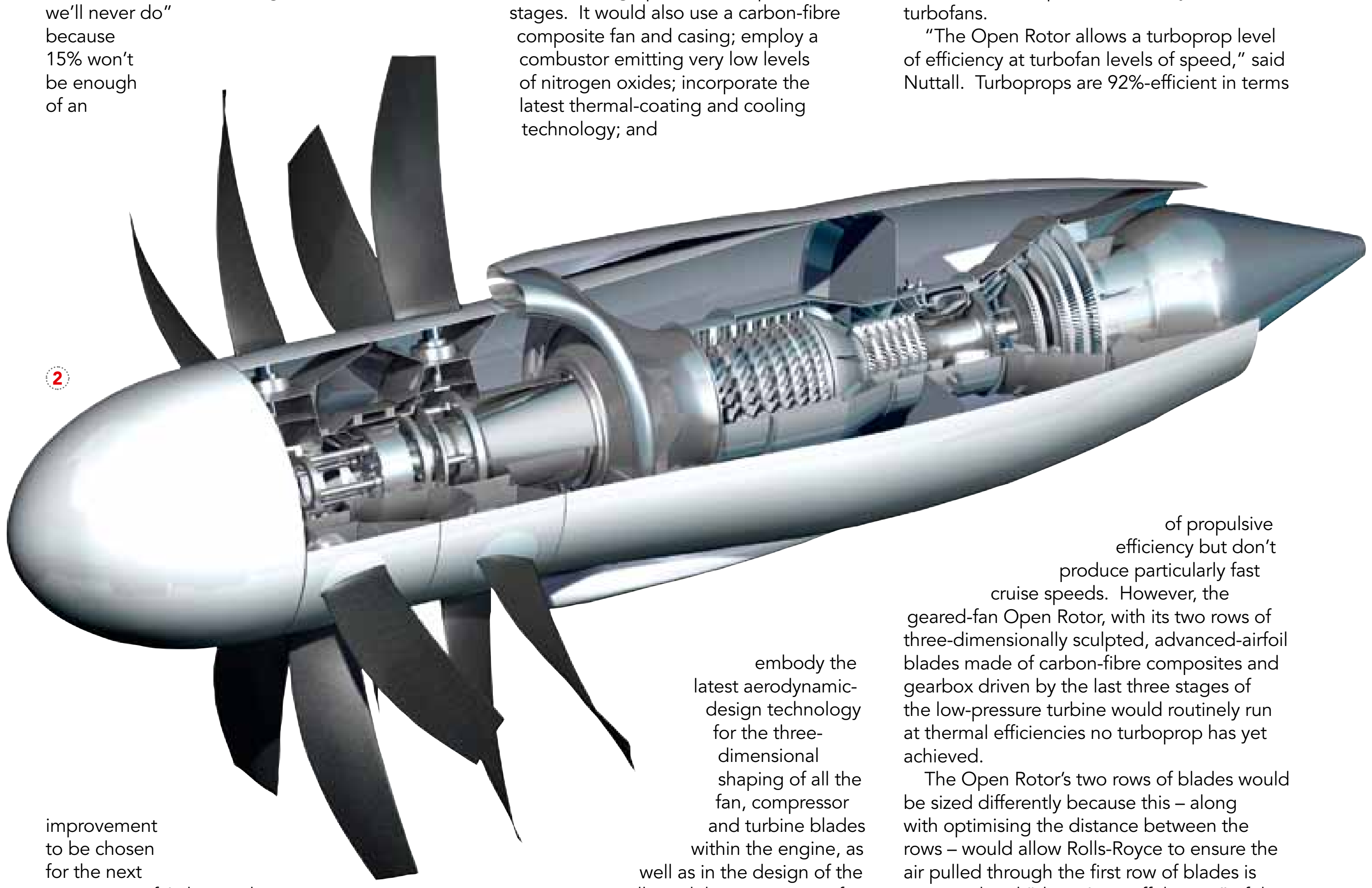

This engine would offer 15% better fuel-efficiency than today's mid-size engines, but Nuttall said it is "an engine we'll never do" because 15% won't be enough of an improvement to be chosen for the next generation of Airbus and Boeing narrowbody aircraft. However, Nuttall said that by 2018 Rolls-Royce would be able to produce a three-shaft advanced turbofan (ATF) design offering a 20% improvement in fuel burn over today's engines and which would be very quiet indeed.

Such an engine would make extensive use of integrally bladed, one-piece rotors (known as 'blisks') as high-pressure compressor stages. It would also use a carbon-fibre composite fan and casing; employ a combustor emitting very low levels of nitrogen oxides; incorporate the latest thermal-coating and cooling technology; and embody the latest aerodynamic-design technology for the three-dimensional shaping of all the fan, compressor and turbine blades within the engine, as well as in the design of the nacelle and the integration of the engine with its pylon.

This engine might be the next one to be developed. However, by 2020 – "plus or minus one," according to Nuttall – Rolls-Royce is confident it can produce an Open Rotor design that does away entirely with the casing surrounding the fan and uses two large but differently sized rows of variable-pitch fan blades to produce a fuel-burn reduction of at least 30% compared with today's mid-size turbofans.

"The Open Rotor allows a turboprop level of efficiency at turbofan levels of speed," said Nuttall. Turboprops are 92%-efficient in terms of propulsive efficiency but don't produce particularly fast cruise speeds. However, the geared-fan Open Rotor, with its two rows of three-dimensionally sculpted, advanced-airfoil blades made of carbon-fibre composites and gearbox driven by the last three stages of the low-pressure turbine would routinely run at thermal efficiencies no turboprop has yet achieved.

The Open Rotor's two rows of blades would be sized differently because this – along with optimising the distance between the rows – would allow Rolls-Royce to ensure the air pulled through the first row of blades is entrained and "doesn't go off the top" of the blades to create vortices and increase drag, said Nuttall. (The second row of blades would be shorter "so it wouldn't be in the first row's blade-tip vortex.")

Each row would have different numbers of blades and would rotate at different speeds. Optimising blade size, blade numbers, blade

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1 Computer generated image of an open rotor pusher variant engine. *Rolls-Royce* **2** Computer generated image of an open rotor tractor variant engine. *Rolls-Royce* **3** Blades of an open rotor test engine, which is being developed by Rolls-Royce under its Option 15-50 technology development programme. *Rolls-Royce* **4** General Electric's all-new engine family – currently labelled NG34 – is based on the very successful CF34, but with 10 to 15% better economics. *General Electric* **5** Snecma recently completed testing of an all-composite fan and casing under a programme known as MASCOT using RTM fans on a CFM56-5C engine. *CFM International* **6** Under its MASCOT programme, Snecma has developed and tested fan blades made with woven RTM. *CFM International*

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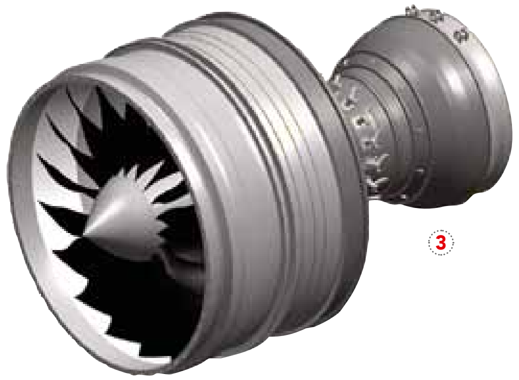
speed and the distance between the blade rows would also help reduce engine noise. Additionally, the two blade rows would contra-rotate because this "takes out the need to straighten the air out" between the blade rows, improving the efficiency of the airflow and making sure the air is linear when it exits the second row of blades, said Nuttall.

The engine itself could be mounted either as an under-wing mount or as a rear-engine mount, though both configurations would come with their own engineering challenges – accommodating a large blade diameter and coping with the fact that the blades are rotating next to the passenger cabin in the former case, and overcoming a substantial centre-of-gravity challenge in the latter.

When engine manufacturers began experimenting with open-rotor designs in the 1980s, the results ran into a brick wall that at the then current state of technology could not be surmounted: engine noise. Unshielded as they were and turning very fast, the blades of the un-ducted fans produced ear-splitting noise levels that were unacceptable in the Stage 3/Chapter 3 world of the late 1980s.

However, aerodynamic design has come a very long way since. "Back when these were running, there was one wide-chord fan blade [design] running in the world – on the Boeing 757," said Nuttall. Now, "Our ability to model airflow is several orders of magnitude better." No longer is engine noise the problem: the blades in the Open Rotor will go round only about one-third as fast as those in a turbofan producing the same amount of thrust.

"We will meet Stage 4 comfortably by 2020, plus or minus one" said Nuttall. "It's not a physics problem any more. Now, the question is, mechanically, how are we going to do it? I'm implying it's easy, but it's not – you've got to be able to change the pitch of the blades independently and the fan is about 170 inches, about the same diameter as the fuselage of the aircraft it powers."



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1 An engineer works on building up the core of an engine for the advanced LEAP-X development programme known as eCore 1. Under eCore 1, CFM International is testing a single high-pressure ratio turbine stage design for LEAP-X. *CFM International* **2** As part of its eCore programme General Electric is developing the TAPS II combustor, which has two concentric fuel nozzles and pre-swirls air and fuel before entering the combustor itself. The objective is to ensure combustion is highly efficient at all times and that the combustor remains lit in flight. *General Electric* **3** Computer generated image of a CFM56 engine built with components currently under development for the LEAP-X programme. CFM International has designated this future engine LEAP56. *CFM International* **4** RTM fan blades fitted on a CFM56-5C engine in a crosswind test facility during Snecma's MASCOT programme. *CFM International* **5** Computer generated image of CFM International's open rotor pusher variant engine. *CFM International*

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But while the challenges of designing and engineering the Open Rotor gearbox are stiff, they are by no means insurmountable, said Nuttall. For a start, the standard planetary gearbox in the Open Rotor would only require about half as much power (say 16,000shp) to produce the same amount of thrust as Pratt & Whitney's PW1000G Geared Turbofan, he claims.

Also, Rolls-Royce now has the results of one-sixth scale experimentation on Open Rotor fan configurations, which it began conducting in the Netherlands in early 2009 (cycling the engine through idle, taxi, take-off, approach and landing), and completed at the Aircraft Research Association facility in Bedford in England with high-speed cruise tests in the autumn of 2009.

"I can say we are very pleased with the results from the experiment," said Nuttall. "We are very happy that the Open Rotor has 25% to 30% better efficiency than current turbofans and 10% to 15% better than any advanced turbofans being promoted. It's definitely quieter than today's aircraft and comfortably meets Stage 4," though he concedes it would be about 10 EPdnb louder than R-R's putative 2018 Advanced Turbofan.

"Also, it would have 20% lower NOx compared with any advanced turbofan, for any given combustor, because of the way a turboprop gets its power, particularly round the airport," said Nuttall.

The NG34

Given that General Electric's CF34 engines power business jets (notably Bombardier's entire Challenger family) as well as regional jets, the CF34 has proved an enormously successful, strong-selling engine line for the company. So successful has it been that GE is determined to develop an equivalent, all-new engine family – currently labelled the NG34, though the name may change – within the next few years.

"We have a clear intent to take a new engine to market in the next decade," said André Robert, Head of Marketing for GE Aviation. GE is aiming to make an NG34 engine available from 2015, the exact date depending on the engine being chosen for an airframe application and the service-entry date the airframer requires.

For the purpose of maximising fuel-burn and maintenance cost improvements, GE is looking at the NG34 as an entire propulsion system "from the pylon down", including the nacelle, the quick engine change (QEC) kit and the engine itself.

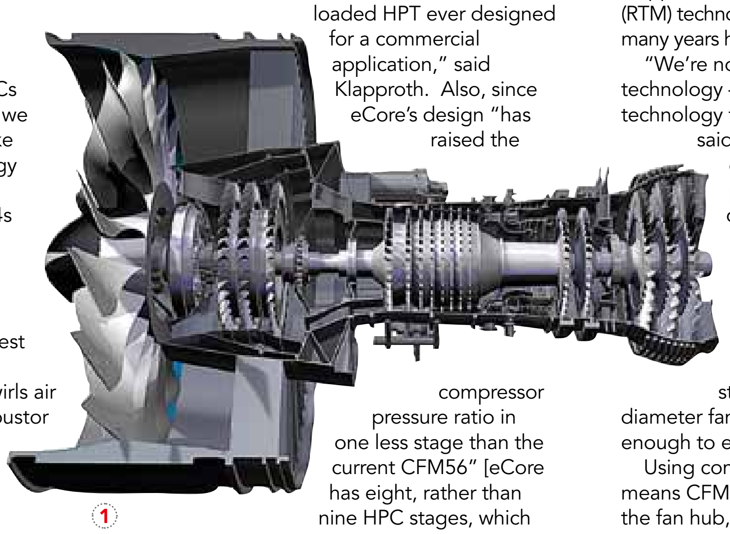
"We will integrate that entire system as one," said Robert. "We're aiming for 10 to 15% improved economics compared with the versions in service today. But what is critical is that the reliability of the current CF34 is perpetuated. High-cycle is critical." Operators have made this very clear to GE, he said.

"Our belief is that a simple, robust architecture is the way to go," using a two-spool, direct-drive architecture rather than [say] a concept such as PW's geared turbofan or Rolls-Royce's Open Rotor.

However, the NG34 will employ some or all of the new technologies that GE is testing in its eCore programme. These are aimed to verify new engine-core technologies that will earn their way into GE and CFM engines through the entire thrust range that the company offers, from low-thrust business jet engines to very high-thrust versions of the new GEnx that would power Boeing's eventual replacement for the 777-300ER.

For instance, said Robert, "There is a plan to incorporate CMCs [silicon carbide ceramic matrix composites] in the engine; eCore as a suite of technologies has CMCs factored into its configuration. As we mature a technology, then we make a determination that the technology earns its way on to the engine."

Additionally, while today's CF34s feature a Kevlar wrap around the fan case, the NG34's entire fan case will be made of carbon-fibre composite. Also being tested in GE's eCore programme is GE's latest TAPS II combustor, which has two concentric fuel nozzles and pre-swirls air and fuel before it enters the combustor itself to ensure that combustion is highly efficient at all times and that the combustor always remains lit in flight.



CFM International LEAP-X Programme

LEAP-X will apply technologies developed by GE's eCore programme, along with an all-composite fan and casing successfully tested by Snecma in its recent MASCOT (Moteur a Aubes de Soufflante en COmposite Taille - engine with composite fan blades) programme, to produce an entirely new CFM International engine that uses GE's new TAPS II combustor. This is a simpler design than the TAPS combustor GE uses in the GEnx big-fan engine, because the LEAP engine is smaller in size and thrust.

While Ron Klapproth, Director of CFM International's LEAP Programme, says CFM hasn't yet decided whether to choose a single HPT (high pressure turbine) stage or a two-stage design, GE's eCore 1 is testing the former configuration and eCore 2 the latter. CFM's rivals believe the partnership already has effectively decided to use a two-stage HPT for LEAP-X. In any event, CFM promises that the engine, which is scheduled to run as a demonstrator in 2012 and could be certified by 2016, will be 16% more fuel-efficient than today's CFM56s.

Whatever architecture CFM does choose, the LEAP-X HPT will be "the most highly loaded HPT ever designed for a commercial application," said Klapproth. Also, since eCore's design "has raised the compressor pressure ratio in one less stage than the current CFM56" [eCore has eight, rather than nine HPC stages, which is a tremendous step forward in terms of aerodynamic loading and performance]," it appears certain LEAP-X will have only eight HPC stages."

At least three of them will be blisks: "In my mind, a minimum of the front three stages, and we're doing trade studies now to extend them further back" into additional HPC stages, said Klapproth.

Additionally, the shrouds for the LEAP-X HPT blades will be made of CMCs, which will be the first time ever that CMCs will be used in a commercial engine, according to Klapproth. CFM also is looking at active clearance control for the engine's turbine casing and plans to use powder-metal fabrication for parts "in the back of the turbine, where the engine is hottest." Additionally, the engine will have "features in the LPT (low pressure turbine) designed to minimize performance deterioration" over time, potentially significant considering engine performance can degrade as much as 3% between shop visits, said Klapproth.

One of the most significant technologies on LEAP-X will be its 18-blade composite fan.

Conventional manufacturer wisdom is that composite fans don't make sense on mid-size engines because to be adequately bird-strike resistant the fan blades need to be too thick to be aerodynamically efficient. However, Klapproth said the woven resin transfer moulding (RTM) technology developed by Snecma over many years has changed the equation.

"We're not relying on today's composite technology – you need next-generation technology to do composite mid-size blades," said Klapproth. Where others' composite lay-up techniques produce two-dimensional composite laminates, which need to be thickly layered to produce the required impact resistance, in Snecma's woven-RTM technology, "composite fibres are stitched together in a 3-D configuration. This gives it the additional strength needed for the smaller-diameter fan," while keeping the blades thin enough to ensure aerodynamic efficiency.

Using composite blades also potentially means CFM potentially can reduce the size of the fan hub, allowing a bigger fan-blade radius for a given fan diameter. "We're looking at that," confirmed Klapproth. Snecma completed major bird-strike and endurance tests on its new woven-RTM fan design this year and it's looking very encouraging."

"To me there's just no doubt that composites are the future," said Klapproth. "Whether it's carbon fibre up the front or CMCs back in the hot section, it's very clear that's the future – and LEAP is the opportunity to bring those technologies in."

To improve bird-strike resistance, LEAP-X fan blades will also use titanium leading edges and CFM will take advantage of this fact to sharpen the shape of each blade's leading edge to improve the efficiency of its airfoil. CFM also has done much work analyzing the best position of the booster radially and axially behind the fan and splitter lip (which splits the air directed to the bypass flow from the air driven into the engine core) to minimise FOD (foreign object debris) ingestion by the core.

Where today's medium-size engines typically produce bypass ratios in the range of 5 to 7:1, CFM is aiming for a ratio of 10 to 11:1 for the LEAP-X, just like the ratios manufacturers are planning for their large turbofans for the Boeing 787 and Airbus A350. Bypass ratios higher than that could actually be counter-productive, said Klapproth – the engine installation on the airframe might need to be so large and heavy that the net effect would be a loss of fuel-efficiency rather than a reduction in fuel burn.

PurePower PW1000G Geared Turbofan

Pratt & Whitney doesn't necessarily agree with GE's position on very high bypass ratios. While PW's Chief Engineer Paul Adams agrees that to re-engine existing aircraft with very high-bypass ratio turbofans could be very difficult, he believes brand-new airframe designs can be designed from the outset to make provisions for the large size of the fan required.

For instance, while the 14,000 to 17,000lbf (62.43 to 75.8kN) PW1000G version chosen to power the Mitsubishi MRJ will have a relatively conservative bypass ratio of about 7:1 (a choice made by Mitsubishi), the 17,000 to 23,000lbf (75.8 to 102.56kN) PW1000G version that will power the new Bombardier CSeries family of 110 to 130-seat narrowbodies from 2013 will have a bypass ratio "in the 12 to 1 class," Adams said.

The PW1000G has also been chosen to power the Irkut MC-21 family of 150-to-210-seat aircraft, Russia's next generation of mainline narrowbody jets. While Pratt & Whitney hasn't yet discussed in detail the specifications of the PW1000G version that will power the Irkut MC-21 family, it is known that the larger versions of the MC-21 family will require an engine with a thrust level of some 30,000lbf (133.77kN). As a result, the PW1000G version produced for the MC-21 will be more powerful than that required for either the Bombardier CSeries or the Mitsubishi MRJ and Pratt & Whitney has confirmed to *AIR International* that it will indeed be producing a 30,000lbf (133.77kN) version of the PW1000G for the Irkut MC-21. Additionally, Pratt & Whitney confirms that the "Irkut engine bypass ratio will be comparable to the ratio for CSeries"

This means that, while the fan diameter of PW1000G for the Mitsubishi MRJ will be a relatively conservative 56in (1.42m), the PW1000G for the CSeries will have a very large fan for the size of the aircraft it powers: 73in (1.85m), compared with the 68.3in (1.73m) of the CFM56-5B, the 61in (1.55m) of the CFM56-7B and the 63.5in (1.61m) of the IAE V.2500-A5, all of which power larger aircraft and are required to produce higher thrust levels. That said, Pratt & Whitney has already rig-tested its PW1000G demonstrator engines perfectly successfully at 30,000lbf (133.77kN).

"For the second-generation Geared Turbofan, we're studying options that could potentially go all the way to the 18 to 20:1 range," said Adams. These likely would include higher-thrust engines for long-haul, widebody applications.

Key to the entire Geared Turbofan concept is the planetary gearbox situated right behind the fan, inside the flow path of the air going to the HPC and having no effect on the engine-core flow path. The gearbox, all of whose components are made of high-grade gear steel, decouples and slows the rotation speed of the fan from that of the low-pressure spool, which drives the gearbox – and ultimately the fan.

The gears in the gearbox produce a 3:1 reduction ratio to slow the rotation speed of the fan down from that of the low-pressure spool. This allows both the fan and the low-pressure turbine to rotate at their optimally efficient speeds – relatively slowly in the case of the fan and very fast in the case of the LPT and the low-pressure compressor it drives.

"We're trying to use the fan to try to get the highest level of propulsive efficiency" – and at the same time, "highly optimized aerodynamics in the core to obtain thermal efficiency," said Adams. "We think the gear is a key enabler in this."

In conventional turbofan engines, the bypass ratio effectively is set by the fan-tip speed and the low-pressure turbine speed and the bigger the fan, the faster its tip speed becomes, explained Adams. In such engines, when fans are made bigger to produce higher bypass ratios, the blade tip ends turn at supersonic speeds when the engine is producing more than about 80% of maximum thrust, creating shock waves that decrease the engine's efficiency and make it much noisier.

Meanwhile, in conventional turbofans, turning a smaller fan faster to produce a higher bypass ratio also isn't optimal, because the fan is directly linked to the low-pressure spool and the LPT has to become much bigger and heavier to run faster. Weight and drag go up and ultimately overtake the specific fuel consumption benefit, Adams explained.

However, in the PW1000G the fan blade rotation speed is about 30% less than that in a conventional turbofan, said Adams. Blade-tip speed is subsonic and there is no adverse shock-wave effect. At the same time, the LPT and the LPC (booster), which it drives run faster than the LPTs and boosters in conventional turbofans because they are not directly linked to the fan. The LPT and booster in the PW1000G run "at speeds much closer to a turbojet-type engine," he said. "The fan and turbine are much more naturally matched."

Their faster rotating speed make the PW1000G's LPT and booster so efficient that, compared with a conventional turbofan engine producing the same thrust, Pratt & Whitney has been able to do away with five to six stages on the PW1000G's low-pressure spool.

The architecture of the PW1000G uses three booster stages, where a conventional turbofan would classically use five; and just

1 Computer generated image of Pratt & Whitney's PurePower 1000G engine as selected to power the new Bombardier CSeries jets. *Pratt & Whitney* **2** Pratt & Whitney completed flight-testing of the PurePower PW1000G demonstrator engine in February 2009. The final phase was completed jointly with Airbus on an A340-600 flight test aircraft comprising 27 flights and more than 75 hours flying. *Airbus* **3** The 17,000 to 23,000lbf version of the PW1000G engine selected for the new Bombardier CSeries jets will have a high bypass ratio, necessitating 73 inch fan blades. *Pratt & Whitney* three in the LPT, where (depending on a manufacturer's decision to trade between fuel efficiency and maintenance cost) a conventional engine would have six or seven stages, according to Adams.

Elsewhere, the PW1000G's architecture and materials technology is less conventional. Every one of the eight HPC stages in the engine is a blisk. The PW1000G has a two-stage LPT and Adams said both stages of the HPT and the stages at the rear of the HPC (where the core air starts becoming very hot) employ powder-metal materials. "We've used a fair bit of powder metal," he said.

Additionally, the annular combustor in the PW1000G uses Pratt & Whitney's latest TALON-X (Technology for Advanced Low NOx) design, which not only employs 'floatwall' inner-lining panels that can expand and contract independently of each other as the engine heats up and cools, reducing wear and thus the amount of maintenance required, but also a 'rich-lean-quench' combustor.

This design "runs the primary zone [of combustion temperatures] rich and then quenches it very quickly," cooling the combustion air off below the temperature-resonance levels at which nitrogen oxides form, said Adams. "We burn quick and we burn rich, but we quench very quickly."

The PW1000G will produce NOx levels "minus 50 [%] and beyond" compared with CAEP 6, ICAO's latest emissions standard, according to Adams. "It's very simple, very durable, low-maintenance cost and extremely safe," while also offering "world-class" emissions performance. "We also have a very, very strong track record of [the combustor] not blowing out," he said.

In the PW1000G's combustor, Pratt & Whitney has stuck with a single-nozzle design rather than the dual-nozzle; concentric-ring design favoured by GE for its TAPS and TAPS II combustors. "We like this architecture and we think we can be extremely competitive in providing world-class emissions and do it with very low maintenance cost," said Adams.

Additionally, the PW1000G's turbine casing will employ active clearance control (ACC), a technology originally developed by Pratt & Whitney and over which it won a patent lawsuit with GE, to minimise any gaps between the casing and the turbine blades while the engine is running.

Adams said Pratt & Whitney has also developed "what we believe is next-generation cooling technology" for the PW1000G's turbine blades in terms of the geometry of the specific cooling-air passages within the blades, and a combination of the materials from which the blades are made and the thermal barrier coatings with which they are treated, to help keep cooling-air requirements down.

At the back end, the PW1000G will have a cut-off nacelle design rather than a full-duct nacelle, with Pratt & Whitney using scalloped chevrons at the rear of the nacelle, as well as acoustic treatments within the engine to reduce exhaust-air noise.

But it is the PW1000G's fan that could prove to be its most exotic technology. Counter-rotating to the low-pressure spool (which rotates in the same direction as the engine's high-pressure spool, Adams said that in this case "we think we end up being more efficient" in terms of core-airflow aerodynamics), the fan will have 18 highly three-dimensionally sculpted blades. However, for now Pratt & Whitney won't say what they are made of, believing it has come up with an exciting new materials concept.

"At this point in time it's a lightweight hybrid," said Adams, noting that because of technology sharing with its United Technologies sibling Hamilton Sundstrand – the world's largest manufacturer of propellers for turboprop and piston-powered aircraft – Pratt & Whitney believes "we have some unique technology" for the PW1000G fan.

"We think we have an extremely good concept," he said. "We're probably not ready to go out to full market on this" in terms of public discussion of the technology, but he believes the company "will be ready for prime time by the summer" and can then say more about exactly what the PW1000G's fan will be made of.

The slow rotation speed and large size of the PW1000G's fan – particularly on the Bombardier CSeries – will create tremendous advantages in two areas quite apart from the impressive 12% fuel efficiency boost Pratt & Whitney promises the first-generation PW1000G will deliver compared with comparable current-generation turbofans.

1 The crew of Airbus A340-600 test aircraft F-WWCA, at Toulouse, France on October 14, 2008, the first test flight of a PurePower PW1000G engine. *Airbus* **2** The PurePower PW1000G demonstrator engine took to the skies for the first time on July 11, 2008 on Pratt & Whitney's Boeing 747SP flying test bed aircraft. *Pratt & Whitney* **3** Close-up shot of the PurePower PW1000G demonstrator engine fitted to the portside inner pylon on Pratt & Whitney's Boeing 747SP flying test bed aircraft N747UT. *Pratt & Whitney* **4** Goodrich produces the engine nacelles for the PurePower PW1000G engine, shown in the open position in this shot. *Pratt & Whitney*

One area is noise reduction. Because the PW1000G's bypass ratio will be so high, the large amount of cold bypass air produced as the engine's main thrust component will mix extensively with the hot exhaust air exiting the engine core and largely mask the noise produced by the exhaust air. Also, because the fan-blade tips are rotating at subsonic rather than supersonic speeds even at maximum thrust, the shock-wave noise associated with supersonic blade rotation speeds will be absent.

The PW1000G's slow fan-blade rotation speeds will also help make the engine much more resistant to foreign object debris – including bird-strikes – than today's engines, Adams believes. "Most damage from bird-strikes comes from fan speed, not bird speed," he said. In current engines, typically, fan blades rotate "five to seven times faster than the bird is flying" – but the PW1000G's blades will be turning more slowly and the forces associated with impact won't be as high. Additionally, the large size of the fan will create more centrifugal force, tending to push FOD out to the edge of the fan and away from the engine before it has chance to enter the booster and engine core.

In the United Technologies group of companies, another sibling of Pratt & Whitney is Sikorsky, which has decades of experience designing and running huge gearboxes in its helicopters. This, along with the fact that PW itself is the world's largest supplier of turboprop engines (with 400 million hours of in-service experience) and also that PW has already run the PW1000G planetary gearbox at maximum power for well over 1,000 hours in rig tests, "helps build our confidence that this should be a flawless entry into service," said Adams.

After completing its entire demonstrator testing for the PW1000G using a PW6000 core, Pratt & Whitney started running the full PW1000G engine core in mid-December 2009. The development plan called for the full PW1000G test programme to begin in the first quarter of 2010 and for PW to begin running the fully configured PW1000G for the CSeries by mid-summer, allowing an entry into service on the new Bombardier mainline jet at the end of 2013.