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CONCEPTS & TECHNOLOGIES FOR THE NEXT GENERATION OF LARGE CIVIL AIRCRAFT ENGINES

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Abstract

The Paper describes key technologies within aircraft engine systems contributing to low emissions products, fuel efficient in the large civil aircraft engine market. Emphasis will be on the architectural, aerothermal, material & sub-system technologies, the corresponding demonstrator programmes and the technology incorporation into new engine architectures.

1 Introduction

Reducing aero engine emissions is of vital strategic importance to the industry, driven by tightening legislation, customer demands and competitive pressures. Large investments are being made in the combustion and controls technology needed to reduce NOx levels by at least 50%, relative to conventional technology. Low emissions, improved fuel efficiency and advanced temperature capability are a major goal of the Rolls-Royce three ongoing engine demonstrator programmes for 2 shaft & 3 shaft architectures: “Advance3” and UltraFan™ for the 3 shaft engine family for wide-body aircraft, “Advance2” for the 2 shaft engine family for middle of market, corporate and regional engine, see figure 1.

Beside the propulsive efficiency, which is in direct correlation to specific thrust or bypass ratio of an engine, the second main contributor to reduced fuel consumption and emission is the cycle, or thermodynamic efficiency. Gas turbines convert the energy from burning fuel into useable work via three main elements – a compressor, combustor and turbine. Work output for higher thermal efficiency increases with [1]:

- Higher overall pressure ratio
- Higher combustor exit temperature, restricted by the high temperature capability combustor and turbine components (with ultimate limits imposed by stoichiometry in combustion)
- More efficient secondary systems (cooling, sealing)

As gas turbines operate in a continuous thermodynamic cycle, they have a higher power density than internal combustion engines. In aero engines, the gas turbine can accelerate air to create thrust and power to drive the LP turbine system which drives the Fan system to generate the majority of the forward thrust. Figure 2 depicts the relative importance of propulsive and the thermal efficiency in this context. Whilst the last paper of the authors [4] concentrated on the thermal efficiency contributions, this current paper will put the emphasis on propulsive efficiency technology.

Key drivers for high propulsive efficiency and finally (integrated with thermal efficiency drivers and power plant weight) fuel burn are:

- Low specific thrust at minimum weight
- Low loss Fan, LPT (low pressure turbine) and bypass duct

Rolls-Royce aims continually to improve the efficiency of its products and the key components that they embody. There is a clear desire to increase component efficiencies and at the same time, reduce weight and cost in order to achieve the optimum technical solution. As can be seen from the range of the most recent products, from the 2000 until today, Rolls-Royce engines have reduced about -15% in fuel burn and improved CO2 emission respectively (see figure 3 a and b). The further emission reduction is supported by technology improvement, especially in the hot section of the engine [2],[3].

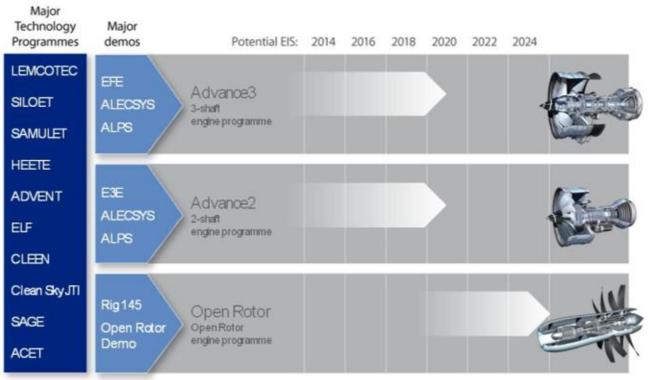

Figure 1: Future Engine Programmes of Rolls-Royce plc

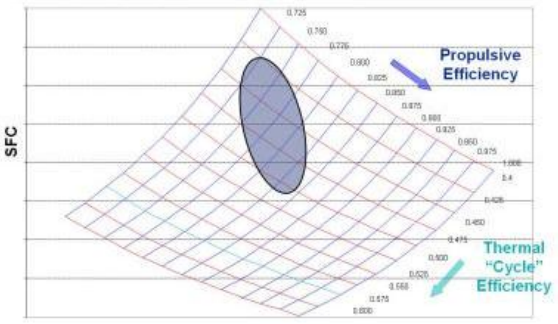

Figure 2a: SFC as a function of propulsive and thermal efficiency

The propulsive efficiency of the engine or power-plant is dominated by the capability of the Low Pressure Fan system to accelerate a lot of air slowly, thereby minimizing shear layer losses and as a further consequence, reduce noise emissions.

There are a number of other factors that can affect the optimum fan diameter, such as nacelle installation losses, nacelle/wing and structures interactions. These also contribute to specific fuel consumption shortfalls, see figure 2b.

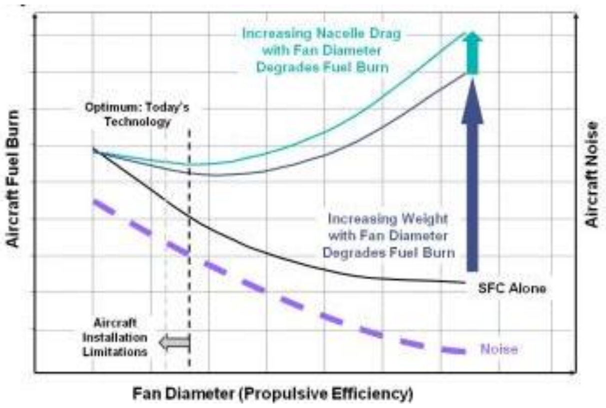

Figure 2b: Aircraft fuel burn and aircraft/engine noise as a function of fan-diameter

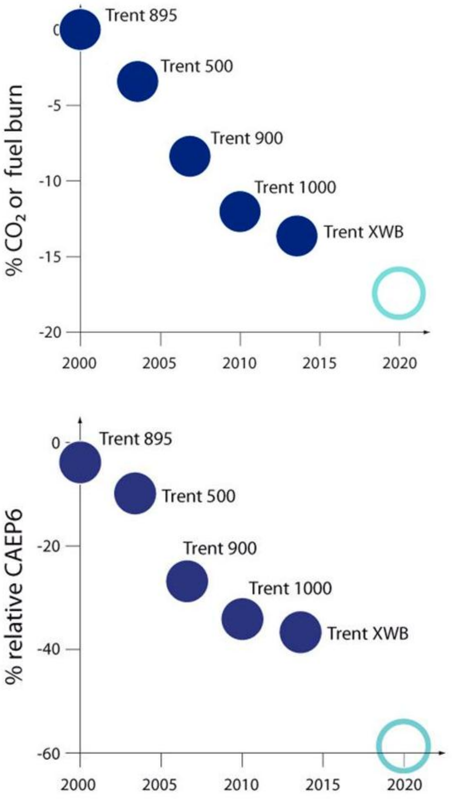

Figure 3: a) SFC/CO2 performance vs. ACARE target and b) % reduction of NOx emission relative to CAEP6

2 Key technology drivers

As already laid out in [1, 2,3 and 4] and in the introduction of this paper, the advancement of the state of the art in engine fuel burn and emission is governed by the thermal efficiency, the propulsive efficiency of cycle and Low pressure system. Both improvements strands need to be achieved at minimum weight, cost and emission footprint.

Thermal efficiency:

Figure 4 is indicative of a typical core sizing chart, which shows quite clearly that for the overall thrust level of the mission there are different ways to achieve the necessary power input from a core to and low pressure system. Either by a moderate sized core with lower compressor delivery temperature (T3) and consequently lower overall pressure ratio of the engine paired with a moderate Turbine entry temperature (T4). Or, alternatively, aim for a higher overall pressure ratio, by increased compressor delivery temperatures and turbine entry temperatures, allowing for a smaller, lighter core and most likely an overall better mission fuel burn. So, in summary, work output increases with higher overall pressure ratio, higher combustor exit temperature, restricted by the high temperature capability combustor and turbine components (with ultimate limits imposed by stoichiometry in combustion) and more efficient secondary systems (cooling, sealing). The thermal efficiency of the engine is therefore dominated by the capability of the compressor to efficiently and reliably compress air to very high levels and the durability of the hot section sub-systems (Combustors and core turbines) in terms of cooling flow consumption, performance and durability (life cycle), in combination with the maximum achievable turbine entry temperature.

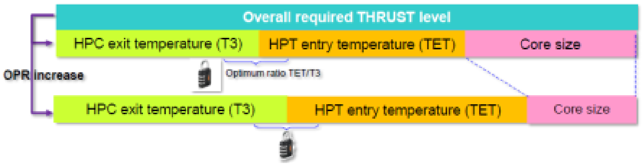

Figure 4: Overall pressure ratio relation to core size and core temperatures

Propulsive efficiency:

The propulsive efficiency of the engine or power-plant is dominated by the capability of the Low Pressure Fan system to accelerate a lot of air slowly, thereby minimizing shear layer losses and as a further consequence, reduce noise emissions. As a consequence, there is a desire to increase fan diameters (‘more air’) and reduce fan pressure ratios (‘slower’) to achieve higher propulsive efficiencies and consequently, when paired with lighter weight materials and design concepts also mission fuel burn. Figure 5 shows the direct impact of fan pressure ratio (FPR) on propulsive efficiency, and also allows for a categorization of the different systems.

Today’s High Bypass ratio civil large engines tend to operate at FPRs around 1.45 - 1.75, whilst higher bypass ratio geared concepts with either variable or fixed pitch fan are more around 1.2-45. Those architectures tend to have the need for geared solutions in order to allow the Fan tips to operate near sub-sonic or in sub-sonic conditions (delivering noise and efficiency improvements). These benefits are somewhat balanced by the need for a fairly heavy power gearbox which drives additional complexity, lubrication and heat management challenges into the engine design. Ultimately, the lowest possible fan pressure ratio can only be achieved if the fan is no longer concealed by a casing and nacelle, but open, and consequently needs a double fan concept to reduce residual swirl and optimize thrust at very low FPRs around 1.04.

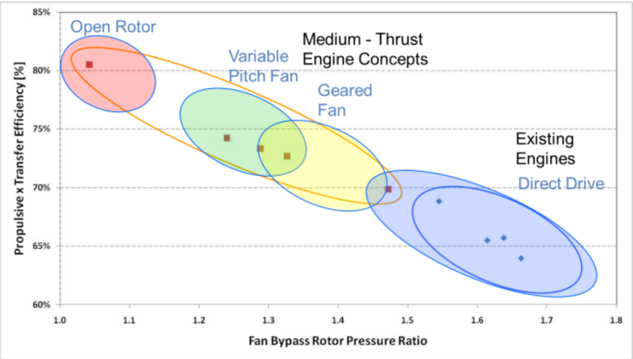

Figure 5: Propulsive Transfer efficiency as a function of Fan pressure ratio

3 The key technology and demonstrator strands

Rolls-Royce targets the next generation of engines to push all parameters to meet the future needs of our customers and maintain a world-leading position on fuel efficiency (Current XWB engine is most efficient engine to enter service). With the ADVANCE and UltraFan^{TM} engines delivering an efficiency improvement of at least 20% and 25% respectively relative to the Trent 700. This is equating to a relative fuel saving respectively of over \$5.3 and \$6.6 million per aircraft per year (calculated at \$3 per US gallon). The enhanced performance of the next generation of engines is based on a number of new developments, including:

- A highly efficient core architecture and enabling technologies.
- A lightweight carbon titanium (CTi) fan system.
- A geared multi stage IP turbine system

In the following, the engine concepts as well as the key technologies will be explained in detail. For ADVANCE, a new core architecture coupled with a lightweight LP system and a suite of advanced technologies will be incorporated into the Advance. For UltraFan^{TM} the new core architecture coupled with a geared IP and variable pitch fan system, along with a suite of further enhanced technologies will be incorporated into the new centerline engine. For both engine architectures, Rolls-Royce decided to invest in a comprehensive demonstration of the technology. Consequently, the engine development programs are supported by a comprehensive and unequalled set of existing technology demonstrator programs such as ALPS (Advanced Low Pressure Systems), EFE (Environmentally Friendly Engine), ALECSYS (Advanced Low Emission Combustion System) and Advance (demonstrator of new core architecture) that cover the whole engine. This is backing up the commitment to ensure that technology is robust, fit for service and applied at the right time for the customer. Figure 6 depicts the main characteristics of the engine concepts and also sums up the main cycle parameters. Here you can see that ADVANCE targets an overall pressure ratio (OPR) of 60+ whilst the UltraFan^{TM} concept is positioned around an OPR of more than 70. The respective bypass ratios are 11 and 15+. The fuel burn saving relative to a Trent700 engine will be 20% for ADNVACE and 25% for UltraFan^{TM}, respectively.

Technology EIS Readiness	2020+	2025+
Bypass Ratio	11+	15+
Overall Pressure Ratio	60+	70+
Efficiency relative to Trent 700	20%+	25%+

Figure 6: ADVANCE and UltraFan^{TM} concept relative to Trent engine

3.1 ADVANCE engine architecture

For the new Advance core architecture to deliver maximum fuel efficiency and low emissions, some changes to the core architecture are undertaken. As all Rolls-Royce large civil engines, this core still takes advantage of the extra degree of freedom in our 3 shaft architecture by redistributing the workload between the intermediate and high pressure shafts. Pushing more compression work on to the high pressure spool results in higher efficiency, delivered by a core with an OPR of more than 60:1 – which will be the highest ever in a commercial turbofan. Key technologies, such as Ceramic Matrix Composites and Carbon Titanium Fan blades and compressor blisks will allow for fewer part and lower weight. Figure 7 shows the key technologies incorporated into the ADVANCE concept, which we will explain in the following in more detail.

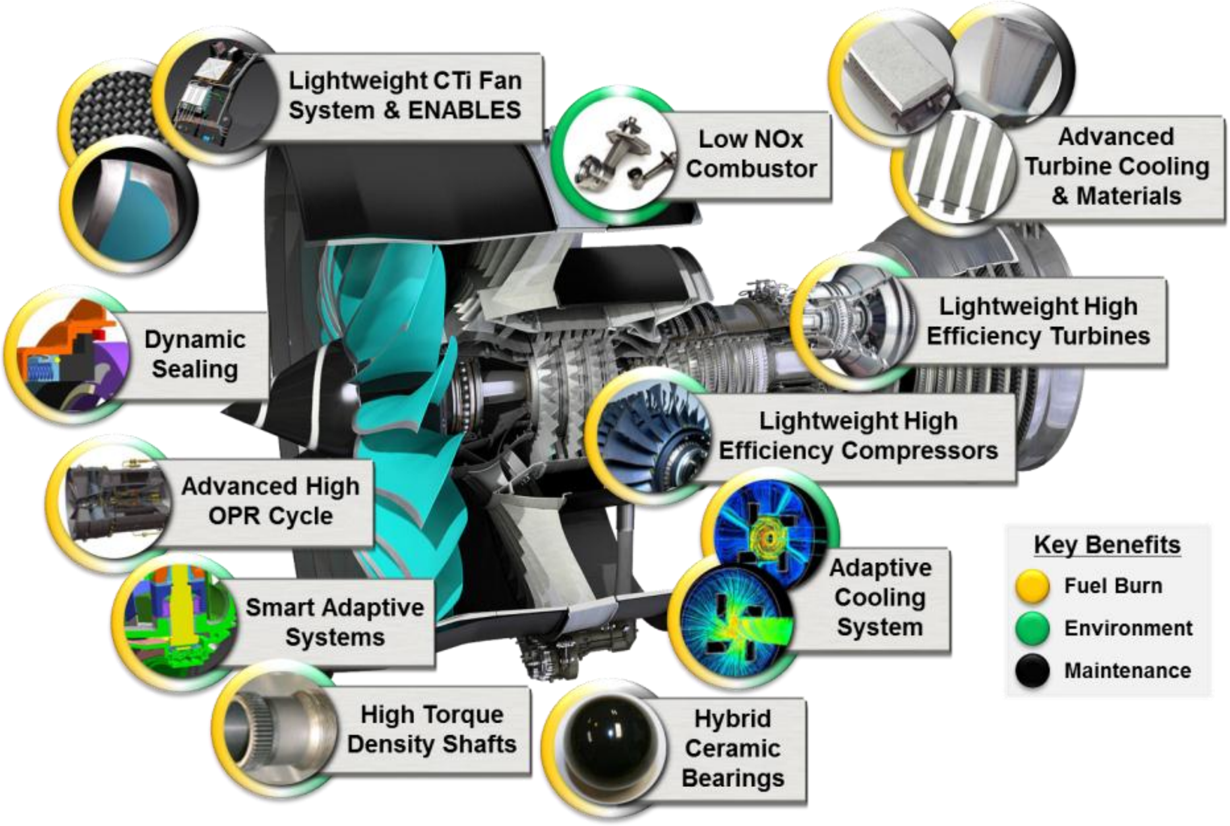

Figure 7: Key technology strands for the ADVANCE engine concept (and benefit category)

Carbon Composite-Titanium Fan Systems

All Rolls-Royce Trent engines feature a wide chord SPFDB (Super Plastically Formed Diffusion Bonded) titanium blade which has proved itself in millions of service hours to be a lighter and more efficient solution than the first generation of composite blades. Clearly, one would only decide to move away from this proven and efficient existing Fan-System, if the replacement would be more efficient and lower weight. So, engines of the future will see increased bypass ratios and fan diameters – in simple terms engines will get physically bigger. As engines get bigger, the weight of the fan system will increase and so it becomes imperative that we identify ways to introduce new, lighter materials but with no loss of overall engine efficiency. Thus, the advance engine concept will feature our new CTi Fan System – CTi standing for the Carbon and Titanium that forms both the fan blades and the fan casing - delivering improved propulsive efficiency at the lowest possible weight. A significant weight saving of around 500-800 lb per engine can be achieved. The Development of the CTi fan system's unique automated manufacturing system is well advanced. The technology already successfully completed some of the crucial bird strike and blade-off tests that are required to prove that the CTi fan system can withstand the rigours of the real world.

Figure 8: Composite CTi (Carbon/Titanium) Fan demonstrator ALPS (view from front).

Low NOx Combustor

The low NOx system ALECSYS has been explained quite detailed in [3] and consequently only the basics will be explained here. Currently there are 2 competing low NOx combustion technologies. Rich quench Lean (RQL) or Lean burn. RQL has been at the heart of conventional combustion technology for many years and is therefore very mature. Lean burn by its name burns fuel on the lean side of stoichiometric thus does not traverse the high stoichiometric, high NOx producing zone. Running lean brings challenges at low power running due to the lean conditions, this means that piloting has to be used to improve operability.

Light & efficient turbo-machinery components

In the main compressor and turbine modules, significant technology introduction such as new and more effective secondary air systems are introduced, which allow for maintaining relative cool disc environment. Bladed disc (Blisk) technology on several Intermediate and high pressure compressor stages as well as 3rd generation high lift technology for the turbines allow for optimum blade counts. In addition, within the hit section, advanced cooling technologies and materials, such as ceramic matrix composites (CMC) will be used. CMC technology is a key contributor to future engine competitiveness due to its higher temperature capability than nickel superalloys, which reduces the use of air for cooling, and through reduced component weight from its lower density. CMC components are formed from woven layers of continuous silicon carbide (SiC) fibre, laid up in tooling to form the required shape, and then surrounded by a ceramic matrix. An environmental barrier coating protects the component from reaction with steam in the gas flow. Provided that they are sufficiently strong, CMCs are ideally suited to turbine seal segments, vanes, blades and combustors. Rolls-Royce has researched ceramics materials since the 1980's and successfully used them in engine applications (e.g. Trent 800 segments), but at the time were hindered by very slow and costly manufacturing techniques. Based on recent advances in manufacturing, we have deliberately increased our efforts and made significant progress in the technology over the last few years, with experience gained on US research and technology programmes (VAATE and F-136) as well as the Environmentally Friendly Engine (EFE) demonstrator will allow for minimum parasitic air consumption and weight, both enhancing fuel efficiency significantly (>1 to 2%) of the overall engine.

Adaptive technologies

Smart adaptive systems are used throughout the new engine concepts, including an advanced turbine tip clearance control system that will continuously monitor the engine in operation and act accordingly to minimise fuel burn at any stage of the flight cycle. Also, an adaptive cooling system that modifies the levels of cooling flows to the levels required throughout the engine flight cycle to improve fuel burn. This system relies on switched vortex valves to operate. This new type of valve allows for changes in cooling air delivered to the hot section without having to rely on any moving parts, solely by fluidic technology a change in air delivery is achieved.

Advanced materials and seals

A suite of sealing solutions to achieve the optimum solution throughout the engine is incorporated into the new architecture, comprising of an optimum mix of traditional labyrinth seals, air riding carbon seals as well as advanced leaf seals. In combination with advanced design algorithms for thermal matching this sealing technology will improve engine fuel burn significantly by improving the air and oil system efficiency. The use of advanced materials in the bearing area, such as hybrid ceramic bearings for lower oil consumption and durability is a further step towards oil-less engines. In addition to this, the advanced materials in the hot section which enable the high OPR cycle and reduced fuel burn, do include dual microstructure alloys, new turbine materials and coatings, as well as the already mentioned Ceramic Matrix Composites (CMCs) for e.g. turbine segments and vanes.

For the high pressure spool, a next generation disc material is a key contributor to future engine competitiveness as the alloy's higher temperature capability enables improved thermodynamic efficiency. This is required for future high bypass ratio architectures and cycles in which the overall pressure ratio and compressor exit temperature (T30) are raised above existing Trent designs.

The current generation of powder nickel disc alloys has taken over 20 years to develop and to achieve service readiness. This is due to the extreme difficulties in producing seemingly conflicting requirements of strength and damage tolerance in safety-critical HP disc rotors at very high temperatures, up to 750°C, and under high loads. Powder technology is a critical materials capability, which has enabled compressor and turbine disc temperatures to rise in Trent engines by over 70°C from an initial capability of 680°C. The next generation disc material will be a powder nickel alloy capable of operating at up to 780-800°C. In additional to damage tolerance and strength, this alloy will also need to show greater resistance to environmental damage and corrosion without a coating. The key initial step is to determine the composition of the alloy that will be taken through the extensive materials and component validation programme.

Finally, new high torque density for advanced shafts allows for an optimization of the discs (especially in the turbine domain) by keeping relatively speaking the bore hole diameters necessary for the accompanying of lower pressure spools at optimum levels.

Advanced controls, monitoring and electrical systems integration

There are a number of activities currently underway looking at advanced controls, future Equipment Health Monitoring (EHM), electrical systems technology and improved airframe / engine systems. A short description of the vision for future systems and integration and outlines the potential benefits are given here. The key areas included are in the nearer term an integrated Engine Health Monitoring (EHM) technology package to significantly enhance service predictability and reduced maintenance burden and cost as well as advanced electrical system demonstration programme. In the medium term strategic activities are:

- Optimised thermal management across systems (oil, air, fuel and power systems)
- Closer integration with airframers regarding systems and controls
- Advanced control methods: condition based control; deterioration management; tune ability
- Closer integration of control and EHM – use of lower integrity systems where appropriate and a new architecture to support this

3.2 UltraFan™

Next-generation turbofan engine designs for commercial transport aircraft seek higher bypass ratios (BPR) and lower fan pressure ratios for improved fuel burn and reduced emissions and noise, increasing fan bypass stream propulsive efficiencies. Also, significant cabin noise benefits can be achieved by potentially avoiding buzz-saw noise, reducing fan broadband and rotor stator interaction noise, and enabling steeper take-off profiles due to additional thrust capability for the air craft by reduced Fan-speeds [5]. The UltraFan™ builds on the core architecture and technologies of the Advance with the incorporation of a geared IP and variable pitch fan system. In addition a further enhanced suite of new technologies will be incorporated into the UltraFan™ engine, including:

- A variable pitch fan systems
- A slim line nacelles
- A power gearbox
- A multi-stage IP system
- Cooled cooling air
- Further use of advanced materials

The variable pitch CTi fan system is a lightweight composite fan system that includes the next generation of our CTi fan blade and a composite casing and an embedded externals system to deliver further weight savings. The addition of the variable pitch system allows the fan blades to be rotated to maintain optimum performance throughout the flight cycle whilst enabling the removal of the thrust reverser from the nacelle. The fully integrated slim line nacelle will be a truly slim line nacelle enabled by the removal of the nacelle thrust reverser thereby providing improved efficiency from reduced weight and drag. The power gearbox to allow for the decoupling of Fan and driving IP Spool will be a lightweight and high efficiency power gearbox and heat management system to enable a low speed fan system to be coupled with a high speed IP system (compressor and turbine). Enabling both systems to run at their optimum speeds. The new, multi stage IP turbine system will comprise of a high efficiency multi stage IP turbine capable of driving both the IP compressor and fan systems.

To allow for the high overall pressure ratio and consequently compressor delivery air temperatures well above 1000 Kelvin the incorporation of cooled cooling air as a system that pre cools the engines cooling air to enable further efficiency benefits and improved component lives in the hot section is essential. It is evident from this, that also the use of more advanced materials, cooling and broader application of CMCs to enable an even higher OPR cycle and further fuel burn reduction is necessary.

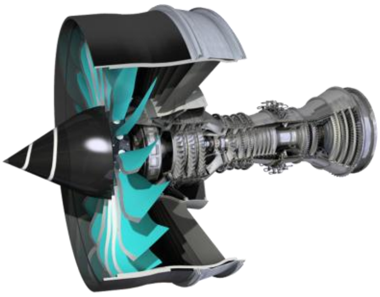

Figure 9: The UltraFan^{TM} engine concept

4. Comprehensive demonstration

Demonstration of technologies and new engine architectures ahead of programme launch is essential as intelligent innovation will only apply fit for purpose technology that gives the right balance of reward versus risk for customers. As a key aspect in ensuring this our next generation engines are backed up by numerous technology programmes, system rigs and demonstrators. With four of our most significant engine demonstrator programmes being:

1. The LP system (ALPS) flight test demonstrator programme focuses on lightweight and high efficiency CTi fan and low pressure turbine systems, and will ultimately flight test these systems.
2. The combustion system (ALECSYS) flight test demonstrator programme focuses on advanced combustion systems, with primary emphasis on the lean burn combustor at an overall engine level, and will ultimately flight test this full system.
3. The Advance Core technologies (EFE) core demonstrator programme focuses on delivering lean burn combustor technology, high temperature and high efficiency turbine technology.
4. The Advance Core architecture (ADVANCE) engine demonstrator programme focuses on validating the core architecture at the heart of our next generation engines.

The Trent 1000 forms the donor engine for the ALPS, EFE and ALECSYS demonstrators. With the Trent XWB the donor engine for the Advance demonstrator. By using our latest engines to prove out these technologies, we benefit from the wealth of knowledge and understanding generated in their EDPs which have utilised the latest analysis and testing capability. Between them, these demonstrators and others will cover the breadth of our next generation Advance engine, with the additional enabling technologies of the UltraFan^{TM} being proven through an extensive rig testing programmes to validate key systems before whole engine demonstration:

- The UltraFanTM demonstrator (UFD) flight test programme focuses on validating the UltraFanTM engine and will ultimately flight test the enabling systems.

Together all of these demonstrator programmes prove new technology at a full systems and engine level to de-risk the technology before it is introduced into service. This ensures that new technology is only introduced when the balance between risk and reward for both Rolls-Royce and the operators is achieved. It’s about the technology buying its way on at systems and ultimately an engine level at the right time for the customer.

5 Enabling technologies and capabilities

Aerothermal Excellence

Product performance is the ultimate differentiator in the market place. Next to high temperature materials our aero-engine product performance is almost solely driven by our capability to innovate, design and realise engine-modules which make most efficient use of the working gas; this is called excellence in aerothermal design. Attention to detail is key for this design capability, and it needs to be continuously updated and improved in terms of methods, tools, people and technology. In recent years Rolls-Royce has started the aerothermal excellence programme to enhance this key enabling strand. Over the last decade, fuel burn improvement of aero engines averaged about 1% per annum. As already laid out, the engine overall pressure ratio will continue to grow, making core engines smaller, which will increase the importance of physical scale, leakage flows and part tolerances. At the same time, adaptive engine concepts (e.g. operational compressor surge margin control) and the need for environmental performance will continue to grow. Aerothermal excellence enables more innovative designs exploiting better understanding of complex physics modelled to the highest possible level, and allow tighter tolerances to be achieved to minimise parasitic losses such as leakages. It improves the scalability of our designs from one thrust level to another. Benefits are:

- Increased aerodynamic efficiency and environmental performance via better understanding and exploitation of physics, innovation in adaptive designs
- Improved engineering productivity via better tools (right first time) and reduced time to market via scalability

Virtual Engine Design capability

Current practice in product development is to design, build and then adapt the product to achieve product specifications. With high performance computing (HPC) capacity growing rapidly around the world, the vision to design and validate product specifications in the computer is closer to becoming reality. This vision will be realised through a Virtual Engine design system that will produce highly accurate simulations of the whole system behaviour. Today, engineers typically run design and analysis software on computers with between 8 and 64 CPU’s (called ‘cores’ in the IT world). More complex simulation to date run on 10,000 HPC cores, and takes a few weeks of non-stop running to complete the simulation of e.g. one fan blade-off event. Next steps will be to utilise the potential of the largest computers in the world which have over 1 million HPC cores running in parallel. 2 years ago Rolls-Royce launched a programme to increase its access to HPC capacity and develop the complex virtual engine models and design systems required to run on it. This also involves the development of simulation software to match the computer chip capability for efficient parallel running on thousands of cores. The programme is now entering into the next phase to deliver improved capability and fidelity ahead of the next large engine development programme to be used on these designs. As engines become more complex the fidelity of our modelling needs to also increase so that we can take risk out of development programmes, shorten time to market and save cost by doing more pre-work and not re-work. Design and validation in the computer will enable many design iterations to be tested in the virtual world. This allows any problems to be discovered earlier in the process, therefore reducing iterations later in the programme when the design is committed to hardware and the cost and time of change are much higher.

Conclusion

The Paper describes key technologies and engine architectures leading to low emissions, low fuel consumption products in the large civil aircraft engine market. Examples are key new product lines of Rolls-Royce as well as technology demonstrators. Emphasis is on the engine architecture, the utilisation of advanced core engine and low pressure system technologies, aerothermal considerations for compressors, turbines and air system, combustion, material & sub-system technologies. Building on an earlier contribution by the authors on hot-end technologies [4] a comprehensive review of the important technologies in the new engine concepts ADVANCE and UltraFan^{TM} and how these technologies enable innovative whole engine architectures is given. Reducing aero engine emissions and fuel burn is of vital strategic importance to Rolls-Royce, driven by tightening legislation, customer demands and competitive pressures. Large investments are being made in the combustion and controls technology needed to reduce NOx levels by at least 50%, relative to conventional technology. Low emissions and advanced temperature capability are a major goal of the EFE (Environmentally Friendly Engine) demonstrator programme as well as the European Clean Sky initiative.

The demonstrator section of this paper reviews the current engine architectural demonstration consideration of Rolls-Royce.

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