Rolls-Royce

Whittle Lecture 2004

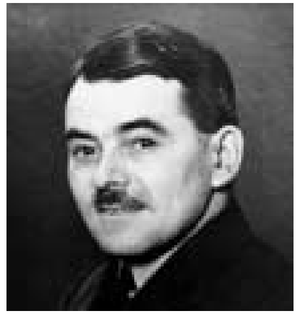
Aero gas turbines

1904 - 2004 a century of innovation

an ever-changing engineering challenge

“The invention was nothing.
The achievement was making the thing work”

Sir Frank Whittle



Preface

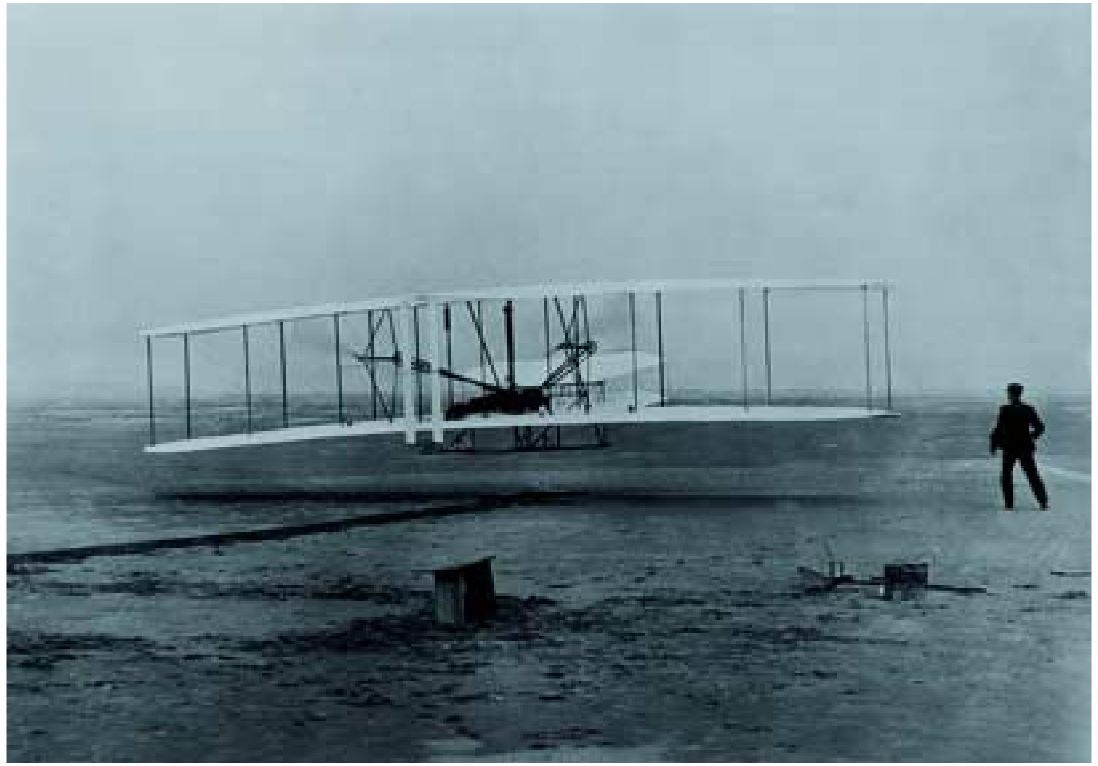
Dr Mike Howse, Director - Engineering and Technology, Rolls-Royce plc
presents
Aero gas turbines - An ever-changing engineering challenge
to the Royal Aeronautical Society
at 4 Hamilton Place, London
on 3 February 2004

Introduction

One hundred and three years ago, after the Wright brothers had attempted another unsuccessful flight, they predicted that it would be another 50 years before manned flight was achieved. Only two years later on the 17th December 1903, Orville Wright achieved the first powered flight, illustrating as Niels Bohr said *"Prediction is very difficult, especially about the future"* **(figure 1)**. Not long after this, on the 4th May 1904 the historic first meeting of Henry Royce and Hon. C. S. Rolls took place, leading up to an agreement in December 1904 when the first motorcars would carry the name 'Rolls-Royce' **(figure 2)**. Since then the Rolls-Royce name has become synonymous with integrity, reliability and innovation associated with a wide range of products in the Aerospace, Marine and Energy sectors. There is an ironic and tragic link between these events, in that C. S. Rolls died in 1910 when his French-built Wright flyer broke up in mid-air and crashed during an aviation display in Bournemouth. During the Rolls-Royce centennial year we look towards the next hundred years with wonder and can only speculate as to where they will take us.

The second fifty years of powered flight have been dominated by the gas turbine. This lecture includes the problems faced by engineers developing aero gas turbines in the past, the challenges faced by the designers of today and the areas where technical advances are going to be needed in the future. Two of the early engineers to tackle the problems of designing a gas turbine were in the UK: Sir Frank Whittle with the first patent for a turbojet engine in 1930 **(figure 3)**, and Dr A. A. Griffith, with the outlining of the concept of the turbofan engine in the 1940's **(figure 4)**. The combination of the early work of these two pioneers formed the basis of the aero-gas turbines of the present day. Both men, in the early days, identified that significant improvements in compressor and turbine component efficiency were necessary for viable gas turbine engines, and both were convinced that these advances were achievable. The motives behind their determined pursuit for success did however differ. Frank Whittle recognised that a gas turbine of adequate efficiency could be used for high altitude and high speed flight with speeds up to 500mph; this at a time when the fastest RAF fighter could not reach 200mph. Dr Griffith, however, saw the gas turbine as the driver of a high efficiency propeller or multi-stage fan, in order to achieve propulsive and fuel efficiencies comparable with those of piston engines. Whittle's quest for simplicity led him to use a centrifugal compressor, as opposed to Dr Griffith who favoured the axial, multiple stage bladed compressor. Although the approaches of these two men were different they faced common engineering challenges, some of which are still very much in existence today.

Technical challenges are often fuelled by changing market drivers. This is exemplified by military air supremacy, which



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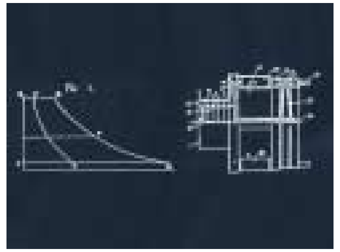

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1 First flight of the Wright Flyer, December 17, 1903
2 Hon. C.S. Rolls *(left)* and Henry Royce *(right)*
3 First patent of a turbojet engine taken out by Frank Whittle in 1930
4 Contra-rotating aft fan engine concept - A. A. Griffith

drove Sir Frank Whittle's early quest for speed and altitude. Another example would be airline operating cost and aircraft range, setting the performance requirements for Rolls-Royce RB211 and Trent high bypass ratio engines. Environmental factors are likely to be the future driver in civil aerospace and military strategies may require affordable high-Mach propulsion in the defence aerospace markets. This lecture explores several technical challenges faced by aero gas turbine engineers: combustion, compressors, turbines, systems, fans, environment and finally returns again to combustion. Through considering these technologies and the inherent advantages of power density and adaptability of a gas turbine, the lecture will endeavour to show that the future promises to be as challenging, changing and exciting as the past.

The Whittle engine and the challenge of combustion

We only need look at a picture of Whittle's W1 engine **(figure 5)**, with its ten large separate combustor cans dominating the engine, to see the magnitude of the challenge that was 'the combustor'. On the 27th January 1936 four partners signed an agreement: the President of the Air Council, O.T. Falk & Partners, Williams and Tinling, and Whittle, thus establishing Power Jets Limited. In 1936 Power Jets eventually signed an agreement, on a cost plus basis, with British Thomson-Houston (BTH) to manufacture their engines.

Throughout 1936 Whittle struggled to establish an organised supply chain in order to build the first prototype engine. He eventually achieved this and the first Whittle engine ran on 12th April 1937. It would not be long before the challenge that is 'the combustor' would become all too apparent. As Whittle recorded in his diary during the first run:

"Pilot jet successfully ignited at 2,000 r.p.m., speed raised to 2,000 r.p.m. by motor. I requested a further raising of speed to 2,500 r.p.m. and during this process I opened valve 'B' and the unit suddenly ran away. Probably started at about 2,300 and using only about 5 h.p. starting power…noted that return pipe jet was overheating badly. Flame tube red hot at inner radius; combustion very bad…"

Whittle noted later in that month, *"By the end of April it was very clear that we still have a long way to go on the combustion problem, and that the compressor was well below its design efficiency."*

The Whittle WU-1 engine **(figure 6)** had a single combustion can burning kerosene. The engine was built with a short shaft connecting the turbine to a centrifugal compressor,


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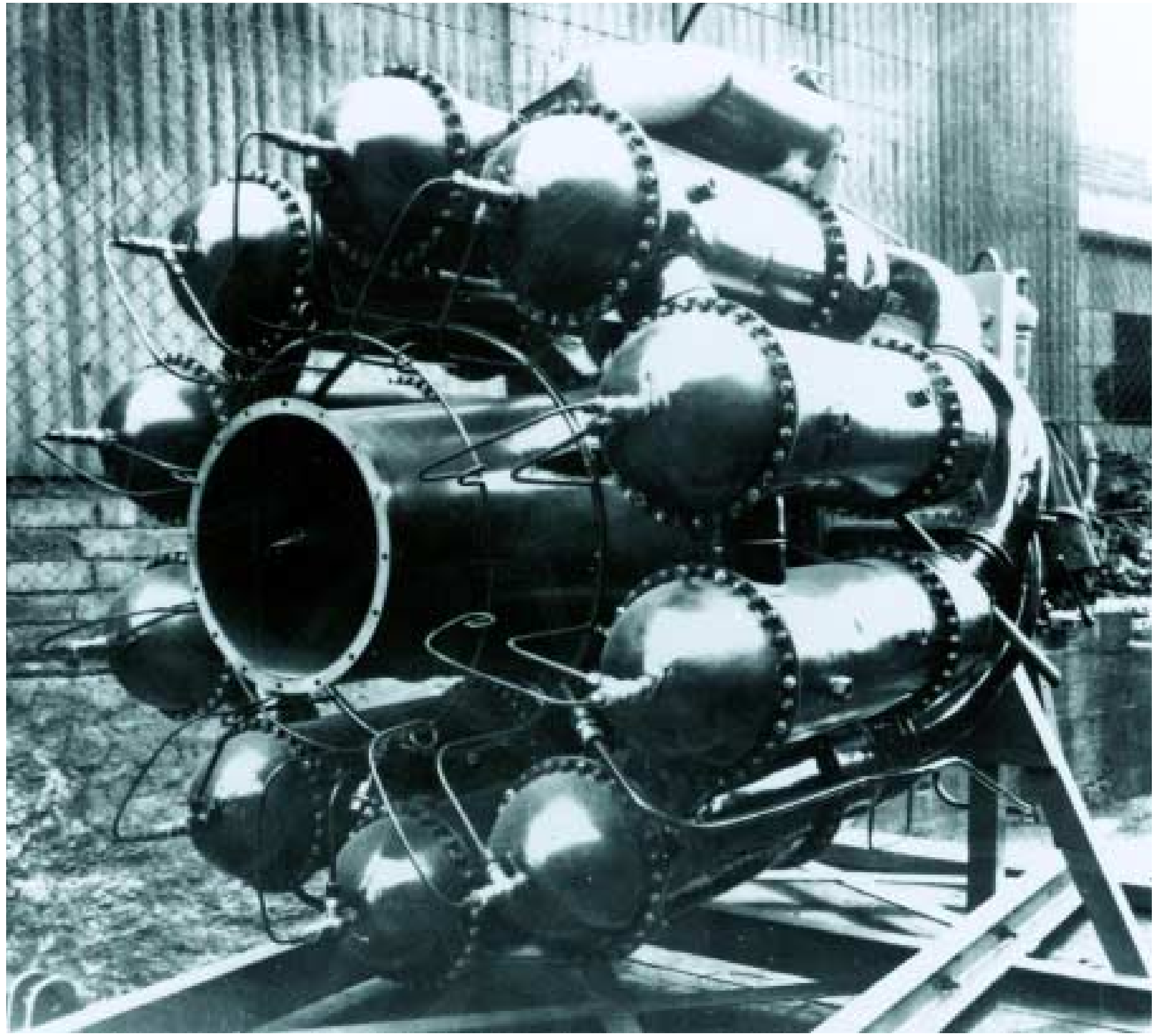
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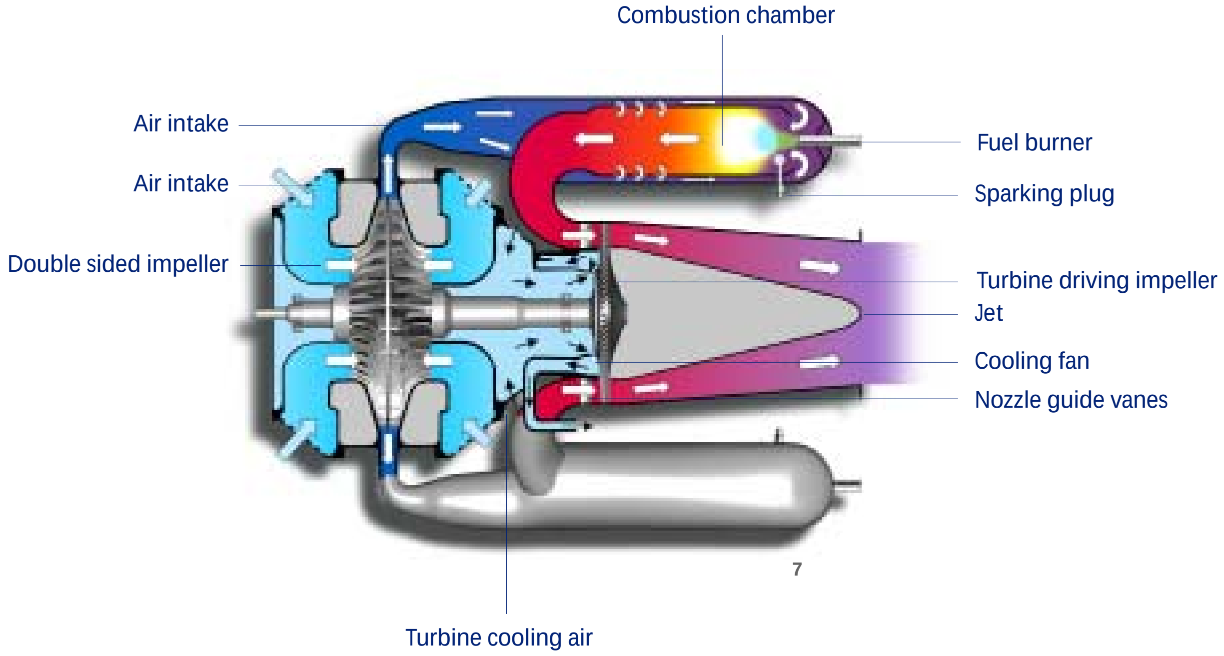
5 Whittle W1 engine
6 First version of the Whittle WU experimental engine

which was designed to minimise 'whirling' or vibration, which could occur at high speeds. It was this short shaft design, which defined the requirement for reverse flow through the combustor, complicating the manufacture and compromising its durability. A number of engine designs were tried but further combustor inadequacies once again caused a new concept, the U-3 version, to be built. It was the U-3 engine which introduced the distinctive shape of Whittle's later engines which so visually highlighted the magnitude of the combustor challenge. This combustor-dominated engine architecture can be observed on the W1, W2, Welland and Derwent engines. Ten separate combustion cans fed directly from the compressor diffuser. The counter flow of the combustion air was continued as a concept, as this provided a mechanism for cooling the outer surfaces of the combustion cans. The flow through the turbine was once again reversed, on this occasion towards the rear, leading into a single exhaust nozzle (as illustrated by **figure 7**). A major proportion of the testing of the U-3 engine was focussed on the combustion system and a significant number of design variations were tried in an attempt to move on from the low pressure fuel supply and vaporisation principal. A key step forward in combustion technology was made by Mr I Lubbock, of the Asiatic Petroleum Co. This was a 'shell' type combustor that atomised high pressure fuel, which was further developed on the U-3 and later utilised on the W.1 flight engine.

Combustion remained a problem through the demonstration runs of the W1 flight engine. Whittle experimented with thirty one different types of vaporiser, and experienced coking up of the tubes and further tribulations with regard to uneven temperature distribution. With the successful integration of the high pressure atomising nozzles came a design basis on which the later engines, W.2B, Welland, Derwent and more recent engines were founded. Past and current combustion developments have virtually eliminated emissions associated with smoke, un-burned hydrocarbons and carbon monoxide. However, NO_x formation remains a difficult problem because of high pressure and temperature conditions, which are needed for the optimisation of efficiency, fuel burn and CO_2 generation. Building on the success of the Trent combustion system, studies initially moved on to examining double annular, staged combustion, which delivers both high power and low power operation in two separate combustors. It came to light that additional cooling air requirements meant the benefits were not necessarily possible and a new approach is now being studied through the ANTLE (Affordable Near Term Low Emissions) project, a collaborative European Union programme led by Rolls-Royce. We are moving towards a lean burn, simple, low cost single annular system with fuel staging through a singular injector, which delivers a large volume of air, reducing peak temperatures during the burning process, thus significantly reducing NO_x **(figure 9)**. Advanced computational



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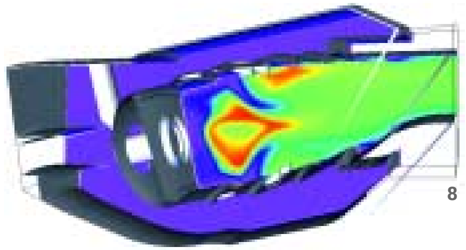

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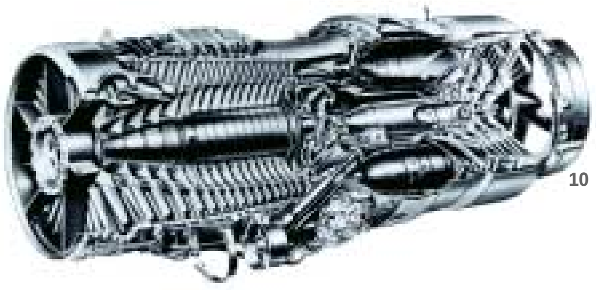
7 W.B 23 "Welland" engine
8 CFD analysis of Trent combustor
9 Comparison between ANTLE injector (left) and Trent injector (right)

fluid dynamics (CFD) analysis is currently being used to optimise the efficiency of combustors, accurately modelling the fuel-air mix and complex fluid flow through the combustion chamber **(figure 8)**. In the longer term the use of ceramics, or ceramic matrix composites (CMCs) offer the potential for significant temperature increases with minimal cooling, thus significantly reducing emissions.

Early jets and the challenge of compressors

At this point we shall move on to consider another fundamental challenge, also identified by both Sir Frank Whittle and Dr Griffith, 'compressors'. It takes only a cursory glance at a cut away picture of the Avon or the Conway engines (**figures 10 & 11** respectively) to understand that compressors were the dominating feature of early axial jets. Whittle's W1 first flight engine had a one stage centrifugal compressor and a pressure ratio of 3:1, the Conway has 17 compressor stages generating a pressure ratio of 15:1, and a modern Trent 900 engine achieves a pressure ratio of 42:1 with 15 compression stages. In 1945 Dr Griffith was finally given the chance to prove his original concept of the axial compressor with the launch of the AJ-65 (A for 'axial' J for 'jet'). During the war he had "openly scorned" all engines with centrifugal compressors, such as the Nene and the first Tay, regarding them as 'temporary stopgaps'. It was acknowledged at the time that an axial turbojet would deliver more thrust per frontal area, however, overcoming the significant technical challenges, both practically and commercially, was not going to be easy. The axial compressor was a step with which Sir Stanley Hooker was not altogether happy. He wrote later in his book, 'Not much of an Engineer' that he…*"hated moving into the unknown on what was obviously such an important innovation in the new field of turbine engines".*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From the AJ-65 developed the Avon engine, which would eventually power the Canberra and the Comet. The Conway engines powering the VC10 showed signs of in-service compressor inefficiencies, illustrating the complexity of the compressor problem and the level of understanding at that time. At the top of climb at max power the VC10's Conway engine LP compressors would sometimes surge, emitting an audible 'pop'. The pilot used to advise the passengers that there was no cause for concern; the engines were just 'clearing their throat!' In recent years the performance of multi-stage compressors in both civil and military engines has been and is being improved by using state-of-the-art CFD flow solvers and

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10 Rolls-Royce Avon engine
11 Rolls-Royce Conway engine
12 Conway powered Douglas DC-8

‘optimisers’ **(figure 14)**. By automating the design process, optimum designs can be achieved at minimum cost and time. Significant improvements have been observed in compressor technology; CFD analysis has yielded up to six times improvement in thermo-mechanical tip clearance optimisation, whilst pressure rise capability per stage (pressure ratio) has increased four fold over the last 40 years. Even today, compressor aerodynamic efficiency can be further improved. However, more significant improvements are likely to be realised through increased stage-loading to reduce parts-count, and the use of integrally bladed disks or ‘blisks’ to reduce weight. Materials in compressor technology have also moved a long way since the aluminium blades used in the Conway, towards monolithic titanium and nickel materials. In the future, titanium aluminide will offer further weight-saving. Titanium is an ideal compressor material in many respects. However, it is susceptible to fires when rubbing occurs at high temperatures. Research is well advanced to develop a non-burn titanium to counter this effect.

The RB211 and the challenge of the turbine

Having considered the issues associated with combustion and compressors we now look at another problem area, ‘the turbine’. Turbines have always provided numerous challenges to the aero gas turbine designer and remain an area where further developments including advances in component efficiencies, temperature capability and cooling air consumption are critical to improving the overall engine performance and efficiency. The best example of the challenge inherent within the turbine can be found by studying the development of the RB211 **(figure 13)**. The RB211 arose out of the requirement for high bypass ratio designs, resulting in smaller cores and higher turbine temperatures. These temperatures increased further on the early engine designs, industry wide, through poor performance and comparatively low component efficiencies. The first RB211-06 started design in mid-1967 and the engine ran at the end of August 1968. The engine was twice the diameter and thrust of the Conway, but 5ins shorter in length. It had a bypass ratio of 5:1 and turbine entry temperature some 150˚C higher. The first RB211-06 engine run had shown us that we had a lot of work to do on both performance and durability. The engine was removed from test due to high pressure (HP) nozzle guide vane bulging after a run to about 20,000lb thrust and a turbine temperature of 1400˚K. Late in 1968, John Bush, Rolls-Royce Engineering Director declared that we had to realise 40,000lb thrust by end March 1969 in order to demonstrate confidence in the engine. This was no mean feat, with an engine that lacked temperature capability and was deficient on performance; at one stage turbine blades were failing after only a few minutes running.

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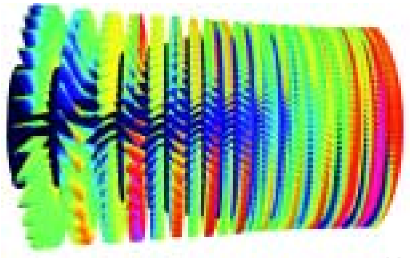

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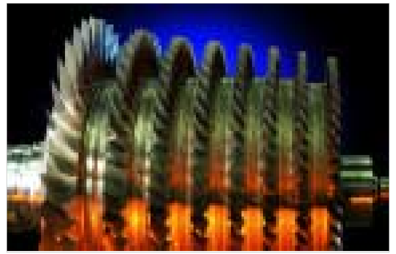

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13 Early version of RB211
14 CFD analysis of compressor module
15 Trent IP compressor module

The original RB211 turbine blade concept was based on the Conway extruded blade that went into service some ten years previously, operating at turbine entry temperatures in the region of 1250-1300˚K. We had not developed our technology further apart from minor changes in the Spey. The use of cast material had been rejected because of concerns about manufacturability, although the Americans were moving rapidly to cast materials. We were therefore left with no choice when the RB211 was launched but to use an extruded blade. Our technologists then embarked on a 'two piece' extruded blade design with complex internal cooling passages and trailing edge ejection. This had good performance, but when tested, had even worse cooling than the extruded blade, with additional concerns over bond integrity. We therefore pressed on with trying to improve the extruded blade on the RB211 - 22B and raised the life from 800 hours to about 3000 hours.

When the RB211-524 was launched, the turbine disc was redesigned to provide high-pressure air to the blade and a cast material was used needing to withstand turbine temperatures of 1500-1600˚K. The cooling configuration was similar to the RB211-22B, but the HP feed allowed it to be film-cooled much more effectively.

By 1977 we had developed new technology on the High Temperature Demonstration Unit (HTDU) test rig and launched a new directionally solidified cast blade with HP cooling air feed. It was designed and validated very thoroughly through carefully planned testing, ensuring that the design intent had been fully achieved. This blade was fitted to the RB211-535C, which had a common HP system with the RB211-22B and has given exceptional service performance on both engine types. Consequently, turbine developments for the RB211-524, and latterly the Trent family have moved towards more complex cooling through the core of the blade **(figure 16, 17 & 18)**, advanced single crystal material and rapid development in the use of Thermal Barrier Coatings (TBCs). The engineering success is highlighted by the fact that today's turbine blades are operating at temperatures over 1800˚K, whilst their base material only has a temperature capability up to approximately 1350˚K! Future advances in turbine blades will involve improvements in the TBCs with the further inclusion of heavy elements, resulting in better thermal properties **(figure 19)**. In the longer term, ceramics could find their way into turbines, offering increased temperature capabilities and reduced cooling requirements, providing the problem of fracture toughness can be overcome. Materials engineering will continue to play a major part in the development of the turbines of the future.


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16b


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16a HP turbine blade showing complex cooling system
16b Turbine blade dissolvable core
17 HP turbine blade
18 Sectioned HP turbine blade showing cooling passages
19 Shroudless HP turbine blade with Thermal Barrier Coating

The Pegasus and the challenge of systems design

In the 1940's, about the same time as the flight of the first jet aircraft (the Von Ohain/ Heinkel He178), Dr A.A. Griffith, Chief Scientist at Rolls-Royce was generating several creative ideas for future jet lift powered aircraft. As a consequence of this early work, Rolls-Royce commissioned the Jet Control Research Unit, commonly known as the 'Flying Bedstead' in the 1950's **(figure 20)**. With the requirement for STOVL (Short Take-Off Vertical Landing), came new challenges for the gas turbine engineer. Aircraft systems and the engine could no longer be considered as separate, there needed to be a fully integrated solution. The challenges of STOVL are two-fold: firstly there are challenges related to the jet engine systems; secondly, the system required for vertical take-off or landing, is completely different from the systems required for 'conventional' flight. These challenges are then compounded by the requirement for a system to enable the transition between the two modes of flight. In the 1960's the Pegasus 1 **(figure 21)** engine stood as the culmination of STOVL developments with 9,000lbf, a thrust to weight (T/W) ratio of 4.33, but a hovering life of only 30 minutes! Early challenges were clear, thrust growth was essential and the component life and reliability had to improve. Throughout the product development of the Pegasus engine several improvements were made including the increase of the T/W ratio to 5.6, which was comparable to engines for the Eagle, Tomcat, Super Hornet etc. Only in present times do we see military engines with superior dry (without re-heat) T/W ratios, namely the EJ200. As the drive towards affordability, reliability and maintainability became more influential in the defence sector, the Pegasus was bound to respond, culminating in the most recent engine, the 11-61, having 40% lower operating costs than the previous 11-21 engine. The 11-61 is rated at 23,800lbf and has hot end engine life of 1000hrs: a vast improvement upon the Pegasus 1 of the 1960's. The Pegasus development was not without a variety of engineering challenges, ranging from aircraft systems to the core engine itself. One such problem was due to the weight limits placed on the aircraft. The Pegasus had short, highly offset bifurcated inlet ducts. This meant that intake air is 'distorted' significantly causing a velocity and static pressure gradient at the fan, reducing efficiency and impacting on static thrust. A constant area duct was developed to counter this effect, which resulted in a static thrust improvement of 2.5%. Another significant technical challenge was that of Hot Gas Re-Ingestion. During a vertical landing the hot gases from the exhaust nozzles can be re-ingested into the engine, at best causing loss of performance, at worst causing the engine to surge. To solve this, external structures called Lift Improvement Devices were fitted deflecting the forward travelling hot gases so they do not reach the fan. The level of integration of the propulsion systems and the aircraft platform make the STOVL design an exciting engineering challenge and the Harrier the unique aircraft it is.


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20 Jet Control Research Unit 'The Flying Bedstead'
21 Rolls-Royce Pegasus engine
22 AV-8B Harrier

The next chapter in the STOVL story came in November 2001, when the US made the Joint Strike Fighter (JSF) the cornerstone of their future combat aircraft requirement, following a period of competitive studies and technology demonstration **(figure 26)**. The JSF will include the unique Rolls-Royce lift technology **(figure 25)** which is the culmination of years of experience, and maintains both Rolls-Royce and the UK position at the forefront of STOVL propulsion. The Rolls-Royce lift system comprises a LiftFan® mechanically driven from a conventional gas turbine supplying the forward vertical lift and a swivelling jet pipe, known as the 3 Bearing Swivel Module (3BSM), capable of re-directing the rear thrust from horizontal to the vertical plane. Aircraft roll control is achieved using thrust nozzles in the wings on extended ducts from the main engine. All of these systems work together automatically controlling the aircraft pitch, roll and yaw, enabling smooth transition between conventional flight and vertical hover and landing in a single controlled manoeuvre. This unique solution allows approximately 40,000lbf of thrust to be developed for vertical lift while only 30,000lbf thrust is required for normal flight. The LiftFan® incorporates a two stage, contra-rotating fan which uses Rolls-Royce proprietary linear-friction welded hollow blisks **(figure 23)**. Blisks or 'bladed disks' are just one of the key technologies utilised in the LiftFan® and enable a 30% weight saving. Blisks will eventually be replaced by 'Blings' **(figure 24)** which use MMC (metal matrix composites) offering up to a 70% weight saving. The bling or 'bladed ring' eliminates the bore of the conventional disk by using a fibre reinforced ring to carry the hoop stresses.


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The Trent engine and the challenge of the fan

It is clear that by looking at a modern day high-bypass engine such as the Trent 900 **(figure 27)**, the dominating feature is the fan, which delivers the vast majority of the thrust. The Trent 900, the latest addition to the Trent family, has been specifically designed to provide reliable and economical power for all variants of the Airbus A380 **(figure 28)**. It incorporates significant new technologies: notably, world-leading swept, hollow fan technology for reduced noise and damage resistance, ribbed titanium containment for reduced weight and cost, and a contra-rotating HP system further improving turbine efficiencies. Fan blade technology has developed considerably since the solid titanium narrow chord fan blades

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23 Blisk or 'bladed disk' technology
24 Bling or 'bladed ring' technology
25 Rolls-Royce LiftFan® and associated systems
26 Joint Strike Fighter 'X-35B' prototype aircraft

of the 1960's. By increasing the chord of the blade, made possible by low weight materials and manufacturing techniques, the need for mid-span support is removed, increasing efficiency by up to 4%. Another advantage of wide chord fan blades is that they are bigger and more robust, making them less susceptible to bird strikes and foreign object damage. With the freedom to design optimum fan blades through advanced flow modelling came the design for the 'swept fan'. The Rolls-Royce hollow titanium swept fan **(figure 29)** has a complex aerodynamic shape, made possible by world leading manufacturing technologies, namely DB/SPF (Diffusion Bonded / Super Plastically Formed). The swept fan further increases damage resistance to bird strikes by reducing the energy imparted to the blade, and centrifuges most debris away from the core of the engine and down the bypass duct. The shape of the blade also forces the airflow into the more efficient centre of the blade passage. By sweeping the blade the shockwave is more oblique to the flow, which significantly reduces the shock losses (by up to 50%). This reduction of shock through the swept design brings a significant fan noise reduction, critical for meeting future noise reduction targets. Further improvements in fan design will result from the detailed aerodynamic modelling of the entire flow regime from the free stream ahead of the intake to the exhaust nozzle, enabling the optimum fan design, including its inlet and outlet systems. The trend for high bypass ratio engines is set to continue and the hollow titanium swept fan blade will remain a key component. The future of fan blade manufacture is likely to bring complex fabrications of metal and composites, for reduced weight, reduced noise and improved aerodynamic efficiency, whilst maintaining the high levels of integrity delivered by the hollow titanium blades.

The large fans of today are subjected to rigorous testing: for example, Fan blade-off containment testing, where the energy generated by a released blade is equivalent to that required to throw a family car 200 ft into the air! The fan blades are tested to withstand the impact of an 8 lb bird whilst running at full speed and four $2^1/_2$ lb birds fired at 200 mph into running engines **(figure 31)**. Further to this the engines and fans have to be able to ingest 14,000 gallons/hour of water **(figure 33)** and 300,000 half-inch hailstones in 30 seconds, fired in at about 200 mph. Today, alongside these tests advanced 3D modelling is undertaken and correlates well with the practical test results **(figure 34)**. The future vision is to be able to replace all tests with simulated models, rather than physical test engines. The future challenge is in convincing ourselves that the dynamic modelling technique is a robust replacement for practical demonstration.

Rigorous testing programmes such as these contribute to improved engine reliability, which is one of the key considerations of our customers. Through conversations with Sir Frank Whittle the outstanding durability levels achieved by

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27 Rolls-Royce Trent 900
28 Airbus A380

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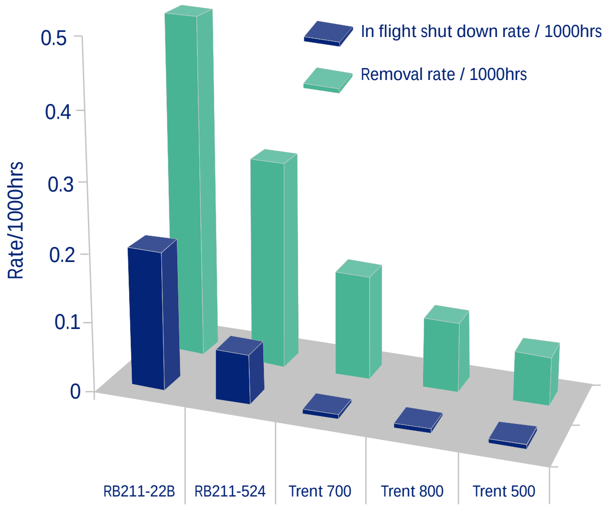

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29 Trent 900 swept fan
30 Rolls-Royce Trent 900 with its advanced, swept hollow fan blades

31 Bird strike testing
32 Improving reliability
33 Water ingestion testing
34 Advanced 3D computer modelling of bird strike testing

modern engines was something he never envisaged would occur. **Figure 32** illustrates how engine reliability has improved through the Rolls-Royce 3-shaft engine family.

Civil aerospace and the future environmental challenge

The longer-term drivers in the civil aerospace market will cause a number of 'step change' technologies to be developed to meet ever more stringent environmental and performance requirements. Sustainable growth means that meeting environmental targets will be the prime concern of aircraft and engine designers. The ACARE (Advisory Council for Aeronautic Research in Europe) goals **(figure 36)** include cutting by half the perceived average aircraft noise levels, reducing CO_2 by 50 per cent, reducing NO_x by 80 per cent and reducing accident rates by a factor of five, all by 2020. Of these targets, CO_2 reduction is by far the most challenging and will require step changes in aircraft design, engine design and air traffic management. When considering these targets and the fact that 50 per cent of the world's aviation fuel is currently used on journeys of less than 1200 nautical miles, two distinct markets emerge; short haul and long haul. Short haul flight is optimised around economics, convenience and comfort, not fuel burn. For these journeys, switching to slower, conventionally shaped aircraft with up to 250 seats, high bypass and pressure ratio engines with high efficiency components, is likely. Aircraft could become larger and operate less frequently. An immediate benefit of 15% CO_2 reduction could come from an improvement in air-traffic management. However, for long haul markets, the drive to maintain current speeds will force novel aircraft designs such as the blended wing body (BWB) aircraft **(figure 35)**. The blended wing offers benefits due to its reduced wetted area and friction drag. However, it poses significant engineering challenges driven by its large size, unique aerodynamic control requirements and passenger perception. The engines also will require a step change in technology towards ultra-high bypass engines. For example the 'Aft' fan (where it is impossible to ignore the resemblance to Dr A.A.Griffith's axial contra-rotation concept described earlier) and the 'Driven fan' concepts **(figures 38 & 39)**. These engines would ideally be located on top of or embodied within the airframe to further minimise the perceived noise levels from the ground. A number of noise reduction programmes are currently underway and have established themselves as key tools for driving down the future noise levels. Examples of these programmes include the Quiet Technology Demonstrator (QTD), which is one of the most comprehensive test programmes ever undertaken to reduce engine noise levels and was the culmination of a year of collaboration between Rolls-Royce and Boeing. Another is the SILENCE(R) (Significantly Lower aircraft Environmental Noise Community ExposuRe). The partners in this project


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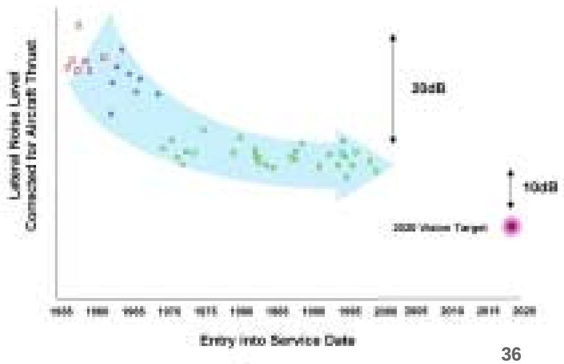

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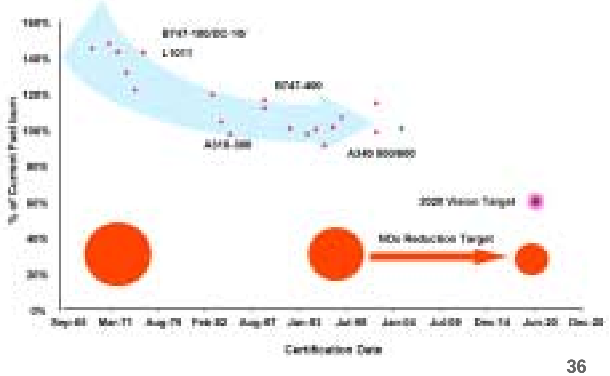

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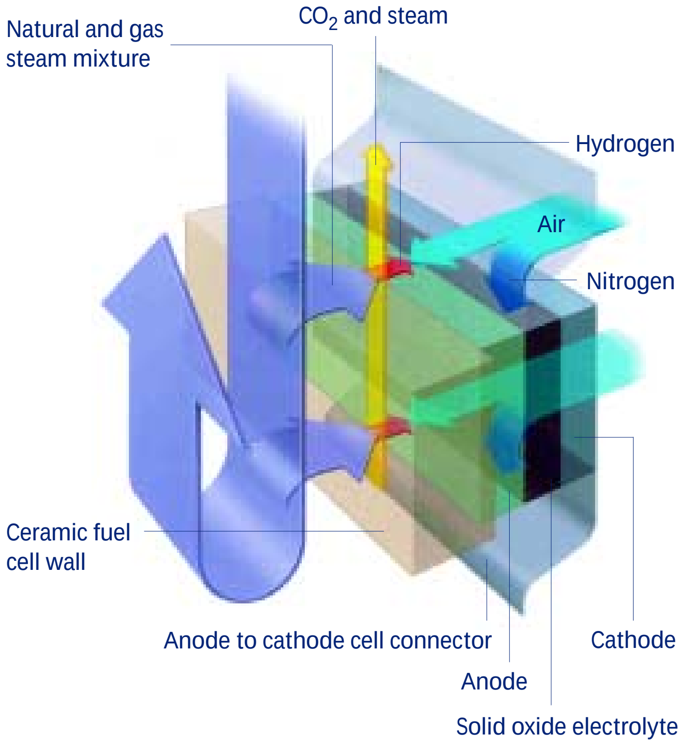
35 Blended Wing Body concept
36 ACARE Targets

include Rolls-Royce, Airbus, MTU, SNECMA, ITP, Shorts, Hurel-Hispano along with a number of European research establishments and universities.

The question of advanced cycles will certainly be addressed in the medium and longer term, noting the civil aerospace drive for engine efficiency. It is increasingly difficult to develop more fuel-efficient, simple-cycle gas turbine engines. Alternative cycles offer significant potential for performance improvement in the region of 5% - 20%. Further to this, increases in cycle temperatures make it increasingly difficult to improve NO_x emissions to meet the ever-tightening emissions targets. As discussed, these future environmental and performance targets will only be achievable through technology step-changes.

Recuperators, regenerators and intercoolers are the three basic types of gas-turbine heat exchanger cycles used for industrial and marine gas turbines. While they have been considered for aero applications, there is currently no engine in production where they have been employed, due to weight and reliability considerations. Recuperators and regenerators transfer waste heat from the engine exhaust to compressor delivery. The heat transfer increases combustor inlet temperature and hence reduces the fuel required to achieve a given turbine entry temperature. Intercoolers are used to remove heat between compressors, reducing inlet temperature to the second compressor. Work input required to raise a given pressure ratio for the second compressor is reduced proportionally to the inlet temperature. Recuperators and regenerators improve thermal efficiency, while providing a small loss in specific power due to the additional pressure losses. Conversely, intercoolers improve specific power but, except at the highest pressure ratios, deteriorate thermal efficiency. A heat-exchanged and intercooled cycle improves both thermal efficiency and specific power, resulting in improved specific fuel consumption (SFC) at all thrusts and added potential for NO_x reduction. It is this cycle on which the Rolls-Royce WR-21, the world's most advanced marine gas turbine engine, is based **(figure 40)**. The intercooled and recuperated engine does, however, hold a significant weight penalty that would have to be addressed for the cycle to become feasible for aerospace propulsion systems. A major future challenge is to produce lightweight, smaller and efficient heat exchangers, which will only come from radically new materials and construction.

The subject of alternative fuels is an obvious one for the future, with the recognition that fossil fuel reserves are in decline. Several proposals have been made to use liquid hydrogen as a fuel for aircraft. Liquid hydrogen (LH_2) is 2.8 times lighter, but with a volume 4 times greater than Kerosene and the storage temperature is considerably colder at –253˚C. Both the increased volume and the LH_2 storage temperature brings severe airframe integration and infrastructure



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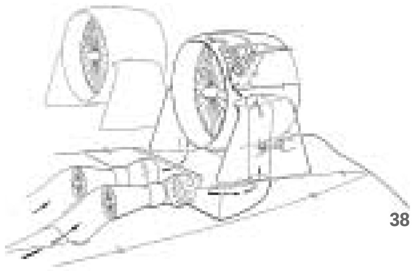

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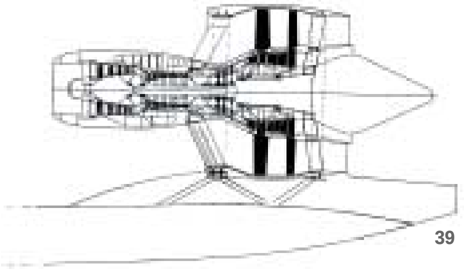

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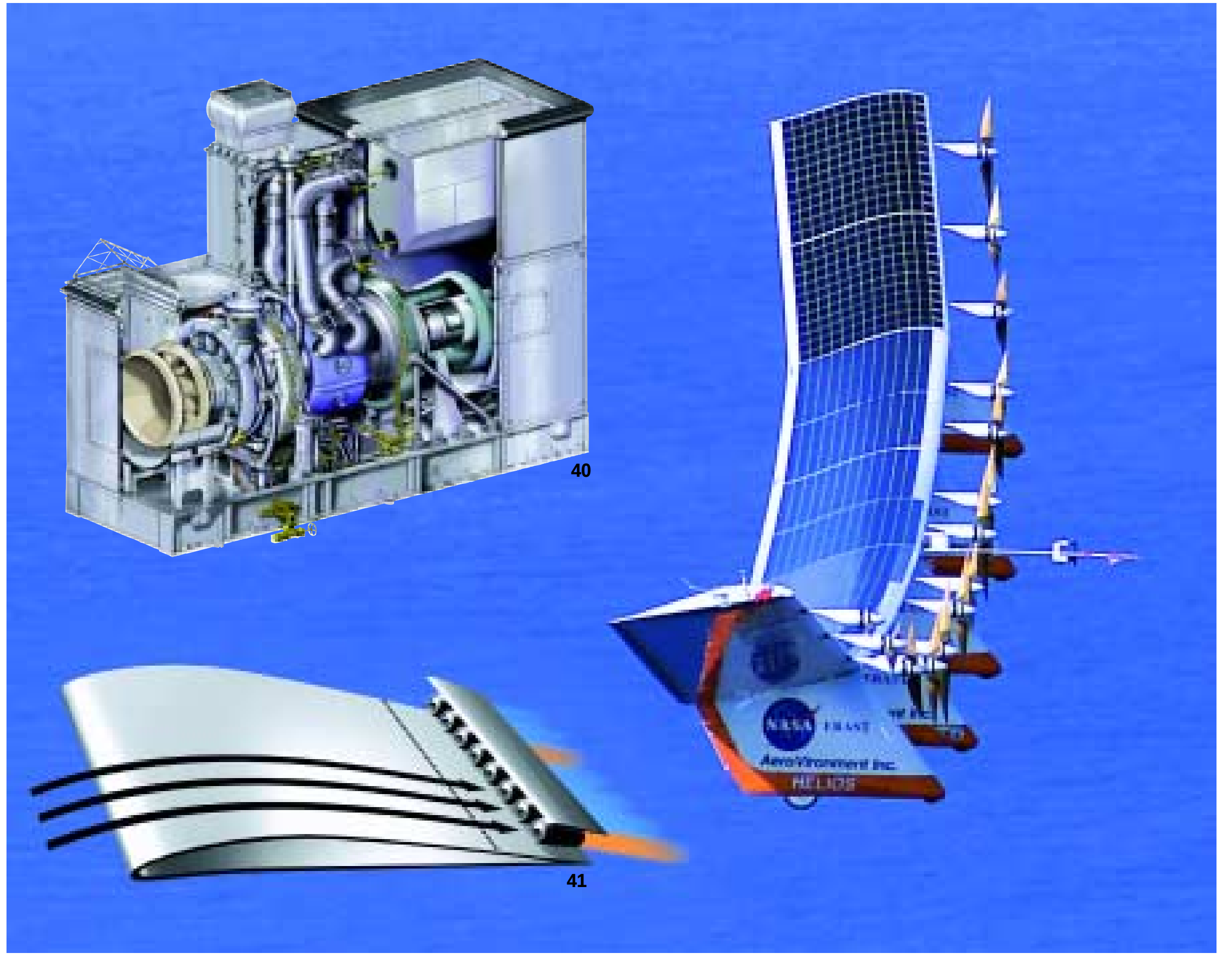
37 Fuel cell technology
38 Driven fan concept
39 Aft fan concept

difficulties, where storage of the fuel is likely to be no longer in the wings of an aircraft, but rather in large bulky storage tanks in an oversized fuselage. The key advantage of the use of LH_2 is the absence of CO_2 emissions. However, 2.5 times more H_20 is produced as a by-product. The effect of water vapour at altitude is currently not fully understood, and is just one of the major questions over the use of hydrogen in aerospace applications. Other challenges are the scale of investment that would be required in a worldwide hydrogen infrastructure, along with the question, will the regulating authorities and the travelling public accept hydrogen as an option?

Looking further ahead we can envisage even bigger challenges. One could imagine different ways of producing the power for aircraft from the burning of hydrocarbons or hydrogen and different systems other than the fan being coupled directly to the power source, so the propulsion and power systems are separated. An extreme example of this concept that has actually flown is the NASA Helios prototype flying wing **(figure 42)**. Here the power is obtained using advanced photovoltaic cells and the sun's energy, this is converted to electrical power and delivered to electric motors, which drive propellers. The Helios was designed as a communications platform. However, we need to carry passengers day and night meaning other power sources in addition to photovoltaic cells would be required, as energy storage devices are unlikely to be developed which are any better than hydrocarbons. A more likely NASA concept is the Mini-engines concept **(figure 41)** where high efficiency cores power multiple fans. This uses gas turbines to provide a number of propulsive jets through ducts, which are particularly efficient aerodynamically because they increase lift and fill the aircraft trailing edge wake. Another version of this idea, which Rolls-Royce particularly likes being in the gas turbine business, involves twenty or more gas turbines along the trailing edge of the aircraft!

A number of sources of power have been proposed where in each case electric power would be produced by one or more central power sources and this would be transmitted to electric motors to drive propellers or fans. While beamed energy, laser propulsion and nuclear fusion seem extremely unlikely, an advanced cycle gas turbine or a fuel cell remains a possibility in the long term.

Fuel cells produce electricity directly from a chemical reaction. Rolls-Royce is developing a solid oxide fuel cell **(figure 37)** which is potentially very efficient through being pressurised by a turbine system and operating at higher temperatures. The initial market is distributed power generation at the 1MW size. However, if there were major advances in ceramic materials and miniaturisation, which can be conceived, then such fuel cells could be envisaged as power sources for aircraft. Such concepts also require orders of magnitude improvement in the power density of electric



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40 Rolls-Royce WR-21 the world's most advanced marine gas turbine
41 NASA Mini-engines concept: High-efficiency cores powering multiple fans
42 NASA Helios prototype electrically powered flying wing

systems. Many interesting engineering challenges can be foreseen in this technology sector.

Future defence aerospace - the challenges of affordability and once again combustion

In the longer term the defence market could split into manned aircraft (such as the Eurofighter Typhoon and Joint Strike Fighter) and unmanned vehicles such as the Global Hawk and future UCAV (Uninhabited Combat Air Vehicle) and UCAR (Unmanned Combat Armed Rotorcraft), with further significant growth most likely in the unmanned sector **(figures 43 and 46)**. The focus on affordability and versatility will drive technologies which can be applied across multiple applications, where dual use technologies will be essential. The general trend towards high Mach number, long range, performance and reliability will drive the developments of multiple use technologies and versatile cores, which are consistent with the US VAATE (Versatile Affordable Advanced Turbine Engine) and the UK FOAS (Future Offensive Air System) programmes. New challenges in the unmanned sector are likely to include advances in prognostic and diagnostic techniques, which are required for autonomous operation, leading to a more 'intelligent engine'. The high temperatures experienced by high Mach number engines, create for engineers new problems regarding acceptable 'hot end' life and reliability. These high Mach numbers and high specific thrusts must be achieved through 'dry engines' i.e. without re-heat/after burn, to reduce the infrared signatures, which compromise aircraft stealth.

Great benefit is envisaged through incorporating 'more- electric' technologies across both the defence and civil sectors, driven by the need for increased functionality, reliability, lower weight and cost, whilst replacing mechanical complexity with more 'elegant' electrical solutions. The More Electric Engine follows on directly from current technology demonstrator programmes such as POA (Power Optimised Aircraft). The replacement of the aircraft Environmental Control System could lead to improvements in fuel burn, while eliminating potential cabin air quality problems. The replacement of the lubrication systems, with oil-less, active magnetic bearings would ultimately lead to the deletion of the entire oil system. A generator, mounted directly on the fan shaft, would deliver power to the airframe systems and all flight control actuators would be electric. There is a requirement to develop a number of critical technologies before these enhancements are practicable: temperature capabilities of electric and magnetic materials, low weight designs, insulation technologies, permanent magnet materials and advanced power electronics. Super-conducting motors and switching devices may eventually be developed to open new applications of electric technologies to aerospace. These areas are currently being addressed through the extensive Rolls-Royce research base.

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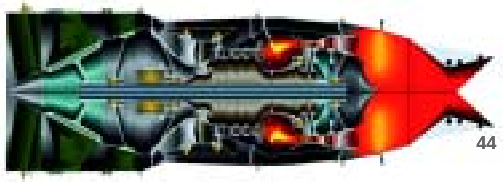

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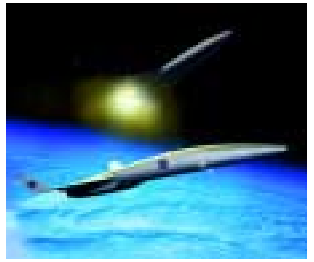

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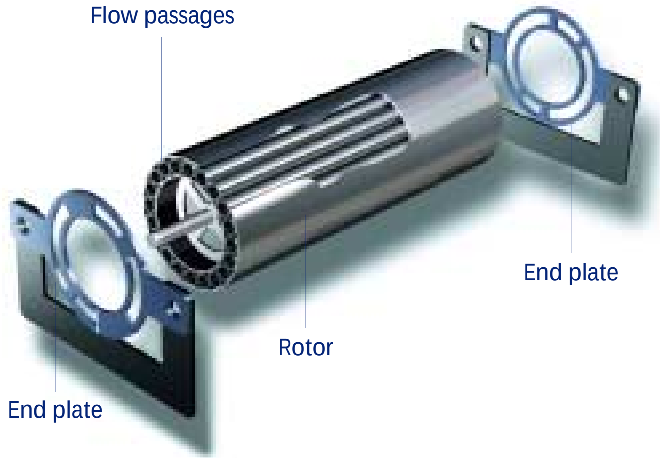

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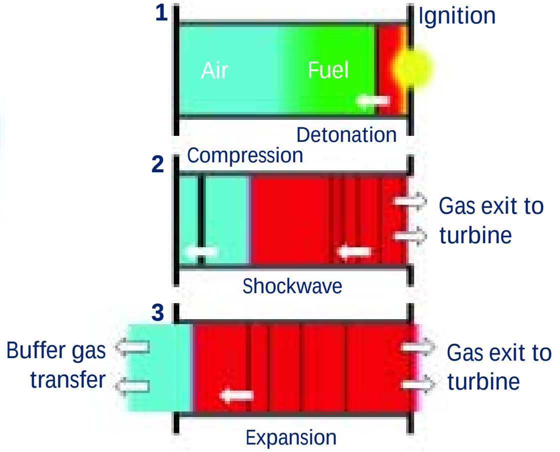

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43 Future defence programmes (unmanned), from left *(Reconnnaissance, UCAV, UCAR and 2^{nd} generation UCAV)*
44 Future defence aero engine concept
45 Space access concept
46 Future defence programmes (manned), reconnaissance / strike
47a Wave Rotor concept
47b Simplified Pulse Detonation cycle

One example of a radically different approach to gas-turbine propulsion technology is the Constant Volume Combustion (CVC) engine, which incorporates Wave Rotor technology with Pulse Detonation Engine (PDE) technology **(Figures 47a & 47b)**. Wave Rotor technology has advanced through the support of NASA and AFRL (Air Force Research Laboratory) funded programmes since 1990, and recent worldwide PDE research has contributed technological advancements in detonative combustion. The concept behind PDE is a simple one. However, major technical challenges remain to make the concept a viable and practical solution. It consists of a tube, closed at one end, which is filled by a mixture of gas and air. A spark ignites the fuel at the closed end and a shock wave propagates down the tube at close to five times the speed of sound. This shock wave compresses and ignites the fuel and air mixture almost instantaneously in the narrow, high-pressure zone. Dozens of these explosions are required per second to produce a useful amount of thrust. The CVC has a broad applicability including a pressure-gain combustor for gas turbines or a stand-alone high-Mach engine. For a conventional gas turbine it is estimated to deliver 5% improvement in SFC for highly advanced engines and 10-14% gains for conventional technology engines. CVC could also deliver a competitive advantage for long-haul, high by-pass fan engines and potential low cost high-Mach engines. However, significant technological hurdles remain: for example, more advanced transient gas dynamic modelling, advances in fuel introduction, advanced high-temperature sealing systems, heat transfer effects and high pressure experiments to establish the ability to initiate the required combustion detonations.

Summary

A gas turbine is a heat engine, which gets its power from chemical energy. To do this efficiently it needs a compression system to compress air with a turbine to drive it. To add value it must then be applied to a useable platform leading to ever more complex systems and configurations. Compression, turbines and systems have been and will continue to be significant engineering challenges. Gas turbine technology will be driven towards ways of reducing emissions and noise for civil aerospace, or affordable high-Mach and unmanned propulsion in defence aerospace. Both of these emphasising that the chemical process of producing energy whether it combustion or otherwise will be a continuing engineering challenge into the future. Due to its inherent power density, efficiency and adaptability, the gas turbine and its technologies will continue to play a dominant role in aerospace, bringing with it massive new challenges and exciting opportunities for the engineers of the future.

Dr Mike Howse OBE FREng FRAes FIMechE CEng CPhys FInstP PhD

Director - Engineering and Technology – Rolls-Royce plc

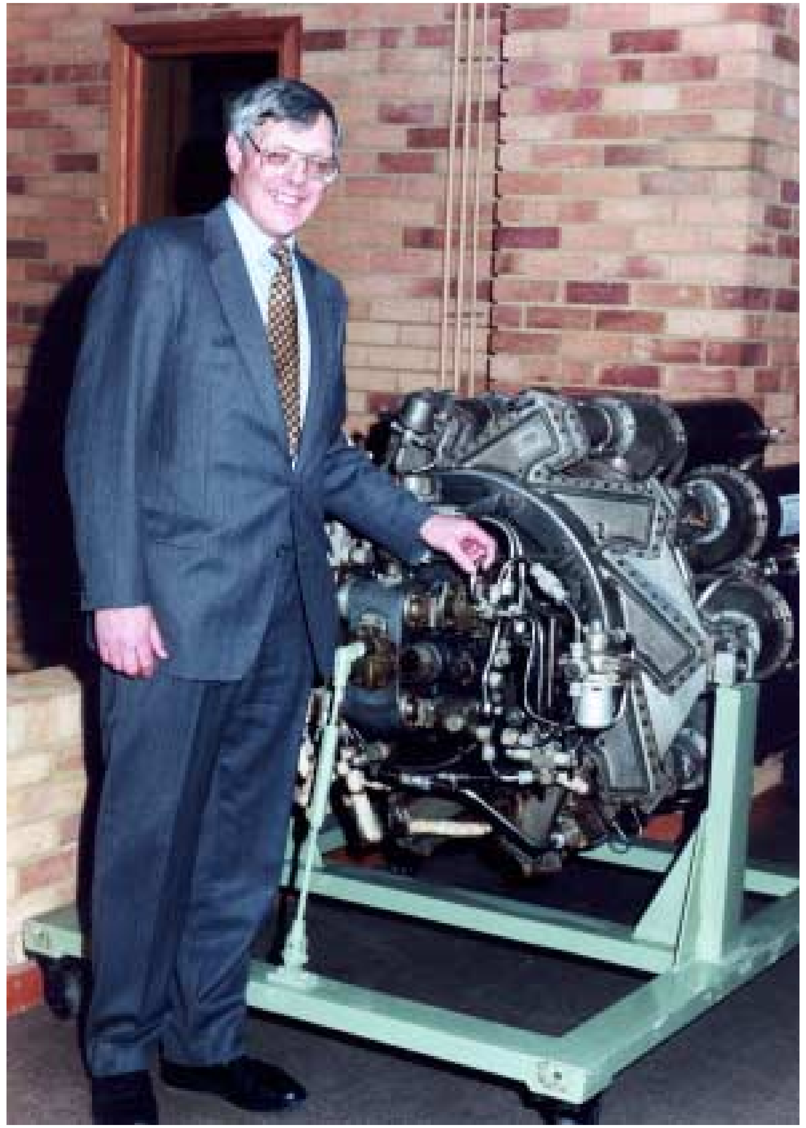
Mike was appointed to the Board of Rolls-Royce plc as Director - Engineering & Technology on 18 October 2001 after more than 30 years in various engineering and technology roles for the Company.

In his early years in Rolls-Royce he worked in Research and Development. Mike carried out research on materials, aero-elasticity and other technologies before joining the RB211 project team in 1981. He was RB211 Chief Engineer in 1984 responsible for the introduction of the RB211-524G into service on the Boeing 747-400 and the RB211-524H for the Boeing 767. He led the concept design work for the Trent engine.

In 1989 he was appointed Head of Advanced Engineering, responsible for the research and demonstrator programmes for both civil and military engines, becoming Director of Engineering for the Military Engine Group in 1991, based in Bristol, responsible for all Rolls-Royce military engine activity including the EJ200 for the Eurofighter, the Pegasus on the AV-8B and future STOVL engine technologies.

In 1995 he became Director of Engineering – Airlines and later Director of Engineering - Civil Aerospace overseeing the wide range of in-service engines and the introduction of the new Trent engine and other variants.

He is a Chartered Engineer, a Visiting Professor at Cranfield University, a Board Member of The Engineering and Technology Board (ETB) and a Fellow of The Royal Academy of Engineering, The Royal Aeronautical Society, The Institution of Mechanical Engineers and The Institute of Physics. He was awarded the OBE in the Queen's Millennium New Year's honours list for services to aerospace and the Royal Aeronautical Society Gold Medal in 2003.



Dr Mike Howse

Sir Frank Whittle OM KBE CB Comdr US Legion of Merit FRS FEng MA

Sir Frank was born in 1907 and educated at Leamington College, RAF Cranwell and Cambridge University. He was an apprentice and flight cadet at Cranwell from 1923 to 1928 and then became a fighter pilot, instructor and test pilot. At Peterhouse, Cambridge, he gained a first-class MA degree in mechanical sciences and spent a postgraduate year on the design of his first jet engine. Between 1937 and 1946 he was seconded to Power Jets Limited for work on the design and development of jet engines.

Sir Frank retired from the RAF in 1948 and was a technical advisor to BOAC on jet aircraft, 1948-52; with the Shell Group, 1953-57; and consultant to Bristol Siddeley/Rolls-Royce on a turbodrill project, 1961-70. He was awarded many prizes, honorary degrees and distinctions by universities and professional and learned institutions for his pioneering work on gas turbines. Whittle was appointed CBE in 1944, CB in 1947, and KBE in 1948. He was made a Commander of the US Legion of Merit in 1946 and was knighted in 1976, going to work in the USA shortly afterwards. The following year he became a research professor at the U.S. Naval Academy, Annapolis, Maryland. In 1986 he was appointed a member of the Order of Merit and was a Fellow of the Royal Society, and of the Royal Aeronautical Society.

After a long battle fighting cancer, Sir Frank Whittle died on 8th August 1996 at his home in Maryland, USA.

Sir Frank Whittle

Acknowledgements

I would like to thank Richard Haigh of the Rolls-Royce Heritage Trust for help in researching the lecture and Tony Bell who has helped with writing the text and with the illustrations.

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The Rolls-Royce Heritage Trust and Rolls-Royce plc Image Resource department have provided many of the photographs and images.

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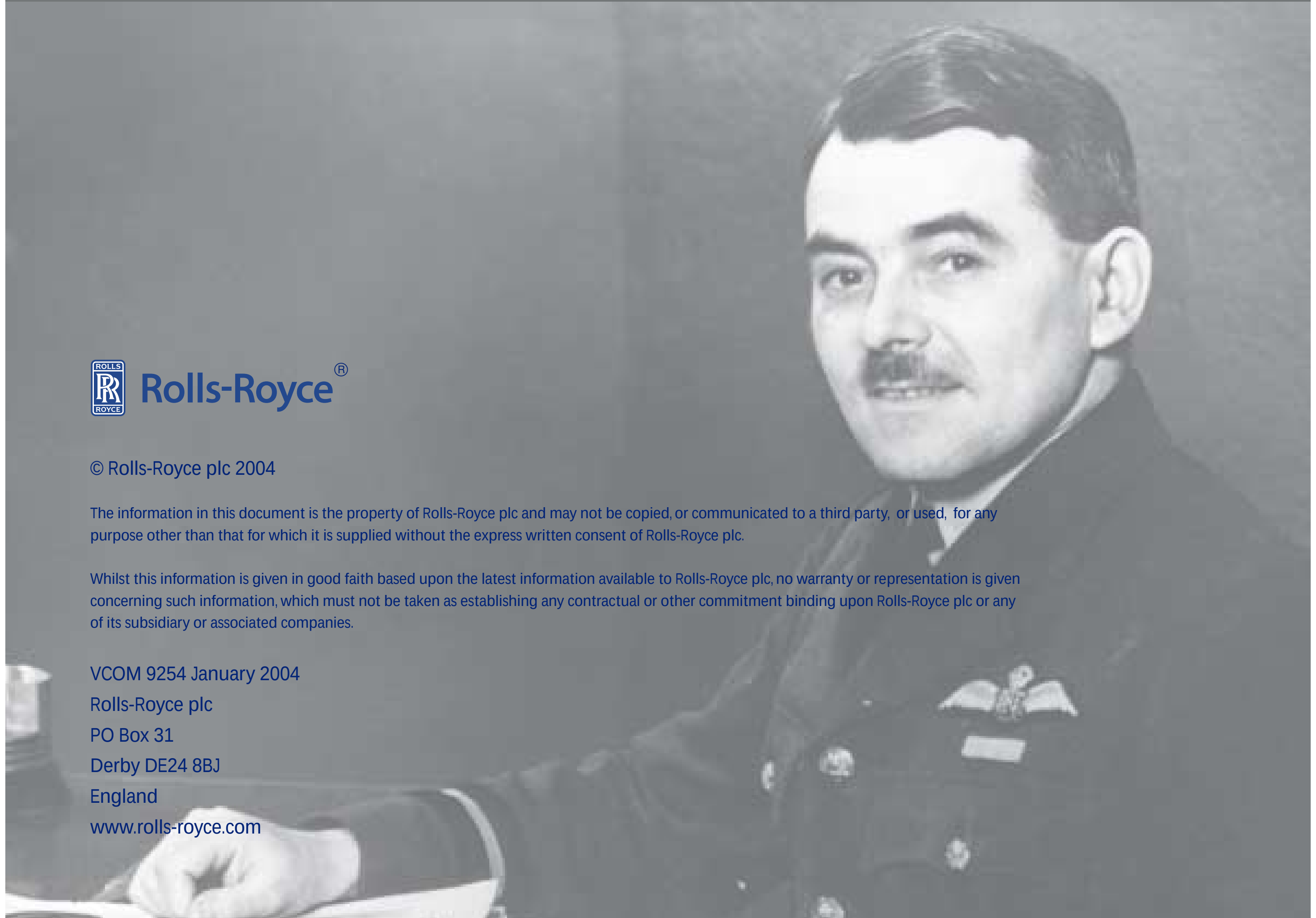
> "The invention was nothing.
> The achievement was making the thing work"
>
> Sir Frank Whittle



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