THIRD GENERATION TURBO FANS ICAS-82-4.5.1

J.F. Coplin
Director of Technology
Rolls-Royce Limited
Derby, England

Abstract

This paper describes the fuel-efficient RB211-535E4 third generation turbo fan. Competitive fuel efficiency is obtained with a derivative engine through improved component efficiency. The change has been concentrated in modules where the scope for advancement is a maximum, whilst minimising the consequential changes with their attendant risks and high costs. The theme is one of improving component efficiency through a progressively deeper understanding of the loss-making processes. Good theoretical design procedures are backed by very accurate and perceptive instrumentation to study the aerodynamic processes at the physical phenomena level. The scope for further progress in fuel efficiency is indicated.

1. Introduction

The conceptual design of the three-shaft RB211 has served us well. Without gimmick or undue fussiness in the detailed design, it has established leadership in fuel efficiency both as a new engine and in terms of fuel efficiency retention. Its modular concept has facilitated development and contributed to a fully competitive level of operating costs. Progressive improvement in fuel efficiency has been made with successive members of the RB211 family by improving component efficiency and moving towards the higher optimum pressure, bypass and temperature ratios that this encourages, in order to obtain cummulative gains from cycle to magnify the basic gain from component efficiency.

In 1977, Boeing, with prospective launch customers, sought an engine for their new fuel-efficient, short-range, twin Boeing 757 aircraft. All around us judged that such an aircraft required a relatively conservative derivative engine of generous core size to maximise the safety and certainty of the aircraft engine combination performing well from its inception into service. As is well known, the Boeing 757 first flew with the RB211-535C derivative engine and will enter service with British Airways and Eastern in 1983. However, competition and the economic pressures for the best possible fuel efficiency caused us to look again at how this might best be done. We concluded that our best course, and the one which gives a thoroughly competitive engine, was to stick with the derivative and improve component efficiency and cycle further still while retaining the greater certainty of the derivative engine. A further version of the RB211-535, known as the E4 engine, was thus conceived, as shown in fig. 1.

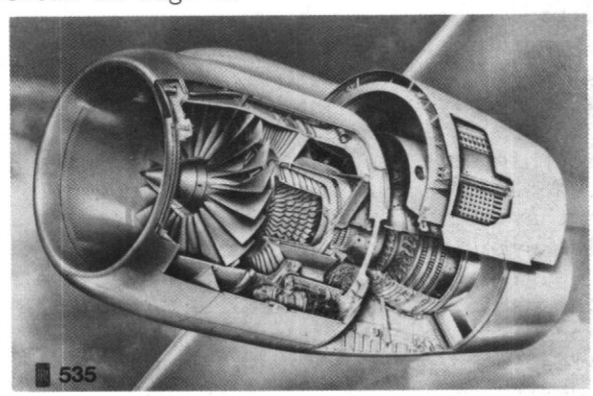


Fig. 1 ¾ Cutaway of RB211-535E4

In any design process, even with the most modest change, there are risks. The derivative approach on a modular engine makes it possible to confine the changes to modules where there is a real benefit, where the risks are worth taking and where really thorough demonstration and certification programmes are economically justified. Consequential change, with its parasitic burden of risk, is minimised.

A major characteristic of our programmes is the use of a component efficiency improvement to provide the economic reward for change. Having made the change, weight saving, cost reduction, maintenance and other improvements are then incorporated to the level of the best substantiated technology, in order to maximise the worth of the change to our customers and to ourselves.

There is always a suspicion that a derivative is a compromise and that it implies minimum scope for further improvement. Unfortunately, there have been examples, in the past, which tend to support the point. However, this is not true in the case of the RB211-535E4, where we have identified additional improvements which are at least as large as those to be found at the start of any new engine. Moreover, through the lower risk of the derivative engine, such improvements are less likely to be eaten up in meeting the basic specification or substituting for new features which have failed to contribute the advantage planned for them or which encounter other severe difficulties and cause them to be removed from the specification.

The RB211-535E4 is a third generation fuel-efficient turbo fan and features some of the most advanced technology. This paper describes some of its more important aspects and, in particular, those which contribute to its competitive level of fuel efficiency. Also shown are some of the items in our Advanced Engineering programme which are being prepared thoroughly prior to commitment into subsequent improved versions of this engine and other members of the RB211 family. Rolls-Royce has had many firsts in the aero-engine field and this experience has taught us to be very careful and very thorough in preparation prior to the service introduction of new technology and new designs. The tools for this extra thoroughness are now better than ever before and I want to illustrate some of them in this paper.

2. Component Efficiency - Cycle Relationship

By far the most important, single parameter in driving towards yet higher fuel efficiency is component efficiency. Without the right very high levels of component efficiency there is no hope whatsoever of being competitive. However, higher component efficiencies require higher pressure, bypass and temperature ratios to maximise the gain. Fig. 2 shows the trend in optimum pressure ratio for an extreme case. Indeed, raising component efficiency alone causes some disadvantages at constant thrust which partially reduce the benefit. The engine

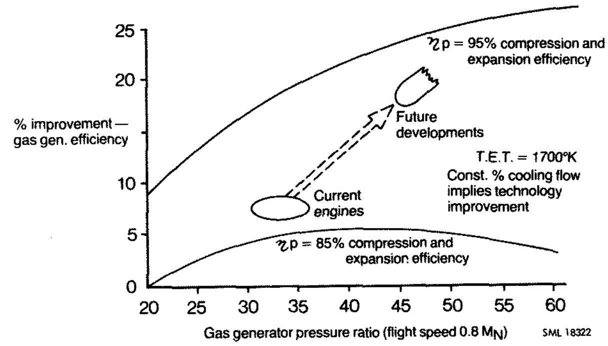


Fig. 2 Component Efficiency Effect on Optimum Cycle Pressure Ratio

cools off, thus reducing temperature ratio. Reducing the turbine cooling air does not fully compensate. The higher optimum pressure ratios and bypass ratios require a higher optimum peak cycle temperature which can only be reached efficiently by working to higher turbine metal temperatures and improved turbine cooling efficiency. Increased turbine blade speed contributes through reducing blade relative gas temperature and this requires advances in turbine blade and disc material strength. The higher bypass ratio emphasizes high specific flow through the use of low hub/tip ratio and high specific flow per unit flow area, in order to minimise offsetting drag and installation penalties, and drives us in the direction of the unclappered,hollow, wide chord fan of 0.3 hub/tip ratio. Fig. 3 shows the effects of hub/tip ratio and specific flow on bypass ratio at a given fan diameter.

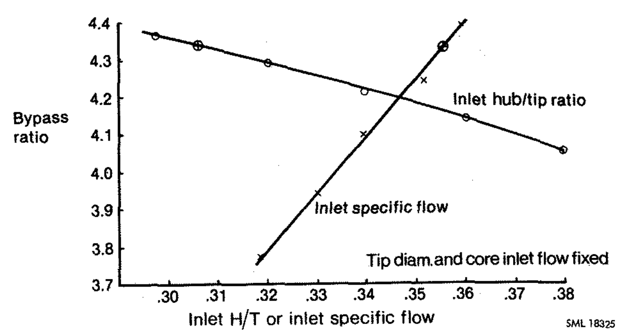
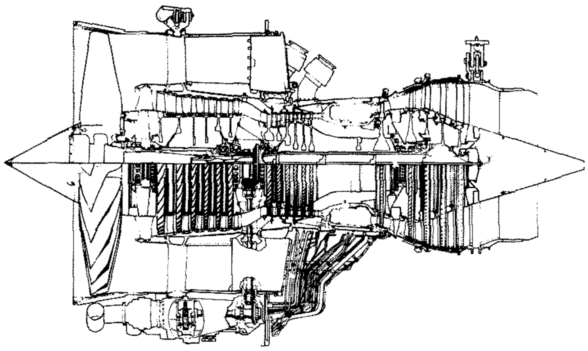


Fig. 3 Change of Bypass Ratio with Inlet Hub/Tip or Specific Flow

3. Cycle

Fig. 4 shows a cross-sectional drawing of the RB211-535E4, while fig. 5 gives its leading cycle particulars. There is



ETG 28391V ISSUE 1

Fig. 4 RB211-535E4 General Arrangement

Leading performance data

Max Cruise	**0.8 Mn**	**35 000ft**
Pressure	Ratio	29
Bypass	Ratio	4.2
Stator	Outlet temp °K	1323

SML 18513

Fig. 5 RB211-535E4

no doubt that had we been pursuing only uninstalled fuel efficiency, we would have chosen a cycle having a slightly higher bypass ratio. At constant component efficiency we might have gained a very worthwhile improvement in specific fuel consumption. However, it would have increased the turbine entry temperature by about $100^{\circ}C$ and substantially increased our dependence upon new technology which is inadequately prepared at this time for service in a very short-range operation, where the engine is subjected to many severe thermal and stress cycles within a normal service life. Moreover, we were able to show that the very compact three-shaft engine could produce a good installation of low drag and accommodate a simple annular mixer which improved the fuel efficiency and cooled off the engine still further in climb. With these advantages, combined with very good component efficiencies through the use of less critical high technology, we found we were able to make a thoroughly competitive level of fuel efficiency without making the engine critically dependent upon high temperature technology which still needs further development and understanding.

For the future our advanced engineering plans cater for the exploitation of the considerable potential of single crystal blade materials, powder disc alloys and thermal barrier coatings, both as direct benefits and magnified through the reduction of effective core size.

4. Component Efficiency - Basic Research

Major strides in component efficiency have been made, particularly on the fan, high pressure compressor, high pressure turbine and intermediate pressure turbine. Less marked, but none the less important, improvements have been made elsewhere.

The basic approach in every case has been one of developing the best possible theoretical design procedure to describe the loss-making process at the physical phenomena level. Perceptive and accurate instrumentation has then been used to observe the physical phenomena as directly and non-intrusively as possible, in order to assess the degree of completeness of understanding. For aerodynamic processes, laser holography and anemometry are especially powerful and have quickened the pace of progress by making it far more scientific and direct than hitherto. Of course, not all losses are purely aerodynamic, and other techniques have been used to measure and explain them.

The theme is one of increasing the understanding at the physical phenomena level to enable fast and scientifically based progress to proceed.

5. Laser Holography and Anemometry - Techniques for Observing and Measuring Aerodynamic Flow

Two complementary optical techniques, holography and laser anemometry, have been used to investigate three-dimensional flow within blade rows of rotating turbomachinery. Holographic interferometry records the density distribution within the flow, and has been used in two-dimensional cascades to provide quantitative measurements of the density field (Reference 1). For three-dimensional flow within blade rows it has been used to show the positions of major flow features such as shocks, vortices, wakes, overtip leakage and boundary layers (Reference 2). Because holography provides a complete three-dimensional visualization of the blade passage at an instant of time, it is possible to look qualitatively at the main features of the flow for a wide range of engine conditions in only a few hours of testing. In contrast, laser anemometry provides quantitative measurements of the flow velocity at spatially resolved locations, but many point measurements at one condition must be recorded in order to build a velocity contour map of the flow in the rotor.

The holographic system uses a double pulse ruby laser to illuminate part of the stationary casing so as to provide a diffuse bright background against which the intra passage flow can be viewed; the camera and viewing window are located over the rotor blade tips (fig. 6).

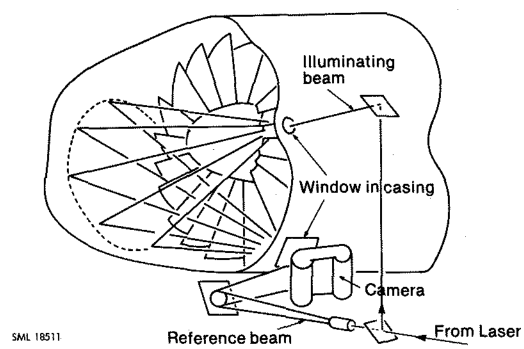


Fig. 6 Schematic Diagram of Holographic System

The double exposure hologram interferometrically compares two views of the flow which are rotated with respect to each other by about 1mm at the blade tips. Accurate triggering of the laser is necessary in order to obtain the optimum view through the selected passage. A major aim of much of the holographic work on fans has been the location of the shock. For an optimum view of this thin 'sheet' it is desirable to be able to look at as acute an angle to the shock as possible; the twist of the blades and the pressure of rotating parts, generally restrict the view to something less than the optimum. Flow visualization holograms can now be routinely recorded, with as many as several hundred holograms of selected passages at a range of test conditions obtainable in four or five hours. The automated analysis of this large amount of data is now needed to match the ease of recording.

For velocity measurements in rotating blade rows, a laser transit anemometer (fig. 7) (or dual focus system) has been found to be most suitable (Reference 2).

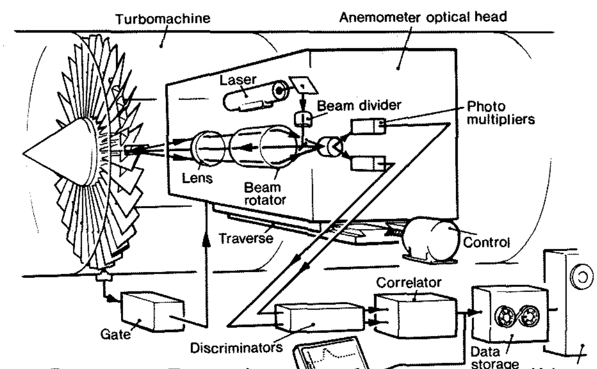


Fig. 7 Laser Transit Anemometer

In this instrument two laser beams are focussed to two small spots (15μm) separated by a known amount (typically 300 to 500μm). Particles entrained in the flow scatter light as they cross the focal region of each beam. The back-scattered light from each beam is then focussed on to two photo-detectors and the interval between the two events timed. Cross correlation of events on the two photo-detectors enables the transit time probability curve for valid crossings to be observed above a background level of random correlations due to flare noise and particles crossing only one of the beams. By rotating the plane containing the two beams about their common axis, correlograms can be built for different orientations of the spots with respect to the flow direction; in this way the flow direction (to 0.2^{o}) as well as its speed can be measured. For measurements within rotating blade rows, the signal from one photo-multiplier is gated to accept data only during a brief period (5 to 10μsec.) in each passage in order to provide spatial resolution. A normal shock can be seen where the velocity contours are steep. The transit anemometer has been chosen for work in turbomachinery because of its excellent flare rejection capabilities (it can measure within ½mm of a blade surface) and its high utilization of available laser light. For the latter reason it is sensitive to the vast number of very small particles that occur naturally in the atmosphere, which obviates the need to provide artificial seeding and ensure that the particles are truly following the flow. However, the relatively time-consuming nature of data acquisition with a transit anemometer has led to the need for a multi-station correlator which will acquire and record successive gated time windows continuously.

6. Fan

The process of making theory and measurement converge at the physical phenomena level is particularly well brought out in the case of the fan where, as shown in fig. 8, we can see a historical progression towards much improved efficiency at increased pressure ratio. Considerable

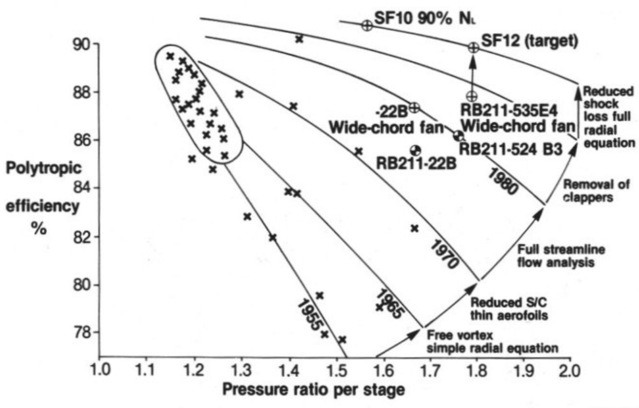


Fig. 8 Single-Stage Fan Progress

detail on the Rolls-Royce fan work is given in a paper by D.J. Nicholas and C Freeman (Reference 3). For completeness I have repeated some facts from their paper. Fig. 9 shows the various, indeed many, sources of aerodynamic loss and the process being pursued to reduce each of them. The current situation is

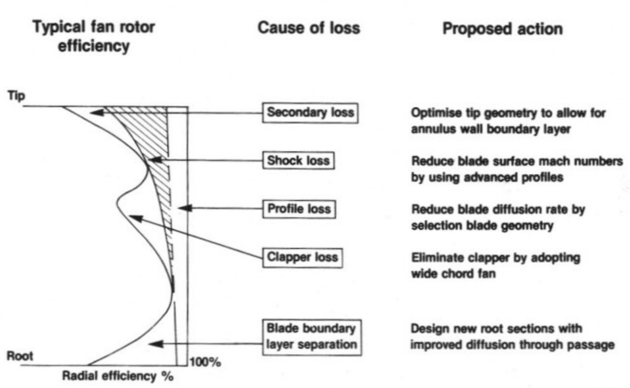


Fig. 9 Fan Performance Improvements

that we have enveloped our fan efficiency bid for the 535E4 with testing on a representative model fan. The results are shown in fig. 10. Fig. 11 shows for a typical case laser holography pictures of the flow around a pair of fan blades and results of anemometry work giving direct

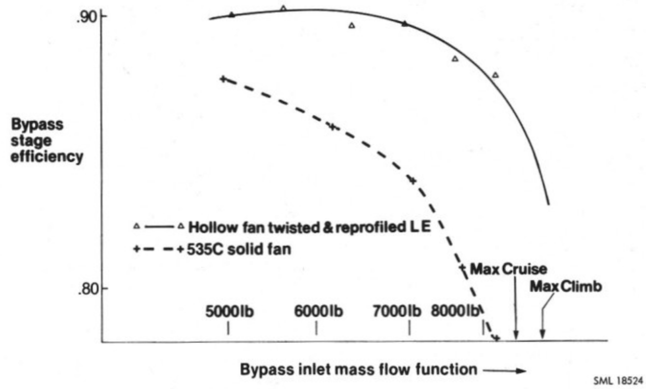


Fig. 10 535E4 Fan Flow vs Efficiency

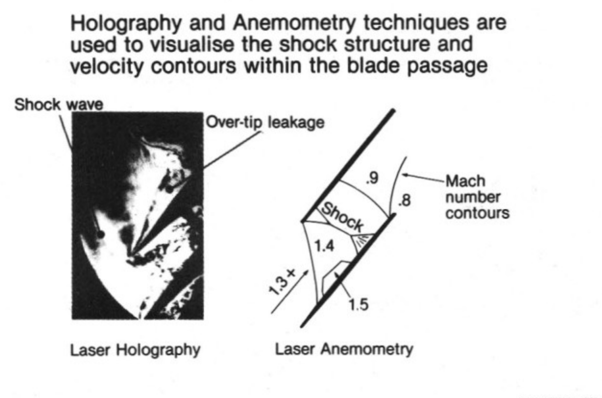


Fig. 11 Flow Visualisation - Rotating Fans

measurements of air flow velocities and directions contributing to a very clear and quantifiable picture of the air flow conditions throughout the fan.

Our future plans include the design of an optimum supercritical fan outlet guide vane of the type shown in fig. 12.

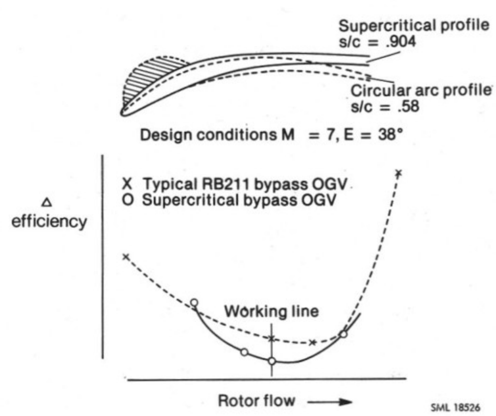


Fig. 12 Supercritical Fan OGV Design

Tests so far have produced a 15% reduction in fan outlet guide vane losses which is worth ½% of the fan overall stage efficiency. Moreover, such a vane provides us with a better structure.

Other programmes include the use of double oblique shock rotor sections which give much reduced shock losses in the rotor tip region as indicated in fig. 13.

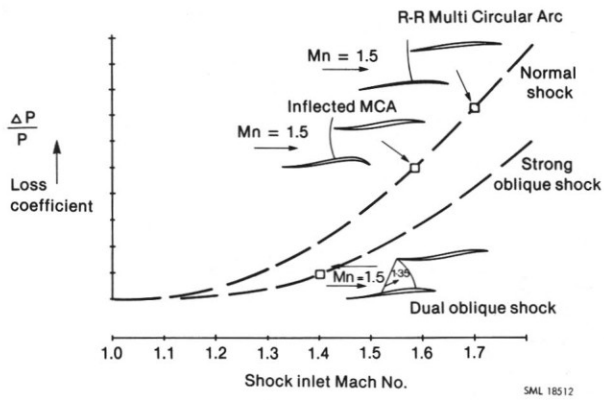


Fig. 13 Transonic Shock Losses for a given Upstream Mn

Whilst we have not obtained all the benefits we can reasonably expect in our test programme, we have been able to produce very encouraging results, both in terms of efficiency and flow increase. The latter is doubly important in that it increases bypass ratio and, hence, propulsive efficiency, without a corresponding nacelle drag increase, and it enables yet more thrust to be obtained from the given fan diameter, thus widening the potential market for the engine.

7. HP Compressor

Very different aerodynamic conditions prevail in the HP compressor from those in the fan or at the front of the core compressor. Mach numbers are lower but there is a considerable velocity profile emphasizing the importance of good three-dimensional design. Whilst the theoretical techniques are not as precise yet as we would like, and with many years of empirical experience behind us, we have featured a three-dimensional design in the HP compressor. We call it End Bend as indicated in fig. 14. Single stage tests have been most encouraging, whilst our first recent multistage test taught us once again the importance of getting the correct result for precisely all the right reasons. A later test of the 535E4 HP rotor has given increased efficiency and increased surge pressure ratio relative to

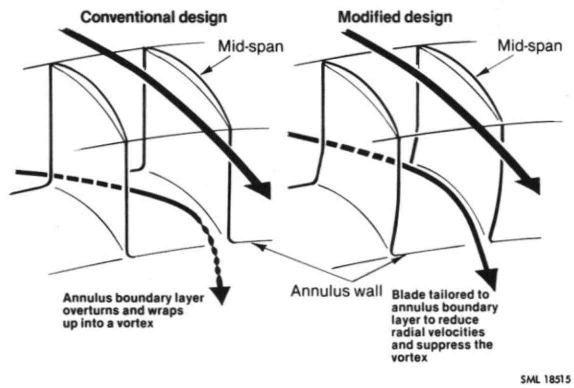


Fig. 14 Design for Reduced Secondary Loss

the best non-end bend standard. A photo of this rotor is shown in fig. 15. Good

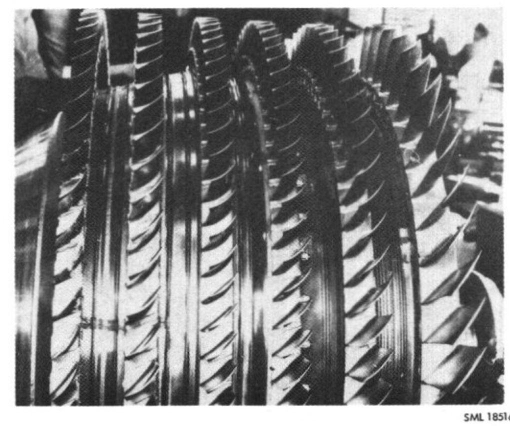
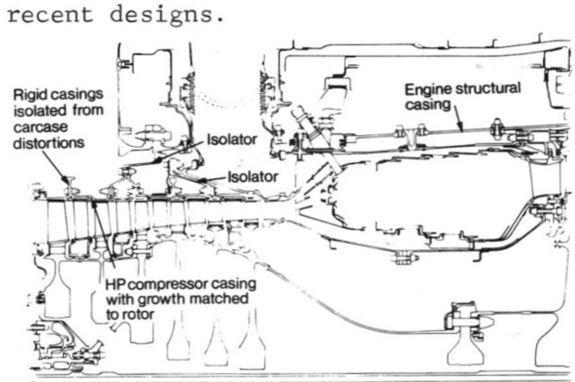


Fig. 15 HP Compressor End Bend Rotor

measurements have indicated the source of the improvement and where the next progress can be expected.

The RB211 HP compressor has had an inherent (or designed in) tip clearance control (fig. 16) which is free from controls, devices and offsetting performance penalties characteristic of many recent designs.



ETG 28393V ISSUE 1

Fig. 16 HP Compressor Casing Inherent Tip Clearance Control

Essentially, the combination of a short, rigid rotor, stiff round casings well centred relative to the bearings and a load path which isolates carcase structural loads and distortions from the casing surrounding the flow path, are the foundation features of the design. Careful flange design and heat path routing give a good match between casing and rotor growths. However, as with so many designs, there is scope for further improvements, particularly in respect of roundness and concentricity. Really accurate tip clearance measurements have been made for two major designs, indicating very clearly what remains to be done to refine the 535 design to make it very good indeed. Fig. 17 shows the measurements which were taken while fig. 18 reveals the degree of perfection expected once the residual out-of-roundness and eccentricity problems have been cured.

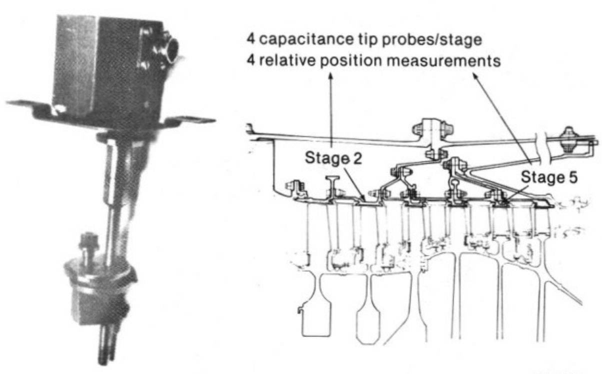


Fig. 17 HP Compressor - Tip Clearance Measurement

Stage	1	2	3	4	5	6	%RMS Clearance
Possible cruise tip clearance (thousands of inch)	2.9	9.6	8.4	10.4	8.5	13.0	0.68

SML 18510

Fig. 18 HP Compressor - Standard of Tip Clearance Control - Once Residual Roundness and Concentricity Problems have been Fixed

A stronger creep resistant titanium, known as T5331S, as shown in fig. 19, is being developed to enable a cleaner and lighter design of HP compressor rotor to

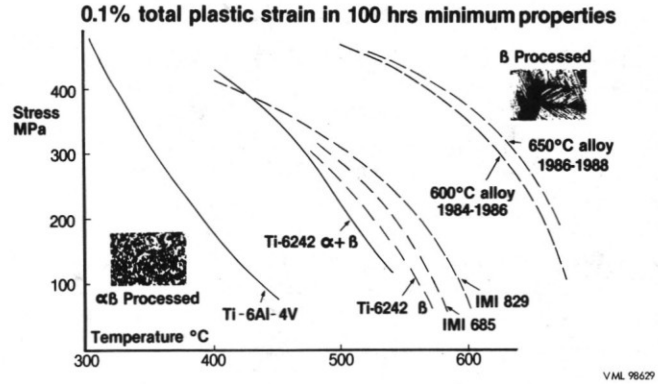


Fig. 19 Intermediate Temperature Materials - Creep Strain Properties for Various Titanium Alloys

be produced. The higher strength weight ratio of this material will permit shallow stator wells. For the future, in addition to normal refinement with the aerodynamics, tip clearance and windage, a more lightly loaded design is being pursued. This offers a basic efficiency improvement directly from the lighter loading and from the more widespread use of controlled diffusion blading which becomes more rewarding at aerofoil mach numbers in the region of 0.75 mach number. Fig. 20 summarizes this advanced engineering activity.

- Extra refinement in casing roundness and concentricity
- Further 3D refinement
- Reduced aerodynamic loadings
- More extensive use of supercritical aerofoil design at near optimum conditions
- Reduced stator wells

SML 18523

Fig. 20 Further HP Compressor Efficiency Improvements

8. HP Turbine

All RB211 engines have an air cooled shrouded high pressure turbine with special features to give very precise inherent tip clearance control. For a given tip clearance a shrouded turbine loses only half the efficiency of its unshrouded counterpart; its shroud segments are easier to cool and leakage between the platforms and around the shanks are easier to control since blade damping is done at the shroud, eliminating the need for special root dampers and long shanks with the extra leakage area they cause. Moreover, it is possible to carry on the shroud a work extracting fence, such that residual overtip leakage and the small quantities of blade cooling air that have to be released at the blade tip, do useful work on the turbine and present the right vector direction on to the following nozzle guide vane. Fig. 21 shows a typical blade and its tip clearance control system.

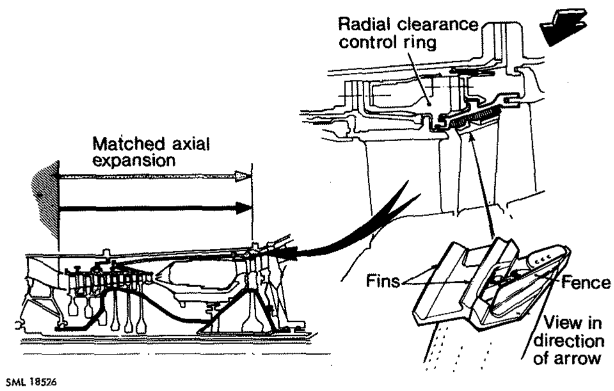


Fig. 21 HP Turbine Tip Clearance Control System

For the RB211-535E4 turbine we have introduced a three-dimensional design on both high pressure nozzle guide vanes and rotor blades. Fig. 22 shows the HP nozzle guide vane. The advanced three-dimensional design is coupled with thermal barrier coatings on the platforms to give an easy cooling system without platform films which have shown themselves to be serious performance losers. All the proven RB211 features of chordal sealing

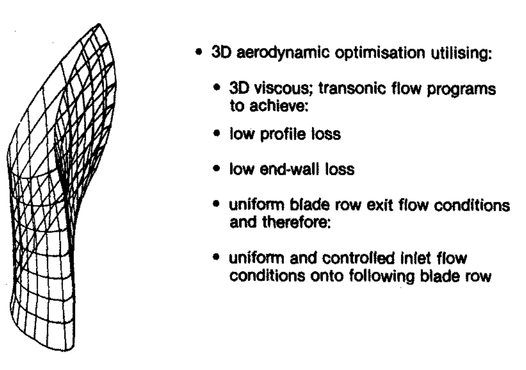


Fig. 22 535E4 HP Turbine Technology

and strip sealing are retained on the high pressure nozzle guide vane (fig. 23) to guarantee freedom from leaks around the nozzle guide vanes as the engine deflects under loads and temperature gradients.

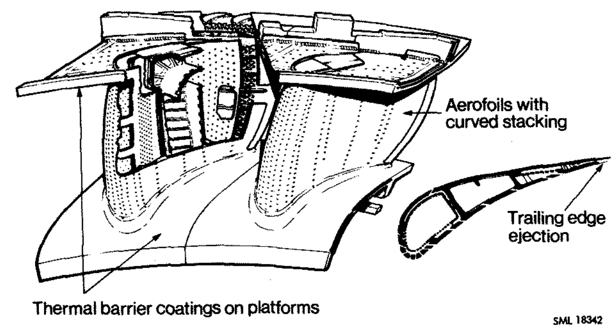


Fig. 23 Advanced Cooling on 3D HP NGV

The rotor blade also features a three-dimensional design, an advanced multi-pass cooling system and pressure side thermal barrier coatings. We have had considerable encouragement with practical tests on thermal barrier coatings, but our results are rather better than our theoretical techniques and, accordingly, we have not made our design critically dependent upon their success. Fig. 24 shows a 535 blade with its thermal barrier coating, while fig. 25 shows the model turbine with its three-dimensional blades.

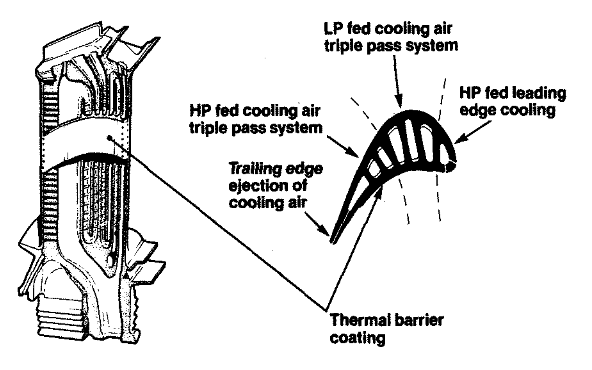


Fig. 24 Advanced High Pressure Turbine Blade

Directionally solidified material has been chosen because we understand it and have proven, good experience. Single crystal offers only a small prize in this turbine and there is yet insufficient knowledge to define all the controls necessary to guarantee that benefit. We feel very sure that single crystal is the way to make turbine blades once the

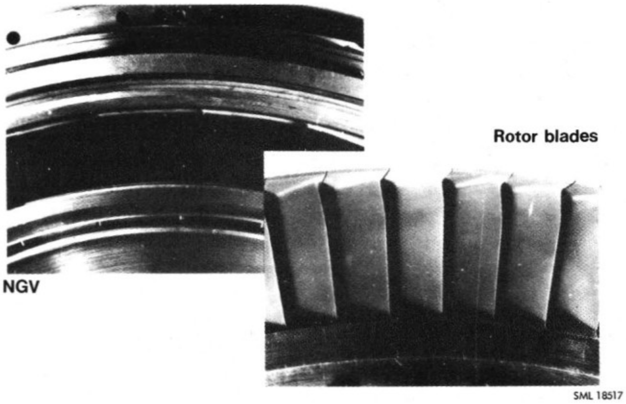


Fig. 25 Model HP Turbine

controls are secured, but it needs a different turbine to maximise its potential, and such a turbine is being prepared in our Advanced Engine programme.

In the special purpose automated plant which went into full production in 1977, we are producing excellent single crystal blades, some are of the existing designs whilst others are more sophisticated. What is already clear is that very complex shapes can be cast and that the process with this plant does not lead to excessive cost penalties for single crystal blades.

Fig. 26 shows one unit of the multi-unit plant.

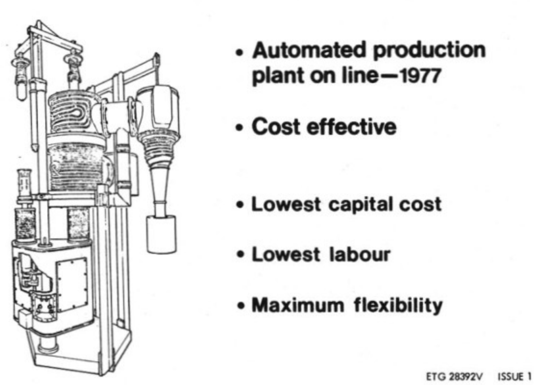


Fig. 26 Automated Manufacture - Directionally Solidified and Single Crystal Cast Turbine Blades

The more advanced turbine, featuring single crystal, will have a higher rim speed to reduce loading. Tests have already shown large increments in efficiency for such designs. Blades with cast-in impingement tubes containing the necessary holes and pedestals, have already been made, as shown in fig. 27. Such

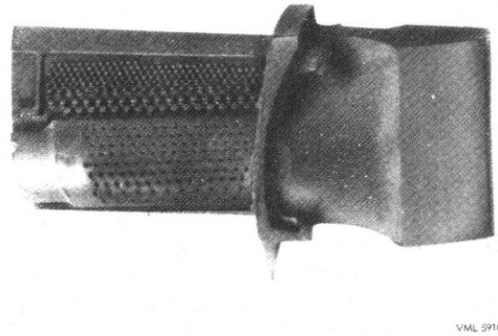
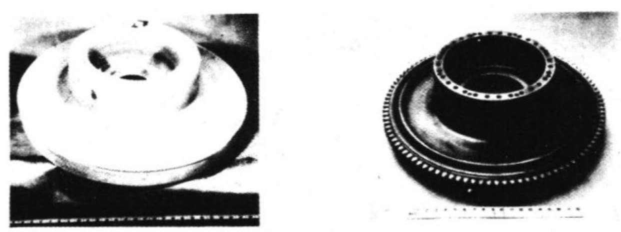


Fig. 27 Single Crystal Turbine Blade with Cast-In Impingement Tube

blades running at higher rim speeds will be carried on powder astroloy wheels of the type shown in fig. 28.



27½" diameter 750lb forging in powder astroloy, (above left) for production of the RB211 HP turbine disc (above right)
Isothermal forged for precise shape, low cost and structure control
Conventional forging in Waspaloy is approximately 25% heavier

VML 98584

Fig. 28 Advanced Materials Technology - Powder Metallurgy Discs

Just as with the aerodynamics, tip clearance control, advanced creep resistant titaniums and other advances, we have taken a cautious line. Great care has been taken to try to understand the physics and metallurgy. From the earliest work on powders, it was clear that considerable effort was required to control the micro-structure to give a material which is defect-sensitive.

Forging work and optimum grain size (not the smallest) are of crucial importance in obtaining the micro-structure which permits a long cyclic life at stress levels above waspalloy. The stress increment is quite modest (+10%) but it does permit a very worthwhile rim speed increase to give reduced aerodynamic loadings which brings a higher turbine efficiency. Extreme stress levels in powder will give the material a very bad reputation and make it all the more difficult for those who want to apply it in a role where it can truly earn its keep.

9. IP Turbine

The RB211 family features an intermediate turbine which has an uncooled rotor blade and a rather low aspect ratio vane through which passes a structure to support intermediate pressure and high pressure turbine bearings. Whilst good levels of efficiency are normal for this design, the vane represents a real challenge from the point of view of controlling secondary flows to minimise aerodynamic loss.

Considerable success has now been achieved with three-dimensional design techniques of the variety shown in fig. 29. Earlier designs produced pockets of

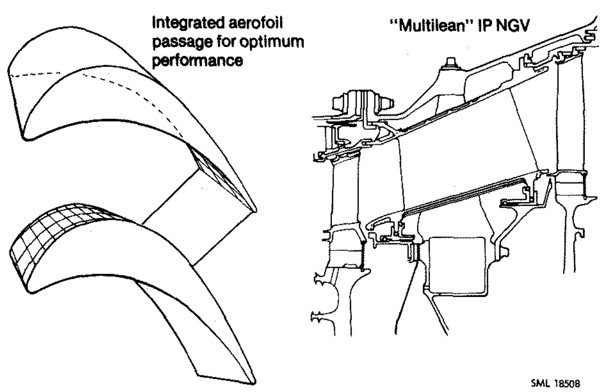


Fig. 29 High Performance IP Turbines

high loss and large deviations from the desired exit whirl angles which the new design has much improved (fig. 30). A 4% efficiency improvement has been obtained, together with a very clear picture of where the next increment will come from.

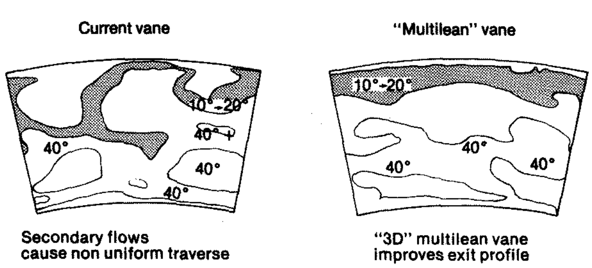


Fig. 30 High Performance IP Turbines - Exit Profile

With such encouraging rewards from three-dimensional designs that have been obtained on several components, it is clear that the intermediate pressure turbine rotor blade and low pressure turbine can be improved in a similar manner to contribute to the engines' ongoing competitiveness.

10. Mixing

Much has been written for decades on the merits of mixing the hot and cold streams of a turbo fan engine. A single nozzle concept (fig. 31) is used on the

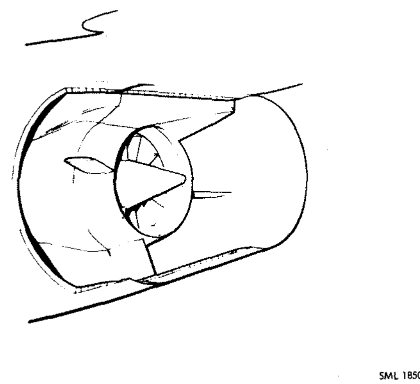
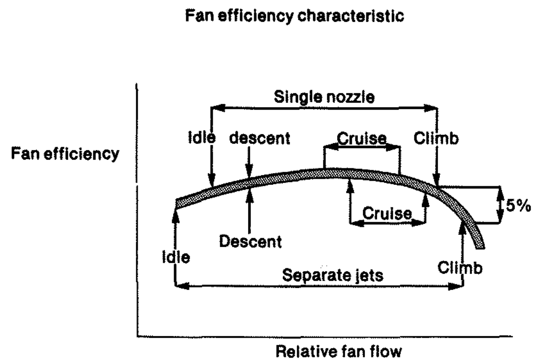


Fig. 31 Single Nozzle Configuration of RB211-535E4

RB211-535E4 which confers worthwhile benefits in terms of fuel efficiency. In a separate jet configuration, fixed areas are normally chosen for the hot and cold exhaust streams, thus fixing the matching of engine components. With a single nozzle each stream can adjust itself to take a varying proportion of the fixed single nozzle area. It can readily be shown that with a 535E4 engine, a favourable rematching of the engine occurs to enable the fan to operate at the most efficient condition throughout all the important regimes of flight. The effect is most beneficial in climb, which is especially important in the relatively short-range operation planned for the Boeing 757. Almost 50% of block fuel is consumed during climb on a 400nm stage length.

Fig. 32 shows the benefits in fan efficiency relative to the separate jets case.

A significant portion of a separate nozzle engine's drag is associated with supersonic drag on the afterbody which envelopes the hot jet pipe and nozzle.



SML 18519

Fig. 32 RB211-535E4 Single Nozzle Powerplant - Fan Efficiency Characteristic

1.5% of cruise specific fuel consumption is typical for this penalty. A single nozzle eliminates this source of loss in exchange for a smaller increase in subsonic scrubbing drag over the larger fan cowl.

Both of these advantages are obtained with a simple annular 'mixer' of very low pressure loss. I use inverted commas because the degree of mixedness is very small and, hence, the direct mixing gain is small.

The RB211 is a relatively short engine and, even when mixed, is shorter than competitive engines making the concept of an engine with a common nozzle a thoroughly practical one. The fundamental weight increase attributable to the extra cowl length is minimised by using composites.

The single nozzle engine has a very effective thrust reverser system in that blanking of the cold stream spoils the hot thrust by giving the hot jet a nozzle which is excessively large. The extra expansion ratio increases fan speed and gives enhanced fan reversed thrust.

For the future it is possible to increase the degree of mixedness at a low pressure loss, thus adding to the improvement in efficiency. Increased mixing at the expense of an increased pressure loss is of low interest.

11. Full Authority Digital Electronic Control (FADEC)

A full authority digital electronic control system offers a small reduction in block fuel consumption relative to that which is obtained by the rather precise hydromechanical fuel control system already on the 535 engine. Such a system also offers a substantial weight reduction. The weight saving accrues from the units which are lighter than their hydromechanical equivalents and from reductions in associated features. British Industry already has considerable service experience on electronic controls amounting to more than 170 million hours, of which 32 million are on the full authority system on the Proteus engine in the Britannia aircraft. As with the other items of technology for improving the RB211-535E4, considerable care is being taken to prepare the ground thoroughly to ensure that the full benefit is obtained in service.

Fig. 33 summarizes the U-K concept in terms of the integrity and reliability features of FADEC.

- FADEC with fault tolerant features will be adopted
- FADEC will be engine mounted
- High integrity from separate duplicated lanes with cross communication of sensors and actuators
- Each lane will have dual microprocessors and independent built-in pressure sensors
- Electronic units will be fuel cooled for maximum reliability
- Control will be powered from dedicated engine mounted generator (with duplicated windings)

SML 18522

Fig. 33 UK FADEC - Integrity and Reliability Features

12. Summary

The RB211-535E4 third generation turbo fan features the advanced technologies listed in Fig. 34 within a derivative engine, chosen to maximise the benefit from those technologies in an engine of

- Wide chord clapperless fan
- 3D designs in core compressor and core turbine
- Inherent precision tip clearance control
- Thermal barrier coatings
- Advanced creep resistant titanium alloy
- Supercritical aerofoil designs
- Single nozzle exhaust
- Compact low drag installation

SML 18520

Fig. 34 Advanced Technology Featured in the RB211-535E4 3rd Generation Turbo Fan minimum risk which we believe to be important for a very high duty, twin-engined, short-range airliner, the Boeing 757.

Additional technology, listed in fig. 35, will be added when adequately substantiated to further improve the fuel efficiency and increase the engine thrust as required to widen the market of the engine.

- **Further refinements to and more widespread application of advanced 3D aerodynamic design**
- **Double oblique shock fan rotor**
- **More extensive use of optimum supercritical aerofoils**
- **Single crystal turbine blades with more advanced cooling**
- **More extensive use of thermal barrier coatings**
- **Reduced aerodynamic loadings on critical components**
- **Forced mixer**
- **Improved sealing — engine and powerplant**
- **Further cycle optimisation**

SML 18521

Fig. 35 Further Technological Advances being prepared for the ongoing Development of the 3rd Generation Turbo Fan

13. References

1. P.J. Bryanston-Cross, T.J. Lang, M.L.G. Oldfield and R.G. Norton Journal of Engineering for Power 103 (1981) 124-130 'Interferometric Measurements in a Turbine Cascade using Image-Plane Holography'.

2. C.J. Moore, D.G. Jones, C.F. Haxell, P.J. Bryanston-Cross and R.J. Parker Proceedings of the International Congress on Instrumentation in Aerospace Simulation Facilities. ICIASF 1981 Record (1981) 244 'Optical Methods of Flow Diagnostics in Turbomachinery'.

3. D.J. Nicholas and C. Freeman 'Recent Advances in the Performance of High Bypass Ratio Fans'.