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# ADVANCES IN TURBINE TECHNOLOGY

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## ABSTRACT

The characteristics of a Gas Turbine Aero Engine of greatest importance to the user are strongly dependent on the technical quality of the turbines. Also the size and cost of the engine are dependent on the number of turbine stages necessary. Not immediately of concern to the user, but very high in the consciousness of the Aero-Engine Manufacturer, is the massive cost of any serious development problem which arises with turbine hardware. Specifically, it is essential that production processes such as casting and fabrication which require extensive tooling should not be disturbed by changes to the engineering design.

These factors place the aerodynamics and heat transfer of turbine blading amongst the most important of the engineering disciplines. Unfortunately, many complex phenomena are involved, requiring large numerical models which interact with other equally large numerical models predicting vibration and structural loads. This paper describes how Rolls-Royce has made progress in achieving a Turbine Technology system in Engineering which meets the requirements of the modern Military or Commercial Engine programmes. It distinguishes the areas where experimental data is necessary and where theoretical methods are adequate, and shows how the needs of data handling and the organisation and control of engineering work have been met using a graphics terminal based computer system.

## 1.0 THE TURBINE TECHNOLOGY REQUIREMENT FOR AIRCRAFT ENGINES

### 1.1 Introduction

In the design and development of a new Aircraft Gas Turbine, engineers are presented with the challenge of designing innovative new turbomachinery which exceeds the performance of previous equipment. This requirement results partly from the competitive nature of the business and partly from the powerful gains in aircraft payload and mission performance which can be obtained from improved engine performance. In the case of cooled turbine blading, many individual technology elements interact with each other to determine the balance between efficiency, life, cost and weight which expresses the overall performance of the product. Achieving the highest overall performance requires that these often conflicting elements are optimised to the greatest possible extent in the design.

Working in this environment, close to the limits of known technology, inevitably involves some uncertainty in design. The worst possible outcome of this is to find after the equipment has entered service that the turbine life is inadequate. In the past such undesirable results have been insured against by basing the design on the configuration of previous successful components, improved by relevant new research results, and then evaluating and if necessary correcting it using experimental hardware. However, the latter is itself an expensive and lengthy process, particularly where high temperature rotating components are involved, and can have a serious adverse effect on the financial return from the whole project.

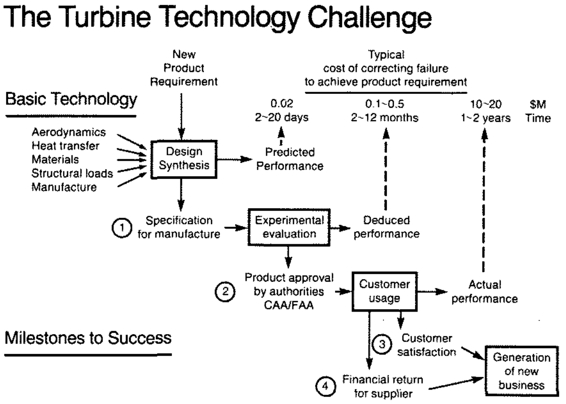


Figure 1

## 1.2 The Cost of Failure in Design

Fig. 1 shows the principal milestones in the successful implementation of a new engine, together with typical relative costs for correcting deficiencies in the turbine design at three stages. Obviously if a deficiency is identified during the design phase it can be corrected most easily. If technology is lacking or uncertainty remains, then alternative modulations to a basic design can be specified so that a selection can be made when comparative experimental data is available. If the deficiency is only recognized during engine testing aimed at achieving official type certification, then serious costs and delays arise due to the need to remake tooling and development hardware. A glance at the configuration of the cooled blading used in current engines shows how difficult this can be, Figs. 2 and 3. Delays in the delivery of aircraft to customers could also arise, leading to additional penalty charges. If the deficiency is first shown by the fleet leader engine in service, or by a cyclic test engine being run ahead of the fleet, then further additional costs may arise due to Warranty payments and the need to reschedule spare parts procurement. Clearly the importance of achieving the highest quality design cannot be overstated.

## 1.3 General Characteristics of the Product

In order to discuss the management of the technology of turbine blading it is necessary first to focus clearly on the characteristics of the components involved. Most of them are illustrated in Figures 2, 3 and 4. (1)

### Castings

Most turbine blading is manufactured from thin walled precision castings which provide rigid lightweight structures capable of internal cooling. Where cooling is necessary, the ceramic cores which form the internal space are high technology components in their own right, having intricate holes and patterns and yet requiring the strength to withstand the pouring and cooling of the metal without fracture or bending. The processes by which the metallic structure is controlled to produce a high yield of Directionally Solidified or Single Crystal components is yet another technology. (2) The tooling necessary to manufacture production quantities of such precision castings, which are cast to finished dimensions both internally and externally on the airfoil, is expensive and time consuming to procure and it is an essential requirement of the blade design that it should be correct from the outset. This means that the aerodynamic and cooling passage definition supplied by turbine technology must be "right the first time", and must allow the achievement of all performance and thermal life objectives.

### Cooling Inserts and Attachments

For the purpose of applying impingement cooling to the airfoil, or the end platforms of stators, it is common to attach to the casting, by welding or brazing, inserts or shaped plates. These devices seal with special locations on the casting so as to provide intermediate chambers in the cooling system. They are most common on the suction surface of the airfoil and on endwall regions, where film cooling must be avoided or minimised to reduce performance loss. They are normally formed by profiled tooling into curved shapes and since they locate on casting features, they too must not be changed after definition.

RB211-535E4 HP nozzle guide vanes

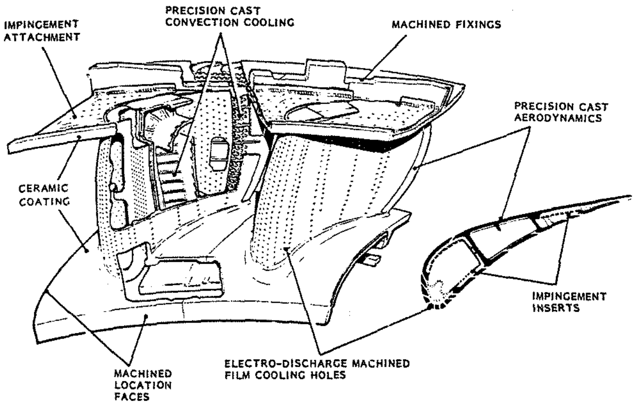


Figure 2

RB211-535E4 HP turbine blade

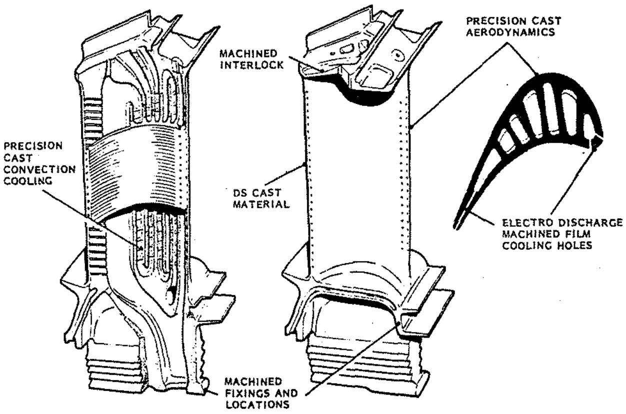


Figure 3

### Impingement and Film Cooling Holes

Impingement and Film Cooling are among the most flexible and the most effective of cooling methods, and they make possible the achievement of a significant measure of cooling system adjustment without the need for casting or insert changes. However it must be recognised that major changes are likely to reduce the efficiency of the system. Particularly attractive are laser drilling systems which allow configuration change by software rather than electrode tooling. Adjustments to the cooling system may be made by varying the distribution of holes, angle of inclination, flow area and hole shape, providing a most fruitful area for innovation and experimental work.(3)(4) However, by their nature they have some important disadvantages, in that the effective flow area is vulnerable to manufacturing tolerances and contamination by dust, and in the case of the film cooling hole a serious stress concentration is introduced in the load bearing wall.

### Machined Locations

Turbine blading is invariably located by machined surfaces at the casing or disc so as to position the airfoil with the correct orientation in the assembly and to prevent leakage which reduces performance. By arranging for the casting to incorporate sufficient excess material in the location and sealing areas it is possible to accommodate the requirements of engine cycle rematching to adjust compressor working line or axial bearing thrust. This is the only practical adjustment of the turbine aerodynamics which is possible after the casting design has been committed, and it is most commonly applied to stators.

RB211-535E4 - HP, IP and LP turbines

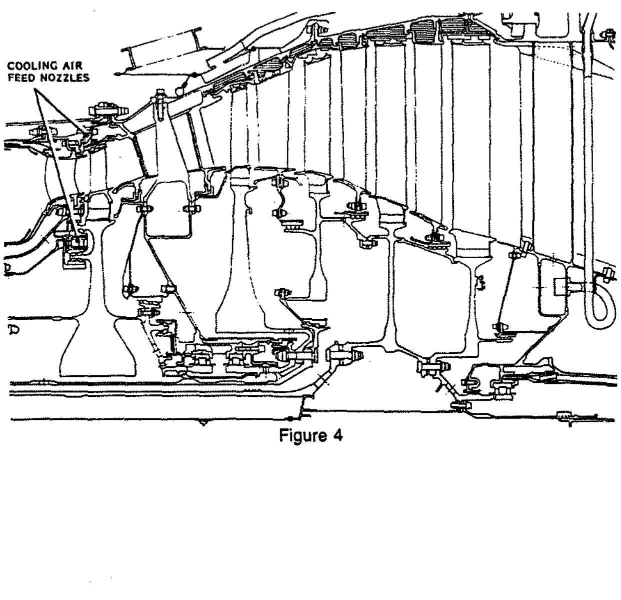


Figure 4

### Cooling Air Supply Pressure

The remaining parameter having a significant influence on the cooling performance of turbine blading is the cooling air supply pressure. In the case of the first stator it is a most critical parameter, since the cooling air pressure only exceeds the gas stream pressure by the amount of pressure loss which the gas stream experiences in passing through the combustor. Since the combustor pressure loss is parasitic to the cycle performance, there is always an incentive to keep it as low as possible. Film cooling is necessary at the leading edge and on the pressure surface of the first stators in all modern engines, and the achievement of a positive film pressure drop under all circumstances requires generous feed areas up to and within the stator airfoil. In the case of subsequent stators and all rotor blades the cooling air supply pressure can be regulated relatively easily by geometric orifices. However, the capacity of the system must recognize significant leaks which may occur transiently during engine acceleration or deceleration, or as a result of the deterioration of seals during service operation. Obviously if the capacity of the cooled blading together with the leaks exceeds the supply capacity, then hot gas may be drawn into the cooling air system at some point giving serious overheating.

### 1.4 The Objective

It was shown in Section 1.2 above that the implications of an unsuccessful turbine design become progressively more serious as the point in time when the problem is resolved slides further back into the certification and production programme. Section 1.3 above showed that absolute priority must be given to achieving the correct definition of the casting and any shaped attachments which join with it to form the basis of the cooling system. Any remaining uncertainty must be capable of being contained within the adjustable parameters of blade setting angle, cooling air feed pressure, and impingement or film cooling hole configuration.

It is appropriate at this stage to pose the question of why uncertainty cannot be accommodated by designing with generous margins. This can indeed be done, but the product which results will not be as good as it could be. For example, significant parts of the blading would be overcooled, requiring additional cooling air which would degrade cycle performance. This could only be recovered by enlarging the turbomachinery, adding to the weight of the engine from the outset, and thereby reducing the technical quality of the product.

It is important also to distinguish between uncertainty and risk. No company can afford to take technical risks in a production engine programme. It is the purpose of Research and Advanced Demonstrator programmes to explore new concepts and operating conditions so that practical experience is always kept well ahead of commercial commitment. An acceptable degree of uncertainty in the design is by definition that which can be resolved without significant expense or difficulty in the course of initial engine testing.

From the discussion so far it can be concluded that the overall objectives in the management of turbine technology activity in engineering must be:

1. TO ENSURE THAT THE DEFINITION OF THE CASTINGS AND INSERTS MADE IN DESIGN IS CAPABLE OF ACHIEVING THE AERODYNAMIC AND THERMAL LIFE REQUIREMENTS OF THE PROJECT.

2. TO MANAGE ANY REMAINING TECHNICAL UNCERTAINTIES IN THE DESIGN SO THAT THEY CAN BE CONTAINED BY THE FACTORS WHICH CAN BE ADJUSTED WITHOUT PENALTY TO THE PROJECT AND THEY CAN BE RESOLVED SO AS TO OPTIMISE THE QUALITY OF THE PRODUCT.

## 2.0 THE IMPLEMENTATION OF TURBINE TECHNOLOGY IN THE MODERN AIRCRAFT GAS TURBINE

### 2.1 Engineering Philosophy

It is obvious that the calculation of the 3D aerodynamics, heat flow and structural loads in and around a turbine blade presents a formidable problem which requires the application of the best available theoretical methods and the most powerful computers. This has been recognized in the industry for some 25 years or more. It has also been apparent for the last 10 years that the number and frequency of such calculations, and the large quantity of data which must be processed to converge a design, demands that such programs be linked in a network to a common data base.(5)(6) Perhaps the most recent realization is that many of the criteria and physical data necessary in order to ensure a successful design cannot be obtained from simple experiments.(7)(8)

Repeatedly on subjects like aerodynamic secondary loss, boundary layer transition, heat transfer performance and material failure, one is forced back to the turbomachinery component rig or the engine itself as the only reliable source of the data or criteria. Moreover it is usually only possible to extract the data in the form in which it can be applied to general use by complex analysis. In effect an analysis system is required which is a mirror image of the design system, so that the basic criteria and physical data can be extracted from known geometry and performance using the same mathematical models.

This philosophy has been applied by Rolls-Royce in satisfying the objective developed in Section 1.4 above, and has resulted in the creation and implementation of a very successful engineering technical system for turbine blading called TACITUS (Turbine Aerodynamics and Cooling Interactive Terminal User Suite). Figs. 5 and 6 illustrate the basic modes of operation of this system. It will be appreciated that it is impossible to generalize on the path or number of iteration loops necessary for a given task.

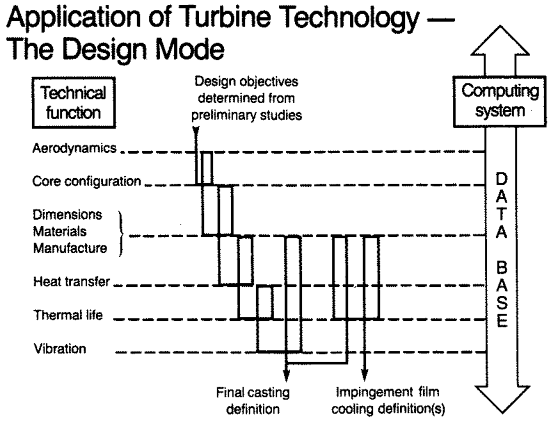


Figure 5

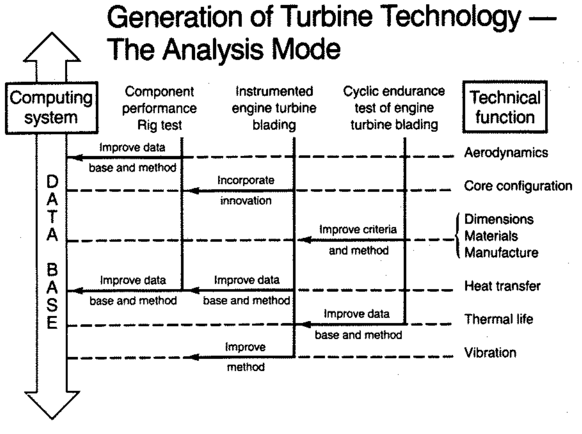


Figure 6

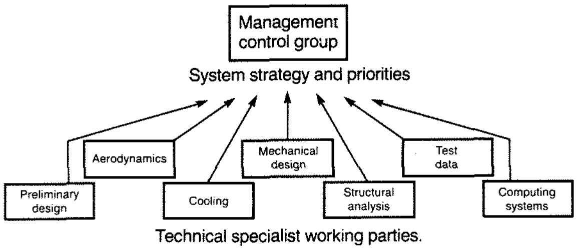
## TACITUS System Characteristics

**Functions**
- Enables a team of engineering specialists to work interactively on the same component
- Provides visibility of technical criteria for management control

**Qualities**
+ Scientifically and numerically accurate within known limits
+ Operationally reliable efficient secure
+ Linked to other systems and data bases
+ Flexible to allow product innovation and technical progress

Figure 7

## TACITUS System — Management Organization



Functions represented in management group and working parties
- Technical specialists
- Software specialists
- User groups

Figure 8

### 2.2 TACITUS Functions and Programs

Implementation of the engineering objectives and philosophy described above led to a technical computing system having the characteristics listed on Fig. 7. Coordination of the engineering and computing requirements during the creation, operation, and development of the system has been achieved through a formally structured management activity illustrated on Fig. 8. This two-level approach allows specific technical issues to be investigated in detail by the relevant Working Party, and decision making and planning to be made by the Management Group in the best interest of the whole system. However, the most crucial elements leading to success were a highly professional, centralized, software team and a large common data-base carrying all related geometrical and technical information in large files. The software has been entirely produced by Rolls-Royce, and is established on an IBM computer network linking 6 different geographical locations within the United Kingdom, as well as the Rolls-Royce Inc. establishment at Atlanta, Georgia.

The principle of the system is that the component configuration is generated using 1D, 2D or quasi-3D analyses which are very fast and interactive, before being analysed by large 3D codes which may at this time take too long to be completed 'on-line'.(9)(10) Even when the 3D codes are available with rapid response, the simple approach to the design task is retained due to the confidence which it gives that previous experience is not being violated. Fig. 9 shows in as much detail as is practical, the programs used in airfoil aerodynamic, cooling and structural analysis.

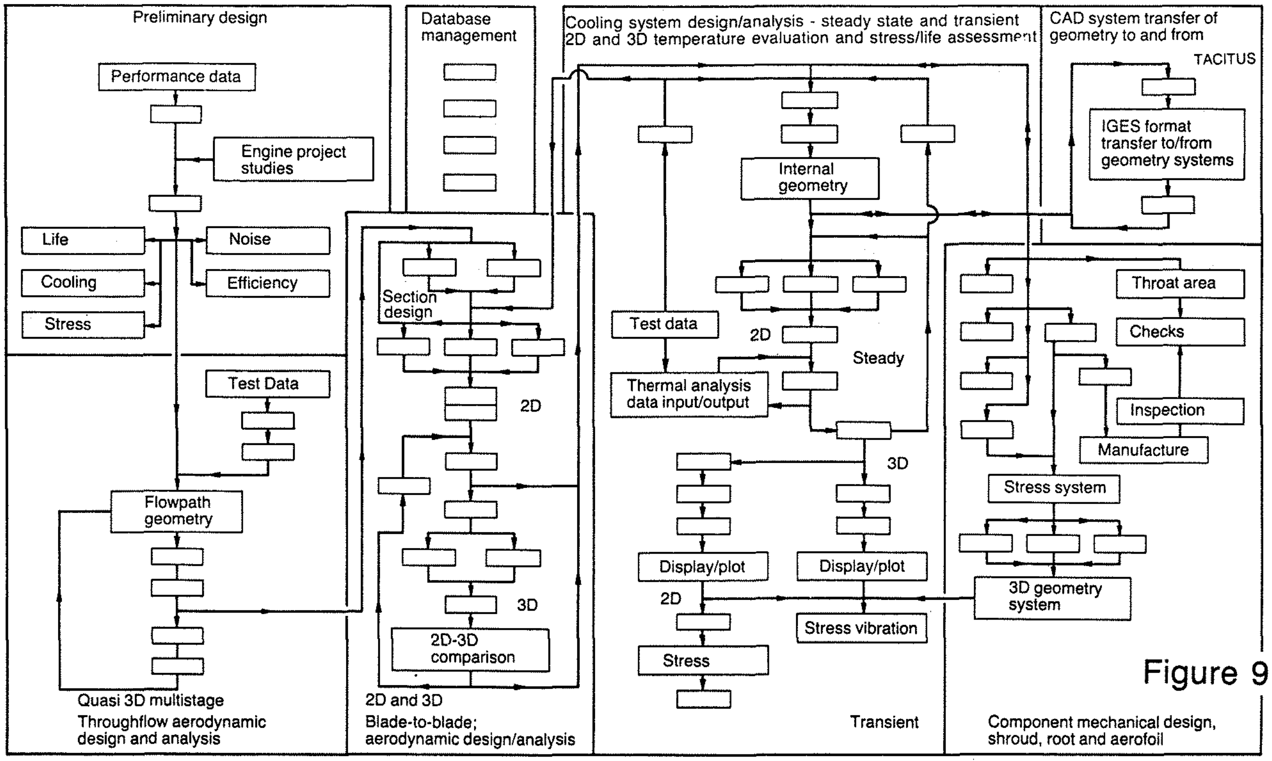


Figure 9

## 2.3 The Role of Experiments in the Advancement of Turbine Technology

### Applied Research

An important role remains for experimental work in explaining and quantifying certain aspects of turbomachinery flow which are fundamental to the theoretical models and the data base used in design. In the view of the authors this will always be the case where unconventional and innovative new configurations are required, on account of the high degree of accuracy to which gas turbine component performance must be predicted. An error of only 1% caused by faulty extrapolation of existing data can seriously impair the viability of an engine project. An example of an activity within Rolls-Royce aimed at avoiding such risks has been research into the aerodynamics of unshrouded HP turbines. Although such a component has not been incorporated in recent production designs, a very extensive turbomachinery research programme during the past 15 years has ensured that a validated data base is available. By contrast, in the case of the (for Rolls-Royce conventional) cooled shrouded turbine considerable progress has continued using the data base established in TACITUS from current production types such as the RB211, RB199, Pegasus and Adour.

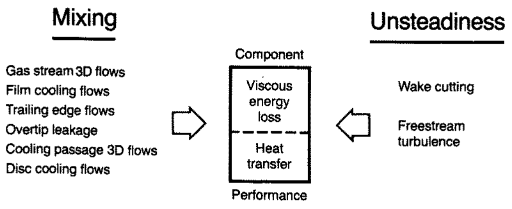
As a generalization, the phenomena which require experimental data are those involving 3D viscous flow losses and heat transfer, and examples are tabulated on Fig. 10. University and industrial research teams who contribute to the advancement of turbomachinery find it essential to link theoretical work with rotating experiments using fast-response non-intrusive measurement systems to resolve blade passing phenomena.(11)(12)(13) In the case of internal cooling systems, very valuable experimental work is performed using large scale stationary or rotating models which can explore local flow and surface heat flux around cooling holes and bends within the casting.(14) The data gathering systems for such experiments are structured to interface directly with the TACITUS system, either by on—line links or in the case of university establishments, by magnetic tape generated by compatible software.

### Turbine Aerodynamic Component Rig Tests

Rotating tests of turbine units, on a special facility which supplies warm high pressure air and absorbs shaft power, continue to be the authoritative measure of turbine performance. The hardware may be that from an actual engine, or specially manufactured using cheaper materials to a simpler less weight conscious design, or a combination of both. It is very difficult to assess the performance of a turbine from the test of an engine or core other than in a global sense, and it is impossible to diagnose the local performance of sections of the blading. The reasons for this are listed on Fig. 11. The layout of two typical test units used by Rolls-Royce are illustrated on Figs. 12 and 13.

The overwhelming advantages of these vehicles are that accurate measurements can be made, and experimental blading can be manufactured in cheap conventional materials. Nevertheless it has been observed that as the basic quality of the original aerodynamic designs has improved during the past 5 years, that the potential for gains through experimental development has diminished. Basically, within the constraints of rotational speed, flowpath dimensions and power output, a new design is now likely to be well optimised, so that further improvements must come from improved technology. Therefore the trend for the future is to use turbine aerodynamic test vehicles exclusively for innovative configurations, and apply the new technology to production projects through the TACITUS system in design.

**Phenomena Depending on Experimental Data to Resolve Uncertainty to Required Accuracy**



- Experiments provide quantitative validation of theoretical models and allow extension to new configurations

Figure 10

**Difficulties in Measuring Turbine Performance in Engines**

- Turbine inlet conditions are hostile and non-uniform
- Cannot reliably separate leakage flows from blade cooling flows
- Cannot separate leakage penalties from basic aerodynamics
- Cannot measure/control clearances all around the turbine
- Close coupling of stages prevents internal performance measurements
- Non-uniformity of mainstream temperature due to cooling air mixing prevents temperature drop power measurements within the turbine

Figure 11

HP engine parts rig

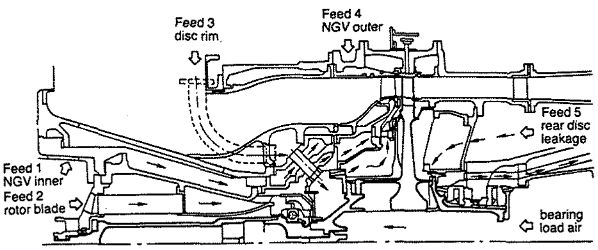


Figure 12

High temperature demonstrator unit

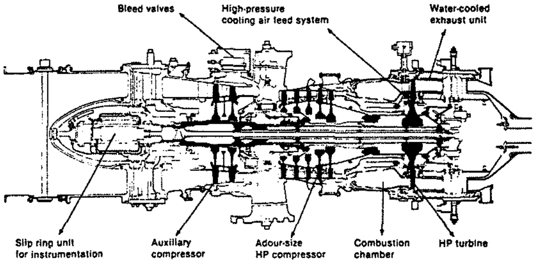


Figure 14

The realization that external heat transfer is strongly affected by the fluid mechanics of wake cutting in subsequent blade rows has resulted in moves to carry out heat transfer related measurements in such aerodynamic test vehicles. The advancement of measurement and test techniques in this direction is gathering momentum.

LP model turbine rig

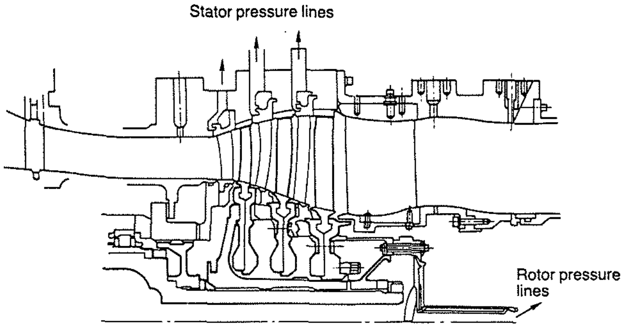


Figure 13

## Core Engine and Engine Tests

The most valuable turbine cooling data is that which is obtained from a properly instrumented core engine running at full pressure and temperature. Such data has been obtained during the past 15 years at Rolls-Royce using the High Temperature Demonstrator Unit, which is dedicated to advanced cooled turbine work. Fig. 14 illustrates the salient features of the test vehicle, which runs with a supercharged air supply. The turbine blading, casing shrouds and the cooling air feed system are extensively instrumented with pressure tappings and thermocouples, and the turbine rotor incorporates low leakage seals to facilitate coolant flow control. A fast response high definition pyrometer can also be employed to increase the coverage of blade temperature measurement.(15) Many cooled turbine configurations have been evaluated including unshrouded blades. Figure 15 shows a turbine blade which first ran in the unit in 1975.

Valuable data on the cooling performance of advanced engine blading can also be obtained during more routine testing using temperature sensitive paint, which indicates contours of constant temperature on the surfaces to which it has been applied. This is universally used on engine programmes which cannot support the extensive turbine instrumentation of the HTDU, and provides a fast and economical way to evaluate alternative impingement and film cooling systems applied to a basic new design. Groups of alternative stator or rotor configurations can be compared under identical operating conditions in a single engine test, without the need for complex and fragile attached instrumentation and leadout wiring.

## 3.0 MAJOR IMPROVEMENTS AND PROGRESS ACHIEVED

### 3.1 HP Turbine Blade Cooling and Service Life

The 10 year period during which the Turbine Technology system here described has been established has witnessed a dramatic improvement in the cost effectiveness and success of HP turbine blade design. More configurations have been studied in more detail during design, fewer configurations have been evaluated by testing, and yet the life achieved has steadily increased. This is most conveniently illustrated by examples from the commercial engine field.(16)

Fig. 16 shows how the number of design changes necessary to achieve a satisfactory operating life has been reduced dramatically from the forged RB211-22B blade to the cast Directionally Solidified RB211-535E4 blade. The latter has not yet accumulated enough service experience to be significant, but the earlier RB211-22B cast DS blade is still in good condition at 14,000 hours. This represents a fourfold improvement over the forged blade. Some of the credit for these advances is due to the metallurgical and ceramic core developments which have taken place in parallel, but the foundation for success was the improved thermal and structural analysis.

Achieved Reduction in Post Certification HP Turbine Blade Modifications

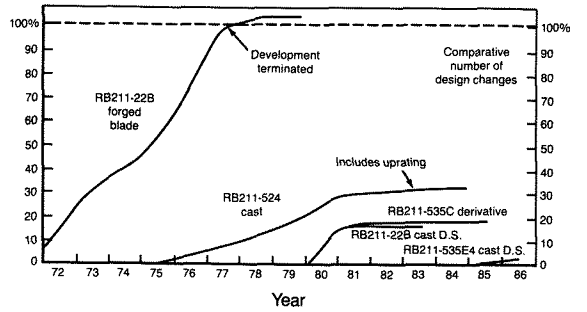


Figure 16

During the design studies leading up to the RB211-535E4 it was established that unusually thick airfoils were necessary in order to minimise secondary flow losses in the high deflection rotor bladerow. Fig. 17 shows three alternative cooling configurations which were subjected to full thermal analysis for comparison purposes in an elapsed time of less than one week.

RB211-535E4 preliminary cooling studies

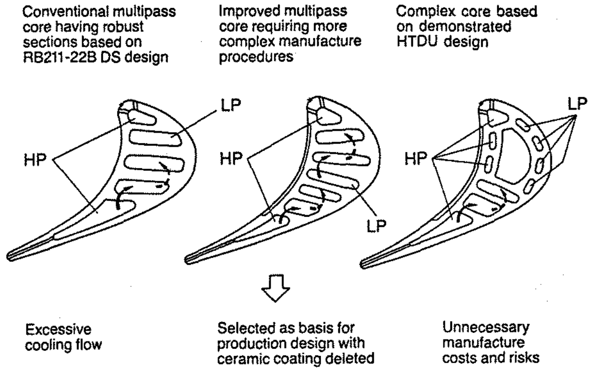


Figure 17

### 3.2 Turbine Efficiency

Accompanying the improvements in blade cooling performance described in Section 3.1 there has been a steady and in some cases spectacular progression in aerodynamic efficiency. In the case of Rolls-Royce commercial engines these improvements have been obtained from improved airfoils, and when combined with the low deterioration characteristics of shrouded blades, have kept the RB211 family competitive with other engines having two additional turbine stages and complex clearance control systems. Fig 18 illustrates the magnitude of these improvements for the RB211-524, which powers many B747 and L1011 wide body transports.

RB211-524 Component efficiency gains through improved aerodynamics

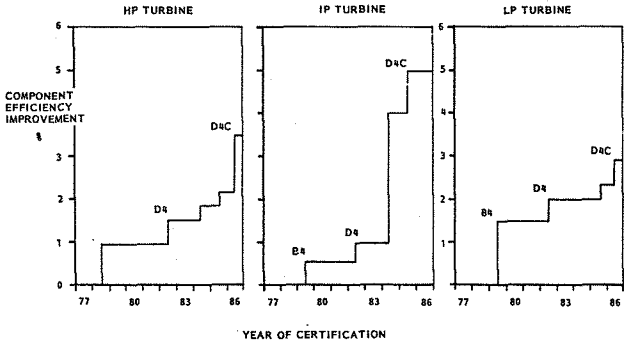


Figure 18

The ability to exploit these aerodynamic improvements requires that the internal cooling system be manipulated with confidence and ease to suit novel curved blade shapes. The innovations first made in the design of the RB211-535E4, and shown on Figs. 2 and 3, have now been taken a stage further in the RB211-524D4. Figs. 19 and 20 show how the cooling has also been enhanced to match the higher cycle pressure ratio and cooling air temperature involved.

RB211-524D4 HP nozzle guide vane redesign

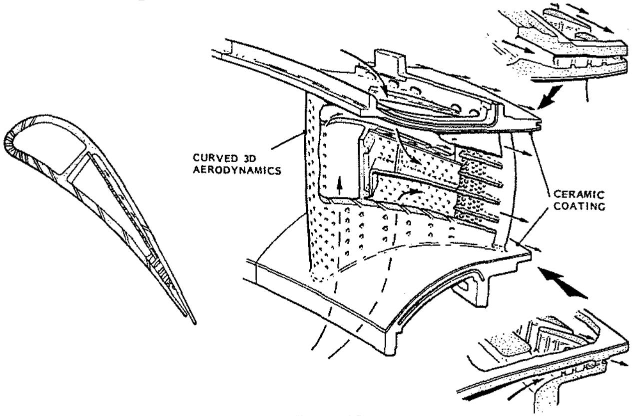


Figure 19

RB211-524D4 HP turbine blade redesign

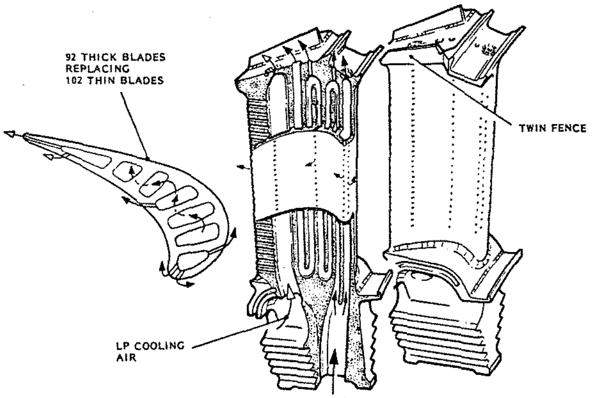


Figure 20

High blade speed unshrouded HP turbines, Figs. 12 and 15, show further potential if the rotor tip seal erosion problem can be contained. This is particularly difficult in the case of long life commercial engines. The application of 3D design methods to the ends of LP turbine airfoils is an obvious development illustrated already on Fig. 13.

### 3.3 Teambuilding and Worksharing

An unexpected and very significant contribution of the TACITUS Computing System has been its role as a teaching system. A considerable effort was put in during the creation of the system to provide on-line HELP routines, backed up by reference manuals, to give the user every possible assistance with the engineering task. Although obvious with hindsight, this has provided a powerful training medium for new professional recruits.

The advantages of size in a high technology industry can only be fully exploited if unnecessary duplication is avoided, and a common technical culture and operating procedure are established at all locations where similar work is done. It is then possible for work to be shared by facilities, as the load generated by individual projects varies. The growth of Rolls-Royce from several separate gas turbine manufacturers has presented many challenges in this area, and the unifying role of a technical computing network to which all contribute has been most beneficial.

## 4.0 SUMMARY AND CONCLUSIONS

Considerable progress has been made during the past five years in the prediction of turbine aerodynamic and heat transfer performance. This allows alternative designs to be evaluated in detail before the selected configuration is committed for manufacture. More accurate prediction results allow shorter and cheaper engine validation and certification programmes as well as improved component performance.

## 5.0 ACKNOWLEDGEMENTS

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