Rolls-Royce RB 211-535 Power Plant

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This paper describes the derivation of the RB 211-535 power plant as a fuel-efficient intermediate thrust size engine for short-haul twin-engined aircraft. It traces, from its conception, the basic -535C, which has a 25% better fuel burn than existing engines in this category, through to engine certification in 1981 and service in 1983. The paper then describes the later version of the engine, the 535E4, generated in response to the increasing importance of fuel burn as oil prices and scarcity increase. This engine maintains the proven background of the RB 211 family but incorporates later advanced technology, giving rise to a further 10% fuel burn improvement and thrust growth potential. By using some of this thrust growth it is shown that this engine is capable of powering existing medium-haul wide-body trijets to produce fuel burn savings of up to 12%.

I. Introduction

THE RB 211-535 is the third generation of the RB 211 family of 3-shaft high bypass ratio turbo fan engines (see Fig. 1). Rated initially at 37,400-lb takeoff thrust it is designed for short-haul application, particularly in twin-engined aircraft.

The origins of the engine go back to the early 1970s with the belief that the industry would soon want the advantages of the big fan engines, then just entering service in wide-body medium/long-haul aircraft, for the next generation of short/medium-haul aircraft. Takeoff thrust requirements at that time were thought to be in the so-called "10 tonne" category for three-engined application and many studies including a collaboration exercise in the mid-70s, were carried out on new engines for this role.

However, in 1976 the shape of the future was determined when the aircraft constructor's thoughts crystallized into a twin-engined aircraft requiring a takeoff thrust in excess of 30,000 lb. The change to a twin immediately placed far greater emphasis on reliability, and the increased thrust requirement made it possible to derive a very attractive engine from the existing RB 211s and by this means also ensure rapid maturity.

Main design work on the RB 211-535C started in February 1977 and the engine was launched when Eastern Air Lines and British Airways ordered the Boeing 757 with the -535C in August 1978—the first Boeing commercial jet aircraft launched with a Rolls-Royce engine. Certification of the engine was achieved in 1981; the engine has met all its targets on performance, weight, noise, emissions, etc., and will enter service in early 1983.

The steady increase in fuel prices through the 1970s escalated markedly towards the end of the decade and this accelerated planned studies into improved fuel consumption versions. These were finalized in July 1980 when Rolls-Royce committed itself to the RB 211-535E4 program. By building on the platform of what had become a very successful -535C development program and then incorporating the latest proven advanced technology, the -535E4 gives fuel consumptions competitive with new designs while still retaining the derivative approach for rapid maturity in short-haul twin-engined applications. The -535E4 is scheduled for certification in December 1983, with entry into service in late 1984.

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II. RB 211-535C

General Description

The heart of the modern aero gas turbine engine is the high pressure system. Because of its difficult working environment of high absolute pressure and temperatures with the smallest blading sizes, it is this part of the engine that requires most attention during development and traditionally causes most problems during in-service operation. Therefore in deriving a new engine for twin-engined application with its emphasis on reliability it is beneficial to start with a proven high pressure system.

Figure 2 shows the general arrangement of the -535C compared with the RB 211-22B rated at 42,000-lb takeoff thrust which has been in service in Lockheed's L1011 aircraft since 1972. The prime requirement for rapid maturity is achieved by using the -22B high pressure system for the -535C. The -22B has been the subject of an ongoing product improvement program to improve performance and durability and the latest features are included in the -535C HP system. In particular these include the latest high pressure feed cast directionally solidified high pressure turbine blade now in service in the -22B fleet (see Fig. 3) and a new high pressure nozzle guide vane of improved aerodynamic profile and reduced cooling airflow requirements.

An improved combustor is specified able to meet likely future emissions requirements and with the latest head and liner wall cooling technology to maximize durability with the lowest cooling airflow usage.

With a smaller thrust requirement than the -22B and the need to minimize frontal area (and hence cowl drag), weight, and manufacturing cost, the -535C has a smaller fan than the -22B. The fan chosen is a 0.86 linear scale of the best RB 211 fan in service—that of the RB 211-524B4. This reduces the total airflow by some 25% compared with the -22B. To retain a high bypass ratio the core flow of the -535C is reduced by approximately 25% by removing the first stage of the -22B intermediate pressure (IP) compressor. The resultant lower operating pressure ratio of the IP compressor also removes the need for the variable angle inlet guide vane, contributing to the high reliability needed for twin-engined operation. Engine testing in an altitude facility and flying test bed has demonstrated excellent handling characteristics with stall-free operation.

The effect of the small reduction in overall pressure ratio on fuel consumption is more than counterbalanced by the higher efficiency of the new turbine components. The intermediate pressure compressor is driven by a single-stage intermediate pressure turbine with an uncooled cast directionally solidified blade and the fan is driven by a three-stage low pressure turbine with cast hollow uncooled blades. While the general proportions appear the same as the -22B, the fact that the design conditions are different has allowed new designs to be used. This new low pressure turbine has been tested at 93% efficiency.

Fan blade containment is achieved with a lightweight titanium casing wrapped with Kevlar—a high strength aromatic polyamide fiber. This has successfully demonstrated containment of a fan blade released in the root shank at maximum fan shaft speed and saves over 100 lb weight compared with conventional containment.

The achievement of low fuel burn is also enhanced by the use of supervisory digital electronic engine control. This provides accurate scheduling of fuel flow over the operating range, leading not only to fuel savings but also to maintenance cost savings due to more precise control of rated operating temperatures; and it also reduces pilot workload. By using an electronic supervisory system trimming a reliable hydromechanical fuel flow regulator, manual reversion is retained in the event of electronic failure.

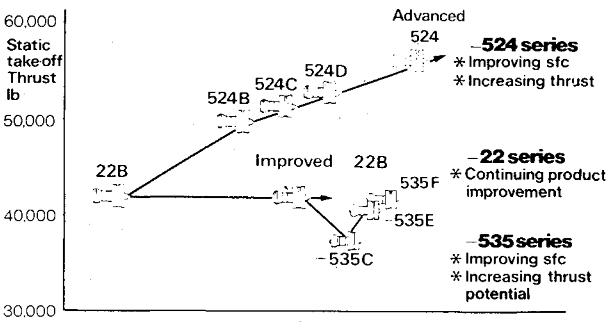

Fig. 1 RB 211 family.

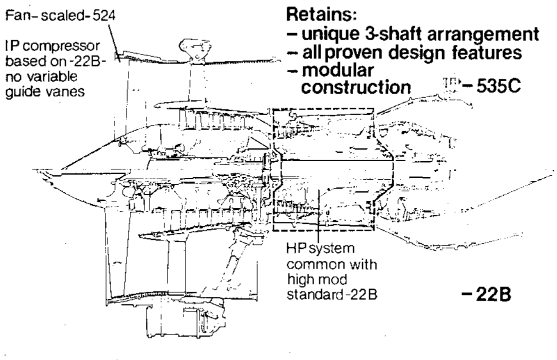

Fig. 2 RB 211-535C derivation.

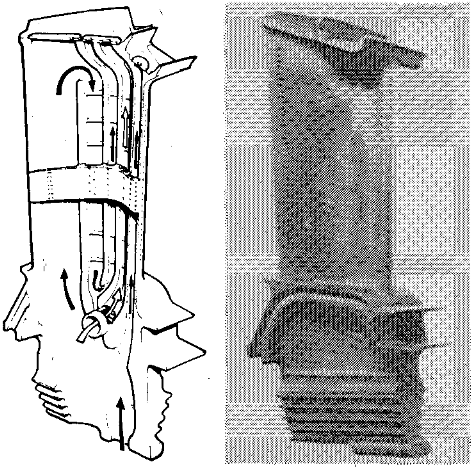

Fig. 3 RB 211 directionally solidified cast HP turbine blade.

It has been Rolls-Royce practice for many years to offer not just a bare engine but the complete propulsion system. As specific thrusts continue to be reduced in the search for better fuel consumption, it becomes increasingly important to ensure that the installation effects are optimized along with the engine. Since the installed performance is affected by cowl drag, bypass duct losses, afterbody drag, nacelle ventilation airflow, thrust reverser leakage, etc., Rolls-Royce believes it is essential for the engine manufacturer to have control of these features as well as being able to influence favorably any possible interference drag effects.

The -535C is therefore being developed as a complete propulsion system. The main components are shown on Fig. 4. The technology is similar to that of the RB 211-22B and -524 with two exceptions. Because of the smaller sized fan it is no longer possible to obtain access to the core engine for borescoping, etc., via the fan nozzle and bypass duct. The bypass duct and fan reverser therefore utilize the "C" duct principle, being split into two halves and hinged from the aircraft pylon. The engine can be removed with the C ducts left in place and vice versa. In addition, the fan cowl doors and fan reverser translating cowl are fabricated in carbon composite/honeycomb material to reduce weight.

Performance

On Fig. 5 the installed cruise specific fuel consumption loop of the -535C is compared with the existing generation of short/medium-haul low bypass ratio engines and also with the -22B and -524B2. It will be seen that the fuel consumption of the -535C is some 25% better than that of the existing low bypass ratio engines contributing significantly to the fuel efficiency of the new generation of short/medium-haul aircraft. It will also be noted that the installed fuel consumption of the -535C is better than that of the -524B2, which has the lowest cruise fuel burn of any existing big fan installation, as measured by the aircraft constructor in a common application.

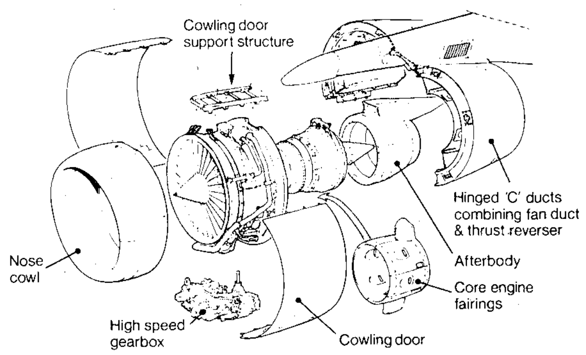

Fig. 4 RB 211-535C propulsion system.

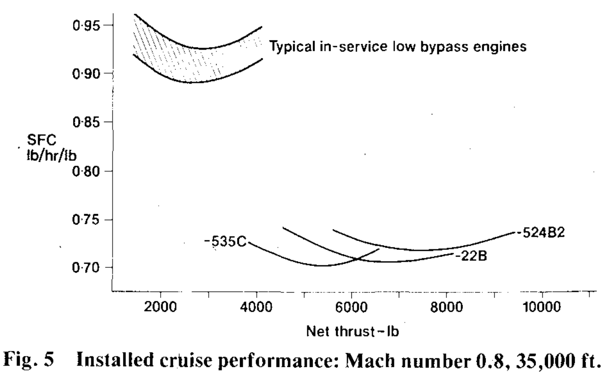

Fig. 5 Installed cruise performance: Mach number 0.8, 35,000 ft.

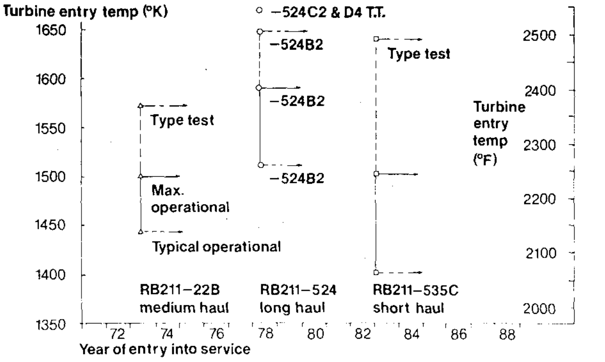

Fig. 6 RB 211 engines: typical, maximum, and type test takeoff turbine entry temperatures.

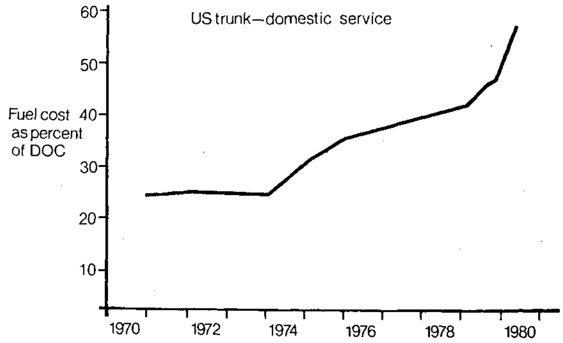

Fig. 8 Impact of fuel cost increases.

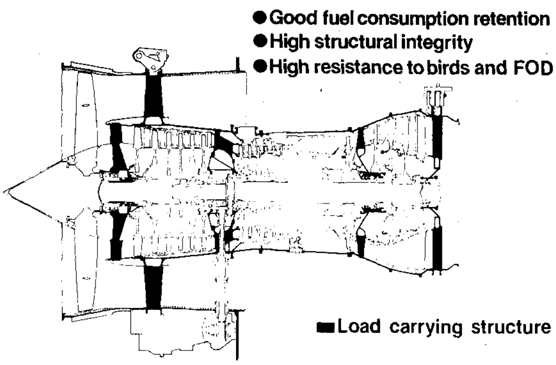

Fig. 7 RB 211-535C design features.

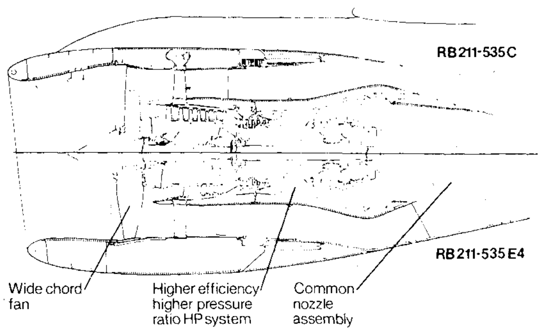

Fig. 9 RB 211-535E4: changes from -535C.

The fan size, and more particularly the core airflow, chosen for the -535C, are such that the thrust ratings required can be met without recourse to excessive turbine entry temperatures. In general, the big fan engines in service today operate on long- or medium-haul routes. The -535C is designed for short-haul operation, where a much greater proportion of each flying hour is spent at takeoff and climb conditions. Figure 6 compares the turbine entry temperatures of the -22B medium-haul engine, the -524B2 long-haul engine, and the -535C short-haul engine for type test (i.e., red line) conditions, maximum hot day takeoff, and typical operational takeoff where the actual rating used is matched to the aircraft weight, runway length, altitude, and day temperature. It will be seen that although the -535C will operate typically at lower turbine entry temperatures than the -22B and -524B2, the engine has been designed and cleared for red line turbine entry temperatures approximately equal to the -524B2. This gives very large operational margins leading to higher reliability and low cost of operation.

Performance Retention

The achievement of a good level of performance on new production engines is of little value if this quickly deteriorates in service. In general, the existing big fan engines have not been as good in this respect as their predecessors.

The retention of initial levels of performance depends primarily on two factors: first, maintaining tight tip clearances between the rotating blades and the static casings and, secondly, maintaining the profile of the aerofoils, some of which operate with supersonic incident flows.

The RB 211 family of engines has a number of special design features to achieve these ends which have been more than adequately proven in service operation. All of these are retained in the -535C design as shown in Fig. 7 and can be summarized as follows:

1) The 3-shaft concept with its four bearing chambers results in a short rigid construction with short bearing spans.

2) The main structural carcase is separated from the aerodynamic flow-path casings. Thus carcase deflections resulting from thrust and *g* loads do not deform the aerodynamic casings.

3) The design of the fan and bypass splitter is such that most of the airborne debris entering the apparent core engine catchment area is actually centrifuged down the bypass duct.

4) All compressor aerofoils are of low aspect ratio and substantial thickness/chord ratio to resist erosion damage.

5) Transient radial and axial tip clearance variations are minimized by inherently matching the radial and axial thermal response rates of rotors and casings without recourse to modulated external case cooling.

6) All turbine blades are shrouded with multifinned tip seals since these are less sensitive to tip clearance effects.

Some of these features cost weight. However, in the -535C this has been more than counterbalanced by the use of the latest design techniques, advanced materials, and constructions such that the power plant takeoff thrust/weight ratio is 10% better than that of the RB 211-22B.

III. RB 211-535E4

General

The cost of fuel over the last decade has far outstripped other costs. Figure 8 shows the cost of aviation fuel as a percentage of direct operating cost for U.S. trunk domestic operations. The rate of increase over the last two years is particularly marked and it shows little sign of abating.

Notwithstanding the fact that the -535C will burn up to 25% less fuel than the generation of engines it succeeds, Rolls-Royce recognized the ever-increasing importance of fuel burn even on short-haul operation, and soon after the launch of the -535C the Company accelerated planned studies into improved performance versions leading to the RB 211-535E4, rated at 40,000-lb static takeoff thrust. The strategy adopted is to retain the derivative concept of the -535C and the proven good features read across from RB 211 service experience and then to incorporate the latest proven advanced technology to give further substantial fuel burn reductions with in-built thrust growth for other applications.

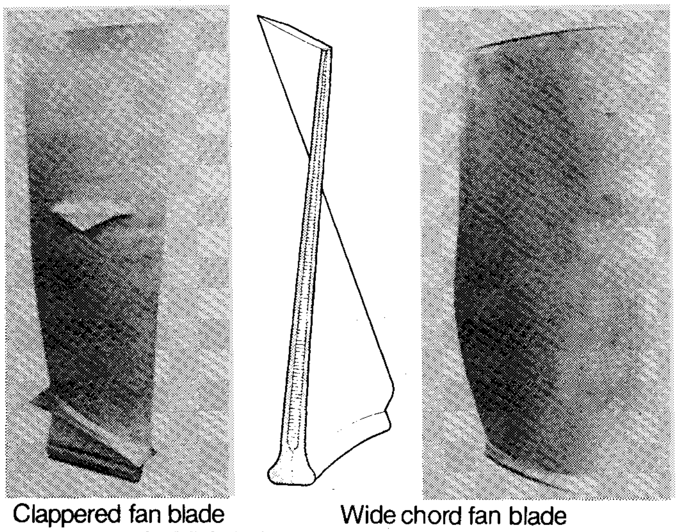

Fig. 10 RB 211 wide-chord fan blade: construction.

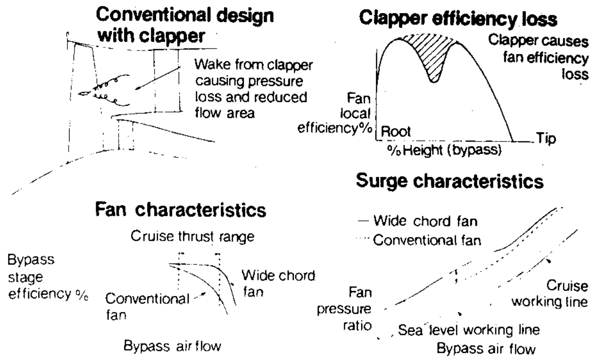

Fig. 11 Wide-chord fan performance.

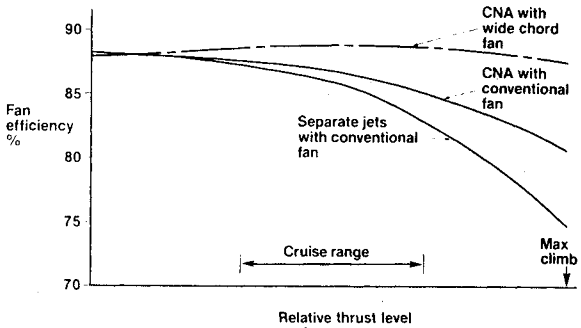

Fig. 12 Effect of common nozzle assembly on fan performance.

There are three main areas of change in the -535E4 design from -535C, namely, the wide-chord fan, improved high pressure system, and the common nozzle assembly (see Fig. 9).

Wide-Chord Fan

All big fan engines in service today have solid titanium fan blades with one or two rows of part-span dampers to ensure aero/mechanical stability. These dampers are in a transonic incident flow regime and cause losses on the component which has the single-most powerful effect on performance. Dampers can be eliminated if the chord of the fan blade can be increased sufficiently to ensure inherent stability. However, the weight penalty of achieving this with a conventional solid fan blade, particularly bearing in mind the need for fan blade containment, is prohibitive.

Rolls-Royce has been working for many years to achieve the performance advantages associated with damper removal without this weight penalty by developing a wide-chord titanium fan blade of fabricated construction. The problem has been to perfect a viable process which will have at least the same mechanical integrity as current solid fan blades. Testing started over ten years ago with laboratory specimens exploring low- and high-cycle fatigue (LCF and HCF) life and foreign object impact capability. The next step was mechanical rig testing on full size blades covering LCF spinning tests, HCF flap tests, bird ingestion, and fan blade containment tests. Finally, over the last seven years full-scale engine tests on -22B and -524 engines have demonstrated that the mechanical properties of the wide-chord fan are at least as good as with solid blades and, in the case of bird strikes, significantly better now that the restraint of the damper has been removed.

The method of construction is shown on Fig. 10. In simple terms the aerofoil and its integral root are formed from two titanium sheets which are chemi-etched on their internal surfaces and then bonded together with an internal titanium honeycomb core by an accelerated diffusion brazing process. The aerofoil surface is then machined. The root is curved to allow better transition of the aerofoil loads into the disk. On the -535E4 this wider chord results in the number of fan blades being reduced from 33 to 22. Figure 11 shows how the removal of the damper with the wide-chord fan blade improves flow capacity, efficiency, and fan pressure ratio: these contribute about 2½% fuel consumption improvement on the -535E4 at typical cruise with further thrust growth capability.

Improved High Pressure System

The RB 211-22B high pressure compressor as used in the basic -535C was designed some years ago. The -524 high pressure compressor was developed later to pass more airflow at a higher pressure ratio for thrust growth. This higher pressure ratio is used in the -535E4; to match the flow capacity to the -535E4 requirement, the -524 high pressure compressor has its outer diameter decreased slightly to reduce blade height, and flow capacity, by about 10%. The use of this compressor, with the aerofoils modified to run more efficiently in the boundary layer, raises the overall pressure ratio at cruise to 28:1 and further improves the efficiency.

The higher compressor pressure ratio reduces the high pressure compressor outlet volume flow and therefore requires a smaller capacity high pressure turbine. In redesigning for this, the latest high pressure nozzle guide vane features a curved aerofoil stack, derived from three-dimensional, viscous flow technology developed in the Rolls-Royce advanced engineering program. This technology achieves low profile and end wall loss resulting in more uniform vane exit gas conditions. The cooling of the high pressure turbine vane and blade has been designed to suit the three-dimensional blading and minimizes cooling airflow usage. This has been achieved by high efficiency multipass/film cooled systems and application of thermal barrier coatings.

The intermediate pressure turbine nozzle guide vane also incorporates three-dimensional flow technology to reduce secondary flow losses. The combined high and intermediate pressure system changes contribute 4% improved fuel consumption at typical cruise conditions.

Common Nozzle Assembly

Earlier Rolls-Royce bypass engines such as the Conway and the Spey had exhaust mixers to transfer energy from the high velocity hot gas stream to the lower velocity bypass stream and hence improve propulsive efficiency. The choice of the mixer design was a careful balance between theoretical mixing gains and associated mixer parasitic losses. On high bypass ratio fan engines the exhaust dynamic head is a much larger proportion of the total head and therefore the engine is much more susceptible to parasitic mixer losses; this has so far

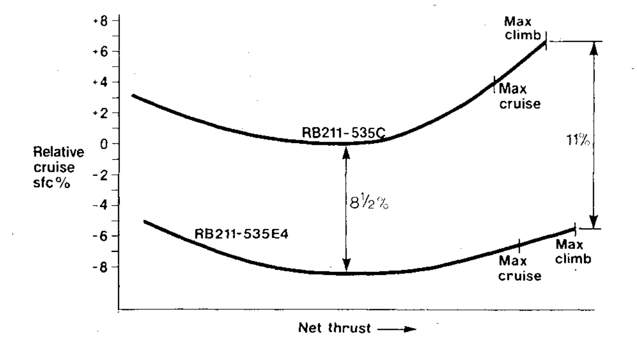

Fig. 13 RB 211-535 cruise performance: Mach number 0.8, 35,000 ft, International Standard Atmosphere (ISA).

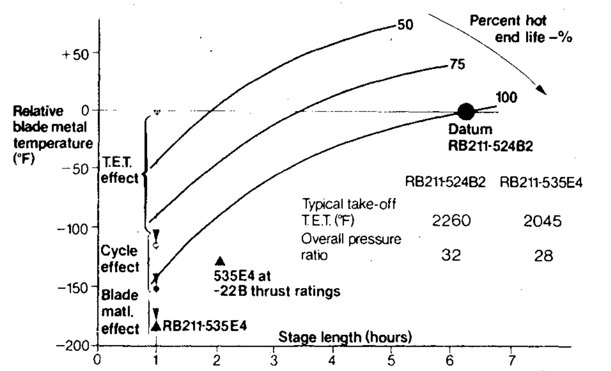

Fig. 14 Effect of stage length and thermodynamic cycle on turbine life.

Table 1 Typical short-haul fuel burn breakdown, 500 n.mi., max passenger payload

	Typical distribution of fuel burn, %	Saving in segment fuel—535E4/535C, %
Taxi	6	22
Takeoff	6	10
Climb	41	9
Cruise	38	8
Descent	5	18
Approach and land	4	10
	100	
Overall reduction in total fuel burn		9.9

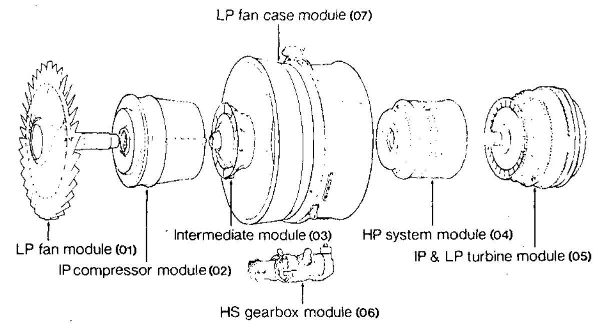

Fig. 15 RB 211-535 modules.

deterred the application of mixers to high bypass ratio engines.

However, recent research work by Rolls-Royce has shown that expanding the fan and core streams through a common propelling nozzle on a high bypass ratio engine with no booster stages on the LP shaft (e.g., a 3-shaft engine), produces performance gains over and above the mixing effect, owing to a thermodynamic cycle rematching effect. With a common propelling nozzle the proportions of the nozzle area occupied by the fan stream and core stream vary over the engine operating range. Thus the engine is effectively operating with variable area fan and core propelling nozzles, although actually with fixed geometry. Reducing the effective core nozzle area reduces the low pressure turbine expansion ratio and thus slows down the low pressure shaft at a given thrust. At high corrected engine speeds, such as climb rating, the fan is normally operating below its peak efficiency owing to high fan blade incident Mach number effects. Reducing the fan speed at a thrust thus increases its efficiency and hence improves the specific fuel consumption. At the same time the fan nozzle effective area is increased, and by careful optimization this is used to shift the fan working line to an area of even higher efficiency. This process is further enhanced by the characteristics of the wide-chord fan (see Fig. 12).

This improvement in specific fuel consumption due to the common nozzle assembly also reduces turbine entry temperature at a given thrust. The inherent shortness of the 3-shaft concept minimizes the external drag due to the increased nacelle area.

Performance

The total effect on performance of the -535E4 changes described above is shown on Fig. 13. It will be seen that at typical cruise conditions the specific fuel consumption of the -535E4 is improved by approximately 8½%. However, the effect of the cycle and the common nozzle assembly rematching effect in further improving the fuel consumption at higher thrust levels is also seen: at maximum climb rating, for example, the fuel consumption is improved by up to 11%. There is also a corresponding reduction in turbine entry temperature at a thrust of up to 75°K (135°F) which can be used to extend hot end life and reduce operating costs or, alternatively, to provide future thrust growth.

The significance in short-haul operation of this flattening of the fuel consumption loop becomes apparent on analysis of typical short-haul segment fuel burn breakdown. This is shown in Table 1, which breaks down the total block fuel for a 500-n.mi. stage. It will be seen that more fuel is burnt at climb conditions than at cruise conditions. The segment fuel burn improvements of the -535E4 relative to the -535C are also shown; in conjunction with attention to low power fuel burn this leads to a total block fuel burn saving of approximately 10%.

The common nozzle assembly also dramatically improves reverse thrust performance. In reverse mode the fan reverser blocker doors divert the fan stream through the reverser cascades conventionally. However, with the common nozzle assembly the core stream now expands to fill the common propelling nozzle by itself. Thus the expansion ratio across the low pressure turbine is increased, reducing the residual core stream forward thrust to very low proportions and hence giving up to 40% more net reverse thrust. Furthermore, because more energy is now being extracted by the low pressure turbine, the core engine conditions of rotational speed and turbine entry temperature required to obtain maximum low pressure shaft speed in reverse are reduced, thus prolonging engine life.

Thus the changes in the -535E4 compared with the -535C have not affected bypass ratio, which remains at approximately 4.5:1, the overall pressure ratio has been increased by about 4 points (to 28:1), while the turbine entry temperature at constant thrust has been reduced. The overall pressure ratio and turbine entry temperature are lower than for other members of the RB 211 family and this is important in the context of short-haul operation. Compared with long-haul operation, each flying hour of short-haul operation has more flight cycles and a greater proportion of time spent at takeoff and climb ratings, with less time spent at the easier cruise ratings. Short haul is very punishing to the engine compared with long haul.

Figure 14 shows the effect on hot end life of stage length and high pressure turbine blade metal temperature. The metal temperature is affected by turbine entry temperature, turbine blade cooling air temperature (i.e., overall pressure ratio), and the basic cooling configuration. The datum is the -524B2 operating over an average 6¼-h stage. Its maximum hot day takeoff turbine entry temperature is 1590°K (2400°F), but for typical operation with flexible ratings the average takeoff turbine entry temperature is 1510°K (2260°F). The overall pressure ratio at cruise is 32:1. This engine is achieving a very satisfactory hot end life on long-haul operation. However, if the same engine cycle were used for short-haul operation, say 1-h stage length, it will be seen that its hot end life, determined by creep and thermal fatigue considerations, would fall to about 35% because of the greater number of cycles per hour and the greater proportion of each hour spent at higher ratings. (This has been recognized in some later versions of the -524, which have been reoptimized for short/medium-haul application.) On the -535E4 over this 1-h stage length the average takeoff turbine entry temperature with flexible ratings is about 1390°K (2045°F), which reduces the turbine blade metal temperature relative to the -524B2 by 67°K (120°F). This increases the life to 85% of datum. The lower overall pressure ratio of the -535E4 (28 compared with 32) reduces turbine blade cooling air temperature and this increases the life to 105% of datum. Finally, the turbine blade material and blade cooling technology of the -535E4 are superior to the -524B2 (cast DS blade compared with conventionally cast blade, etc.), increasing the life to 125% of datum. Thus even on arduous short-haul operation the cycle chosen for the -535E4 will give a superior hot end life to that of the higher overall pressure ratio, higher turbine entry temperature -524B2 optimized for its long-haul operation.

Figure 14 also shows the effect of capitalizing on the inbuilt thrust growth potential of the -535E4 by uprating it to the thrust of the RB 211-22B (i.e., 42,000-lb static takeoff thrust). It then becomes a candidate for installation in existing wide-body trijet aircraft for medium-haul operation. It will be seen that the effect of this uprating on hot end life is just counterbalanced by the effect of the longer stage length (assumed to be 2 h on average). Relative to existing engine installations this would produce a block fuel saving on typical operations of up to 12%, owing to the better fuel consumption and lighter power plant weight, or give range increases at maximum passenger payload of up to 20%.

The Future

The RB 211 is a very modular engine with the main turbo machinery components being conveniently split into major modules (see Fig. 15). This facility has already been exploited in developing the RB 211-524 by progressively incorporating technology improvements in modular form as they have become proven in the advanced engineering program. By this process the -524 cruise fuel consumption has already improved from the -524B standard to the -524B4/D4 standard by 5%, with substantially more to come.

The same process is planned for developing the -535E4 beyond the committed standard defined here. Work is already in progress in advanced engineering programs on the following: 1) further improved efficiency from the wide-chord fan no longer restricted by midspan dampers; 2) prescribed velocity distribution core compressor aerofoils for higher efficiency; 3) higher efficiency, higher rim speed, high pressure turbine; 4) further cooling and ventilation airflow economies; and 5) continued development of the common nozzle concept.

These are expected to lead to a fuel consumption improvement of at least 3% on the -535E4 after its initial certification.

IV. Summary

The concept of the -535 program has been generated to meet the specific requirements of short-haul twin-engine operation. By using the derivative approach, retaining all the proven good features of the RB 211 family while designing out those which service experience has shown to be less satisfactory, rapid achievement of maturity and reliability is assured. By choosing a thermodynamic cycle matched specifically to short-haul operation and concentrating on incorporating the latest proven advanced technology to achieve the highest component efficiency levels and reduced secondary airflow usage, very low levels of fuel consumption are achieved.

The soundness of this approach has been confirmed by the success of the -535C development program. There have been remarkably few development problems, the program has run ahead of schedule and the cruise specific fuel consumption targets have been achieved during development. This has provided the springboard for the inclusion of further advanced technology in the -535E4 and beyond.

Acknowledgment

My thanks are due to many colleagues at Rolls-Royce whose contributions have been used here.