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Developing the Rolls-Royce Tay

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ABSTRACT

Description & Application

The paper traces the evolution of the Tay engine, launched in response to the requirement for an engine suitable for powering a FAR Part 36 Stage 3 noise compliant aircraft in the 70-100 seat range. The engine, which is derived from the Spey (RB183) Mk 555 installed in the Fokker F28 aircraft, incorporates several latest technology features a number of which are already in service in large turbofan engines. Modularity and maintainability are key areas which have been addressed in the design of the engine; these are discussed in regard to operation in service.

Results, Conclusions & General Observations

The eight engine/two year development programme from first engine run to Type Approval by the United Kingdom Civil Aviation Authority is reviewed with detail description of some of the more important and interesting tests. Certification by the US Federal Aviation Administration was subsequently achieved under reciprocal cross-validation procedures. Flight certification of the two lead aircraft applications is now complete.

With completion of type certification of the baseline engine and production deliveries now underway, attention is being turned to growth derivative versions of the engine: an uprated version, due to come on stream late 1988 in an increased weight version of the Fokker 100 has now commenced its certification programme - and further growth capabilities are being explored.

INTRODUCTION

In 1983, P J Ashmole presented a paper entitled "Introducing the Rolls-Royce Tay". This paper covered the design of the Tay engine as seen at a very early stage of its development. Since that time the Tay has passed through a full development and certification programme and is now in service in the Gulfstream GIV executive jet and the Fokker 100 regional airliner.

It is worthwhile to review the pedigree of the Tay and reasons for its development, followed by a look at the engine in detail and the rigorous certification testing required to clear the engine for commercial use.

BACKGROUND

Older low bypass ratio jet engines were rather noisy. This was largely a consequence of their high jet velocities generating noise external to the engine when the jet plume mixes with ambient air. With toughening of international legislation (from FAR Part 36 Stage 2 to Stage 3 in the USA), engine noise reduction was mandatory and exhaust suppressors were an immediate, yet unattractive, option. The best solution was a reduction in jet velocity which could only be achieved by increasing the bypass ratio. This also gives incidentally a major performance improvement.

The Rolls-Royce RB183 Mk 555 (Spey) engine on the Fokker F28 was no exception to this and work began in the early 1980s to develop a quieter powerplant for developments of the F28.

At the same time as Fokker were looking

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at F28 developments, it became apparent that the new engine was ideally suited for a development of Gulfstream Aerospace's GIII business jet offering improved range, payload and quietness. The Gulfstream aircraft was not restrained by international noise restrictions but there was a need to quieten the aircraft to satisfy local airport restrictions and to adopt a positive "good neighbour" policy.

In designing the engine to meet the requirements of both the long range, high performance executive jet and the short to medium range, 100-120 seat airliner, Rolls-Royce set out to meet the following design requirements:

1 Low environmental impact - the engine had to meet all current and proposed international noise legislation requirements and comply with the regulations controlling smoke and exhaust emissions.

2 Low cost of ownership - to be achieved by offering a low fuel burn, competitive maintenance costs and a high level of reliability and dependability from start of operation.

3 It was decided that these objectives had to be achieved by means of a cost-effective design concept which minimised engine development costs and hence first cost to the operator, and incorporate the modular construction successfully applied in the RB211 family.

It was considered from the start that these requirements could best be achieved by adopting the derivative design approach similar to that employed in the 535 variant of the RB211 family and which is widely regarded within the industry as the most reliable large fan engine in service. This derivative design approach combines a careful blend of mature experience and proven advanced technology features, either extensively developed in advanced engineering demonstrator programmes or already operating in service.

The core of the RB183 Mk 555 was selected to provide the heart of the new engine from the outset, this being the latest and most reliable of the Spey family. To this, the best fan technology available was added together with other advanced technology features from the 535 to produce a quiet, highly reliable derivative engine, figure 1.

In keeping with a long standing Rolls-Royce tradition, the engine was christened with the name of a British river. The Tay takes its name from a famous salmon river flowing out of Loch Tay in the Grampian mountains in central Scotland.

Tay integrated design philosophy

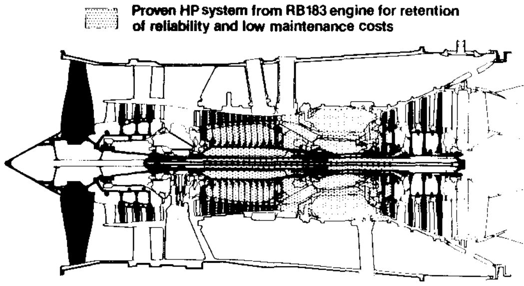


Figure 1

In the event, it was the Gulfstream aircraft, the GIV, which launched the Tay programme in March 1983. This was followed in October of the same year by the first engine orders for the new Fokker 100. A third application for the Tay followed in 1986 with the re-engining of the BAC-111 by the Dee Howard Corporation of Texas.

As one can imagine, these applications require a range of thrusts which the Tay is able to provide under three distinct engine marks:

The Tay 620, rated at 13,850 lb take-off thrust (at ISA, SLS conditions) powers the Fokker 100 whilst Gulfstream IV uses an engine closely related to the Tay 620, having the same take-off thrust but reduced climb and cruise thrust, designated the Tay 611.

These engines are now fully certificated and flying in service on both types of aircraft. (Figure 2).

The versatile Tay

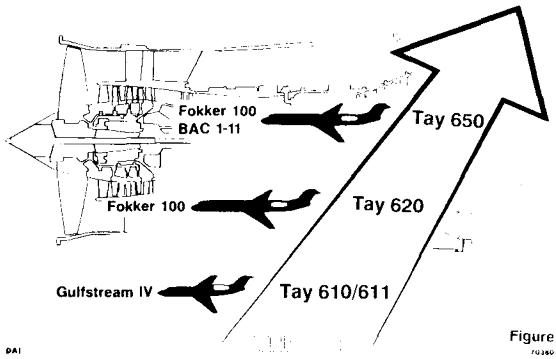


Figure 2

The third engine mark, the Tay 650, is a development of the Tay 611/620 providing 15,100 lb of take-off thrust. Both the re-engined BAC-111 and higher performance versions of the Fokker 100 use Tay 650 power.

The Tay 650 was launched in July 1985 as the first stage of a committed programme of development which is matched to airframe manufacturers requirements. The essential differences between the Tay 650 and Tay 611/620 are a new advanced technology high pressure turbine, an improved combustor and a minimal (0.8 in, 20.3 mm) increase in fan diameter, illustrated in figure 3. These items, plus other minor improvements will be discussed in the appropriate sections later in this paper.

Tay 650 — Major changes from Tay 620

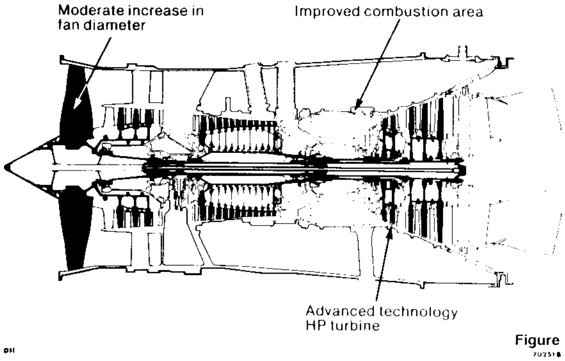


Figure 3

ENGINE DESCRIPTION

There are many features of the Tay design worthy of further examination. These will be covered in individual sections, beginning at the front of the engine and working rearwards.

The Wide Chord Fan

As mentioned earlier, it was Rolls-Royce's intention to incorporate into the Tay the best fan technology available. To this end, the wide-chord fan was selected, scaled directly from the RB211-535E4.

The wide chord design is intrinsically stiff enough to eliminate the need for mid-span snubbers. This radical departure from traditional designs brings with it many benefits including:

- Improved efficiency
- Improved surge margin
- Greater resistance to Foreign Object Damage (FOD)
- Better noise characteristics.

Conventional fan blades have narrow chords and require snubbers to control vibration. These snubbers are located roughly at mid-span where the flow is supersonic and they cause significant blockage and loss of efficiency. In order to delete the snubbers, the chord of the blade had to be increased by about 40% to maintain control over vibration. The associated gain in efficiency can be seen in Figure 4 compared to a conventional design.

Tay uses the most efficient fan design

Typical fan efficiency profile

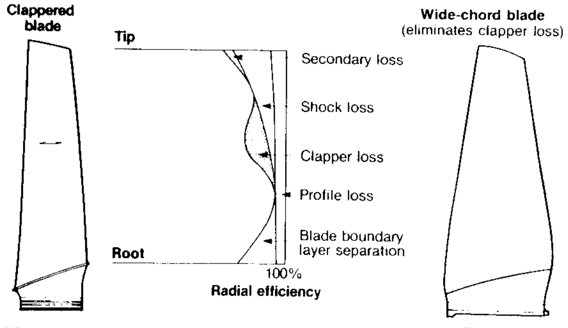


Figure 4

The low aspect ratio fan has also demonstrated higher levels of stability margin, Figure 5, which allows the engine matching to be optimised to further enhance performance. These performance gains are illustrated in Figure 6.

Wide-chord fan increases surge margin

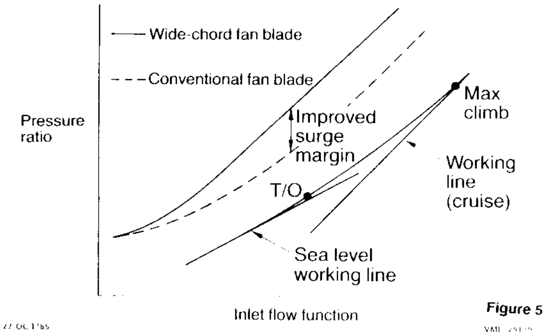


Figure 5

Fan flow efficiency comparison

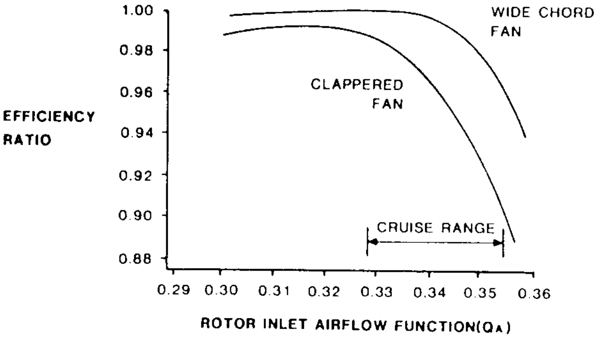
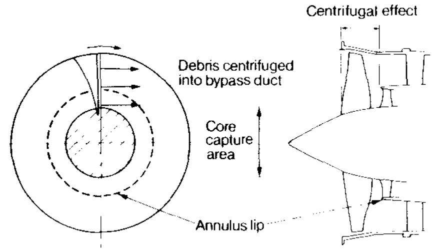


Figure 6

In high bypass ratio engines, the fan tends to centrifuge a proportion of debris or foreign objects entering the intake into the bypass duct. Wide chord fan design gives a greater axial distance between the leading edge of the fan and the splitter as a result of its increased chord. This gives more time for debris entering the nacelle to be centrifuged out to the bypass duct and pass harmlessly out of the rear of the engine. See Figure 7.

Tay design features to resist FOD



- Annulus lip positioned to allow maximum centrifugal effect and hence minimum core capture area
- Wide-chord high strength fan
- Sturdy low aspect ratio IP compressor blades and vanes

Figure 7

The increased chord also means that each blade moves a larger amount of air than its predecessor and therefore for a given flow, fewer wide chord blades are required - 22 in the case of the Tay.

This smaller number of blades matched to the number of stators leads to a significant change in noise transmission losses through the rotor relative to a conventional narrow-chord fan. This can mean a reduction of approximately 2 EPNdB at approach power compared to a conventional narrow-chord snubbered fan, as well as reductions in rearward radiated noise through the bypass duct.

The diameter of the Tay fan was chosen to be 44 inches as this optimised the noise characteristics when providing the required bypass ratio of 3 and suitable fan pressure ratio to give the best altitude cruise performance. It is manufactured as a solid titanium forging retained in the fan disc by a curved dovetail root, and was subjected to much development and certification testing as will be seen later.

Intermediate Pressure (IP) Compressor

The fan root alone does not produce as much pressure rise as the four stage LP compressor of the RB183 Mk 555. To maintain high pressure compressor entry conditions unchanged as is required in keeping the Tay HP system exactly as the Spey, an additional supercharging compressor is required. This boosts approximately 25% of the fan flow before passing it to the HP compressor. For simplicity of layout this is coupled to the fan shaft (see Figure 8) so that the fan and intermediate pressure (IP) compressor become an integral unit.

The disadvantage of this arrangement is that the fan effectively prevents the IP compressor responding to HP compressor capacity changes during engine transients making it usual to include a bleed valve between the two to dump excess IP compressor delivery air and thus prevent surge of the IP compressor.

Tay high-efficiency LP compressor system

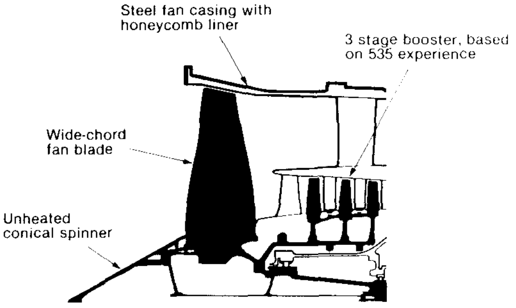


Figure 8

Three modestly loaded stages were chosen for the Tay Intermediate Pressure Compressor which, with minimal development, achieved sufficient surge margin, with no loss of working efficiency, to allow the bleed valve to be deleted. The Tay is the only engine known to Rolls-Royce which has a coupled fan-IP compressor arrangement which does not require a handling bleed on the IP compressor.

The aerofoils have been designed using the latest computer aided techniques employed in the RB211-535E4 to increase aerodynamic efficiency and contribute to reduced fuel burn. Spacing between rotor blades and stators has been carefully optimised to minimise forward noise generation.

High Pressure System

The HP core consisting of a 12 stage compressor, 2 stage HP turbine and tubo-annular combustion system, together with the fuel control system, is almost exactly as the existing RB183 Mk 555, with only detailed cooling changes. The HP compressor consists of twelve separate rotor discs mounted on a two-piece steel shaft, coupled to the forward end of the HP turbine shaft, see figure 9.

Tay HP compressor system

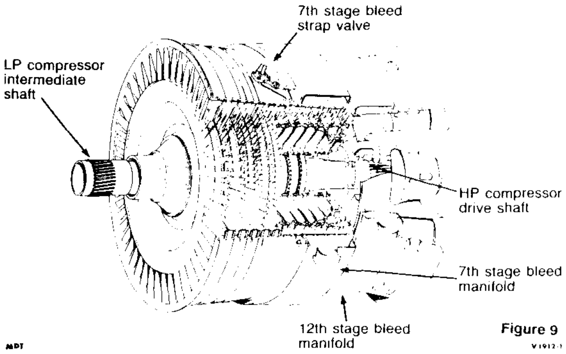
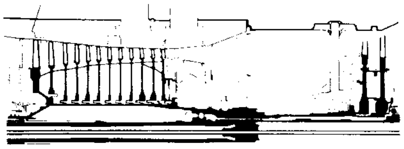


Figure 9

The HP system is designed to provide a high compressive efficiency at the high speed at which the engine runs during take-off and cruise. To enable the engine to run at the low engine speeds normally associated with starting and ground running an airflow control system is used. This consists of variable guide vanes at the HP compressor inlet linked to an annular bleed valve in the casing surrounding the seventh stage of the HP compressor. This control system, powered by a hydraulic actuator resonding to a non-dimensional HP rpm signal, limits the mass of air supplied to the combustion section at low speed, but reduces this control as the engine speed increases.

The integration of the LP system with the core has been designed to maintain core inlet and outlet conditions similar to those in the RB183 Mk 555, so ensuring that the hot section reliability for which the RB183 Mk 555 is famous, will be maintained. Figure 10.

Tay HP system — Proven in the RB183 Mk555



- **Correct size for Tay engine duty**
- **Over 7 million hours direct experience**
- **Proven excellent reliability**
- **Moderate turbine entry temperature and speeds**
- **Rugged construction**

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Figure 10

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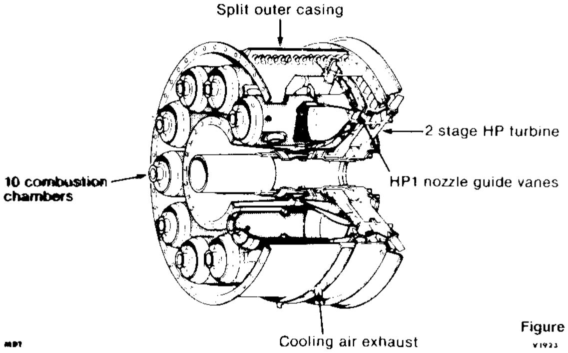
Combustion

The problems of combustor design have been increased in recent years because concern over pollution has led to regulations on the control of emissions from aircraft engines. These regulations have already been adopted in some countries and there is no doubt that the trend will continue. This means that the combustion engineer must now address the difficulty of reducing smoke and gaseous emissions throughout the engine range in addition to the more conventional problems of durability, exhaust gas temperature, pattern factor, relight etc.

The Tay retains the well-proven tubo-annular combustion system of the Spey family of engine and, although changes have been made, much of the Spey experience and hardware has been retained. Figure 11. Annular combustion was assessed but the position of the HP turbine support, a basic construction feature of the engine, plus an increase in the number of fuel injectors, adding cost and weight, precluded this change. One distinct advantage of tubo annular combustors has been the ability to test and develop single combustor on rigs which can achieve engine maximum operating conditions. This has enabled major improvements to be incorporated in a fast and cost-effective manner.

Tay combustion and turbine system (04 module)



MDT

Figure 11

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A disadvantage of a tubo-annular system, however, is that the combustor has a high surface area to volume ratic and therefore needs a relatively large amount of cooling. The cooling air can have a detrimental effect on emissions performance by quenching combustion reactions and entraining partly burned products. Therefore, to meet the stringent levels which have been set for engine emissions it was necessary to reduce the cooling air requirements of the Tay combustor significantly below conventional levels.

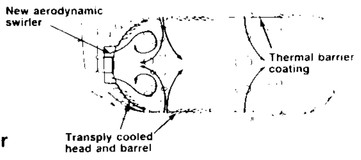
The method used to reduce the cooling air flows was to employ the Rolls-Royce pseudo transpiration material called Transply.

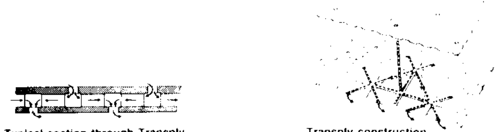
The air which is saved by the use of Transply is used in optimising the primary zone and intermediate zone stoichiometry which, combined with the use of an aerodynamic curved vane swirler, results in the required levels together with acceptable metal temperature, ignition, etc. The combustion chamber is shown in Figure 12.

Tay – Low emissions combustion chamber

Benefits include —

- **Improved mixing**
- **Reduced cooling air**
- **Lower metal temperatures**





Typical section through Transply

Transply construction

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Figure 12

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Transply is produced by brazing together two laminates of a high temperature nickel alloy containing an interrelated pattern of holes and channels, produced by electro-chemical machining. This provides an advanced cooling configuration in sheet form with an overall thickness typical of current combustor materials. Figure 12 shows how two-laminate transply is assembled. Various standards of two-laminate Transply have been produced with different combinations of holes in the feedside and hot gas side laminate.

The metering of the flow through Transply is carried out by the feedside holes through which the coolant enters from the external annulus. The air then impinges on to the opposite face and is then led away from the impingement chamber via channels to the outlet holes; these holes being arranged to provide an optimum external film coverage.

The excellent heat transfer properties of Transply have been further enhanced by the application of a ceramic thermal barrier coating.

Low Pressure Turbine

The low pressure turbine in the Tay is a design based on the RB211-535 turbine. To retain aerofoil loading at proven levels, the number of stages was increased from the Spey's two to three. At the same time the opportunity was taken to incorporate technology acquired during the RB211 programme. A major design objective was to achieve a turbine suitable for planned growth variants of the engine to around 17,000 lb of thrust, without significant modifications.

Computer aided engineering has significantly improved the quality of turbine design which can be achieved. Detailed throughflow and blade-to-blade analyses are used to converge upon optimum profiles and stack.

The complete aerodynamic philosophy was validated by running a heavily instrumented 0.65 scale rig. The corrected test results indicate that the new turbine achieves an efficiency about 3% greater than the Spey. Figure 13.

Comparison of Spey & Tay LP Turbine Performance

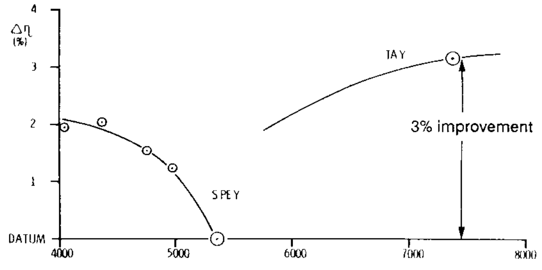


Figure 13

The LP turbine design represents a balance between noise, performance, reliability and weight.

Forged blading has been largely replaced by solid cast aerofoils. The final rotor stage remains as a forging however, as this is where higher strength can be used to offset turbine weight. Solid castings suffer no weight or performance penalty in small turbines, and can be produced more competitively than hollow castings.

The axial gaps between the blading were increased in the new turbine to reduce noise generation. Increased blade numbers have been incorporated to move the blade passing frequencies beyond the audible range. The increased gaps also reduce the risk of blade vibration due to wake excitation. This philosophy has contributed to earning the engine an excellent reputation for quietness.

In general, derivative technology has been applied to the mechanical design, which ensured high reliability and a straightforward certification programme.

Mixer

Mixing of the bypass and core flows takes place in the advanced design deep-chute forced mixer. Figure 14. This forces the two streams to mix efficiently, reducing mean jet velocity and therefore cutting down on sound-generating aerodynamic shear, while at the same time improving propulsive efficiency. Mixing efficiencies of up to 75% have been demonstrated giving a cruise sfc benefit, over free mixing, of about $1\frac{1}{2}\%$. A development of the Tay mixer is being used in the latest 524G variant of the RB211 engine for the Boeing 747 and 767 aircraft.

Tay 12-lobe mixer unit

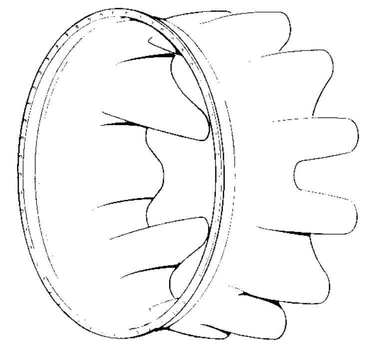


Figure 14

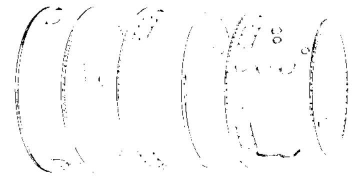
Bypass Duct

The bypass duct, composed of three separate sections, is constructed in lightweight, noise attenuating carbon fibre reinforced composite material, saving both weight and cost. A 25% weight saving has been achieved over the more conventional titanium alloys. Figure 15. The Tay is the first commercial engine to incorporate a bypass duct made entirely from carbon-fibre material.

Tay — Lightweight bypass duct

Benefits of carbon fibre bypass duct —

- Low weight
- High strength
- Readily repairable
- Acoustically-lined for low noise



Rolls-Royce has over 20 years experience in composite engine components

Figure 15

Nacelle and Thrust Reverser

The Tay engine is currently supplied as a bare engine, the nacelle being separately procured by the airframe customers. For the committed applications twin nacelles are rear fuselage mounted.

The nacelle position and length requirements are consistent with the provision of a common nozzle/mixed exhaust system, similar to the earlier Spey applications.

To achieve reverse thrust, a single pivot target type thrust reverser is used which forms the forward thrust nozzle when in the stowed position, see Figure 16. Reversers are a safety requirement for landing on wet and icy runways when wheel braking efficiency is greatly reduced.

The nacelle/thrust reverser assembly is common to both the Fokker and Gulfstream applications, and was co-developed by both manufacturers. A different design of nacelle is being introduced on the re-engined BAC1-11.

Thrust Reverser - Deployed

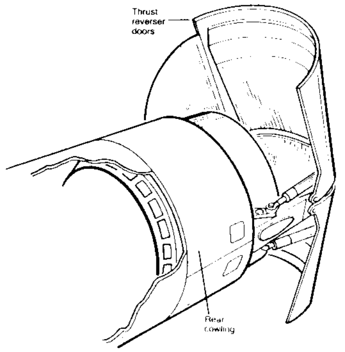


Figure 16

MODULAR CONSTRUCTION

In common with other modern Rolls-Royce engines, the Tay is built of a series of modules, with the benefits of:

- lower maintenance costs
- quicker turn-rounds
- lower inventories

Each of the seven modules (see Figure 17) may be handled as an entity capable of removal and replacement. Modules containing rotor parts are supplied ready balanced, and precision couplings ensure accurate re-assembly.

Module changes may be effected without the need to return the engine to the repair and overhaul shop, thus reducing time spent on maintenance and enabling the engine to be returned to service more rapidly.

Tay modularity for lower maintenance costs

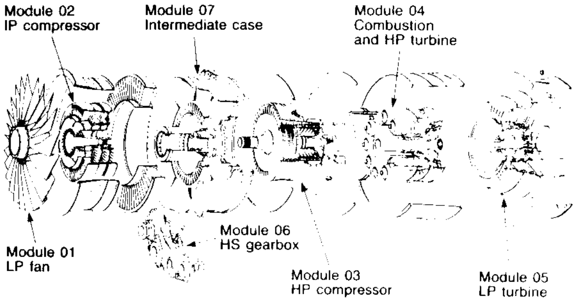


Figure 17

MAINTAINABILITY

Line maintenance checks of the engine have been scheduled to coincide with aircraft checks both for improved efficiency and economy. The engine has extensive borescope access and provision for magnetic chip detectors. This was a prime aim in the design of the engine.

Another very important factor in the design is unit accessibility, so the Tay systems are grouped externally on the lower fan and intermediate case for ease of access. Accessories and controls are similar to those proven in over 35 million hours of service experience in RB183 Mk 555 and Spey operations. Change times have been kept to a minimum with over 65% of accessories capable of being replaced in under 30 minutes. This all adds to a smooth transition from RB183 Mk 555 to Tay from the point of view of the maintenance team.

Removal and installation of the engine is achieved with minimum down-time, with the capability of engine change within 3 hours by a three-man team, followed by a maximum of 15 minutes ground running to ensure satisfactory operation.

TAY 650 DESIGN CHANGES

Relative to the Tay 620, the Tay 650 gives a 9% increase in maximum take-off thrust and a 15% increase in maximum continuous, climb and cruise thrusts resulting in improved operational capability without compromising the life and reliability of the basic Tay design. The Tay 650 introduces an advanced technology HP turbine system to accommodate higher operating temperatures. The latest aerodynamics, cooling and materials technology have been incorporated to improve efficiency, maintain component lives and retain excellent reliability. See figures 18 and 19. This technology has been proven in over half a million hours service with the RB211-535E4.

A 0.8" increase in fan diameter on the Tay 650 results in a 5% increase in total mass flow through the engine.

Tay 650 design philosophy

- Provides significant thrust increase
- High reliability and low sfc retained
- Preserves Tay concept of
  - cost effectiveness
  - low environmental impact
  - low cost of ownership

Generating improved payload range and/or field performance

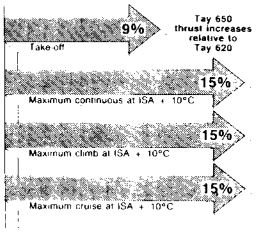


Figure 18

Tay 650 features

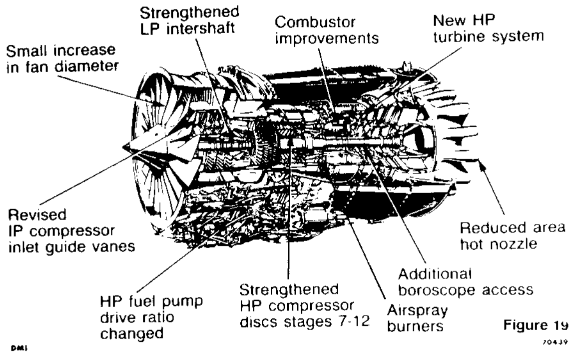


Figure 19

New HP Turbine

The first three rows of aerofoils of the two stage turbine are cooled. The challenge was to design a turbine which maintained the high level of performance of the existing machine whilst providing reliabilty at the higher ratings. As with the LP turbine the RB211 family style was adopted.

The axial chord of the turbine components was fixed by the requirement for minimum change. Profiles were chosen which provide space for efficient cooling geometries and reduce the sensitivity of the blading to incidence. The annulus height was generally increased in order to achieve an optimum balance between aerodynamic and cooling performance. Introduction of the new HP turbine gave an opportunity to introduce improved mechanical design, Figure 20.

Tay 650 - Advanced technology HP turbine

- Design incorporates
- Improved aerodynamics
- Advanced cooling
- Maximum use of today's proven technology for excellent reliability

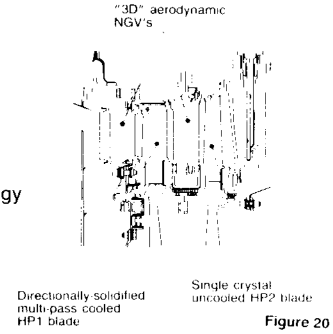


Figure 20

Rotor tip seal segments were lined with abradable honeycomb cell material. Overtip leakage of annulus gas is thus reduced due to the tip clearance being only as large as required to provide clearance at the operating condition of maximum closure.

The first stage rotor blade is cast directionally solidified for increased creep strength and the second stage blade is cast as a single crystal. These strong materials are protected from corrosion by aluminising to provide a good overall thermal life expectancy for the turbine. The nozzle guide vane profiles were designed by 3 Dimensional computer methods to control the secondary flows which would otherwise degrade the aerodynamic performance.

Engine testing has shown the turbine to possess a higher efficiency than the Tay 611/620, despite requiring significantly more cooling flow to combat the increase in turbine entry temperature.

By focusing greater attention on mechanical detail the sealing of the turbine was improved by 2% of total core flow compared with the previous turbine.

The turbine has successfully completed a 150 hour type test running to a maximum first stage rotor inlet total temperature of 1538K (1265C).

Combustor Changes

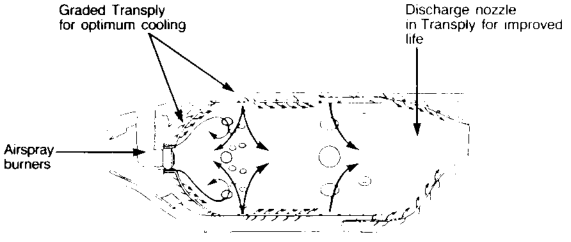
Work has been underway to produce an improved durability combustor for the Tay 650 which operates at higher temperatures than the Tay 611/620, Figure 21. This new combustor has been specified with:

- multigrade Transply in which the Transply flow is tailored to the differing demands of various combustor zones.

- a Transply discharge nozzle. Rig and engine testing has shown that, because of the complicated geometry of the nozzle, Transply is far superior to conventional cooling in this application.

- an airspray fuel injector. This has been chosen in place of the pressure jet injector since it provides more margin on emissions compliance which may be traded off for increased cooling air.

Tay 650 combustion improvements



● Designed to accommodate higher temperatures without compromising life, efficiency, or cleanliness

Figure 21

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Other Changes

Added minor adjustments are required for the Tay 650 to meet the increased load. These include area changes at the core engine intake and mixer nozzle for matching purposes, strengthened HP compressor discs and LP intershaft to accommodate the higher duty.

NOISE

From the outset the Tay was designed to minimise commmunity noise. Both the aerodynamic and mechanical design of an engine influence the final noise characteristics and, for the Tay, these were optimised in conjunction with engine performance, weight and integrity, so as to generate the minimum noise. Each engine component was carefully designed to reduce its source noise, and then acoustic liners were used to further reduce the noise radiated. Special attention was paid to the relative balance between the component noise sources so that the overall engine noise signature was a minimum without unnecessary suppression in any particular area.

The increase in bypass ratio and the incorporation of a forced mixer has made a significant reduction in jet mixing noise and, therefore, noise sources hitherto unimportant required close inspection, especially those associated with the turbomachinery. The special noise features designed into the Tay which have most impact on these noise sources, important at low to mid powers, are (see Figure 22):

- Optimised fan blade and vane ratios which, together with optimised axial separations, produce an acoustically "cut-off" blade passing frequency tone and low harmonic levels. This route has been successfully used in the past and was perhaps best proven by the low noise levels from the RB211-535E4 engine.

- The booster design also has optimum blade/vane ratios, together with suitable gaps, to reduce both direct booster and fan-booster interaction tones.

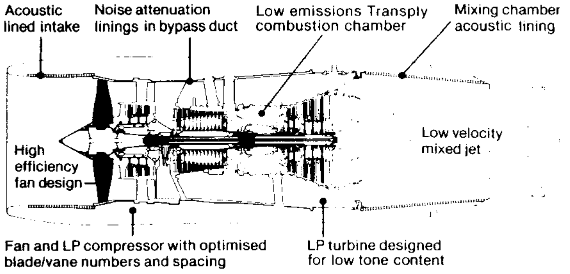
- Forward radiated fan noise is further minimised by including acoustic liners in a flow matched nacelle.

- The HP system, basically retained from the Spey 555, maintains its low levels of combustion generated noise.

- The LP turbine, which drives the fan and booster, has been designed with high blade numbers (to minimise subjective impact) and large separations between blade and vanes (to reduce source levels).

- Further reduction of turbine noise is ensured by incorporating an acoustic liner in the final-nozzle mixing chamber. This liner also reduces combustion and rearwards radiating fan noise.

Tay — The good neighbour



Minimal noise and emission levels demonstrated during testing

Figure 22

DKT 70290

The incorporation of these noise reduction features in the Tay has produced an extremely quiet engine, even for its thrust and bypass ratio class. A substantial margin of compliance with all current FAR Part 36 and ICAO Annex 16 noise legislation in the Fokker 100 and Gulfstream GIV aircraft has been achieved.

It can be easily demonstrated that several older turbojet powered aircraft which are currently certificated to Stage 2 can very easily be made to comply with the more stringent Stage 3 rules if re-engined with the Tay; examples include the BAC1-11-400 and -500, the DC9 series and the B727 aircraft. Operators of these older aircraft could find replacement of older engines with the Tay an economic solution if the operation of Stage 2 aircraft are selectively prohibited or banned locally or internationally.

It is interesting to contemplate the reduction in noise over the last few years. Compared with the Spey engine series, the Tay derivative is some 25dB to 35dB quieter!

PERFORMANCE

The market desire for good fuel efficiency, whilst compromised by the cycle choice, has not been sacrificed in terms of the new component efficiencies. The performance features designed into the engine are:

- High efficiency wide chord snubberless fan with bypass section pressure ratio chosen for good mixing efficiency and hence fuel consumption.
- Low pressure loss bypass duct.
- High efficiency LP turbine and exhaust cone.
- Low loss multi-lobe forced mixer for both noise and performance benefits.
- Flared convergent propelling nozzle featuring a high thrust co-efficient.

The take-off rating on the Tay has been chosen to suit the requirements of aircraft performance, noise and core maintainability. The engine is currently on offer covering a take-off thrust range of 13,850-15,100 lb, flat rated to ISA+15°C (86°F) at sea-level static conditions, illustrated on Figure 23.

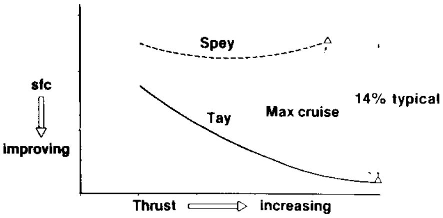
Improvements in fuel efficiency are typically illustrated by Figure 24, showing a gain of 14% over a Spey RB183-555 engine at max cruise conditions.

Tay for the Fokker 100 — Basic data

Mark number		620	650
Aircraft		Fokker 100	Fokker 100
At Take-off (ISA sls)			
Thrust	lb	13850	15100
Flat-rated to	°C (°F)	30 (86)	30 (86)
Inlet mass flow	lb/sec	408	425
Bypass ratio		3.03	3.10
Turbine entry temp	K (°F)	1327 (1929)	1369 (2005)
Overall pressure ratio		15.6	16.4
At Cruise (30000 ft, 0.73Mn, ISA)			
Thrust	lb	3600	4084
sfc	lb/lb/hr	0.69	0.70
Dimensions			
Fan tip diameter	in	44.0	44.8
Length	in	94.7	94.7
Basic engine weight	lb	3100	3340

Figure 23

Tay — Improved fuel efficiency and thrust



Derived from:
— higher bypass ratio and mass flow
— advanced technology components
— advanced internal mixer

Figure 24

DEVELOPMENT TESTING

The testing involved in developing the Tay is a combination of work specifically involved in perfecting new components and a full programme of certification tests.

An enormous amount of component rig testing is carried out which started long before initial engine run and continues to the present day in a continuous effort to improve component design.

Alongside this, a full engine certification programme is carried out under the close scrutiny of the United Kingdom Civil Aviation Authority (CAA), see Figure 25.

Engine type certification

Items for compliance/demonstration

Integrity

- ● Structural strength including mounting loads
- ● Rotor blade integrity/vibration
- ● Rotor blade containment
- ● Rotor (fan) blade off
- ● Rotor unbalance
- ● Rotor overspeed/cyclic life
- ● Gyroscopic/bearing loads
- ● Cooling air system integrity
- ● Overspeed/overtemperature
- ● Bird and foreign object ingestion

Functional

- ● Performance and handling
- ● Cold starting
- ● Flight relighting
- ● Icing/de-icing
- ● Rain, hail and snow ingestion
- ● Thrust reverser and air intake compatibility
- ● Air offtake contamination
- ● Exhaust emissions
- ● Fuel and oil temperatures
- ● Contaminated fuel

- ● Type approval test
- ● Function and reliability testing

Figure 25

Some parts of the engine could cause a hazard to the aircraft should they fail. These parts are identified during the certification of the engine by a failure mode and effect analysis. Appropriate precautions are then applied to achieve the necessary high level of integrity.

For example, all the major rotating components in the engine (that is, compressor and turbine discs) are subjected to the most rigorous controls which start with the material production and continue through the design process (validation of stresses and the environmental conditions of pressures , temperatures and vibration) and subsequent manufacture through to declaration of the life of the component (based on accumulated experience incorporating full-size component testing to failure supported by laboratory specimen testing and prior service experience).

The Tay engine development programme was made up of a total of 8 engines with first engine run ahead of schedule on 1 August 1984. Less than two years later, in June 1986, the Tay 610 and 620 were jointly certificated by the CAA. Subsequently, both marks of engine were certificated by the US Federal Aviation Administration (FAA) under reciprocal cross-validation procedures. Subsequent uprating of the Tay 610 took it to the 611 standard now in service.

Let us now look at some of the more interesting tests in the Tay certification programme.

Fan Blade Off Test

The aim of this test is to confirm the integrity of the engine in the unlikely event of a fan blade release. It is required that all engine components are contained within the nacelle and that the engine runs down in a smooth and controlled manner.

In preparation for the test, the engine to be used was heavily instrumented and one fan blade specially machined to fit a small explosive charge into the blade root and weaken the same blade to ensure satisfactory blade release.

The engine was then run up to "red-line" low pressure shaft speed and the charge detonated. As expected, all debris, including the released blade, was retained within the engine. Shortly after detonation, the emergency fuel shut off valve tripped the fuel supply to the engine which ran down smoothly. The fuel supply was not turned off at the control until 15 seconds after detonation, as required by the authorities.

Bird Ingestion Testing

Bird-strike tests are among the most exacting for a new engine. Regulations cover two tests for the Tay; firstly the ingestion of three 1½ lb birds such as gulls and secondly the ingestion of a single 4 lb bird.

The 1½ lb bird test is probably the most critical civil test, where the 3 birds are ingested at engine operating conditions representative of aircraft lift-off; the regulations require that the engine should continue to develop at least 75 per cent of take-off power so that the aircraft could fly a circuit and land safely.

This test was carried out on a full engine in contrast to the 4 lb bird test which, with prior agreement of the authority, was carried out on a "bird ingestion rig".

This assembly allows a complete fan set or single blade to be spun in a vacuum and birds are injected at speeds representative of aircraft forward speed. This rig is also used for investigative testing. The Tay completed these tests very satisfactorily, with no significant loss of fan blade material.

Type Test/MAT

Two tests which are very closely related are the Type Test and Mod Approval Test.

The Type Test is the first formal test carried out by the engine for the certification authorities. It is carried out using a full specification production standard engine, tested to a six hour schedule as shown in Figure 26. This cycle is repeated twenty-five times, in order to make life as hard as possible for the engine.

Type approval 150 hour endurance test

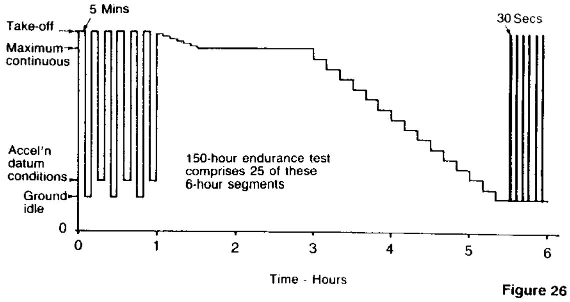


Figure 26

VML 3237/1/1

The Tay 610/620 completed the Type Test with flying colours, a result which confirmed the inherent durability of the Tay engine.

Following the Type Test, modifications may be cleared for use on the engine by running a Mod Approval Test (MAT). Here, an engine containing the new components is run to a schedule identical to that of the Type Test.

Other Tests

Other tests worthy of mention include Altitude Handling, Relighting, Engine Icing and Endurance testing.

All these tests must be carried out to the satisfaction of the authorising body, in this case the CAA.

The Altitude Handling was carried out at an altitude test facility at the Royal Aircraft Establishment in Pyestock, where the engine was tested to a simulated altitude of 51,000 feet. At these conditions, the engine retained all handling characteristics as required by the CAA without surge or instability.

A further part of this test is to induce an engine surge at altitude; this was done as required but only after gross malscheduling of the variable Inlet Guide Vanes.

A repeat of the altitude handling test is carried out in the aircraft during aircraft certification. This is often performed in a more severe environment than can be simulated on a rig eg in buffet, sideslip, wind up turns, with cabin bleed off etc. These conditions demonstrate the most adverse control settings at which the engine could be expected to operate.

Another simulated altitude test is relighting, this time carried out at Rolls-Royce's own Altitude Test Facility. In this test, the engine was re-lit at various conditions within a guaranteed envelope and also at various points outside the envelope. All representative relights were successful.

Engine Icing tests are another demanding component of the development/certification programme. The engine was placed on a rig and run at conditions which encouraged icing when water was sprayed towards the inlet.

The Tay engine features an unheated nose cone with a stiff rubber tip. Once ice build-up begins on the tip of the nose cone, an imbalance is introduced which induces enough movement to dislodge any ice before it gets large enough to damage engine components as it passes through the engine. Fan blade design also ensures self shedding of ice from the blades.

Full engine compliance was achieved with the Tay with spontaneous ice shedding from the fan occurring before any undue vibration became apparent. The engine continued to run satisfactorily in ice at low idle even at four times certification water flow.

Endurance testing must be carried out over and above the Type Test limits to confirm the engine's durability through a large number of cycles. In this test, the Tay completed 14,000 cycles, equivalent to something like six years typical service.

TAY 650 DEVELOPMENT

With the introduction of the Tay 650 to the product range, a new development programme was initiated to work specifically towards certification of the Tay 650 in August 1988. This programme, involving a total of 8 engines dedicated to the Tay 650 development, began in December 1986 with the first engine run. Since that time many tests have been carried out as shown on figure 27. These tests concentrate on ensuring that the changes made to the base engine do not in any way degenerate the proven safety and integrity of the Tay.

Tay 650 development programme

- First run ahead of schedule on 12th December 1986
- From December 1986 onwards a total of 8 engines allocated exclusively to 650 development
- First mod approval test successfully completed in June 1987
- Type test scheduled for April 1988
- Approximately 7000 development bench hours are planned to Tay 650 certification

Percentage breakdown of test programme

Fan and IP compressor	Straingauge	2.6
HP compressor	Straingauge Temperature survey	3.0
Combustion and turbine	Straingauge Thermal paint Cooling air survey	13.9
Functional	Performance ATF Bearing load emissions Cold room	21.2
Noise		8.2
Mod approval test		17.2
Cyclic		33.8

Figure 27

With the most significant differences in the Tay 650 being ones of increased component loading and a new HP turbine, a significant proportion of the development programme has been concerned with straingauge and temperature tests. To these must be added tests such as Type Tests and Mod Approval Test which are required to certificate a new mark of engine.

Once again, the Tay has shown itself throughout this most recent development programme to be an excellent engine in all respects, demonstrating the benefits of sound derivative design.

IN SERVICE

As discussed at the beginning of this paper, at the time of writing, there were 3 committed applications of the Tay engine:

1. Gulfstream IV - Tay 611
2. Fokker 100 - Tay 620 & 650
3. BAC1-11 re-engining - Tay 650

Of these, the first two are in commercial service, the GIV entering service in June 1987 and the Fokker 100 following early this year.

The Gulfstream IV, a development of the highly successful GIII, offers improved noise, payload, range and fuel efficiency. Replacing the Spey Mk 511s with two Tay 611 engines produces an aircraft/engine combination to meet these requirements.

The Fokker 100 is essentially a modernised stretch of the Rolls-Royce RB183 Mk555 powered basic F28 aircraft A considerable amount of re-design has been carried out to ensure the new aircraft meets all known noise/emissions regulations and is generally updated for the 1980s and beyond.

The Tay 620 powerplant is used for aircraft weight of upto 98,000 lb (max take-off weight) and the Tay 650 for higher performance versions at 98,000 lb (max take-off weight) and above.

Thirdly, the BAC1-11 re-engining programme offers an opportunity for operators of the highly successful BAC1-11 aircraft to increase the life of theairframe by meeting noise/emissions regulations in the same way as previous marks of the Tay

FUTURE DEVELOPMENT

The Tay story does not end with the Tay 650. At the time of writing, a series of engine developments were being studied, with thrusts reaching levels up to 17,500 lb, Figure 28. Principal applications for these engines may include DC9, 727 and 737 re-engining as well as future 100-120 seat aircraft developments.

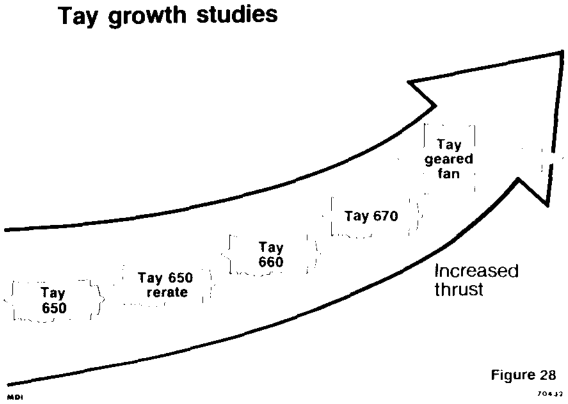


Figure 28

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