ELEVENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 87

THE CONCEPTION AND DEVELOPMENT OF A FAMILY OF SMALL ENGINES FOR THE 1990'S

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September 10-13, 1985
London, England

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Abstract

This paper reviews the process of conceiving and evolving a strategy, design, and a development programme for an aero-engine by a European team pooling their expertise and particularly their experience. A new aircraft engine family, the RTM 322, is used to illustrate the setting of project priorities and how sometimes difficult decisions are made for strict adherence to these priorities.
Significant changes in the formulation of development programmes whilst incurring some increase in front-end costs should produce major rewards in terms of "right first time" results and lowering of the risk levels.Finally advanced engineering programmes to substantiate growth potential of the family are discussed.

1) Introduction

This paper describes the philosophies and thought processes that went into the conception, evolution and design of a new family of small gas turbine engines emanating from the industries of the United Kingdom and France.

All design is a compromise despite the quest for perfection. Naturally we all convince ourselves that our designs are compromised less than anybody else's. Yet it's never surprising that two machines conceived to do exactly the same job turn out to be different in many ways. The reason, of course, is that there is still a human element left in the design process. The human element is understandably dominant when there are aesthetic qualities to be considered but this is hardly the case with basic mechanical hardware such as an engine.

An engine operation is based on the established laws of physics and for any given state of technology, there ought to be only very minor deviations from a unique solution to any propulsion problem.

Nevertheless, differences there still are, and compromises there will always be and on that basis competition survives.

2) Conception

Rolls-Royce Limited in the U.K. and Turboméca S.A. in France first teamed on a formal basis in 1966. The teaming, which is in fact manifested as a legally registered joint company, arose from the requirement of the governments of the two countries for a new power plant for a new fighter aircraft. The joint company designed and produced a successful turbofan engine called the ADOUR and together with its exports sales the business generated by this programme has been to the immense benefit of both nations. The engine is soon to be used by the U.S. Military as part of a training system for naval pilots. It was entirely natural therefore that the joint company should wish to build on its success with the ADOUR engine and seek further business with other projects.

Market surveys showed that the most obvious requirement was for a turboshaft engine in the 2/3000 shp class to fill the emerging needs of collaborative European helicopter programmes.

Using a factor of an increase of 15 to 20% in the launch costs as a result of a two-company teaming, examination of the business case for the turboshaft variant alone indicated a potentially profitable programme and when variants of the engine in turboprop and turbofan form were added, it was seen that a substainable European small engine industry could be ensured providing the disciplines of the project priorities were up-held.

3) Project Priorities

Careful thought led to 4 prime project requirements

3.1 Low Costs

It was the view of both parent companies that the acquisition and operating costs of small engines were becoming increasingly dominant to almost all countries through out the world with the possible exception of the U.S. Government.

3.2 Competitive Performance

Careful analysis of the performance levels of existing competitive engines showed that significant and probably costly changes were necessary to make a quantum change in performance with the new engines. It was decided therefore that the overall performance level of the new engine should be targeted to merely produce a performance advantage compared to existing engines without compromising the primary objective of low costs.

3.3 Low Risk Level

It was felt that the risk level should be consistant with the use of fully demonstrated technology and manufacturing concepts in order that the business case forecasts should be realistically achieved.

3.4 Growth Potential

Since the project was launched with no firm and committed application and mindful of the less than sublime art of helicopter power requirement prediction, straight forward and inexpensive growth potential was to be built in from day one, again to minimise any deleterious affects on the business case potential.

4) Demonstrator Background

The best resources of Rolls-Royce and Turboméca had been directed at the demonstrator process for a sound technology base over the last ten years.

The individual component research programmes were brought together in a series of three demonstrator engines (See Fig.1), all of which had a degree of government backing.

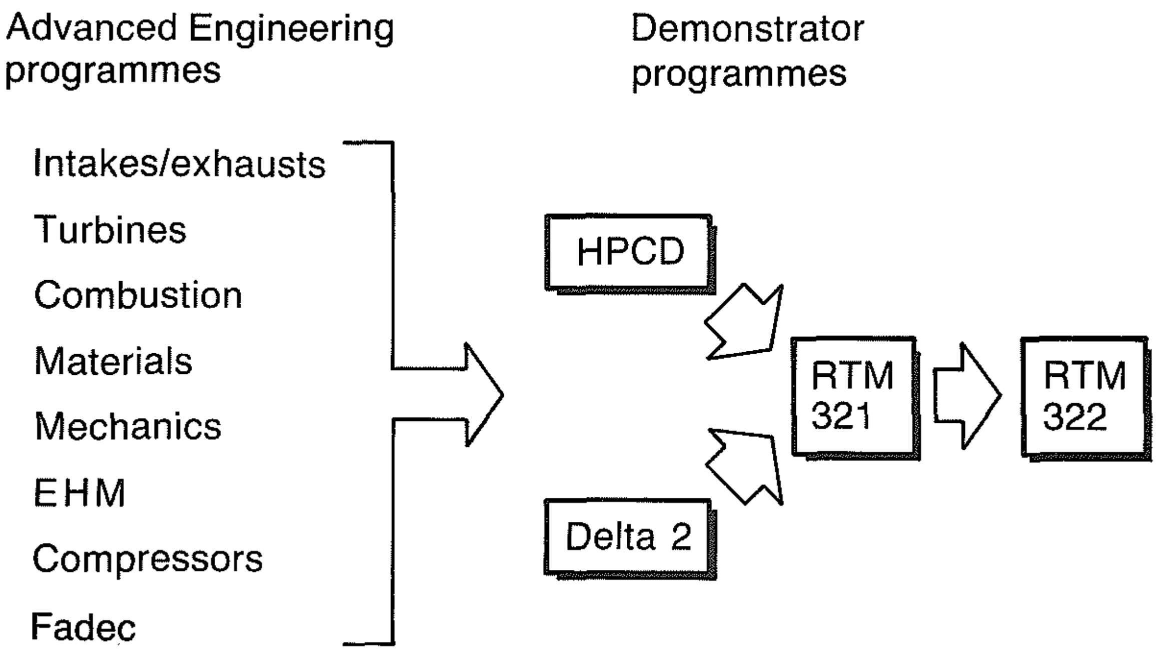


Fig.1 Demonstrator background

4.1 Delta 2

This is a Turboméca demonstrator engine aimed at using the simplest and most robust compression system to produce current levels of performance with the lowest number of components.

It also incidentally, uses a single stage turbine to drive the compressor and thus provides an extremely useful data base for the single/twin gas generator turbine decision to be made later. (See Fig. 2)

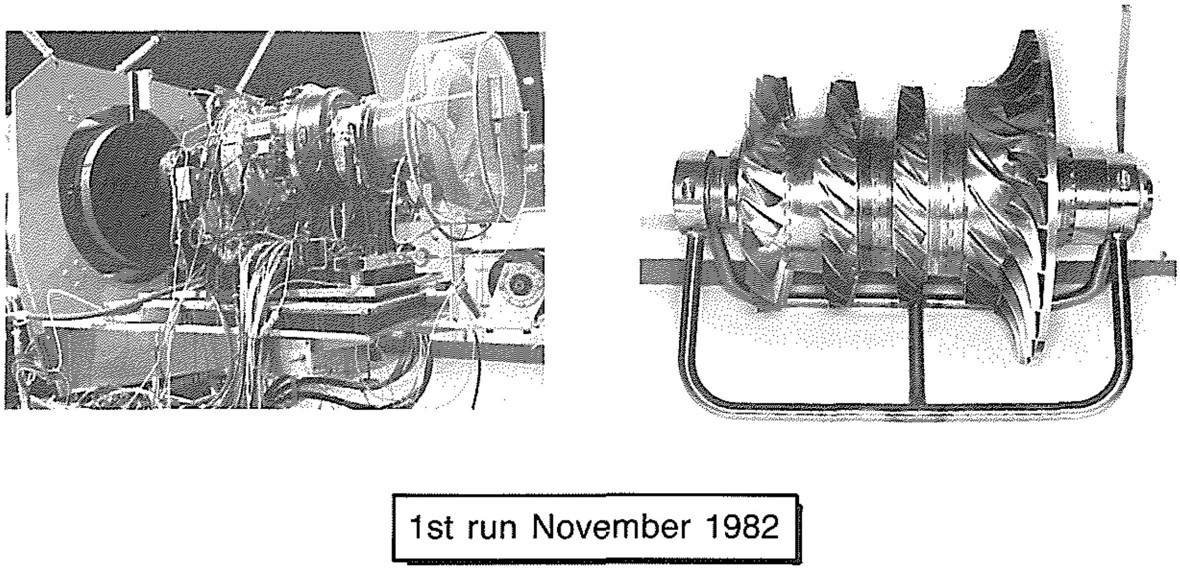
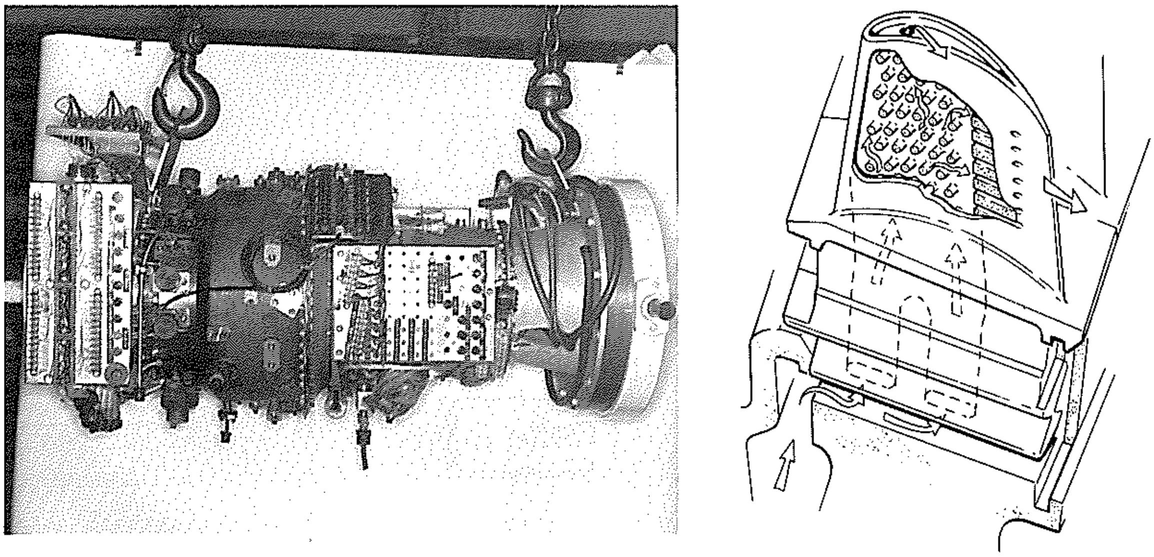


Fig.2 Delta 2 demonstrator engine

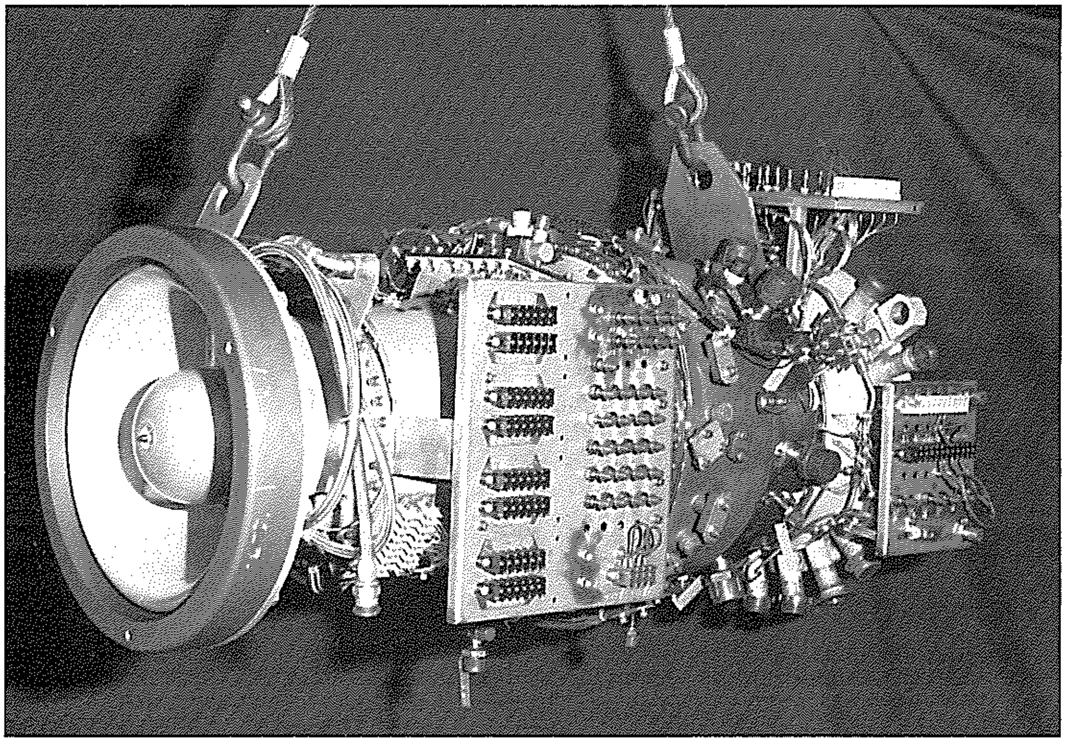
4.2 HPCD

This is a Rolls-Royce demonstrator engine aimed at producing optimised designs of cooling in small turbine arrangements. (See Fig. 3)



1st run February 1977

Fig.3 High Pressure Core Demonstrator



1st run November 1983

Fig.4 RTM 321 demonstrator engine

4.3 RTM 321

This is a joint RRTM demonstrator engine representing an initial attempt to bring together the technologies demonstrated in the above two engines. It was test marketed and shown to be un-competitive in terms of being too close in power, design concept and manufacturing technology to the existing engines. (See Fig. 4). However, it produced valuable background information for the final project definition.

5) Worksplit

The programme as it stands is shared equally between the two companies and thus it was important for an early agreement on work split to be reached. Experience on other collaborative programmes convinced both companies of the need for a minimum number of interfaces and in essence there turned out to be just one (See Fig. 5). That is to say Turboméca are responsible for the front of the engine and Rolls-Royce for the rear.

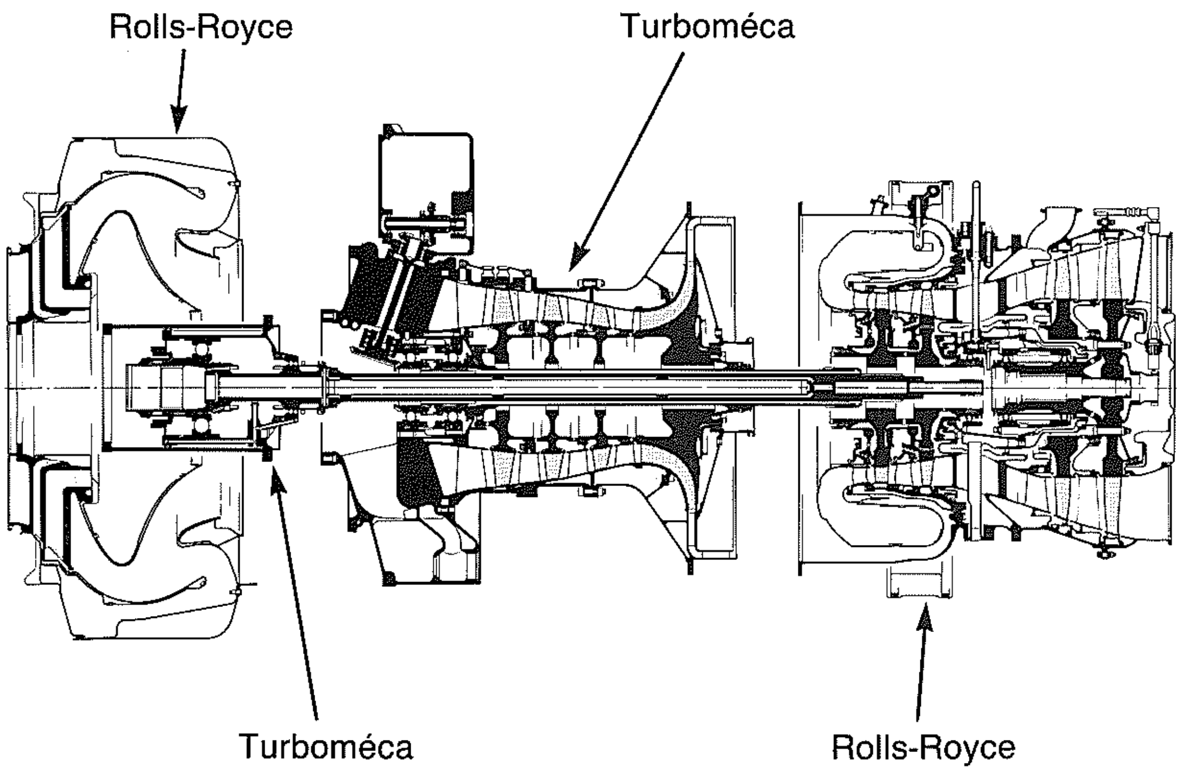


Fig.5 Company worksplit

Naturally, there are other arrangements required and for example Rolls-Royce are responsible for the Inlet Protection System and Turboméca for the drive shaft and dynamics. Achieving sound, solid interface control early in the programme is considered essential.

6) RTM 322 Definition

Against the four prime project priorities defined in para 3. the RTM 321 was up-graded as follows:-

6.1 Sizing
The engine was scaled up by approx. 10% in mass flow as a base-line to meet the growing power needs for transport and attack helicopters, a nominal take off/IRP of 2100 shp ISA SL was selected.

6.2 Cycle
The normal cycle trade-off studies showed that to comply with the low manufacturing cost/simplicity priority, for the growth variant of the engine a pressure ratio of 18 and a TET of the mid 1500/1600K were optimum. Translating this back to the launch turboshaft variant a P.R. of 14.7 and a conservative TET would result and as these figures had been more than adequately validated in the demonstrator engines referred to in section 4 the low risk priority was complied with.
The choice of a single or twin gas generator turbine set was difficult. Obviously the single would be very dominant in the low cost objective. However, the twin scored heavily in the competitive performance, risk and growth priorities and won out in then end.
Some consideration was given to selecting a twin spool gas generator separating the axial and centrifugal sets but the trade-off studies showed that the beneficial effects only became dominant as the engine size increased. i.e. if the RTM 322 was to be a 5000 shp engine instead of 2000 shp, we would probably have gone for a twin spool gas generator.

6.3 Inlet Separator
We would have to say that generally speaking we believe the inlet protection system for a helicopter power plant is more efficiently and cost effectively achieved as part of the aircraft intake system. However, the engine companies generally have a greater degree of expertise on the subject of ballistics and dust separation and thus the interface becomes difficult. The decision was made with this engine however, to offer a separator with the engine but that it should in no way form an integral part of the engine in a structural or functional sense. The engine can therefore be operated without it in an aircraft system that features its own device. On this basis, we have felt it necessary to perform research programmes over the last ten years to understand and develop the techniques for optimum operation and sizing of inlet protection systems.

7) Design To Costs

When you get right down to it this is the hardest discipline of all and the designers spend all their waking hours grappling with the problem.
It was decided to integrate the detail design team with the manufacturing engineers from the earliest possible moment since, as explained later the engine was to be made off production tooling from day one.
The clear aim was to produce as much of the engine as possible by modern casting techniques and the use of near net shape forgings. Recognising the high degree of commonality in companies supplying to the aero engine trade, it has to be

accepted that there is in reality probably less competitiveness in this particular subject than people would have you believe.
Nevertheless the detail design of the engine has been deemed to be highly successful in achieving the design to cost target by the maximum use of castings to a degree higher than in any other engine, we believe.

8) Detail Description

The launch version of the RTM 322 family is the -01 turboshaft, a compact, forward drive engine of 2100 shp at take-off S.L. ISA conditions.

Using the technology advances of the last ten years, design simplicity with a low part number count is the fundamental concept.

The gas generator spool comprises a three stage axial plus single stage centrifugal compressor, a reverse flow combustion chamber and a two stage axial flow turbine. The free power turbine spool has a two stage axial flow turbine which is connected to a forward mounted output drive via a transmission shaft. The gas generator and power turbine spools are supported on rolling element bearings grouped together in only two bearing chambers. Maximum use of structural castings, has been made to minimise production lead times and cost. See Fig. 6.

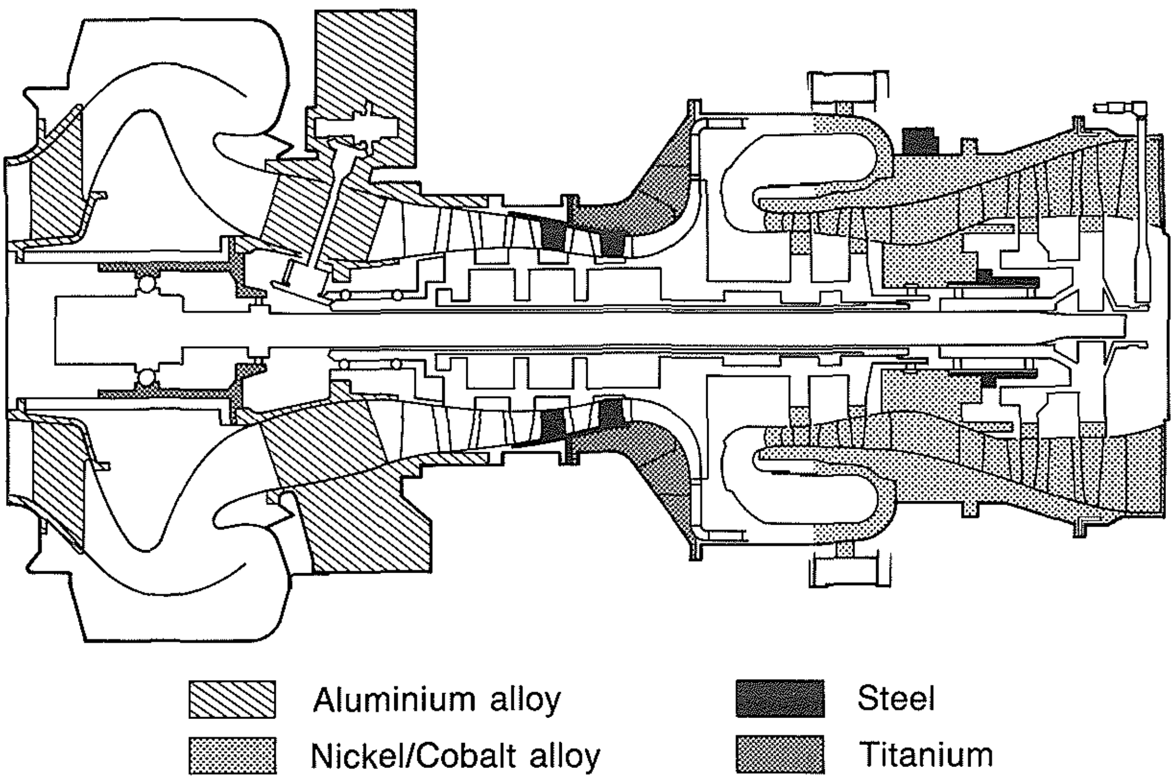


Fig.6 Use of castings

For ease of maintenance the engine is of fully modular construction, See Fig. 7.

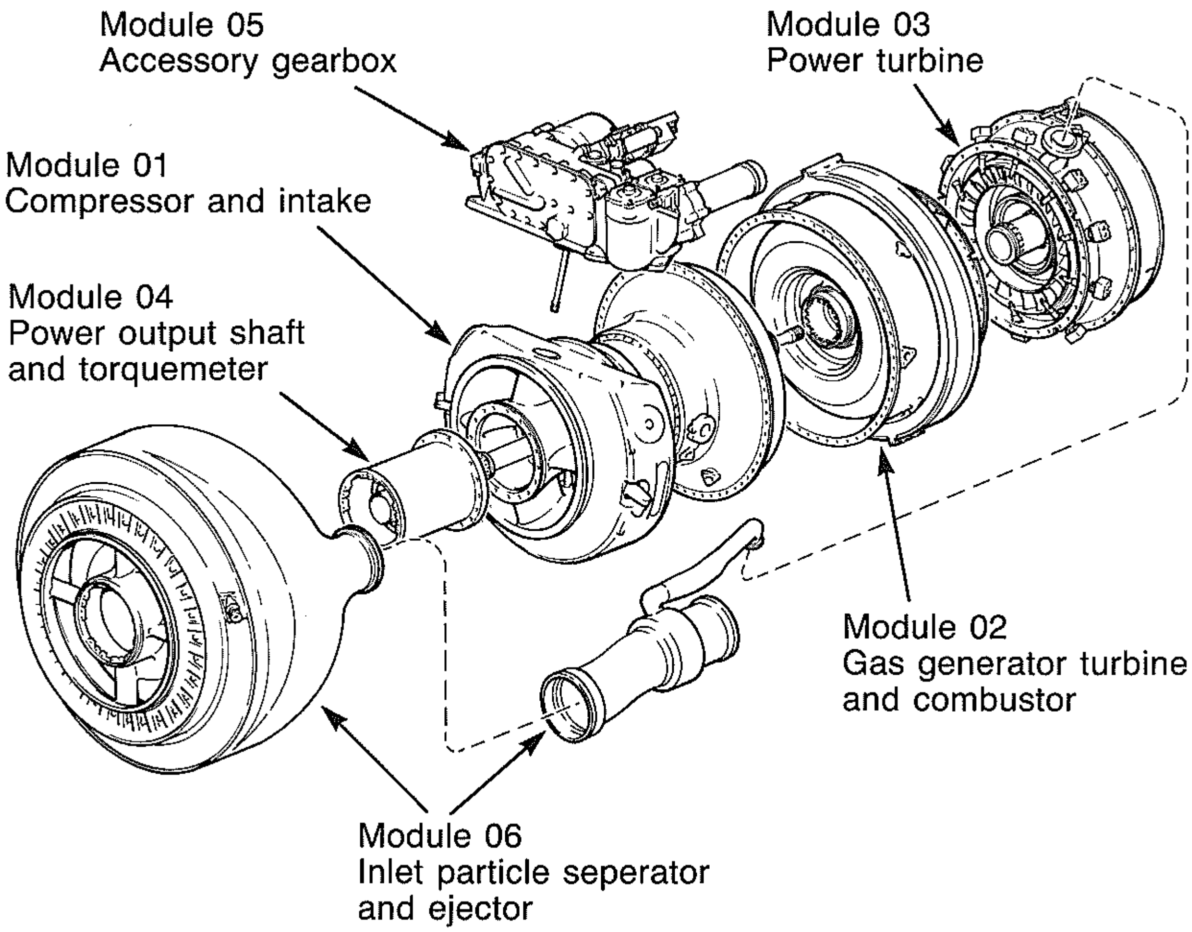


Fig.7 Engine modules

These modules are:

M01 Compressor and Intake Module
M02 Gas Generator Turbines and Combustor
M03 Power Turbine
M04 Power Output Shaft and Torquemeter
M05 Accessory Gearbox
M06 Inlet Particle Separator and Ejector

In the compressor the combination of axial stages with a single centrifugal stage allows a reduction in the total number of compression stages required and reduced length compared to an all axial design. Close coupling of the axial and centrifugal stages allows still further reduction in overall length, adequate blade speed for the latter axial stages being achieved by the characteristic hump back annulus line employed. The use of a final centrifugal stage permits very good integration into the rest of the engine when used, as it is, with a reverse flow combustion chamber. Surge free operation is ensured by the adoption of variable geometry for the inlet guide vanes and first stage stator vanes.

The three axial compressor rotors are machined as bladed discs from titanium forgings. They are connected together and to the similarly machined titanium impeller by curvic couplings, clamped axially by a central tie bolt. Integrally bladed discs offer the lowest cost solution and provide for a simple assembly avoiding any problems with separate rotor blade attachements and the corresponding stress concentrations. The blades are of rugged, low aspect ratio proportions, with the variable vanes having a robust operating mechanism, leading to enhanced compressor durability. The principle objection to blisks i.e. that of FOD is removed by the use of a highly efficient inlet protection system.

The front frame, which has an integrally cast oil tank supports a top mounted accessory gearbox and its bevel drive system. All transfer of fluids between the front frame, oil tank, accessory gearbox and all accessories is accomplished by integrally cast or machined conduits, the engine being notable for the minimal number of external pipes employed. See Fig. 8.

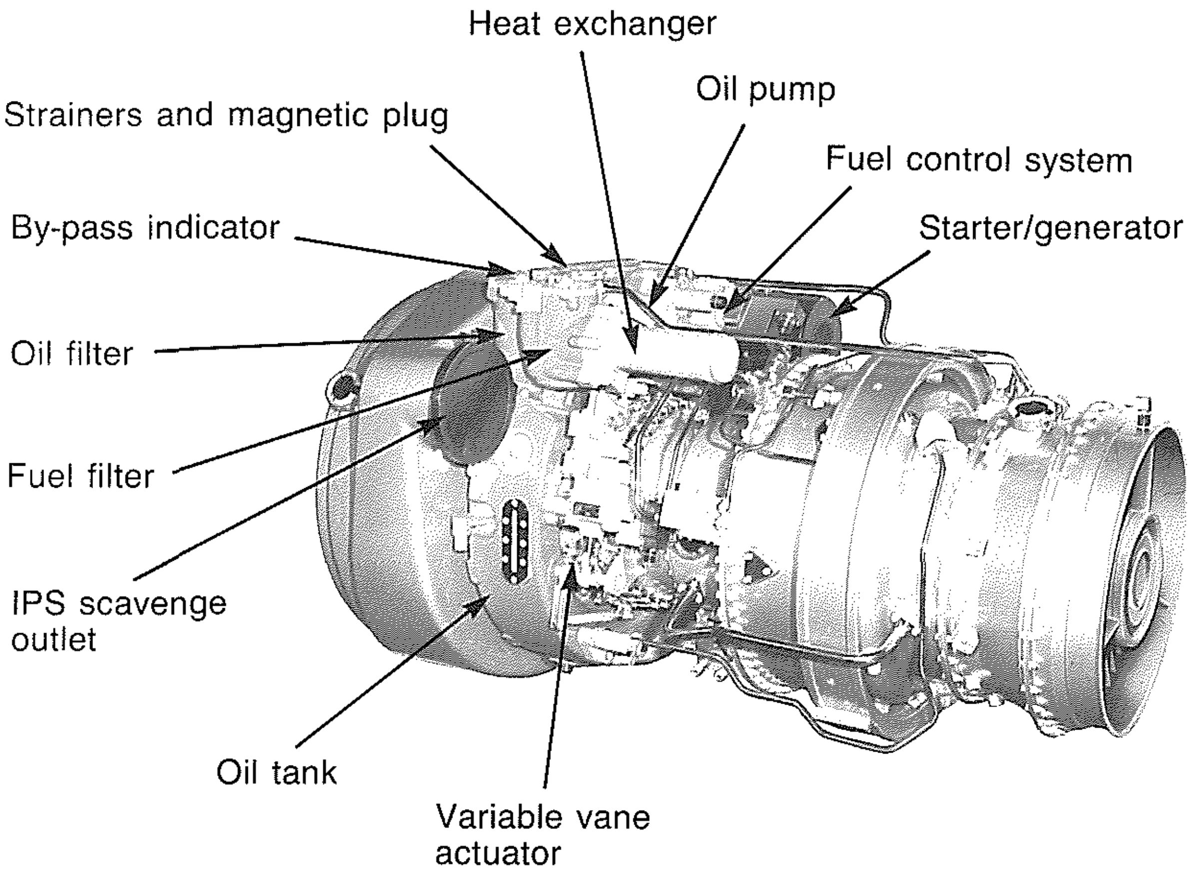


Fig.8 External view of engine

The accessory gearbox provides suitable mountings for the accessories required for starting, fuel supply, control and lubrication. All accessories are mounted on the rear face of the gearbox, and being positioned above the engine are readily accessible for maintenance, and in the least vulnerable area for ballistic strike.

The reverse flow combustor is mounted on 6 radial pins and surrounds the gas generator turbines. This arrangement minimises the required span between the gas generator spool bearings obviating any shaft dynamics problems. The combustor's large volume gives superior starting and idle performance, low pollution emissions and good altitude re-light capability. Vaporisers were selected in preference to pressure atomisers for their simplicity, low fuel pressure requirement, tolerance to a range of fuels, low luminosity burning characteristics and lower manufacturing costs.
The gas generator turbine nozzles are air cooled and of segmented construction to eliminate the thermal stress problems inevitably associated with integral nozzle rings and non uniform gas temperature.

Although a fairly modest turbine entry temperature has been selected for the launch engine, the nozzle cooling arrangements are of advanced design to ensure that the low metal temperatures associated with long lives are attained. The advanced cooling arrangements are integrally cast in the vanes, and the use of segments allows their cost effective incorporation since the yield associated with segments is proportionately higher than for complete rings. A further benefit of segmental construction is that when overhaul is eventually required, repair or replacement of individual segments is possible.

The gas generator turbine discs are separately bladed, the blades of stage 1 being air cooled and directionally solidified, whilst that of stage 2 are uncooled single crystal material. The discs are located to each other and to

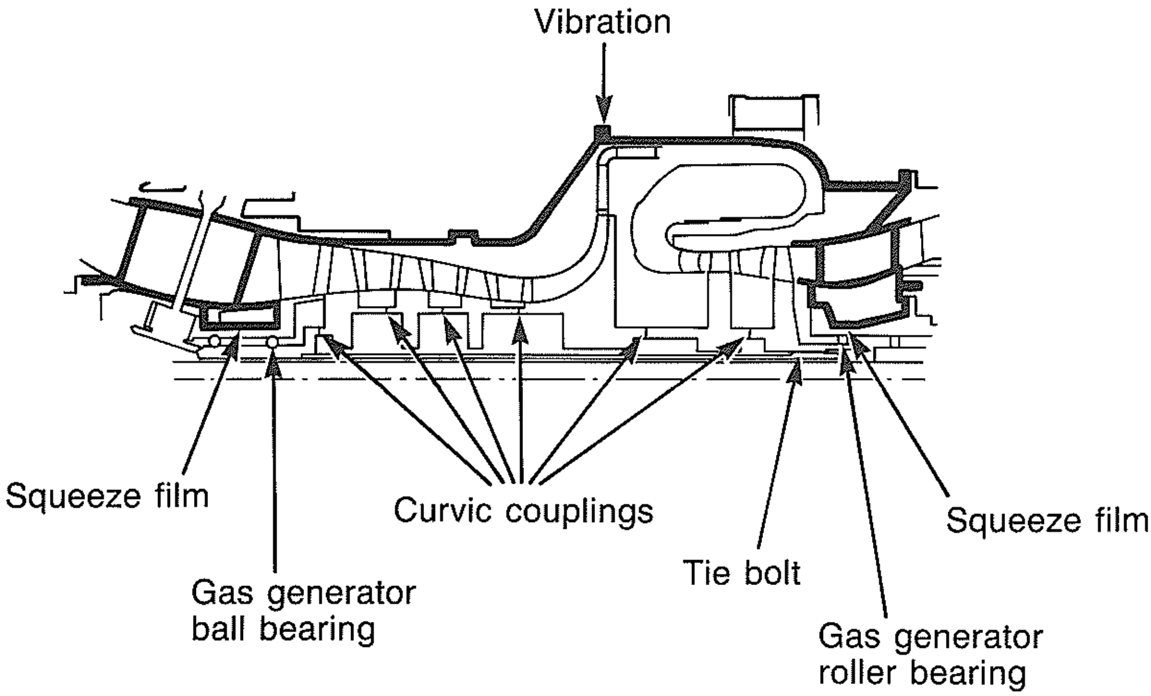


Fig.9 Gas generator shaft arrangement

the compressor impeller by curvic couplings, axial retention is by a nut screwed onto the aft extension of the compressor tie bolt.

Fig. 9. illustrates the complete gas generator shafting arrangement. A twin ball bearing arrangement is featured at the front of the compressor, both bearings sharing the net axial load from the spool, but only the aft bearing of the pair providing radial location. This latter bearing is supported within a squeeze film damped squirrel cage. The roller bearing aft of the turbines is also squeeze film damped.

Considerable effort is required to engineer an environment suitable for an oil lubricated bearing at the 'hot-end' of a small gas turbine. A major design objective therefore was to have only a single turbine bearing chamber. The RTM 322's basic configuration of a single, rigid gas generator spool with straddle mounted bearings, in conjunction with an overhung power turbine has made this possible. The chamber is supported within the transition duct conveying mainstream gases from the gas generator turbine to the power turbine, see Fig. 10. The chamber is sealed at front and rear by an

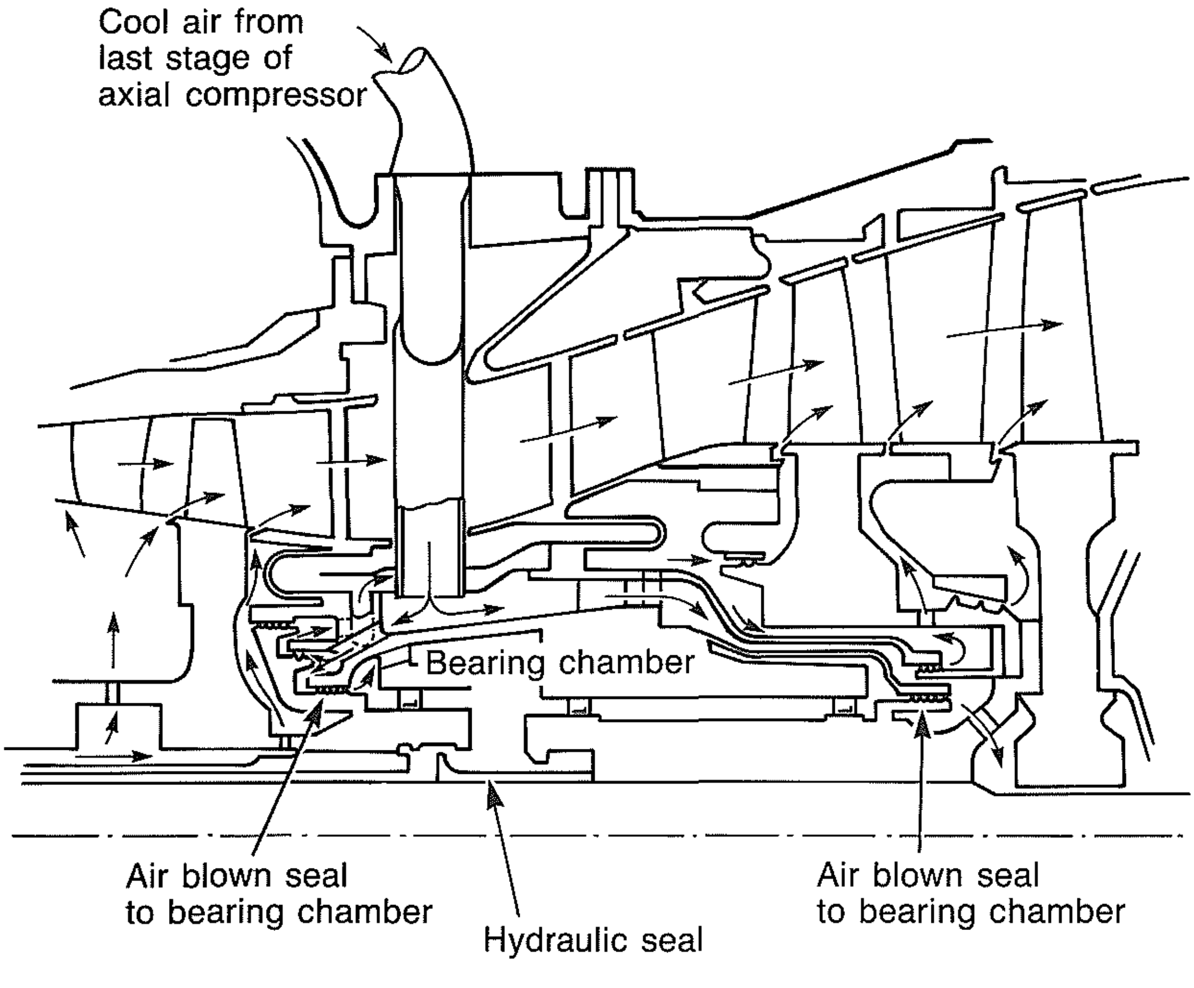


Fig.10 Turbine bearing chamber

air blown labyrinth seal, and by a dipping hydraulic seal between the two spools. The air system provides for the actual bearing chamber to be surrounded by cool air bled from the last stage of the axial compressor. No high pressure, and hence high temperature air, is permitted to enter the bearing chamber or its air jacket, nor is there any requirement for an overboard or otherwise wasteful bleed.

The power turbine is entirely conventional except for featuring the latest 3D aerodynamic blading.

The optional inlet particle separator module provided with the launch turboshaft engine separates foreign objects and dust by a combination of ballistic trajectory focusing and high meridional flow curvature. Scavenge air containing the majority of the inlet particle contaminants is collected in a scroll and exhausted overboard. Swirl vanes have not been used in the separator to avoid potential vane blockage problems, unwanted bounce modes and large scavenge path pressure losses. The absence of such pressure losses frees the design from the need for a high pressure rise mechanical pump, allowing the use of an ejector powered by gas bled from the engine at power turbine entry.

Trade off studies were conducted to determine the optimum way of scavenging the inlet particle separator system, see Fig.11. The use of an ejector powered by gas bled from the power turbine inlet plane was eventually selected on the basis of high reliability and minimum weight, at the expense of modest power loss.

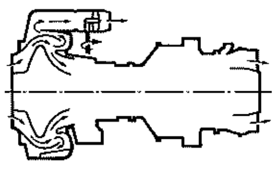
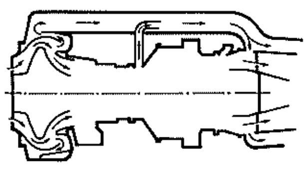
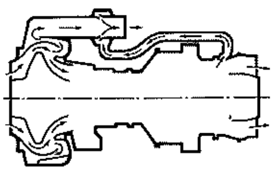
		Power loss %	Weight lb	Durability reliability	Technical risk
	Fan driven from accessory gearbox	0.5	26 + Acc. g/b drive	Poor	Low
	Exhaust driven ejector and P_2 assist at idle	5.6	19	Good	Med
	Power turbine bleed driven ejector	2.4	15	Good	Low

Fig.11 IPS scavenge alternatives

9) Development Programme

Every recent engine development programme in both companies was examined during the composition of the programme for the RTM 322. This is essential since it forms well over half of the total launch cost of a project and therefore a very careful line has to be steered between cost and risk.

The total programme concept was seen in 4 phases. (See Fig. 12)

1) Demonstration of technology (already accomplished but to be extended)
2) Design verification.
3) Certification.
4) Maturity.

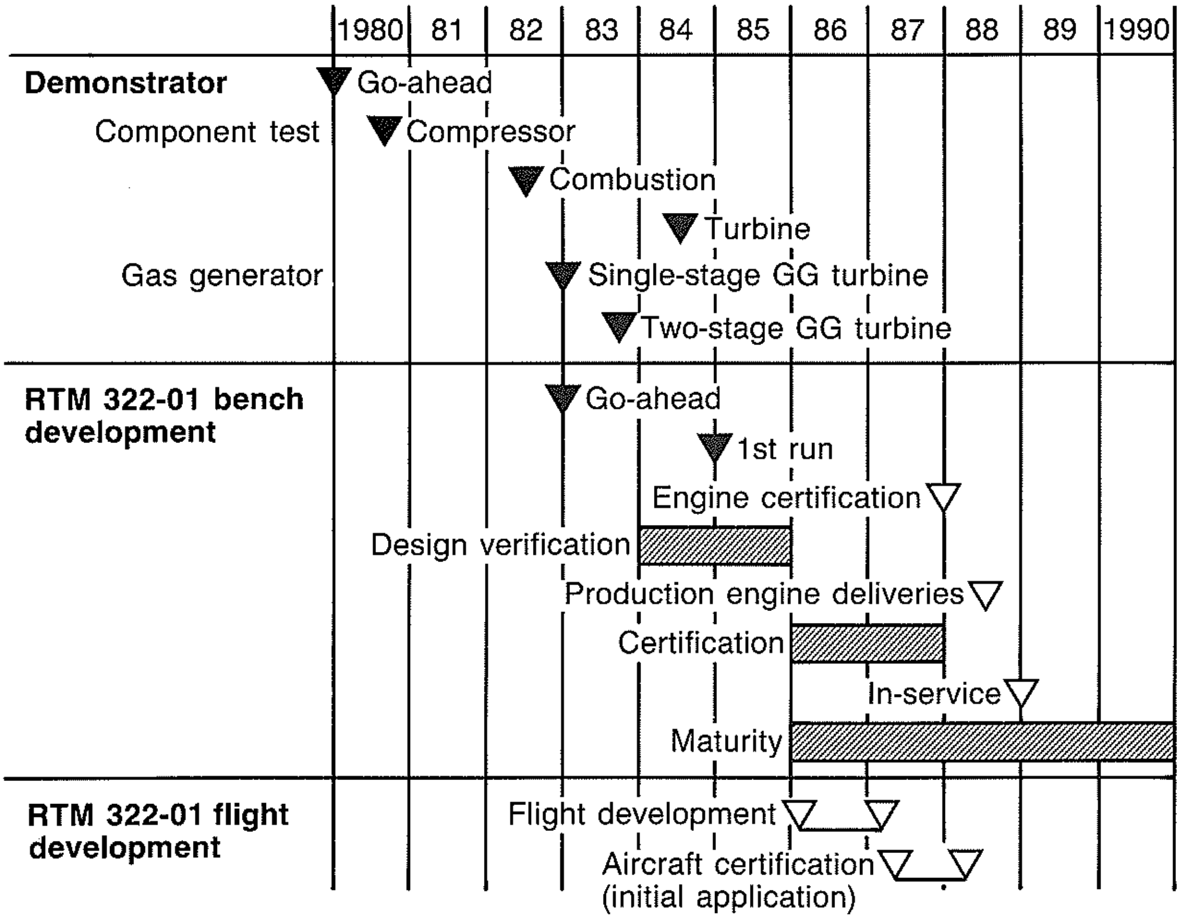


Fig.12 Development programme

In each of the last three phases, the majority of the development engines would be dedicated to the phase objective.

In the Design verification phase, the objective is to show that the engine works in the manner in which the designers expect it to work. Heavily instrumented engines are subjected to as well-thought-out and as effective tests as possible i.e. the emphasis is on quality rather than quantity in terms of build up of hours. This phase also includes a preliminary flight test programme and practice for the higher risk certification tests.

The Certification phase is aimed at the lowest possible risk. It really is starting to be too late, too disruptive and too expensive if there are fundamental changes surfaced during this phase.

The maturity phase is the build up to the fleet leader in service operation. It is, as well as being a matter of evolving the most effective and efficient form of testing, a matter of very comprehensive logistics planning with back up test facilities, engines and spares.

The question of spares and component standards is basically one of confidence. The aim is to produce as much of the engine off production tooling from day one, to understand the flexibility of the production tooling to cope with any design changes found necessary and finally to produce enough spares to ensure the development programme never stops for want of hardware.

The confidence comes mainly from the demonstrator phase. We estimated that 75% of the programme cost is effectively committed by the time of project definition, showing the critical nature of the front end thinking.

10) Audit

It was felt necessary to submit the whole concept of the project i.e. design, programme, costings and market to the most rigorous audits by senior personnel in both companies not associated with the project.

Following this endorsement, the whole process was repeated with senior government officials in the U.K. and France. Once again a positive response was achieved and the governments of both countries decided to contribute to the funding of the project.

A further opportunity presented itself to subject the project to an assessment by the U.S. Army and although we would not expect to have a "quotable" statement from such an august agency, we like to think that in general they endorsed our efforts.

11) Further Partnership

Rolls-Royce Turboméca Ltd has always been receptive to other partners joining the project and it is strongly believed that the Italian aero engine industry will soon be taking an active part in the programme.

Additionally, an agreement has been signed with MTU of Germany to co-operate on the engine in the marketing and production and support phases.

Finally we are very encouraged by the interest shown by some companies in N. America in considering serious licensing arrangements.

12) Lessons Learned

The lessons learned during the conception and launch phase can be summarised as follows:-

12.1 Confirmation that cost is the dominant factor in small engines (notwithstanding reliability which is fundamental to all aviation equipment).

12.2 Current technology should be directed at simplicity i.e. accomplishing the performance with fewer, easier to manufacture parts and hence at reduced cost and increased reliability.

12.3 Small improvements in SFC are not cost effective in small engines in terms of payload/range and operating costs.

12.4 Establishing the proven technology base is essential and has a dramatic effect on the launch costs and reliability at entry into service.

12.5 A planned growth path (up to 40%) is essential for helicopter turboshafts particularly until helicopter designers perfect the art of predicting power requirements.

12.6 The construction of the development programme and particularly the spares and logistics support is being constantly refined and is a process which is advancing almost as fast as those of design and manufacturing.

12.7 The most important lesson of all is to make the Project Director establish the project priorities at the outset and then stick to them. If he doesn't stick to them, you can be sure that nobody else will!

Acknowledgement - The authors of this paper wish to express their appreciation to the Directors of Rolls-Royce Turboméca Ltd. for the use of the information on the RTM 322 engine.