

FOURTEENTH EUROPEAN ROTORCRAFT FORUM

Paper No. 24

ENGINE ASPECTS IN THE DESIGN OF ADVANCED ROTORCRAFT

W. Muggli

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

H. Rick

Technische Universität, LFA
Munich, Germany

20-23 September, 1988
MILANO, ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

ENGINE ASPECTS IN THE DESIGN OF ADVANCED ROTORCRAFT

W. Muggli

Messerschmitt-Bölkow-Blohm GmbH
Munich, Germany

H. Rick

Technische Universität, LFA
Munich, Germany

Abstract

Tiltrotors could play a major role in tomorrow's civil commuter service. A successful introduction of this new transportation system will mainly depend on its overall economy, the engines playing a major role in the operating cost calculation. This paper will illustrate the mutual influence of the aircraft and the engine design, evaluated by means of total operating cost changes.

The design procedure was based on the preliminary mission requirements for a 30 PAX EUROFAR Tiltrotor and the calculations were carried out with a new computer code, especially developed for the solution of this problem. The main features of this code are shortly summarized.

Next, a baseline aircraft and a baseline engine is described and its special mission requirements are discussed. Total operating cost estimations indicate a major share for the investment related costs and for the maintenance costs while the fuel costs amount to about 9% only.

The influence of engine mass, price and performance on the overall a/c design as well as on the operating costs is summarized in a sensitivity matrix. A special sequence is set up, indicating the necessary change of the separate engine parameters in order to achieve a 1% reduction of the total operating costs respectively.

Based on these sensitivities, engine technology projections and the design optimization are shortly addressed. A specific fuel consumption of 210 g/kWh under cruise conditions seems to be feasible and with this engine the total operating costs of the tiltrotor can be reduced to 2265 dollar per flight hour.

1. Introduction

There are a lot of aircraft concepts that could be named advanced rotorcrafts: improved helicopters, compounds, tilt wings, tiltrotors and others. Each of these configurations has got its own requirements concerning the engine design and operation and a discussion of all of them would be rather lengthy. Therefore, the study presented here will take care of the configuration only that seems to have a promising future: the tiltrotor.

The design and the optimization of the overall concept is highly influenced by engine aspects, the most important of which are favourable performance, excellent reliability, low operating costs, low installation mass and compact exterior dimensions. As the tiltrotor, discussed within this paper will be operated in the civil intercity commuter service, its overall profitability will be the most important design criteria. This is normally expressed in terms of total operating costs and costs per seatmile.

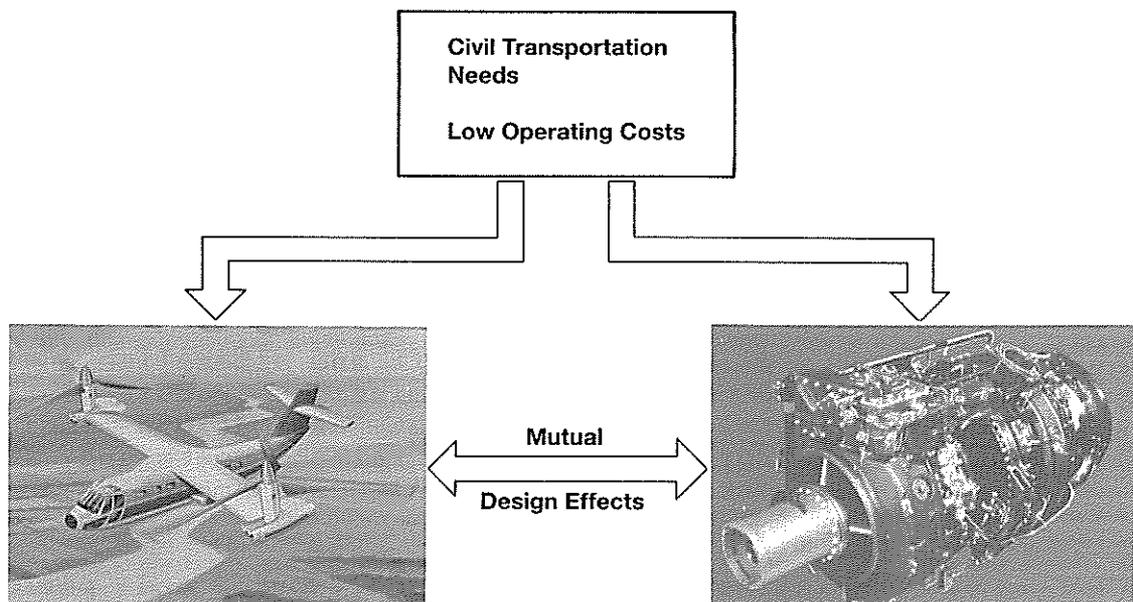


Figure 1. Three Slogans: Tiltrotor, Gasturbine Engine, Low Operating Costs

The main target of this study is to quantify the overall design influence of the most interesting engine parameters such as engine mass, specific fuel consumption, etc. The results pointed out should help the engine manufacturer in the definition of an optimized tiltrotor engine.

2. Computerized Design Methodology

The calculations were carried out with a new computer code allowing the simultaneous consideration of the engine and the complete aircraft. The main structure of this code is shown in fig. 2. In principal it consists of three major groups:

- input definition, mainly in terms of specifying the separate mission sections
- physical models for the design and performance calculation of all the relevant t/r components, such as rotor, wing, engine etc
- operating cost estimation model which is run once the iterative layout procedure for the overall aircraft has converged.

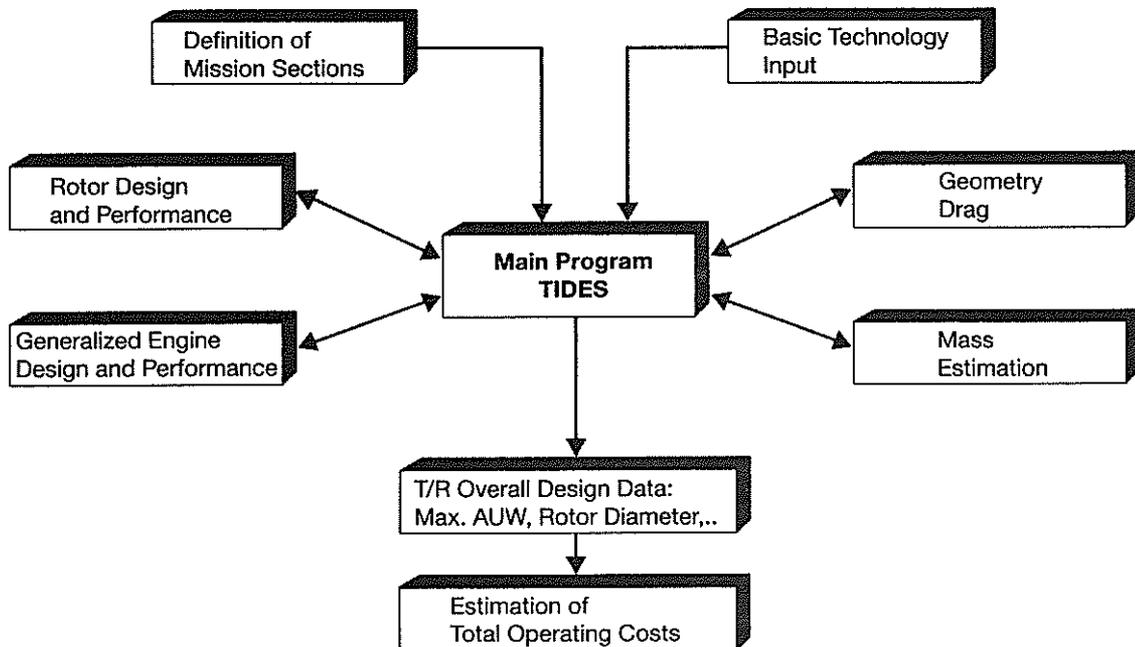


Figure 2. Main Structure of the Tiltrotor Design Computer Program

Whilst the first and the last group are rather small and can be handled easily, the physical models do not only size the computer program but they will also be decisive for the quality of the overall design results. One main task was therefore to find out modelizations which represent a good compromise between size and execution time on the one hand and the physical quality on the other hand. The models introduced can be shortly summarized as follows:

Rotors: blade element theory based on measured

2D-profile polars; some empirical corrections for Reynolds numbers, throughflow model, etc.

Engines: non linear simulation technique of the stationary performance taking account of ambient temperature and pressure, ram effect, power turbine speed and rating structure; further models handle the engine size and the fuel flow.

Wing: generalized formulas and polars with empirical corrections.

Drag: simplified approach based on geometry data and empirical aerodynamics.

Masses: semi empirical formulas validated by means of existing a/c (XV-15,V-22,etc).

Applying simple trial and error iteration technique, the problem always converged rapidly. Thus, together with flexible input output devices the simulation program turned out a powerful tool for this layout and trade off study. All the engine aspects, which will be discussed in more detail lateron, could be introduced to the program rather easily.

Concerning the definition of the mission sections precise data are not yet available as the marketing and infrastructure studies are just underway. Therefore, typical requirements for a civil commuter mission have been assumed. These are summarized in table 1.

-
- 30 passengers, 90 kg each

 - 2 men crew plus 1 flight attendant

 - 600 nm range

 - Fuel reserves: 87 nm at V_{BR}
45 min at V_{BE} at 5000 ft

 - Cruise altitude: 7500 m

 - Cruise speed: 300 kts

 - Engine load at cruise speed: < 97 % MCR

 - Category A with max. AUW at SL/ISA

 - Climb with MCR (Maximum Cruise Rating)
-

Table 1. Preliminary Mission Requirements

3. Baseline 30 PAX Tiltrotor

3.1 Overall Design

The baseline tiltrotor layout, by means of which all the trade off designs will be evaluated is shown in fig. 3 and the corresponding characteristic data are summarized in table 2. The conventional high wing aircraft features a T-tail, stationary wing mounted engines and a main landing gear, designed to fulfil the proposed crash requirements. The final configuration has been found by a sensitivity analysis, varying basic parameters such as wing loading or disk loading while always maintaining the required mission profile. High loading of the wing and the rotors dropped the structural and the drive system mass considerably and due to the lighter aircrafts the mission fuel burnt decreased too. On the other hand, wing and rotor loadings must not be too high as the rotor blade loads during conversion from h/c-mode to a/c-mode and vice versa are growing thus requiring additional structural rotor mass to keep the necessary width of the conversion corridor.

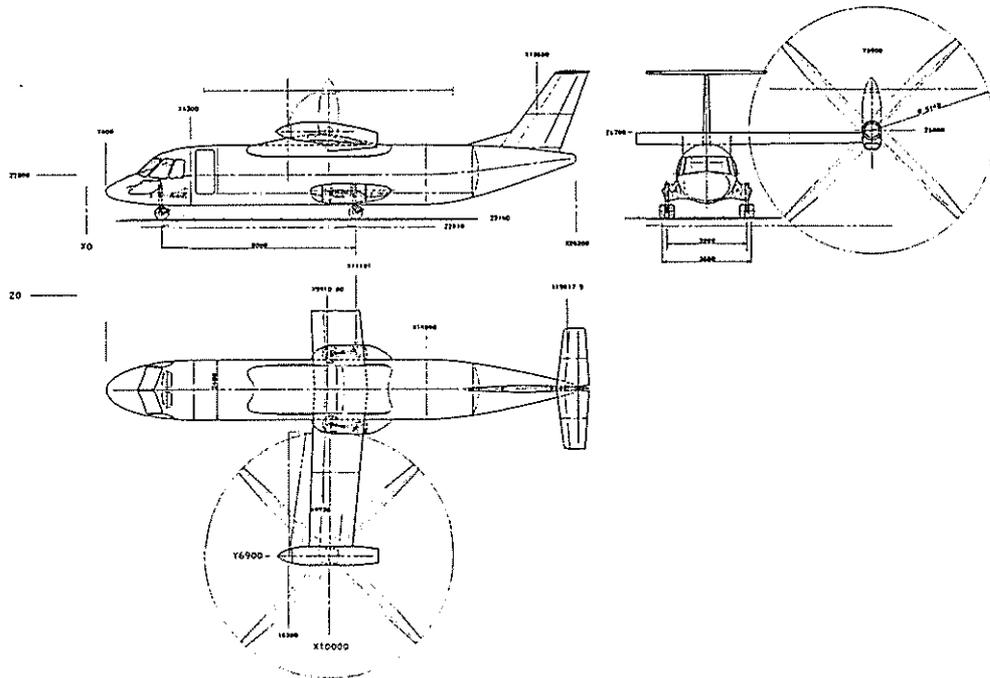


Figure 3. Baseline 30 PAX Tiltrotor

Compared to most of the conventional helicopters, all the advanced rotorcraft configurations suffer from a rather high value for the empty mass to max. AUV ratio. The application of new materials, specifically the use of composites for the wing, the rotors, parts of the airframe and the control surfaces as well as the introduction of latest control technology will help to save design mass and

to decrease the tiltrotor inherent mass drawbacks. An empty mass share of about 63% for the fully equipped 30 PAX a/c seems to be feasible.

• Maximum AUW	13110 kg
• Empty mass (fully equipped)	8290 kg
• Empty mass/max. AUW	63.2 %
• Fuselage length	19.4 m
• Fuselage diameter	2.48 m
• Wing span	13.8 m
• Wing area	27.5 m ²
• Rotor diameter	10.28 m
• Rotor disk loading	79 kg/m ²
• Number of blades	4
• Rotor type	bearingless
• Engines, max. cruise SL/ISA	2550 kW

Table 2. Main Design Data of the Baseline Tiltrotor

3.2 Baseline Engine

The baseline aircraft features two theoretically designed engines which will demonstrate performance characteristics of typical modern turboshaft engines, such as the RTM322 or the CT7-6. The required output power for the mission key points is summarized in table 3 and from this some tiltrotor specific design conclusions can be drawn:

- for normal mission operation, i.e. both engines are operating, the highest load will occur during cruise. An engine take off power will not be required and most of the mission time is flown with engines running near to max. cruise rating. This well balanced power management will give the t/r a big advantage concerning engine design, maintenance and life and will eliminate one basic drawback of typical h/c operation.
- in case of an engine failure in the critical phase of the vertical take off procedure the remaining engine shall demonstrate a rapid power response to keep the rotor speed decrease rather low. Therefore, the t/r engine shall feature modern control technique, excellent

acceleration capability and at least 40% excess emergency power compared to max. cruise rating. This power should be available for 30 seconds

	HOG AEO	Cat. A OEI	Conversion Climb	Cruise
Flight Conditions	500 m/ISA+20	SL/ISA		7500 m/ISA 300 KTAS
Installed Power Required	2 × 1791 kW	1 × 3440 kW (100 % HOG)		2 × 1298 kW
Rotor- and PT Speed n_2	100 %	100 %	100 % → 80 %	80 %
% of Rated Power	90 % of MCR	100% of OEI-30s (≡ 140 % of MCR)	Gear Box Limit or 97 % MCR	95 % MCR
Mission Time Share (300 nm Distance)	≈ 0 %	0 %	≈ 17 %	≈ 60 %

Table 3. Baseline Tiltrotor Performance Characteristics in the Mission Key Points

which seems to be sufficient to get out of the critical flight condition. Concerning the physical modelization of this transient flight maneuver some simplification was necessary for introduction into the design program. At the moment this is done by demonstrating full HOG capability under the ambient conditions to be considered.

- under cruise conditions the rotor speed has to be lowered in order to increase the propulsive efficiency. As the circumferential speed of the power turbine reduces by the same amount, the mean work coefficient goes up considerably. This means that typical turboshaft engines feature a rather bad power turbine efficiency resulting in low power output and high SFC. A different PT design, for example restaggering the vanes and blades for a special t/r-engine will reduce this detrimental effect. From this, the t/r will profit in terms of lower SFC for the cruise flight and by increased power output during OEI operating conditions where the power turbine features a very high expansion ratio and some percent reduction of speed.

- concerning the compressor design, again both mission key points ask for an optimum efficiency at high values of reduced compressor speed. In cruise flight this is due to low inlet air temperatures, while at OEI operation this will occur because of a high mechanical shaft speed.

The baseline engine is shown in fig. 4. Preliminary calculation results for the corresponding thermodynamic properties with the engine running at max. cruise rating SL/ISA are plotted too. The overall layout is based on

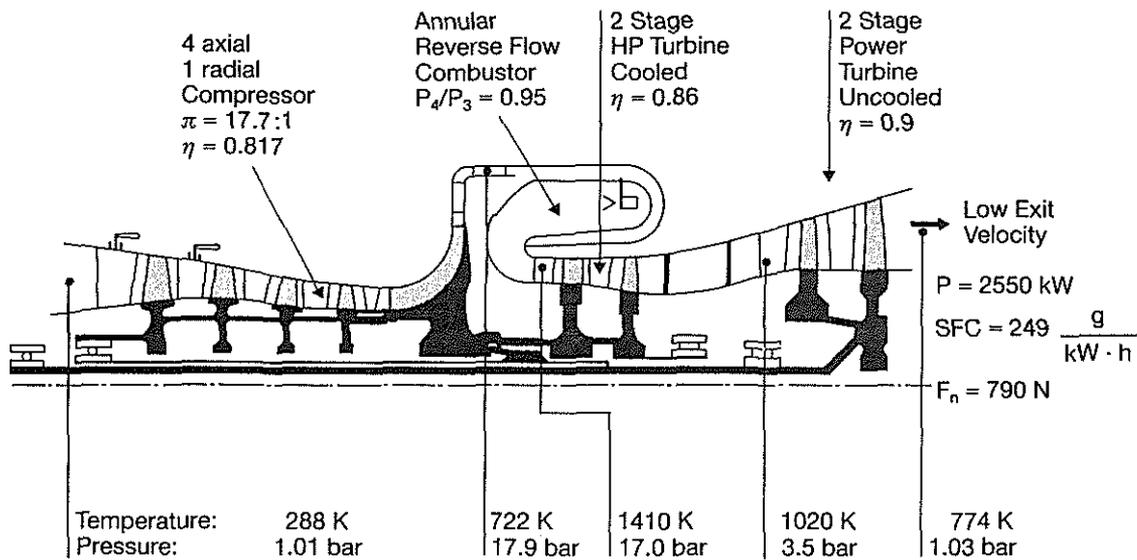


Figure 4. Baseline Engine Configuration. Cycle Data at Maximum Cruise Rating SL/Standard

typical modern turboshaft engines and is not optimized to the special t/r conditions. The maximum cycle temperature is selected rather moderate keeping in mind engine life and high OEI overpower requirements in case that one engine fails.

Concerning the diffuser design a low level for the exit velocity is preferred. Despite the fact that more engine thrust, which would require a higher exit velocity might be helpful in cruise flight, the advantages of maximizing the shaft power output for OEI operation overweighs. Moreover it has to be considered that due to the stationary installation any engine thrust is lost for the h/c-mode operation. The resulting exit diameter of the diffuser is 56 cm.

The mass estimation was based on an empirical approach as shown in fig. 5. As the mass of turboshaft engines is normally expressed in relation to the take off power (TOP), this power level has to be defined for the baseline engine too. Assuming a typical value of 15% overpower compared to max. cruise, 2930 kW are calculated for the TOP rating. Based on an estimated power to mass ratio of 10, the dry engine mass will be about 300 kg. Overall length is 1600 mm, the maximum diameter 650 mm.

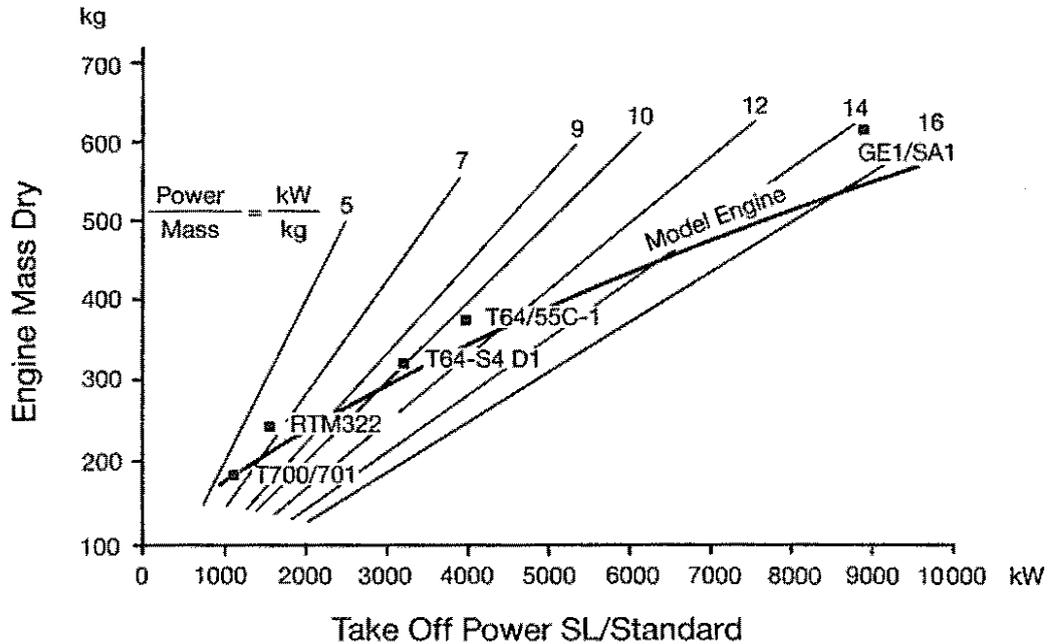


Figure 5. Engine Mass Modelization

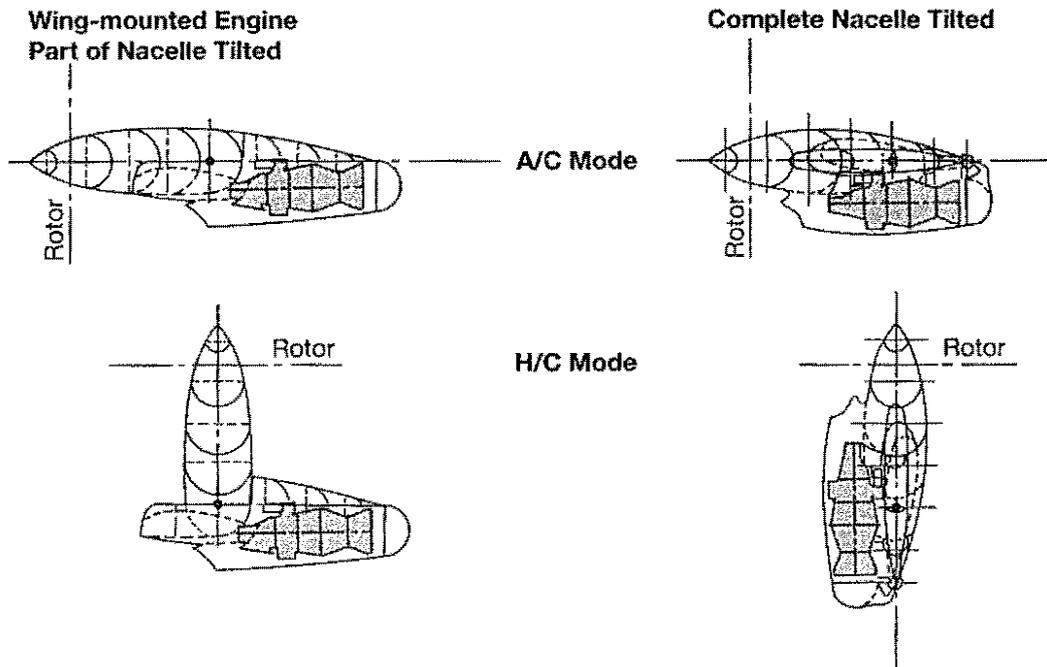


Figure 6. Engine Installations Considered

The engine is installed within a nacelle located at the wing tip respectively. Two different nacelle configurations, as shown in fig. 6 have been designed and evaluated. Shortly summarized, the complete tiltable nacelle seems to have advantages for the gearbox and drive system design while the stationary installed engine can offer many advantages from the engine point of view. Further detailed investigations will be necessary to find the best solution. At the moment the stationary installed engine is preferred.

3.3 Operating Costs

A first estimation of the operating costs for the baseline t/r is shown in fig. 7. The calculations were carried out under the following basic assumptions: investments of 13 million dollar, an average one hour trip, a fuel price of \$.33/kg, an average fuel consumption of 610 kg/h and 2000 FH per year. Due to the high investments,

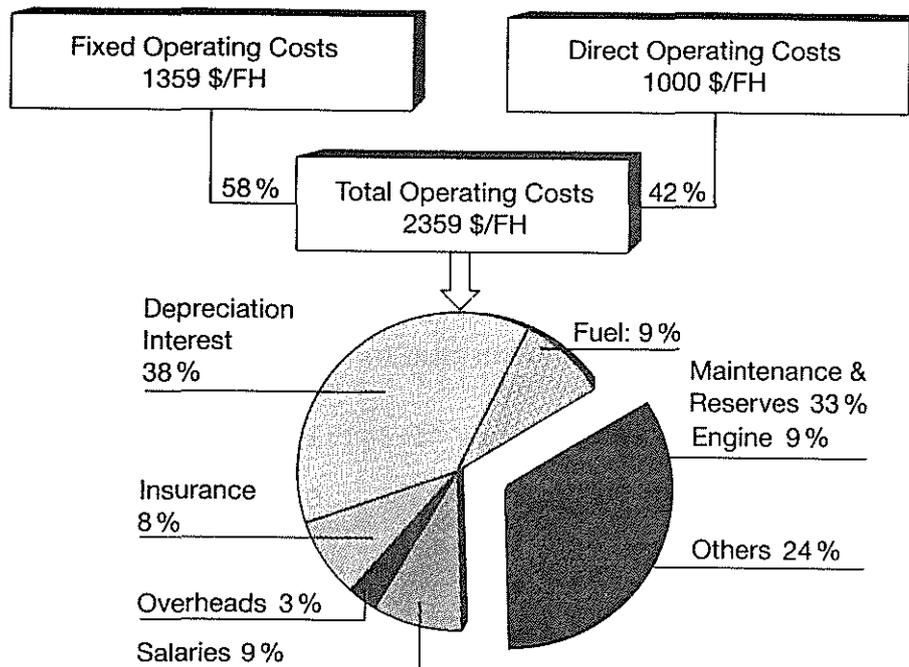


Figure 7. Baseline Tiltrotor Total Operating Costs

the fixed operating costs amount to 58% of the total operating costs. Within the remainder of 42% for the direct operating costs, maintenance and reserves contribute a 79% share thus leaving only 21% for fuel and oil. Relating the separate expenditures to the total operating costs, the fuel share decreases to around 9% while the maintenance and reserves take one third of the total. Concerning the maintenance and overhaul costs of the engine itself, 200 \$/FH were calculated, which are about 25%. The main total operating cost driver are depreciation and interest with a 38% share. Costs per seatmile amount to 0.4 dollar, assuming an average utilization of 80% and 2% return on investment.

4. T/R Design Sensitivity Analysis

The baseline t/r and its baseline engines as described above shall be taken now to evaluate the effect of variations of several engine design parameters on the overall t/r layout and operating costs. A summary of these parameters is shown in table 4.

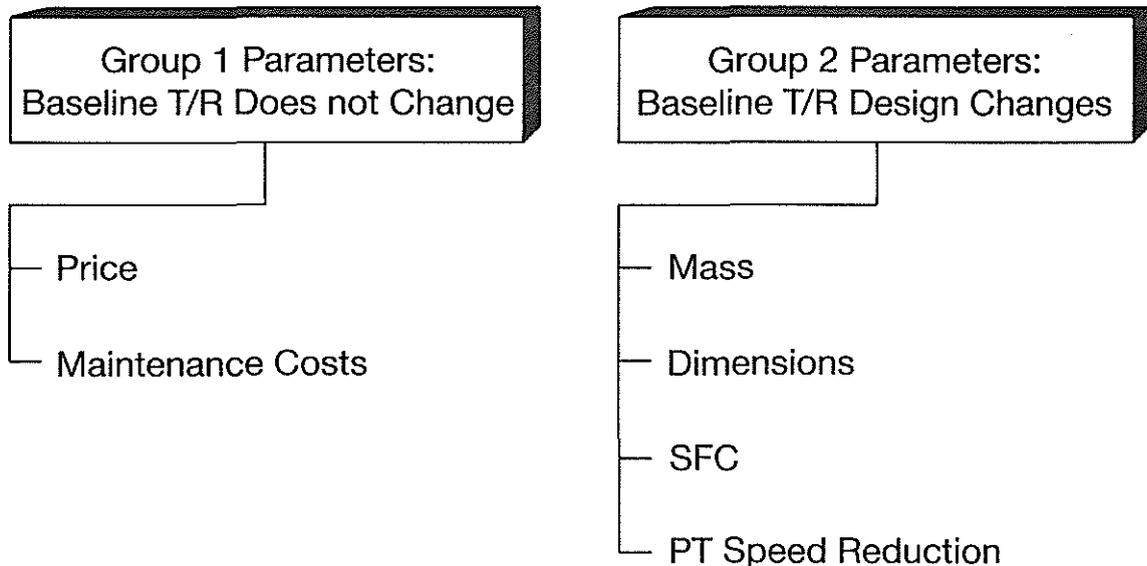


Table 4. Engine Design Parameters Varied

Two different groups have to be differentiated: the first includes parameters, which, when changed will not lead to attendant changes in the design of the baseline tiltrotor and engine; in contrast, variations of parameters of the second group will always result in a complete new aircraft and engine. These variations were based on the assumption that all aircrafts fulfil the same mission, have got the same fuselage and feature an identical disk loading, tip speed, solidity, wing loading and rotor to fuselage clearance. The final results in terms of changes to the required fuel mass, max. AUV and total operating costs are summarized in table 5 in terms of a sensitivity matrix. A detailed discussion is given in the following.

A) Engine Price (-10% change)

For the baseline aircraft about 20% of the total investment will be necessary for the engines, i.e. one engine should cost about 1.3 million dollar. Lowering this engine price by 10%, the total operating costs decrease to 2336 \$/FH. This means a reduction of 1% compared to the baseline value of 2359 \$/FH.

B) Engine Maintenance (-10% change)

It has already been shown for the baseline t/r that the engine caused maintenance costs will amount to 9% of the total operating costs. Therefore, a reduction of 10% of the engine maintenance costs down to a value of 180 \$/FH will reduce the total operating costs by 0.9%.

C) Engine Mass (power/mass ratio 10% increased)

In the baseline aircraft the installed engines contribute about 8% to the empty mass. Their dry mass is estimated by means of an empirical line as shown in fig.5. To investigate the effect of a 10% lighter engine, this line is lifted by 10% and introduced to the computer code. The new tiltrotor features 153 kg or 1.2% less max. AUV. Only 70 kg of this value are due to the engines themselves, the remainder is composed of the attendant changes in wing mass, rotor mass etc. and of 16 kg less fuel. Concerning the total operating costs, a reduction of 0.9% is achieved.

D) Engine Dimensions

It is rather difficult to generalize the influence of the engine dimensions on the aircraft drag as this will mainly depend on the type of installation selected. Small changes in the range of 10% diameter seem to have a negligible influence on the shape of the nacelle and the resultant change of drag.

E) Engine Specific Fuel Consumption (10% improved)

The thermodynamic cycle of the baseline engine can be improved by several technology steps such as better compressor and turbine efficiencies, increased cycle temperature level, higher pressure ratio, less pressure losses and less internal cooling air required. Without going into more detail, the influence of a 10% improvement of the baseline engine SFC value, which was 249 g/kWh at max. cruise SL/ISA shall be calculated here.

The effects on the tiltrotor design are rather strong: the empty mass decreases by 190 kg (-2.3%) and the fuel mass required is 208 kg lower (-11.4%), i.e. both together yield -398 kg (-3%) for the max. AUV. The resulting reduction for the operating costs, which amount to 2308 \$/FH (-2.2%) now, again demonstrates that the direct influence of the fuel will be rather low as long as the fuel price moves at the level assumed.

F) PT-Speed Reduction Influence (1%-point improved)

The a/c rotor blades will have to be designed as a compromise between hover and cruise requirements, which can be shortly summarized as high thrust capability in hover and optimum efficiency for cruise flight. Concerning the cruise

efficiency, the t/r inherent problem occurs that the rotor diameter is by far too big and therefore, the necessary high values for the blade loading can be reached only if the circumferential speed is considerably reduced.

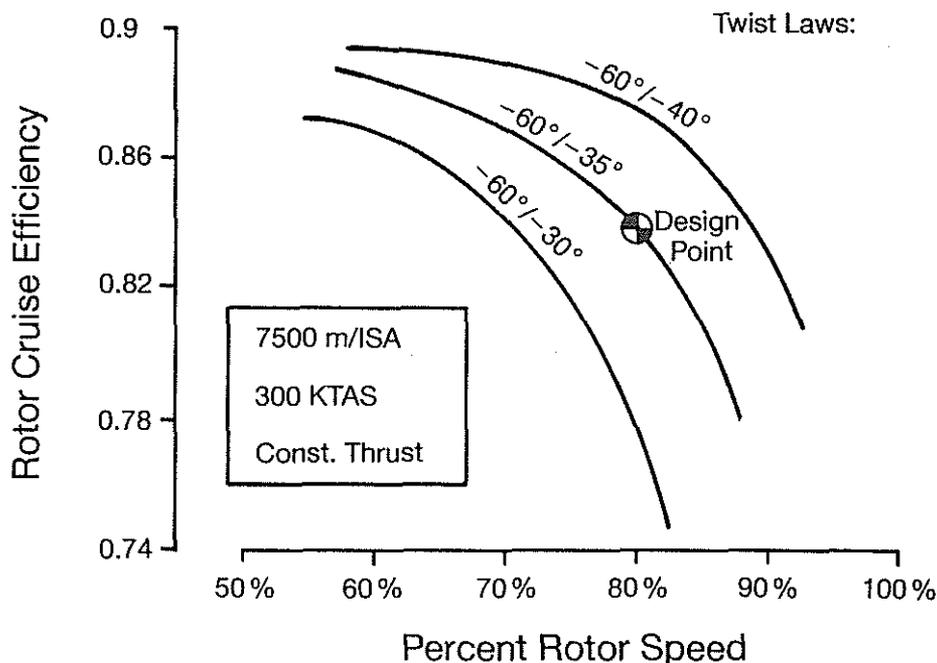


Figure 8. Influence of Speed Reduction on Rotor Cruise Efficiency

This influence is shown in fig. 8 for three different blade twists. The efficiency has an maximum near 60% speed and drops more or less at higher speeds depending on the twist law respectively. As the rotor blade designed to the upper twist law (-60°/-40°) can deliver a rather poor maximum h/c-mode thrust only, it will need more solidity and the additional mass for the hub and the blades jeopardizes the fuel mass advantages. The best preliminary compromise turned out to be the twist shown for the mid line. The really final twist law has to be worked out in a special study that will have to consider all the dynamic and aeroelastic problems as well as the aerodynamics of the special profiles selected.

The baseline engine power turbine, whose off design behaviour had been taken from typical turboshaft engines does not like high speed reductions as can be seen from fig. 9. Under normal cruise conditions, i.e. speed 20% lowered and 95% max. cruise rating, the relative reduced speed is 0.834 and the corresponding efficiency amounts to 82.5%. This is 7.5%-points less than the peak efficiency. For the sensitivity analysis the dashed line was introduced then, which means 1%-point less efficiency drop at the upper operating conditions. The results achieved are similar to the SFC influence divided by ten: 0.3% less max. AUV, 1.2% less fuel and 0.35% lower operating costs.

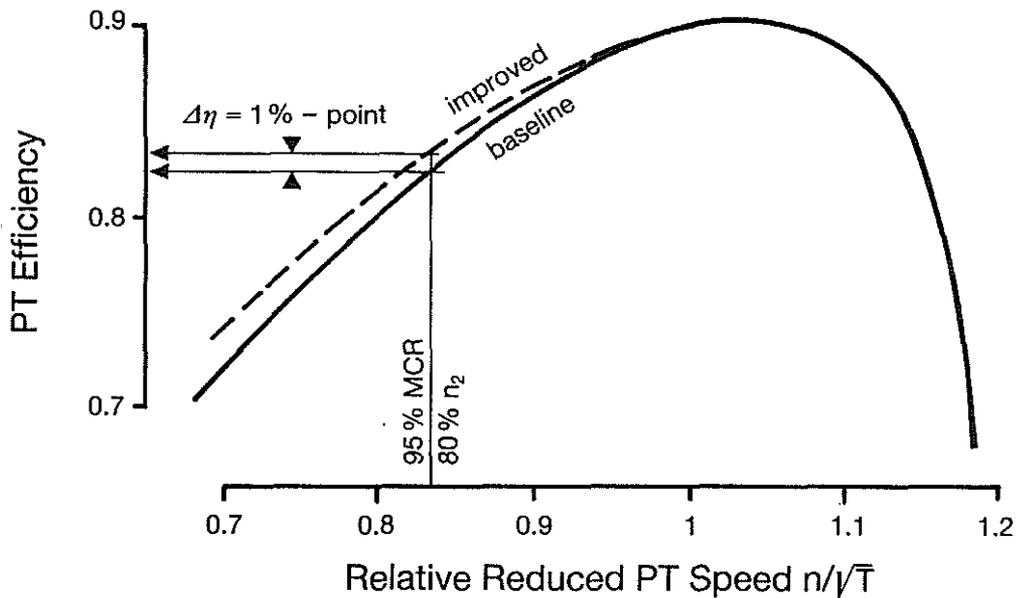


Figure 9. Power Turbine Performance. Baseline Engine and Improved Design

Engine Parameter Changed	Quantity Changed	Resulting Change in		
		Mission Fuel	Max. AUW	Total Operating Costs
Price	-10%	0	0	-1.0%
Maintenance Costs	-10%	0	0	-0.9%
Mass	Power Mass :+10%	-0.9%	-1.2%	-0.9%
Dimension	Small Changes Will Have Marginal Influence			
Basic SFC	-10% (Improved)	-11.4%	-3%	-2.2%
Power Turbine Efficiency Due to Speed Reduction	+1% - Point	-1.1%	-0.3%	-0.2%

Table 5. Tiltrotor Design Sensitivity Matrix

Summarized Sequence

As already mentioned above, the results of these variations are summarized in a sensitivity matrix as shown in table 5. The effects of the separate parameters can be best compared if the magnitude of change is calculated that delivers an equal reduction of 1% for the operating costs. This new sequence is shown in table 6.

● SFC of basic cycle:	-4.5%
● Power turbine efficiency: (due to speed reduction)	+4.5% points
● Engine price:	-10%
● Power/mass ratio:	+11%
● Maintenance costs:	-12%

Table 6. Necessary Change of an Engine Parameter to Reduce the Total Operating Costs by 1%

5. Optimized T/R Engine

After all the tendencies for the engine design have been worked out, a new t/r engine could be defined, perfectly optimized for our t/r operation. However, this problem can only be solved if generalized models are available to predict the engine price, maintenance costs, life and mass respectively. As some of these models are not available, this complete optimization cannot be performed here and therefore, the following considerations shall demonstrate some tendencies only.

Two engines will be shortly addressed:

- the recuperative engine
- the improved baseline engine

A) Recuperative Engine

Gasturbines with a heat recovery cycle are known to offer excellent SFC values and this concept could be advantageous for long range mission aircrafts. Engine manufacturers have spent a lot of theoretical and experimental work on the development of this engine type but a really successful design is still missing. Without going into deep details, some principal characteristics shall be pointed out here.

A schematic drawing of this engine type is shown in fig. 10. Heat exchanger engines have got a rather low pressure ratio in the range of 10, thus the work can be done by a compressor with one axial and one radial stage and by a one stage high pressure turbine. Compared to the simple cycle engine, four stages and accordingly some mass can be saved in this part of the engine.

However, the recuperator itself is a very voluminous part and together with all the piping and mounting required it adds a lot of mass. The recuperative engine will need ceramic materials to be run at high cycle temperatures necessary to achieve the SFC improvements anticipated. Assuming 80% heat exchanger efficiency and 8% pressure losses, a SFC value of 195 g/kWh is calculated, i.e. 22% better than the baseline value.

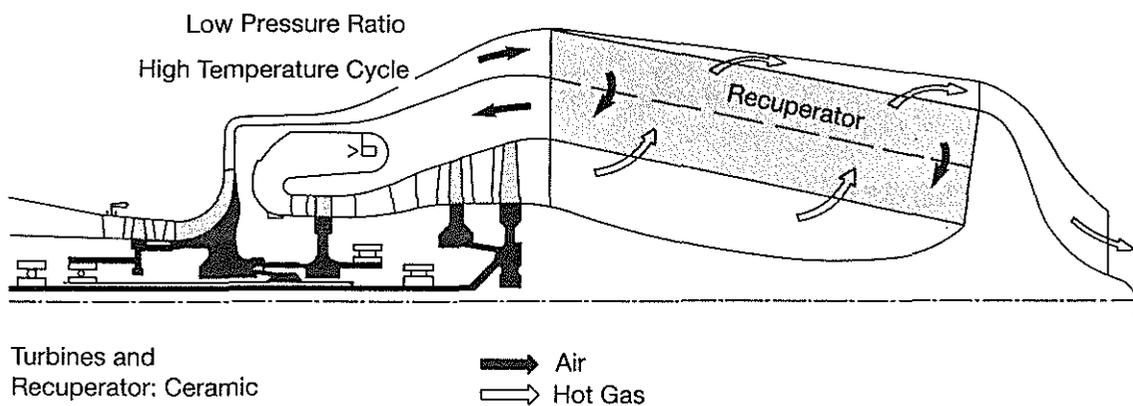


Figure 10. Schematic Drawing of a Heat Recovery Engine

Based on earlier studies, dedicated to the design of heat exchanger engines a rough estimation of the engine price and mass can be tried: compared to the baseline engine, the price could be about the same while the mass could be 50% more. Assuming further on same maintenance costs and same life for both engine concepts, the evaluation of the operating costs reduces to SFC advantages against mass and size drawbacks.

Taking the mass and SFC sensitivities from table 6, both parameters would yield about 5% influence on the operating costs thus compensating each other. Keeping in mind that the bigger exterior size could feature a no longer negligible drag increase in cruise flight, the heat exchanger engine will hardly be able to push away the simple cycle engine, mainly if this type is really optimized for the t/r operation. However, things may change if the fuel price would be twice as high or even more.

B) Improved Simple Cycle (Baseline) Engine

It has been mentioned already that the baseline engine design will offer some potential for optimization of the performance. At the fuel driving cruise design point the engine could feature a considerable improvement of the SFC if all components are especially designed to these operating conditions. To give a preliminary feeling which value for the cruise SFC seems to be feasible at all, the following thermodynamic cycle has been calculated:

- full ram effect at cruising point
- 80% compressor efficiency
- 1400 K combustor exit temperature
- 86.5% high pressure turbine efficiency
- 90% power turbine efficiency at 80% speed.
- assumptions for cooling air, shaft losses, etc same as for the baseline engine

The resulting specific fuel consumption amounts to 210 g/kWh, i.e. a 10% improvement compared to the baseline engine is achieved. If it is further assumed that the mass of this new engine can be calculated with the baseline power to mass function of fig. 5, the effects on the overall design of the tiltrotor can be shown.

The results, summarized in fig. 11, indicate a 4% reduction of the total operating costs. Compared to the SFC sensitivity value, pointed out in table 5, the reduction is a little bit more, as in this case attendant changes of the maintenance costs had been considered too.

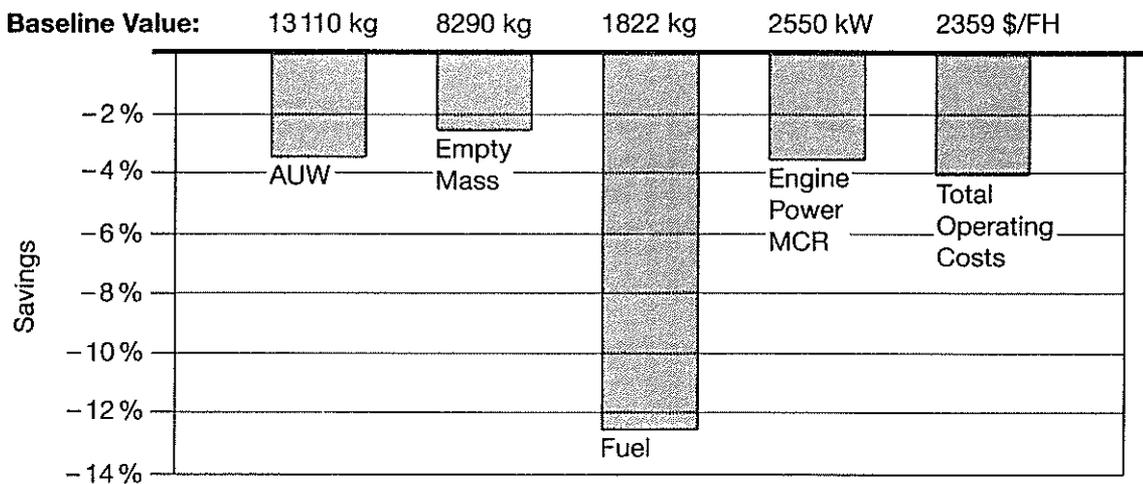


Figure 11. Savings for a T/R Design with the Improved Simple Cycle Engine (Cruise SFC = 210 g/kWh)

The influence of the fuel price on this design is shown in fig. 12. Doubling the fuel price, i.e. from 0.33 \$/kg to 0.66 \$/kg, the total operating costs increase by 7.9% from 2265 \$/FH to 2444 \$/FH. The share of the fuel moves from 8% to 15% while the dominating depreciation and interest costs reduce from 38% to 35%.

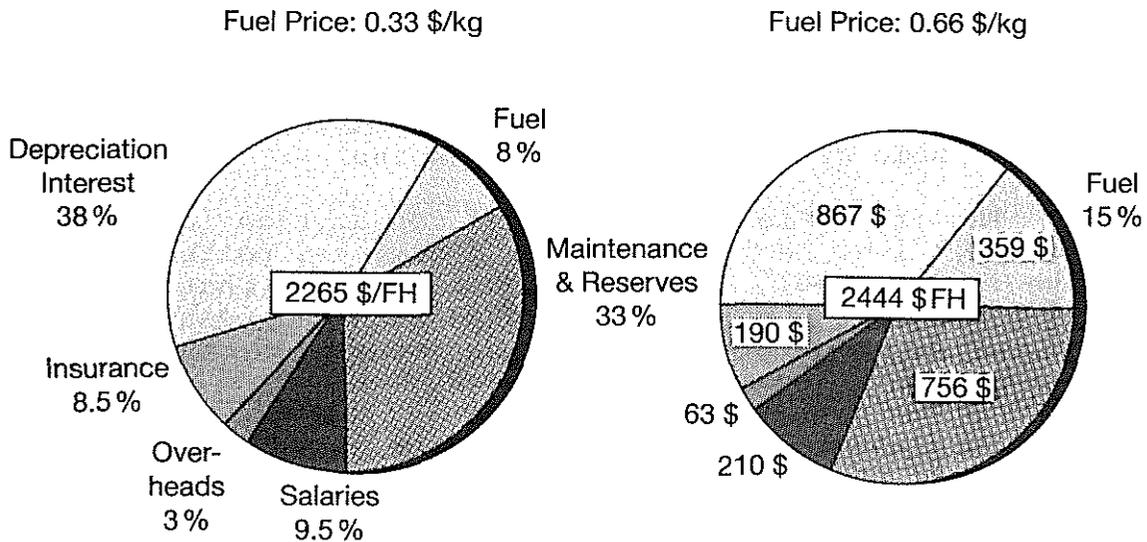


Figure 12. Influence of Fuel Price on Operating Costs. T/R with Improved Simple Cycle Engine.

6) Conclusions

- Due to the special power requirement characteristics of the tiltrotor aircraft best assumptions exist to reach long engine lifetimes: most of the mission time, the engine will run close to maximum cruise rating, higher loads will not be required and the number of cycles per flight hour will be rather low.
- To cover the requirements for Cat. A starts, the engine should be provided with an OEI 30s emergency rating delivering at least 40% excess power output (compared to max. cruise). Rapid power response and short acceleration times will help to decrease the rotor speed reduction following the power loss of one engine.

- The performance of the compressor and the turbines should be optimized to the special conditions of the cruise flight. Concerning the power turbine design, high speed reductions have to be taken into account.
- The total operating costs are dominated by the investment and maintenance costs. The latter ones have been estimated on the basis of helicopter experience and mission requirements, but the more favourable assumptions of the t/r operation should allow some improvements.
- The fuel costs will move in the range of 10% of the total operating costs only, naturally depending on the fuel price respectively. On the contrary, Engine maintenance costs as well as the engine related investment costs are of the same order and take a one third share each. Therefore, the t/r engine should not only be an optimum performance engine but also an light weight, low cost and low maintenance cost engine.

References

1. M.L. Early and P.K. Zeiner: "Influence of Engine Variables on Future Helicopter Systems" AGARD-LS-148, Paper No. 5, 1986
2. J.B. Wilkerson and R.S. Taylor: "Civil Tiltrotor Aircraft: A Comparison of Five Candidate Designs" presented at the 44th AHS Forum, June 1988
3. J. Andres, H. Huber and J. Renaud: "The Tiltrotor Aircraft: A Response to the Future?", presented at the 12th ERF, Paper No. 4, September 1986
4. Study Team - Boeing, Bell and NASA: "Civil Tiltrotor Missions and Applications: A Research Study", NASA CR 177452, July 1987
5. M. Giraud: "Power Level Influence on Architecture of Small Helicopter Turboshaft Engines" presented at the International GTC, June 1986