HELICOPTER TURBOSHAFT TECHNOLOGY EVOLUTION

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Abstract

Based on the large experience of TURBOMECA in the field of helicopter turboshafts, this document describes the turboshaft technology evolution from the 50's to nowadays.

The following points are addressed:

- Performance and thermodynamical cycle: specific power, power to weight ratio, specific fuel consumption, pressure ratio and turbine inlet temperature.
- General Arrangement: single shaft to twin shaft evolution, power shaft location, architecture simplification.
- Components progress and associated materials improvement : compressor, combustor and turbines.
- Control system evolution.

Future trends and objectives above the progress accomplished during the last 40 years are given as a conclusion.

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1. TURBOMECA experience in the field of helicopter turboshafts

Since years 50's, TURBOMECA has built a solid and large experience in the field of helicopter power plant. Indeed, for 40 years, TURBOMECA has produced more than 45000 helicopter turboshaft engines and cumulated more than 67 millions of running hours.

The Figure 1 shows the three main generations:

- During the 50's and 60's , ARTOUSTE, ASTAZOU and TURMO engines have covered the 300 to 1200 kW power range.
- From the 70's, this range has been completed by the ARRIEL 1, a 500 to 600 kW engine and the MAKILA a 1200 to 1400 kW engine. These two turboshaft engines which have been in production for 20 years have a large success in the world.
- Since the 80's, TURBOMECA has developed a new generation of turboshafts which results from extensive research using modelisation tools, test rigs and demonstrator engines and giving the availability of new efficient components. This new turboshaft family is composed of:
    - ◊ ARRIUS engine covering the power range 350 to 500 kW.
    - ◊ ARRIEL 2, a 630/640 power class engine derivated from ARRIEL 1 by the embodiment of a new hot end.
    - ◊ TM 333 engine covering the power range 650 to 800 kW.
    - ◊ MTR 390, a 950/1000 kW power class engine developed in cooperation with MTU and ROLLS-ROYCE.

◊ RTM 322 covering the power range 1600 to 1800 kW developed in cooperation with ROLLS-ROYCE.

All these new engines are either already in production or finishing their qualification process. They combine perfectly with ARRIEL 1 and MAKILA engines to offer a complete range meeting today and tomorrow helicopter requirements.

The Figure 2 shows the large number of helicopters equipped or being equipped with TURBOMECA engines. This illustrates the strategy developed since years 60's which consists in being present on helicopter range from 1.5 to 10 tons.

This large experience allows to describe the turboshaft technology evolution over the last 40 years.

2. Performance and thermodynamical cycle evolution

The main parameters to illustrate the performance improvement are:

- The power-to-weight ratio.
- The specific power which is the power to mass air flow ratio.
- And the specific fuel consumption.

The Figure 3 shows the evolution of the power-to-weight ratio at take-off rating according to TURBOMECA experience for 40 years. It is important to notice that between ARTOUSTE 2 and ARRIUS 2, this ratio has more than doubled.

In the same way, the **Figure 4** shows the significant increase of the specific power at take-off rating achieved from the first to the latest engine generations.

Finally, the Figure 5 shows the specific fuel consumption decrease at take-off rating which has to be associated with a significant simplification of engine architecture.

These performance improvements are achieved with more and more ambitions thermodynamic cycles depending mainly on pressure ratio, turbine inlet temperature and component efficiencies.

The **Figure 6** shows pressure ratio evolution from first engine generation (around 5:1) to the new modern generation. The achieved pressure ratios result from a compromise with a minimum number of stages and a high efficiency:

- Single stage centrifugal compressor for ARRIUS engine.
- Two axial plus one centrifugal compressor for TM 333 engine.
- Twin centrifugal compressor for MTR 390 engine.
- And three axial plus one centrifugal compressor for RTM 322 engine.

As it is shown on **Figure 7** in reference to first generation engines, the turbine inlet temperature increase has reached 300 K on ARRIUS 2, ARRIEL 2 and TM 333 turboshaft with uncooled single crystal blades and 400 K on MTR 390 and RTM 322 turboshafts with cooled single crystal blades.

3. Architecture evolution

- The first significant evolution of turboshaft architecture has been the transition from single shaft turbines, like ARTOUSTE and ASTAZOU families, to power turbine turboshafts the first of which has been the TURMO engine.

  Even if single shaft turbines were well known for their transient performance, the embodiment of power turbine concept brought significant advantages with respect to helicopter performance and reliability (Cf. Figure 8):

  ◊ Suppression of the helicopter clutch.

  ◊ Increase of the safety during handling near thermal limits.

◊ Easier suitability for twin engine helicopters.

◊ Improved performance due to the basic principle and the associated operating lines in compressor map, as it is shown on **Figure 9.** This leads, for an example to a SFC decrease by about 10% in cruise conditions.

- The second significant evolution in turboshaft design has been the introduction of concentric through power shaft like on ARRIUS, TM 333, MTR 390 and RTM 322 engines in replacement of rear power output like on MAKILA engine or of external power shaft like on ARRIEL engine (Cf. **Figure 10**).

  A concentric through shaft which needs the mastery of higher stress level in disk hubs and of super-critical rotors, improves engine compacity, decreases the number of bearing chambers and associated costs and permits either a front or a rear power output.

- All these design evolutions have a main guideline which is the simplicity in order to decrease acquisition and ownership costs. The **Figure 11** illustrates this trend by comparing ASTAZOU 14, ARRIEL and ARRIUS engines.

  This comparison brings to light that the number of aerofoil grids has been divided by two even if the pressure ratio has slightly increased.

  But a simple architecture design needs:

  ◊ A high performance level for each components : compressor, combustion chamber, turbines, control system.

  ◊ The development of new appropriate materials.

  ◊ The mastery of new bearing and rotor dynamic technologies. This is illustrated by Figure 12.

4. Major components progress

4.1 Compressor

In order to increase the performance and to decrease the number of stages, the centrifugal compressor plays a major part in TURBOMECA compressor design. The progress achieved in the field of centrifugal compressors leads on one hand to a simultaneous increase of pressure ratio and efficiency and on the other hand to the capability to couple two centrifugal stages on the same shaft without any variable geometry or bleed valve.

The **Figure 13** illustrates the performance evolution with respect to pressure ratio and efficiency for a single stage centrifugal compressor. This performance evolution is associated to the continuous improvement of modelisation tools.

The pressure ratio evolution is associated to a significant increase of the impeller peripheral speed, roughly 10 m/s per year as it is shown on **Figure 14.** This has been obtained simultaneously with a constant life improvement.

The requirements for a centrifugal compressor with respect to mechanical properties cover a temperature range from 300 to 600 °C. Titanium alloys used for more than 30 years are the most appropriate materials to fulfill these requirements.

The Figure 15 shows the different titanium alloys applied to centrifugal impellers from TA6V to Ti6246.

The intermetalics TiAl and Ti_3Al which are currently in development will be the appropriate alloys for high temperature use.

4.2 Combustion chamber

From the beginning to nowadays on ARRIEL and MAKILA, TURBOMECA engines are characterized by their centrifugal injection combustion chamber. This special design offers several advantages such as a low pressure fuel pump and an integrated high pressure turbine nozzle cooling.

The most important technology evolution has been the introduction of a reverse flow combustion chamber on the new engine generation (see Figure 16). This chamber design increases engine compacity by shortening the gas generator core; it also suppresses the injection wheel which is a limited life rotative part.

In addition to that major architecture evolution, significant progress has been obtained with respect to fuel injection system and wall cooling technologies.

Air blast injectors are replacing vaporizors improving the exhaust temperature distribution, starting and transient performance.

Optimized multi-hole cooling his replacing film cooling technology, thus improving combustor life.

The most appropriate materials for combustion chamber are today Nickel alloys such as NC22FeD (HASTELLOY X) and NC22W14 (HAYNES 230).

New materials in development or qualification are ASTRALLOY or MA956 (ODS) associated with casting manufacture process for cost reduction.

In reference to first engine generation, the combustion chamber life has already been multiplied by ten. The new challenge for the combustion chamber is to combine starting and transient performance, particularly extinction limit, with the new Lean Premixed Prevaporized (LPP) technology necessary to meet low emission requirements.

4.3 Turbines

The dominating trend in the turbine field is also the decrease number of stages. The aerodynamical and mechanical progress permits to replace two axial stages by high expansion ratio single stage for high pressure turbines and for power turbines of low and medium power class engines (300 to 800 kW).

The diagram shown on **Figure 17** illustrates the technological leap forward achieved when single stage turbines have been introduced in the new generation engines.

If a single stage high pressure turbine takes advantage of the natural temperature decrease due to high expansion rate, it requires the mastery of high aerodynamic and mechanical loads. The Figure 18 shows the associated blade peripheral speed increase which is roughly 100 m/s in reference to first engine generation.

The blade material is of course a key issue for turbine inlet temperature increase. The **Figure 19** shows the importance of single crystal alloys for turboshaft small size turbine blades. Indeed single crystal alloys allow to put back the introduction of cooled blades for low and medium power turboshaft engines.

5. Control system evolution

Parallel to turbomachinery technology evolution the control system technology moved step by step from simple hydromecanical systems to Full Authority Digital Electronic Control System (FADEC).

The **Figure 20** shows this step by step evolution. The single shaft turbine first engine generation, like ARTOUSTE and ASTAZOU family, was equipped with a single loop hydromecanical system.

The introduction of power turbine concept required a twin loop system which remains entirely hydromecanical on TURMO and ARRIEL engines.

Then an hybrid system has been introduced on MAKILA engine, composed of an hydromecanical loop for gas generator control and of an electronical loop for power turbine control. This power turbine electronic loop is an analogic technology one on MAKILA 1A/1A1; it is a digital technology one on MAKILA 1A2.

The first Full Authority Digital Electronic Control (FADEC) system has been qualified on ARRIUS 1 and TM 333 engine in 1988. It is a single channel FADEC equipped with a manual mechanical backup.

After this first FADEC technology step, the Airworthiness requirements evolution needs more sophisticated systems such as:

- A single channel FADEC with protected manual backup which has been qualified on ARRIEL 2 and ARRIUS 2 engines.
- A single channel FADEC with protected electrical backup which is qualified on MTR 390.
- A double channel FADEC without backup which has been qualified on RTM 322.

Despite this quick technology evolution, it is important to notice that a full hydromecanical system derived from ARRIEL 1 one has been qualified on ARRIUS 2F engine for cost priority reason.

6. Conclusion - Future trends

The technology improvements achieved during the last 40 years make a new generation of turboshaft engines available, which meet the specific requirements of a modern helicopter:

- Performance trade-off between OEI ratings and specific fuel consumption at low power.
- Growth potential.
- TBO, reliability, maintainability, DOC.
- Transient performance.

In addition, to these turboshaft specificities which becomes more and more severe, new requirements are emerging such as:

- Noise and emissions.
- Adverse conditions self-protection (ice, snow, sand, ...).
- Infrared signature.
- Rotor containment.

In reference to the new engine generation, the objectives for the next coming years can be summarized as follows:

- SFC = - 10% to - 20%.
- Power to weight ratio: + 40% to + 50%.
- Specific power: + 30% to + 50%.
- LCC: - 15% to - 30%.

The Figure 21 shows the future architecture trends to meet these new requirements. They are driven by simplicity and cost reduction.

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[5] BELAYGUE P., VIGNAU H., "Le compresseur centrifuge, composant essentiel des turbomoteurs de petites et moyennes puissances", AGARD, 82nd Symposium of the PEP, October 1993.

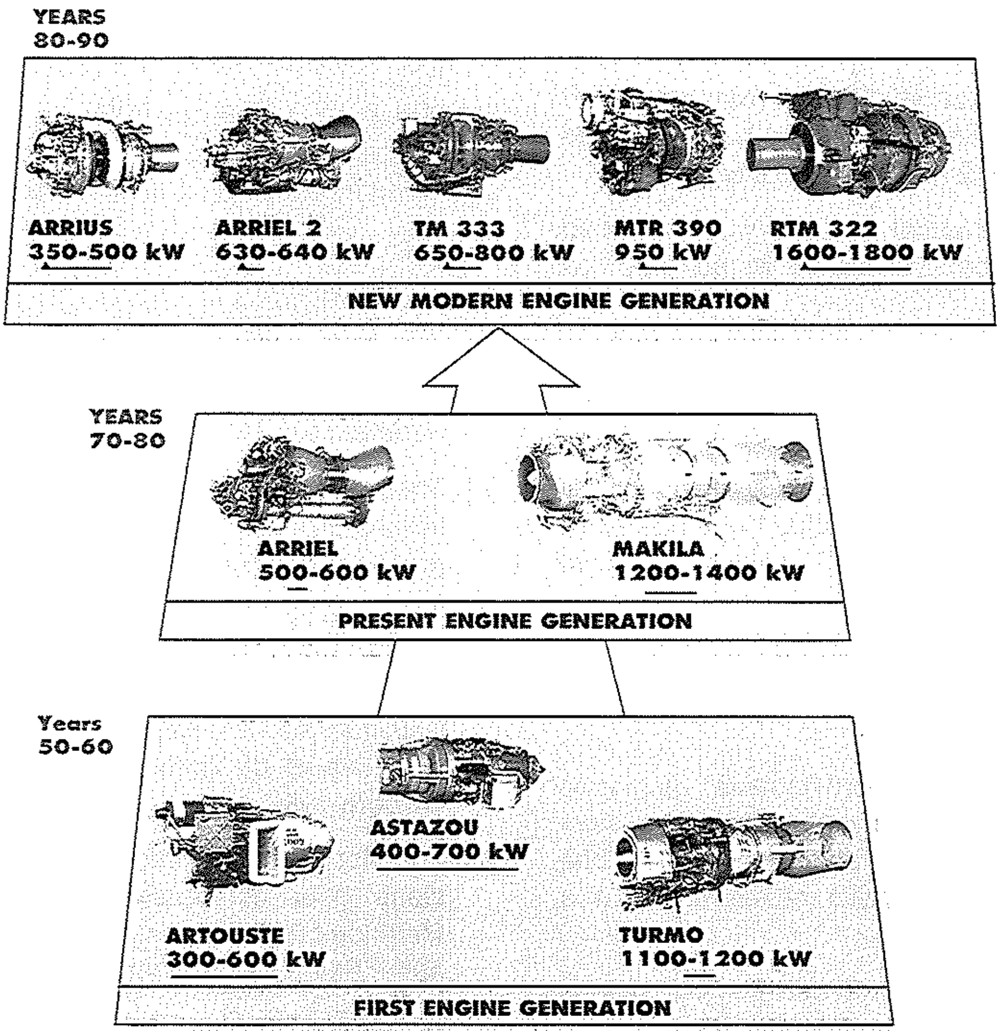
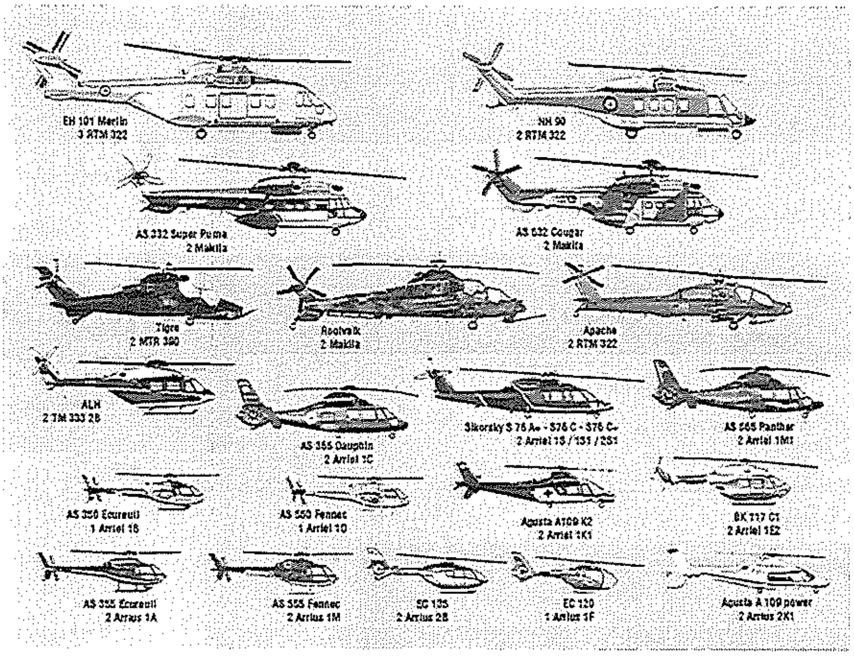


FIG. 1 Turbomeca experience in the field of helicopter power plants

1970 - 2000

New modern engine generation

Present engine generation



1950 - 1970

First engine generation

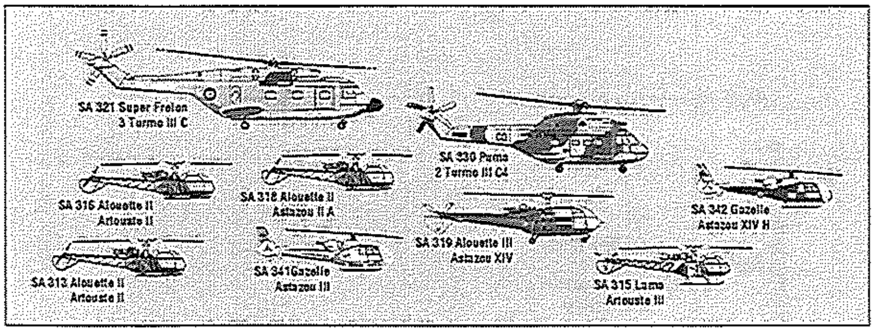


FIG. 2 Turbomeca experience

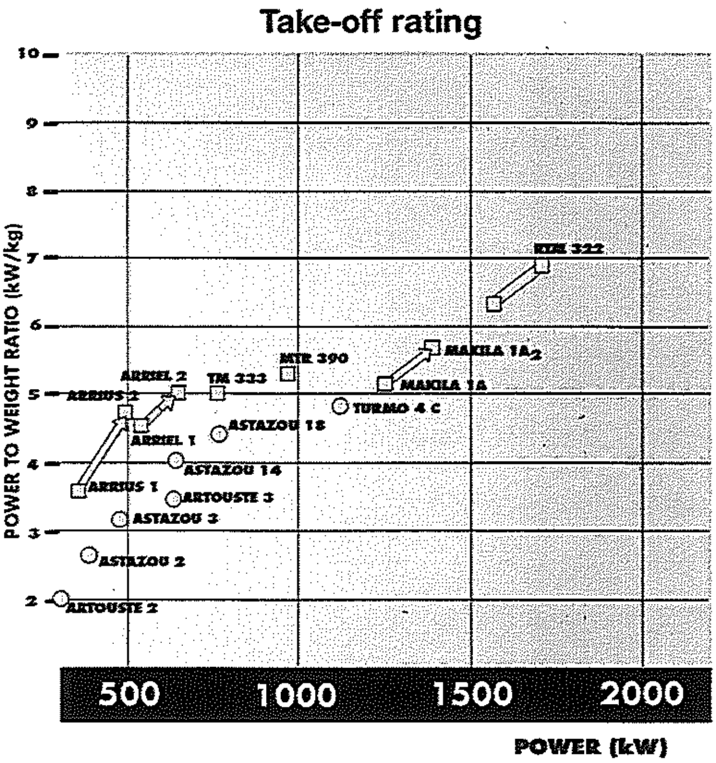


FIG. 3 Power to weight ratio evolution

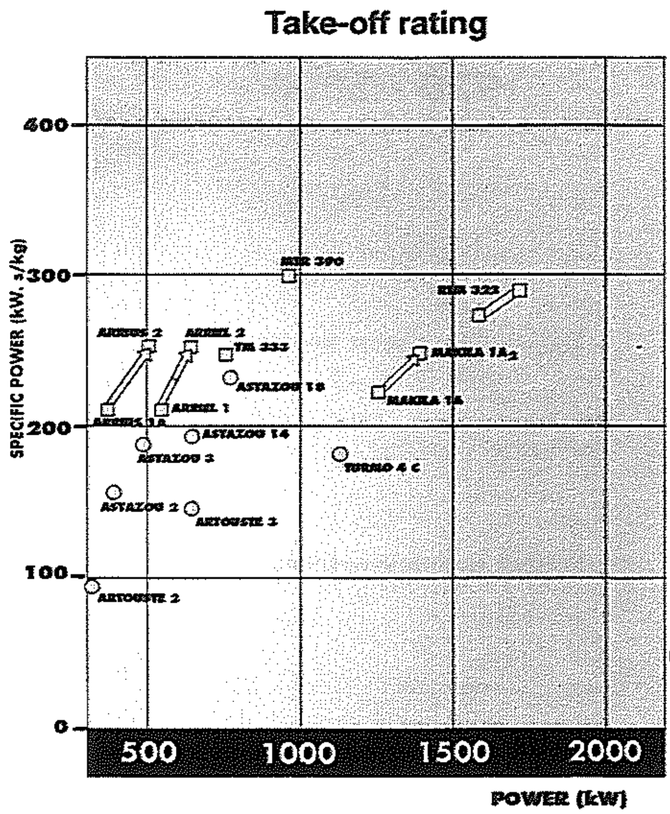


FIG. 4 Specific power evolution

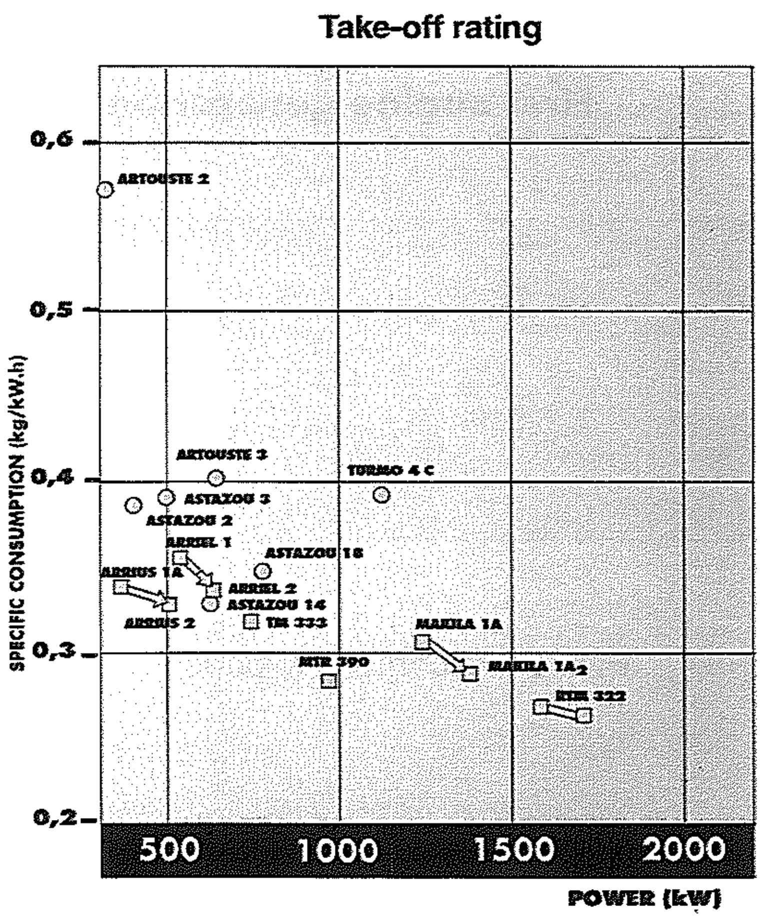


FIG. 5 Specific fuel consumption evolution

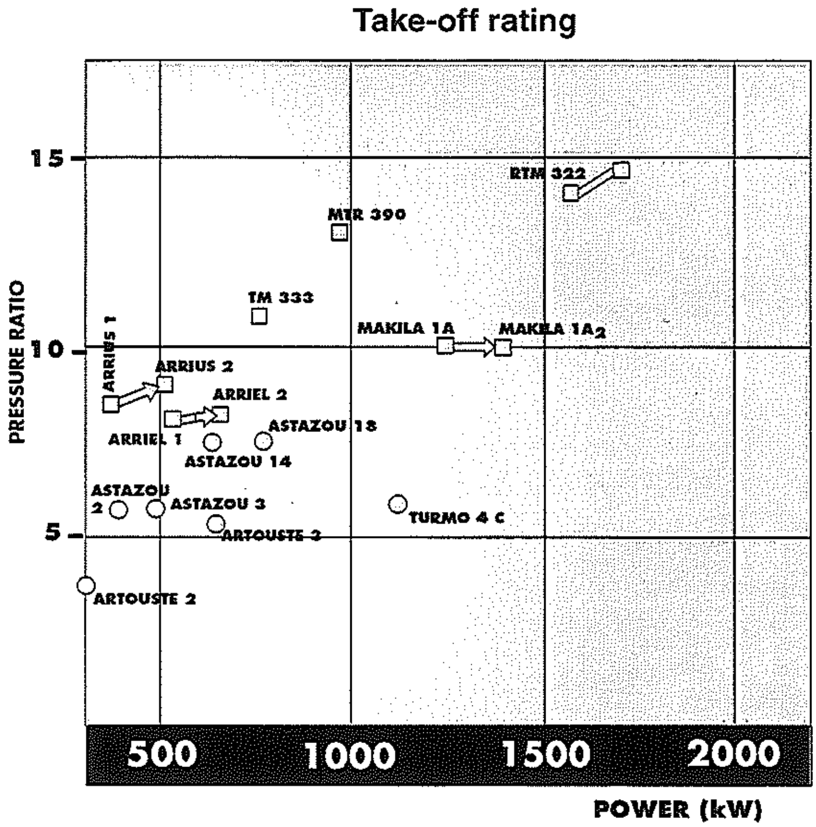


FIG. 6 Pressure ratio increase

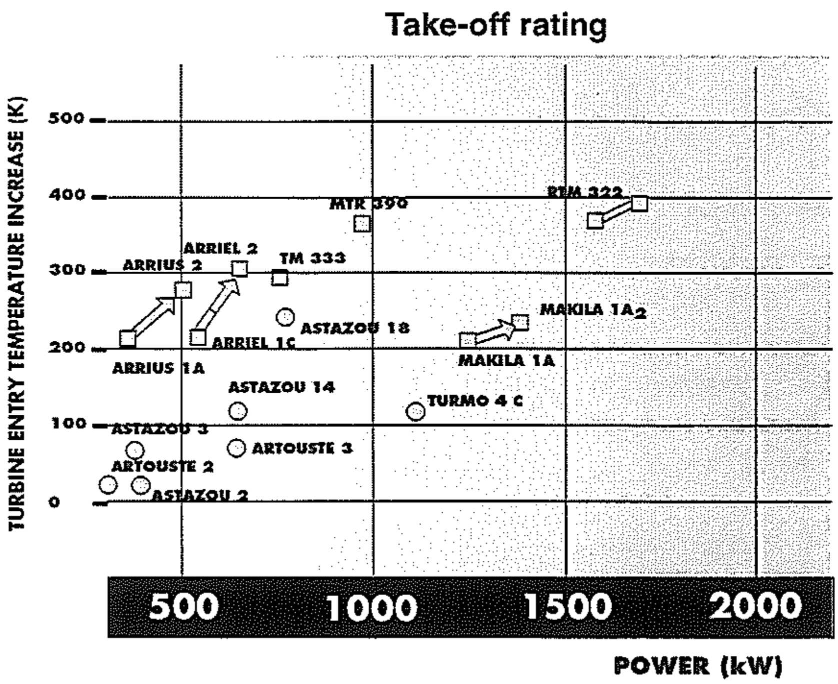
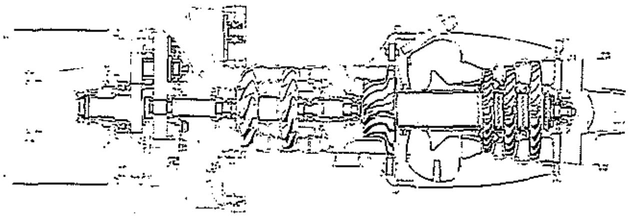


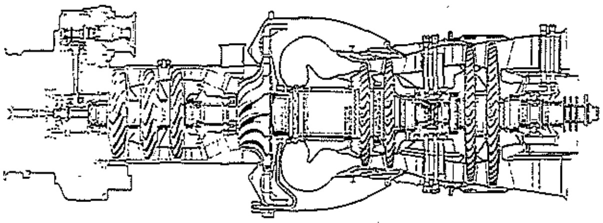
FIG. 7 Turbine entry temperature increase

Single shaft turbine ▶ Power Turbine

ASTAZOU XIV



MAKILA



- **Clutch suppression**
- **Safety increase**
- **More suitable for twin engine helicopters**
- **Improved performance**

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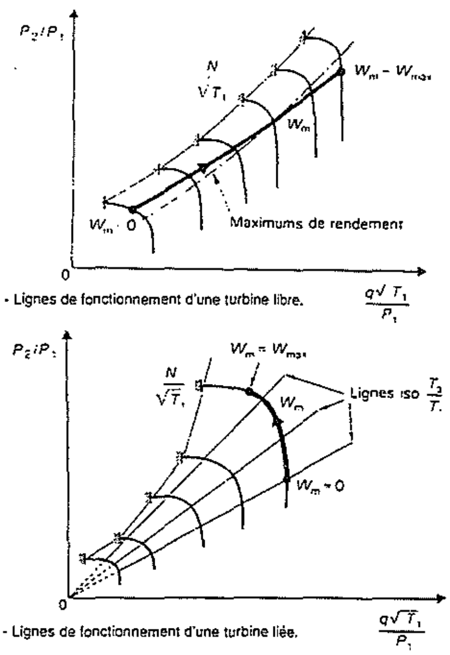
FIG. 8 Architecture evolution ; single shaft turbine to power turbine

Single shaft turbine ▶ Power Turbine
Operation principle



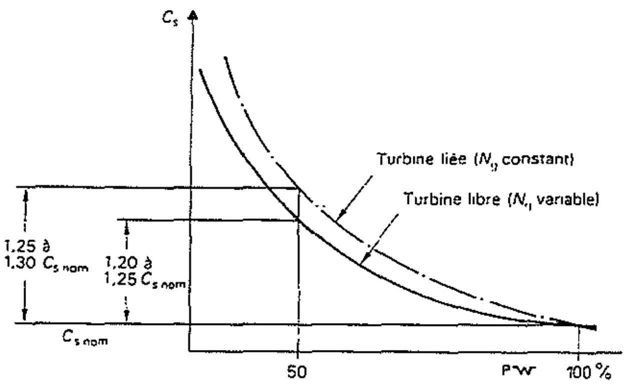


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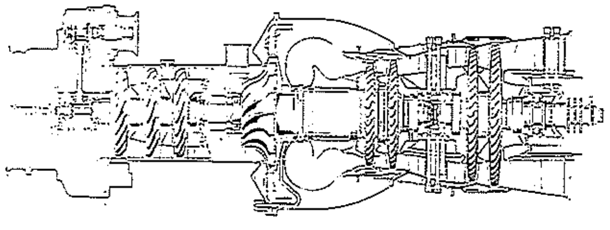
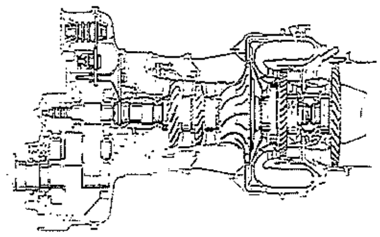
FIG. 9 Single shaft turbine / power turbine : operation principle

Power shaft

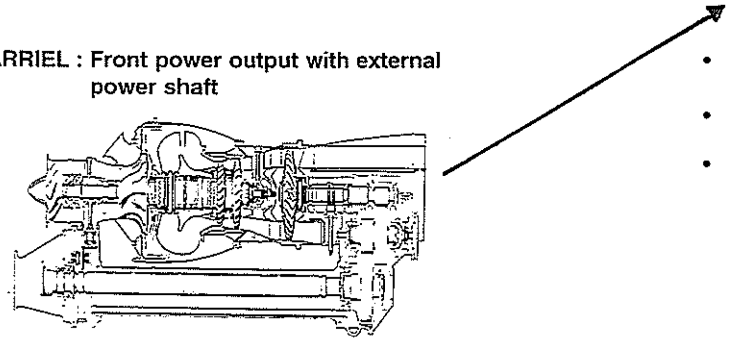
MAKILA : Rear power output



TM 333 : Front power output with concentric through power shaft



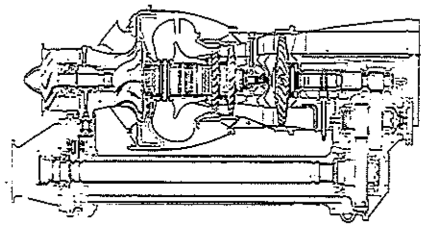
ARRIEL : Front power output with external power shaft



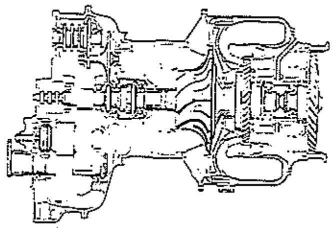
- Compacity improve
- Bearing chamber number decrease
- Supercritical rotor

FIG. 10 Architecture evolution : Power shaft

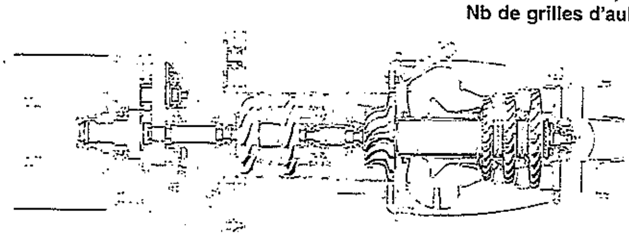
New trend ▶ Simplicity



ARRIEL 1 P / p = 8 : 1
Nb de grilles d'aubages 12



ARRIUS P / p = 8.5. : 1
Nb de grilles d'aubages 7



ASTAZOU XIV P / p = 7.5. : 1
Nb de grilles d'aubages 15

FIG. 11 Architecture evolution : trend to simplicity

A Simple Architecture Needs High Performance Level Components

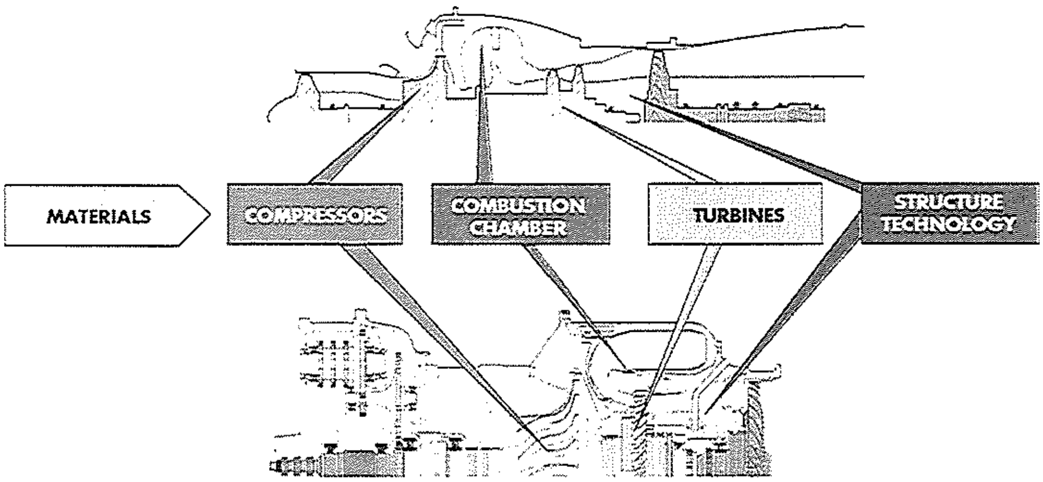


FIG. 12 Architecture evolution :
simplicity and high performance components

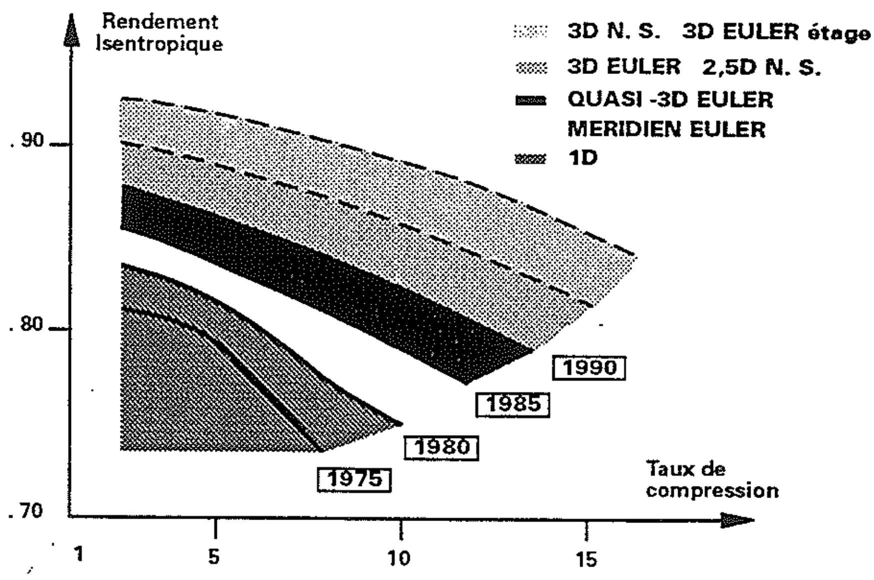


FIG. 13 Single stage centrifugal compressor
performance condition

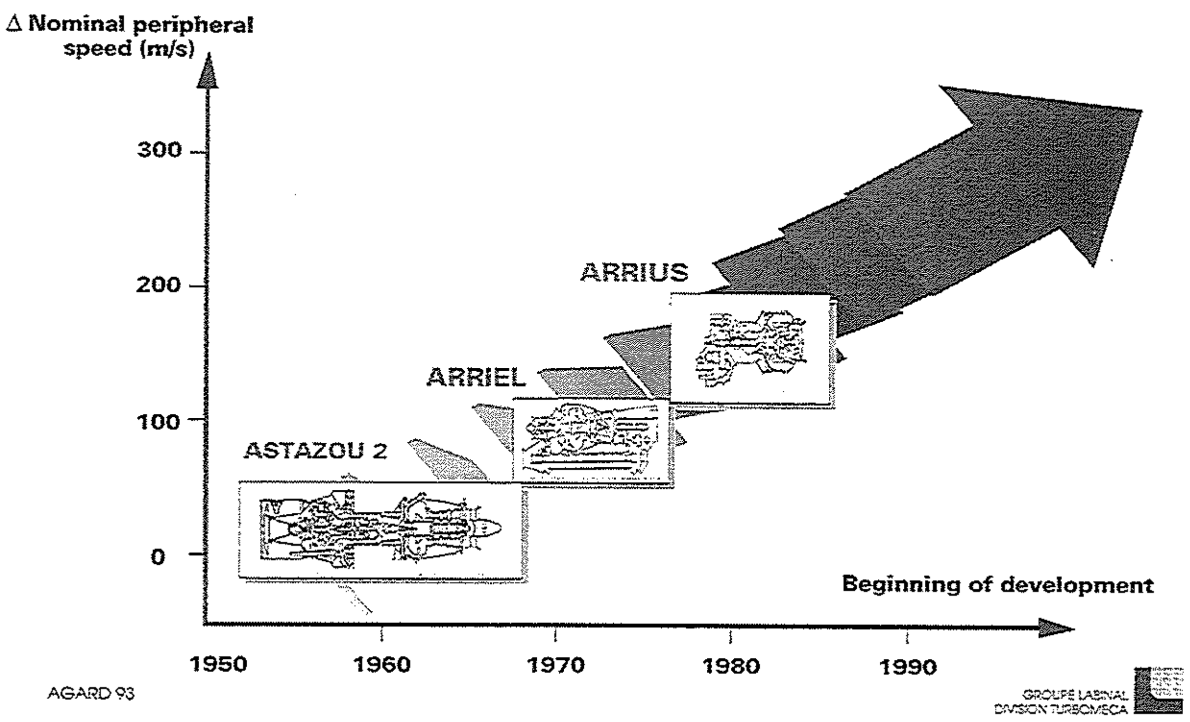


FIG. 14 Centrifugal compressors
Nominal impeller peripheral speed improvements

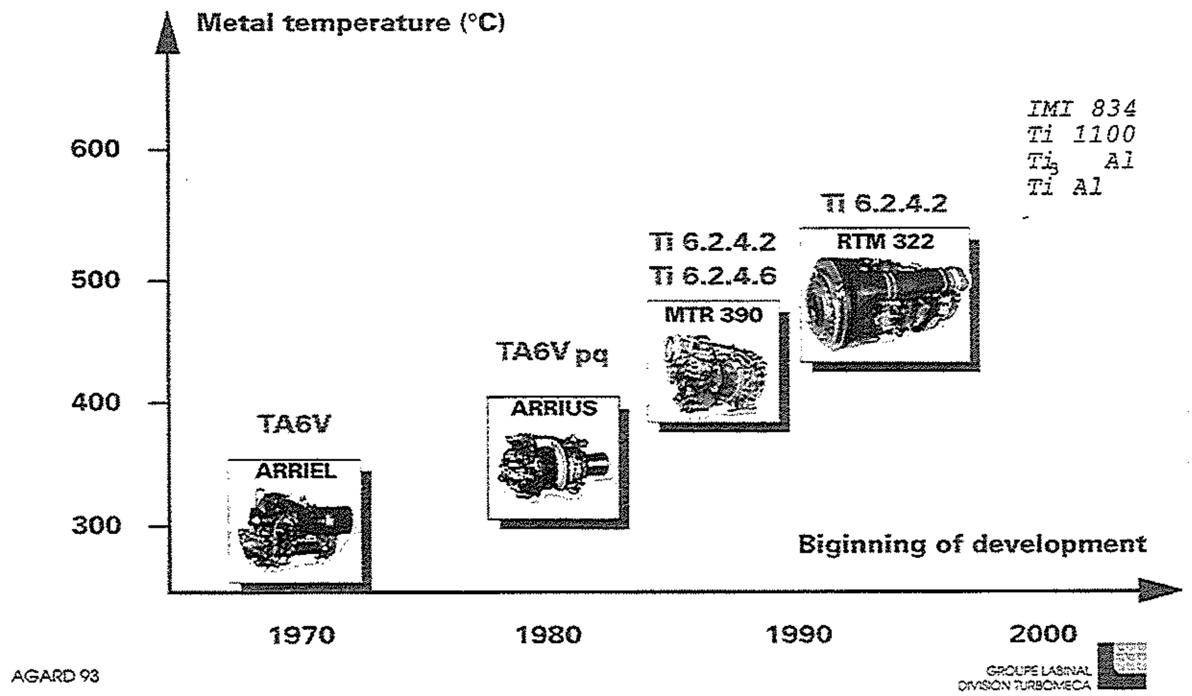


FIG. 15 Titanium alloys applied to centrifugal impellers

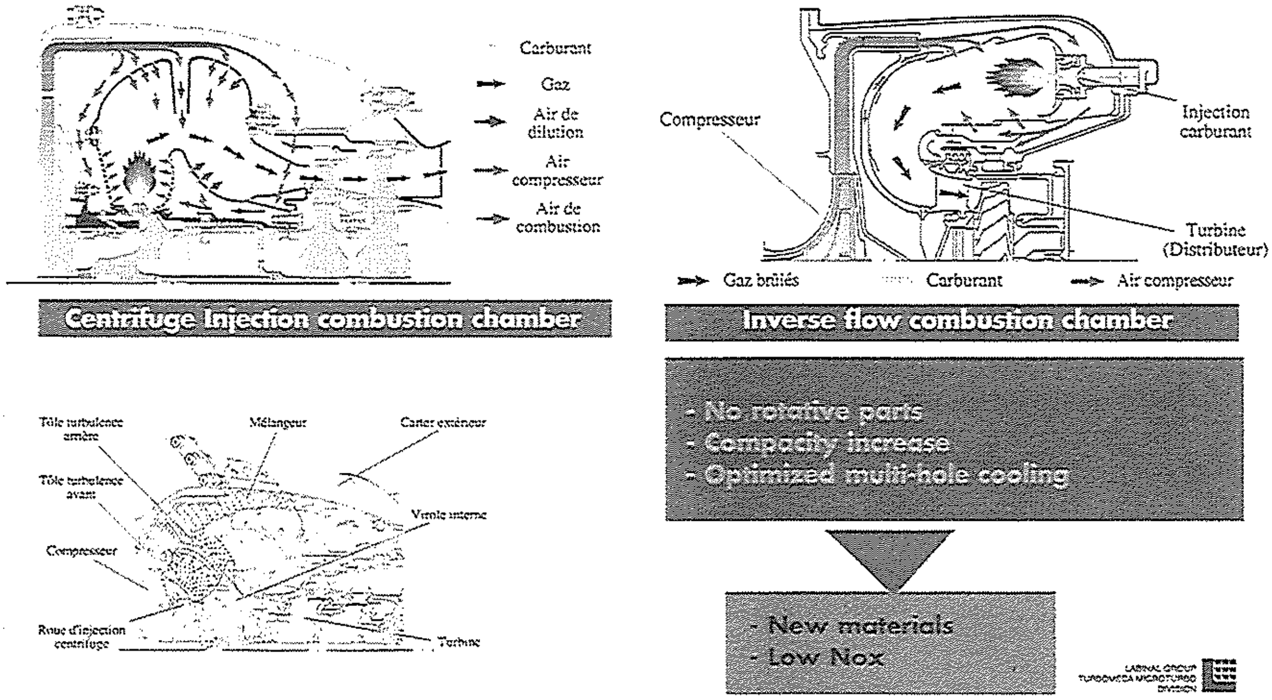


FIG. 16 Combustion chamber evolution

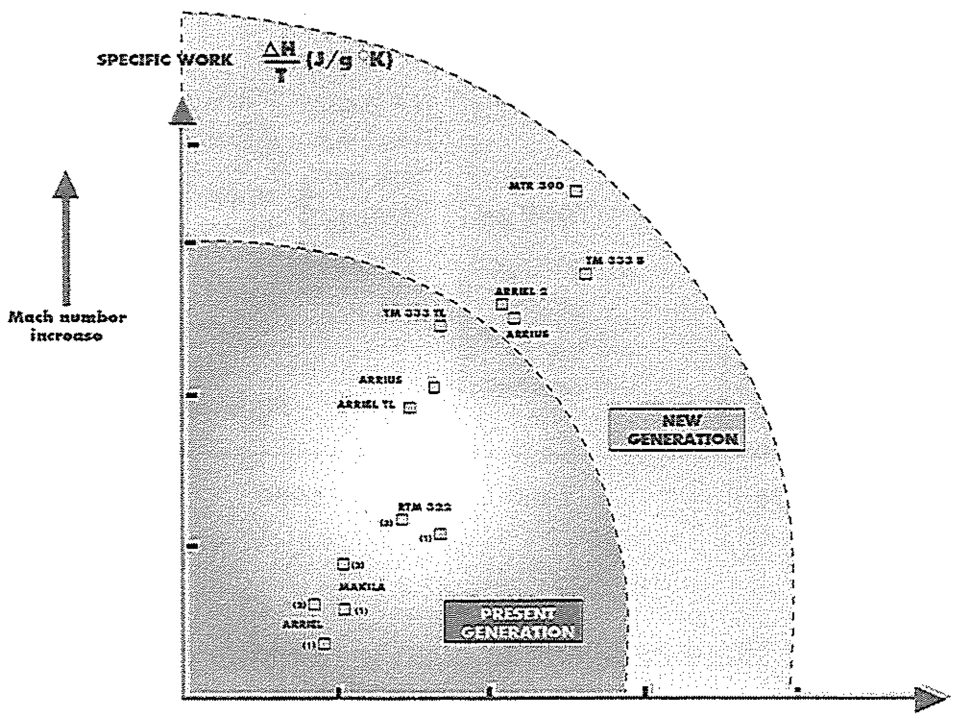


FIG. 17 Turbine performance evolution

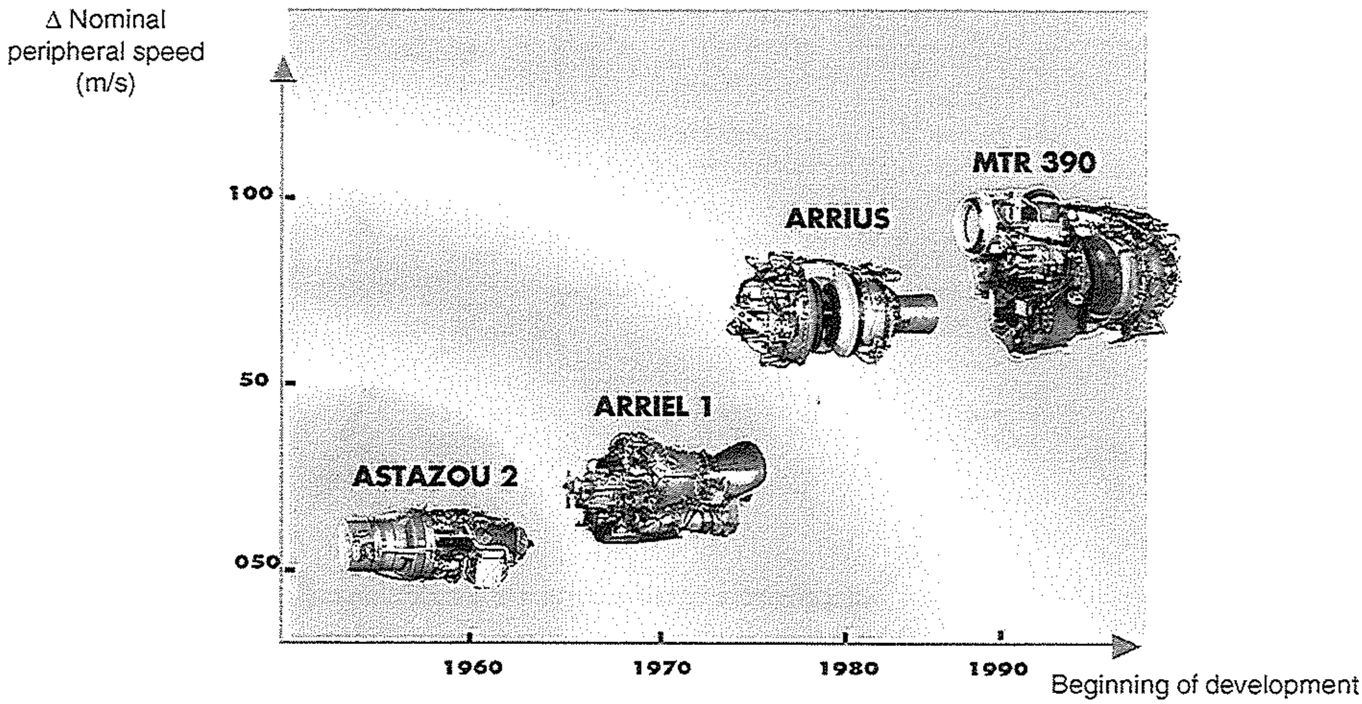


FIG. 18 HP Turbines :
Nominal blades peripheral speed improvements

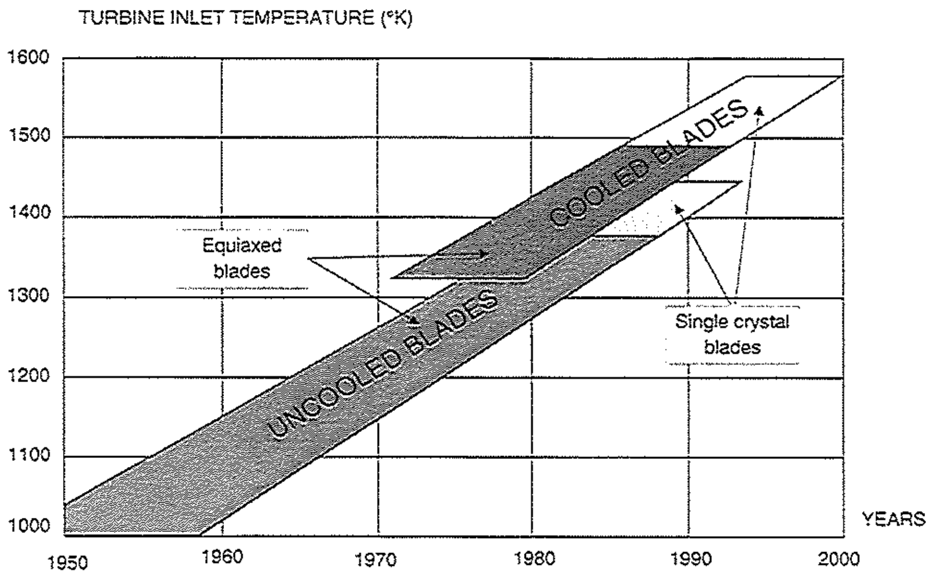


FIG. 19 Turbine material evolution

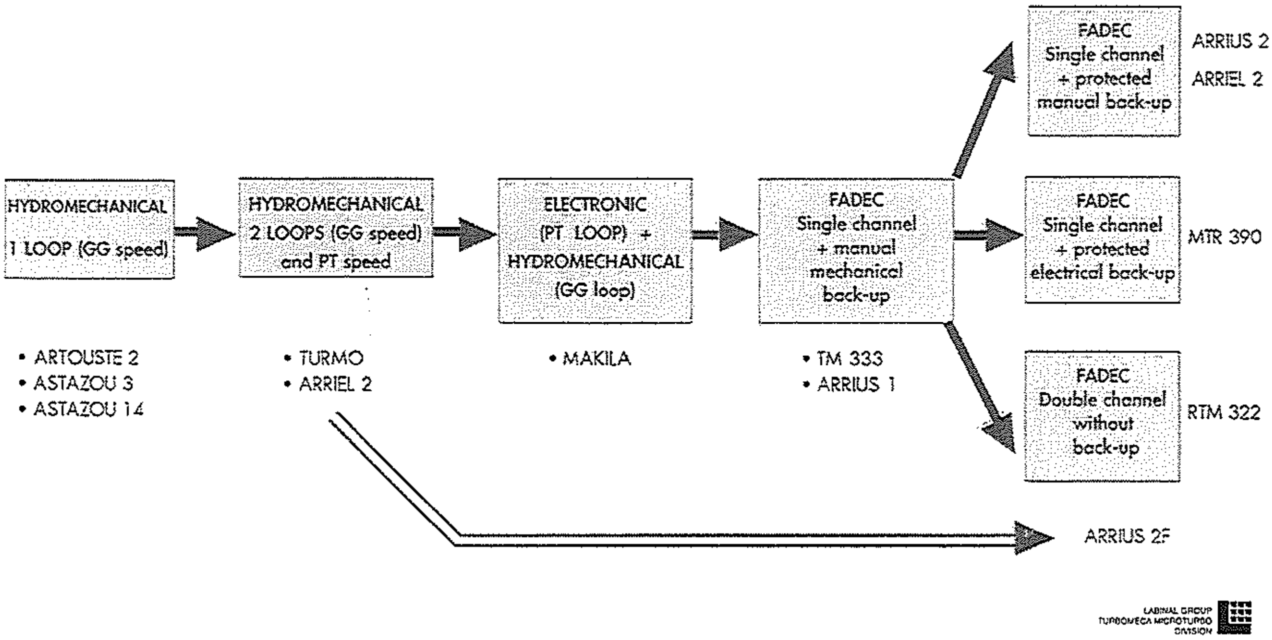


FIG. 20 Control system evolution

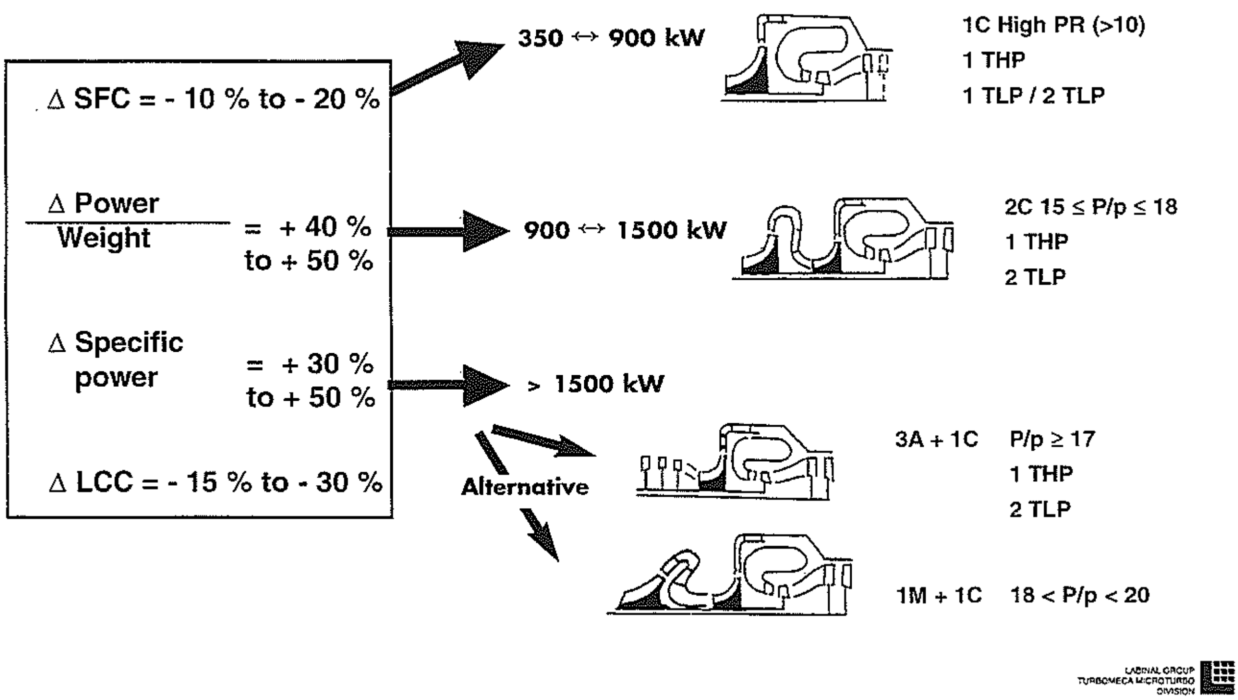


FIG. 21 Future trends