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TOWARDS A RENEWAL OF THE PROPELLER IN AERONAUTICS

D. Berger and P. Jacquet

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16. Abstract

The history of airplane propulsion is surveyed from the early 50's through the development of turbo-propulsion. Reasons for the renewal of interest in propeller-propulsion are discussed and the potential market for propeller-powered planes is analyzed. Technological developments such as use of composites and progress in reducing maintenance costs are described. The article sees a definite use for propeller planes in certain applications such as long-distance cargo planes in the future.

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TOWARD A RENEWAL OF THE PROPELLER IN AERONAUTICS

D. Berger** and P. Jacquet***

1. INTRODUCTION

/01*

A brief historical summary will permit an understanding of the reasons for this renewal.

Propulsion by propeller was universally used in the 50's, associated with piston engines or turboprops.

The appearance in the early 60's of the long-distance aircraft, Boeing 707 and Douglas DC 8 and then the short-distance aircraft, DC 9, Boeing 737, Boeing 727, and Caravelle, which were characterized by greater passenger comfort (noise, vibrations) and faster flying, marked the end of the use of the propeller by all national and regional airlines on all types of flights.

Lockheed's Electra was the last large propeller aircraft program. Propelled by four Allison turbines of 3750 h.p. each, it could transport 100 passengers up to 3700 km. Begun in 1954, it was tested in 1957 and put into service in 1958. A total of 170 planes were built. The English Vanguard, whose first flight took place a little more than a year after that of Electra, did not really make it onto the market: 43 planes were built.

At the same time as Electra was being designed, engine builders were developing the first by-pass turbine engines:

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*Numbers in the margin indicate pagination in the foreign text.

** Preliminary Projects Department Chief, Aerospatiale Aviation Division

*** Preliminary Projects Engineer

the Rolls Royce Conway, which made its first flights in 1959 on a DC8-40 and a Boeing 707-430 and was put into service by American Airlines at the beginning of 1960.

- the Pratt & Whitney JT3D, which made its first flight in 1960 on a Boeing 707-120 and was put into service by American Airlines as of 1961.
- the CJ805 Aft-Fan from General Electric, which made its first flight on a Convair 990 in 1961 and was put into service in 1963.

It can thus be said that the propeller was replaced by the fan before the jet engine.

Since that time, propulsion by propeller has been used /02 mainly by private aviation, certain business planes, and commuter lines covering limited areas with older planes such as the Fokker 27, the BAE 748, and the Nord 262. We also mention the Vickers Viscount, which was used for a long time on the less busy routes of some large airlines.

Regional routes were thus covered by second level airlines with jet engine planes like the DC9-30 or Boeing 737. This was possible until the beginning of the 70's due to the very low price of the US gallone (10 cents) which allowed profitable use of jets over short distances in spite of the fact that their fuel consumption is much higher than that of propeller planes. On the other hand, their commercial attractiveness was very superior to that of the turboprop (noise, comfort, speed, etc.), which had not changed since the middle of the 50's. There was, in effect, a stagnation of propeller technology during the 50's and 60's, because of few investments by industry.

This technology was reconsidered as a result of very significant increases in fuel prices after 1973 and of the deregulation of American air transportation by the Carter administration in 1978. This new policy led to a complete reorganization of the American internal network.

Thus, numerous technical, economic, and political reasons led to a resurgence of interest in propulsion by propeller. This was manifested by the initiation in 1975 of many programs for short-distance airplanes equipped with turbo-props: DHC 7, Embraer 110, DORNIER 228, then DHC 8, Embraer 120, Casa-Nurtanio 235, ATR42, SF 340.

These programs were aided by a renewed effort to improve propellers, motors, and gearboxes, which made it possible to build economical and reliable propulsion devices.

This report will discuss:

- The reasons leading to the present renewal of interest in propellers;

- The manifestations of this renewal, including new airplane programs as well as research and studies conducted by makers of propellers, airplanes, and engines. Particular emphasis will be placed on the French research program "Propellers for High-Speed Aircraft" aimed at evaluating the interest in new propeller designs to be used on airplanes capable of flying at speeds between Mach 0.7 and 0.8;

- Briefly, the development of the turbo-propulsion technologies which promoted this renewal of interest.

2. REASONS FOR THE RENEWAL OF INTEREST IN PROPULSION BY PROPELLER /03

2.1. The Price of Engine Fuel

This is the determining factor which led to reconsideration of turbo-props, despite their traditional faults: noise, limited speed, high maintenance costs.

Figure 2 shows the changes in fuel prices since 1970 and predictions until the end of this century. The cross-hatched area corresponds to a hypothetical "reasonable" increase in fuel prices of 2-4% per year (in value): a price of $1.50/USG (exchange rate of 7/80) is reached in 1993-98. A "catastrophic" scenario is also considered, with an 8% per year increase in average growth rate; a price of $3.00/USG (exchange rate 7/80) would then be reached before the end of the century.

Figure 3 shows the influence of fuel prices on DOC [direct operating cost]. The case shown is for an ATR 42 on a commuter-type flight of 200 nm. It is shown that the DOC increases 25% when the price of engine fuel doubles (from $1-2/USG).

Figure 4 shows the changes in the structure of the DOC for American TRUNK airlines since 1973. It shows that engine fuel now represents more than 50% of the DOC and that a decrease in specific consumption will be a determining factor for use costs.

2.2. Advantages of the Propeller

The continuous transformation of energy in fuel under pressure (or suction) from an airplane engine is characterized by thermopropulsive output η_{tp}.

Translator's Note: USG = U.S. Gallon

Output is linked to specific consumption, more generally used, by the relationship:

$$\eta_{tp} = \frac{1}{Cs} \frac{Vo}{Qf}$$

where Vo is the speed of the aircraft and Qf the caloric power of the fuel.

It can also be written:

$$\eta_{tp} = \eta_{th} \times \eta_{p}$$

where η_{th} is the <u>thermal output</u> (characteristic of the cycle) <u>/04</u> and η_{p} is the <u>propulsion output</u>.

A turboprop and a turbofan of the same technological level will have the same thermal output: the best type of power source will thus be that having the best propulsion output.

It can easily be shown that:

$$\eta_{p} = \frac{2\ Vo}{2\ Vo + \Delta V}$$

where ΔV is the difference between gas ejection velocity and Vo.

On the other hand, propulsion force T can be written:

$$T = D . \Delta V$$

where D is the flow of air caused by the machine.

The same suction can thus be obtained by strongly accelerating a small air flow (as with a reaction engine) or by slightly accelerating a large air flow; this second case, that of a propeller, will lead to better propulsion output and thus to better specific consumption, given equivalent technology. Figure 6 illustrates the change in propulsion output as a function of the cruising speed and of the type of propulsion.

2.3. The US Deregulation

The Carter administration decided in 1978 to deregulate the use of U.S. domestic routes. This led first and second level airlines to abandon very short flights (less than 200 or 300 nm) which they were making with DC9-30s, B727s, and B737s, which ceased to be profitable when the price of fuel increased considerably.

Figure 7 shows, for a fuel price of $1.20/USG, that the DOC of a bi-turboprop plane such as the ATR 42 is better than that of an old short-distance jet when the flights are shorter than 400 nm, despite the difference in size.

Figure 8 shows how the length of a flight varies with the fuel price, until the point at which the DOC of the bi-turboprop plane is less than that of the jet.

The abandoned routes were taken over by third level (commuter) airlines, who covered them first with old planes (F.27, BAE 748, N 262) or low-capacity planes (Twin-Otter, Beech 99).

2.4. The Market /05

2.4.1. Commuter planes

Market studies show that commuter airlines now need modern planes equipped with turboprops and with a capacity of 30 to 60 passengers. Figure 9 shows that the market should represent more than 2000 planes from now until the end of the century.

2.4.2. Short-distance planes

There is a large market (2000 planes from now to the end of the century) for short-distance planes for 100-150 passengers. In effect, the present planes (B737, B727, DC9) with old engines (JT8D) at low dilution rates (~ 1), which are noisy and consume a great deal of fuel, are nearing the end of the line. One part of this market could be taken by turboprop planes, which are certainly slower but consume much less fuel than jet engine planes. The low capacities (80-100 seats) associated with the shortest flights are the best argument, because speed is less important in terms of total time for short flights.

2.4.3. Market conclusions

Statistics show that 60% of the fuel consumed by airlines is on flights shorter than 1000 nm (Figure 10).

It is thus possible to understand the interest in propulsion units with better specific consumption than present engines, even if some reduction in velocity, acceptable for short flights, is necessary.

It appears that a vast market exists for economical planes with propellers (for speeds of less than Mach 0.7) or even propfans (for speeds of up to Mach 0.8) if they live up to their promises.

3. MANIFESTATIONS OF THE RENEWAL

3.1. Aircraft Programs

Commercial studies have shown that there is a market for more than 2000 planes with turboprops in the 30-60 seat range from now until the end of the century.

On the basis of its AS 35 studies, the Aérospatiale [French aerospace organization], in collaboration with Aéritalia, built the ATR 42, a plane designed to carry 42 passengers for 700 nm.

Other programs were begun by DeHavilland, Embraer, Casa-Nurtanio, Saab-Fairchild (Figure 11). /6

The ATR 42 was studied for wide operational flexibility, a very important characteristic for commuter lines (Figure 12).

Figures 13 and 14 compare the consumptions and utilization costs of the ATR 42 and its competitors. It is shown that the ATR 42 is better in DOC as well as in fuel for a typical average commuter flight of 200 nm.

Although its design is conventional, the ATR 42 makes use of the most modern technologies (Figure 15).

Among other projects now under way is the BAE ATP. This plane, derived for the HS748, will be able to carry 60 passengers. It is designed with 6-blade propellers.

These new propellers (straight but using new profiles) should fill the gap between standard propellers allowing speeds on the order of Mach 0.5 and rapid propellers ("propfans") which should allow speeds of Mach 0.7 to 0.8. We note that the ATP will remain confined to speeds of less than Mach 0.45, mainly due to its old design.

3.2. The American "Propfan" Program (ATP Program: "Advanced Turboprop Project"

The propfan is a propeller with many blades (8 to 12) allowing high air speeds (Figure 16).

The American program is directed by Hamilton Standard and financed by NASA. It unites the following engine and aircraft builders:

- Hamilton Standard has designed highly charged propellers with special shapes: fine profiles, feathered ends of the blades allowing significant noise reduction (Figure 17), very significant chords.

  These shapes are made possible by the use of composite materials.

- Allison, General Electric, and Pratt and Whitney have designed turboprops capable of supplying the necessary power (15000 SHP) to propell a 100-150 seat plane (Figure 18).

  In their study, Pratt and Whitney used technologies developed under the E3 (Energy-Efficient Engine) program. This program, under the auspices of NASA, works for a significant decrease in specific consumption of turbofans.

  The first gearbox designs were from Hamilton Standard, but /7
  Pratt and Whitney in particular will design and build the gearbox itself.

- Plane builders: the three main American plane builders (Boeing, Douglas, Lockheed) evaluated the propfan design.

  It involves either putting new engines on existing planes (Douglas DC9) or using prototypes built around this new type of propulsion (Boeing, Lockheed).

  The conclusions were very optimistic, in general, except for Boeing which, going over the estimates made by Hamilton Standard, used more sound insulation (Figure 19).

The initial program called for a propfan plane to be put into service in 1995.

In 1980, the manufacturers and airlines involved proposed expansion and acceleration of this program, aiming to begin service in 1990. This acceleration was not approved by the U.S. Congress, due to the priority given to military programs.

The two present main objectives concern testing a propeller 9 ft in diameter (for which the contract with NASA should be signed in May 1982) and the study of counter-rotating propellers. In addition, studies of various types of air intakes (ring-type, shark-type, etc.) should take place at the end of the year (Figure 20).

3.3. French Research Program: "Propellers for High-Speed Aircraft" /8

3.3.1. Organization

This program is financed by the following organizations: STPA, DRET, and DGAC [expansions unknown].

Its size necessitated the creation of a specific organization to coordinate the efforts of the various contractors.

This coordination is done by the Aircraft Division of the Aérospatiale, which is also in charge of work done on evaluating the High-Speed Propeller concept.

ONERA is responsible for the development of calculation methods as well as testing and measurement techniques.

The Helicopter Division of the Aérospatiale is in charge of the study, building, and testing of the propeller, with the aerodynamic definition of the model provided by ONERA. It is also responsible for obtaining technical and economic information necessary to study plane preliminary projects from the Aircraft Division.

On the basis of specifications from the Helicopter Division, the company Ratier Figeac will study and build the mechanical assemblies designed (hubs, pitch control, power chain and fairing. It will participate in obtaining technical and economic information concerning these assemblies.

3.3.2. The program

General objective. This program will permit the validation of several methods of designing transonic propellers by testing a model in a wind tunnel. The Aircraft Division of the Aérospatiale will evaluate the potential advantages of the High-Speed Propeller design in two aircraft programs.

Axes. The program has three main axes:

- developing basic aerodynamic, acoustic, and structural methods.

- building and testing a model propeller 1 m in diameter at S1 Modane to validate the methods developed. This test represents the most important part (design, building) of the program (Figure 21).

- evaluating the design: the eventual advantages of /09 this type of propulsion will be evaluated in two aircraft programs, one using a turbofan and the other a propfan.

Aircraft prototypes. To evaluate the merits of High-Speed Propellers, it will be necessary to surmount a certain number of practical problems linked to their use on prototype aircraft. For each possible solution, it will be necessary to estimate performance, mass, and cost. These problems are related to:

- power source: the generator must supply around 15000 HP (11200 kW) to the reducer: the related maintenance costs will be the determining criteria for the airlines.
- aircraft-propulsion integration: it will be necessary to evaluate the influence of the propeller wash on the aerodynamics of the aircraft, the acoustic treatment of the fuselage necessary for noise levels acceptable to the passenger, etc.
- aircraft design: wings above or below, standard horizontal or T-shaped tail, size of tail rudder, positioning of engines, etc.

Two aircraft programs will be used to support this study: one short-distance 100-seat plane and one long-distance plane with approximately 200 seats. For each of these programs and for each type of power source (turbofan, propfan), aircraft will be designed which are "adapted" to the following three cruising speeds: Mach 0.7, 0.75, and 0.8 (Figures 22 and 23).

We consider that it is necessary to compare aircraft designed for their type of propulsion and not a new High-Speed Propeller version of an existing design: the comparison would be invalid because the new technologies of the turbines are too different.

The aircraft described correspond to a basic design. It will then be necessary to study the changes in terms of operating costs and fuel consumed for:

- design changes
- power source changes (disk charge, top speed),
- technological approaches used: for example, acoustic insulation principle.

3.3.3. The future

/10

These studies will be followed attentively by French engine makers (TURBOMECA and SNECMA).

It is in effect necessary that, in addition to the specific "Propeller" studies described in this program, studies be developed for gas turbines and high-power gearboxes.

We emphasize that acquiring knowledge about propulsion is a long-term undertaking. It is necessary to begin by investing in research far ahead of the applications. Research under way today has a double objective: maintaining competitiveness with French plane builders and developing nationwide design capabilities for modern propellers.

4. TECHNOLOGY DEVELOPMENT

The use of turboprops could only be revived with the improvement of technology related to propellers, gas generators, and fuselage soundproofing. It is now possible to achieve noise levels and comfort acceptable to a clientele accustomed to the comfort of jets, with reduced operating costs (fuel and maintenance).

4.1. Propellers

The most significant progress concerns the materials used. The use of composite materials allows substantial gains in mass (Figure 24) (50% for 14 ft diameter); improvement of the dynamic response of the blades, due to the natural buffering of these materials and of the sandwich structure; better resistance to fatigue; and easier repairs, due to the modular design (lower maintenance costs).

Composite materials also allow more elaborate designs: very fine profiles, feathered blades.

Significant improvements can also be seen with respect to the aerodynamics of profiles due to use of modern calculation methods.

4.2. Propulsion units /11

The most basic progress concerns maintenance costs. Their reduction is made possible by modular design of the various units, better reliability, more simplicity, and longer life of each component (Figure 25).

These improvements in design should allow abandoning "planned" maintenance in favor of "as necessary" maintenance, using automatic devices for isolation and diagnosis of problems.

The use of turbofan technologies will allow better cycling and thus a decrease in specific consumption, which will be further improved by the use of electronic controls, more precise and more reliable than the present hydromechanical controls.

5. CONCLUSIONS

There is no doubt that we are at the beginning of a return to the propeller plane: the successive increases in the price of fuel, the higher and higher portion that fuel represents in operating costs, and the progress of turbopropulsion technology are the principal factors.

But how far will this new fascination go?

- If it involves building planes with average cruising speeds (on the order of Mach 0.65), equipped with "standard" propellers, there are hardly any technical questions. The market will indicate the best speed/consumption compromise as a function of the type of utilization planned.

  In this regard, the ATR 42 is the main element in a /12 family of propeller-driven transportation aircraft which the Aérospatiale hopes to develop in the years to come and on which work has already begun.

- If it involves building a 150-seat plane cruising at Mach 0.8, propelled by two 15000-SHP propfans, considerable technical difficulties must still be surmounted. The most important are:

  . aeroelasticity: considering its shape and how thin the profiles are, the propfan blade will have "flight" shapes very different from the "constructed" shapes. It will be necessary to be able to calculate these balanced shapes and to evaluate the related performance losses. It will also be necessary to master prediction of variation in all areas of operation.

- gearboxes: achieving very high-powered gearboxes which are at the same time light and reliable is a difficult undertaking which goes far beyond present knowledge in this area.

- noise: although ground noise levels produced by propfan planes will probably be lower than those of present aircraft, a very significant problem appears concerning noise level in the cabin: the level outside the fuselage would be on the order of 135 dB (OSPL), and a reduction of 45 dB must thus be made by the wall of the plane to reach the level of 90 dB acceptable in the cabin. The feasibility of even achieving this, with an acceptable increase in mass, has not been demonstrated. (A conventional fuselage achieves a reduction of 15 dB.)

Our conclusion could be: yes to the propeller, but not for everything.

There certainly exists a place for the turboprop, in terms of commercial cargo and maximum distance, but its frontiers are not yet well defined. The Aérospatiale, like other builders, is working to better know this range of capability from a technical as well as a commercial standpoint.

SUMMARY

- <u>INTRODUCTION</u>: why speak of "renewal"?
- Reasons for the renewal of interest in propulsion by propeller:
  - . fuel prices
  - . advantages of the propeller
  - . U.S. deregulation
  - . the market
- Technology development.
- Manifestations of the renewal:
  - . aircraft programs
  - . the Propfan program (US)
  - . the High-Speed Propeller program (French)
- <u>CONCLUSIONS</u>.

Figure 1

PRICE OF FUEL

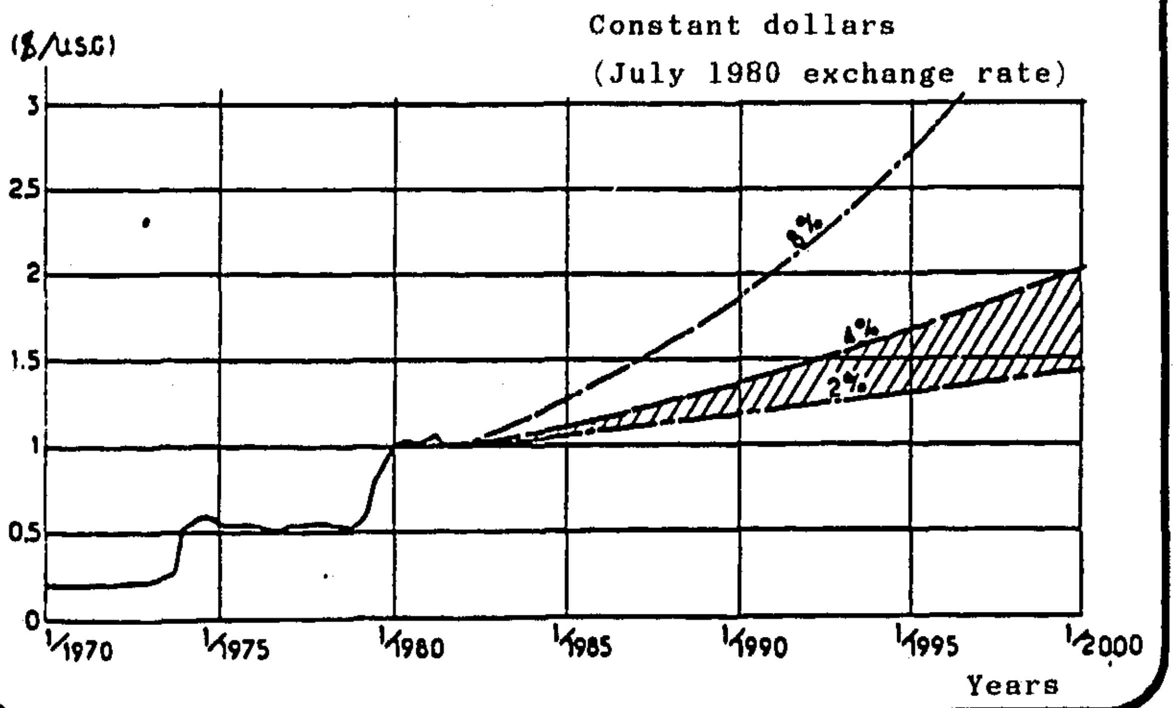


Figure 2

INFLUENCE OF THE PRICE OF FUEL ON THE DOC

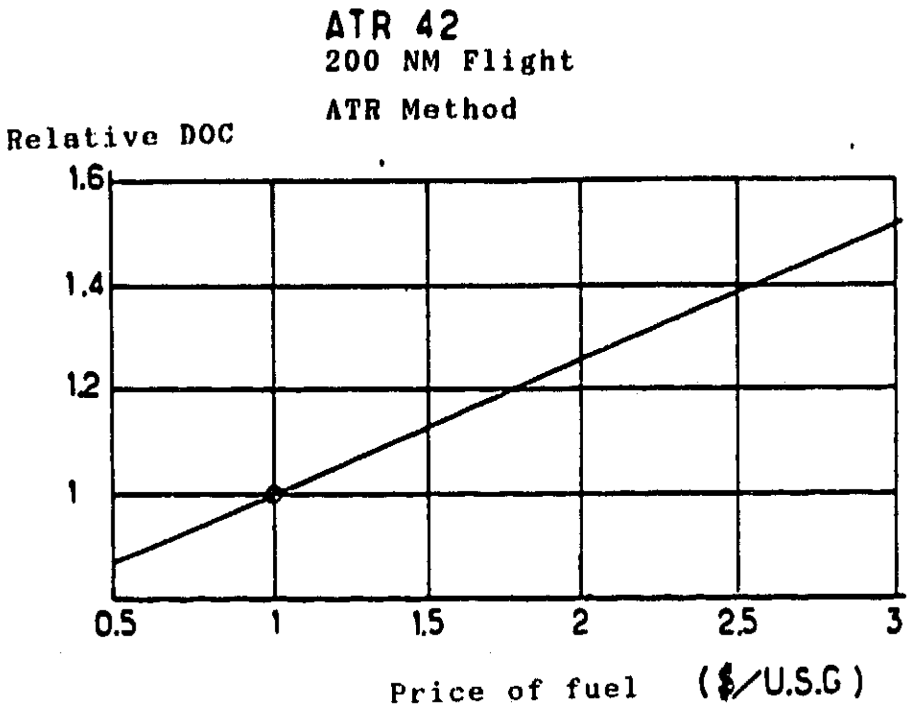


Figure 3

CHANGE IN STRUCTURE OF THE DOC

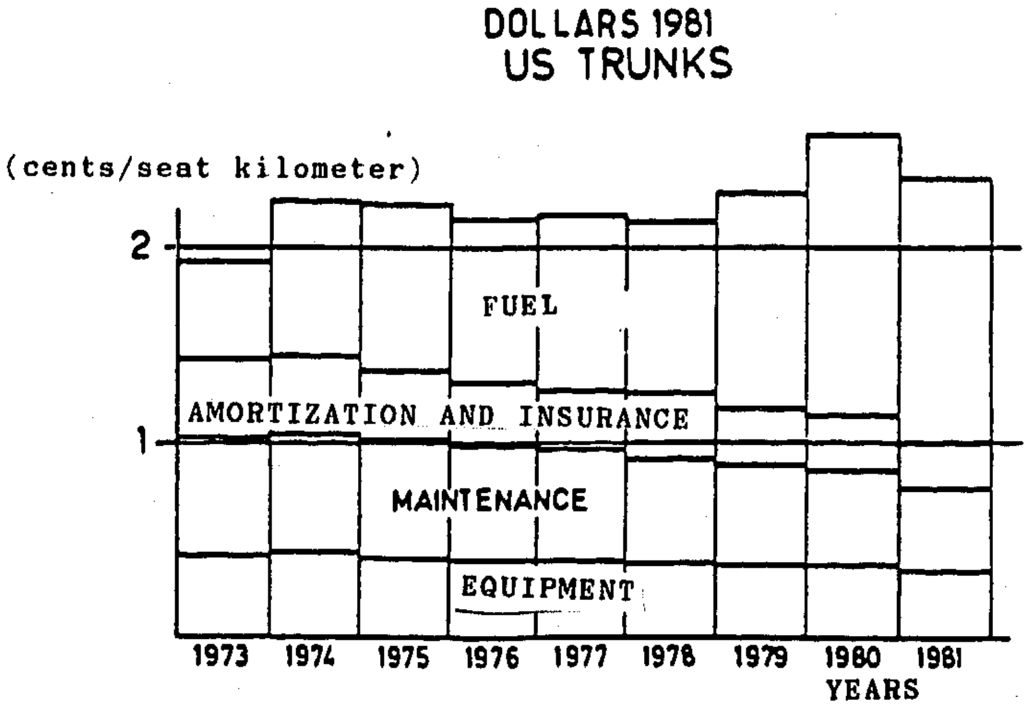
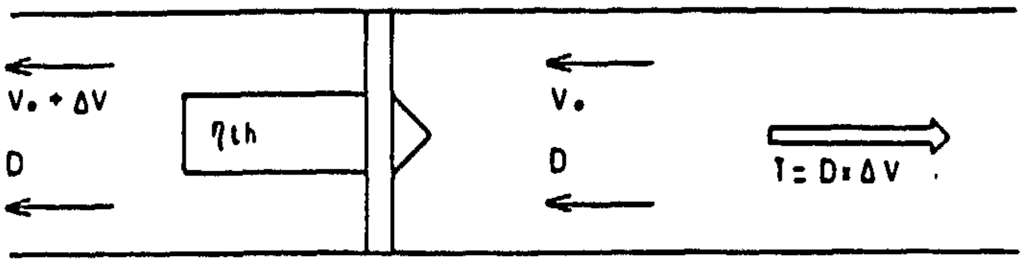


Figure 4

OUTPUTS



$\eta_{tp} = \eta_{th} \times \eta_{p}$

Propulsion output : $\frac{2V_0}{2V_0 + \Delta V}$

Thermal output

Thermalpropulsive output $\frac{1}{CS}$ $\frac{V_0}{QF}$

Figure 5

PROPULSION OUTPUT

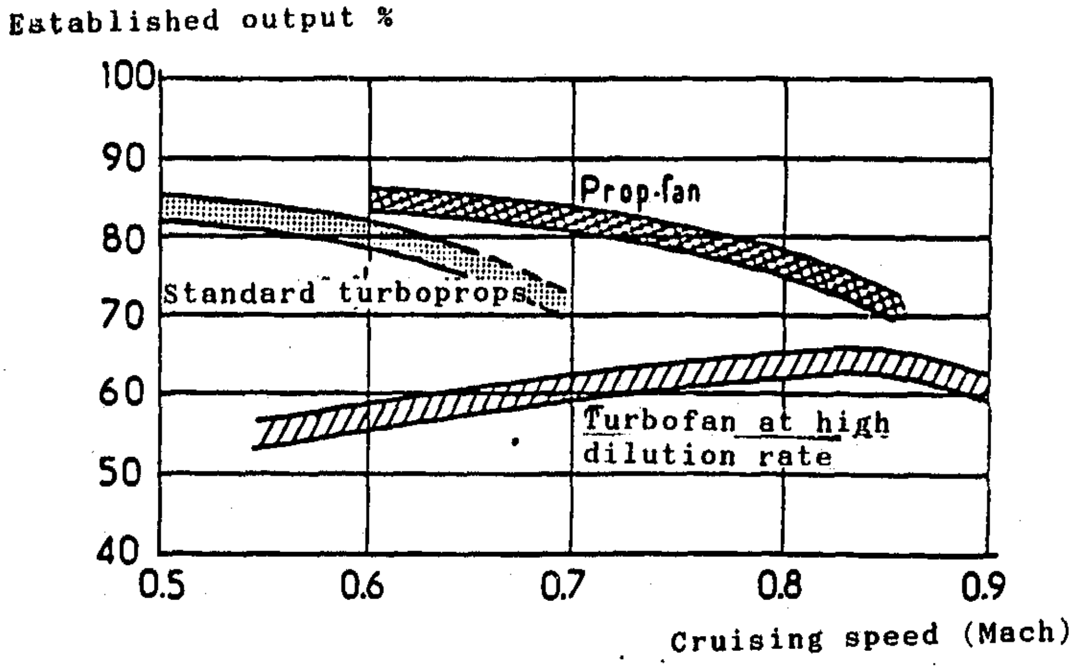


Figure 6

DOC - COMPARISON BETWEEN ATR 42 AND DC9-30

ECONOMIC CONDITIONS 1981

PRICE OF FUEL: $1.20/USG

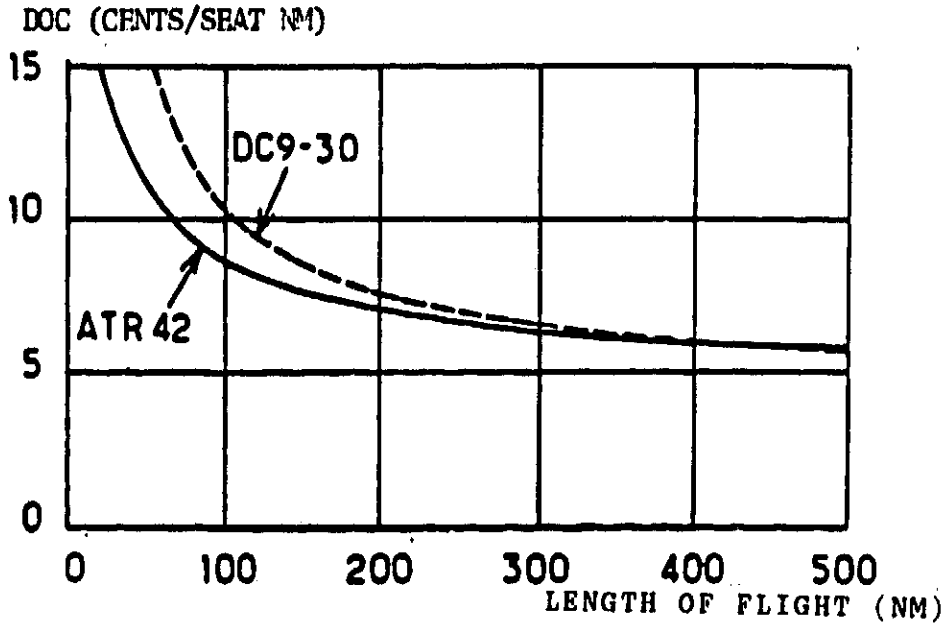


Figure 7

DOC - COMPARISON BETWEEN ATR 42 AND DC9-30

ATR 42 BETTER THAN DC9-30
FOR FLIGHTS SHORTER THAN:

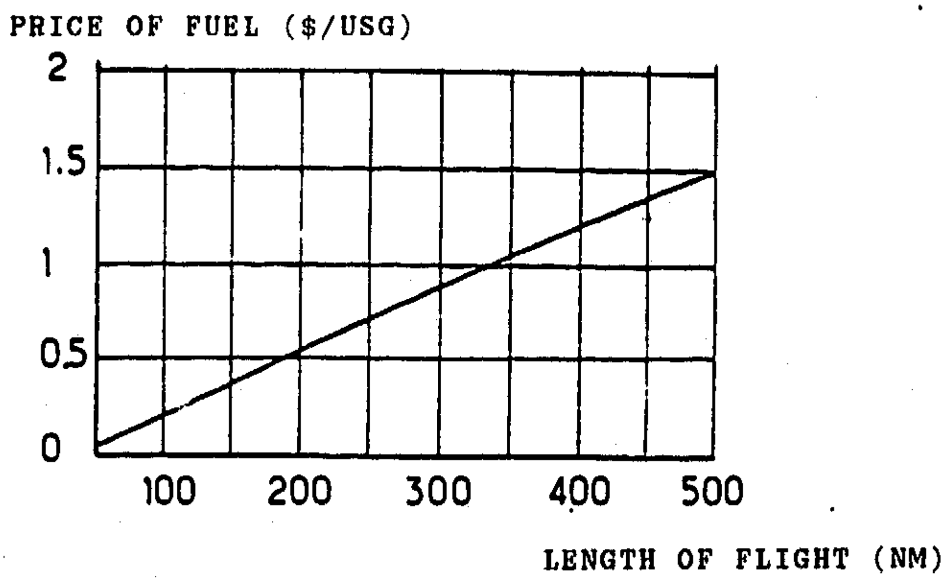


Figure 8

PROPELLER PLANE MARKET

- TURBOPROPS AND PISTON ENGINES
- FLEET COMPLETELY RENEWED IN THE YEAR 2000

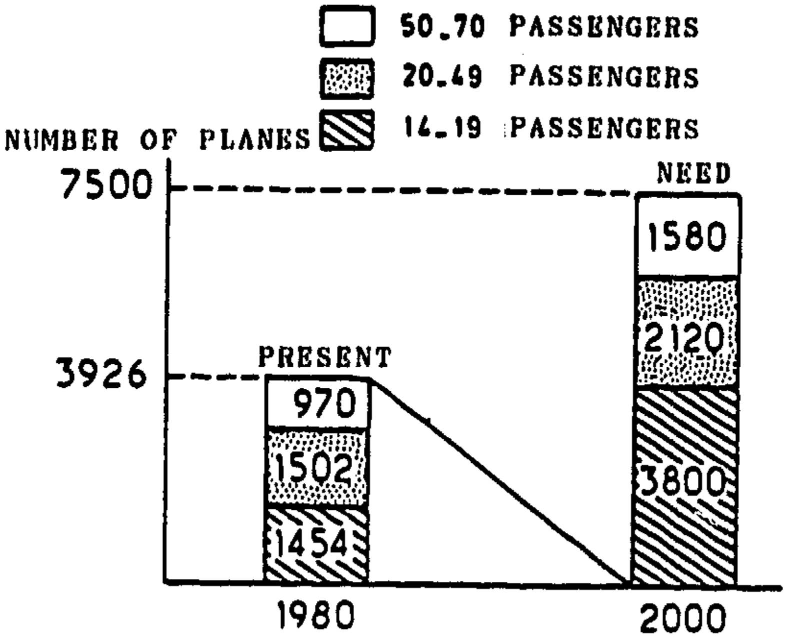


Figure 9

AIRCRAFT USE OF FUEL

- WESTERN AIRLINE COMPANIES

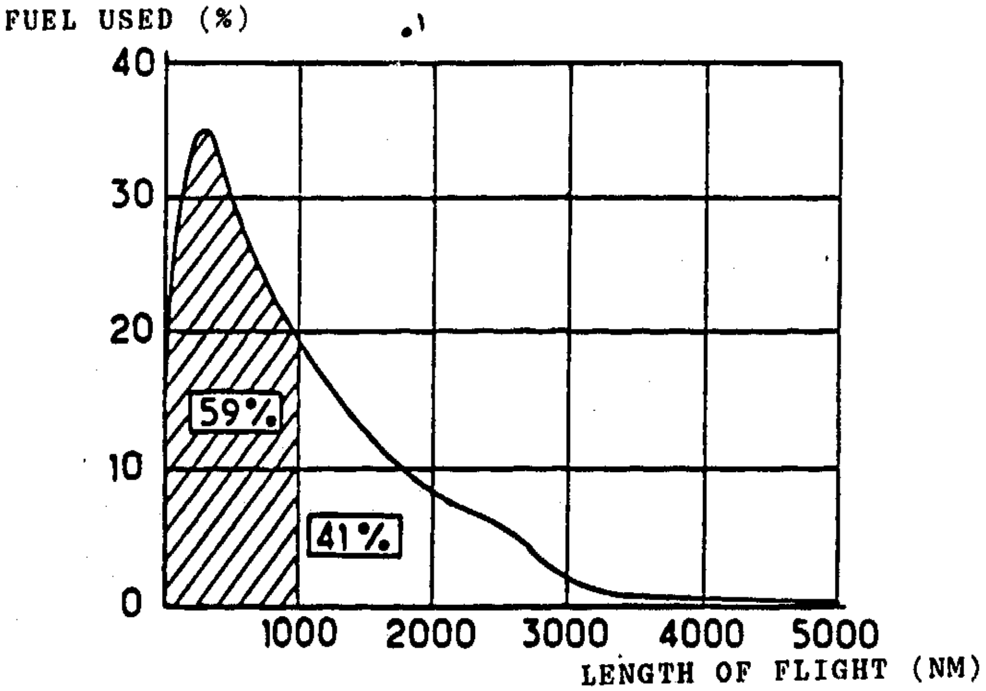


Figure 10

NEW COMMUTER PROGRAMS

	NUMBER OF SEATS	NOMINAL FLIGHT (NM)
ATR 42 (AEROSPATIALE & AERITALIA)	42	700
DHC 8 (DE HAVILLAND OF CANADA)	36	600
EMBRAER 120	30	500
SAAB-FAIRCHILD SF 340	34	700
CASA NURTANIO CN 235	34	780

Figure 11

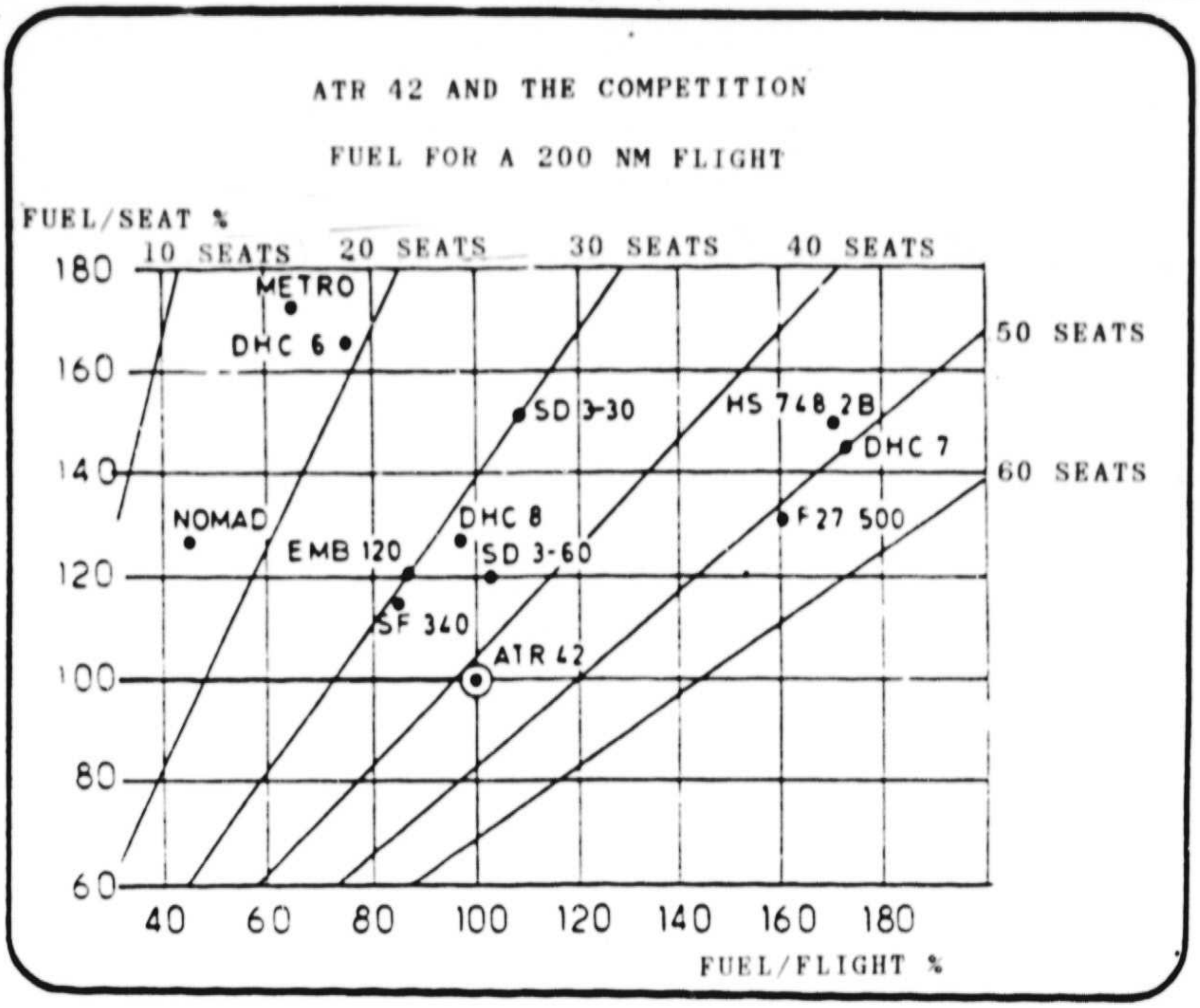
ATR 42 : FLIGHTS

42 PASSENGERS → 700 NM
OR → 4 FLIGHTS OF 100 NM

29 PASSENGERS → 1400 NM
OR → 8 FLIGHTS OF 100 NM

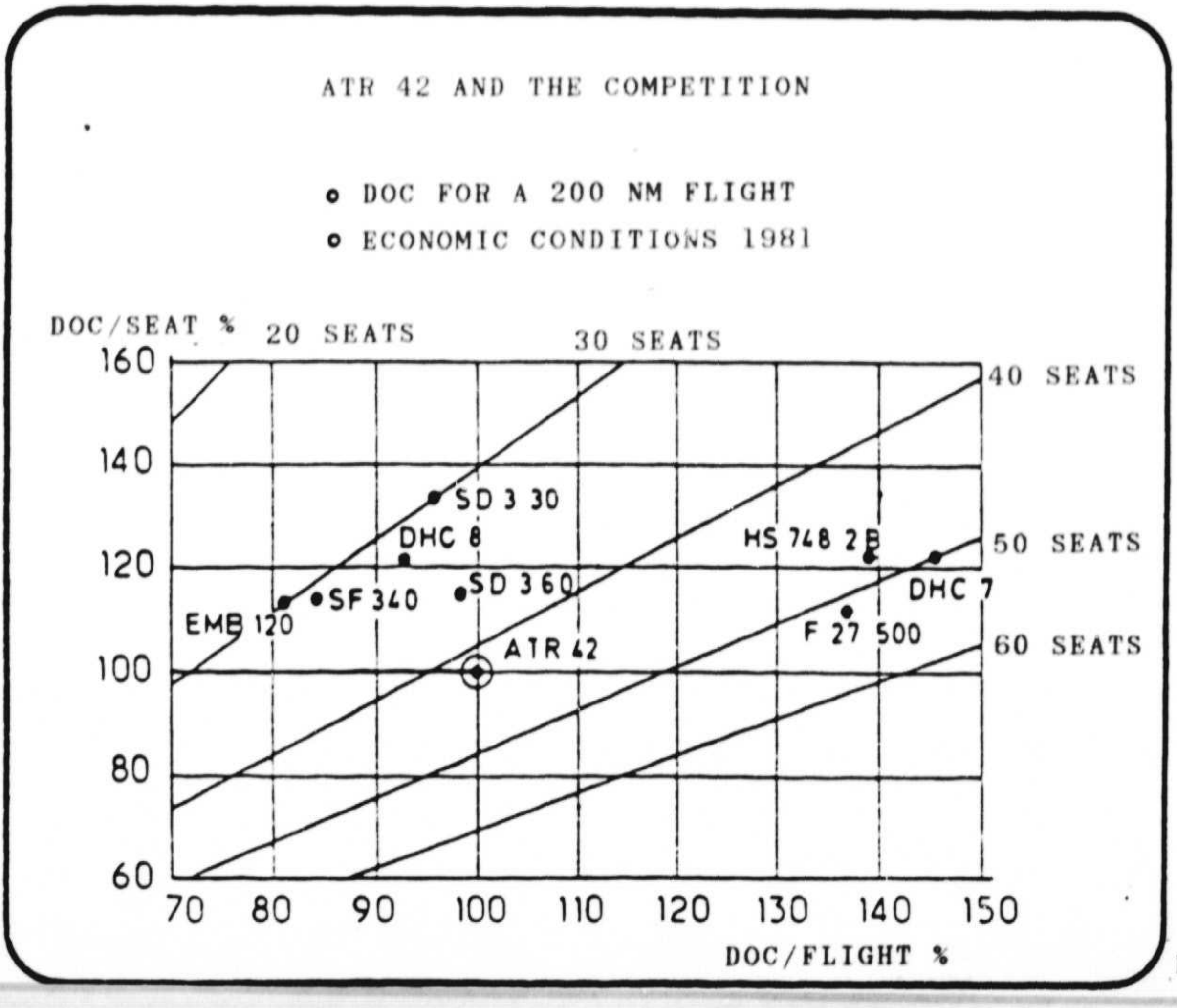
MILEAGE → 2800 NM

Figure 12


ATR 42 AND THE COMPETITION

FUEL FOR A 200 NM FLIGHT

Figure 13


ATR 42 AND THE COMPETITION

- DOC FOR A 200 NM FLIGHT
- ECONOMIC CONDITIONS 1981

Figure 14

ATR 42 TECHNOLOGIES STUDIED

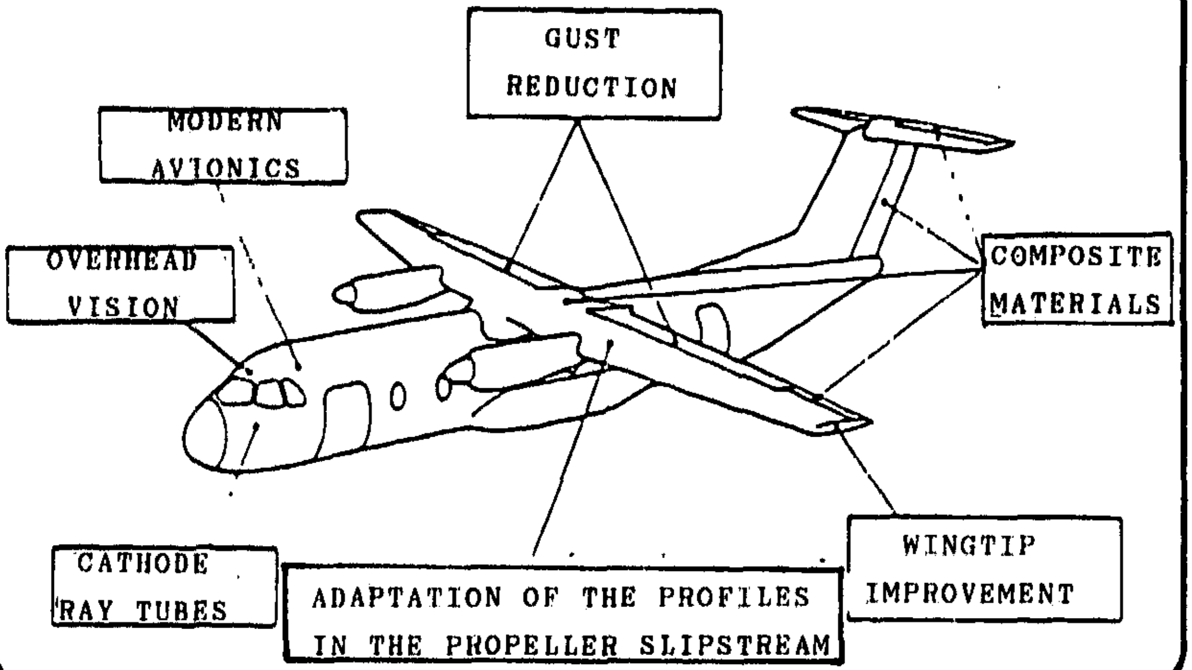


Figure 15

PROPFAN

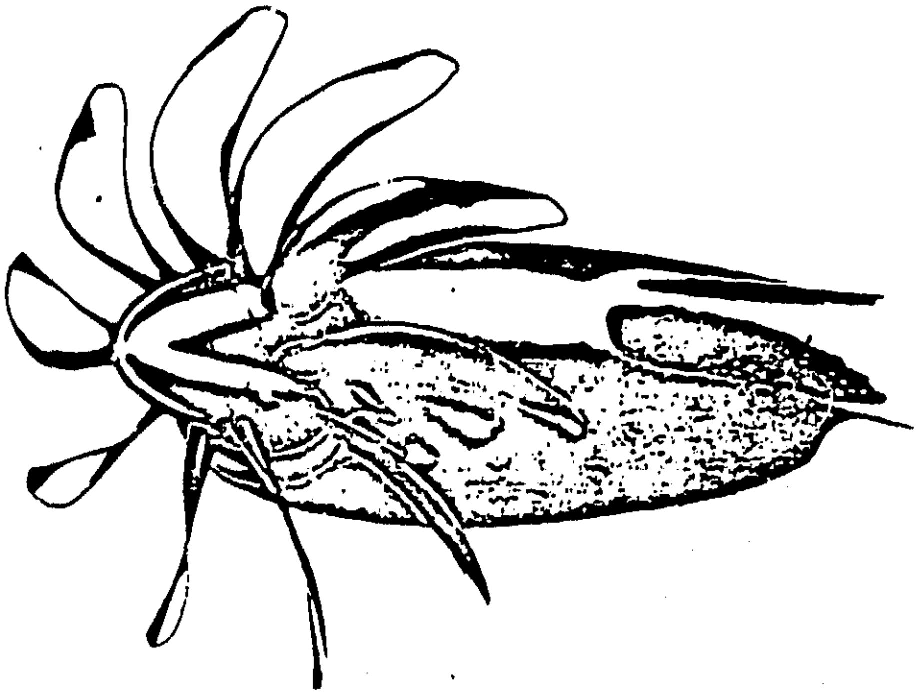


Figure 16

PROPFAN EFFECTS OF FEATHERING

- TOP SPEED: 244 m/s (800 ft/s)
- M= 0.8

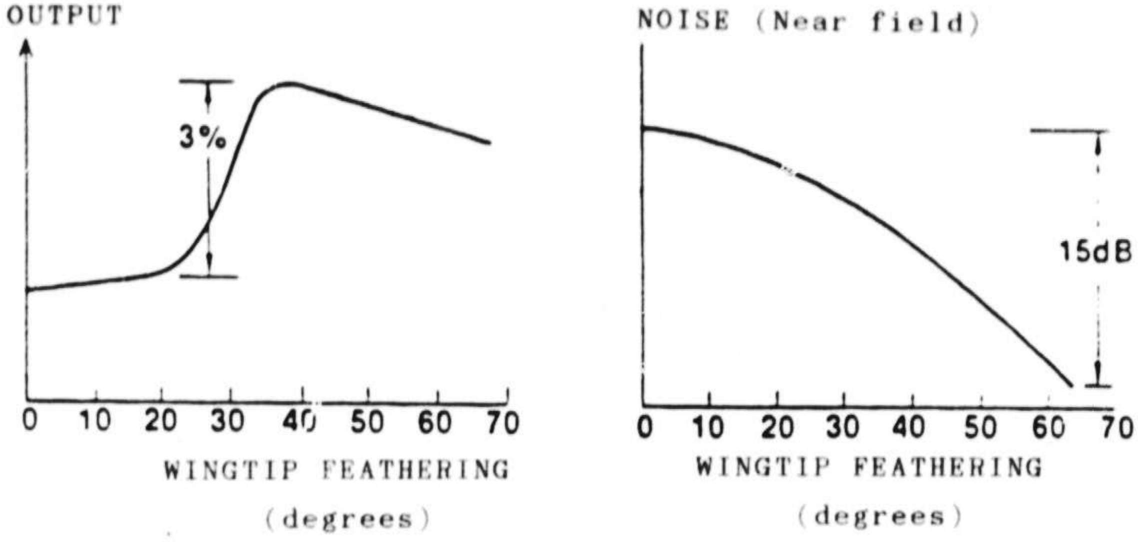


Figure 17

GAS PROPFAN GENERATOR

- PRATT and WHITNEY STS 589
- 15000 HP

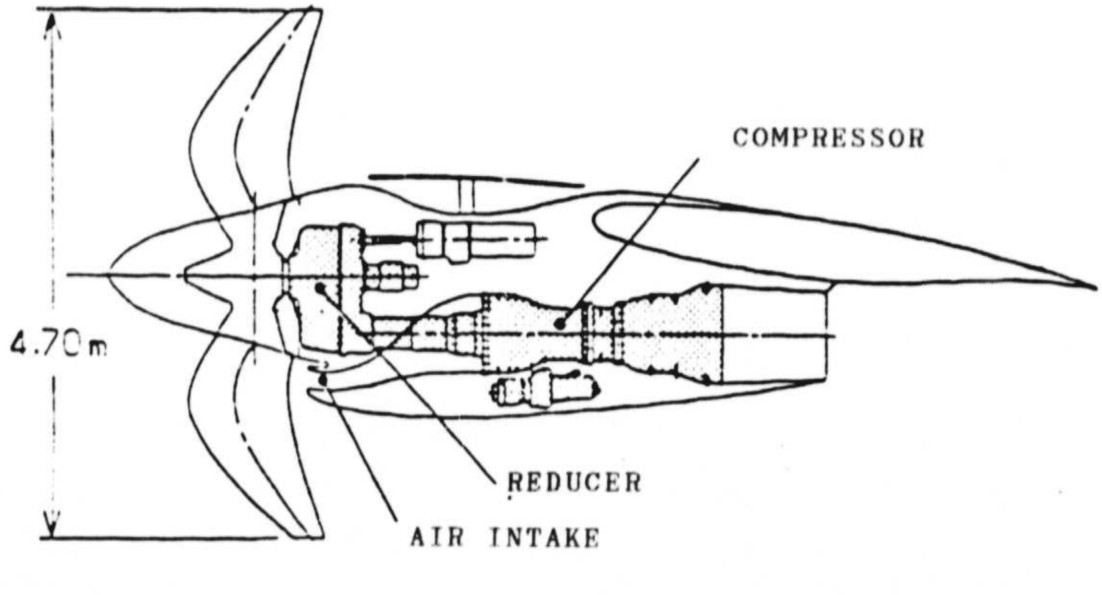


Figure 18

PROPFAN: CONSUMPTION GAINS

- COMPARED TO A TURBOFAN PLANE OF THE SAME TECHNOLOGY

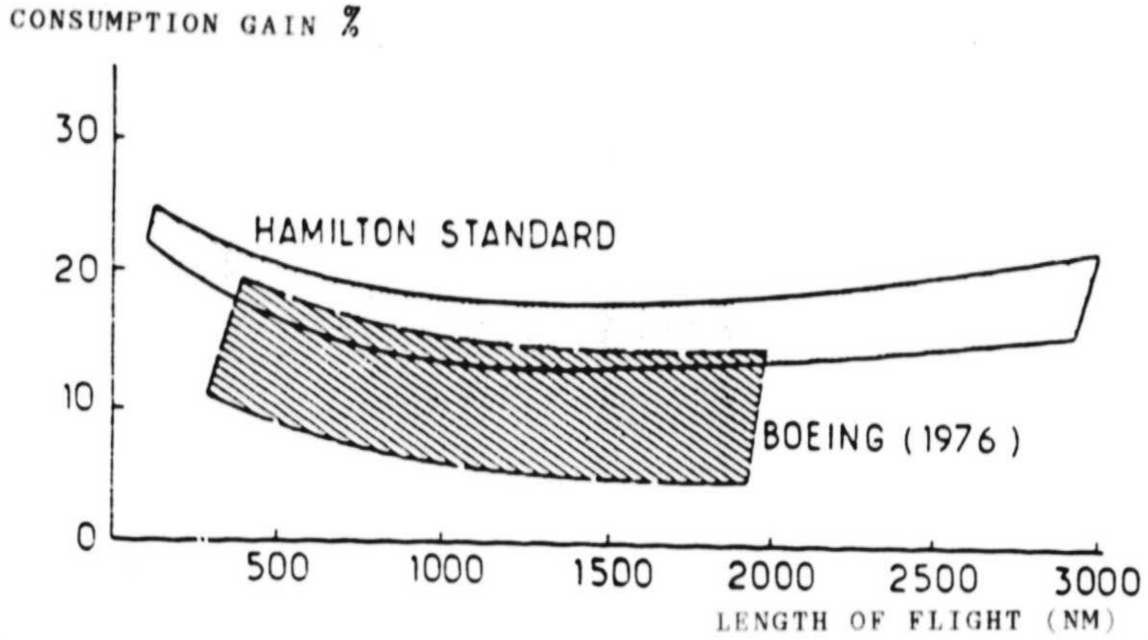


Figure 19

PROPFAN: STUDIES AND TESTS

- 9-FT PROPELLER TEST
- STUDY OF COUNTER-ROTATING PROPELLERS
- AIR INTAKE TESTS

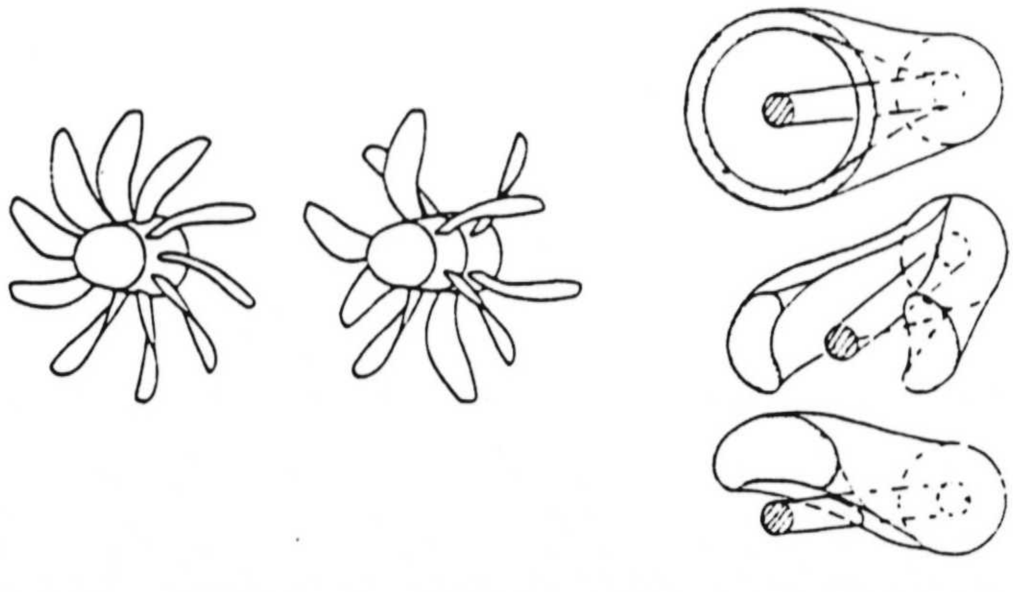


Figure 20

PROPELLERS FOR HIGH-SPEED AIRCRAFT

- MODEL H1 FOR TEST AT MODANE

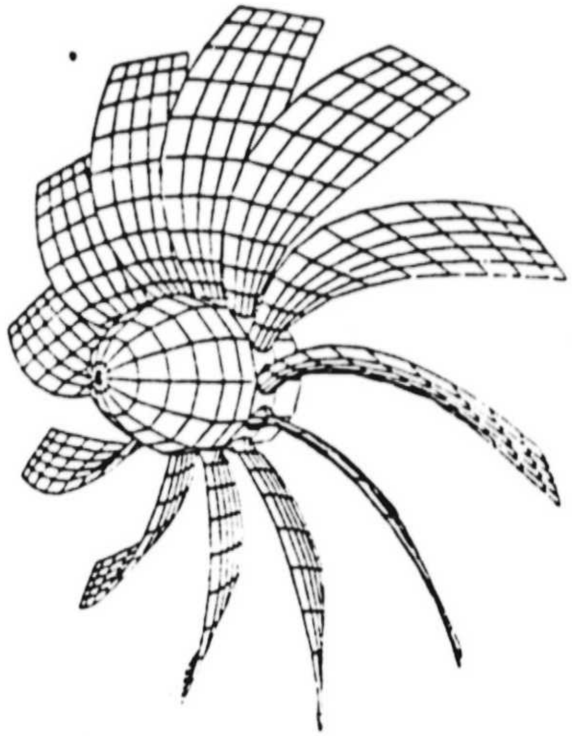


Figure 21

PROPELLERS FOR HIGH-SPEED AIRCRAFT

SHORT-DISTANCE CRAFT

- 100 PASSENGERS
- 1000 NM

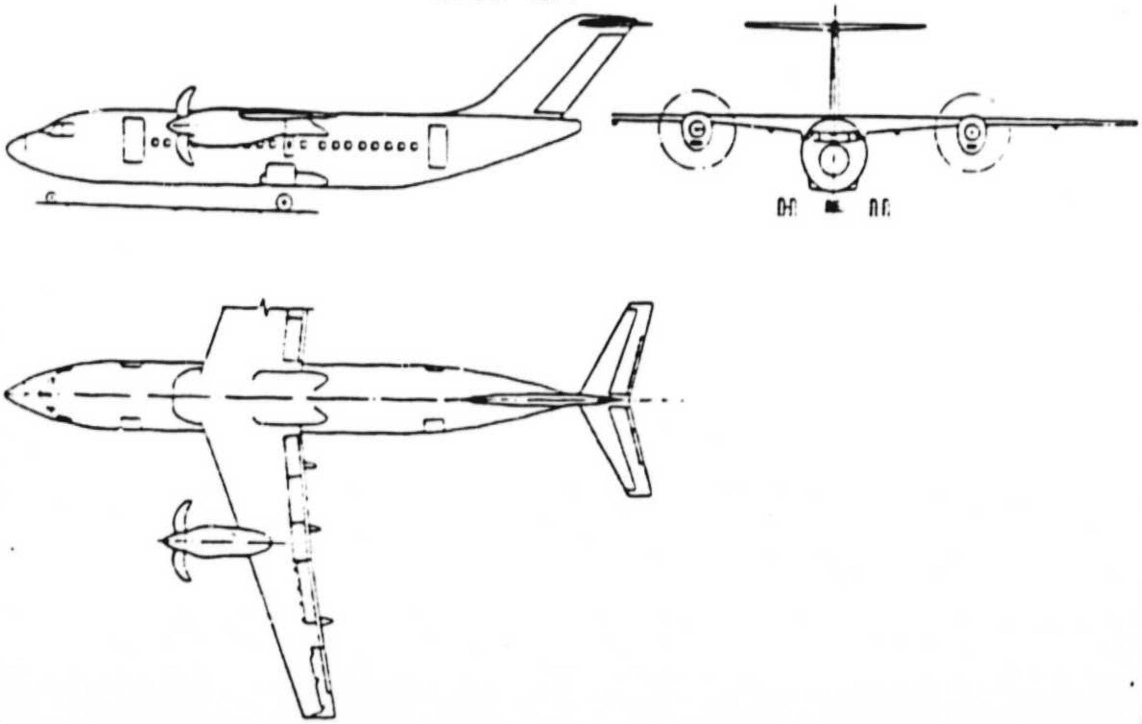


Figure 22

PROPELLERS FOR HIGH-SPEED AIRCRAFT

LONG-DISTANCE CRAFT

- 236 PASSENGERS
- 6000 NM

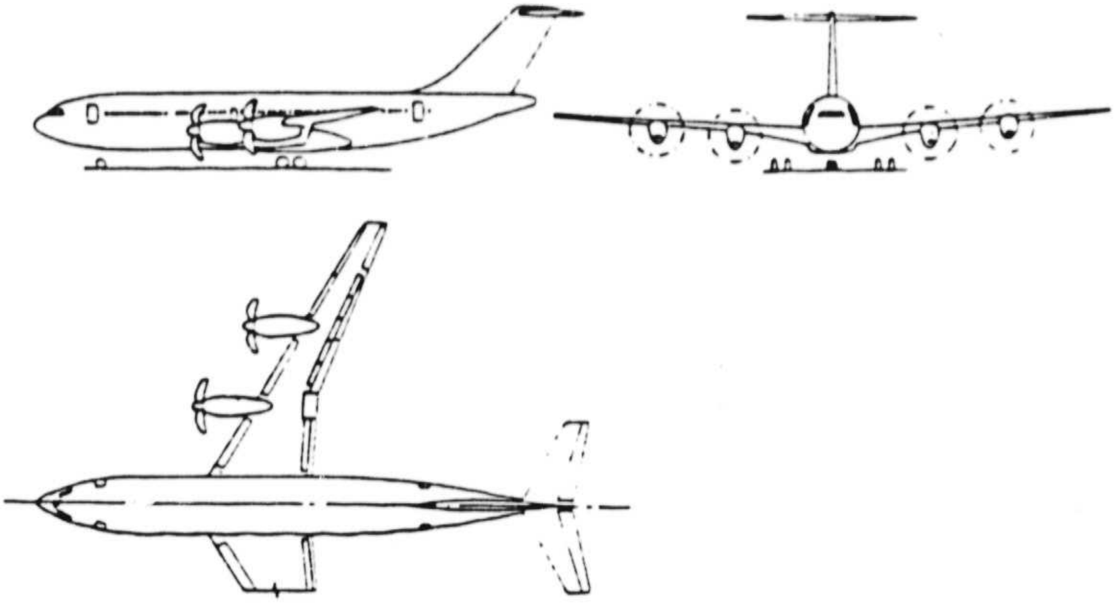


Figure 23

- PROPELLER MASS
  Source: DOWTY
  4 BLADES

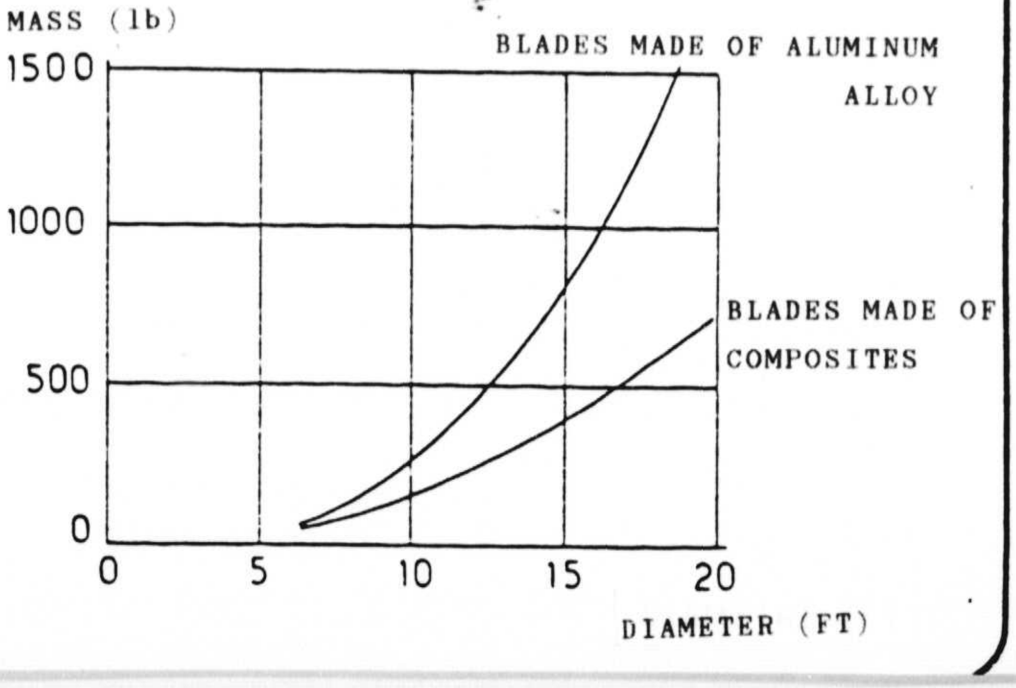


Figure 24

MODULARITY

- PROPFAN
- PRATT and WHITNEY STS 589

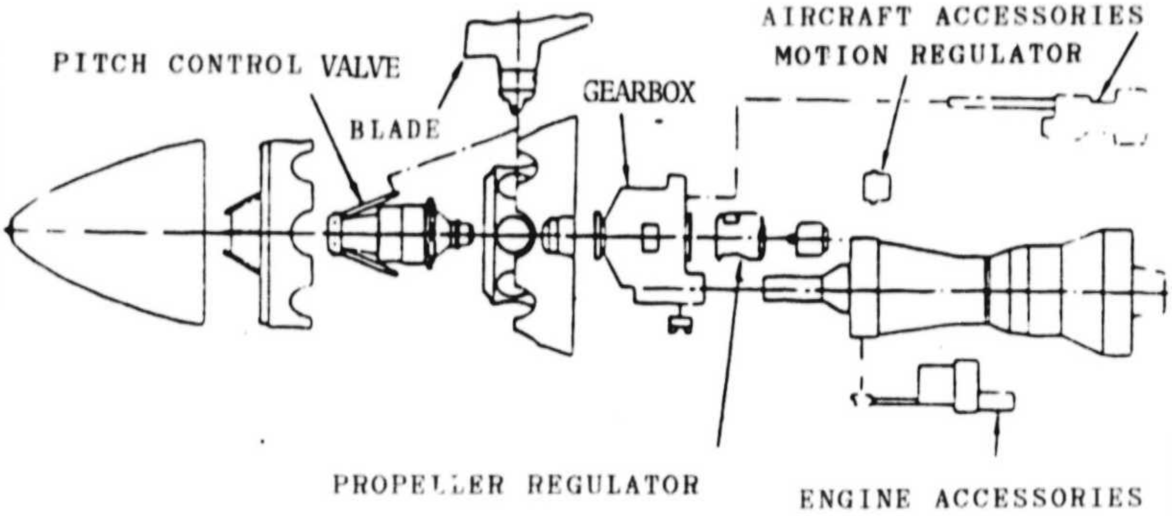


Figure 25