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ADVANCED TURBOPROP POTENTIAL FOR HIGH SPEED

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Over the last four years, there has been a significant amount of technical progress on an advanced propulsion concept called the Prop-Fan. I want to discuss this progress and what it might mean regarding high speed business aircraft. The Prop-Fan propulsion system is an advanced propeller driven by a turboshaft engine. The rotor technology is being pursued in NASA's ACEE program. Advancements in aerodynamics, acoustics, structures, and mechanical execution are involved and I'll touch on each of these subjects.

The major benefit attributed to the Prop-Fan is fuel savings resulting from improved performance. This propulsion device is aimed at airspeeds above 0.55 Mach where the turbofan is today's standard. Therefore, the key objective is high performance at high subsonic Mach number which results in fuel saved and reduced operating costs. However, in achieving this goal, certain other characteristics must not be sacrificed. It is necessary to remain a good neighbor around the airport, it is necessary to have a comfortable interior environment, and the aircraft safety must be uncompromised. All of these constitute the goals being worked towards in the Prop-Fan programs being conducted by NASA with Hamilton Standard participation.

Typically the turboprop on a business aircraft operates below 0.55 Mach, more in the area of 0.45 Mach, with very high efficiencies. The Electra turboprop had high efficiencies up to 0.6 Mach. Beyond these airspeeds, the efficiency drops off and the turbofan is king. The productivity of a 0.8 Mach turbofan versus a 0.5 Mach turboprop has clearly been demonstrated in the commercial passenger carrying market. With the Prop-Fan, the inherently high propeller type efficiencies are extended out to the turbofan operating regime of 0.8 Mach. With core engines of comparable technology, the Prop-Fan offers significant fuel savings over the entire Mach number range up to 0.85. I have generalized the projected fuel savings with Prop-Fans in place of turbofans based on a variety of aircraft studies conducted by Boeing, Douglas, both Lockheeds, Pratt & Whitney, General Electric, NASA and United Technologies. It shows maximum fuel savings at short and very long operating ranges. For short range aircraft, the mission is dominated by climb and descent, generally keeping airspeed below design capability. At very short range, it shows that a high design speed is not relevant to fuel usage. There is a bucket at 1500 to 2500 nautical miles with increasing fuel savings at longer ranges. Here, the fuel saving is reducing gross weight and a compounding effect takes place. Another attribute of the Prop-Fan is that further fuel savings are achieved by just reducing airspeed; this is not the case with the turbofan.

Let's compare the general characteristics of this advanced Prop-Fan with the typical business aircraft turboprop. I have already mentioned the significant difference with intended airspeed range. Coupled with this is operating altitude; the higher the Mach, the higher the altitude. Typically propellers are operated in cruise at maximum efficiency which translates into lower power loadings. This generally works out well for low speed aircraft which end up being sized for climb conditions. As design Mach is increased, the propeller becomes sized by cruise and selecting a power loading for peak efficiency would result in very large diameters. So, some efficiency is sacrificed for size and a higher power loading is selected. The blade count is increased to maintain high cruise efficiency levels and good low speed performance as well. The rpm's are similar but Prop-Fan favors the lower side to minimize the transonic effects as airspeed is increased.

In both aerodynamics and acoustics, it is necessary to design for operation of a large portion of the rotor area in the transonic regime. 800 fps at 0.8 Mach results in a tip helical Mach of 1.14. The key to maximizing aerodynamic efficiency is to eliminate compressibility losses and this is done by using the thinnest airfoils possible, consistent with structural integrity. Blade sweep is used in a manner similar to wing sweep to reduce the effective Mach number the airfoil section operates at. Nacelle shaping is accomplished to reduce the velocity through the disk with the primary emphasis to controlling inboard root choke, Area ruling is used in conjunction with nacelle shape to minimize drag losses in the root where the solidity is high. Lastly, an advanced airfoil shape may allow thicker airfoils or less sweep by raising the section critical Mach number above the point where compressibility losses rise rapidly. Three generations of model Prop-Fans have been designed, fabricated, and tested. Advanced aerodynamic analyses have been developed from existing propeller and fan expertise and applied to the design tasks. The aero analysis treats the inboard blade area as a cascade like a turbofan and the outboard area like a propeller. Only compressible 2D airfoil data are used. Both the effects of the nacelle and blade sweep are accounted for. With advanced design methods, achieving aerodynamic efficiency improvement at high Mach is accomplished with a methodical approach and a high confidence of success in place of the emperical, that is, cut and try approach.

The advanced aero design methods are allowing a fairly rapid focussing towards designs which improve upon Electra turboprop efficiencies. Of course, you can see that even the 1950's turboprop technology used in the Electra, which is the same as that used on the P3, is far superior to the typical general aviation turboprop. This is a direct result of the operating Mach number. The general aviation turboprops are designed to be highly efficient at 0.4 to 0.5 Mach cruise. The Electra technology offers no improvement there, but holds efficiency up high out to 0.6 Mach where it begins to drop off rapidly. Prop-Fan technology offers small gains at 0.6 Mach but holds efficiency up high out to 0.85 Mach. The Electra achieves efficiency improvement over general aviation turboprops through lower blade thickness ratios, both at the blade tips and roots. The Prop-Fan makes use of all the aerodynamic concepts discussed earlier: Thickness ratio, blade sweep and nacelle shaping. Wind tunnel test results on two-foot model Prop-Fans have demonstrated 80% efficiency which is the program objective. Additional aero/acoustic designs are expected to improve upon these results by a few percent. Demonstration of this should occur next year. Further improvements in efficiency can be obtained by recovering swirl. As much as eight efficiency points are lost in the slipstream of a single rotation rotor. Portions of this are recoverable by having the wing act as stator vanes or by using a counter-rotating propeller.

As with aerodynamics, controlling the acoustic levels required advanced concepts and design methodologies. Both far field noise around the airport and interior noise in cruise must be controlled. Concepts which have been considered in acoustic analysis conducted to date include reduced thickness ratio, reduced tip speed with increased blade count, optimum blade planform including swept shapes, and advanced airfoils. Let's consider their impact on far field noise. Noise reductions in the far field have typically been achieved by reducing tip speed; this is a very powerful noise reducing means, but in the past has been accompanied by performance reductions as well. This traditional means of noise reduction can be accomplished without performance decrement by increasing rotor diameter, but this is usually an unattractive alternate. Studies with new acoustic design methodology indicates that significant noise reductions can be achieved with improved airfoils, higher blades count, and a more optimum blade shape. Both airfoil optimization and increasing the blade count have a compound impact on noise by reducing noise in themselves but also improving efficiency so that for constant thrust, a smaller diameter can do the same job. Improved blade shapes, including sweep, reduce noise significantly without diameter changes.

The advanced acoustic method mentioned above is a procedure developed specifically for Prop-Fan cruise near field noise control but is generally applicable for any turboprop noise analysis. The noise method recognizes the components of tone noise associated with thickness, loading, and quadrupole. Thickness and loading are linear components and are directly related to the blade surface pressure and geometric definition. Quadrupole is a non-linear component related to the velocity derivatives in air around the airfoil. Non-linear effects are important when the airfoils are operating near their section critical Mach number. This method which recognizes the details of the blade allows much more effective noise reduction designs.

As mentioned earlier, blade sweep can be a very effective means for performance improvement, that is, increasing efficiency and reducing noise. The advantages of sweep for Prop-Fan are quite significant for high subsonic airspeed where the blade tip helical Mach number is supersonic. The character of the aerodynamic and acoustic improvements differ in that efficiency peaks at about 40 degrees of tip sweep while noise continues to decrease as sweep increases. The reason is that noise reduction is attributed to eliminating compressibility effects as with aero and also to a cancellation phenomenon. In fact, the cancellation of source noise by sweep can be accomplished for subsonic tip helicals as well, once compressibility has been eliminated. For the latest Prop-Fan blade design efficiency is up two percentage points and near field noise is down 18 dB compared to a straight blade. For the Prop-Fan, near field source noise at 0.8 Mach cruise is only one-third of the story associated with a comfortable interior of about 80 dB(A). In order to achieve this very quiet aircraft interior noise level, source noise reductions are being pursued and the source noise objectives are considered achieveable. Recent interior noise data indicates that further reductions are possible by correctly handling phasing and rotation effects. Synchrophasing can reduce the level in the peak noise area substantially. Finally, the fuselage is designed for attenuation and there is about 20 dB noise reduction for a standard turbofan type fuselage. Increased noise attenuation fuselage designs are under study and are considered practical. So, at 0.8 Mach it is possible to achieve a quiet interior. At lower Mach number it becomes easier.

The blade concept for improved efficiency and reduced noise must be structurally sound. Blade construction is key to a propeller/Prop-Fan design. It establishes the structural dynamics, is the major weight contributor, sizes the mechanical components, and establishes the maintenance and reliability philosophy The spar-shell blade construction concept, where the spar is metal structure and the shell is lightweight fiberglass, offers a large weight reduction over the traditional solid aluminum blade and allows the shaping of the blade for enhanced performance with fewer constraints. This spar-shell concept is safer and offers improved reliability and enhanced maintenance. Reliability is improved in several ways such an integral (buried) blade heater and individually replaceable blades. Failure probability is reduced by eliminating surface damage as a source of structural degradation. Hamilton Standard has accomplished blade designs for swept blades using traditional beam analysis and the more sophisticated finite element analysis technique. The accuracy and the level of information resulting from finite element analysis is quite superior to beam analysis. The stresses and deflections are defined everywhere on the spar, in the bond, and on the shell; and the mode shapes and natural frequencies are more precisely defined. The use of this advanced analysis technique will provide a blade design with high structural confidence and light weight. The Prop-Fan blade construction concept is an extension of the very successful current production fiberglass blade configuration. The highlights of the Hamilton Standard metal spar-composite shell experience are 5000 blades manufactured of 22 different designs. Thirteen achieved flight test status and four of these achieved production. The estimated blade flight time is 1.7 million hours.

I have reviewed the last 20 plus years of Hamilton Standard blade safety experience and the data shows about 35 million flight hours between in-flight blade fractures on reciprocating engines and no in-flight fractures on turbine engines in 60 million hours. This compares with general aviation data indicating about one million flight hours between fractures. A review of our blade fractures indicates that all were due to damaged exterior surfaces operating in the high engine vibratory environment of a recip. Elimination of the recip environment has eliminated blade fractures. It is projected that elimination of the environmental damage to the blade structure will reduce the probability of failure. Coupling this with improved structural analysis techniques should virtually eliminate blade failures.

A study recently done for NASA determined the reliability and maintenance costs for a typical turboprop propulsion system such as the Electra. Specific problem areas were isolated and improved upon in a preliminary design of a new Prop-Fan propulsion system. It was found that significant reliability improvements and maintenance cost reductions could be achieved for both the propeller and the turboprop related portions of the gearbox. In both cases, adoption of a modern on-condition maintenance philosophy, thereby eliminating scheduled major maintenance and overhaul, reduced costs in half. It was found on the Electra gearbox that the non-turboprop functions of engine and airframe accessory drives accounted for about 25% of the gearbox unscheduled maintenance costs. Such drives are necessary for any propulsion system and should be accounted with the core engine for turboprops as they are for turbofans. Lastly, as mentioned earlier on advanced blades, improvements in cost can be made as a result of improved reliability and modularity. Simplified component hardware, individually removed with simple procedures finally results in dollars per flight hour which are very low. The propulsion system maintenance cost is dominated by the turbine core engine, not the propulsive device.

Advanced design techniques when applied to advanced turboprops or Prop-Fans operating at high subsonic Mach number have improved performance over both conventional turboprops and high bypass turbofans. They additionally offer uncompromised safety and high reliability/low maintenance characteristics. Application of this propulsion concept extends the traditional turboprop utilization in General Aviation to high Mach where significant gains can be achieved over turbofans.

ADVANCED TURBOPROP POTENTIAL FOR HIGH SPEED

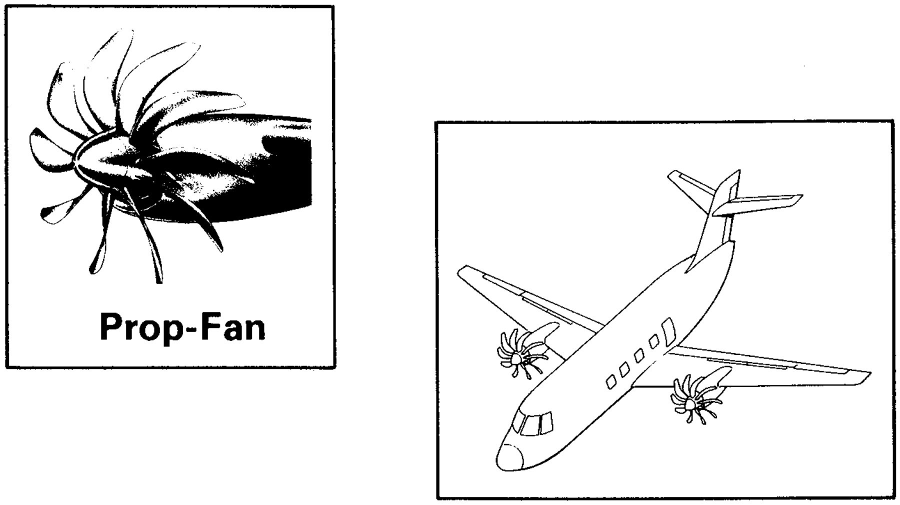


Figure 1

ADVANCED TURBOPROP OBJECTIVES

- Improved Performance Above M = 0.55
- Low Airport Noise
- Turbofan Interior Comfort
- Enhanced Structural Integrity
- Reduced Operating Costs

Figure 2

VARIATION OF INSTALLED EFFICIENCY

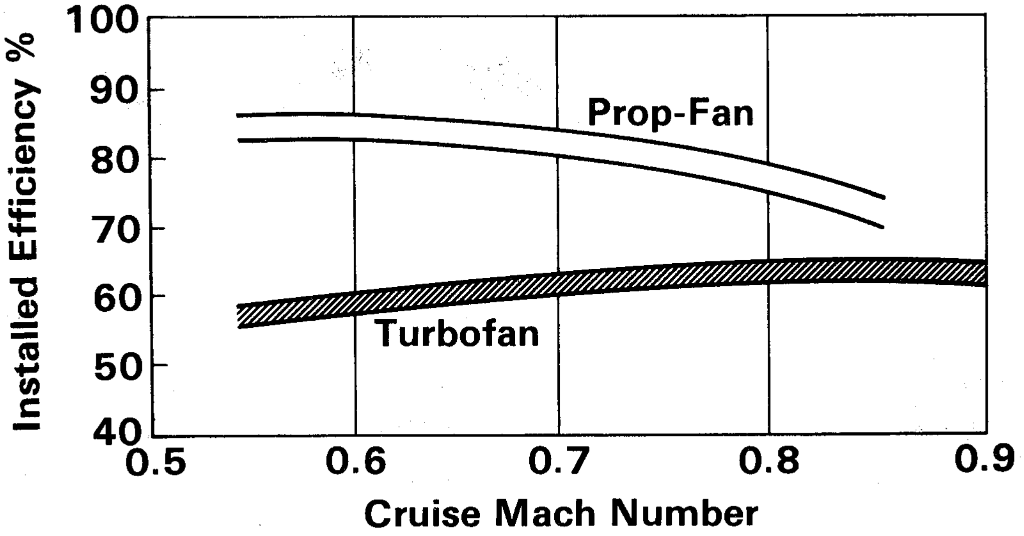


Figure 3

FUEL SAVINGS
Prop-Fan Vs. Turbofan

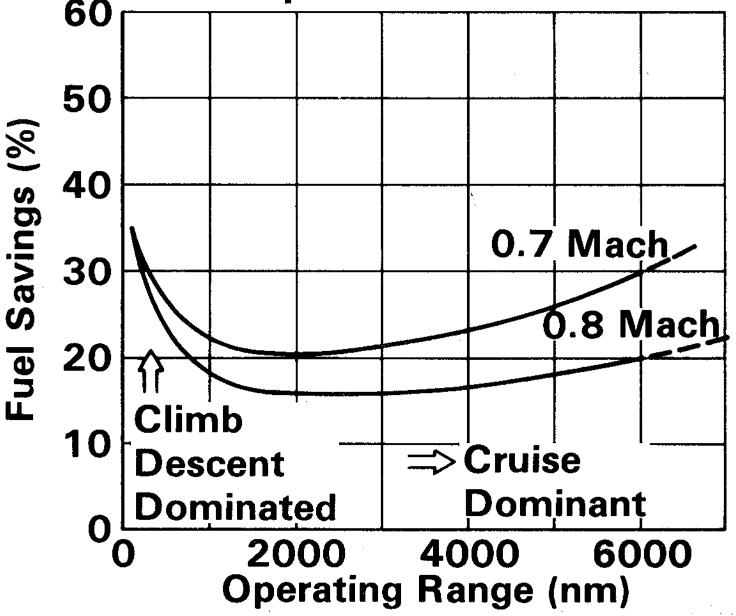
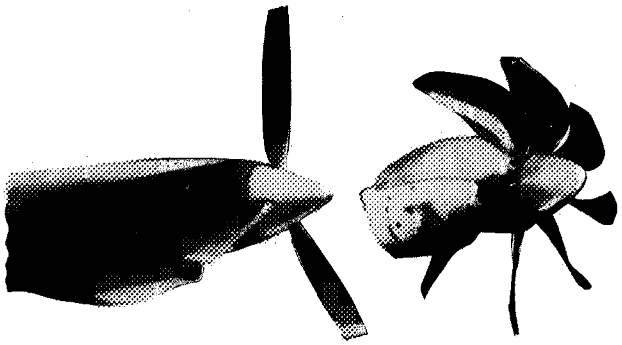


Figure 4

TURBOPROP COMPARISON



	Conv. Turboprops	Prop-Fan
Mach	0.3 to 0.5	0.6 to 0.8
Altitude (Ft)	15K to 30K	25K to 45K
Power/Dia^2	5-10	20-40
Blades	3 to 5	6 to 10
Tip Speed (Fps)	800 to 950	700 to 800

Figure 5

ADVANCED AERODYNAMIC CONCEPTS

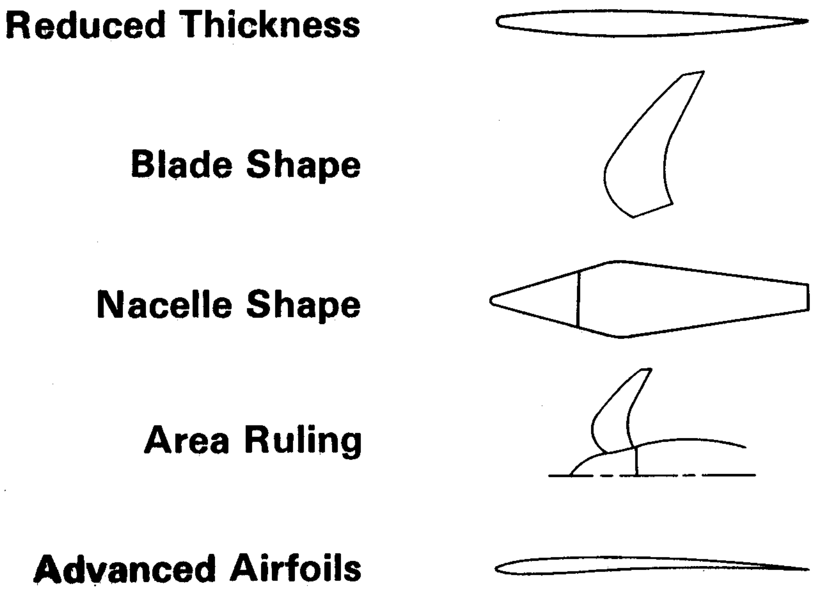


Figure 6

ADVANCED AERO ANALYSIS

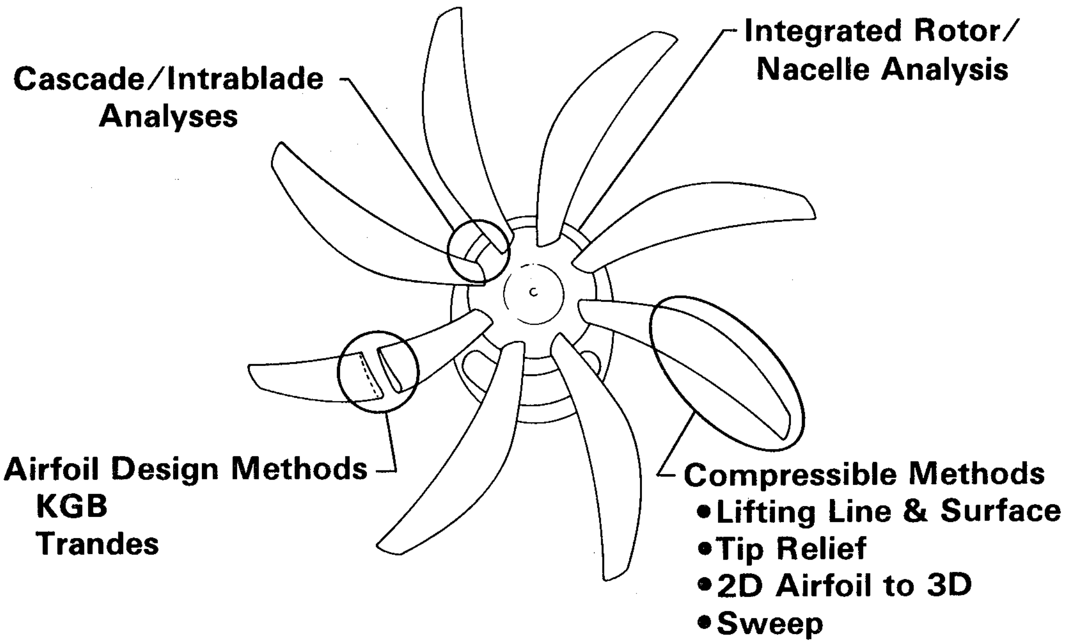


Figure 7

TURBOPROP UNINSTALLED CRUISE EFFICIENCY TRENDS

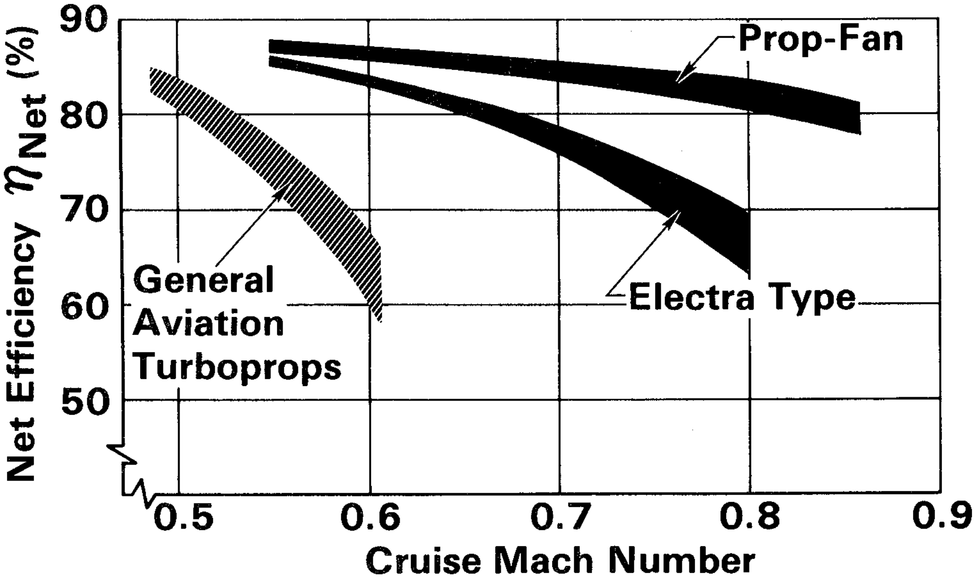


Figure 8

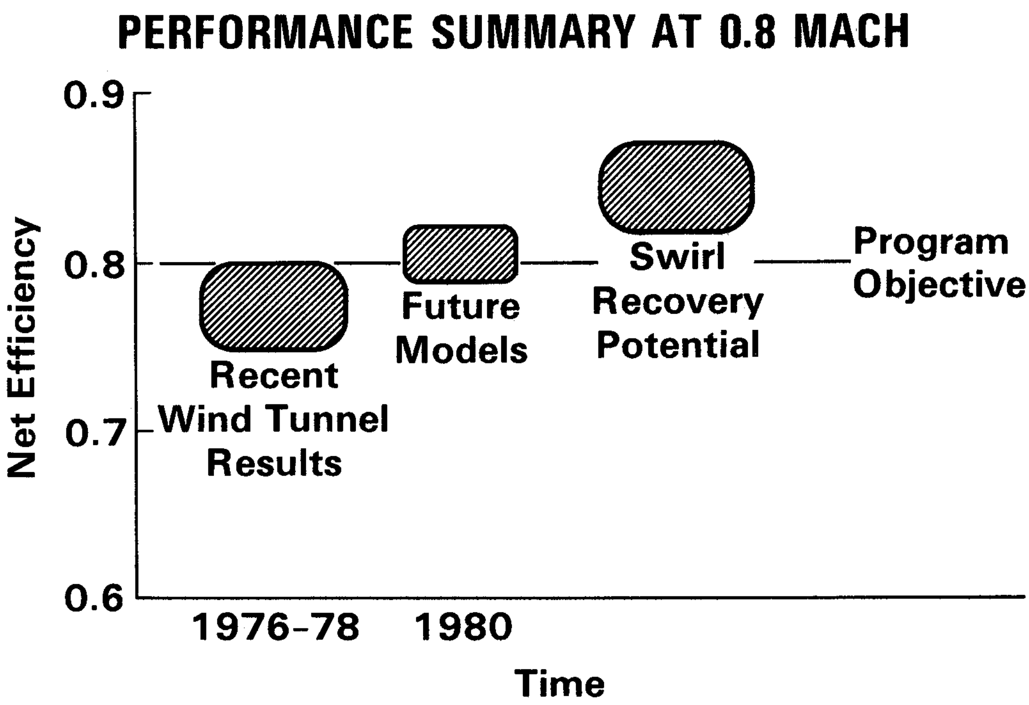


Figure 9

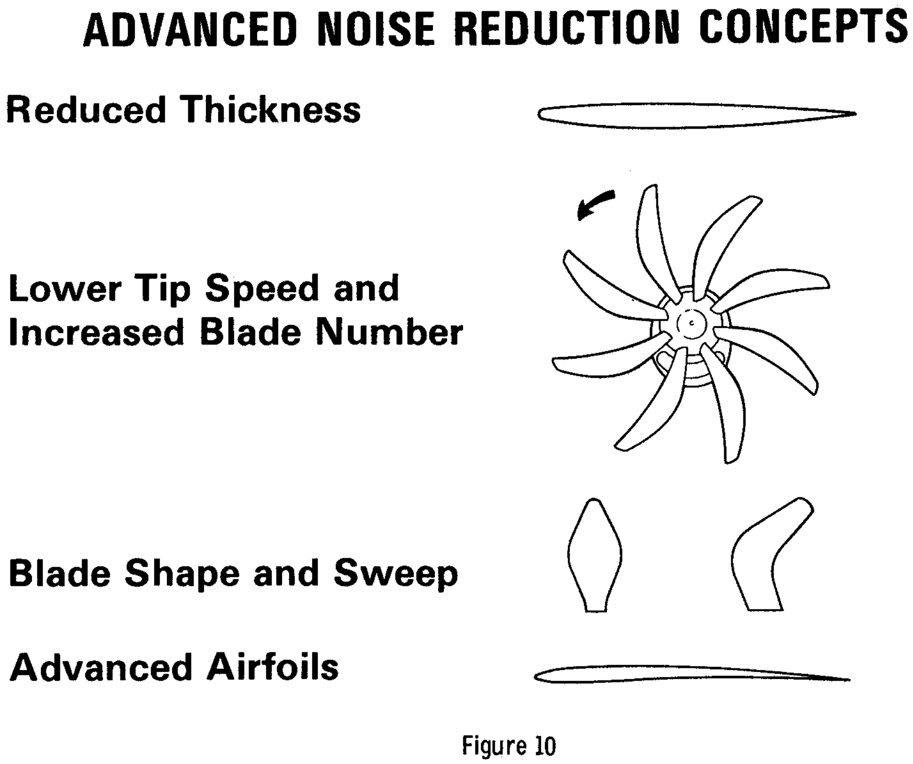


Figure 10

FAR-FIELD NOISE REDUCTION POTENTIAL

(Constant Thrust)

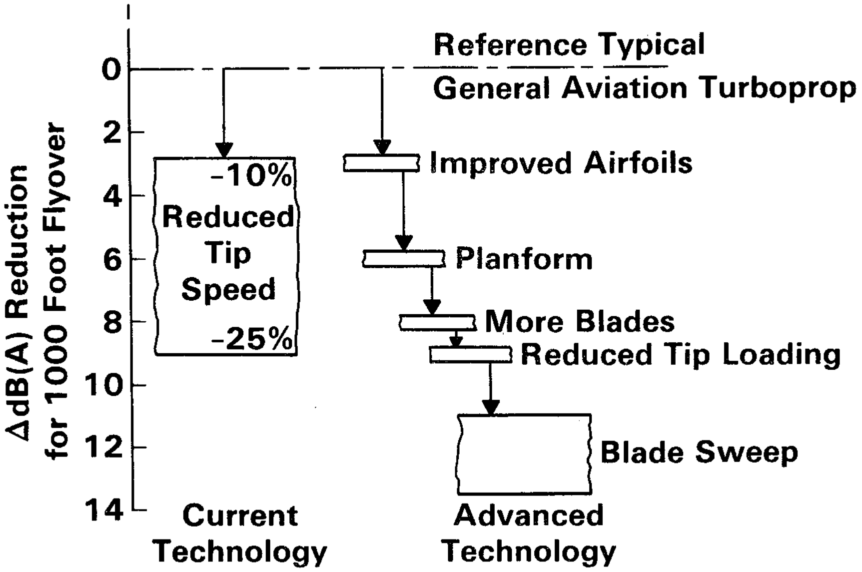


Figure 11

ADVANCED ACOUSTIC ANALYSIS

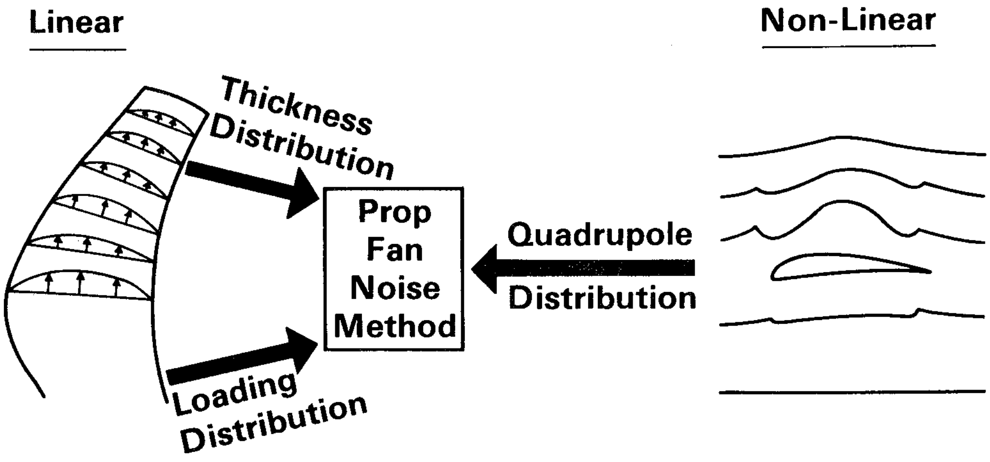


Figure 12

EFFECTS OF BLADE SWEEP

0.8 Mach Cruise
800 Ft/Sec Tip Speed

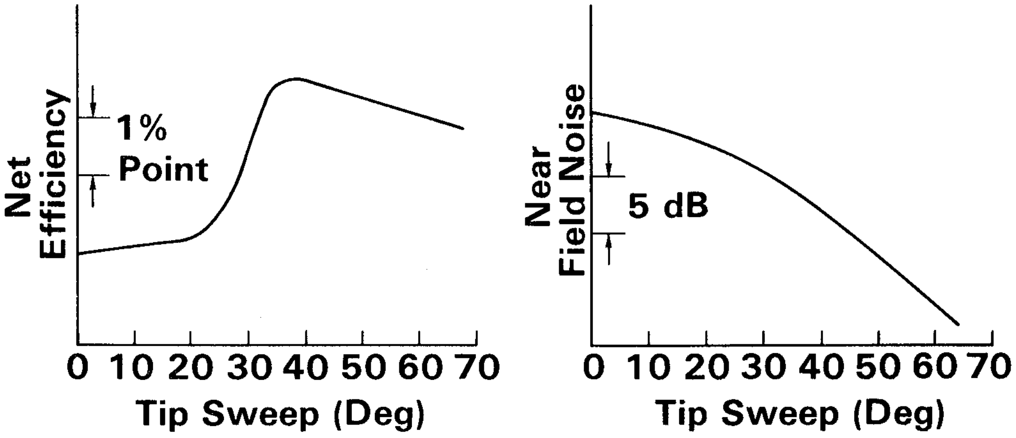


Figure 13

ACHIEVING THE CABIN NOISE GOAL

0.8 Mach Cruise

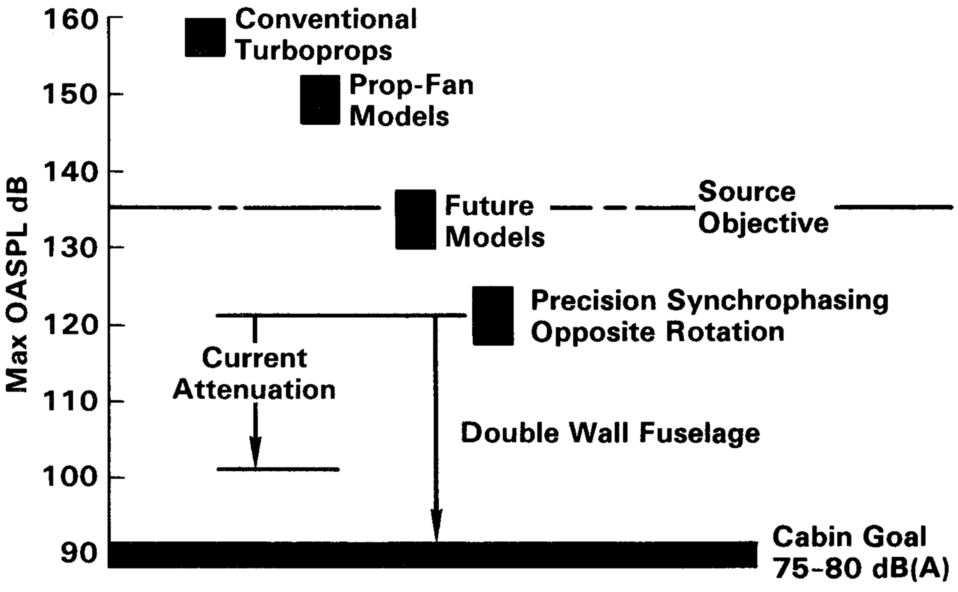
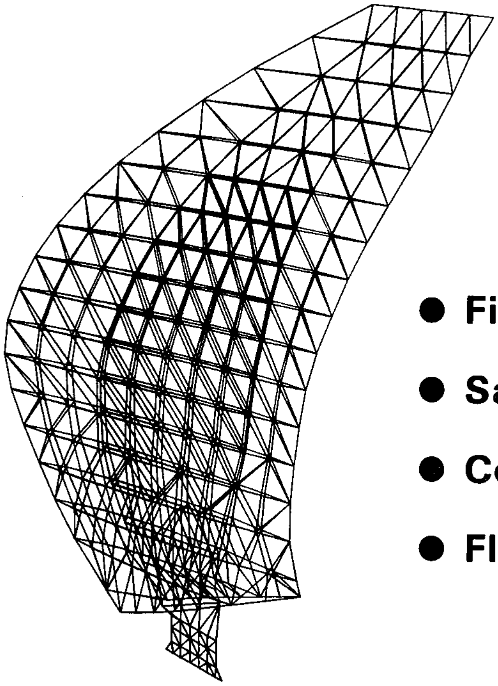


Figure 14

COMPARISON OF METAL SPAR-COMPOSITE SHELL AND SOLID ALUMINUM BLADES

- 25-50% Weight Savings
- Enhanced Performance
- Greater Safety
- Reduced Maintenance

Figure 15



ADVANCED BLADE DESIGN TECHNIQUES

- Finite Element Analysis
- Safe Stresses and Deflections
- Controlled Natural Frequencies
- Flutter Free

Figure 16

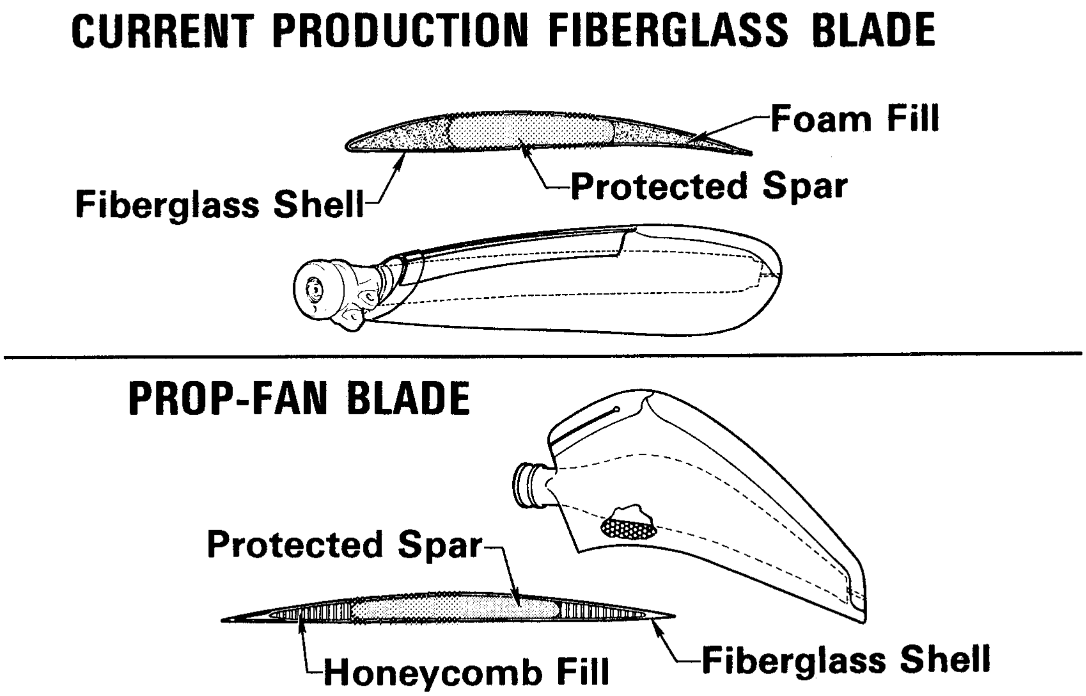


Figure 17

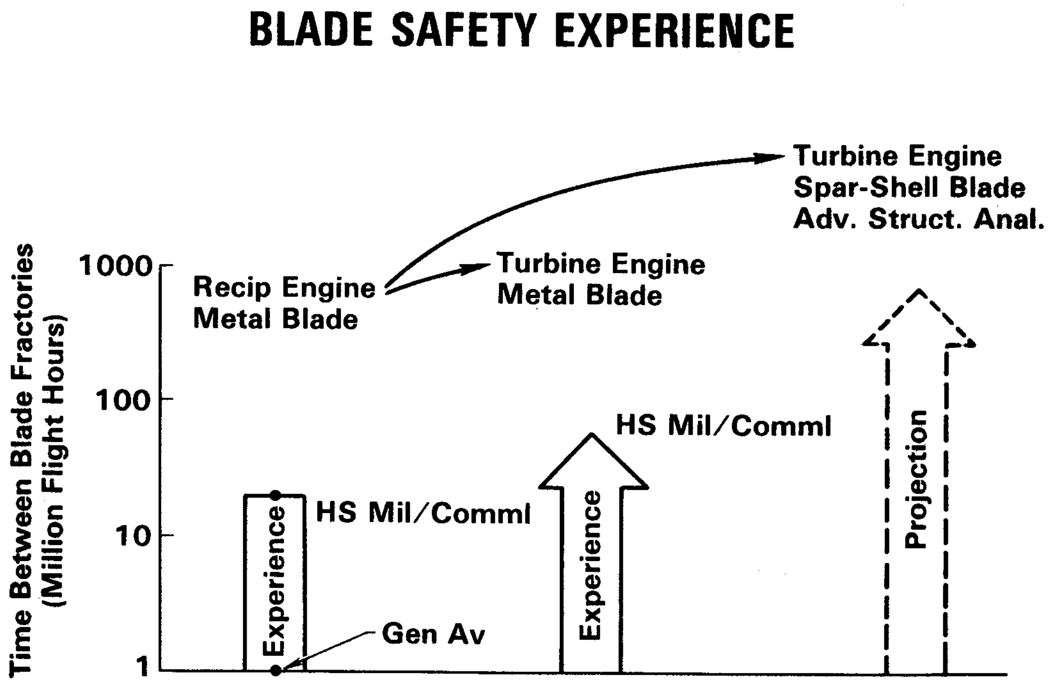


Figure 18

REDUCED MAINTENANCE

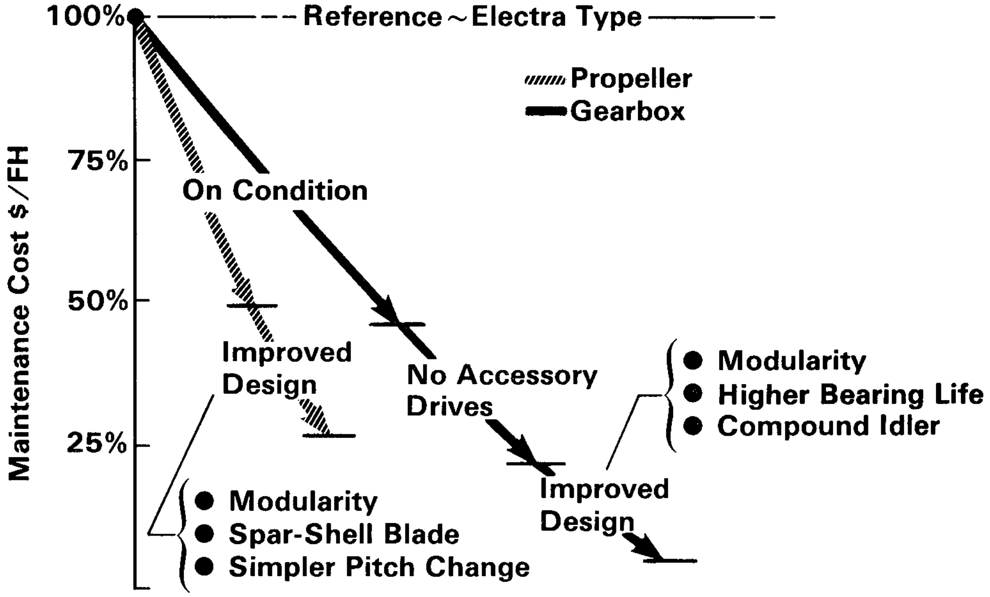


Figure 19

SUMMARY

Advanced Turboprops Can Meet Objectives

- Improved Efficiency
- Low Noise Profile
- High Safety & Reliability

And Offer New Potential for General Aviation

Figure 20