Advanced Turboprop Cargo Aircraft Systems Study

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Parametric studies were conducted to define the effects of advanced propeller (propfan) characteristics on aircraft direct operating costs (DOCs), fuel consumption, and noiseprints. Selected propfan aircraft realized 21% fuel savings and 14% lower DOCs relative to advanced turbofan aircraft. While both the propfan and turbofan aircraft satisfied current federal noise regulations, the propfan aircraft had smaller noiseprints at 90-EPNdB noise levels but larger noiseprints at lower noise levels. Several techniques for reducing the propfan aircraft noiseprints were explored; some of these contribute substantial reductions in noiseprint areas. Also, a propfan aircraft for the C-X role was studied.

Introduction

FUTURE air cargo faces two serious threats: the rising cost and uncertain availability of fuel and curtailed operations due to noise regulations around airports. This paper summarizes some of the results of a Lockheed study[1] of an advanced turboprop (propfan) propulsion system concept[2] that has been proposed as a means of reducing the impact of these two threats. The propfan, as shown in Fig. 1, is a highly loaded, multiblade turboprop system that incorporates advanced aerodynamic and structures technology in the propeller to provide high aerodynamic efficiency and low noise at flight speeds up to 0.8 Mach number for altitudes of 30,000 ft and above.

Numerous aircraft system studies from as early as 1974 have predicted that the propfan system will reduce fuel consumption by from 15 to 30% compared with aircraft equipped with turbofan engines of equivalent technology. Subsequently, since 1976, research programs have been underway to analyze the propfan and to establish a data base through wind tunnel tests on several models.

More recently, attention has been focused on the noise characteristics of this advanced turboprop. Analytical noise prediction methods, acoustic test results of scale models, and aircraft studies show that the noise of propfan powered aircraft will be below the levels specified by the Federal Aviation Regulations (FAR) for new certified aircraft.

Current federal regulations specify that noise certification measurements for aircraft be taken at three discrete locations for a type of flight profile that is considerably different from that typically flown in normal commercial operation. Consequently, two aircraft may satisfy the regulations equally, but they may be perceived by the neighboring community as radically different, because one is heard throughout a much larger area around the airport than the other. The extent of the area affected by the aircraft noise at a specified or higher level, the noiseprint area, is probably a better measure than the federal regulations for determining if a new aircraft will be a quiet neighbor that will not face operational curfews owing to noise. This is not a recommendation that aircraft noiseprint areas be incorporated into any federal regulations. Such action is unnecessary because public and commercial demands will force aircraft manufacturers to minimize noiseprint areas in the design of future transport aircraft if they are to be bought and flown.

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Technical Approach

Objectives

The objectives of this study were to explore the effects of using advanced turboprop propulsion systems to reduce the fuel consumption and direct operating costs of cargo aircraft, to determine the impact of these systems on aircraft noise and noiseprints around an airport, and to compare the results with those for turbofan aircraft designs.

Guidelines

The aircraft configurations generated in this study were to be ready for introduction into service in the early 1990s and were to incorporate those technologies projected to be available in the mid 1980s. All of the configurations were required to carry containerized cargo in a pressurized compartment on a domestic flight of 2295 n.mi. Furthermore, they were required to exhibit operational compatibility with existing transports of similar capability. This means that they would operate from fields as short as 8000 ft, and that landing approaches would be on a 3-deg glideslope at speeds not exceeding 135 knots.

For the economic analyses, the fleet was sized as a function of payload and speed for an annual productivity of 15.4-billion revenue-ton n.mi. Cost was in 1980 dollars, and fuel prices of from 50 to 100 ¢/gal were considered.

Advanced Technology Applications

Advanced technologies applied to these aircraft included supercritical airfoils, composite materials, advanced engines, a Hamilton Standard advanced propfan, and active controls. Graphite/epoxy composite materials were used for secondary structure throughout the aircraft and for primary structure in the empennage. Pratt & Whitney STF477 turbofan and STS487 turboshaft engines were used as the baseline powerplants to ensure a high degree of commonality for the comparative analyses. These two engines are of the same family of designs by one manufacturer and have equivalent technology levels.

Turboprop Aircraft Studies

Basic Configuration

The basic aircraft configuration is shown in Fig. 2. All of the payload is carried in the fuselage and is loaded straight-in through either an aft fuselage door or a nose visor door. The

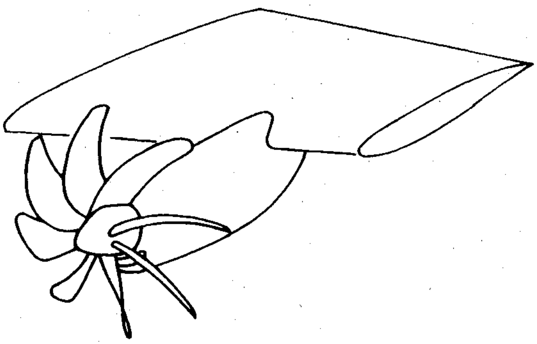

Fig. 1 **Propfan propulsion system.**

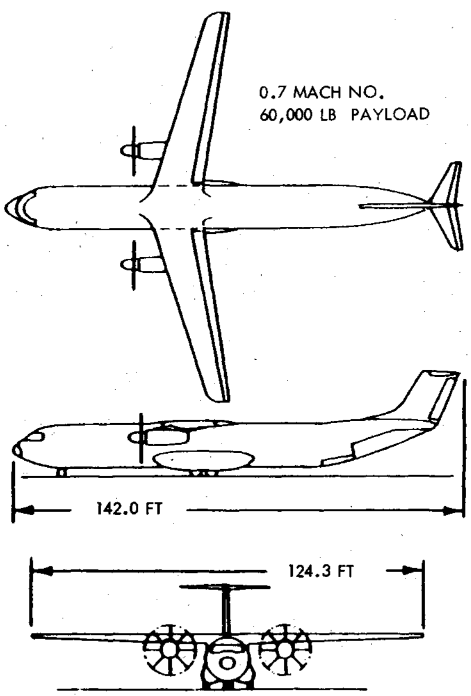

Fig. 2 **Baseline aircraft.**

wing is mounted sufficiently high on the fuselage at approximately midfuselage length so that it does not compromise the cargo compartment design. Pitch and directional flight controls are provided by a T-tail empennage mounted on the aft fuselage.

Other pertinent features include conventional fuselage mounted landing gear and engines attached to the underside of the wing. Two engines were used on the smaller payload aircraft, while four engines were used for the larger ones to limit the propeller size. In all cases, the engine centerline is 13.5 ft above the ground. With a minimum propeller tip to ground clearance of 3.5 ft, the propeller is limited to a maximum diameter of 20 ft.

Parametric Studies

Parametric studies were conducted for turboprop aircraft to identify the effects on direct operating costs, fuel consumption, and noiseprint areas due to variations in the performance, geometry, propulsion system, and fuel price characteristics listed in Table 1. The 2- and 4-container payloads fit into a single-row cargo compartment. The larger payloads used a two-row arrangement in part of the compartment.

Typical results on the "cost of quietness," that is, the impacts on block fuel and direct operating costs of reducing noiseprint areas, are shown in Fig. 3 for a 4-container payload case at 0.8 cruise Mach number. The graphs in the figure

Table 1 Turboprop aircraft parametric variables

Mission	
Cruise Mach number	0.6, 0.7, 0.75, 0.8
Payload containers	2, 4, 6, 9[a]
Initial cruise altitude, 1000 ft	25, 27, 30, 33, 36
Aircraft wing geometry	
Sweep angle, deg	10, 15, 20, 25
Loading, lb/ft^2	90, 110, 130
Aspect ratio	7, 10, 13, 16
Propeller	
Tip speed, ft/s	670, 750, 840
Number of blades	6, 8, 10
Nominal disk loading, hp/ft^2	35, 50, 60, 80
Cost	
Fuel price, ¢/gal	50, 75, 100

[a] Each container unit represents a payload weight of 15,000 lb.

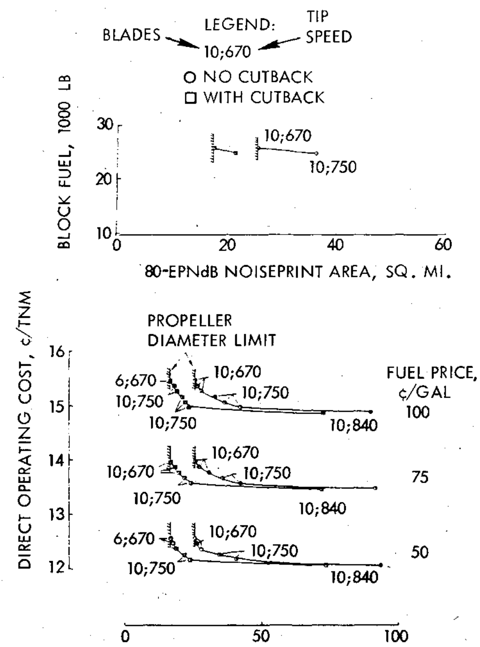

Fig. 3 Cost of quietness for 0.8 Mach number and 4-container payload turboprop aircraft.

provide optimum designs for minimum noiseprint areas at an 80-EPNdB noise level‡ under full-power and cutback§ conditions for three fuel prices. The number of propeller blades and the tip speeds are listed for each of the designated points. In every case, the minimum noiseprint occurs when the propeller diameter reaches a limit of 20 ft.

By comparing results for a single fuel price, the effect of changes in payload size becomes apparent, as illustrated in Fig. 4. Of the three payloads considered initially, aircraft designed for the 4-container payload have considerably lower operating costs than those with a 2-container payload and slightly lower costs than those with a 6-container payload for a given noiseprint area. This latter result merely reflects the inefficiency of trying to design for a 6-container payload, which is the size that requires a transition from one to two rows of containers.

To find the best speed for the 4-container payload, cost results from Fig. 3 and similar plots for 0.6 and 0.7 Mach

‡An 80-EPNdB noise level is an upper limit on noise which will not awaken an average person.

§Cutback power consists of full power through takeoff and climb to 1000-ft altitude, followed by a power reduction to the minimum levels permitted by FAR 36.

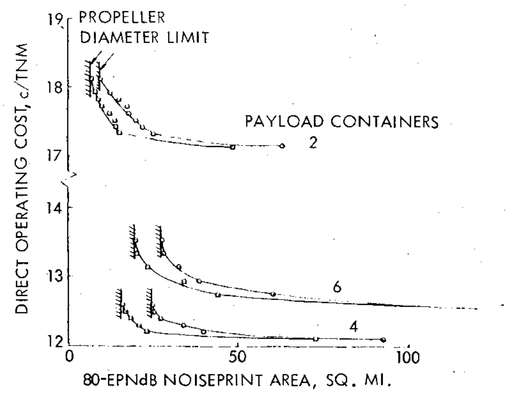

Fig. 4 Effect of payload on cost of quietness for 0.8 Mach number turboprop aircraft with 50 ¢/gal fuel.

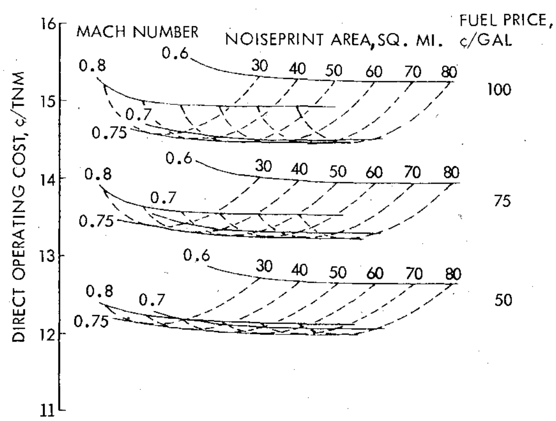

Fig. 5 Comparison of speed effects for 4-container payload turboprop aircraft.

numbers were combined, as in Fig. 5. With the results in this carpet-plot format, optimum trends and values are more readily apparent. At the lowest fuel price, minimum costs occur at a Mach number of 0.75 for all of the noiseprint areas. As the fuel price increases, the optimum Mach number decreases and eventually reaches a value of 0.73 for the highest fuel price of 100 ¢/gal. Because the curves of constant noiseprint area are very shallow near the optimum, a Mach number of 0.75 was selected for point design aircraft studies.

The investigation of payload size indicated that larger payloads, than those originally considered, are required to achieve efficient aircraft designed with two rows of containers. Consequently, a 9-container payload was specified for further analysis because it produces an efficient cargo compartment with two adjacent rows of four containers each, followed by a single container in the center of the tapered portion of the aft fuselage. Also, if the aircraft is to be considered for joint civil and military applications, the corresponding payload weight of 135,000 lb is just adequate for carrying one fully equipped main battle tank.

Selected Designs

Three aircraft were selected from the parametric results for further study. They have been designated the No. 1 compromise aircraft, No. 2 quietest aircraft, and No. 3 compromise aircraft.

As used here, the term "compromise" means a subjective attempt to mimimize direct operating cost and noiseprint area simultaneously. Thus, a compromise aircraft is selected from the "knee" of the DOC vs noiseprint area curve, and hence is neither the quietest nor lowest DOC aircraft.

Figures 6-8 provide three-view drawings of the three aircraft, while the major characteristics of each are summarized in Table 2.

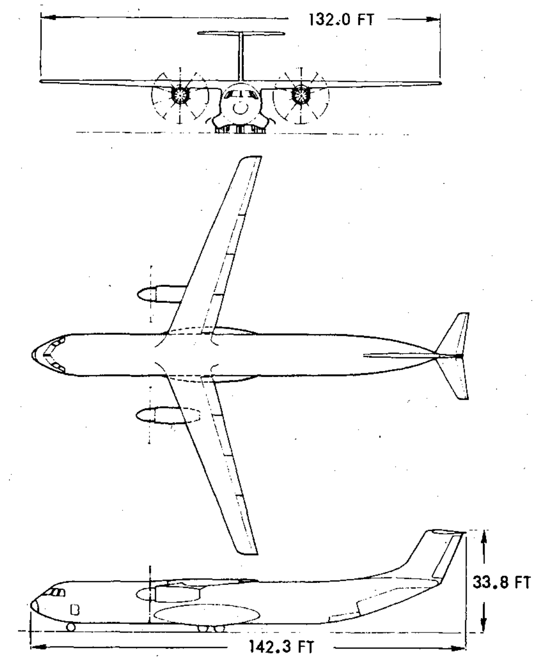

Fig. 6 Layout of No. 1 compromise turboprop aircraft.

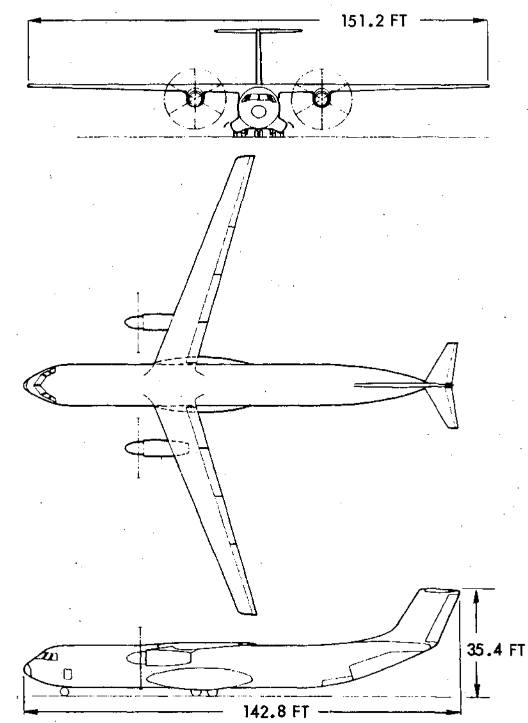

Fig. 7 Layout of No. 2 quietest turboprop aircraft.

Noise Characteristics

For all cases, the three aircraft are quieter than the FAR 36 limitations. When there is concern for minimizing the noise impact on the airport community, however, the size of the total area affected by aircraft noise is of interest. The boundary around the noiseprint area is defined by the sequence of positions on the ground where a specified minimum noise level is reached. For this study, noiseprint areas have been calculated for noise levels of 70, 80, and 90 EPNdB. The shapes of these areas are indicated by the contours in Figs. 9-11 for the three selected aircraft. Owing to the thin, long nature of the noiseprint areas, the takeoff and approach portions are shown separately, but the overlap of the two portions at the approach end of the runway is accounted for in determining the total noiseprint areas.

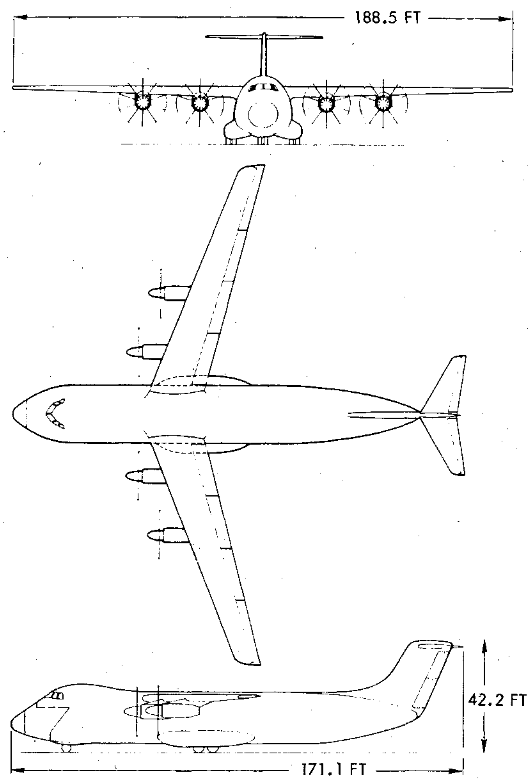

Fig. 8 Layout of No. 3 compromise turboprop aircraft.

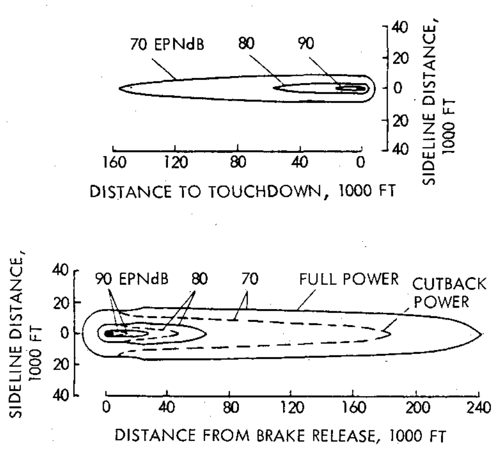

Fig. 9 Noiseprints for No. 1 compromise turboprop aircraft.

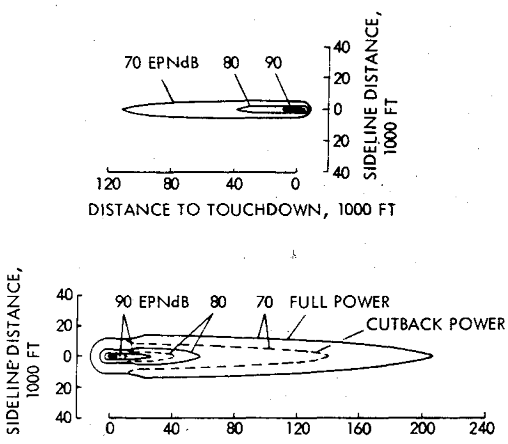

Fig. 10 Noiseprints for No. 2 quietest turboprop aircraft.

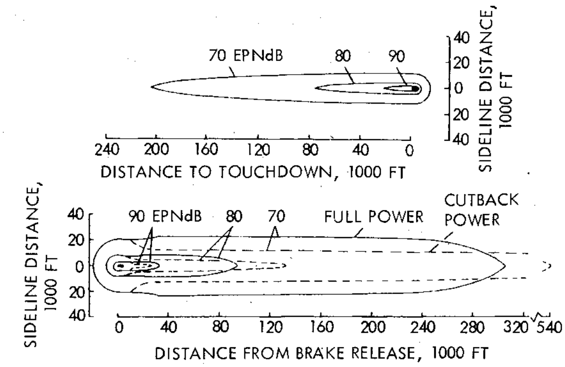

Fig. 11 Noiseprints for No. 3 compromise turboprop aircraft.

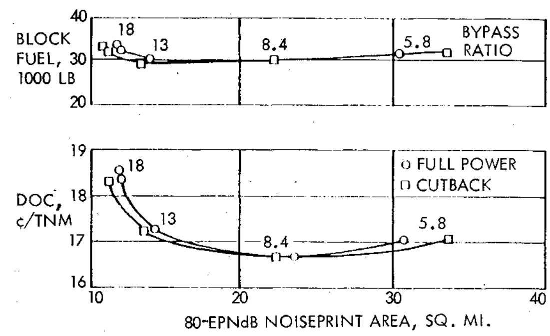

Fig. 12 Cost of quietness for 0.75 Mach number and 4-container payload turbofan aircraft.

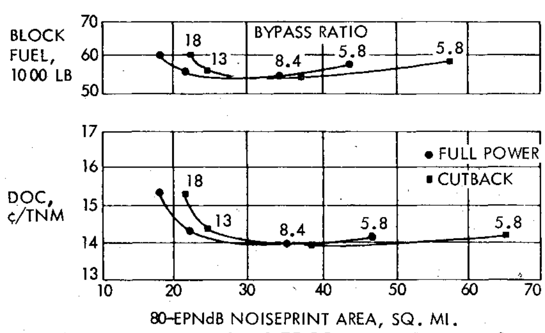

Fig. 13 Cost of quietness for 0.75 Mach number and 9-container payload turbofan aircraft.

Two sets of takeoff contours are presented: one for a normal full-powered condition and the other for a cutback power case. In the cutback case, after the noiseprint closes, i.e., the specified minimum noise level for the noiseprint is no longer perceived on the ground, power can be gradually increased to enhance climb performance. Care must be exercised, however, to assure that the minimum noise level of the noiseprint is not subsequently experienced on the ground.

Reference Turbofan Aircraft Studies

Three reference aircraft were developed in this study—one for comparison with each selected turboprop aircraft. To minimize the differences between the turboprop and turbofan-powered aircraft and allow attention to be concentrated on just the comparative effects of the two propulsion systems, each reference aircraft has the same delivery capabilities as its corresponding selected aircraft. That is, both aircraft to be compared have the same payload, cargo compartment, cruise speed, and altitude. Furthermore, they are subject to the same operating constraints such as field length and approach speed.

Table 2 Selected turboprop aircraft characteristics

Characteristic	Turboprop aircraft No. 1 compromise	No. 2 quietest	No. 3 compromise
Payload containers	4	4	9
Cruise Mach number	0.75	0.75	0.75
Cruise altitude, 1000 ft	33	33	33
Propeller blades	10	6	10
Tip speed, ft/s	750	670	750
Disk load, hp/ft^2	50	43	50
Diameter, ft	18.5	20	18.4
Wing aspect ratio	12	15	12
Loading, lb/ft^2	123.3	122.4	122.8
Weights, 1000 lb			
Operating	88.6	97.1	171.8
Fuel	29.6	30.0	58.9
Payload	60.0	60.0	135.0
Ramp	178.2	187.1	365.6
Field length, ft	5524	6157	4973
80-EPNdB noiseprint area, mi.^{2}	32.0	22.3	63.7
Direct operating cost,[a] ¢/TNM	14.7	15.0	13.3

[a] Fuel at 100 ¢/gal.

Table 3 Selected turbofan aircraft characteristics

Characteristic	Turbofan aircraft No. 1 compromise	No. 2 quietest	No. 3 compromise
Payload containers	4	4	9
Cruise Mach number	0.75	0.75	0.75
Cruise altitude, 1000 ft	33	33	33
Engine			
Bypass ratio	10	13	10
Power setting	0.77	0.80	0.85
Wing aspect ratio	13.45	16	12
Loading, lb/ft^2	125	125	125
Weights, 1000 lb			
Operating	90.7	99.7	166.3
Fuel	37.3	37.7	71.3
Payload	60.0	60.0	135.0
Ramp	188.0	197.4	372.6
Field length, ft	8018	7722	8074
80-EPNdB noiseprint area, mi.^{2}	20.4	14.3	30.7
Direct operating cost,[a] ¢/TNM	16.9	17.5	14.5

[a] Fuel at 100 ¢/gal.

Parametric Analysis

The three reference turbofan aircraft were chosen from the results of parametrically varying wing loading and aspect ratio, and engine bypass ratio and power setting.

Variations in engine bypass ratio were included by considering four design point engines with ratio values of 5.8, 8.4, 13, and 18. The weight and performance characteristics of each engine were developed, in consultation with Pratt & Whitney, from the basic STF477 turbofan engine by using Lockheed's propulsion cycle analysis program.

The approach used in this parametric study paralleled that followed for the turboprop aircraft. The results of direct operating cost and block fuel vs noiseprint area are shown in Figs. 12 and 13.

Selected Designs

The major design parameters selected to define the three reference turbofan aircraft are listed in Table 3 along with the major characteristics that were determined for each. The values for the mission features are the same as for the three selected turboprop aircraft for eventual comparative purposes. Figures 14-16 are three-view drawings of these three selected aircraft.

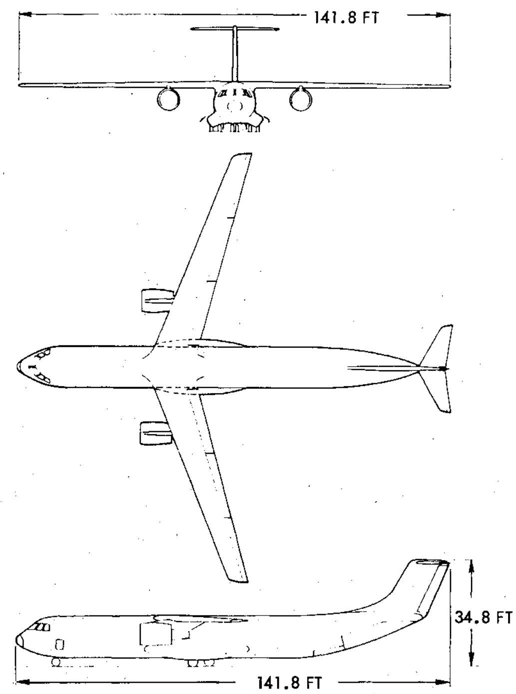

Fig. 14 Layout of No. 1 compromise turbofan aircraft.

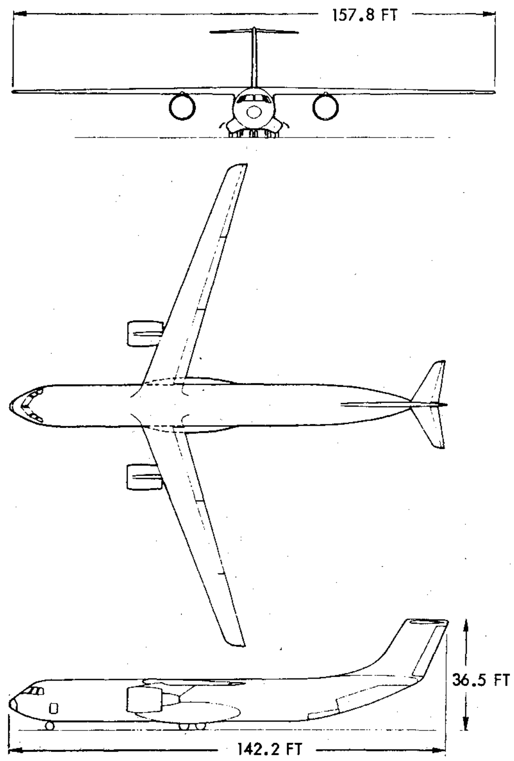

Fig. 15 Layout of No. 2 quietest turbofan aircraft.

Aircraft Comparison

Figure 17 graphically highlights the performance benefits that each turboprop aircraft enjoys relative to its counterpart turbofan aircraft. In every case, the turboprop wins with lower ramp weights and less block fuel used, resulting in higher fuel efficiencies, lower DOCs, and shorter field lengths. The magnitude of some of the benefits is particularly noteworthy, with fuel savings of 17 to 21%, 21 to 26% improvement in fuel efficiency, and DOCs down by 8 to 15%. The 20 to 38% shorter field lengths are also significant because this means that the turboprop aircraft can operate

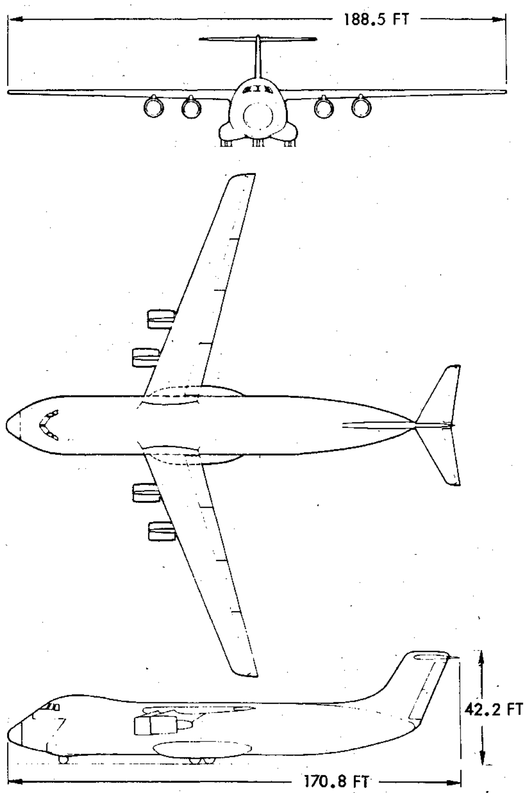

Fig. 16 Layout of No. 3 compromise turbofan aircraft.

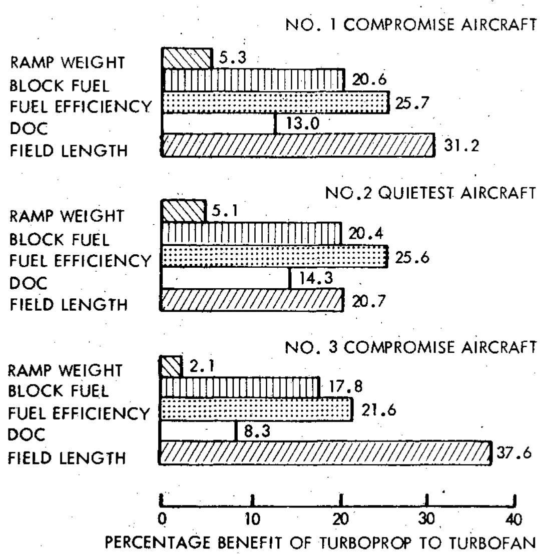

Fig. 17 Turboprop aircraft performance benefits relative to turbofan aircraft.

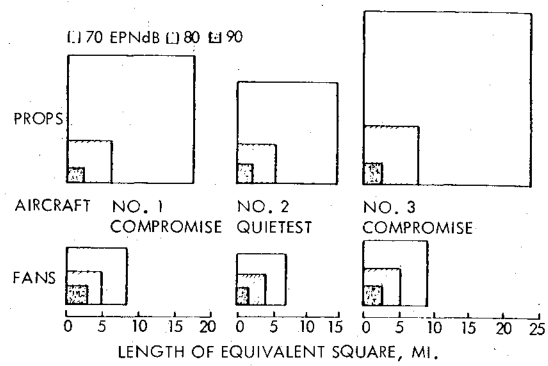

Fig. 18 Noiseprint comparison.

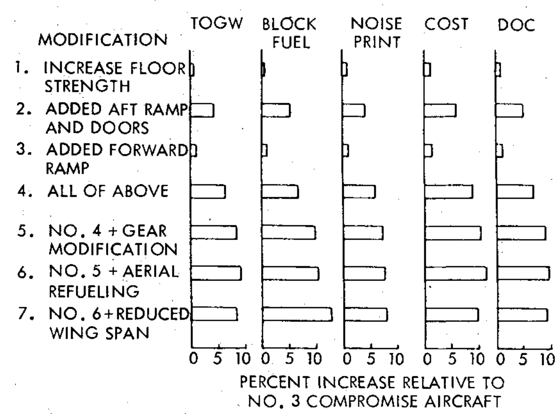

Fig. 19 Effects of modification for C-X mission application.

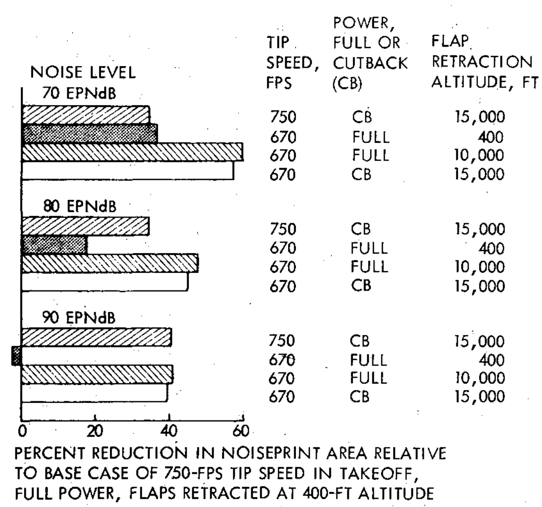

Fig. 20 Effects of variable tip speed propeller.

into small airports that may not be accessible to turbofan aircraft.

Although not shown on the figure, both the turboprop and turbofan aircraft have about 20% lower fuel consumption than today's commercial aircraft. Thus, the turboprop offers a total potential fuel saving of about 40% in comparison with current aircraft.

Because of the tapered and elongated nature of the noiseprints which necessitated presenting them in two parts, the impacts of cutback and different noise levels are not easily visualized. To overcome this, the noiseprints have been converted into squares of equivalent area for the comparison shown in Fig. 18.

At the 90-EPNdB noise level, the turboprop aircraft have smaller noiseprints than the turbofan aircraft; the reverse is true for the two lower noise levels. Reference 1 provides a detailed discussion of how the different climb capabilities, forward speed effects, and atmospheric noise attenuation interact to cause these results.

It is apparent from this figure that the noiseprint areas for the turboprop aircraft are more sensitive to variations in noise level, or source noise, than are the turbofan aircraft. For example, a 10-EPNdB reduction in the noise level produces only a three to fourfold increase in the noiseprint area for the turbofan aircraft, but a tenfold increase in that of the turboprop.

Special Studies

Several areas were identified during the study as meriting further investigation. Three of the areas that were pursued are summarized next.

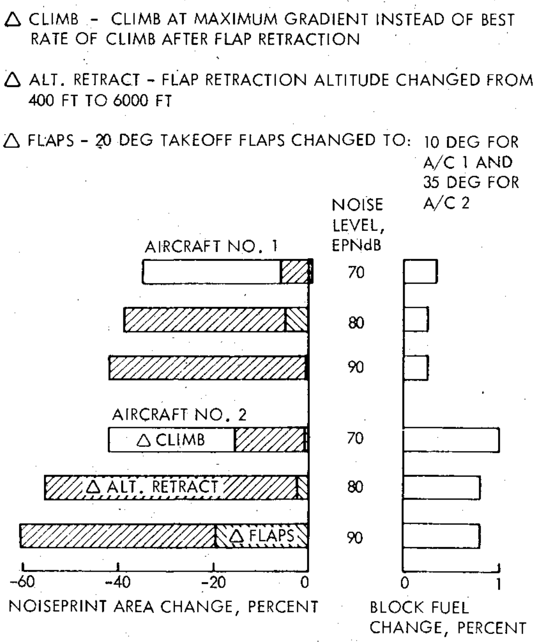

Fig. 21 Effects of flight profile variations.

C-X Mission Application

Considerable emphasis has recently been placed on the concept of a common aircraft for civil and military use. While all of these study aircraft were designed for civil use only, the benefits obtained with the advanced turboprop propulsion system are substantial enough to be considered for military use also.

The Air Force's C-X mission was selected as a prime military application because of the close match between its mission requirements and the capabilities of the No. 3 aircraft from this study. The task, in general, was to determine what changes would be required to make the No. 3 aircraft meet the C-X specifications and what would be the effect of these changes on the aircraft design with minimal resizing.

Analysis of the C-X specifications identified the need for the following six physical changes to the design of the No. 3 aircraft:

1) increased cargo compartment floor strength for heavy tracked vehicles;

2) addition of an aft ramp and door for aerial delivery capability;

3) addition of an integral forward ramp for use at austere fields;

4) modification of the landing gear for soft field operations;

5) addition of an aerial refueling capability;

6) reduction of the wing span from 195 to 185 ft to permit simultaneous operation of two aircraft on ramps at small austere airfields.

Figure 19 shows individual and collective effects of these modifications on the gross weight, block fuel, noiseprints, and costs of the baseline aircraft. Based on these results, it appears that the No. 3 turboprop aircraft requires only minimal modifications at relatively small penalties to serve as a common aircraft for both civil needs and the Air Force's C-X requirements.

Variable Tip Speed Propeller

Our results showed that the propeller is the primary noise source on a turboprop aircraft, and furthermore, that tip speed is the characteristic most responsible for the propeller noise. While reducing the tip speed does tend to produce a quieter propeller and aircraft, the lower speed means less performance, which must be compensated for by going to a larger, and somewhat noisier propeller and engine. An alternative for reducing the noiseprint is to operate the propeller at a lower tip speed when in close proximity to the ground. Such an approach was investigated for the No. 1 compromise aircraft.

In this analysis, the aircraft was assumed to be unchanged, having been sized for cruise at a propeller tip speed of 750 ft/s. Takeoff, climb, and landing performance were revised based on using the same engine and propeller but with the propeller speed reduced to 670 ft/s. Owing to the lower speed, the takeoff thrust available is reduced which increases the field length but decreases the noiseprint, as illustrated in Fig. 20, for the two lower noise levels. The greatest benefits with the low tip speed occur when the flaps remain down. Further reductions in propeller tip speed to 600 ft/s, or keeping the flaps deployed to some other altitude, may prove even more beneficial.

Alternate Takeoff Profiles

Originally, all of the aircraft took off with the flaps deflected at 20 deg and achieved an obstacle speed 10 knots above the minimum safe speed. Upon reaching an altitude of 400 ft, the flaps were retracted and the aircraft continued on to cruise altitude at their maximum rate of climb.

Variations to this procedure were investigated for the No. 1 and No. 2 aircraft to determine if the noiseprints could be reduced. Keeping the flaps deployed to higher altitudes was consistently most beneficial in reducing the noiseprints.

Figure 21 shows the maximum noiseprint area reductions and the corresponding block fuel penalties that were realized at three noise levels for the two aircraft from varying the takeoff flight profile. The benefits are that up to 60% reductions in the noiseprints are possible with the penalties being less than a 1% increase in block fuel.

Conclusions

Advanced turboprop propulsion systems offer potentially significant benefits over turbofan propulsion systems and merit further development. Relative to advanced turbofans, advanced turboprop aircraft exhibited up to 21% fuel savings, 14% lower direct operating costs, and 38% shorter field lengths. In comparison to current turbofan aircraft, fuel savings up to 40% may be anticipated.

Operation at cruise Mach numbers below 0.8 becomes increasingly attractive as fuel prices increase and become a greater percentage of aircraft operating costs.

A propeller tip speed of 750 ft/s and a sea-level disk loading of 50 hp/ft^2 provide effective compromise values for minimizing aircraft costs and noise.

Accuracy of predicted noise source levels are critical to the study results.

An advanced turboprop aircraft can, with minimal design modification, serve as a joint civil/military airlifter.

Recommendations

For the U.S. to realize the maximum benefits from the potential fuel savings, all efforts related to the development of the propfan propulsion system need to be accelerated to make the technology available as soon as possible.

Design studies of large-size turboshaft engines and gearboxes in the 15,000 shaft-hp range need to be initiated because the largest current systems are only about one-third of the required size.

Wind tunnel tests and analysis are recommended to determine propeller/wing aerodynamic interference effects and the effects of the propeller on the aerodynamic and structural performance of a supercritical airfoil.

References

[1]Muehlbauer, J.C. et al., "Turboprop Cargo Aircraft Systems Study," NASA CR-165813, Nov. 1981.

[2]Dugan, J.F. Jr., Gatzen, B.S., and Adamson, W.M., "Prop-Fan Propulsion—Its Status and Potential," SAE Paper 780995, Nov. 1978.