Propulsion System Design for the ATT

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The NASA funded Advanced Transport Technology (ATT) systems studies are directed at identifying the optimum propulsion system characteristics required for a low noise, low emissions level engine designed for an advanced commercial transport that employs the supercritical wing technology. This transport could be in service in the late 70's or early 80's and would be designed for transcontinental and international ranges with cruise speeds up to Mach 0.98. This paper will review the significant results of the propulsion system study and the implications in the propulsion design concept and acoustically treated nacelle of meeting a noise level 10-15 EPNdb below FAR Part 36.

Introduction

DURING the past decade a revolution has occurred in commercial air transportation. Today, swift, convenient, safe and economical airline service is available to almost any region of the world. The long-range transport airplane has been the foundation of this system and has provided a worldwide example of U.S. aerospace excellence and technical/economical success. The modern aircraft powerplant has played a major role in achieving this status.

Recognizing the vital part that the long-range airplane plays in world commerce, NASA is studying the application of advanced technologies to the next generation of long-range aircraft to assure that future designs will be fully responsive to national needs. This ATT program consists of a broad evaluation of the benefits of technology advances in aerodynamics, propulsion, structures, controls and avionics. The Langley Research Center has directed parallel studies of the over-all system and the airframe, including propulsion integration. Close coordination has been maintained with the Langley system study contractors during this propulsion system study.

In evaluating new airplanes, it is especially important to recognize that the general public, and particularly airport neighbors, want transport aircraft to be quiet and clean (low in emissions). They also want limitations of airport encroachment on the adjacent community. The propulsion system plays a dominant role in achieving these social objectives and for this reason first priority in this program was given to making the study engines quiet and clean. Improvements in engine performance, reliability/maintainability and economics were also achieved subject to first meeting these social goals.

The propulsion study conducted under the ATT contract had three primary objectives: 1) Evaluate engine cycles which meet future noise and emission goals with minimum system penalty at Mach 0.95–0.98; 2) Evaluate the impact of advanced propulsion technology on noise, emissions, performance and the over-all aircraft system; and, 3) Recommend to NASA the necessary programs to acquire this technology.

This paper will review the results of the preliminary engine design studies conducted at Pratt & Whitney Aircraft directed toward defining propulsion concepts that would reduce aircraft noise levels between 10 and 15 EPNdb below FAR (Federal Air Regulations) Part 36.

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Discussion

The objective of the ATT study was to determine the optimum propulsion system characteristics for an advanced technology, long range, commercial transport aircraft that employs supercritical wing technology to permit efficient flight near the speed of sound. Since these new aircraft must exhibit improved noise and emission characteristics, the studies were directed toward the selection of those engine cycles which yielded low noise and emissions with minimum total aircraft system economic penalty.

NASA established two minimum noise levels to be attained with advanced propulsion concepts in combination with a fully treated nacelle. Full nacelle treatment included extensive acoustical wall treatment, inlet rings, a fan duct splitter and primary tailpipe treatment. The noise requirements are illustrated in Table 1.

The treated noise levels of FAR-10 and -15 EPNdb are for an aircraft that is operated in the conventional manner during take-off and approach. The noise goal of FAR-20 EPNdb assumes the use of aircraft operating procedures, such as automatic flap retraction during climb out and steeper glide paths during approach for landing, to further reduce the measured noise. The potential noise reduction from operating procedures will be discussed later in this paper.

After extensive parametric engine cycle studies, two cycles were selected that met the established noise targets with minimum penalty to the over-all aircraft system. Predictions of aircraft take-off gross weight and airline direct operating cost (DOC) and return on investment (ROI) for over 240 different propulsion cycle combinations were made to arrive at the selected cycles shown in Table 2.

The single most important result of the ATT study is the low engine source noise and high performance potential of a low tip speed, spaced, two stage fan. Why a two stage fan?

Commercial engines designed for operation in the early 1980's will operate at combustor exit temperatures several hundred degrees higher than the latest model turbofans being produced today. Operation at higher temperatures

Table 1 Noise goals

Certification date	1979	1985
Treated noise minimum	FAR-10db	FAR-15db
Noise goal		FAR-20db
Noise minimum	Nacelle wall acoustic treatment plus inlet rings and fan duct splitter	
Noise goal	Full treatment plus aircraft operating procedures for noise abatement	

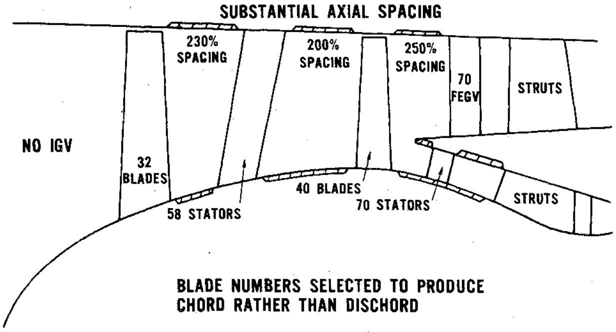

Fig. 1 Flow path for the low-noise fan design.

requires higher fan pressure ratios for optimum cycle performance and minimum fuel consumption. Depending upon the bypass ratio selected, fan pressure ratios of 1.9 to 2 and higher are required.

The question then becomes whether it is better to obtain the desired fan pressure ratio with a high tip speed single stage fan or a low tip speed two stage fan. Advanced technology projections indicate that a single stage fan designed for a fan pressure ratio of 1.9 would require a fan tip speed of 1800 fps. A similar design point two stage fan would have only a 1200 fps tip speed. The lower tip speed of the two stage fan results in a significantly higher fan efficiency and, therefore, a lower fuel comsumption. The lower speed does result in a tougher design job for the low pressure turbine that drives the fan.

Of course, the most attractive feature of the two stage fan is the lower engine source noise due to the low fan tip speed. Table 3 illustrates the noise comparison of a high tip speed single stage fan and a low tip speed two stage fan at maximum power take-off sideline and a typical approach power setting. The cycle design point is identical for both engines. Bypass ratio is 6.5 and the fan pressure is 1.9 at the Mach 0.98 cruise design point. The cruise design tip speeds are 1800 and 1200 fps. The tip speeds shown in Table 3 indicate the lapse rate between cruise and takeoff. Approach indicates a further reduction in tip speed due to approach at approximately 30% power.

During approach, the two stage fan tip speed is below sonic velocity resulting in a 6 EPNdb lower noise level.

The low noise design features of the two stage fan are shown in Fig. 1. Substantial axial spacing allows the wake from each row of airfoils to attenuate before reaching the downstream row of airfoils. The spacing indicated is the percentage increase in the projected axial tip chord of the upstream airfoil. The number of blades and stators in each row was selected to avoid discrete blade passing frequencies and harmonics.

In order to obtain the desired low noise levels, it is necessary not only to reduce engine source noise but also use extensive nacelle acoustic treatment. Figure 2 illustrates the installation of the JT9D engine on the 747-200 that has been certified for FAR Part 36. Acoustic Treatment is represented by the heavy black lines and is located on the inlet wall, fan exit duct (including a short duct splitter) and in the primary tailpipe.

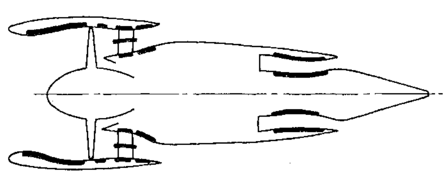

Fig. 2 JT9D nacelle treated to meet FAR Part 36.

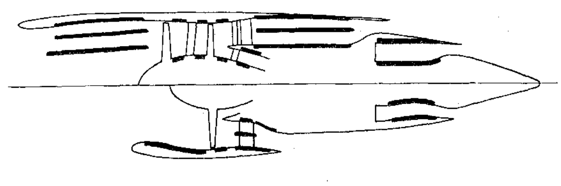

Fig. 3 1985 ATT and JT9D treated nacelle comparison.

For contrast, the 1985 ATT engine and nacelle required to obtain a 15db reduction below FAR Part 36 is compared with the JT9D in Fig. 3. The second stage of the two stage fan is aligned with the single stage fan of the JT9D. In addition to wall treatment, two inlet rings and one fan duct splitter are required to obtain the necessary noise attenuation.

Even with the extensive amount of nacelle treatment incorporated in the ATT design, a significant improvement in treatment effectiveness will be required over present technology if the noise targets are to be realized.

Improved acoustic material effectiveness will occur in the form of increased peak attenuation, broader band width and reduced weight penalties. Improvements in band width and peak attenuation assumed in this study are shown in Fig. 4.

Jet noise levels at velocities below 1000 fps play a significant role in determining total engine noise levels. Figure 5 shows the jet noise improvements expected as additional research provides a better understanding of the mechanism and control of this noise source.

Estimated noise levels for the STF429 and STF433 engines are shown in Figs. 6 and 7. With extensive nacelle treatment the STF429 meets its -10 EPNdb noise goal. Similarly, the STF433 meets its -15 EPNdb noise goal at all three noise measurement conditions. The top of the bar graphs indicate the untreated noise level. The cross-hatch area illustrates the noise reduction due to the acoustic treatment in the nacelle (wall plus two inlet rings and one fan duct splitter). Total jet noise level is also indicated.

Various operational procedures were considered for the reduction of aircraft noise. The major factor involved in the majority of the operational procedures was the reduction in thrust required, thereby resulting in reduced noise.

Increasing the glide slope angle from the customary 3° to 6° reduces the normal approach power by one-half. This technique may be applied to either the two segment or the single segment approach and can reduce approach noise levels between seven and thirteen EPNdb, respectively. The two segment approach includes a transition from 6° to 3° approximately 1 naut mile from the runway threshold, whereas

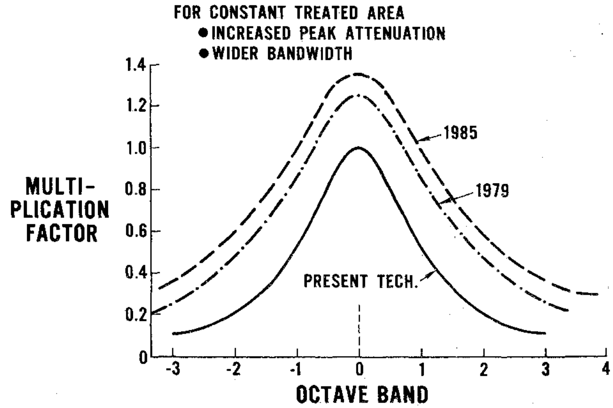

Fig. 4 Assumed improvements in bandwidth and peak attenuation.

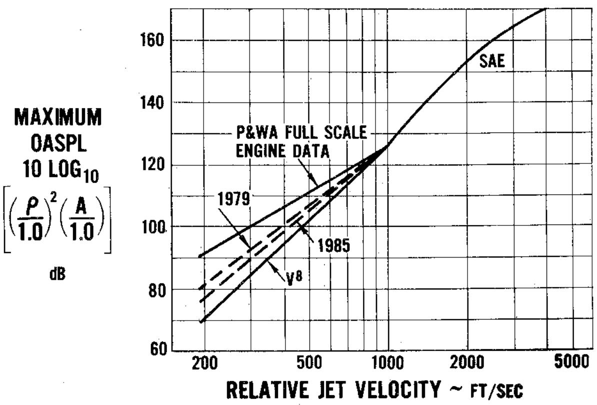

Fig. 5 Jet noise improvement as a function of velocity.

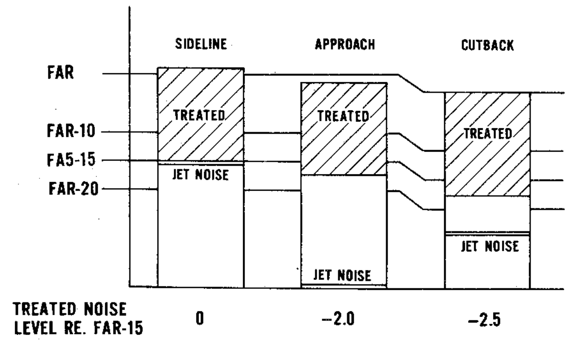

Fig. 7 Estimated noise levels for three STF433 engines.

the single segment approach maintains a constant 6° to the runway.

Increased approach speed will permit the use of lower flap settings which will also reduce noise by lowering approach power setting. This occurs because at reduced approach flap settings, the aircraft lift-drag ratio is improved and, therefore, less thrust is needed to maintain the desired flight path. A 10 knot increase in approach speed, for example, results in a 5 EPNdb reduction in approach noise.

Approach noise can also be reduced by decreasing wing loading (larger wing area). The noise reduction obtained from use of a 10% lower wing loading is approximately 3.5 EPNdb.

Cutback noise can be reduced by using automatic flap retraction after takeoff. The early retraction of flaps after takeoff reduces the thrust required at cutback by improving the aircraft lift-drag ratio. In using early flap retraction the aircraft gains a slightly increased altitude at cut-back but, more importantly, an improved lift-drag ratio. The resulting noise reduction at the 3.5 naut mile noise measuring station is approximately three EPNdb.

A summary of the noise reductions obtained from the use of operational procedures is shown in Fig. 8.

In addition to evaluating the noise reduction properties of acoustic treatment applied to turbofan inlet and discharge ducts, it is also necessary to examine the pressure and friction losses resulting from such treatment and their effect on engine and aircraft performance.

Figure 9 presents relative thrust loss vs bypass ratio for different amounts of acoustic treatment. In terms of relative thrust, the base level is considered to be bare hard wall ducting. When full wall treatment is added to the inlet duct and the aft fan duct, the relative thrust loss is small, about 0.5% at bypass ratio 3 to about 1% at bypass ratio 10. This loss in thrust is due to a small increase in frictional loss from perforated plate rather than hard wall. The lower curve shows the thrust loss when 2 inlet rings and one duct splitter are included in the engine nacelle. The thrust loss at bypass ratio 3 amounts to about 4% and increases to about 7% at bypass ratio 10. Preliminary studies indicate that two inlet rings and one duct splitter in addition to full wall treatment are about the maximum desired from the standpoint of maximizing acoustic suppression while minimizing thrust and SFC losses, both internal and external to the nacelle. The inclusion of additional inlet rings

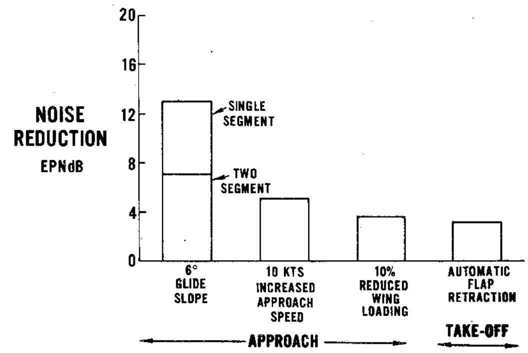

Fig. 8 Noise reduction summary.

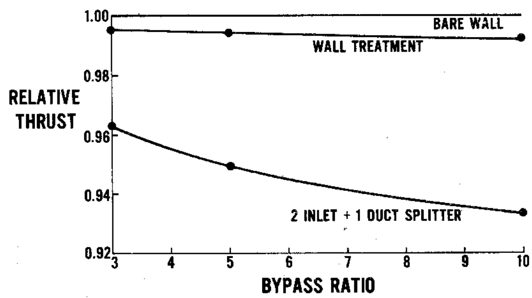

Fig. 9 Thrust loss due to noise treatment.

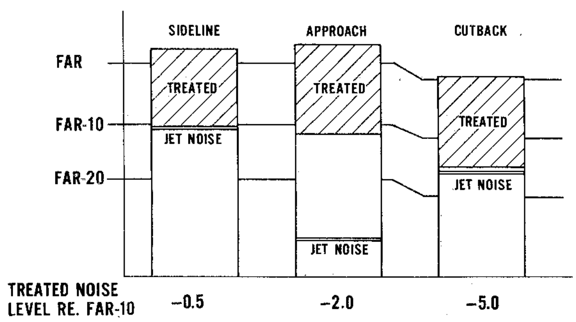

Fig. 6 Estimated noise levels for three STF429 engines.

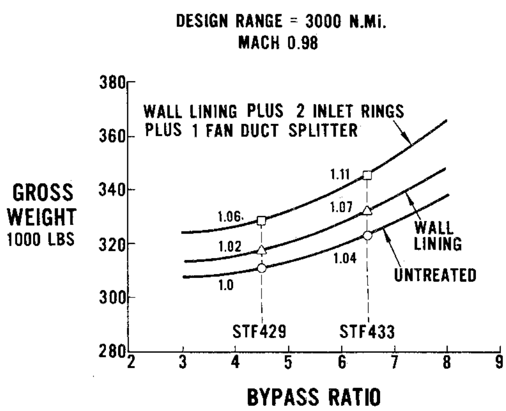

Fig. 10 Gross weight comparison for 3000 naut mile range.

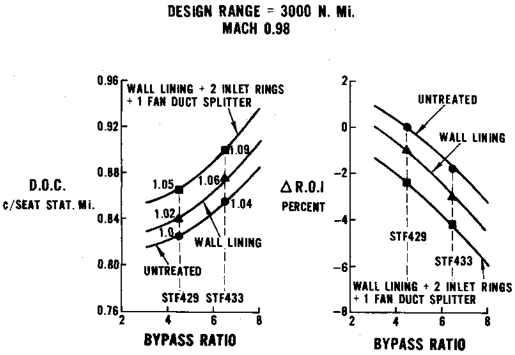

Fig. 11 Economic comparison for 3000 naut mile range.

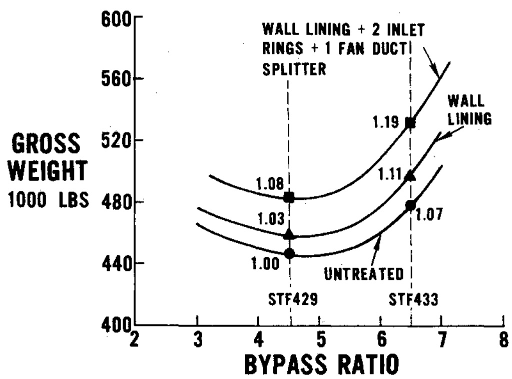

Fig. 12 Gross weight comparison for 5500 naut mile range.

or duct splitters could create a severe blockage penalty with increased Mach numbers in the inlet and fan duct. This could be alleviated by increasing nacelle diameter to allow the Mach number levels to drop to their design values. However, such an increase would increase the weight of the nacelle structure and the surface area of the nacelle and most likely would increase the interference drag penalties on the nacelle.

Systems evaluation results for the STF429 and STF433 engines at the 3000 naut mile design range are shown in Figs. 10 and 11. Three noise treatment configurations were evaluated: an untreated nacelle, an acoustically lined nacelle, and an acoustically lined wall combined with two inlet rings and one fan duct splitter.

For the STF429 engine, the increase in gross weight, direct operating cost (DOC) and reduction in return on investment (ROI) resulting from the use of maximum nacelle acoustic treatment are on the order of 6% in gross weight, 5% in DOC and −2.5Δ% in ROI. The STF433, which is designed for 5 EPNdb lower noise levels than the STF429, incurs further penalties of about 5% in gross weight, 4% in DOC and −2Δ% in ROI.

Table 2 Cycles selected

	1979	1985
Engine designation	STF429	STF433
Bypass ratio	4.5	6.5
Number of fan stages	2	2
Nonmixed flow	yes	yes
Predicted noise levels with treated nacelle	-10db	-15db

Table 3 1985 cycle selection[a]

	Sideline		Approach	
	1-Stage	2-Stage	1-Stage	2-Stage
Fan tip speed, fps	1600	1043	1142	750
Noise, untreated, EPNdb	110.3	106.9	111.9	106.3
Noise, treated, EPNdb	94.6	92.2	96.6	90.5
1-Stage vs 2-Stage, EPNdb	+2.4	–	+6.1	–

[a]Bypass ratio = 6.5, fan pressure ratio = 1.9, 3 engines at 40,000 lb thrust.

A comparison of the STF429 and STF433 engines was also made in the 5500 naut mile design range airplane (Fig. 12). The longer range aircraft is more sensitive to the pressure losses in the inlet and fan exit duct from the addition of acoustic treatment than is the shorter range aircraft. The addition of full acoustic treatment to the STF429 results in a gross weight increase of approximately 8%, a 6% DOC increase and an ROI difference of −3Δ%. To obtain the lower noise of the STF 433 requires additional penalties of 11% gross weight, 10% DOC and −3.5Δ% ROI.

It should be noted that the STF429 and STF433 represent different certification dates and levels of advanced technology. The lines connecting the two engines on Figs. 10–12 are only intended to indicate trends with increasing bypass ratio and decreasing noise. If the STF433 represented 1979 technology rather than 1985, the trends would be even steeper.

Summary

Extensive parametric engine cycle studies were performed to optimize the propulsion system for an Advanced Technology Transport (ATT) planned for commercial operation in the 1980's. The engine cycle selected is a twin spool turbofan with a low tip speed, widely spaced two-stage fan that provides both low noise and optimum cycle performance.

The noise goals established for the ATT study of FAR part 36 minus 10 EPNdb for 1979 commercial service and FAR part 36 minus 15 EPNdb for 1985 can be met with cycles utilizing the low tip speed, spaced two-stage fan in combination with extensive advanced acoustic treatment in the nacelle. Two circumferential acoustic rangs are required in the inlet and one circumferential acoustic splitter is required in the fan exit duct.

However, as evidenced by the gross weight and economic penalties described for the use of inlet rings and a fan duct splitter, it is imperative that advanced technology research programs be directed toward attaining the noise goals with minimum system penalties by reducing the number of or eliminating the inlet rings and fan duct splitter. This should be pursued by research to improve treatment effectiveness and via engine concepts with the lowest possible untreated source noise.

The two-stage fan offers the lowest noise potential with low tip speed and low fan pressure ratio per stage. In addition, optimum cycle performance is obtained by generating the high over-all fan pressure ratio required for low cruise fuel consumption at a low tip speed with a high fan efficiency.

Operating procedures for noise abatement during approach and climb-out after takeoff offer important noise reduction potential. As engine noise is reduced to these low levels, airframe generated noise from extended flaps and landing gear may become controlling.