18. QUIET ENGINE PROGRAM

PRELIMINARY ENGINE DESIGN AND AIRCRAFT INTEGRATION

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SUMMARY

Design studies sponsored by National Aeronautics and Space Administration have resulted in identification of engine cycle characteristics, engine mechanical configurations, and component aerodynamic design parameters which allow turbofan airplane power plants to operate with lower noise output. Preliminary designs of such engines have been made to define the weight and size compromises resulting from design considerations for engine quieting. Engine noise output is predicted to be significantly lower than that produced by currently operating engines. Integration of the quiet engine with a typical subsonic jet transport has been investigated. Study results indicate that useful turbofan engines designed for low noise production are compatible with subsonic jet transport systems.

INTRODUCTION

The acoustic suppression technology reviewed earlier holds great promise of allowing reduction of the turbomachinery noise produced by airplane engines. In addition, the NASA is very interested in quieting engines by minimizing production of noises at their sources.

Design considerations for the quieting of airplane jet engines have been the subject of a NASA study program over the past 2 years. This Quiet Engine Definition Program has been directed toward selection of thermodynamic cycle characteristics and mechanical design features which will produce quiet engines to power subsonic commercial jet transports. An engine would be considered quiet if it produced take-off and landing-approach noise levels on the ground significantly lower, by ≈15 PNdB, than those of the JT3D and JT8D engines. If such noise reductions can be gained through engine design features alone, further reductions through the application of suppressors would produce a truly quiet airplane power plant.

The quiet engine program at the NASA Lewis Research Center began in late 1966 with a study of the effects of high bypass turbofan cycle characteristics on engine jet noise levels, fuel economy, engine size, and airplane payload and range. The quieter engine was known to be most needed for the long-range four-engine airplanes; therefore, compatibility with the Boeing 707 and McDonnell Douglas DC-8 was made an engine design guideline.

Many years of NACA and industry experience in jet-exhaust noise-suppression work have indicated that little reduction in jet noise through the application of mechanical devices such as lobe and tube suppressor nozzles can be expected. Therefore, emphasis was placed on achieving the lowest practicable level of jet noise through proper selection of turbofan-engine cycle parameters. The turbofan engine has the well-known feature of allowing the slowing of average exhaust velocity and, as a result, lowered jet noise production and improved propulsive efficiency.

DISCUSSION

The results of the calculations in determination of turbofan jet noise and physical size as functions of the various cycle characteristics can be plotted on a single map such as that in figure 1. This figure shows the noise produced by the fan and core exhaust streams at take-off power over a range of bypass ratio and fan pressure ratio for a selected combination of turbine temperature ratings and for a fixed overall cycle pressure ratio. The trends in jet noise output and physical size of the engine shown in this figure are indicative of those found at all other chosen temperature and cycle pressure ratio values.

When jet-exhaust noise is reduced through proper application of a high bypass ratio cycle, the fan of the turbofan engine becomes the dominant noise source. Core engine compressor noise and turbine noise must be contended with, but until fan noise is greatly reduced, they do not become dominant. The jet noise levels possible at bypass ratios greater than 4.0 in figure 1 are very low compared with the total noise developed by current engines. If the fan noise can be reduced through design and acoustic suppression to those jet noise levels, a truly quiet power plant will be achieved.

The cycle studies performed at NASA Lewis Research Center provided a field of interesting cycle points around bypass ratio 5.0. More detailed engine configuration studies in cooperation with the turbine engine industry were then initiated. Pratt & Whitney Division of United Aircraft Corporation was contracted (Contract no. NAS3-10497) under the Quiet Engine Definition Program in July of 1967 and began a parametric study of engine performance, size, weight, and jet and fan noise output for turbofan engines covering the following range of cycle characteristics:

Cruise thrust, lb	4900
Take-off thrust, lb	20 000 to 25 000
Bypass ratio	3 to 8
Fan pressure ratio	1.3 to 1.7
Compressor pressure ratio	15 to 30
Turbine inlet temperature, cruise, $^{\circ}F$	1600 to 2100
Turbine inlet temperature, take-off, $^{\circ}F$	1600 to 2300

The results of this study provided no clearly best choice for a quiet engine cycle, but indicated that potentially attractive engines were possible at any bypass ratio between 3.0 and 8.0.

Selected sets of engine parameters were given to Pratt & Whitney and to a second definition program contractor (Contract no. NAS3-10496), the Allison Division of General Motors, for the preliminary design phase of this program. These seven sets of engine characteristics are shown in table I. Designs of these engines were done in such detail that those considerations in mechanical arrangement, flow-path configuration, and component design which would lead to selection of a single quiet engine candidate could be identified for a more detailed design analysis.

The seven preliminary designs provided good basis for comparison of several engine mechanical design features and their influence on size, weight, and predicted noise output of the engines. Air flow-path considerations, mechanical arrangement, and component operating problems were identified for two- and three-spool engines, for one- and two-fan stages, and even for the unconventional concept of counterrotating fan stages.

Throughout these preliminary designs, the presently known design features for fan quieting were applied. Fan inlet guide vanes were avoided. Fan mechanical speeds giving subsonic blade relative velocities were maintained. Fan rotor-to-stator spacing was made as great as practically feasible. No detailed fan aerodynamic designs were made in these preliminary studies; thus, only the major effects of fan slowing and spacing were investigated.

Schematic arrangements of the resulting designs for the four engines at bypass ratio 5.0 are shown in figures 2 to 5. The predicted noise levels quoted in these figures are peak values for a four-engine airplane at take-off power during a flyover at an altitude of 1000 feet and for approach power at an altitude of 300 feet. The corresponding total noise and 118 and 100 PNdB on approach. None of these noise levels assume the use of acoustic suppression materials in the engine nacelles.

Comparison of the characteristics of these bypass ratio 5.0 engines reveals these facts about the fan configurations studied:

(1) A two-stage fan, properly spaced out for noise purposes, causes an engine to be very long and heavy.

(2) Based upon the fan noise prediction techniques available today, a two-stage fan would be somewhat noisier than its single-stage equivalent.

The second point mentioned is very important to the development of a quiet turbofan engine. Both contractors agreed in their noise predictions (and NASA has found no data to dispute them) that the two-stage fan must be at least 3 decibels noisier than a single-stage fan without inlet guide vanes. The point in question is the influence that the level of aerodynamic loading has on the noise output of a blade now, since each stage of the two-stage fan can be more lightly loaded than a single-stage fan which does the same work. At this time it is predicted that the quietest fan will be a single-stage fan.

The counterrotating two-stage fan has been dropped from further immediate consideration because considerable development time and effort would be required to supply the aerodynamic design data needed for incorporation of such a fan into an operating engine system.

The two-stage fan noise and weight penalty considerations tend to rule out an engine lower in bypass ratio than about 5.0 as a candidate for a quiet engine. The turbofan cycle energy balance causes low bypass ratio to optimize with higher fan pressure ratio, both for low jet noise and for best fuel economy. A single-stage fan cannot be designed to produce a high fan pressure ratio greater than about 1.60, particularly when mechanical speed of the fan rotor is being kept low for noise reasons. The quiet engine should have a bypass ratio somewhat greater than 5.0, therefore, to give near-optimum cycle performance with the single-stage fan and to gain the jet-exhaust velocity and jet-noise reductions attainable with the higher bypass ratio.

Engines of higher than 6.0 bypass ratio were dropped from consideration in this engine definition program because of installation and noise output considerations. The fans of very high bypass engines must be very large, as can be seen in figure 1, so that installation under the wings of the current four-engine jet transports would be difficult and integration into new airplane designs would be a severe problem. Also, the aerodynamic drag penalty associated with the large nacelle body housing of such an engine tends to counterbalance the fuel economy advantages of higher bypass ratio. Secondly, the study results for Pratt & Whitney engine C indicated very little jet and fan noise improvement for an 8.0-bypass-ratio engine compared with that for the 5.0-bypass-ratio engine with a single-stage fan.

Another consideration in choice of mechanical configuration developed from our design studies for the several engines. It became apparent that the most desirable spool arrangement for a quiet engine would be one which isolated the fan, apart from any compressor stages, on the low pressure rotor. The fan drive turbine is compromised in work output per stage and in stage efficiency because of the low rotational speed imposed by fan speed limitations for noise reasons. If the low turbine is made to produce only the work required by the fan and no core engine compressor work, the engine benefits in size, weight, and performance. Isolation of the fan spool also allows modification of the aerodynamic design of the fan, to slow it down or speed it up, or even to change its size and bypass ratio, independently of the core engine. Major changes in core compressor and turbine design need not be made with each modification in fan design as an engine is developed aerodynamically, mechanically, and acoustically.

On the basis of these considerations, it was determined that the engines to be designed in more detail under our definition program would have a bypass ratio between 5.0 and 6.0, would use a single-stage fan operating at low speed on an isolated rotor spool, and would incorporate the rotor-to-stator spacings found feasible in the preliminary designs. Specific descriptions of the two engines resulting from the subsequent design work are included in reference 1.

NASA has required that the selection of quiet engine cycle characteristics, mechanical arrangement, and component designs be made with minimum noise output as a major constraint. It has been apparent from the start that design for attainment of low noise output will unfavorably affect the engine in size, weight, and perhaps, performance. Sacrifices in these areas are inevitable when the fan is limited in speed, the blade rows are spaced out, and turbine inlet temperatures are limited on take-off because of noise considerations. On the other hand, the engine resulting from these studies is intended to be an operational and completely usable power plant for subsonic jet transports. In order that the goal of airframe compatibility might be upheld and that the question of the possibility of quiet engine "retrofit" on today's airliners might be answered, NASA initiated an engine/airframe integration study program with Douglas Aircraft Company (Contract no. NAS3-11151). This program parallels the engine definition program; thus, installation considerations can be used in engine selection decisions.

The Douglas program began in January of this year. The first task in that study provided preliminary nacelle and pylon design for installation of a single-stage-fan version of a 5.0-bypass-ratio quiet engine on the DC-8 model 61. Fan-inlet and fan-discharge duct suppressors were included in the nacelle design so that realistic installed-engine weights and dimensions for a very quiet power plant would be maintained. Figure 6 shows the resulting installation on the inboard position of the DC-8 wing. The study ascertained that engine integration was possible, that ground clearance was adequate, and that no modifications to the airframe would be required for installation of an engine of this size and weight.

The second task in the Douglas program involved analytical determination of performance of the DC-8 with this preliminary engine and comparison with the present airplane configuration. Some results of this performance study follow:

Weight increase of 6720 lb per airplane

1800-foot shorter take-off field length

No cruise Mach number decrement

400-mile better range at volume-limited payload

2000-foot higher initial cruise altitude

Minimum retrofit cost ≈ 4 million dollars

It is a heartening fact that no serious compromises in airplane performance result from replacing the current DC-8 power plant with the larger and heavier quiet engine. Indeed, general improvement is expected in range, take-off distance, and initial cruise altitude. The economics of engine retrofit however are formidable. The replacement of four engines, nacelles, and pylons will cost at least $4 000 000.

Subsequent tasks in the integration program involve determination of detailed performance and retrofit information for the final selected engine configuration from the engine definition program. Aerodynamic model tests are being conducted with the DC-8 quiet engine configuration in the Ames 12-foot-high Reynolds number tunnel and the Ames 11-foot transonic tunnel. Flutter tests are being performed to determine whether wing structural modifications would be required because of aeroelastic limitations. Detailed costs of nacelle and pylon retrofit kits and the costs of retrofit labor and out-of-service time are being determined. Operating costs for the airplane with quiet engines are being predicted.

CONCLUDING REMARKS

Nothing to date in the engine definition and engine integration studies has indicated that the goal of producing an engine system which can be both significantly quieter in operation than current turbofan engines and completely compatible with subsonic transport airplane systems is being compromised.

REFERENCE

1. Kramer, James J.: Quiet Engine Program - Detailed Engine Designs. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 19 herein.)

TABLE I

PRELIMINARY ENGINE DESIGNS

	ALLISO			PRATT AND WHITNEY			
	A	B	C	A	B	C	D
BYPASS RATIO	3	5	5	3	5	8	5
FAN PRESSURE RATIO	1.7	1.5	1.5	1.7	1.6	1.35	1.6
ENGINE SPOOLS	3	3	3	2	3	2	3
FAN STAGES	2	2	1	2	2	1	2
				(COUNTER-ROTATING			

SIDELINE TAKE-OFF JET NOISE

NOISE FOR 4 ENGINES SIZED FOR 4900 lb CRUISE THRUST

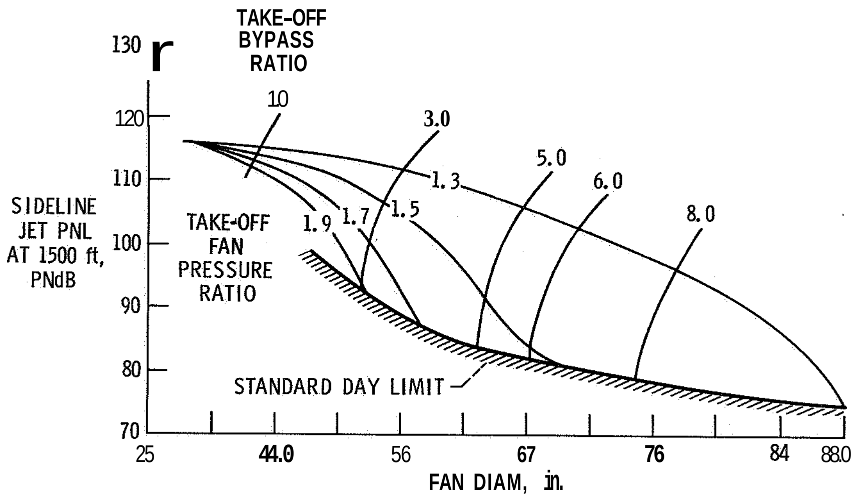

Figure 1

ALLISON "B" BYPASS RATIO 5.0

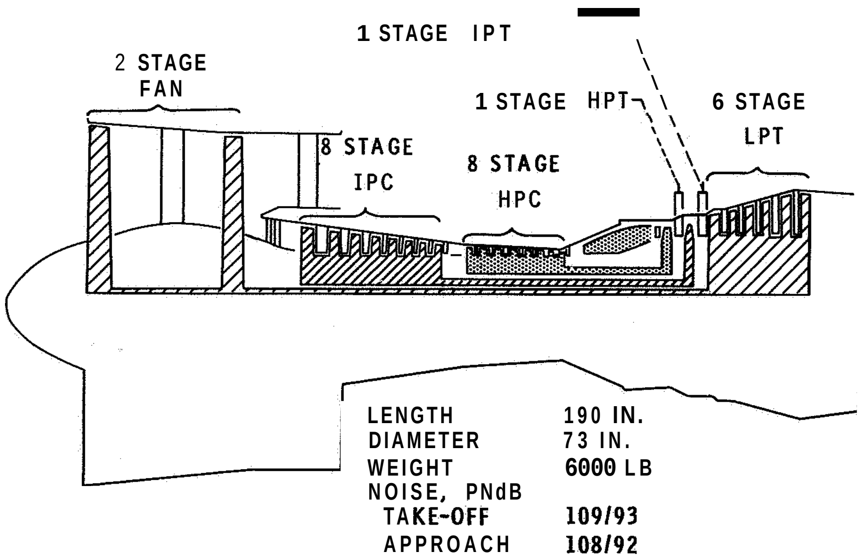

Figure 2

ALLISON "C" BYPASS RATIO 5.0

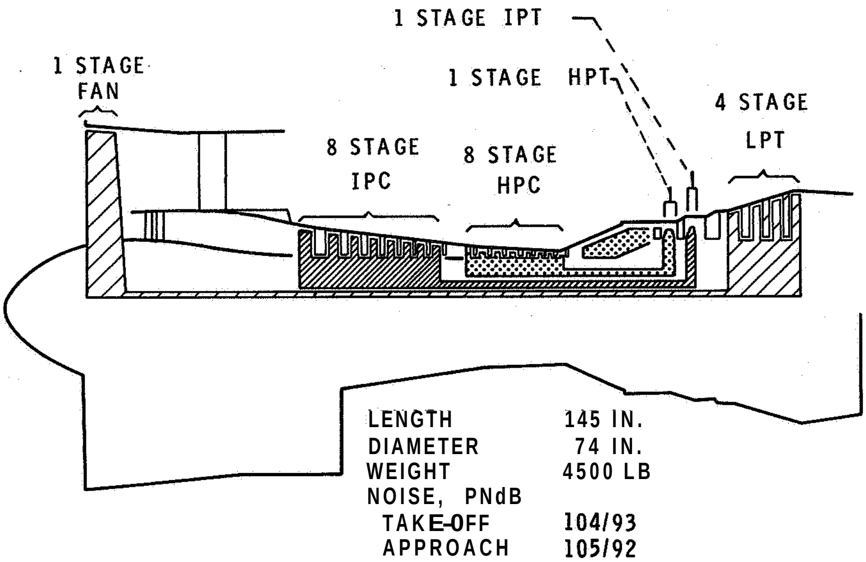

Figure 3

PRATT AND WHITNEY "B" BYPASS RATIO 5.0

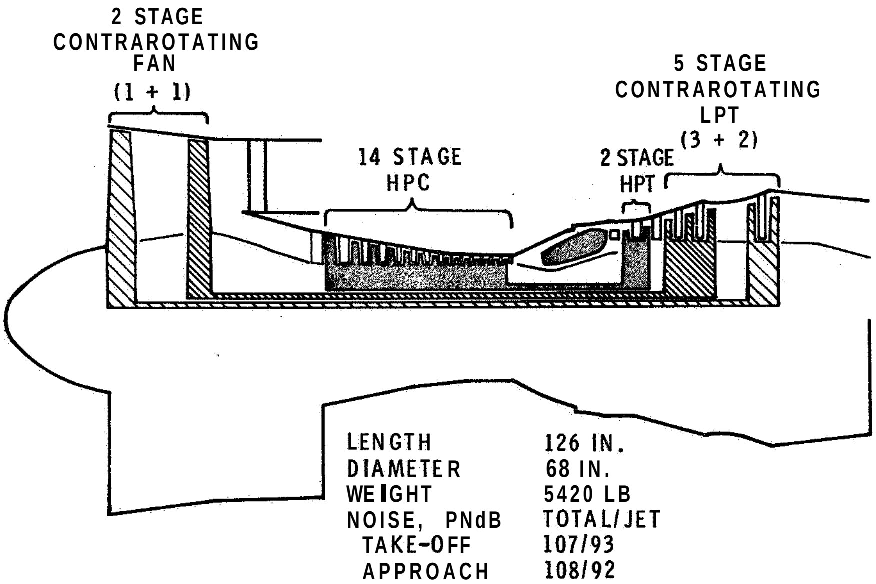

Figure 4

PRATT AND WHITNEY "D" BYPASS RATIO 5.0

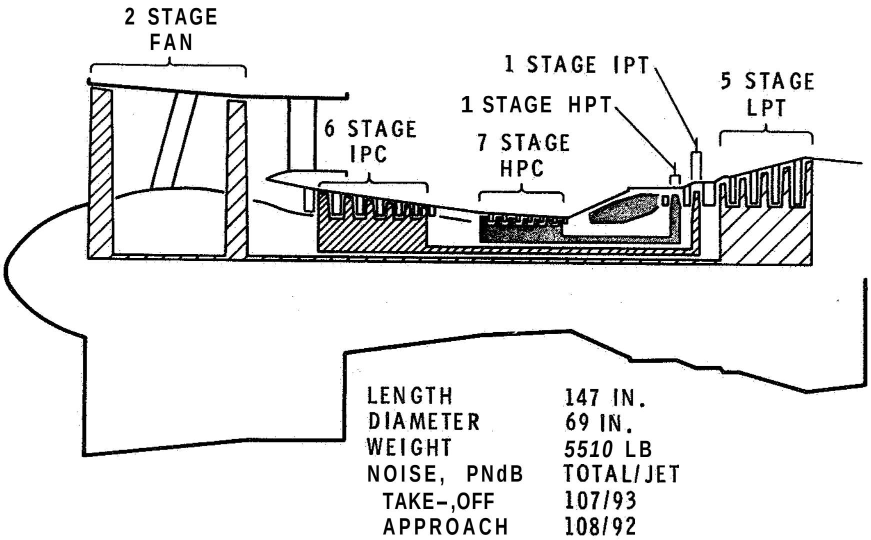

Figure 5

DC-8-61 QUIET ENGINE NACELLE

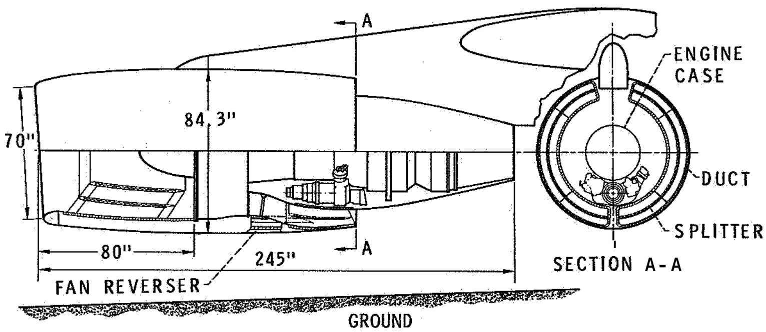

Figure 6