9. DESIGN CONCEPTS

By Robert E. Pendley

McDonnell Douglas Corporation

SUMMARY

Engineering design studies were made of alternate approaches to the reduction of noise radiating from the fan section of the Pratt & Whitney Aircraft (P & WA) JT3D engines as installed in McDonnell Douglas DC-8 airplanes with short-duct nacelles. The basic approach studied was to install acoustically absorptive duct linings in the fan inlet and exhaust ducts. A brief investigation was also made of another approach involving the reduction of fan rotational speed at landing thrust by varying the area of the primary exhaust nozzle.

The studies generated several concepts for acoustically treated duct designs for which flyover-noise estimates indicated that the landing approach noise could be reduced approximately 7 to 10 PNdB. Overall evaluation of the results of the design concept studies led to a selection of two treated inlet configurations and one exhaust duct configuration for evaluation in the succeeding ground-test phase of the program. The two inlet configurations incorporated acoustically absorptive linings – (1) on the walls of the cowl and standard center body and on two concentric ring vanes and (2) on the walls of the cowl and an enlarged center body and on one ring vane. The selected fan-exhaust-system design provided acoustical linings in an exhaust duct **24** inches longer than the existing ducts. This design is compatible with the existing primary thrust reversers, but requires a new fan-thrust-reverser design.

Acoustical and engine performance data were measured during JT3D tests with a simulation of the variable-area primary-nozzle concept for fan-speed control. The data obtained indicated that the fan-speed concept could not provide a significant reduction of JT3D flyover noise.

INTRODUCTION

The initial study phase of the McDonnell Douglas Corporation part in the NASA treated-nacelle program required engineering design studies of alternate approaches to the reduction of blade-passage-frequency noise radiated from the fan section of the JT3D engine. The goals and constraints applicable to the approaches are discussed in reference **1.** The designs were to produce substantial reductions in landing-approach noise levels, with no increase in take-off noise. It was required that evaluation of the designs be performed, with consideration given to acoustical effectiveness and effects on airplane and engine performance. At the conclusion of these studies, designs were to be selected for investigation in the succeeding ground-test phase of the program.

The purpose of this paper is to summarize the work performed in carrying out the above tasks. It includes a discussion of the method by which candidate designs were evolved, general descriptions of representative configurations studied, and a discussion of the evaluations performed. The studies were basically concerned with the application of acoustical-lining technology (discussed in ref. 2) to the fan inlet and exhaust ducts. However, another concept was investigated briefly. This concept was intended to reduce the fan speed required for a given landing thrust by controlling the primary-nozzle area. The studies of both concepts are discussed herein.

SYMBOLS

A_{ns}	area of noise source taken as projected annular area of fan inlet or exit, square feet
A_t	treated (acoustically lined) surface area of ducts, square feet
F_g	engine gross thrust, pounds
h	height of duct channel separating acoustically lined surfaces (subscripts 1 and 2 used to denote different regions of inlet duct), feet
N_1	fan rotational speed, rpm
APNL	reduction of perceived-noise level, PNdB
δ_{amb}	ratio of ambient pressure to standard-day sea-level atmospheric pressure
λ	wavelength of sound, feet
θ_{t_2}	ratio of inlet absolute total temperature to standard-day sea-level atmospheric temperature

DISCUSSION

Preliminary Considerations

One of the important constraints of the study was that the nacelle modifications investigated be applicable to the installation of the Pratt & Whitney Aircraft (P & WA)

JT3D engine in the short-duct nacelles of the McDonnell Douglas DC-8 airplane. These nacelles are illustrated in figures 1 and 2.

The fan air-inlet ducts of these nacelles are provided with relatively thick inlet lips to produce high inlet pressure recovery (and therefore thrust) at take-off conditions. (See fig. 1.) As a result, a substantial volume exists between the inlet duct skins and the exterior nose-cowl skins. This volume is utilized for the installation of oil and pneumatic-system heat exchangers, the nose-cowl ice-protection system, and related piping, valves, and ducting. The auxiliary inlet directly beneath the inlet lower lip admits cooling air to the oil and pneumatic-system heat exchangers.

Figure 2 shows the exhaust nozzle of the short fan-exhaust duct, the primary exhaust nozzle, and fan and primary thrust reverser components in the normally retracted (forward thrust) position. The duct splitters indicated extend through the full length of the exhaust duct, and thus divide each exhaust duct into separate channels.

In order to minimize the cost of incorporating noise-suppression features within the nacelle, design solutions were sought that would require the fewest changes to existing nacelle components. Thus, efforts were made to incorporate suppression features without affecting the nacelle components previously mentioned, as well as the equipment between the exhaust duct and the engine case, the pylons, and the mechanical and subsystem interfaces between the nacelles and pylons.

The first step in the study was the definition of the separate reductions required in the noise propagating through the fan inlet and exhaust ducts. A study of available ground- and flight-test data indicated that the landing-approach peak flyover perceived noise from JT3D engines was due to the noise radiated from the fan exhaust and that the peak perceived noise radiated from the fan inlet was approximately 3 PNdB lower. It was therefore considered that achievement of the study goals would require a 10-PNdB reduction of noise from the fan exhaust duct and a 7-PNdB reduction of noise from the inlet.

Next, an estimate was made of the acoustical-lining area A_t needed to accomplish the required noise suppression within the inlet and exhaust ducts. Existing duct-transmission-loss data obtained in the laboratory (ref. 3), together with the meager data previously obtained from flyover-noise tests with treated fan ducts (ref. 4), were used to prepare figure 3. In this figure, the noise-source area A_{ns} is taken as the annular area of the fan inlet or exit, the channel height h is the distance separating acoustically lined duct surfaces, the wavelength λ used is that corresponding to the frequency for which maximum attenuation is desired, and the noise suppression APNL represents the amount of reduction predicted for low altitudes during landing approach.

Figure 3 does not account for a number of factors that may be important, such as the intensity and distribution of noise within the duct, the shape or orientation of lining surfaces with respect to the noise source, and the possible effect of the duct configuration on the far-field noise distribution. The use of this figure in estimating the potential noise suppression of alternative design concepts was tempered by recognition of, and allowance for, these qualifications.

Figure 3 indicates that the duct channel height is an important variable. Economy in the required lining area can be achieved if the linings can be installed with relatively small channel heights between facing surfaces, although care must then be taken to minimize aerodynamic losses.

Inlet-Duct Concepts

Design. - The first consideration of inlet-noise suppression dealt with the installation of linings on the existing surfaces of the inlet duct and engine center body, as symbolically indicated by the heavy lines in figure 4. On the basis of figure 3, it was predicted that this design concept would fall short of the inlet noise-suppression requirement because of the limited area treated and the unfavorably large channel heights separating the lining surfaces.

During the landing approach, the fundamental blade-passage frequency (the component of the noise that controls the landing perceived-noise level) is about 2500 Hz. The wavelength of the sound waves at this frequency is about 0.47 foot (about 5.5 inches). The annular area of the fan inlet is about 12 square feet. In the region of the center body (where $h = h_1 \approx 18$ inches ≈ 1.5 feet) (see fig. 4), the ratio h/h would be about 3.3, and the treated area required for 7 PNdB (see fig. 3) would be about 25 times 12 or about 300 square feet. In the cowl region ahead of the center body (where $h = h_2 \approx 50$ inches), the ratio h/X is about 9 and the treated area would be about 700 square feet. Since both of these treated-area requirements are far in excess of the inlet-duct and center-body surface areas, concepts were developed to incorporate the required treated area within narrower channels with more effective values of h/λ.

Two such inlet-duct concepts are illustrated in figure 5. The installation of concentric ring vanes with acoustical linings on each of their sides simultaneously increases the lining area and reduces the channel height. Similarly, the installation of radial vanes with linings on each side of the vanes increases the lining area functioning at smaller channel heights. In this inlet configuration, the channel height corresponds to the circumferential distance between adjacent vanes.

The "light-bulb" inlet illustrated in figure 6 is another concept providing more lining area at reduced channel heights. These objectives are accomplished by enlargement of the acoustically lined center body. The cowl wall must be displaced outward in order to provide sufficient flow area at the center-body maximum-diameter station. The axial distance from this station to the inlet lip and to the fan inlet must be made sufficiently large to prevent excessive curvature to the cowl wall and the downstream center-body surface. The minimum length of the cowl is thus determined by these aerodynamic shaping requirements. Concentric ring vanes can also be incorporated in the light-bulb inlet concept.

The design illustrated in the right-hand side of figure 6 is one of the retractable lining concepts investigated. Under conditions when noise suppression is not required, the acoustically lined surfaces would be retracted from the aerodynamic flow path, as illustrated by the position of the lined surfaces in the lower part of the sketch. With the linings stowed in this manner, inlet total-pressure (and engine performance) losses, arising from the aerodynamic flow over linings, vanes, or supporting struts, are avoided. When noise suppression is required, the lined surfaces are deployed as illustrated in the upper part of the sketch. The linings are installed on a number of segmented flaps located around the entire periphery of the inlet cowl.

Evaluation.- In evaluating the four concepts shown in figures 5 and 6, it was found that the radial-vane concept offered no advantages in estimated weight or engine performance relative to the two-concentric-ring concept. In addition, the wakes from the radial vanes could be chopped by the fan rotor blades in such a way as to increase the noise that must be absorbed by the treated surfaces in the inlet or exhaust ducts. For these reasons, the radial-vane concept was dropped from further study.

An evaluation of the three remaining configurations is summarized in tables I and 11, where the changes tabulated are those estimated relative to the existing nacelles in service.

As indicated in table I, 73.0 square feet of lining area was made available in the two-concentric-ring configuration within the present cowl length. It was estimated that the design could exceed the inlet-noise-suppression requirement of 7 PNdB.

The light-bulb inlet design required an increase in cowl length of 21 inches, owing to the internal aerodynamic shaping requirements mentioned previously. With acoustical linings installed on the internal surfaces and on the concentric ring, 100.5 square feet of lining surface was provided. The incremental nacelle weight was twice that of the two-ring inlet configuration. It was estimated that the design might provide 2 to 4 PNdB more noise reduction than the two-ring design.

The retractable lining design was typical of the other designs of this type that were studied in that only limited lining areas could be provided without substantial increases in cowl length and weight. The large change in weight resulted from the actuating mechanisms and the complicated cowl structure. As table I indicates, the particular retractable concept discussed herein was expected to fall short of the required inlet-noise reduction of 7 PNdB.

The three inlet designs would affect the drag, specific fuel consumption, airplane empty weight, and depreciation and maintenance expense, each to a different degree. The net effect of the changes in these variables is accounted for by an estimated increment in direct operating cost (DOC) as presented in table II. These increments were calculated by using simple change factors that relate changes in operating cost elements to independent changes in drag, specific fuel consumption, and weight.

As table II indicates, the DOC would be increased the least by the two-concentric-ring inlet design. The DOC increment due to the light-bulb inlet design was substantially higher than that of the two-concentric-ring inlet because of its higher predicted weight, drag, and duct total-pressure loss. The retractable lining design would result in the highest DOC increment of the three inlets. Although this design does not have the cruise-fuel-consumption increase associated with linings in the inlet-duct aerodynamic flow path, the additional weight more than eliminated this benefit.

In view of the disproportionate relationship between the estimated DOC increments and noise reductions of the retractable lining concept, this concept was not investigated beyond the initial study phase. Of the remaining two concepts, the two-ring inlet was preferred since it was estimated that the required noise reduction could be achieved with the least DOC increment. However, since the reliability of the methods used to estimate noise reduction had not been validated, it was judged unwise to continue the program into the ground-test phase with only the two-ring inlet design. The light-bulb inlet design was believed to offer added assurance of achieving the inlet-noise-reduction goal; therefore, both the two-ring and light-bulb designs were selected for ground testing. In selecting the two-ring design, the possibility of achieving the required inlet-noise suppression with only one of the two rings installed was recognized. It was therefore required that the ground-test inlet be designed to permit testing with the inner ring removed.

Fan-Exhaust-Duct Concepts

Design.- The first approach studied for the suppression of fan noise was that of installing acoustical linings within the internal surfaces of the existing short-duct configuration. The design provided linings on the inner and outer duct walls and on each side of each of the four splitters in each duct. The treatment on the splitters would be similar to that on the ring vanes in the two-ring inlet or the light-bulb inlet, and would require splitters about 1 inch thick. In order to compensate for the duct area blocked by the thicker splitters, the inner and outer wall contours were expanded. The expansion resulted in an aerodynamically undesirable increase in local wall curvature and an acoustically undesirable increase in channel height. However, the exhaust nozzle outlet was unchanged in shape and, therefore, no change was required to the existing fan thrust reversers or external aerodynamic profiles. (See fig. 2.) It was estimated that a total of 34.7 square feet of linings could be provided within the exhaust ducts of each nacelle.

However, on the basis of figure 3, the design would fall short of the desired noise reduction. Acoustically more effective designs were therefore investigated.

Figure 7 illustrates a concept in which the 34.7 square feet of duct linings within the existing short-duct configuration are supplemented by an additional 17.3 square 'feet of lining area on two retractable side panels. These panels would normally be stowed flush with the external contours in recesses on the cowl sides forward of the fan exhaust nozzle. When noise suppression is required, they would be translated rearward on a track-and-roller system to the position indicated in the top sketch of figure 7. In this position, additional noise reduction would be accomplished by the absorptive linings on the inside surfaces of the side panels. The panels conformed approximately to the curved shape of the fan discharge jets but they are positioned sufficiently outboard to permit a flow of free-stream air between the panels and the discharge jets.

It would be necessary that the panels be retracted before the fan thrust reversers are actuated. (See fig. 7.) An interlock system would be provided to prevent the inadvertent simultaneous extension of side panels and fan reversers.

Although the side-panel concept was compatible with the continued use of much of the existing nacelle components, it would require the development of a new actuation-and-control subsystem. A comparative study was therefore made of the design illustrated in figure 8. The exhaust ducts were lengthened to provide, internally, the estimated lining area required to meet the noise-reduction goal. The overall exhaust-duct length was increased from 24 inches to 48 inches. The average duct channel height was decreased from 8 inches to 6 inches. Linings would be installed in the inner and outer duct walls and on each side of the splitters.

The existing fan thrust reversers cannot be used with this concept because of the diminished space between the engine case and the nacelle contour immediately downstream from the fan exhaust. A target-type thrust reverser consisting of a single pivoting bucket on each side of the nacelle could be accommodated within this area, however. Although this type of fan reverser is not as effective as the existing cascade reverser, it can provide an overall reverse-thrust effectiveness equal to that of other airplanes known to have satisfactory reverse-thrust levels. The existing primary thrust reversers can be used unchanged with this design.

Evaluation. - Some basic characteristics of the two exhaust systems studied are compared in table 111. Although the configuration with the treated short ducts and retractable side panels would increase the nacelle weight by 200 pounds, the 48-inch exhaust-duct design would result in a weight reduction. This result is due to the lower weight estimated for the simpler target-type thrust reverser relative to the weight of the existing cascade reverser. The weight saving in the thrust reversers exceeds the weight increment of the treated 48-inch ducts relative to the existing 24-inch ducts. As table 111 indicates, more lining area was provided and a higher probability of achieving the noise-suppression goals was estimated for the 48-inch ducts.

The net effect of the two designs on the estimated direct operating cost is indicated in table IV, which shows a smaller estimated DOC increment for the 48-inch duct design than for the 24-inch duct design. However, the initial retrofit cost would be somewhat higher for the 48-inch duct design than for the 24-inch duct design. Although the 48-inch design does not require development of side panels and their actuating mechanism, it requires a new thrust-reverser development and more change to the nacelle components located between the existing fan-exhaust ducts and the engine case. On the other hand, the 48-inch ducts have less wall curvature and a more favorable flow area distribution than the 24-inch ducts. The effects of these factors, together with the effect of the lighter weight of the design, leads to lower estimated maintenance and fuel costs. These savings were sufficient to offset the increased depreciation due to higher retrofit cost.

The discussion of table III indicates that the target type of fan thrust reverser for the 48-inch exhaust-duct concept results in a substantial weight saving relative to the existing fan thrust reversers. Although the lighter reversers are also compatible with the components in the 24-inch exhaust-duct concept, this reverser design (with its associated weight benefit) was not applied to the 24-inch duct concept. The reason for not using the simple reverser is that the DOC increment would become even less favorable for this concept because there would be an increased depreciation resulting from the target-type reverser that would more than offset the airplane performance improvements resulting from the lighter nacelle weight.

In view of the superior noise reduction and DOC effects estimated for the 48-inch duct design, this concept was selected for testing in the succeeding ground-test phase of the program. (See ref. 5.)

Fan-Speed Control

The concept of controlling the relative speeds of the two rotors of the JTSD engine was investigated to determine its potential for noise reduction. The concept provided for in-flight reduction of the primary-nozzle exhaust area, which reduces the pressure drop across the fan-drive turbine. As a result, at any given level of landing thrust, less power would be available for the low-pressure rotor, and the rotational speed of the fan stages would be decreased while the primary thrust and the exhaust velocity would be increased. The possibility of a net reduction in perceived-noise level would depend on the relative magnitudes of the reduction in discrete-frequency noise from the fan and the increase in broadband noise from the primary jet exhaust.

Three conical primary nozzles of 50, 60, and 80 percent of normal discharge area were tested on the JT3D-3 engine. The test results (fig. 9) show that the concept was successful in the sense that, for a given gross thrust, a substantial reduction in fan speed was realized by the reduction of primary nozzle area. Although the maximum available thrust permitted by engine operating limits would be reduced for operations at reduced nozzle area, sufficient thrust would be available to meet steady-state landing-approach thrust requirements (approximately 4000 to 5500 pounds per engine) at nozzle areas as low as 50 percent of standard. Far-field noise measurements, however, indicated that, for a given thrust, the reductions in fan noise were largely offset by the increased jet noise. It thus appeared that the concept offered little promise, and its investigation was terminated.

CONCLUDING REMARKS

The results of the investigation of design concepts in the initial study phase are summarized as follows:

1. Design concepts based on the installation of acoustically absorptive materials in the fan inlet and exhaust ducts of a JT3D nacelle were studied. It was estimated that several of the concepts could lead to a reduction in flyover noise beneath the landing approach path of 7 to 10 PNdB. These concepts had varying effects on direct operating costs.

2. An inlet configuration with acoustical linings on the duct and center-body walls and on two concentric ring vanes appeared to be the most promising of the inlet concepts studied. Analysis of this configuration indicated that it could achieve the inlet-noise reduction required with the least effect on airplane direct operating costs.

3. It was estimated that the exhaust-duct noise-reduction goal could not be met by the application of acoustical linings to the exhaust-duct surfaces within the existing short-duct nacelle configuration. Of the alternative designs studied that provided the required additional lining area, the most promising design was the one in which acoustical linings were installed on the walls and splitters of an exhaust duct 24 inches longer than the existing ducts. The design was compatible with the existing primary thrust reversers, but it required a new fan-thrust-reverser design.

4. The concept of reducing the fan rotational speed by reducing the primary-nozzle area was found to be incapable of providing significant noise reduction.

5. Two inlet designs and a lengthened exhaust duct design, all incorporating acoustical linings on their internal surfaces, were selected for tests in the succeeding ground-test phase.

REFERENCES

1. Norton, Harry T., Jr.: Introductory Remarks on Nacelle Acoustic Treatment Application. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 8 herein.)
2. Mangiarotty, R. A.; Marsh, Alan H.; and Feder, Ernest: Duct-Lining Materials and Concepts. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 5 herein.)
3. Marsh, Alan H.; Elias, I.; Hoehne, J. C.; and Frasca, R. L.: A Study of Turbofan-Engine Compressor-Noise-Suppression Techniques. NASA CR-1056, 1968.
4. Pendley, Robert E.; and Marsh, Alan H.: Turbofan-Engine Noise Suppression. J. Aircraft, vol. 5, no. 3, May-June 1968, pp. 215-220.
5. Marsh, Alan H.; Zwieback, E. L.; and Thompson, J. D.: Ground-Runup Tests of Acoustically Treated Inlets and Fan Ducts. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 10 herein.)

TABLE I

INLET EVALUATION

BASIC CHARACTERISTICS

CONFIGURATION	CHANGES PER-NACELLE			
	LENGTH, in.	WEIGHT, lb	LINING AREA, ft^2	A PNL PNdB
TWO CONCENTRIC RINGS	0	150	73.0	9 TO 11
LIGHT BULB	21	300	100.5	11 TO 13
RETRACTABLE LININGS	6	440	53.0	3 TO 5

TABLE II

ESTIMATED DIRECT OPERATING COST INCREMENTS

INLETS

CONFIGURATION	ΔDOC, PERCENT
TWO-CONCENTRIC RINGS	1.2
LIGHT BULB	1.7
RETRACTABLE LININGS	2.0

TABLE III

EXHAUST SYSTEM EVALUATION

BASIC CHARACTERISTICS

CONFIGURATION	CHANGES PER NACELLE			
	DUCT LENGTH, in.	WEIGHT, lb	LINING AREA, ft^2	APNL, PNdB
24-in. EXHAUST DUCT AND SIDE PANELS	0	200	52.0	6 TO 9
48-in. EXHAUST DUCT	24	-105	70.5	8 TO 11

TABLE IV

ESTIMATED DIRECT OPERATING COST INCREMENTS

FAN EXHAUSTS

CONFIGURATION	Δ DOC, PERCENT
24-in. EXHAUST DUCT AND SIDE PANELS	1.5
48-in. EXHAUST DUCT	1.3

MODEL DC-8 SHORT DUCT NACELLE
THREE-QUARTER FRONT VIEW

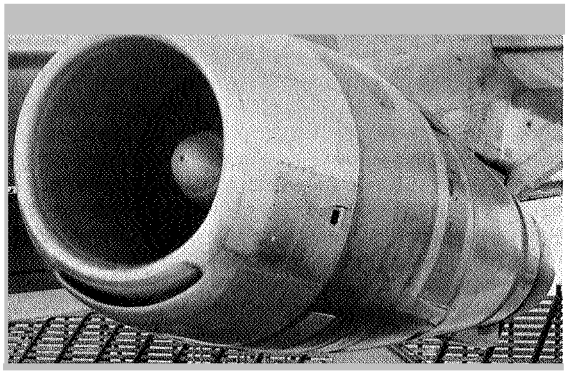

Figure 1 L-68-8557

MODEL DC-8 SHORT DUCT NACELLE
THREE - QUARTER REAR VIEW

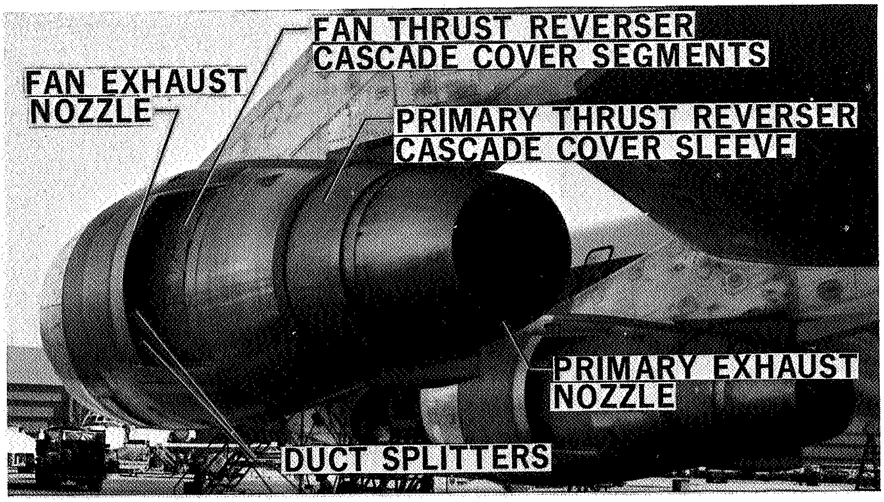

Figure 2 L-68-8558.1

ESTIMATED DUCT-LINING AREA REQUIREMENT

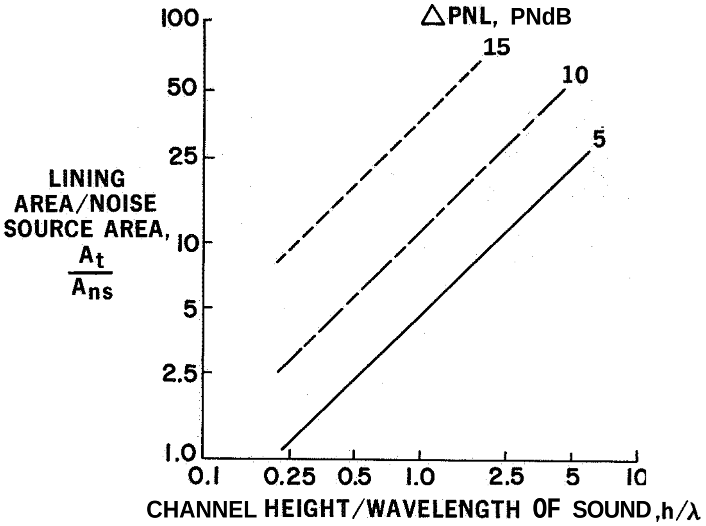

Figure 3

LINING INSTALLATION IN EXISTING INLET DESIGN

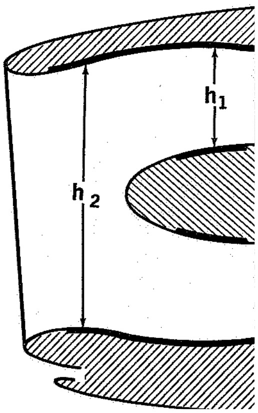

Figure 4

INLET CONFIGURATIONS STUDIED

TYPES OF VANES

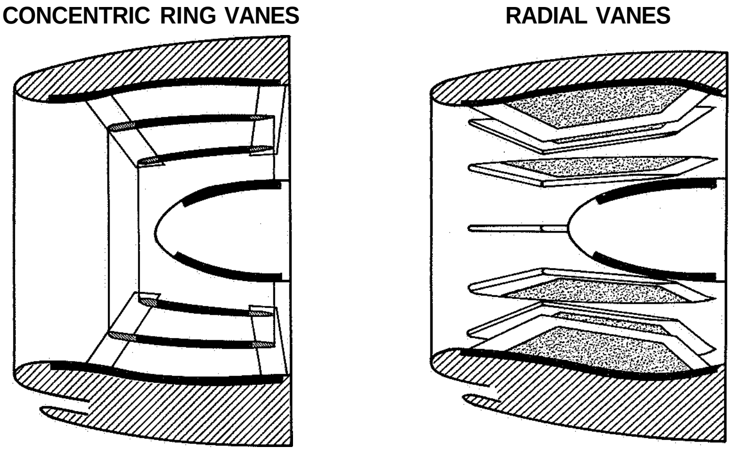

Figure 5

INLET CONFIGURATIONS STUDIED

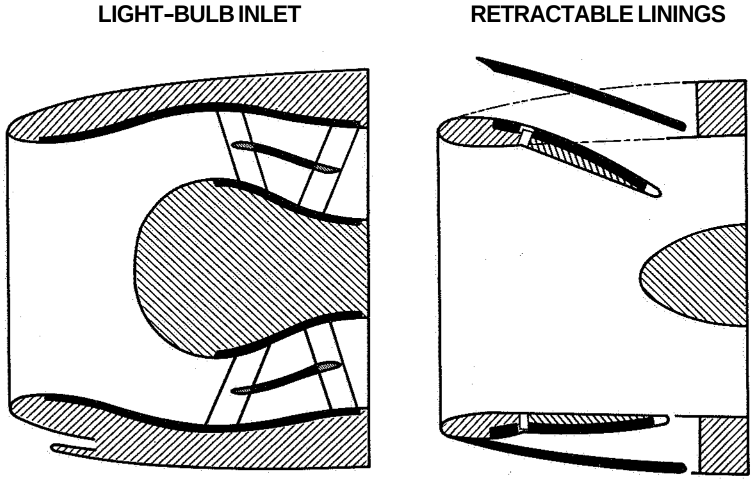

Figure 6

RETRACTABLE-SIDE-PANELS CONCEPT

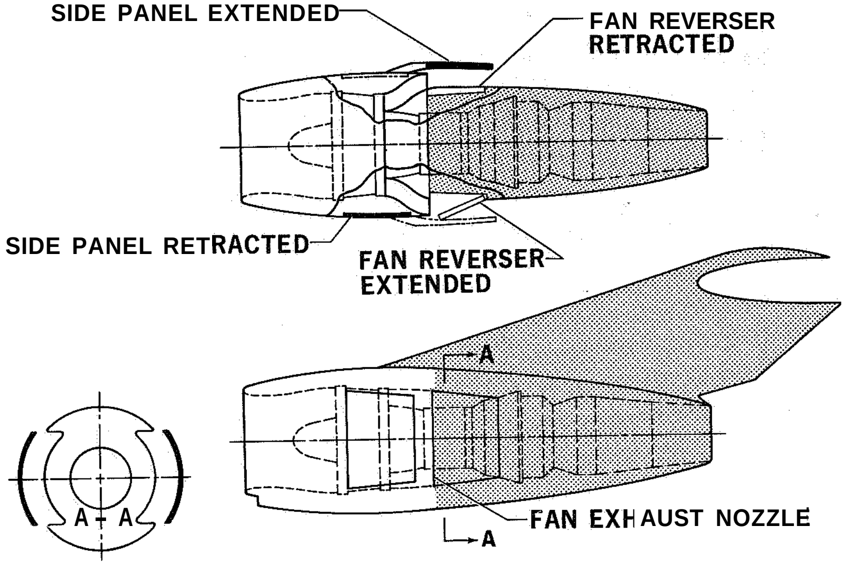

Figure 7

48-INCH FAN EXHAUST DUCT

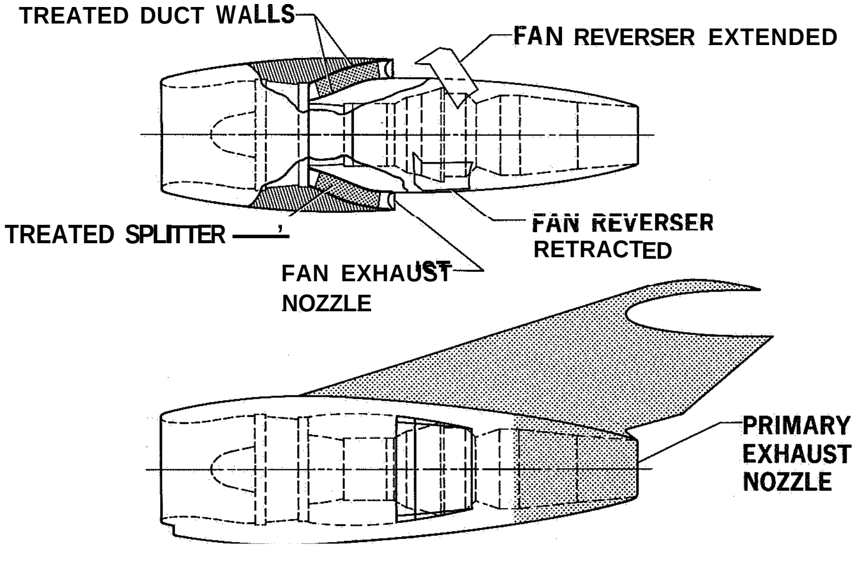

Figure 8

EFFECT OF PRIMARY NOZZLE AREA ON FAN-SPEED–THRUST RELATIONSHIP
JT3D-3 ENGINE

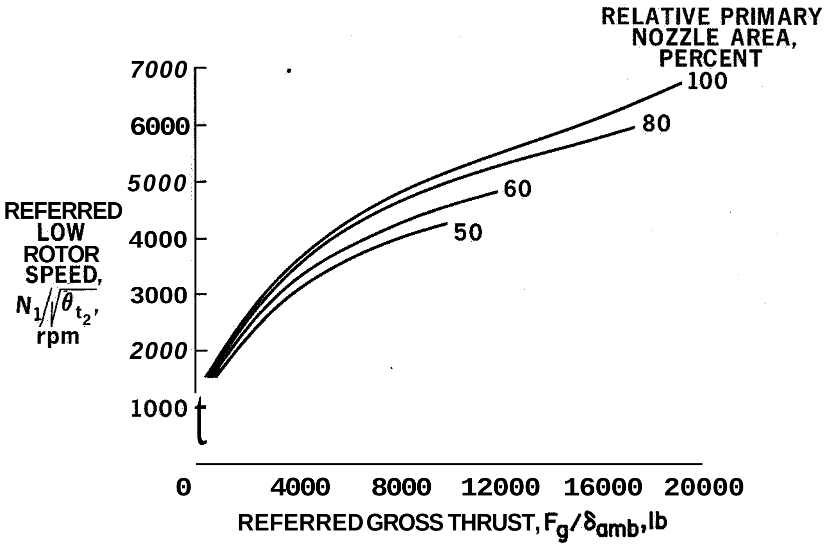

Figure 9