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DEVELOPMENTAL DESIGN, FABRICATION, AND TEST OF ACOUSTIC SUPPRESSORS FOR FANS OF HIGH BYPASS TURBOFAN ENGINES

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Prepared by
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16. Abstract

An analysis procedure was developed for design of acoustically treated nacelles for high bypass turbofan engines. The plan was applied to the conceptual design of a nacelle for the NASA/General Electric quiet engine typical of a 707/DC-8 airplane installation. The resultant design was modified to a test nacelle design for the NASA Lewis quiet fan. The acoustic design goal was a 10 dB reduction in effective perceived fan noise levels during takeoff and approach. Detailed nacelle designs were subsequently developed for both the quiet engine and the quiet fan. The acoustic design goal for each nacelle was 15 dB reductions in perceived fan noise levels from the inlet and fan duct. Acoustically treated nacelles were fabricated for the quiet engine and quiet fan for testing at the NASA Lewis Research Center. Performance of selected inlet and fan duct lining configurations was experimentally evaluated in a flow duct. Results of the tests show that the linings perform as designed.

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TABLE OF CONTENTS

PAGE

SUMMARY 1

INTRODUCTION 3

CONCEPTUAL NACELLE DESIGN TRADE STUDIES 4
Attenuation Requirements 4
Aerodynamic Design 10
Lining Optimization 10
Acoustic Lining Configurations 14
Fan Duct Lining Attenuation 18
Inlet Lining Attenuation 18
Predicted Nacelle Performance 18
Aerodynamic performance 18
Acoustic performance 21

QUIET ENGINE NACELLE 21
Aerodynamic Design 21
Inlet design 21
Fan duct design 25
External contours 28
Estimated performance 28
Acoustic Linings 28
Lining material 28
Inlet linings 28
Fan duct linings 32
Estimated performance 38
Nacelle weight 38
Nacelle Systems 38
Anti-icing system concept 38
Thrust reverser concepts 42

QUIET FAN NACELLE 42
Aerodynamic Design 42
Inlet design 42
Fan duct design 46
Estimated performance 46
Acoustic Linings 46
Inlet linings 48
Fan duct linings 48
Estimated performance 53
Nacelle weight 53

DISCUSSION OF RESULTS 55
CONCLUSIONS 56
SYMBOLS 57
REFERENCES 58

LIST OF FIGURES

NUMBER		PAGE
1.	Acoustic lining design plan	5
2.	Attenuation requirement plan	6
3.	Component noise data at 60% fan speed (approach)	7
4.	Component noise data at 90% fan speed (takeoff)	7
5.	Attenuation spectrum used in attenuation trade studies	9
6.	Attenuations acheived based on minimum treated area	9
7.	Quiet fan acoustic lining attenuation requirement	9
8.	Effect of number of inlet acoustic rings on inlet length	11
9.	Inlet contours – quiet engine conceptual nacelle	12
10.	Inlet contours – quiet fan conceptual nacelle	12
11.	Fan duct contours – quiet engine conceptual nacelle	13
12.	Fan duct contours – quiet fan conceptual nacelle	13
13.	Effects of duct geometry on attenuation and impedance requirements	15
14.	Attenuation recovery with lining designed for sheared flow	16
15.	Inlet acoustic lining design – conceptual nacelle	16
16.	Fan duct acoustic lining design – conceptual nacelle	17
17.	Comparison of predicted fan duct attenuation with requirement – conceptual nacelle	19
18.	Flow duct evaluation of fan duct linings – equal impedance on opposite walls	19
19.	Flow duct evaluation of fan duct linings – constant lining on each wall	20
20.	Flow duct evaluation of inlet linings	20
21.	Quiet engine nacelle configuration	23
22.	Effect of inlet configuration on required acoustic treatment	24
23.	Effect of inlet configuration on inlet length	24
24.	Inlet contours – quiet engine nacelle	26
25.	Inlet area progression – quiet engine nacelle	26
26.	Fan duct contours – quiet engine nacelle	27
27.	Fan duct area progression – quiet engine nacelle	27
28.	Typical lining construction	30
29.	Location of inlet linings – quiet engine nacelle	31
30	Predicted inlet lining attenuation spectra – quiet engine nacelle	33
31.	Flow duct evaluation of inlet linings – quiet engine nacelle	33
32.	Quiet engine nacelle inlet rings and centerbody before assembly	34
33.	Location of fan duct linings – quiet engine nacelle	35
34.	Comparison of measured and predicted attenuation in fan duct segment containing double layered lining	36
35.	Flow duct evaluation of fan duct linings – quiet engine nacelle	36
36.	Quiet engine nacelle fan duct linings before assembly	37
37.	Predicted attenuation at takeoff power – quiet engine nacelle	39
38.	Predicted attenuation at approach power – quiet engine nacelle	39
39.	Nacelle installed on quiet engine at NASA Lewis engine test facility	40
40.	Schematic of inlet anti-icing system	41
41.	Primary thrust reverser concept	43

LIST OF FIGURES (CONT'D.)

		PAGE
42.	Movable cascade fan thrust reverser concept	43
43.	Fixed cascade fan thrust reverser concept	44
44.	Inlet contours – quiet fan nacelle	45
45.	Inlet area progression – quiet fan nacelle	45
46.	Fan duct contours – quiet fan nacelle	47
47.	Fan duct area progression – quiet fan nacelle	47
48.	Location of inlet linings – quiet fan nacelle	49
49.	Predicted inlet lining attenuation spectra at 60% fan speed – quiet fan nacelle	50
50.	Quiet fan nacelle inlet	51
51.	Location of fan duct linings – quiet fan nacelle	52
52.	Predicted fan duct lining attenuation spectrum at 90% fan speed – quiet fan nacelle	52
53.	Predicted attenuation at 90% fan speed – quiet fan nacelle	54
54.	Predicted attenuation at 60% fan speed – quiet fan nacelle	54

LIST OF TABLES

NUMBER		PAGE
I	Effects of sheared flow on inlet lining requirements	17
II	Predicted conceptual nacelle aerodynamic performance	22
III	Predicted conceptual nacelle acoustic performance	22
IV	Predicted aeroydnamic performance – quiet engine nacelle	29
V	Characteristics of quiet engine nacelle inlet linings	31
VI	Characteristics of quiet engine nacelle fan duct linings	35
VII	Weight of quiet engine nacelle acoustic linings	41
VIII	Estimated anti-icing system airflow requirements	41
IX	Predicted aerodynamic performance – quiet fan nacelle	48
X	Characteristics of quiet fan nacelle inlet linings	49
XI	Characteristics of quiet fan nacelle fan duct linings	52
XII	Weight of quiet fan nacelle acoustic linings	53

SUMMARY

An analysis plan was developed for design of acoustically treated nacelles for suppresion of fan generated noise from high bypass turbofan engines. The plan was followed in developing two conceptual nacelle designs. The first was a flight nacelle for the NASA/General Electric quiet engine typical of a 707/DC-8 class airplane installation. The quiet engine nacelle design was modified to a design for the NASA Lewis quiet fan. Measured noise data from the NASA quiet fan were used for acoustic design of both conceptual nacelles. Nacelle internal lines were based on predicted aerodynamic performance of the quiet engine and measured aerodynamic performance of the quiet fan.

The two conceptual nacelle designs were subsequently converted into detailed designs, and ground test nacelles were fabricated for the quiet engine and the quiet fan. Design objectives for the nacelles were:

- 15 PNdB suppression of fan noise from the inlet and fan exhaust ducts.
- Design and construction techniques representative of current aircraft practice.

Each inlet was designed to minimize the amount of acoustic lining subject to minimization of inlet length. The resultant inlet for each nacelle has a treated cowl and three rings treated on both sides. A fixed treated centerbody is attached to the inlet rings by struts. The nacelle fan ducts are treated on inner and outer walls and each has a single ring treated on both sides. The acoustic facing sheets are polyimide resin, glass fabric laminates.

Acoustic flow duct tests were conducted on selected lining configurations typical of the inlet and fan duct. Comparison of test results with attenuation predictions show that the linings have satisfactory acoustic performance.

Predicted peak noise reductions with the fabricated nacelles are summarized below. The predicted attenuations are those expected during test; consequently the attenuation obtained with fan noise suppression is limited by jet and turbomachinery noise floors.

Nacelle	Quadrant	Peak Attenuation – PNdB	
		Approach	Takeoff
Quiet Engine	Forward	12.8	10.3
	Aft	9.4	6.0
Quiet Fan	Forward	13.9	12.6
	Aft	11.1	13.7

The installation thrust losses for the quiet nacelle due to acoustic treatment are estimated to be 5.0 percent at takeoff power and 6.5 percent at cruise power. The cruise thrust specific fuel consumption increase is 5.4 percent.

Significant results of the program are:

- A three-ring inlet, one ring fan duct design provides the best aeroacoustic performance of the configurations considered.
- Broadband acoustic lining designs are required for satisfactory noise suppression of this class of fans.
- Flow duct test results confirm that the design procedure developed results in linings which satisfy acoustic requirements.
- The acoustic design goal of 15 PNdB fan noise reduction cannot be observed during quiet engine testing because of jet and turbine noise floors.

INTRODUCTION

The NASA Lewis Research Center has sponsored research to reduce aircraft engine noise for the past several years. The experimental quiet engine program began in 1967 with study contracts to Pratt & Whitney Aircraft and Detroit Diesel Allison for development of design concepts to reduce fan noise from turbofan engines. In 1969, a contract was awarded General Electric to design, fabricate, and test three experimental fans which include design features for noise reduction. Two of the fans, designated A and B, were low tip speed fans. The third fan, designated C, was a high tip speed fan. Following full scale testing of the three fans at General Electric and NASA Lewis, fan A was selected for installation on a modified General Electric CF-6 core engine to form the NASA Quiet Engine, Mark I.

Concurrent with the General Electric quiet engine development program, NASA engineers designed a low tip speed fan with noise reduction features. This fan was fabricated and tested at the NASA Lewis Fan Test Facility.

Results of these efforts demonstrated that proper fan design can significantly reduce noise generation. The studies also showed that added benefits would result from properly designed acoustic lining in the inlet and fan duct. NASA Lewis awarded Contract NAS 3-14321 to the Wichita Division of The Boeing Company in July 1970. The objective of the contract was to develop a systematic procedure for design of acoustic linings to reduce noise from the fans of high bypass ratio turbofan engines. The contract was amended in November 1971 to include design and fabrication of acoustically treated nacelles for the quiet engine developed by General Electric and the quiet fan developed at NASA Lewis.

This report summarizes the acoustic lining design procedure that was developed. It also describes the design, fabrication, and expected performance of the two nacelles constructed as part of the contract. Detail description of the specific studies conducted during the contract are reported in References 1 through 8.

CONCEPTUAL NACELLE DESIGN TRADE STUDIES

A procedure has been developed for design of acoustically treated nacelles. The procedure was applied to two conceptual nacelle designs. One conceptual design was a flight nacelle for the General Electric quiet engine with Fan A. Engine performance data used in the design were obtained from Reference 9. Fan noise data used for lining design were measured data for the NASA quiet fan, which is described in References 10, 11, and 12. Primary jet and turbine noise estimates were supplied by General Electric. The acoustic design goal was a 10 dB reduction in effective perceived noise levels with takeoff and landing thrust levels and flight profiles typical of a 707/DC-8 class airplane.

The second conceptual nacelle was designed for the NASA quiet fan. The objective was to modify the flight nacelle design for installation on the quiet fan test facility, while retaining the internal aerodynamic characteristics of the flight nacelle. Since the quiet fan noise characteristics were used as a basis for the flight nacelle design, the acoustic linings were the same for both conceptual nacelles.

The initial element in the nacelle design procedure was establishment of attenuation requirements for the inlet and fan duct linings. Based on these requirements, trade studies were performed to locate acoustic linings for maximum attenuation subject to an acceptable internal aerodynamic design. The acoustic lining face sheet characteristics and honeycomb core depths were selected to maximize attenuation rates for the duct geometry and the aeroacoustic environments within the nacelle. Attenuation spectra predicted for the lining were compared with the attenuation requirements to assure that the requirements were satisfied.

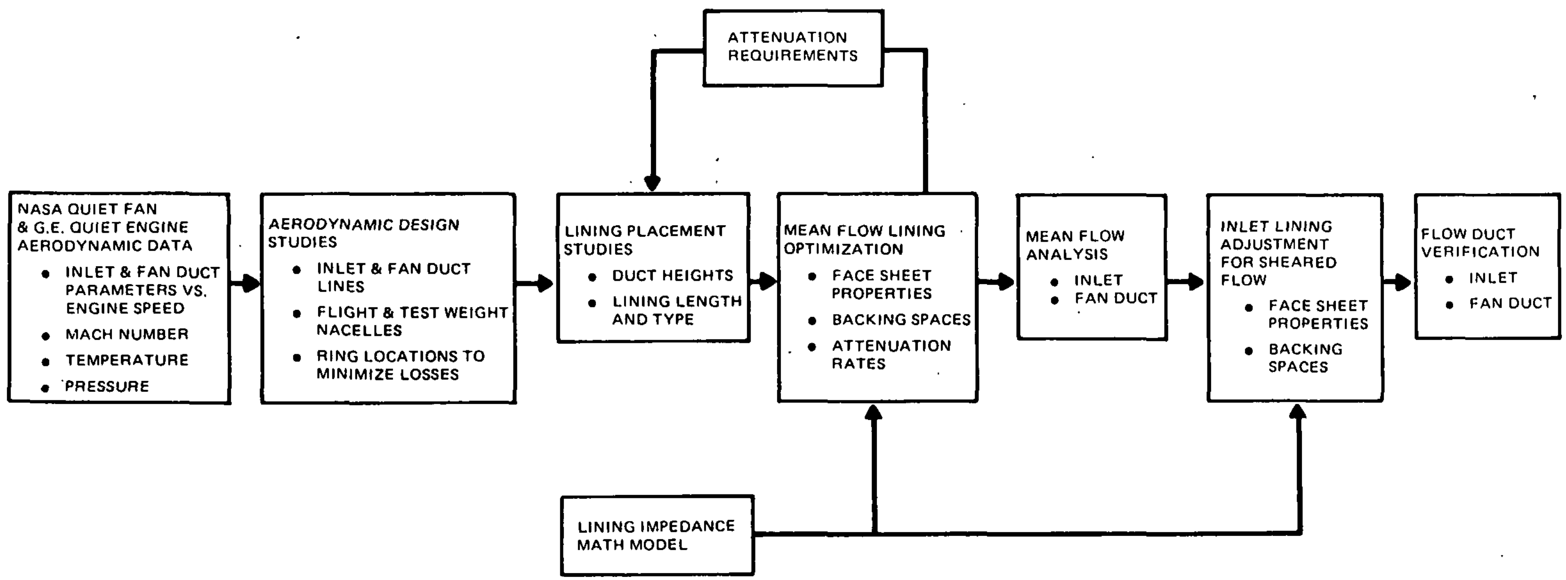
The following sections summarize results of the acoustic lining conceptual design and predicted acoustic performance. Figure 1 illustrates the elements in the conceptual nacelle design.

Attenuation Requirements

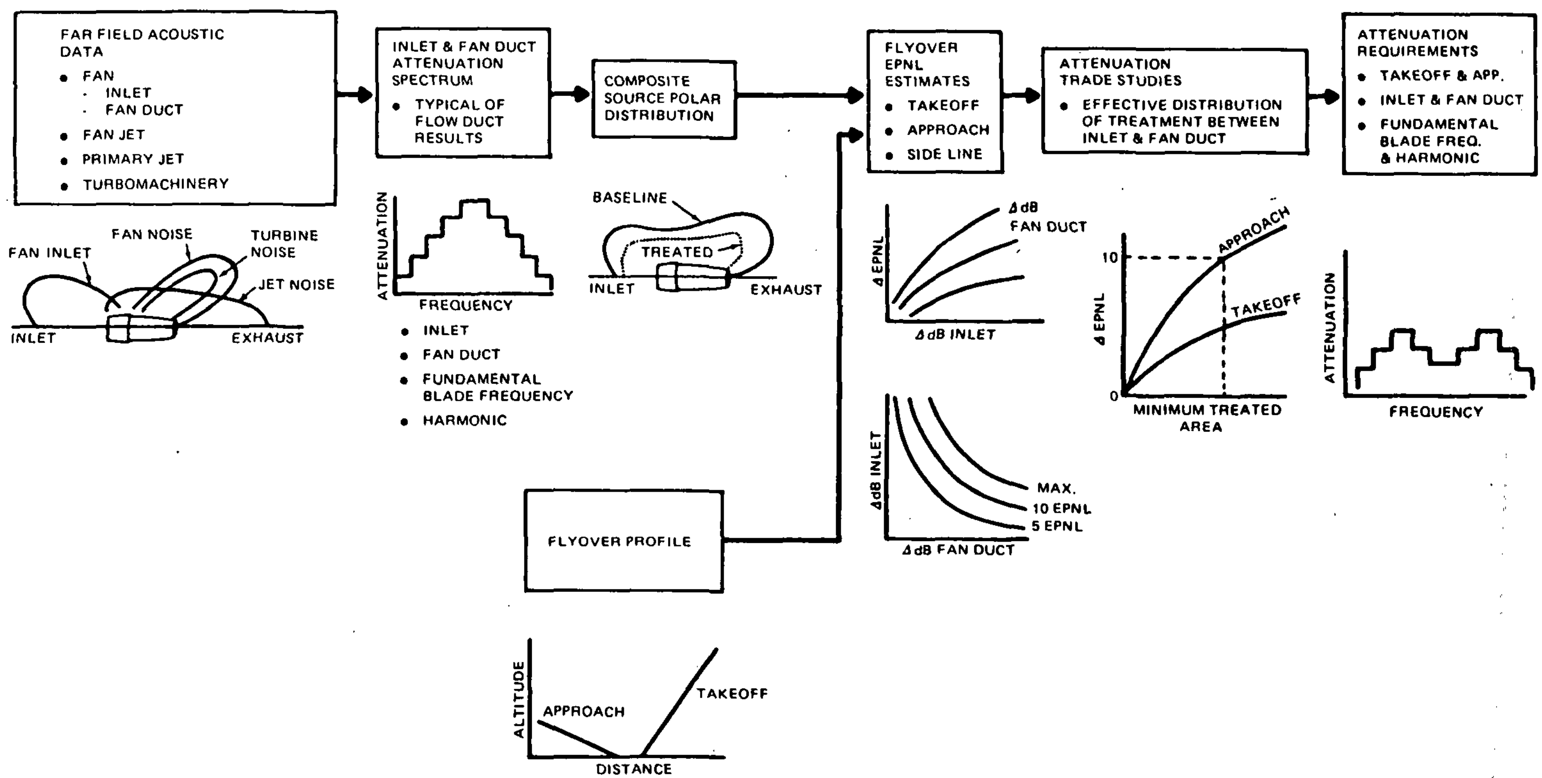
Lining attenuation requirements were established to meet flyover noise reduction objectives while minimizing the amount of acoustic lining required to achieve the attenuation. The plan followed to obtain the attenuation requirements is shown in Figure 2.

Measured polar noise spectra from the NASA fan were combined with estimated primary jet and turbine noise from the core engine to form a total acoustic spectrum in terms of individual noise sources. Figure 3 is a plot of the perceived noise level (PNL), along a 45.72 m (200 ft) radius, for the individual noise sources at the approach power setting. The data show that fan noise is dominant in both the forward and aft quadrants. Significant contributors to fan noise at approach power are the fundamental blade passage frequency at 1874 Hz and its second harmonic at 3748 Hz. Noise suppression centered at both of these frequencies is required to achieve the EPNdB reduction goal. Turbine noise is the next significant source below fan noise in the aft quadrant.

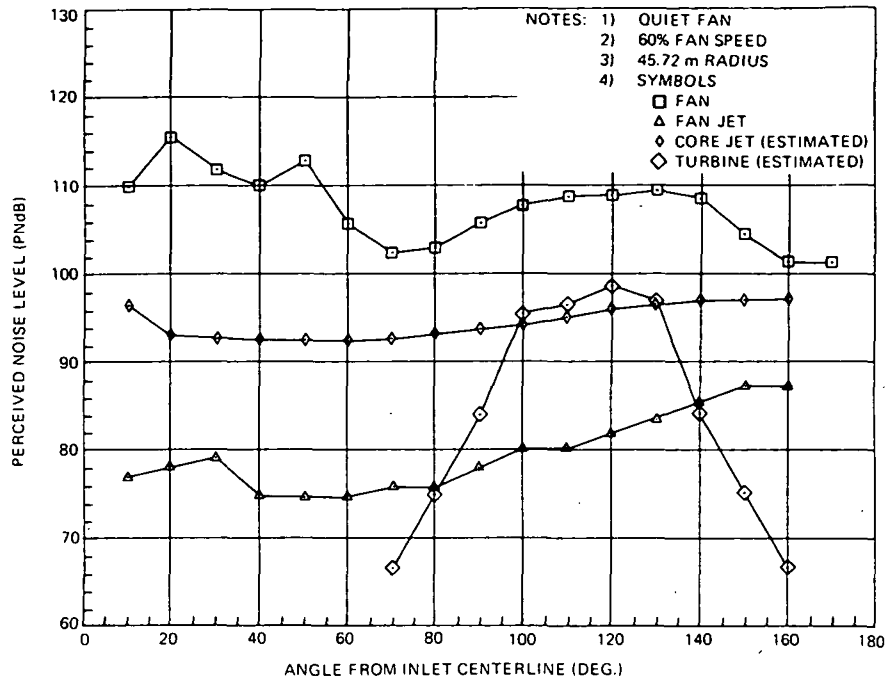
Figure 4 shows the perceived noise levels along a 45.72 m radius for the individual noise sources at takeoff power. Fan noise contributions are approximately equal in the forward and aft quadrants. Primary jet noise is the significant source below the fan noise. Attenuation of the fundamental blade passage frequency at 2812 Hz and its second harmonic at 5624 Hz are required at takeoff power for efficient suppression of fan noise to the noise floor.



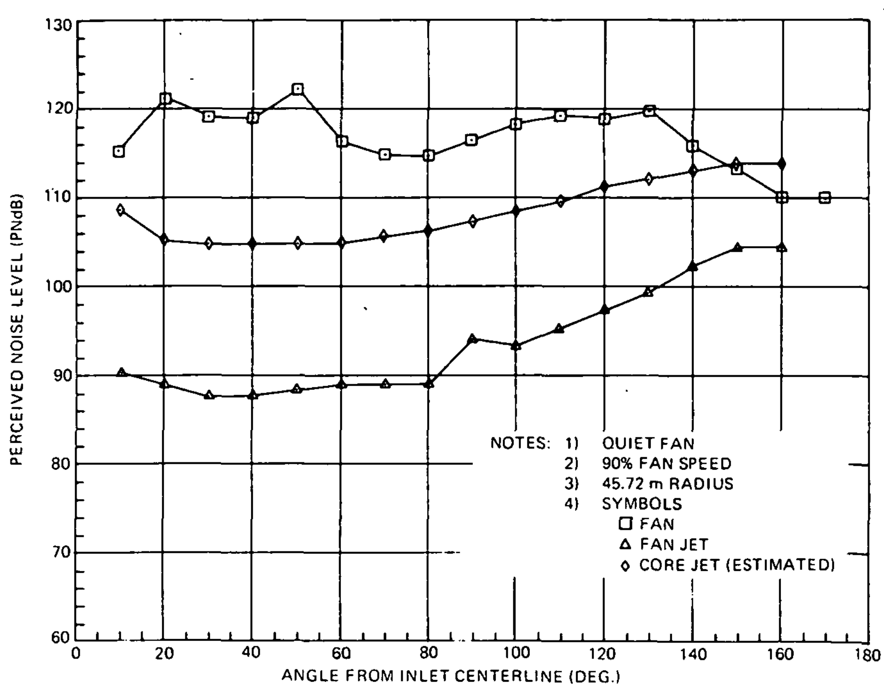
ACOUSTIC LINING DESIGN PLAN
FIGURE 1



ATTENUATION REQUIREMENT PLAN
FIGURE 2



COMPONENT NOISE DATA AT 60% FAN SPEED (APPROACH)
FIGURE 3



COMPONENT NOISE DATA AT 90% FAN SPEED (TAKEOFF)
FIGURE 4

A trade study was performed to determine the amount of attenuation required in the inlet and fan duct to achieve the 10 EPNdB reduction goal at takeoff and approach. A 1/3 octave attenuation spectrum, Figure 5, typical of flow duct test results, was applied to the far field fan noise spectra in the forward and aft quadrants. These attenuation spectra were centered at the fundamental blade frequency and the second harmonic. The magnitudes of the two attenuation spectra were varied to change the relative distribution of attenuation between the fundamental and harmonic. The distribution of attenuation between inlet and fan duct noise was also varied.

Each attenuated fan noise polar spectrum was combined with turbomachinery and jet noise to form a composite polar spectrum. This spectrum and the appropriate flight profile were processed by a digital computer program to obtain an EPNL value. The result is one EPNL value for each attenuation distribution. Peak attenuations of 0, 5, 10, 20, and 30 dB were applied in all possible combinations to the fundamental blade frequency in the inlet and fan duct and to the second harmonic of the blade frequency in the inlet and fan duct. A four-dimensional interpolation was performed to identify attenuation spectra which give a 10 EPNdB reduction at takeoff and approach.

A cursory analysis was performed to minimize the amount of acoustic treatment required to achieve the 10 EPNdB attenuation goal. The weighting function used to minimize treated area is:

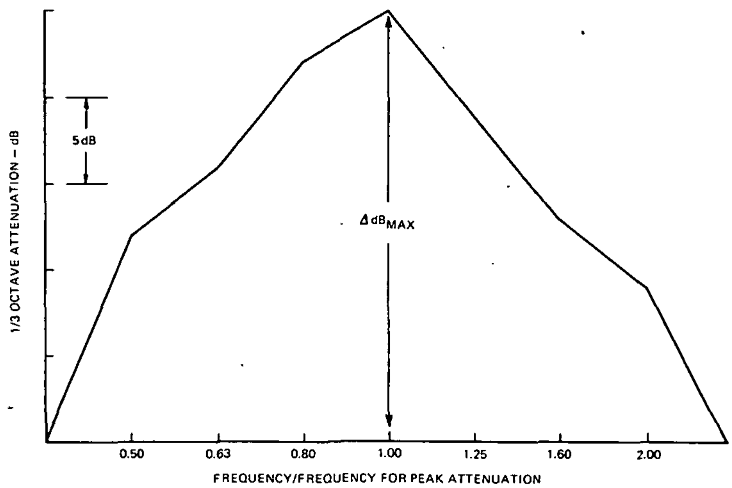
$$\phi\left(\frac{\text{Treated Area}}{\text{Flow Area}}\right) = \left(\Delta dB^{5/3}_{\text{fundamental}} + 1.6\,\Delta dB^{5/3}_{\text{harmonic}}\right)_{\text{inlet}} + \left(\Delta dB^{5/3}_{\text{fundamental}} + 1.75\,\Delta dB^{5/3}_{\text{harmonic}}\right)_{\text{fan duct}}$$

This equation, based on a rectangular duct optimation procedure described in Reference 13, is valid for values of the parameter Hf/c between 0.5 and 4. The optimization procedure maximizes the one octave bandwidth attenuation level of a noise source, which has a constant SPL level for one octave and zero elsewhere. The function ϕ weights equally the acoustic effectiveness of inlet and fan duct linings, although theory shows that inlet linings can provide higher attenuation levels for a given duct geometry, Mach number, and sound frequency. Inlet and fan duct linings were weighted for equal effectiveness because the effect of sheared flow on inlet lining performance was not well understood during the conceptual nacelle design.

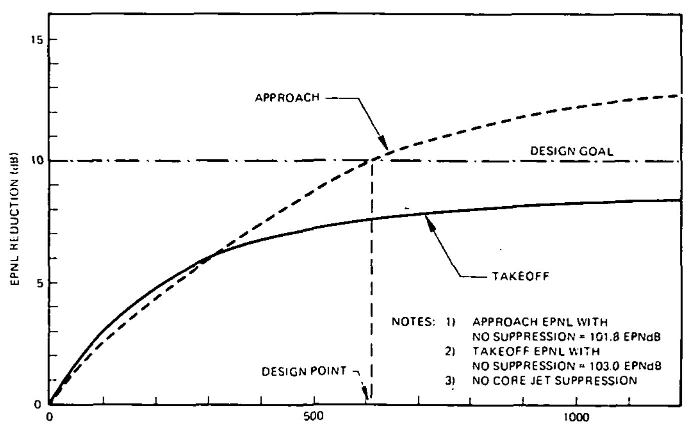
The function of treated area, ϕ, was evaluated for each combination of attenuations which gave a given EPNL reduction. The combination which minimized ϕ was selected for each EPNL reduction. Figure 6 shows the attenuation achieved as a function of the minimum value of the function ϕ required to obtain that attenuation. The results show that the 10 EPNdB reduction goal could be achieved at the approach condition. The goal could not be achieved at takeoff without core jet suppression.

The attenuation requirements for the approach condition were selected as those which gave a 10 EPNdB reduction with the minimum value of the weighting function, ϕ. Takeoff attenuation requirements were selected to obtain 7.5 EPNdB reduction at takeoff. The The acoustic lining attenuation requirements, based on minimum ϕ, are shown in Figure 7 for the inlet and fan duct at the approach and takeoff fan speeds.

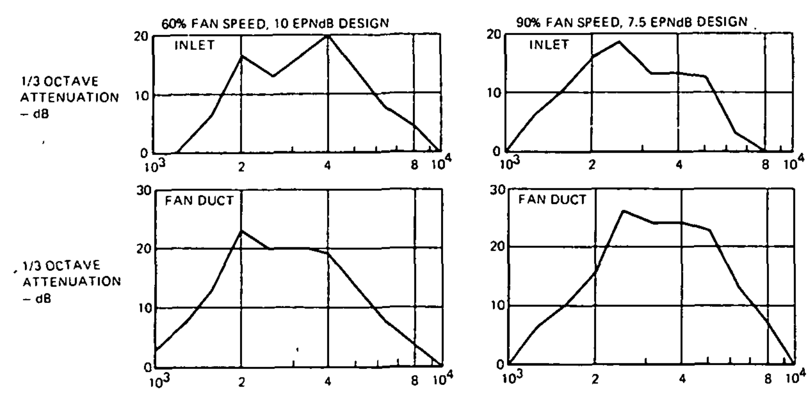
Complete results of these trade studies are presented in Reference 6.



ATTENUATION SPECTRUM USED IN ATTENUATION TRADE STUDIES
FIGURE 5



ATTENUATIONS ACHIEVED BASED ON MINIMUM TREATED AREA
FIGURE 6



QUIET FAN ACOUSTIC LINING ATTENUATION REQUIREMENTS
FIGURE 7

Aerodynamic Design

A preliminary design analysis was performed to determine the number and location of the inlet acoustic rings for satisfactory attenuation with minimum aerodynamic performance losses. Inlet length requirements for zero, two, three, and four-ring inlets are shown in Figure 8. Each configuration was selected for 10 EPNdB reduction at approach. These results show that the inlet length is minimized with three rings.

The controlling factor for configurations with less than three rings is the ring length required to accommodate the necessary treated area. As the number of rings is increased, ring lengths and duct heights decrease. The effect of decreasing duct heights is to increase the required cell depth of the acoustic lining and, therefore, the ring thickness. As ring thickness increases, the inlet inner cowl diameter must also be increased to maintain a given inlet flow area. To avoid flow separation, the inlet length must be increased to maintain a satisfactory diffusion angle, θ .

As a result of this analysis a three-ring inlet configuration with an unlined centerbody was selected for the conceptual nacelle designs. The centerbody was unlined so that the existing centerbody and drive shaft of the quiet fan could be retained. The rings were located on selected streamlines defined by an axisymmetric compressible potential flow field analysis. A subsequent analysis was made with the rings in their selected locations to verify that flow would remain attached to the inlet surfaces.

Figures 9 and 10 are schematics of inlet internal lines for the conceptual flight nacelle and the NASA quiet fan nacelle, respectively. The shaft shown through the inlet in Figure 10 is the shaft that drives the fan.

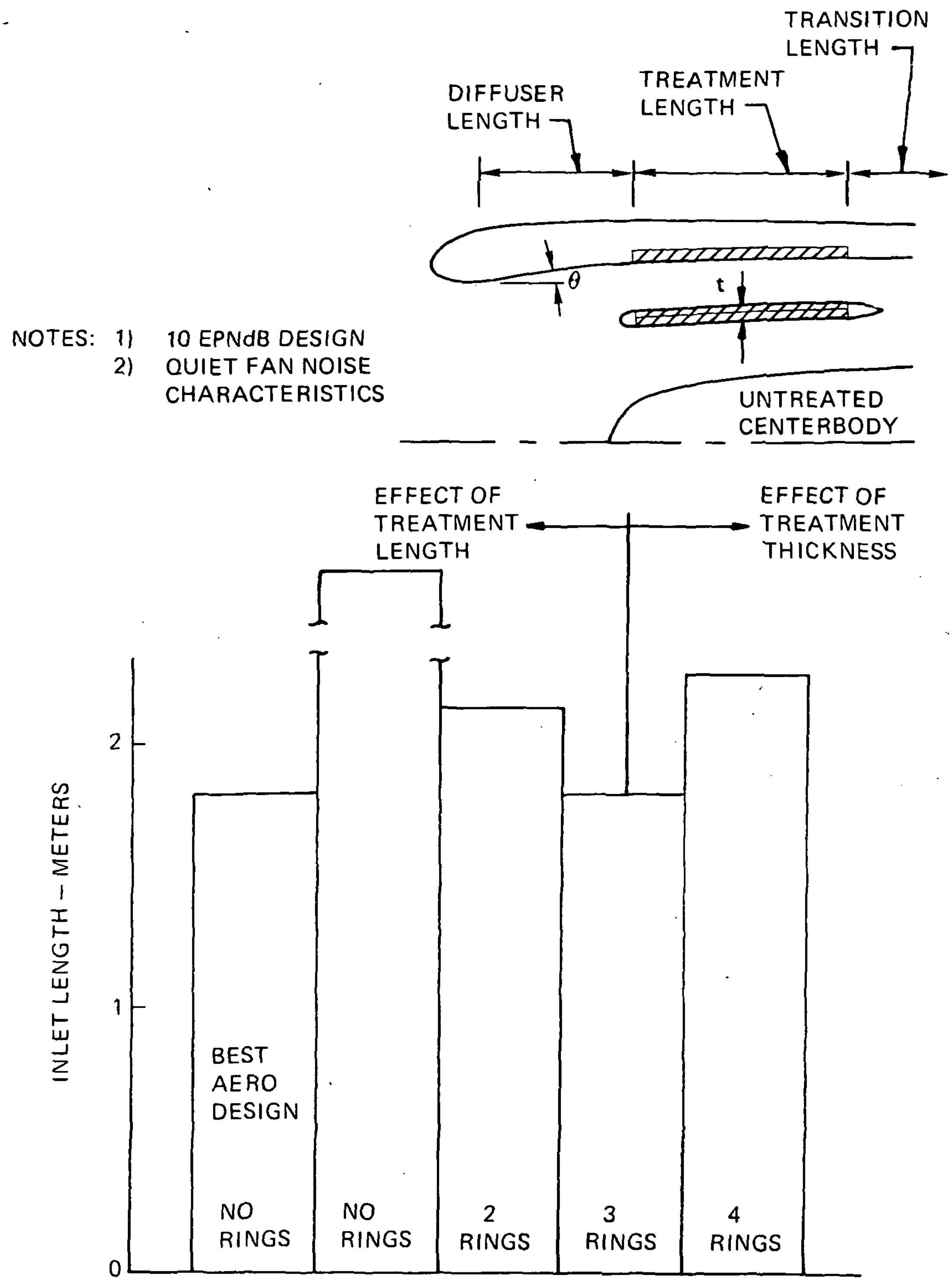
The fan ducts of both conceptual nacelle designs have acoustic linings on the inner and outer cowl walls with a single ring treated on both sides. Figure 11 is a cross section of the flight nacelle fan duct and Figure 12 is a schematic of the fan duct for the quiet fan.

A complete description of the nacelle aerodynamic design of the two conceptual nacelles is given in Reference 5.

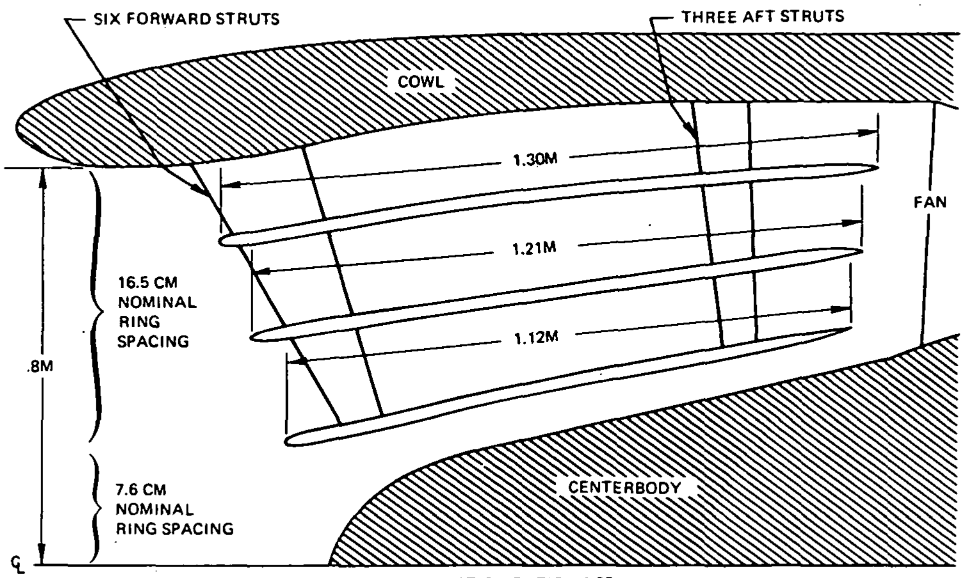
Lining Optimization

Two digital computer programs were used to establish optimum lining impedance requirements. Both programs are based on solution of the convected wave equation. One program neglects boundary layer effects on sound propagation. This program was used exclusively for fan duct lining optimization and initially during optimization of the inlet linings. The second program was used to reoptimize the inlet linings with consideration of boundary layer effects.

Basic data required to establish the optimum lining impedance are: duct geometry, Mach number, total temperature and pressure, origin of sound with respect to flow direction, optimization frequency, and boundary layer thickness and profile. These data are used in an interative procedure to establish the lining impedance which maximizes attenuation of the least attenuated acoustic mode which can propagate in the treated duct. The optimum impedance was conservatively selected where the first and second symmetric modes become indistinguishable and have equal attenuation, which has been maximized (Reference 14).

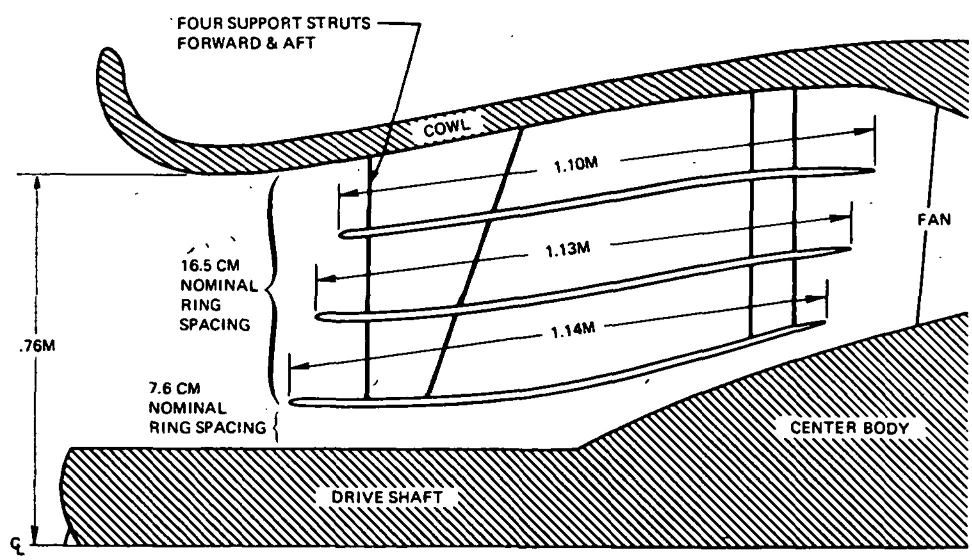


EFFECT OF NUMBER OF INLET ACOUSTIC RINGS ON INLET LENGTH
FIGURE 8



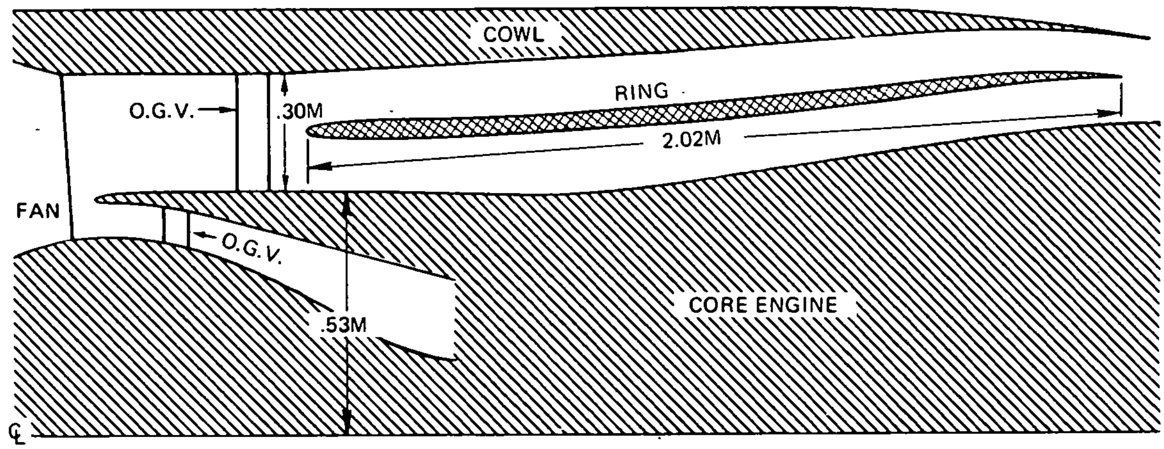
NOTES: 1) CONTRACTION RATIO = 1.25
2) TREATED AREA = 25.6 SQ M.
3) STRUTS EQUALLY SPACED

INLET CONTOURS – QUIET ENGINE CONCEPTUAL NACELLE
FIGURE 9



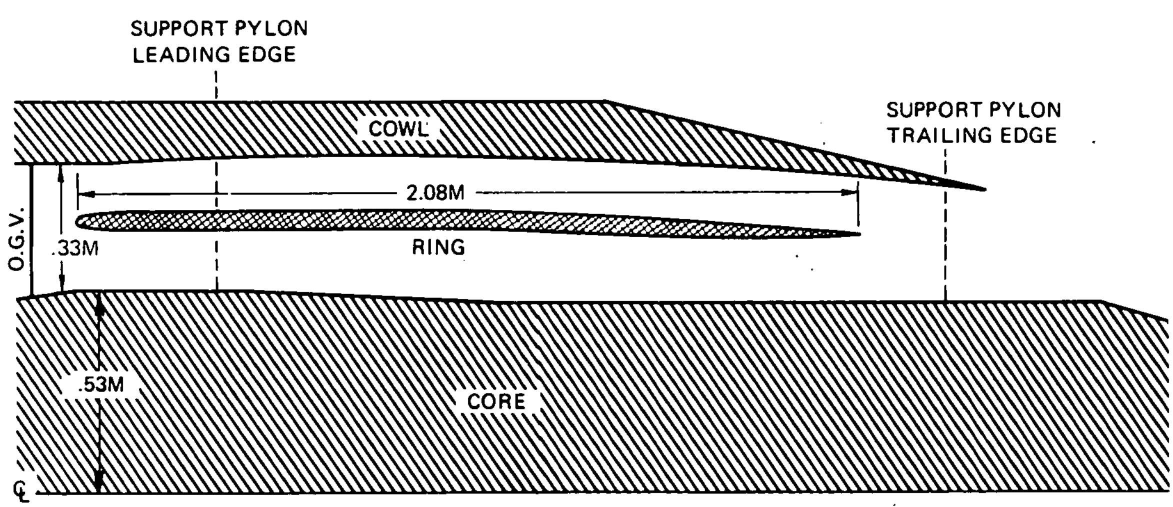
NOTE: TREATED AREA = 25.6 SQ. M.

INLET CONTOURS – QUIET FAN CONCEPTUAL NACELLE
FIGURE 10



NOTES: 1) RING SUPPORTED BY NACELLE STRUT AND BY ACCESSORY DRIVE SHAFT PYLON
2) TREATED AREA = 27.8 SQ M.

FAN DUCT CONTOURS – QUIET ENGINE CONCEPTUAL NACELLE
FIGURE 11



NOTES: 1) RING ATTACHED TO SUPPORT PYLON
2) TREATED AREA = 31.1 SQ. M.

FAN DUCT CONTOURS – QUIET FAN CONCEPTUAL NACELLE
FIGURE 12

Parametric trade studies were performed to determine effects of duct geometry variations on lining attenuation rates and optimum impedance requirements. The results were used in selecting and locating inlet and fan duct rings and identifying the optimum impedances. Typical results of these trade studies, based on uniform flow in a rectangular duct with opposite walls treated with the same acoustic linings, are shown in Figure 13.

The inlet linings were subsequently reoptimized to correct for sound refraction effects of the boundary layer. This is necessary since inlet linings designed for mean flow may have greatly reduced effectiveness when a boundary layer is present. Figure 14 shows the potential loss of attenuation as a function of boundary layer thickness for a lining optimized for mean flow. The figure also shows the attenuation which can be regained by designing the lining considering boundary layer effects. In general, required resistance decreases and reactance increases when an inlet lining is reoptimized for boundary layer effects. A detailed description of the boundary layer effects on performance of inlet linings is given in Reference 8.

Acoustic Lining Configurations

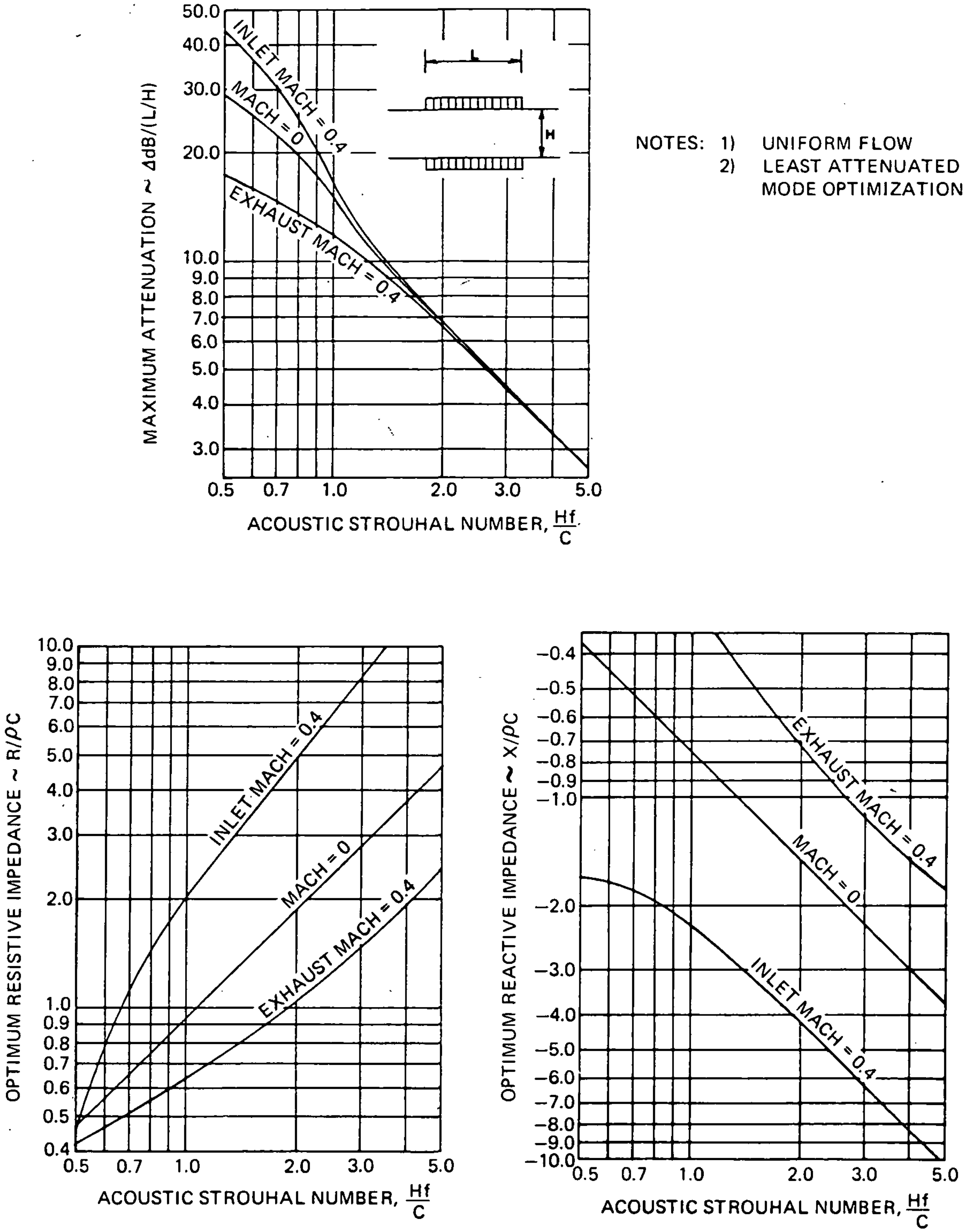
Candidate acoustic materials were perforated sheet and polyimide resin impregnated, glass reinforced facing sheets. Reference 1 describes results of impedance tests with grazing flow for both types of materials. The polyimide resin laminate system was selected for the following reasons:

- Structural load carrying capability
- Service test experience in airline use
- Continuous operating temperature compatible with engine compartment ($400^{o}F$)
- Allows segmentation acoustic linings with continuous structure

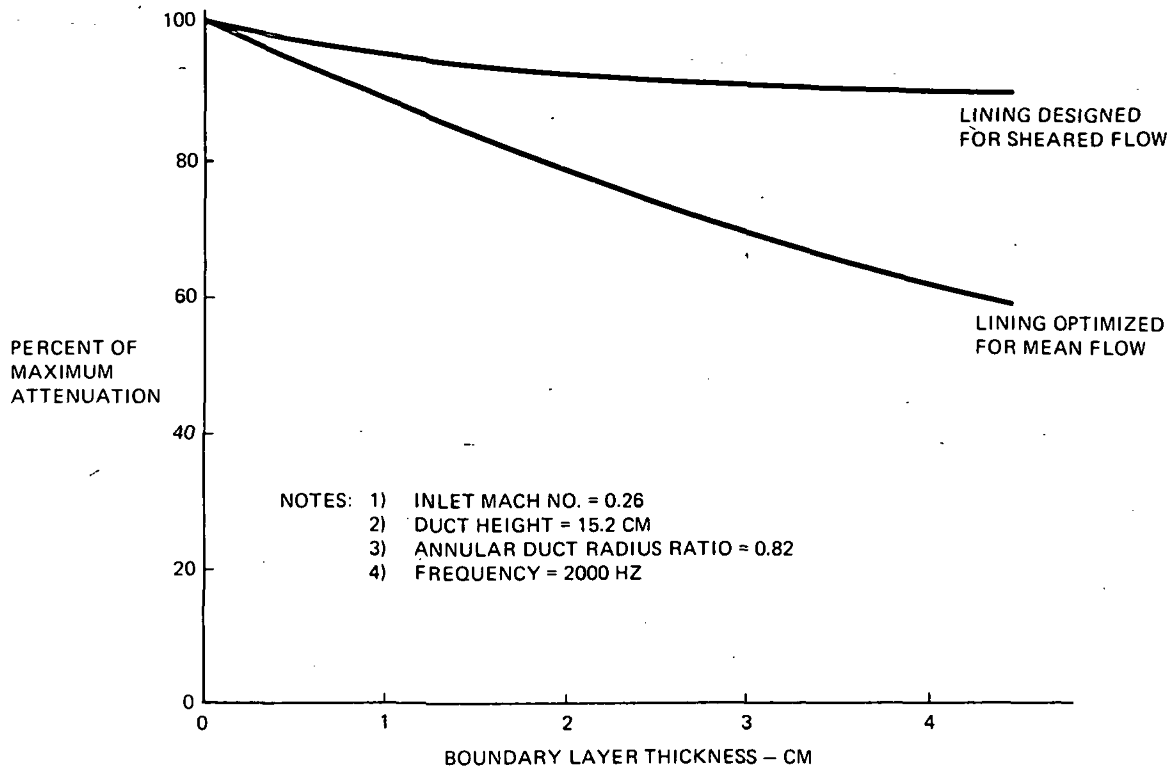
A digital computer program was used to select lining configurations which have impedances approximately equal to the selected optimum values. Results of this analysis are number of plies of polyimide impregnated cloth and the honeycomb backing depth. The selected properties for the inlet linings are shown in Figure 15. The linings were designed in two segments: one tuned for the fundamental blade passage frequency, and the other tuned for its second harmonic. The inlet design condition was 60 percent fan speed, representing approach power, because the attenuation requirements were more severe at this speed.

The effects of sheared flow on the selection of inlet linings is shown in Table I. The table compares the optimum inlet lining requirements considering mean flow with those considering sheared flow. As noted previously, the effect of sheared flow is to reduce the required resistance and increase the required reactance.

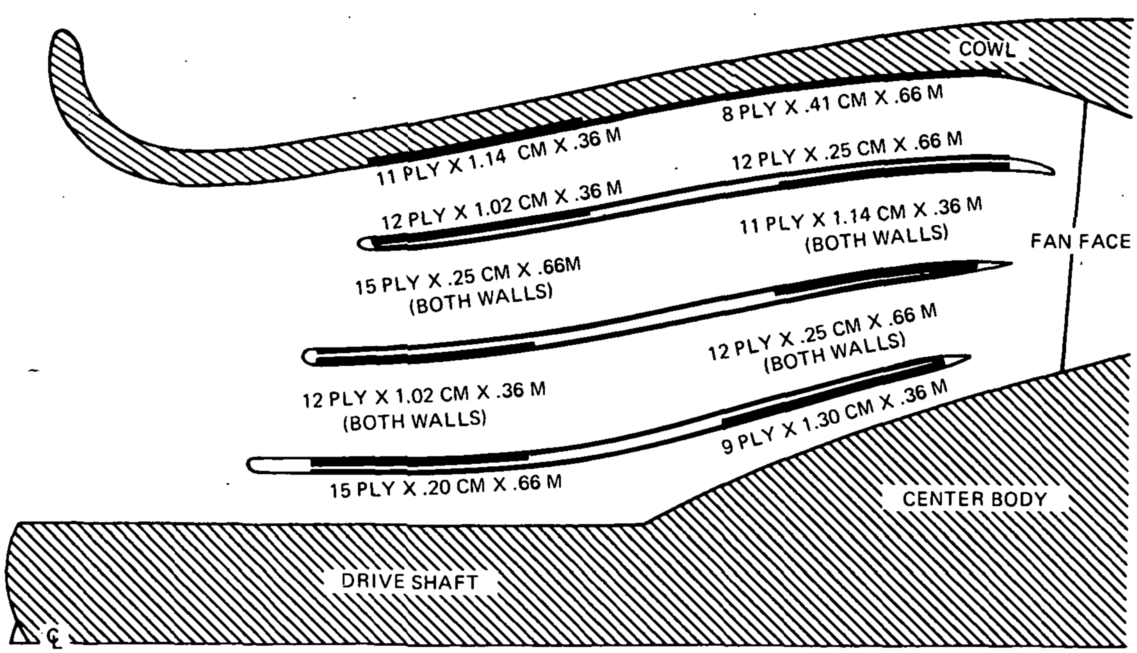
The fan duct lining configuration is shown in Figure 16. Takeoff fan speed was the design condition because of more severe attenuation requirements at this speed. The fan duct linings are also segmented to provide attenuation at the fundamental blade passage frequency and the second harmonic.



EFFECTS OF DUCT GEOMETRY ON ATTENUATION AND IMPEDANCE REQUIREMENTS
FIGURE 13



ATTENUATION RECOVERY WITH LINING DESIGNED FOR SHEARED FLOW
FIGURE 14

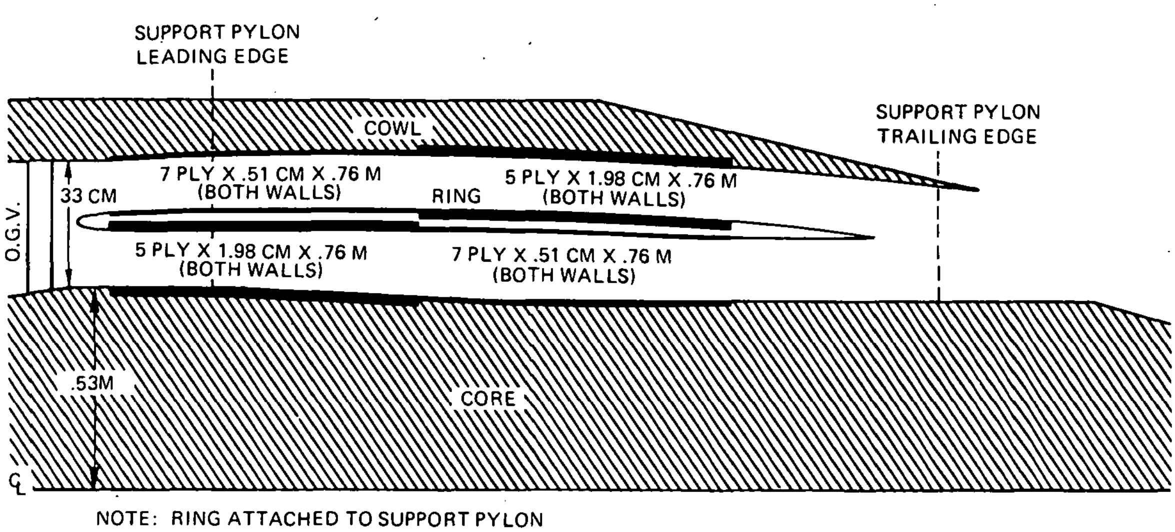


INLET ACOUSTIC LINING DESIGN – CONCEPTUAL NACELLE
FIGURE 15

TABLE I
EFFECTS OF SHEARED FLOW ON INLET LINING REQUIREMENTS

LINING LOCATION		MEAN FLOW REQUIREMENTS				SHEARED FLOW REQUIREMENTS				BOUNDARY LAYER[1] THICKNESS (CM)
		NO. OF PLIES	CAVITY DEPTH (CM)	R/ρc	X/ρc	NO. OF PLIES	CAVITY DEPTH (CM)	R/ρc	X/ρc	
OUTER CHANNEL	COWL	12	.96	1.4	− 1.4	11	1.14	1.2	− 1.3	4.16
		17	.21	3.0	− 2.5	8	.41	1.0	− 2.0	6.35
	RING	12	.96	1.4	− 1.4	12	1.02	1.4	− 1.4	.96
		17	.21	3.0	− 2.5	12	.25	1.9	− 2.4	2.34
OUTER MID-CHANNEL	FORWARD	17	.20	3.1	− 2.6	15	.25	2.5	− 2.7	.94
	AFT	12	1.05	1.3	− 1.3	11	1.14	1.2	− 1.3	2.26
INNER MID-CHANNEL	FORWARD	12	.98	1.3	− 1.3	12	1.02	1.4	− 1.4	.96
	AFT	16	.22	3.2	− 2.7	12	.25	1.8	− 2.3	2.18
INNER CHANNEL	FORWARD	18	.19	3.2	− 2.6	15	.20	2.6	− 3.0	1.02
	AFT	9	1.24	1.0	− 1.2	9	1.30	.9	− 1.2	2.31

[1] Based on estimated 1/7th power turbulent boundary layer profile averaged for individual lining segments.



FAN DUCT ACOUSTIC LINING DESIGN — CONCEPTUAL NACELLE
FIGURE 16

Fan Duct Lining Attenuation

Acoustic performance of the selected fan duct lining was evaluated with a digital computer analysis program (Reference 7). Pertinent assumptions in the analysis are:

- Constant velocity across the duct
- Duct end impedance effects are negligible
- Flow is irrotational, inviscid, and adiabatic
- Convective wave equation is applicable to sound propagation mechanism
- Annular duct can be approximated by a rectangular duct
- Equal pressure amplitudes of acoustic modes at the beginning of the lining

The analytical attenuation predictions were compared with attenuation requirements to ensure that the lining design was satisfactory. Figure 17 compares the predicted attenuation with the requirements for the fan duct lining at the takeoff fan speed.

The fan duct lining configuration was experimentally tested in an acoustic flow duct to verify the analytical predictions. Figure 18 compares the measured attenuation to the requirement. The results show that the required attenuations were achieved except in the frequency range where the flow duct noise floor was significant.

A second flow duct test was performed with the same duct geometry; however, for this test linings with the same characteristics were located on the same wall. This meant that the opposing linings has different impedances. Figure 19 shows the measured data again compared to the design requirement. The results show that the panels are no longer tuned to the desired frequencies. This is expected since the linings were designed considering the opposing wall to be lined with the same material.

Inlet Lining Attenuation

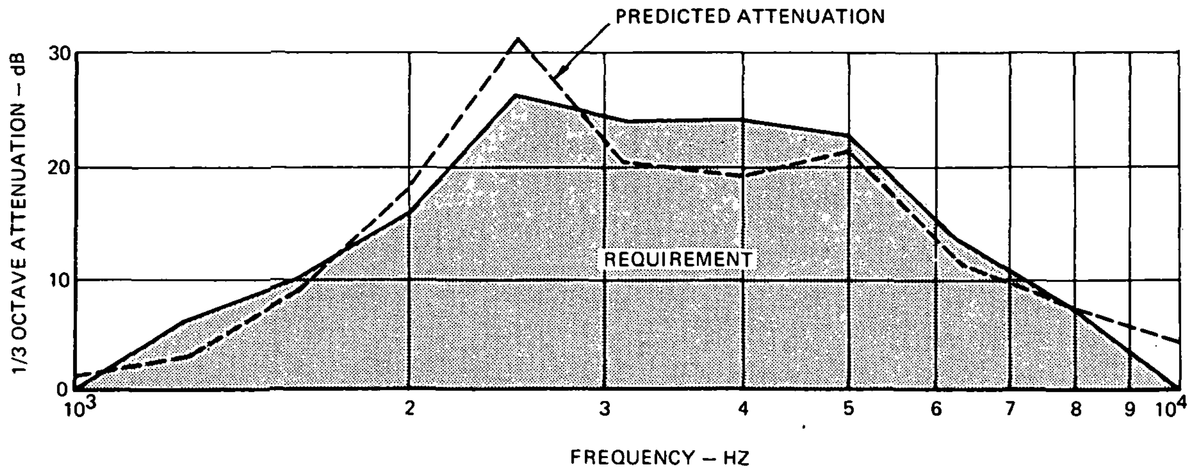
The inlet attenuation was analyzed considering the sheared flow profile in the inlet. With the exception of flow profile, the same assumptions are made as in the fan duct analysis.

The outer channel of the inlet was simulated in the flow duct and lining attenuations recorded at Mach numbers corresponding to takeoff and approach fan speeds. Figure 20 shows the measured attenuation for the approach fan speed, which was the inlet design condition.

Predicted Nacelle Performance

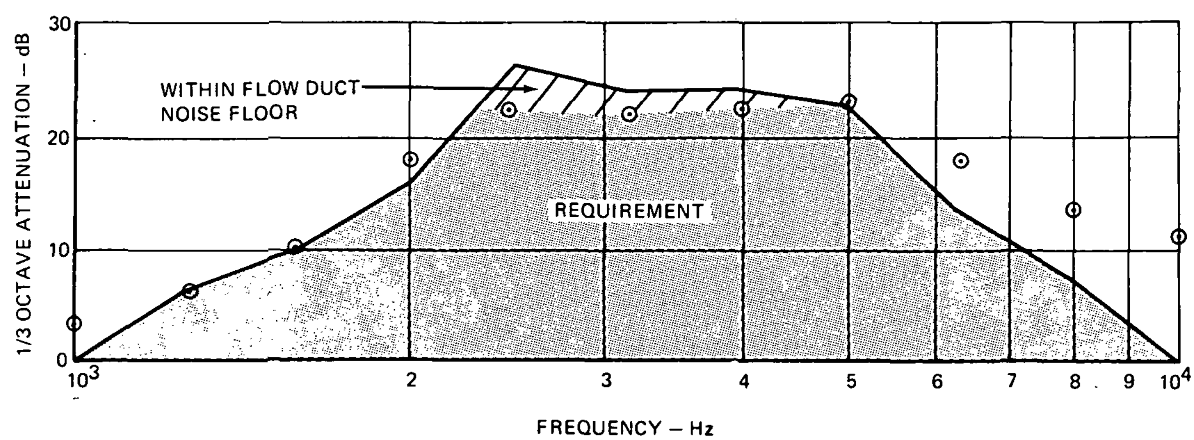
Aerodynamic performance.– The two conceptual nacelle designs were analyzed to determine total pressure losses in the inlet and fan duct at particular flight conditions. The conditions selected for the flight nacelle were takeoff thrust at zero velocity and .82 Mach cruise at 10,670 m altitude (35,000 ft). External nacelle drag was also estimated at the cruise condition. The quiet fan nacelle aerodynamic performance was based on inlet and fan duct losses at approach and takeoff fan speeds.

NOTE: TAKEOFF CONDITION



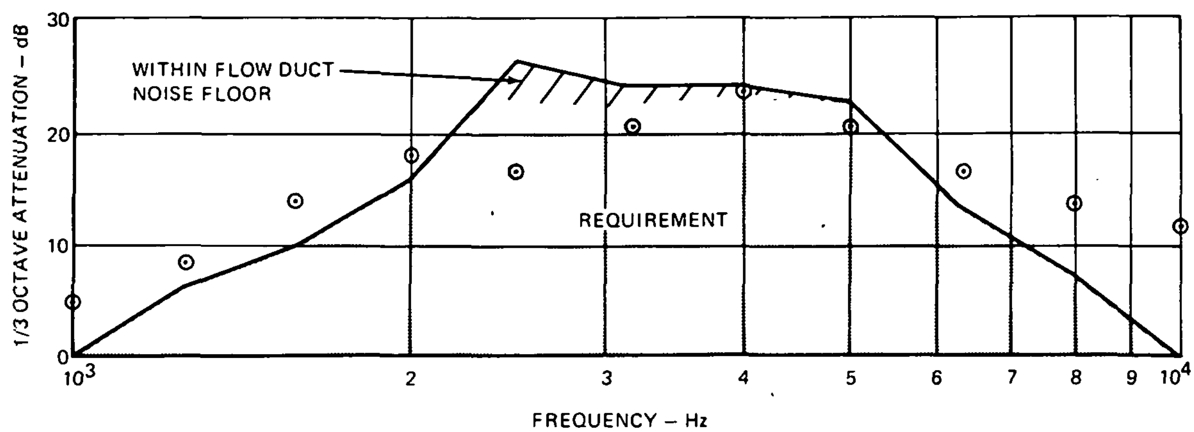
COMPARISON OF PREDICTED FAN DUCT ATTENUATION WITH REQUIREMENT – CONCEPTUAL NACELLE
FIGURE 17

NOTES: 1) ⊙ MEASURED ATTENUATION IN FLOW DUCT
2) EQUAL IMPEDANCE ON OPPOSITE WALLS
3) TAKEOFF CONDITION



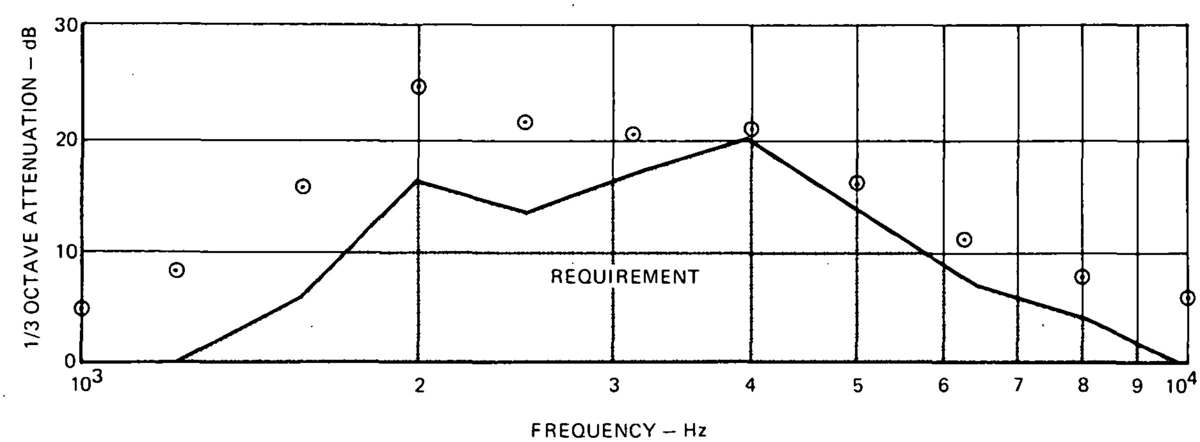
FLOW DUCT EVALUATION OF FAN DUCT LININGS, EQUAL IMPEDANCE ON OPPOSITE WALLS
FIGURE 18

NOTE: 1) ⊙ MEASURED ATTENUATION IN FLOW DUCT
2) CONSTANT LINING ON EACH WALL
3) TAKEOFF CONDITION



FLOW DUCT EVALUATION OF FAN DUCT LININGS, CONSTANT LINING ON EACH WALL
FIGURE 19

NOTE: 1) ⊙ MEASURED ATTENUATION IN FLOW DUCT
2) FLOW DUCT CONFIGURATION FOR INLET OUTER CHANNEL
3) APPROACH CONDITION



FLOW DUCT EVALUATION OF INLET LININGS
FIGURE 20

The internal pressure losses were based on skin friction drag only. The other drag components were small by comparison because the ring thickness to chord ratio was low and because the rings have no areas of flow separation. The skin friction of the acoustic lining was experimentally measured to be 1.85 times that of a flat plate. These losses are compared to a nacelle without rings or acoustic linings.

Table II summarizes the estimated pressure and thrust losses at the conditions analyzed. The takeoff thrust loss due to acoustic treatment was estimated to be 3.9 and 4.7 percent for the flight nacelle and quiet fan nacelle, respectively.

Acoustic performance.— Table III lists the predicted conceptual nacelle acoustic performance at approach and takeoff power settings. The design goal of 10 EPNdB reduction at the approach condition was achieved. A 7 EPNdB reduction was achieved at the takeoff condition. This includes a 0.5 EPNdB penalty due to nacelle aerodynamic losses causing a decreased altitude over the takeoff measurement station. These noise predictions assume that the core engine jet velocity is reduced by the airplane forward velocity prior to calculating the core jet noise. If this assumption is not valid, the estimated noise reductions are reduced to 9.5 and 4 EPNdB at approach and takeoff, respectively.

Predicted maximum noise reductions of the NASA quiet fan are estimated to be 11 to 13 PNdB along a 61 m (200 ft) arc in the inlet quadrant. Peak reductions in the aft quadrant are estimated to be 10 to 11 PNdB depending on fan speed.

QUIET ENGINE NACELLE

The second phase of this study was detailed design and fabrication of an acoustically treated nacelle for the NASA/General Electric quiet engine with fan A.

The acoustic design goal for the quiet engine nacelle was a fan noise attenuation of 15 PNdB. The nacelle was also designed to provide reduced attenuation levels of 5 and 10 PNdB. The reduced levels can be demonstrated by taping selected parts of the acoustic linings. Internal lines were selected to be typical of flight nacelle design with internal losses minimized. The nacelle configuration is shown in Figure 21. The following sections summarize its design and expected performance.

Aerodynamic Design

The quiet engine nacelle is designed to be representative of a flightworthy nacelle; consequently, factors affecting the performance of the nacelle at cruise flight conditions are considered in the design, as well as the takeoff and approach conditions. The external lines of the nacelle are also designed to be representative of a minimum drag nacelle, excluding wing/nacelle interference.

Inlet design.— Acoustic analysis revealed that the inlet should contain three rings, each approximately 3.3 cm thick with 1.02 m of treatment length. A long treated centerbody containing .76 m of acoustic treatment was also required. Figures 22 and 23 summarize the trade studies used to select this configuration. Figure 22 shows that a three-ring design requires less area than a two-ring design. It also shows that use of a lined centerbody with a three-ring inlet reduces the required treated area 20 percent below that if the centerbody is unlined. The inlet length is minimized with a three-ring design as shown in Figure 23. A three-ring inlet designed for 15 PNdB reduction in perceived noise level is approximately the same length as a nacelle designed for good aerodynamic performance.

TABLE II
PREDICTED CONCEPTUAL NACELLE AERODYNAMIC PERFORMANCE

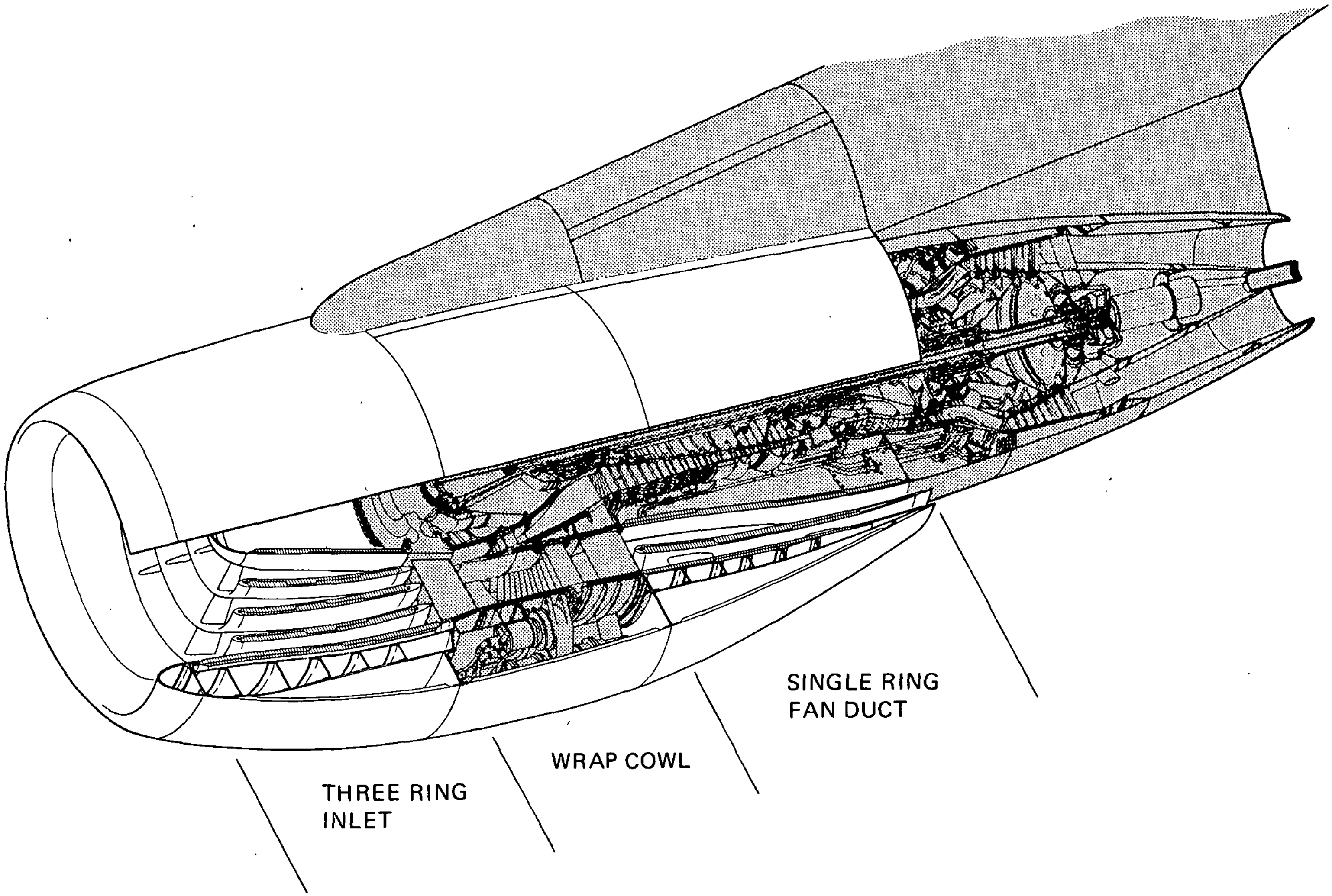
CONDITION		INLET PRESSURE LOSS (%)	FAN DUCT PRESSURE LOSS (%)	THRUST LOSS (%)	TSFC INCREASE (%)
Quiet Engine Nacelle	Takeoff	1.0	1.9	3.9	–
	Cruise Mach = 0.82 Altitude = 10,670 m	1.0	2.7	4.8	4.0
Quiet Fan Nacelle	Takeoff	1.1	2.6	4.7	–
	Approach	0.4	0.8	–	–

Note: Performance is compared to a nacelle without acoustic linings or rings.

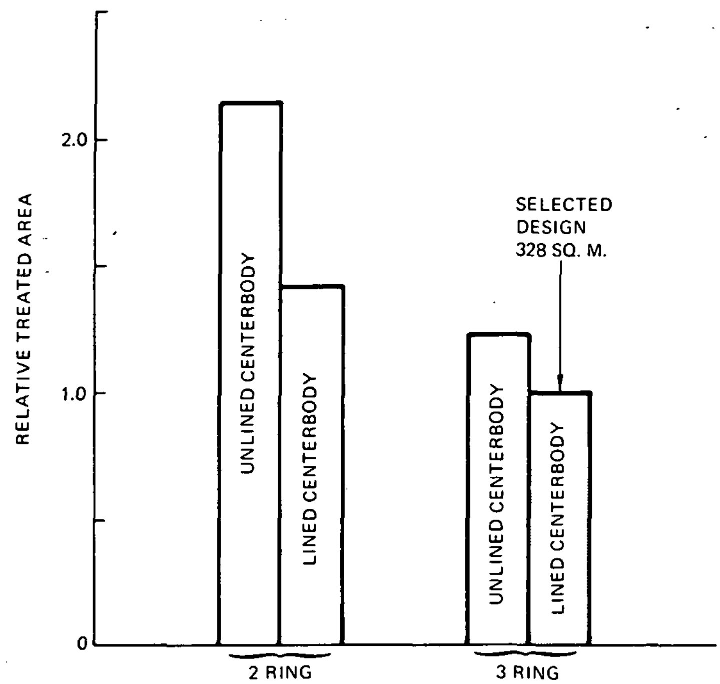
TABLE III
PREDICTED CONCEPTUAL NACELLE ACOUSTIC PERFORMANCE

CONDITION		APPROACH	TAKEOFF
QUIET ENGINE NACELLE ΔEPNL – EPNdB	GOAL	10	7.5
	FAN NOISE REDUCTION	10.5	10
	ENGINE NOISE REDUCTION WITH RELATIVE JET VELOCITY CORRECTION	10.00[1]	7.5[2] 7.0[3]
	ENGINE NOISE REDUCTION WITHOUT RELATIVE JET VELOCITY CORRECTION	9.5[1]	4.0[2]
QUIET FAN NACELLE MAXIMUM ΔPNL AT 61 m AND INDICATED ANGLE FROM INLET CENTERLINE	INLET QUADRANT	11 at 20°	13 at 50°
	EXHAUST QUADRANT	10 at 130°	11 at 100°

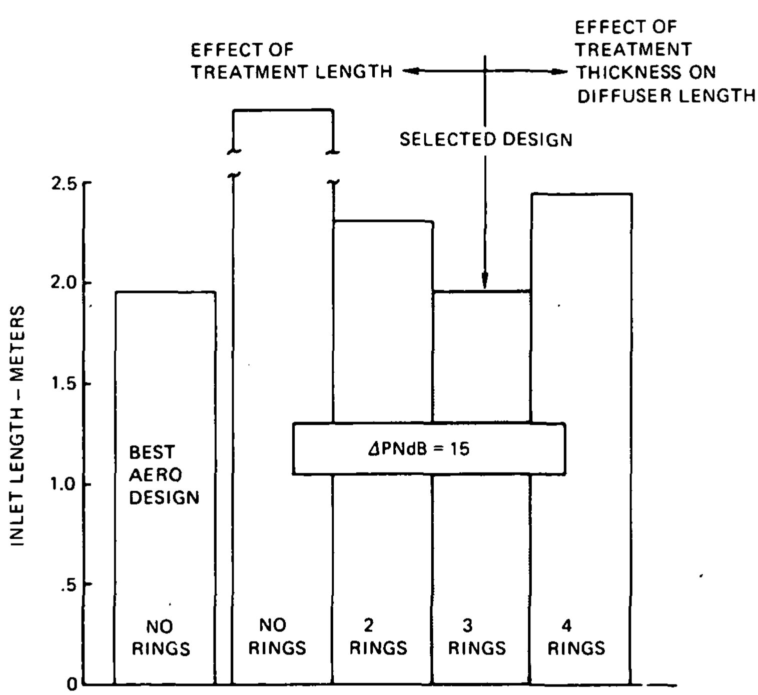
[1]AIRPLANE PERFORMANCE EFFECTS ARE NEGLIGIBLE
[2]NEGLECTS AIRPLANE PERFORMANCE LOSSES
[3]INCLUDES AIRPLANE PERFORMANCE LOSSES



QUIET ENGINE NACELLE CONFIGURATION
FIGURE 21



EFFECT OF INLET CONFIGURATION ON REQUIRED ACOUSTIC TREATMENT
FIGURE 22



EFFECT OF INLET CONFIGURATION ON INLET LENGTH
FIGURE 23

The inlet throat area was sized for a one dimensional throat Mach number of .77 at the engine maximum referred airflow. The maximum referred airflow, given in Reference 9, is 452 kg/sec. This occurs for maximum power at Mach .376 and 10,670 m altitude. The required throat area for .77 Mach at this airflow is 2.01 m^2. Based on this throat area and the acoustic constraints, an outer cowl contour was selected for satisfactory inlet area progression with centerbody and rings included.

The centerbody contour was designed so that inlet wall passages would be approximately parallel. The inlet throat was positioned 1.75 m from the fan face. The inlet lip contraction ratio was 25% with a 2.5:1 ellipse for the highlight to throat contour. The upper cowl external contour was sized to give minimum drag at cruise. The shape is a NACA-1 inlet contour for the .82 Mach number design.

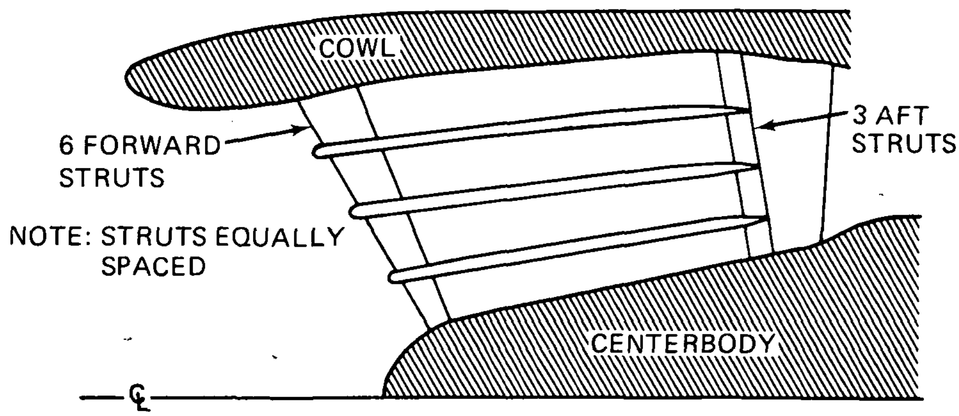
An axisymmetric compressible potential flow field analysis was performed on the inlet cowl and centerbody at the takeoff power setting. Based on this analysis, three streamlines were selected for location of the acoustic rings. The streamlines were selected for approximately equal spacing between rings. The rings were made 3.3 cm thick and had constant thicknesses for .88 m on the inner ring, .97 m on the center ring, and 1.04 m on the outer ring. Each ring had a biconvex trailing edge and a 3:1 elliptic leading edge. With the rings located on the desired streamlines, the inlet was reanalyzed with compressible potential flow field studies at the takeoff, approach, and cruise conditions. In addition, boundary layer analyses were performed at the takeoff and cruise conditions. These showed that the flow would remain attached to the inlet surfaces. The final inlet design for the quiet engine with Fan A is shown on Figure 24 and the area progression for the inlet design is shown on Figure 25.

Fan duct design.— Acoustic analyses determined that the fan duct required a single acoustic ring 3.8 cm thick and 1.52 m long. The 3.8 cm ring thickness was required for 1.22 m of the lined length. The maximum fan duct length was selected for access to the core engine aft cowl. This located the fan nozzle near the maximum core cowl diameter. Inner and outer fan duct lines were developed for smooth area progression with the acoustic ring present. Provision was also made for a three percent fan duct nozzle increase from the nominal 1.155 m^2 to reduce exhaust velocities and fan jet noise. The nacelle strut pylon and accessory tower shaft pylon lines were furnished by General Electric for the quiet engine. Pylon contours are given in Reference 15.

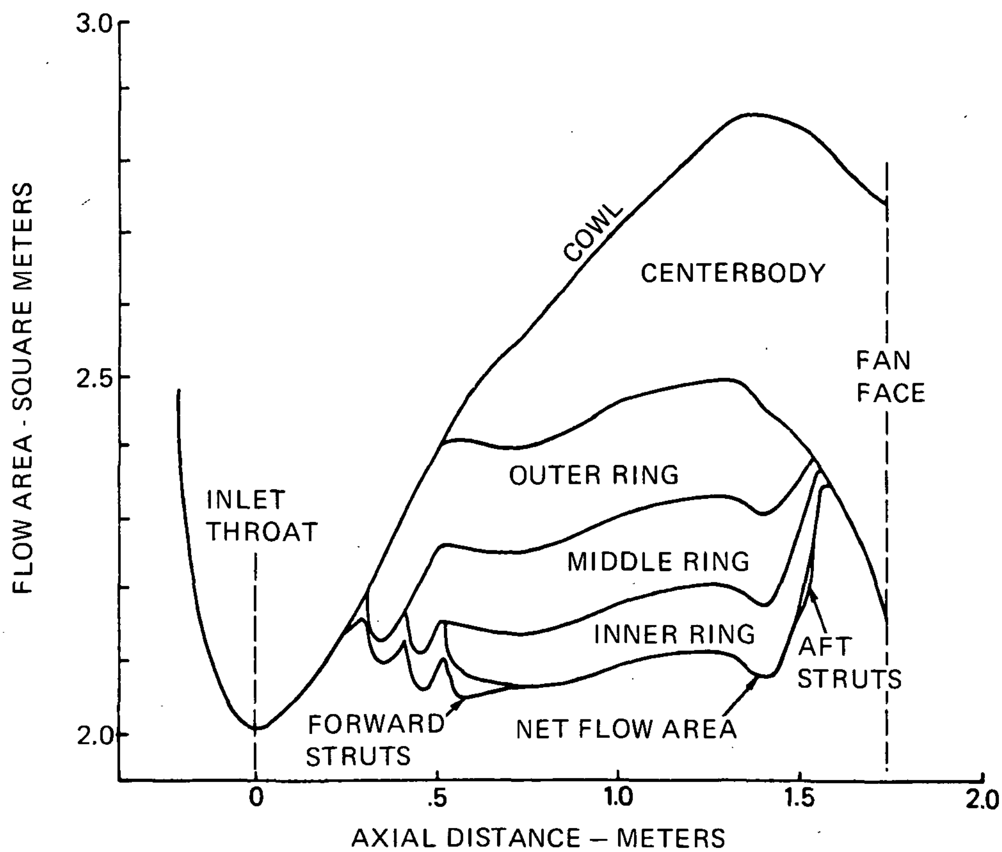
The inner and outer walls of the fan duct were selected as circular arcs in cross section. The fan duct configuration was analyzed with axisymmetric compressible potential flow field studies at the takeoff power setting. From this analysis, a streamline was located on which to place the acoustic ring. The ring was located on the streamline and had a 2.67:1 elliptic leading edge. The ring was 3.8 cm constant thickness for the front 1.22 m and then tapered to the trailing edge over a distance of 45.7 cm. This fan duct configuration was then reanalyzed using axisymmetric compressible potential flow field and boundary layer growth studies. No separation or adverse flow regions were found in the fan duct.

The upper cowl external surface was shaped as a cylinder of the maximum nacelle diameter and had a boattail radius at the aft end of approximately four times the maximum diameter.

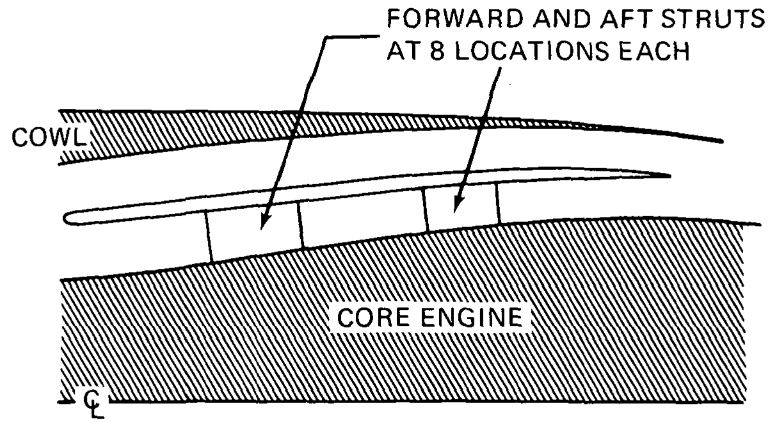
The fan duct contours developed for the quiet engine nacelle are shown on Figure 26 and the area progression is shown on Figure 27.



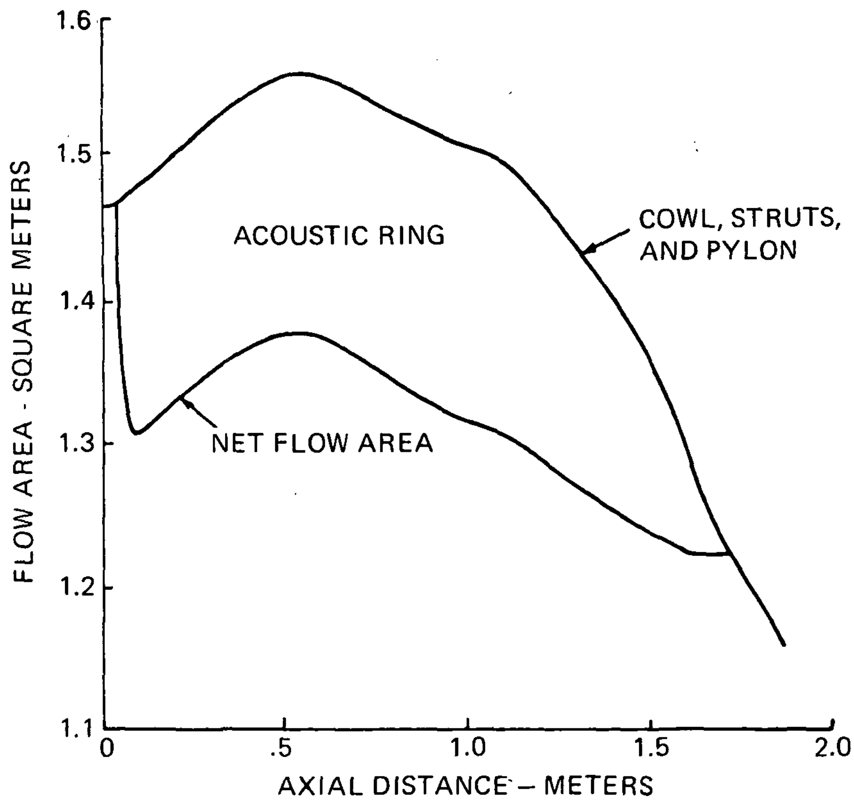
INLET CONTOURS – QUIET ENGINE NACELLE
FIGURE 24



INLET AREA PROGRESSION – QUIET ENGINE NACELLE
FIGURE 25



FAN DUCT CONTOURS – QUIET ENGINE NACELLE
FIGURE 26



FAN DUCT AREA PROGRESSION – QUIET ENGINE NACELLE
FIGURE 27

External contours.– The external contours of the quiet engine nacelle are not axisymmetric because the engine accessories are located on the fan case. For this reason, the lower half of the nacelle is larger than the upper half to clear the accessories which were designed for a much larger engine. The lower fairing is not necessarily that which would be used for a flightworthy nacelle since the required shape must be designed for a specific airplane and confirmed by wind tunnel testing. The forward and aft upper contours of the external cowl have been described in the inlet and fan duct sections.

Estimated performance.– The losses associated with the acoustic treatment were evaluated for the quiet engine with fan A at the takeoff and cruise flight conditions. Engine performance losses are based only on internal skin friction drag. Since the rings have a small thickness/chord ratio and are located on streamlines, profile drag was assumed negligible.

The inlet has 32.79 m^2 of acoustic treatment and 6.69 m^2 of smooth wall. The fan duct had 33.63 m^2 of acoustic treatment and 5.76 m^2 of smooth wall. The procedure used in estimating the performance of the nacelle is outlined in Reference 5. The estimated nacelle performance is summarized in Table IV.

Acoustic Linings

The required attenuation spectrum for fan A has a broad bandwidth since the fan has relatively low blade passage tone noise levels with respect to broadband fan noise. The basic design approach employs three single layer linings to provide the attenuation necessary for a 15 PNdB reduction in fan noise. The linings are tuned to the first, second, and third harmonics of the blade passage frequency at approach power fan speed. The linings on each wall of a channel were segmented with opposing walls having the same acoustic properties. Consequently, the configuration was readily adaptable to theoretical analysis. Although only three types of lining are in each channel, in some cases the same type was located in two different positions in the channel to minimize ring thicknesses and reduce the associated aerodynamic performance losses.

Lining material.– The face sheet material selected for the acoustic linings was a laminated glass fiber cloth impregnated with polyimide resin. The face sheet resistance is varied by the number of plies of glass fiber cloth in the laminate. Since each lining segment requires a different acoustic impedance, both the face sheet resistance and backing cavity depth must be segmented.

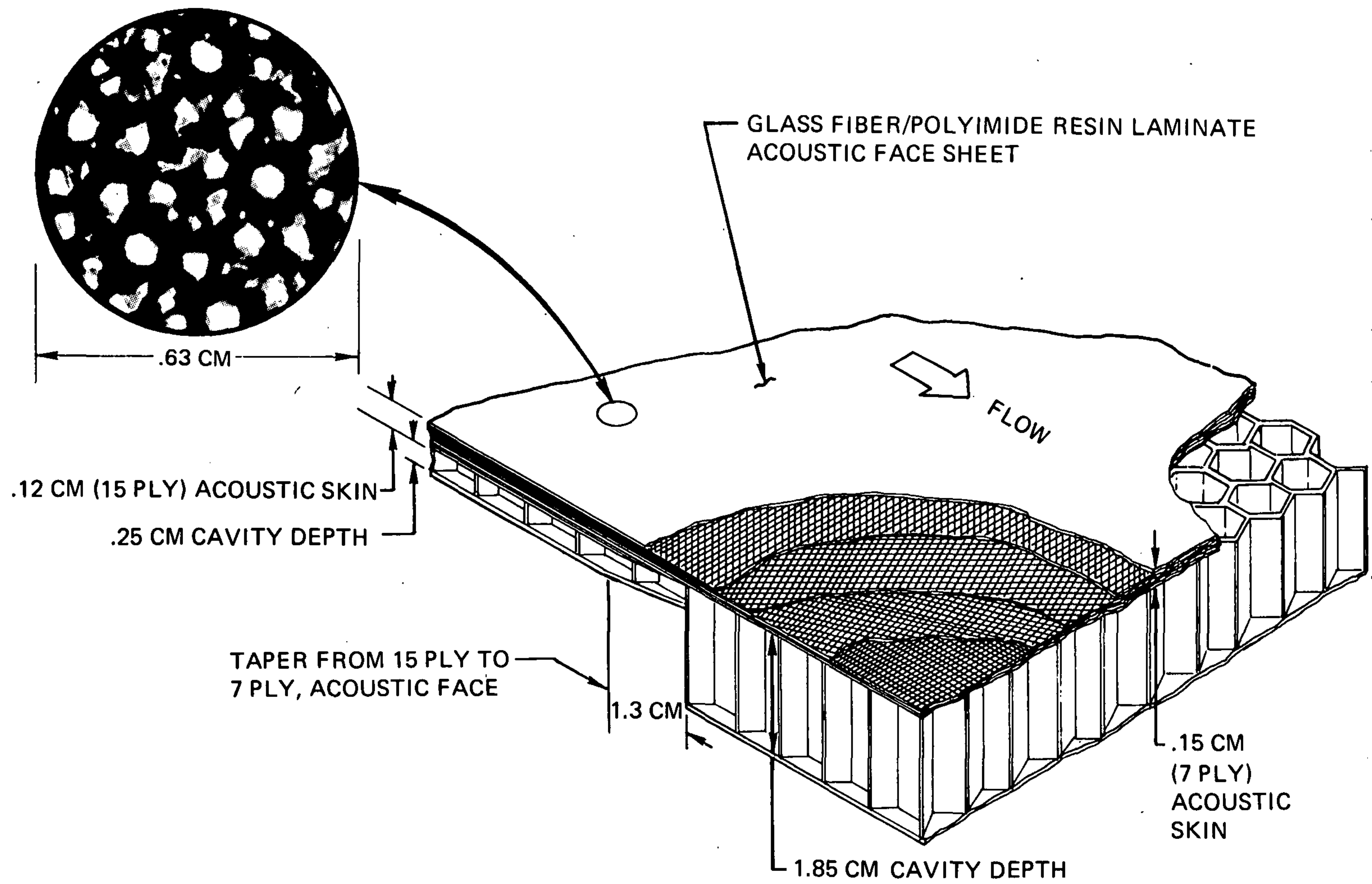
An example of a segmented lining construction is shown in Figure 28. This example is an inlet cowl lining in the quiet engine nacelle. The layers of glass cloth are arranged with an angular orientation which provides uniform permeability of the porous structure. The sketch shows a uniformly smooth aerodynamic surface with no loss in treated area during the transition from one lining segment to the next. The polyimide/glass fiber facing sheet is bonded to a honeycomb cell structure; an impervious backing sheet is also bonded to the honeycomb.

Inlet linings.– Figure 29 is a cross section of the inlet showing the arrangement of the segmented linings. Table V lists the composition, tuned frequency, and impedance of each lining at the approach power setting. Lining lengths are given for the maximum attenuation configuration and two lower levels of attenuation which provide approximately 5 and 10 PNdB reductions in fan noise at the design condition. The lower levels can be achieved by taping the linings to reduce their effective lengths.

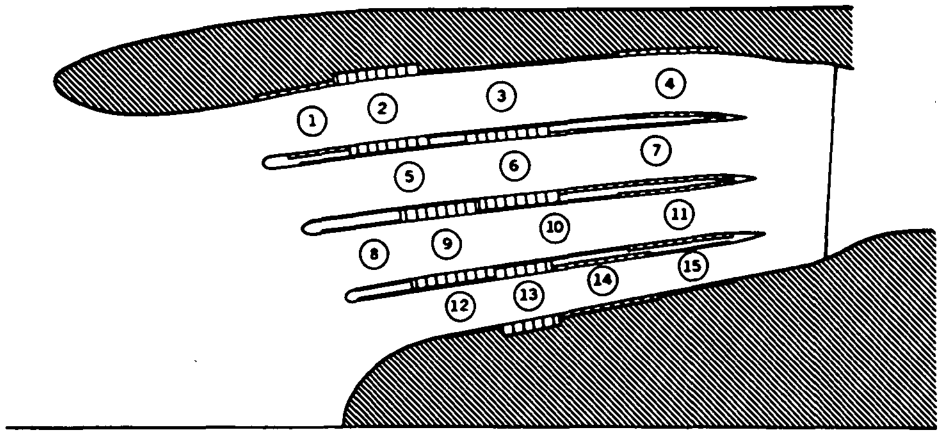
TABLE IV
PREDICTED AERODYNAMIC PERFORMANCE – QUIET ENGINE NACELLE

CONDITION	INLET ($32.8\ m^2$ TREATMENT)		FAN DUCT ($33.6\ m^2$ TREATMENT)		THRUST LOSS DUE TO TREATMENT	TSFC INCREASE DUE TO TREATMENT
	PRESSURE LOSS (Treated)	PRESSURE LOSS (Untreated)	PRESSURE LOSS (Treated)	PRESSURE LOSS (Untreated)		
Takeoff	1.61%	.23%	3.31%	1.1%	5.0%	3.9%
Cruise M = .82 10,670 m	2.0%	.36%	4.66%	1.51%	6.4%	5.4%

Note: Reference performance is for a nacelle without acoustic linings or rings



TYPICAL LINING CONSTRUCTION
FIGURE 28



LOCATION OF INLET LININGS – QUIET ENGINE NACELLE
FIGURE 29

TABLE V
CHARACTERISTICS OF QUIET ENGINE NACELLE INLET LININGS

LINING SEGMENT	TUNED FREQUENCY (Hz)	NUMBER OF PLIES		CAVITY DEPTH (CM)		AVERAGE IMPEDANCE		LINING LENGTH (CM)		
		OUTER WALL	INNER WALL	OUTER WALL	INNER WALL	$R/\rho c$	$X/\rho c$	MAX.	10 PNdB	5 PNdB
1	3000	14	15	.43	.38	2.2	-2.2	20.3[1] 15.2[2]	10.2	0
2	1500	8	8	1.88	1.88	.9	-1.2	20.3	15.2	10.2
3	4500	12	13	.23	.20	2.0	-2.8	50.8	20.3	10.2
4	3000	11	12	.51	.48	1.6	-2.1	25.4	15.2	10.2
5	4500	15	15	.18	.18	2.9	-3.2	40.6[1] 35.6[2]	17.8	7.6
6	1500	7	7	1.88	1.88	.7	-1.3	20.3	15.2	10.2
7	3000	12	12	.51	.51	1.7	-1.9	45.7	25.4	17.8
8	4500	15	15	.38	.38	2.5	-2.4	20.3[1] 15.2[2]	0	0
9	1500	8	8	1.83	1.83	.8	-1.4	20.3	15.2	10.2
10	4500	13	13	.21	.21	2.2	-2.9	35.6	20.3	7.6
11	3000	11	11	.56	.56	1.5	-1.8	25.4	15.2	10.2
12	4500	15	15	.19	.19	2.7	-2.9	35.6[1] 15.2[2]	0	0
13	1500	5	4	2.23	2.48	.4	-1.1	15.2	10.2	7.6
14	3000	10	10	.61	.61	1.4	-1.5	25.4	15.2	10.2
15	4500	10	10	.30	.30	1.6	-1.9	20.3	20.3	7.6

[1] OUTER WALL

[2] INNER WALL

The effect of considering sheared flow in the inlet lining design is illustrated by lining Segment 1 in the outer channel. The lining on the cowl requires a 14 ply facing sheet with a .38 cm cell depth to achieve the proper impedance at the approach design condition. The opposing lining requires a 15 ply laminate and a .43 cm cell depth. The difference in lining requirement is due to different boundary layer characteristics on the respective surfaces.

The expected lining attenuation spectra for each inlet channel are shown in Figure 30. The results are based on a uniform velocity in the inlet.

Acoustic performance of the inlet outer channel was evaluated in the flow duct facility. Results of the test at the design condition are compared with a theoretical prediction of the expected attenuation in Figure 31. The theoretical prediction was made assuming uniform flow in the inlet. The measured attenuations agree well with the theoretical predictions. These results shows that if sheared flow effects are considered in inlet lining design, attenuations predicted assuming uniform flow can be attained.

The inlet ring segments and centerbody prior to assembly are shown in Figure 32.

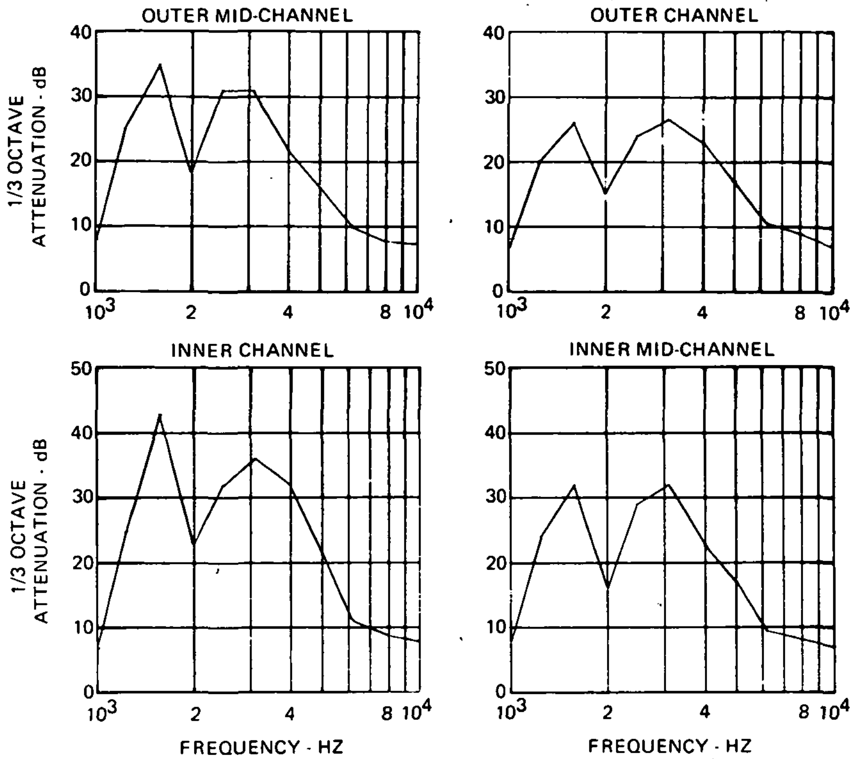
Fan duct linings.– The fan duct lining configuration is shown in Figure 33 and Table VI. The linings are segmented as in the inlet to provide an adequate attenuation bandwidth for the first three harmonics of the blade passage frequency. The order of the linings is staggered between the two channels to minimize thickness of the circumferential ring. To further minimize ring thickness, Linings 1 and 6 in Figure 33 were tuned to 2100 Hz rather than at the first harmonic of 1500 Hz. The resultant deficiency in low frequency attenuation was recovered by locating a segment of double layer lining in each cowling wall.

The double layer lining was designed for maximum attenuation at two frequencies. The selected frequencies in this application were the first and third blade passage harmonics at 1500 and 4500 Hz. The double layer lining was opposed by a single layer lining designed for 4500 Hz. Consequently, the opposing linings are each tuned for 4500 Hz. At 1500 Hz, the double layer lining is effective but the opposing single layer lining is ineffective. To account for this in the lining design, the double layer lining impedance at 1500 Hz was selected as if the effective channel height was twice the actual height. The attenuation spectrum of this combination can be predicted analytically by two separate analyses: one which considers the low frequency lining, and one which considers the two higher frequency linings.

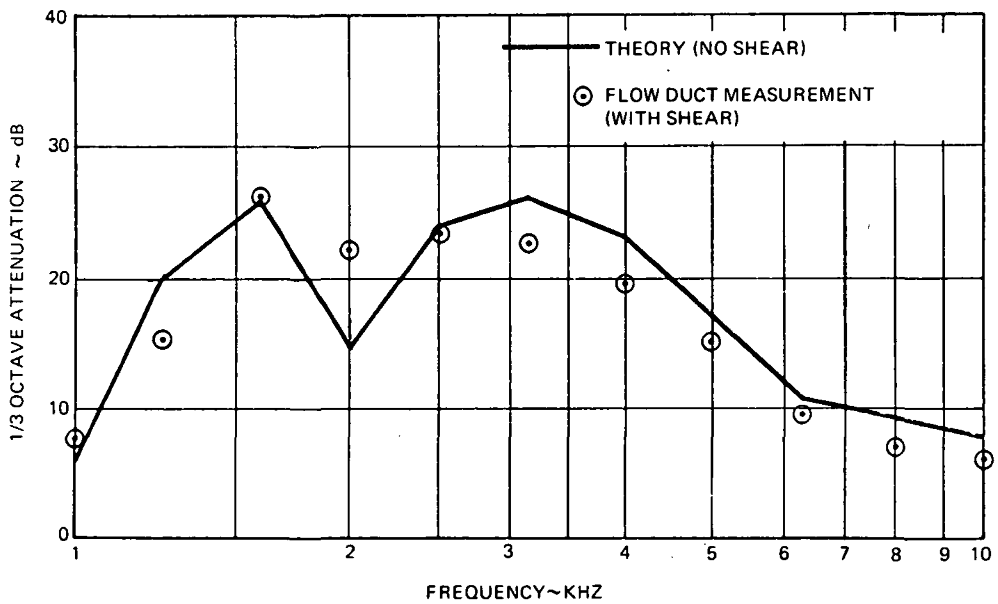
The 38 cm lining segment containing the double layer lining was evaluated in the flow duct. The attenuation results are compared with the theoretical prediction in Figure 34. The desired broadband attenuation spectrum and tuning were demonstrated by the test.

The results of a flow duct test of total fan duct lining are shown in Figure 35. The data points, which are measurements, exceed the theoretical predictions except at the third octave center frequencies between 2000 and 4000 Hz. In this frequency range, the actual peak attenuation could not be measured because of the flow duct facility noise floor. The test data show that the theoretical predictions were conservative at the higher frequencies.

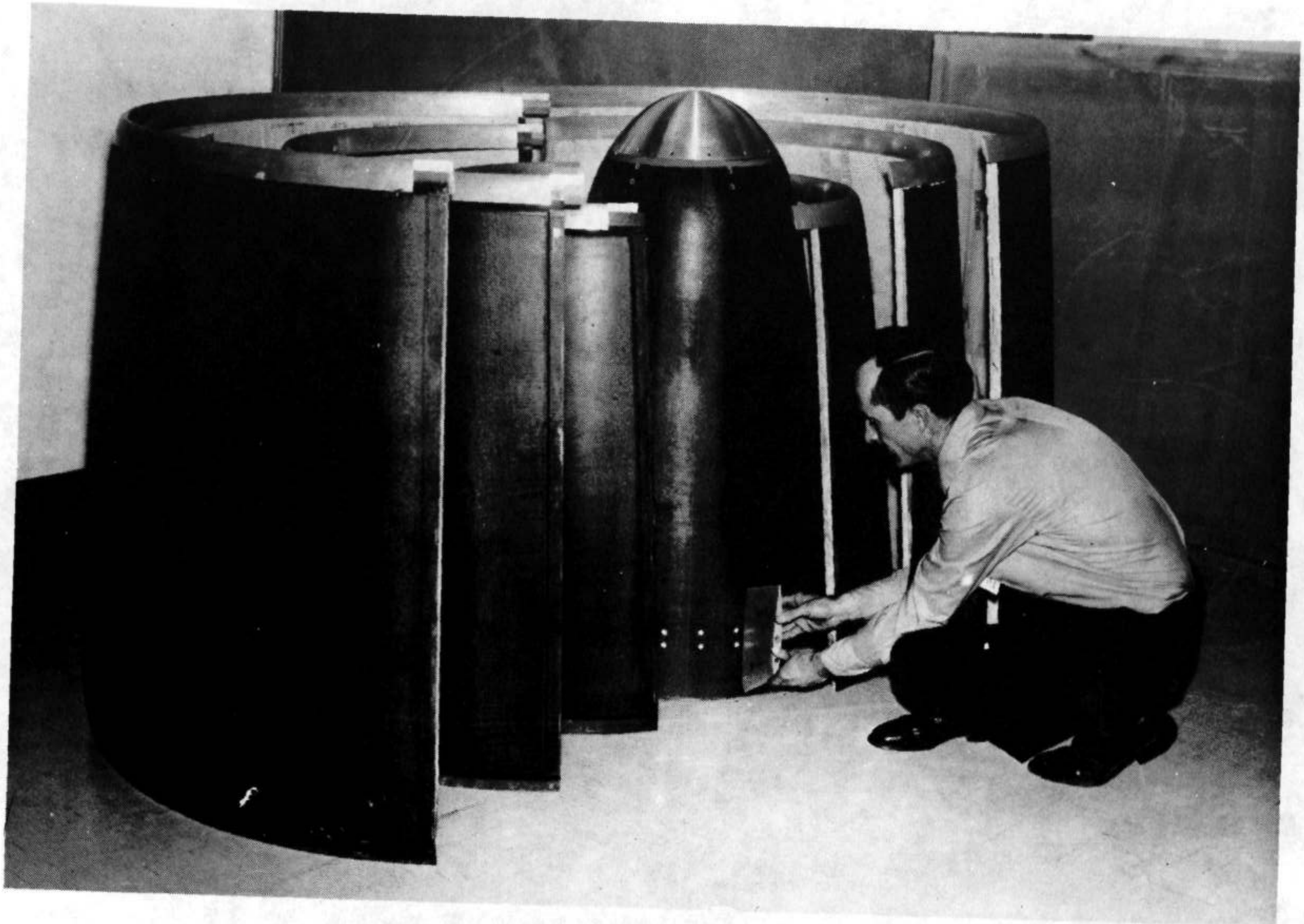
Figure 36 shows a segment of the fan duct ring and outer cowl wall lining prior to assembly.



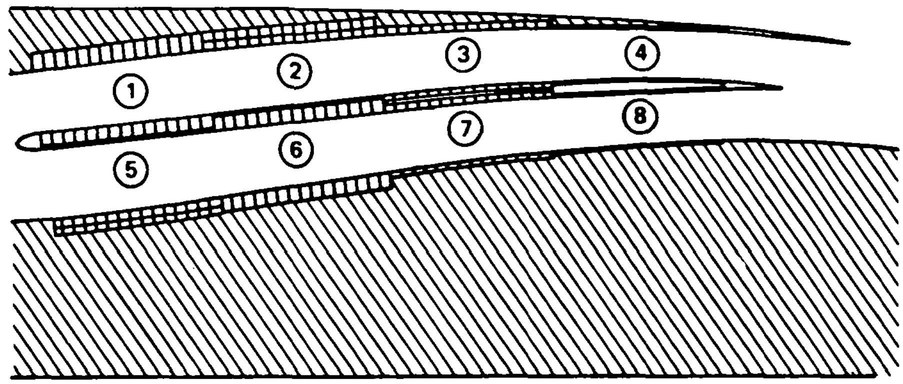
PREDICTED INLET LINING ATTENUATION SPECTRA AT APPROACH – QUIET ENGINE NACELLE
FIGURE 30



FLOW DUCT EVALUATION OF INLET LININGS – QUIET ENGINE NACELLE
FIGURE 31



QUIET ENGINE NACELLE INLET RINGS AND CENTERBODY BEFORE ASSEMBLY
FIGURE 32



LOCATION OF FAN DUCT LININGS – QUIET ENGINE NACELLE
FIGURE 33

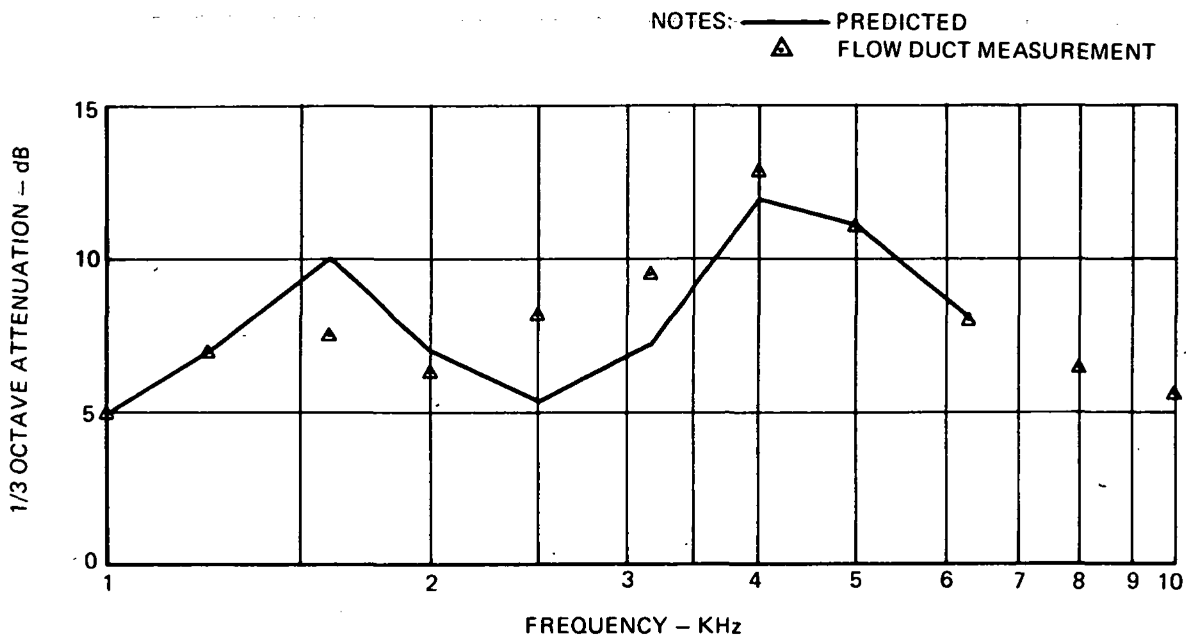
TABLE VI
CHARACTERISTICS OF QUIET ENGINE NACELLE FAN DUCT LININGS

LINING SEGMENT		TUNED FREQUENCY (HZ)	NUMBER OF PLIES	CAVITY DEPTH (CM)	AVERAGE IMPEDANCE $R/\rho c$	AVERAGE IMPEDANCE $X/\rho c$	LINING LENGTH (CM) MAX.	LINING LENGTH (CM) 10 PNdB	LINING LENGTH (CM) 5PNdB[1]
①		2100	5	2.54	.5	-.3	38	22.8	38
②	SINGLE LAYER	4500	7	.61	1.0	-.7			
	DOUBLE LAYER	1500 4500	4[2] 9[3]	1.32[2] 1.91[3]	.8 1.0	-.5 -.7	38	30.5	38
③		3000	6	1.52	.7	-.4	38	22.8	38
④		4500	7	.69	.9	-.6	38	0	38
⑤	SINGLE LAYER	4500	8	.58	1.0	-.7			
	DOUBLE LAYER	1500 4500	4[2] 9[3]	1.27[2] 1.83[3]	.8 1.0	-.5 -.7	38	30.5	38
⑥		2100	5	2.54	.5	-.4	38	22.8	38
⑦		3000	6	1.52	.7	-.4	38	22.8	38
⑧		4500	6	.69	.9	-.6	38	0	38

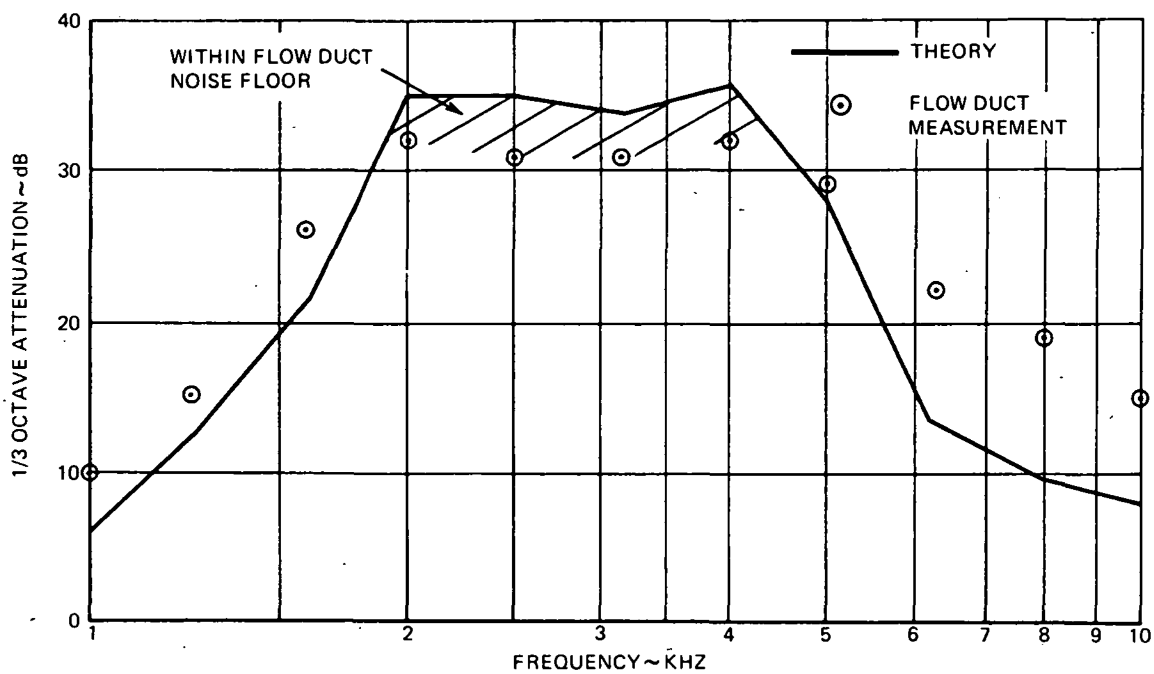
[1] RING REMOVED FOR 5 PNdB CONFIGURATION

[2] OUTER LAYER OF DOUBLE LAYER LINING

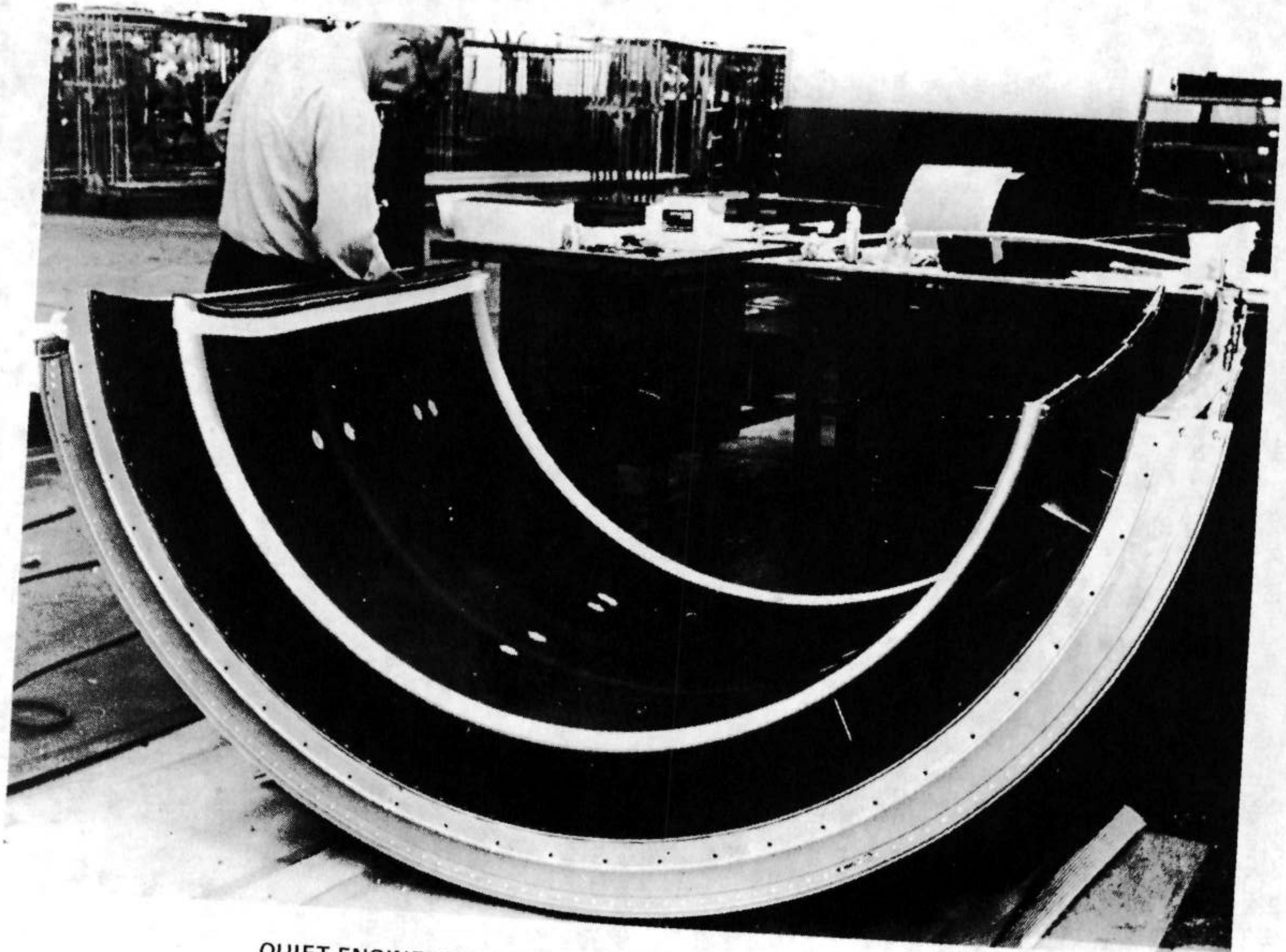
[3] INNER LAYER OF DOUBLE LAYER LINING



COMPARISON OF MEASURED AND PREDICTED ATTENUATION IN FAN DUCT SEGMENT CONTAINING DOUBLE LAYERED LINING
FIGURE 34



FLOW DUCT EVALUATION OF FAN DUCT LININGS – QUIET ENGINE NACELLE
FIGURE 35



QUIET ENGINE NACELLE FAN DUCT LININGS BEFORE ASSEMBLY
FIGURE 36

Estimated performance.— The predicted engine noise attenuation at takeoff power due to the acoustically treated nacelle is shown in Figure 37. The predictions assume uniform directivity of the attenuation spectra. The data show reductions in perceived noise levels along a 304.80 m (1,000 ft) sideline in 10° intervals from 10° to 160° from the inlet centerline. The maximum attenuation in the inlet quadrant occurs at 40°. At this angle, the predicted attenuation is 10.3 PNdB. Contributions of jet noise and attenuated fan noise to the predicted PNdB are approximately equal at this location. The maximum attenuation in the aft quadrant is predicted to be 6.0 PNdB at 120° from the inlet centerline. At this location, jet noise is the dominant contributor to the perceived noise level. The predictions do not consider changes in noise directivity patterns, noise reflection due to duct impedance discontinuities, and attenuation due to partial choking of the inlet flow. Consequently, the predictions are considered conservative.

Figure 38 shows the predicted engine noise attenuation at approach power along a 112.78 m (370 ft) sideline. The maximum expected attenuation in the inlet quadrant occurs 30° from the inlet centerline. The predicted attenuation at this location is 12.8 PNdB. Maximum attenuation in the aft quadrant occurs at 140° from the inlet centerline. The predicted attenuation at this location is 9.4 PNdB. Jet noise is the dominant contributor to perceived noise at this location. Lower attenuations are predicted between 100° and 130° because turbine noise dominates the perceived noise level.

Figure 38 also shows predicted attenuations for the two nacelle configurations with reduced treated areas. The effect of reducing the treated areas is apparent in the inlet attenuations. The effect of fan duct attenuations is less significant because of the turbine and primary jet noise levels in the aft quadrant.

The predictions for both power settings show reduced levels of attenuation in the aft quadrant. In each case, fan noise contributions to perceived noise are less than jet noise contributions at each angle in aft quadrant.

A photograph of the nacelle installed on the quiet engine at the NASA Lewis Engine Test Facility is shown in Figure 39.

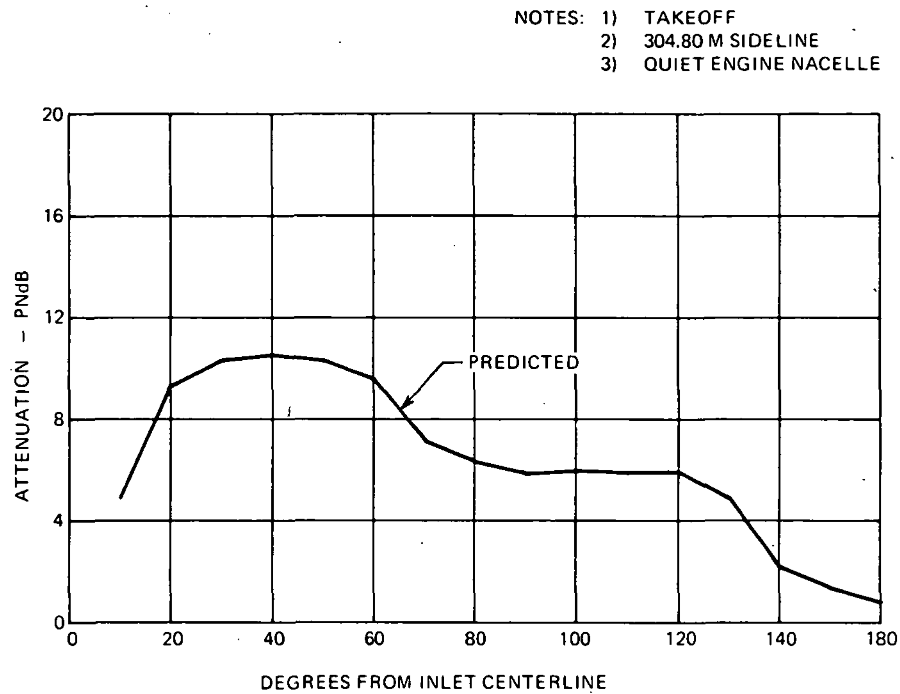
Nacelle weight.— Total weight of the ground test quiet engine nacelle is 1394.4 kg. Approximately 50 percent of this weight, 685.7 kg, is due to acoustic treatment with the balance due to support structure, outer cowlings, and other nontreated surfaces. The weight distribution of the acoustic linings by location is given in Table VII. These weights are not typical of flight nacelle construction.

Nacelle Systems

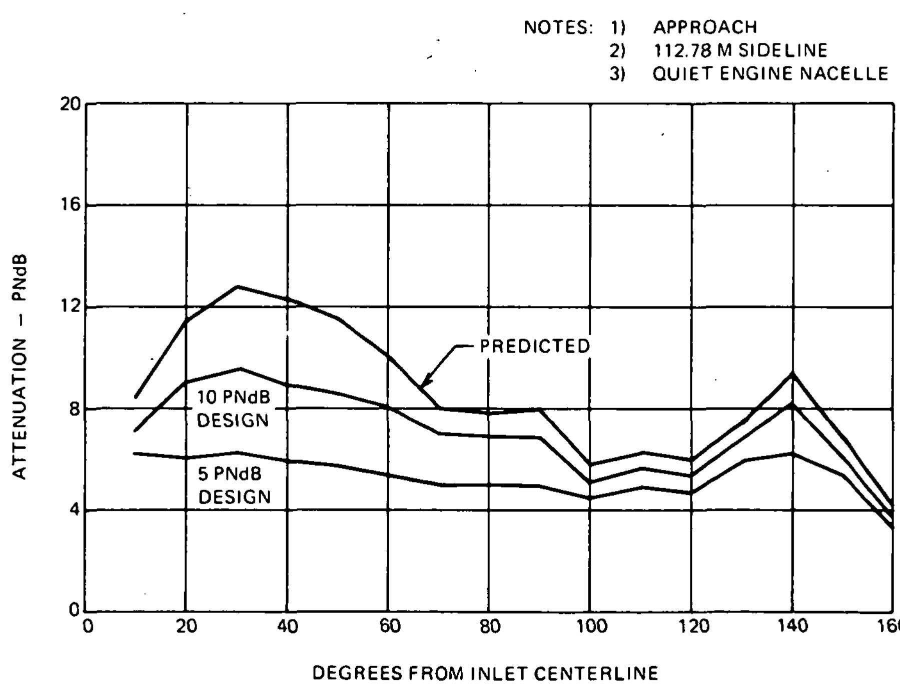
Anti-icing system concept.— A conceptual design of an inlet anti-icing system was developed for the quiet engine nacelle. The design flight condition was a Mach 0.4 holding pattern at 4572 m altitude (15,000 ft.). The icing condition assumes a liquid water content of 0.35 gm/m^3 with a mean droplet size of 15 microns.

The system design is shown schematically in Figure 40. Engine bleed air at 204°C is mixed in an ejector with secondary air drawn from the inlet cowl. This mixed flow at 149°C is exhausted along the cowl upstream of the acoustic lining or passes through the ring support struts to exhaust upstream of the ring acoustic linings. Estimated anti-icing airflow requirements at the design condition are given in Table VIII for each inlet surface.

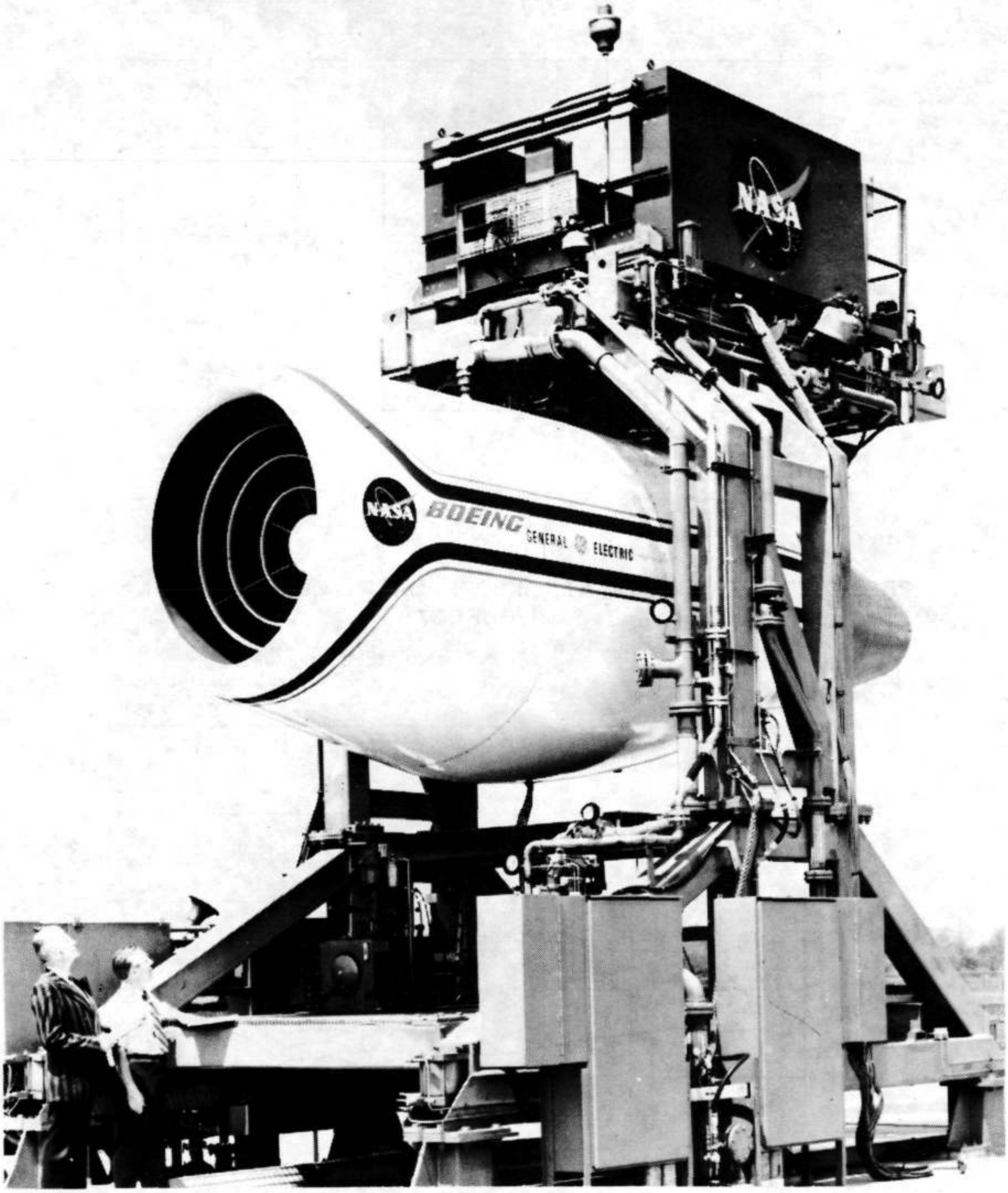
It is estimated that 75 percent, or 86 kg/min of the total mixed airflow will be required from engine bleed air.



PREDICTED ATTENUATION AT TAKEOFF POWER – QUIET ENGINE NACELLE
FIGURE 37



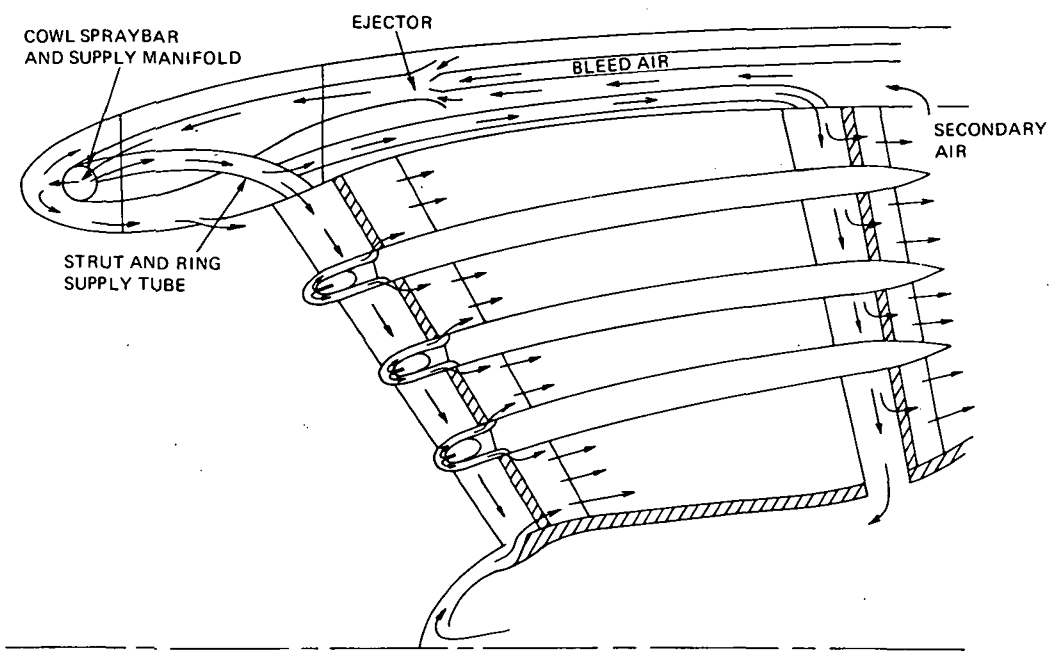
PREDICTED ATTENUATION OF APPROACH POWER – QUIET ENGINE NACELLE
FIGURE 38



NACELLE INSTALLED ON QUIET ENGINE AT NASA LEWIS ENGINE TEST FACILITY
FIGURE 39

TABLE VII
WEIGHT OF QUIET ENGINE NACELLE ACOUSTIC LININGS

ITEM		WEIGHT – kg	TREATED AREA – sq m
INLET	Cowl	98.0	8.45
	Outer Ring	122.9	10.13
	Mid-Ring	87.1	7.34
	Inner Ring	55.3	4.92
	Centerbody	20.4	1.95
	TOTAL	383.7	32.79
FAN DUCT	Outer Cowl	96.6	10.50
	Splitter	124.7	15.70
	Inner Cowl	80.7	7.43
	TOTAL	302.0	33.63
TOTAL NACELLE		685.7	66.42



SCHEMATIC OF INLET ANTI-ICING SYSTEM
FIGURE 40

TABLE VIII
ESTIMATED ANTI-ICING SYSTEM AIRFLOW REQUIREMENTS

SURFACE	AIRFLOW AT 149°C – kg/min.
Cowl	29.5
Outer Ring	23.6
Mid-Ring	17.2
Inner Ring	11.3
Centerbody	25.4
Struts	7.7
TOTAL	114.7

Thrust reverser concepts.—A limited evaluation was performed to select thrust reverser concepts for the primary and fan flows. Target, deflector, and cascade reversers were considered in the evaluation. Since the quiet engine has a high bypass ratio, approximately 80 percent of the thrust is developed from the fan duct at reverse thrust power settings. Consequently, a low efficiency, mechanically simple target thrust reverser was selected for the primary stream. A schematic of the target reverser in its deployed position is shown in Figure 41.

A cascade thrust reverser concept with blocker doors was selected for the fan duct because of its relatively high thrust reversal efficiency. Two cascade configurations were considered. The first, shown in Figure 42, has movable cascades which form part of the outer nacelle cowling when not deployed. The reverser is actuated by deploying blocker doors into the fan duct to force the fan exhaust through the cascades. Application of this concept to the quiet engine nacelle would require an increase in fan duct length to accommodate the reverser with no decrease in ring length.

The second configuration, shown in Figure 43, has fixed cascades located under the outer cowl at the forward end of the fan duct just aft of the engine support structure. The fan thrust reverser is actuated by aft translation of the outer cowl and ring which exposes the cascades. A linkage from the ring leading edge to a series of blocker doors in the outer cowl pulls the doors into the fan duct as the ring moves aft. This concept requires no increase in fan duct length and has the advantage of positive deployment of all blocker doors simultaneously.

QUIET FAN NACELLE

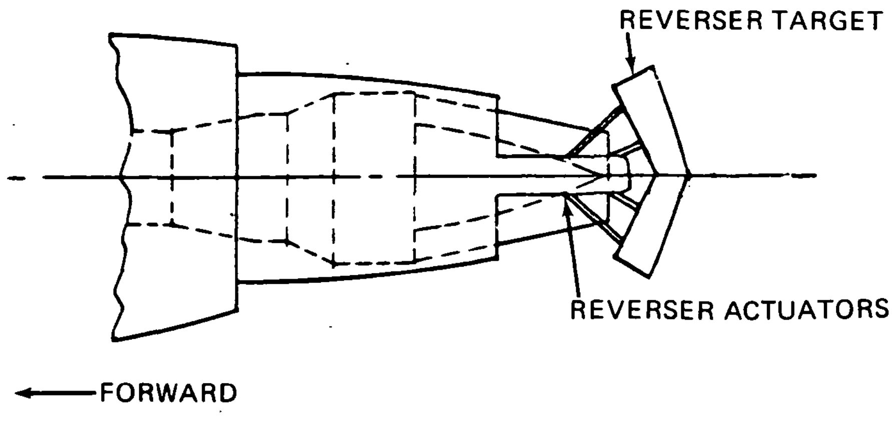
The acoustic design goal for the NASA quiet fan was the same goal used for the engine nacelle: a fan noise attenuation of 15 PNdB at polar angles where inlet and fan duct radiated noise are maximum. Internal lines were selected to minimize internal losses.

Aerodynamic Design

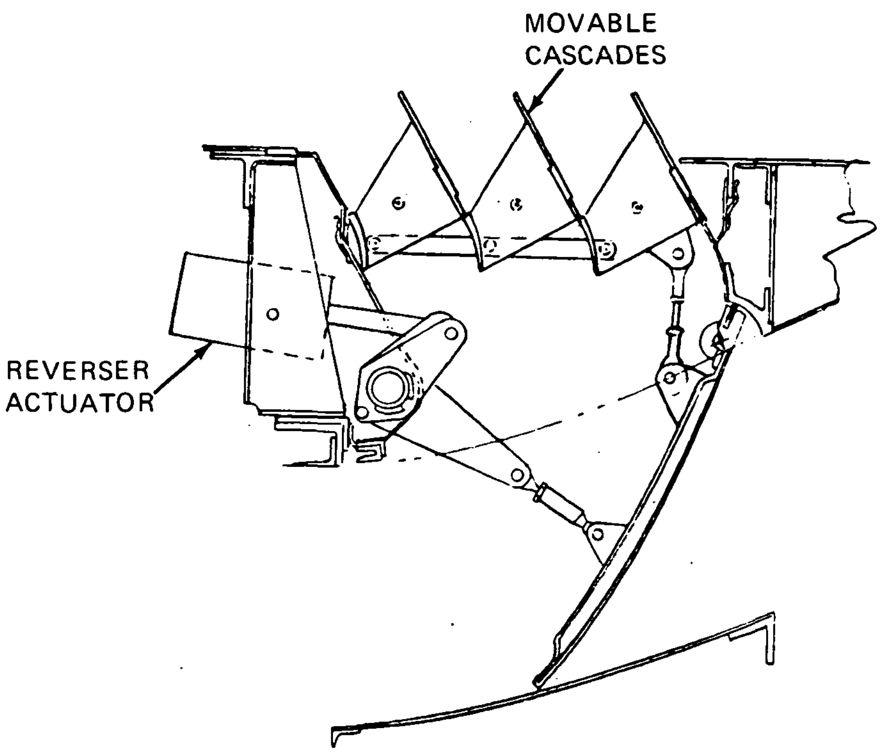
The NASA quiet fan nacelle uses the inlet shell of the quiet engine nacelle. The outer two inlet rings have the same contours as the quiet engine nacelle but have different acoustic characteristics. A new inner ring, centerbody, and a completely new fan duct were designed.

Inlet design.— As a preliminary design for the quiet fan nacelle inlet, the quiet engine lines were used with an adapter at the rear to mate with the fan case and a circular arc bellmouth at the lip. The fan test facility contains a 40 cm diameter drive shaft which passes through the inlet. Consequently, the centerbody was modified to provide clearance for this shaft. This configuration was analyzed using compressible axisymmetric potential flow field calculations at 90 percent fan speed. A boundary layer analysis showed that separation would occur on the inner surface of the inner ring. To correct this, the forward half of the inner ring was changed in contour and position to align the leading edge with the incoming streamlines. At the same time, the centerbody shape was altered, the length becoming greater and the angle more shallow. This was done to provide room for support strut attachment points at the front of the centerbody. The revised inlet configuration was analyzed with compressible potential flow studies for the 90 percent and 60 percent speed conditions. Boundary layer analyses did not show separation on any of the flow surfaces.

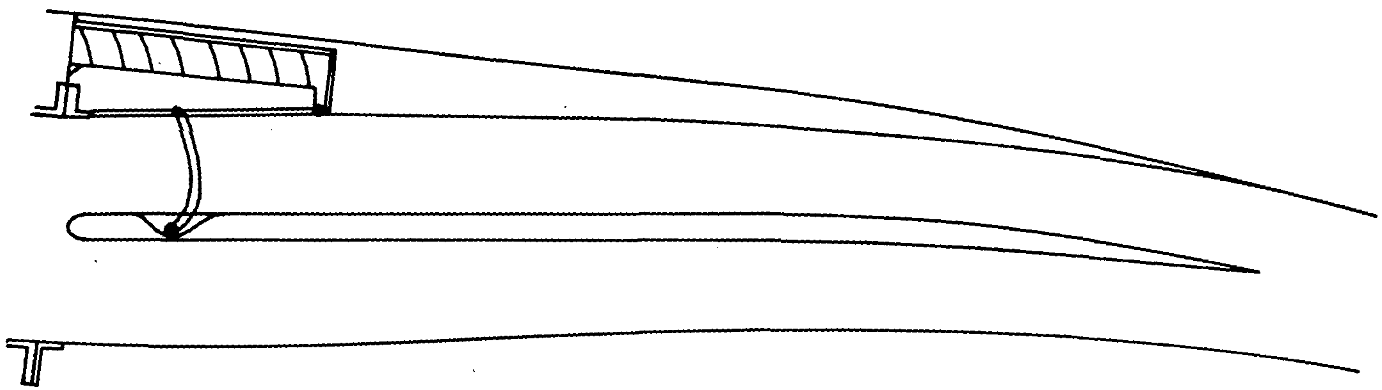
The inlet configuration is shown on Figure 44 and the area progression on Figure 45.



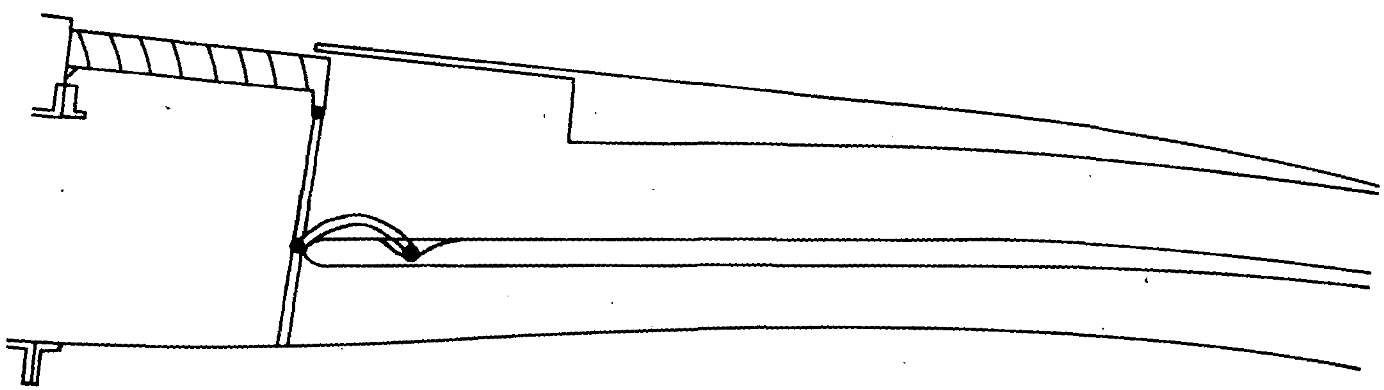
PRIMARY THRUST REVERSER CONCEPT
FIGURE 41



MOVABLE CASCADE FAN THRUST REVERSER CONCEPT
FIGURE 42

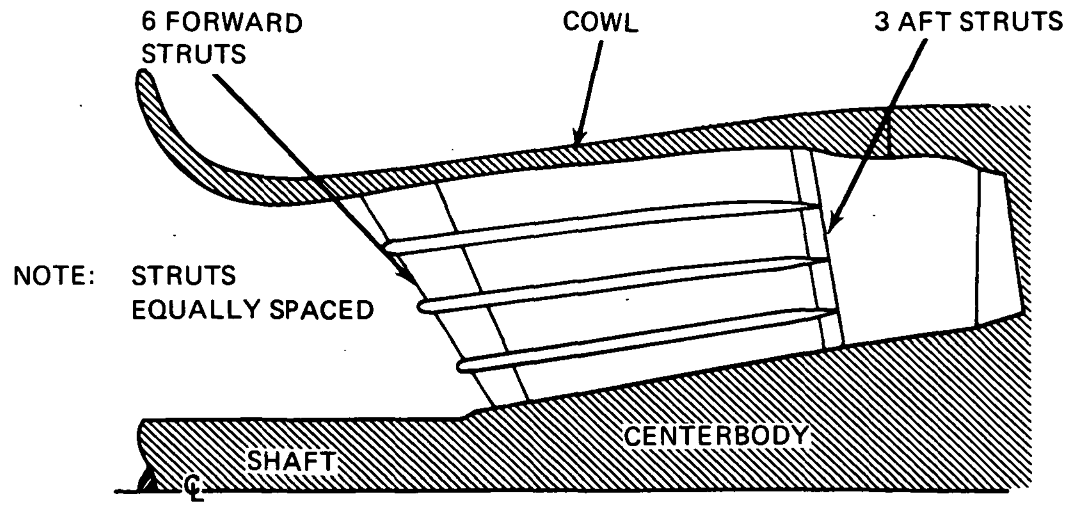


STOWED POSITION

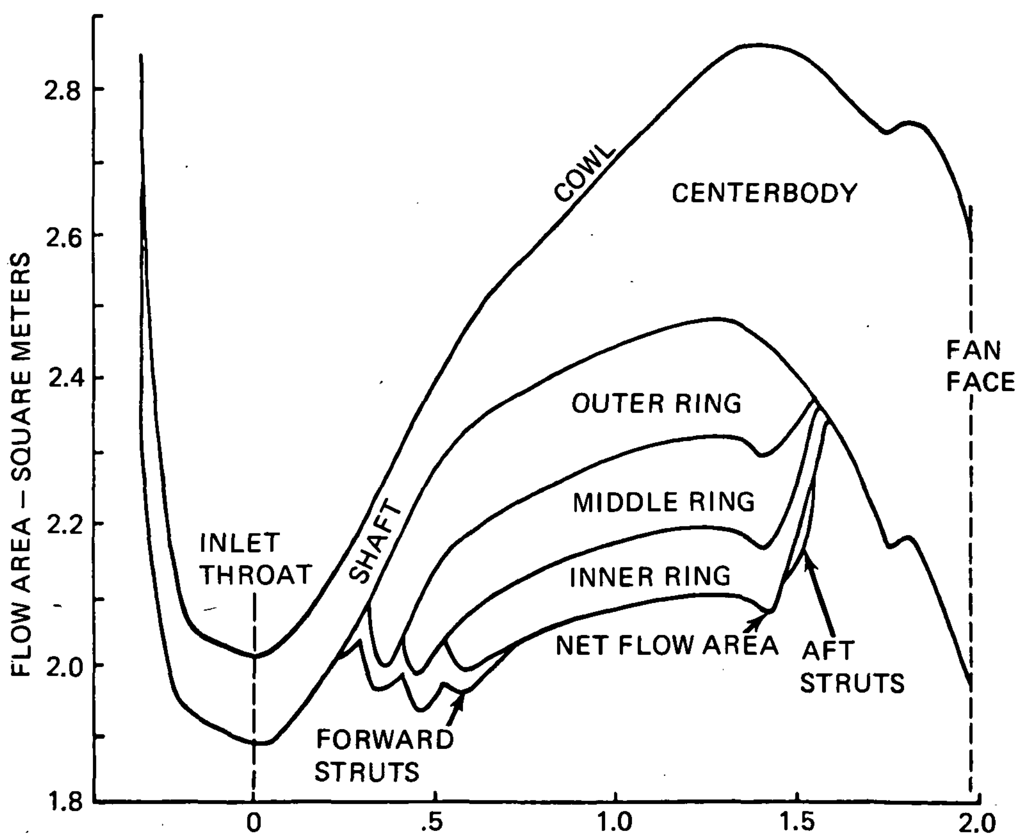


REVERSE THRUST POSITION

FIXED CASCADE FAN THRUST REVERSER CONCEPT
FIGURE 43



INLET CONTOURS – QUIET FAN NACELLE
FIGURE 44



INLET AREA PROGRESSION – QUIET FAN NACELLE
FIGURE 45

Fan duct design.– A preliminary acoustic analysis showed that the fan duct should contain a single ring with 2.28 m of treatment and have provision for 51 cm of 5.3 cm thick lining. This last requirement dictated that, when backed by a thinner liner, the ring would have to be 6.1 cm thick for a minimum of 1 m.

The inner shell of the existing fan facility exhaust duct was used for the new treated fan duct but the flow line was not followed. The flow line was made such that a 5.3 cm thick liner could be incorporated in the inner wall. An approximation of the ring was made so that an area progression in the fan could be made to determine the fan duct outer wall contours. The fan duct requires two different nozzle areas, 1.222 m^2 1.387 m^2. This requirement and the lining length requirement made it necessary to lengthen the fan ducts 45.7 cm over the existing quiet fan exhaust ducts. A large radius tail cone was also incorporated at the end of the fan ducts.

This preliminary configuration was analyzed using axisymmetric compressible potential flow field studies. From this analysis, a streamline was located to place the ring for equal duct heights on each side. The ring had a 3.08:1 elliptic leading edge and increased in thickness from 1.65 to 6.1 cm over a distance of 63.5 cm. A constant 6.1 cm thickness was then retained for 1 m and then tapered gradually from the 6.1 cm thickness to the trailing edge over a distance of 76 cm.

This fan duct configuration was then analyzed using axisymmetric compressible potential flow field calculations for the 90 percent and 60 percent fan speed conditions. No evidence of boundary layer separation was found at either condition.

The contours developed for the fan duct and the area progression are shown on Figures 46 and 47, respectively.

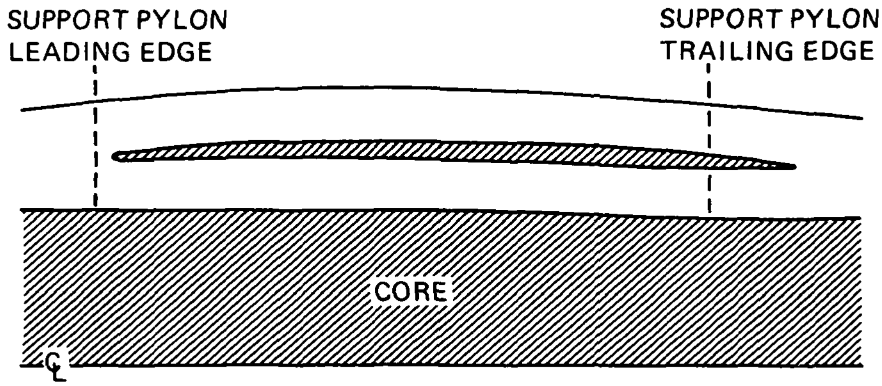
Estimated performance.–The performance of the quiet fan nacelle was estimated with respect to the pressure losses occurring at the 60 percent and 90 percent fan speed. The pressure losses are based only on the skin friction drag on the surfaces. Since the rings have a small thickness/chord ratio and are placed on streamlines, the profile drag is negligible compared to skin friction. The inlet has 33.1 m^2 of treatment and 8.1 m^2 of smooth skin and the fan duct has 43.0 m^2 of treatment and 7.5 m^2 of smooth skin. The pressure losses were calculated using the procedure outlined in Reference 5. A skin friction coefficient 1.85 times that of smooth plate was used for the polyimide/glass fiber acoustic linings. The estimated nacelle performance is summarized in Table IX.

Acoustic Linings

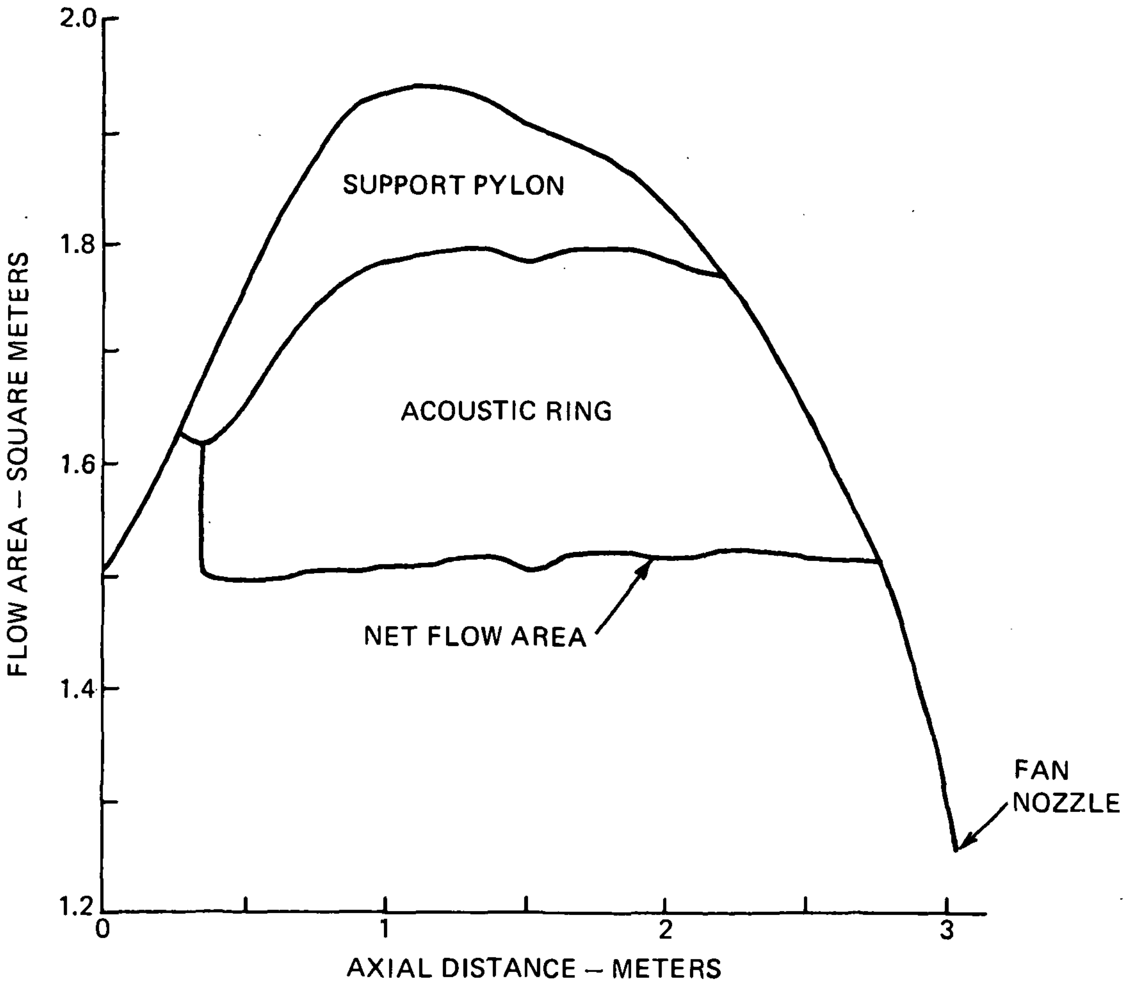
The required attenuation spectrum for the NASA quiet fan has a broad bandwidth since the fan has relatively low blade passage tone levels with respect to broadband fan noise. The acoustic lining consists of segmented linings to provide broadband attenuation characteristics over a frequency range which includes the first two blade passage harmonics.

The selected design condition for the inlet linings was 60 percent fan speed which is typical of an approach power setting. The fan duct lining design condition was 90 percent fan speed which is typical of a takeoff power setting.

Polyimide resin impregnated, glass fiber cloth laminates were used for all of the acoustic lining face sheets.



FAN DUCT CONTOURS – QUIET FAN NACELLE
FIGURE 46



FAN DUCT AREA PROGRESSION – QUIET FAN NACELLE
FIGURE 47

TABLE IX
PREDICTED AERODYNAMIC PERFORMANCE – QUIET FAN NACELLE

CONDITION	INLET (33.0 m^2 TREATMENT) PRESSURE LOSS (Treated)	PRESSURE LOSS (Untreated)	FAN DUCT (43.0 m^2 TREATMENT) PRESSURE LOSS (Treated)	PRESSURE LOSS (Untreated)
90% Speed	1.7%	.29%	3.24%	1.07%
60% Speed	.81%	.14%	1.7%	.56%

Note: Performance is compared to a nacelle without acoustic linings or rings

Inlet linings.– Inlet lining segments are tuned at four frequencies to provide the required bandwidth at the design fan speed of 60 percent. The tuned frequencies are 1600, 2000, 3000, and 4000 Hz. The majority of the linings are single layered, however, three segments of double layered linings are included in the inlet.

Figure 48 is a schematic cross section of the inlet showing the arrangement of the linings. Table X lists the composition, tuned frequency, and impedance of each lining at the 60 percent fan speed. Lining lengths are given for the maximum attenuation configuration and two lower levels of attenuation.

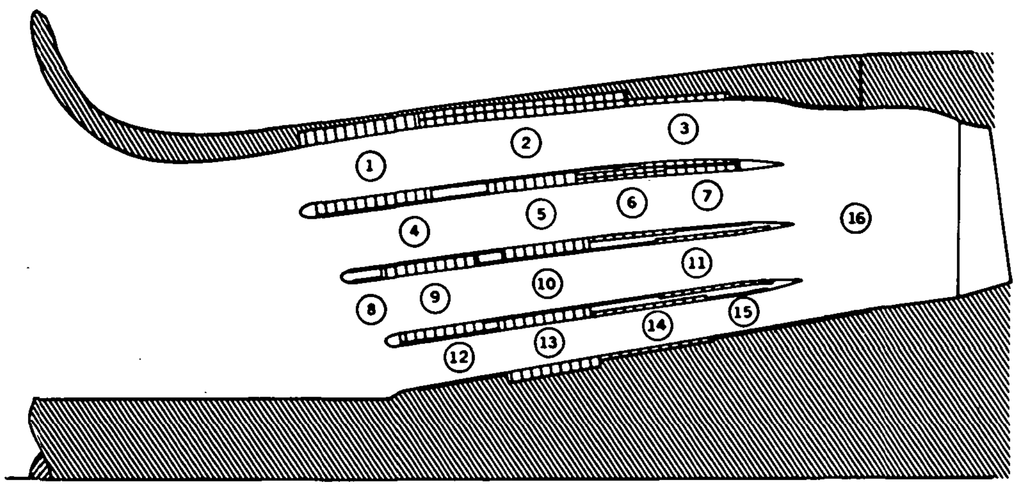
The inlet linings were designed considering the effects of sheared flow on the effective impedance of the linings. The effect of this consideration can be illustrated by the requirements for lining Segment 10 in the second channel outward from the centerbody. With no sheared flow effects considered, the required lining would be a 19 ply laminate with a .20 cm core depth. However, in the presence of sheared flow, the required lining is a 12 ply laminate with a .30 cm core depth.

The predicted attenuation spectrum for each inlet channel is shown in Figure 49 for the 60 percent fan speed. The prediction shown for the outer inlet channel does not include the cowl wall lining segment aft of the ring trailing edge. The predictions are based on a uniform velocity in the inlet.

A photograph of the assembled inlet is shown in Figure 50.

Fan duct linings.– Figure 51 is a cross section schematic of the fan duct lining configuration. The lining consists of single layer lining segments tuned to one of five frequencies. The lining characteristics and tuned frequencies at the 90 percent fan speed design condition are shown in Table XI.

The predicted lining attenuation spectrum at the 90 percent fan speed is shown in Figure 52. This prediction does not consider the effects of the fan duct cowl linings forward of the ring.

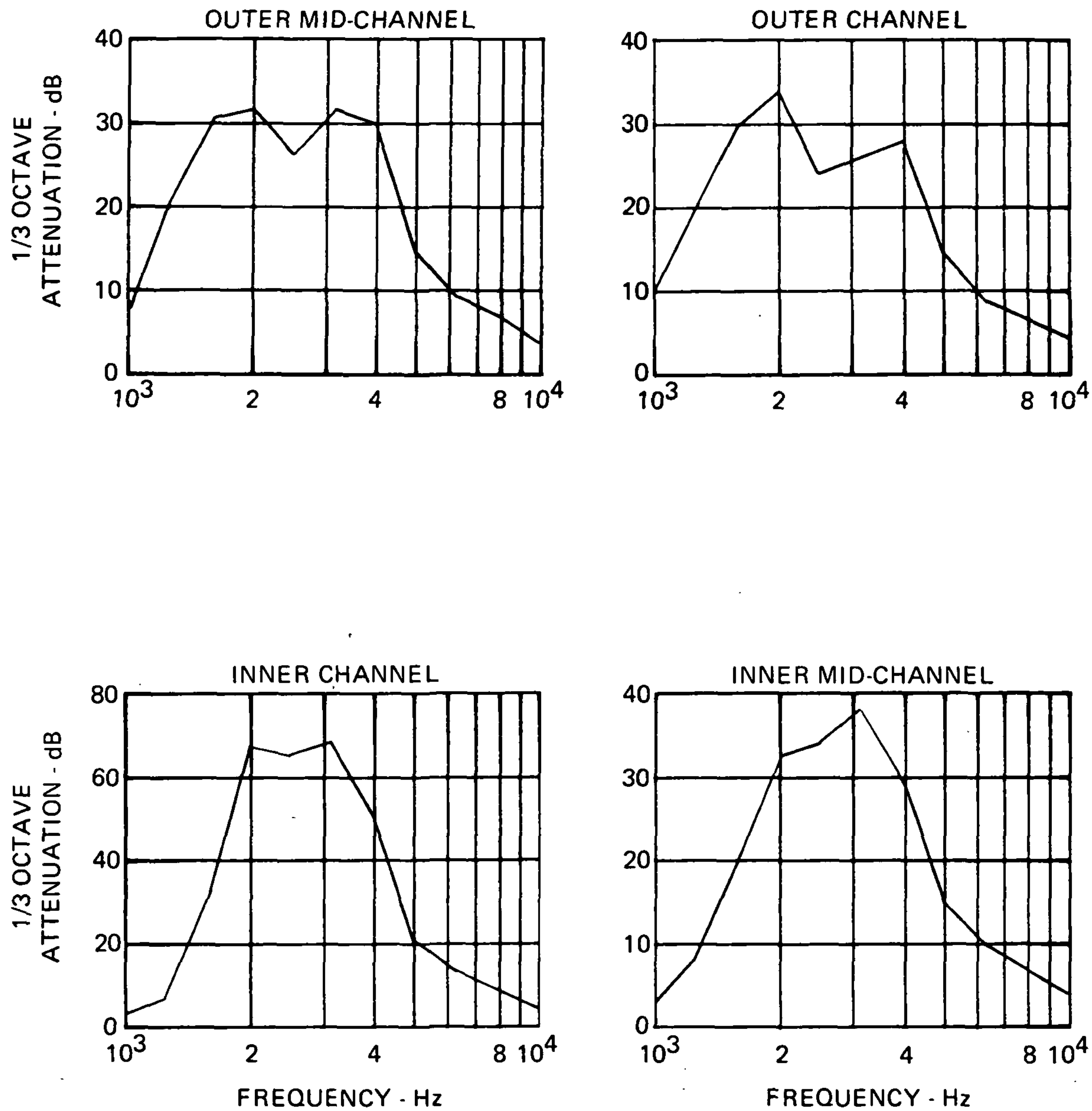


LOCATION OF INLET LININGS – QUIET FAN NACELLE
FIGURE 48

TABLE X
CHARACTERISTICS OF QUIET FAN NACELLE INLET LININGS

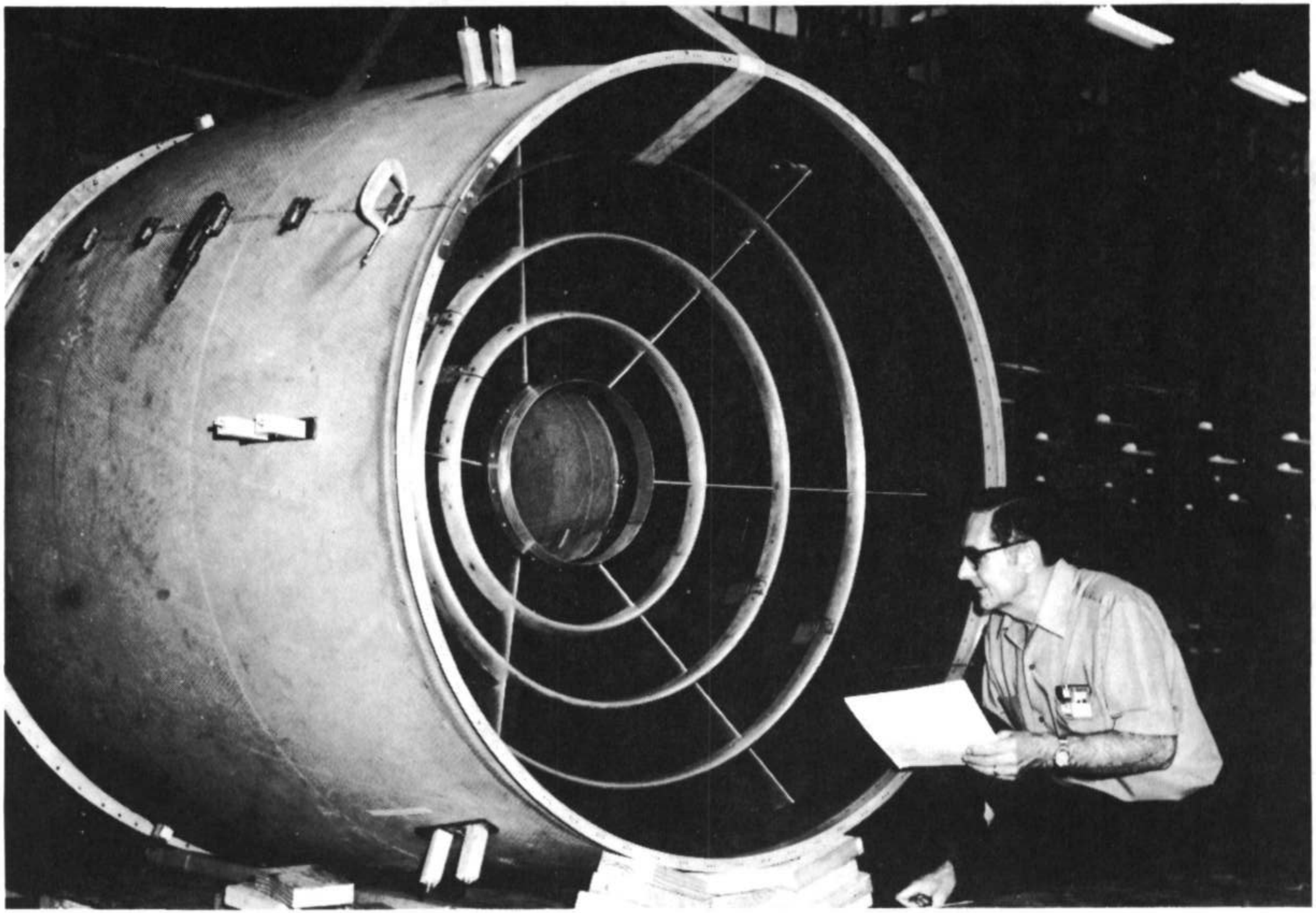
LINING SEGMENT	TUNED FREQUENCY (Hz)	NUMBER OF PLIES	CAVITY DEPTH (CM)	AVERAGE IMPEDANCE		LINING LENGTH (CM)		
				$R/\rho c$	$X/\rho c$	MAX.	10 PNdB	5 PNdB
1	2000	11	1.04	1.3	-1.4	30.5	22.8	10.1
2 DOUBLE LAYER SINGLE LAYER	1600 4000 4000	6[1] 23[2] 13	.51[1] .70[2] .25	2.1 2.0 2.0	-1.6 -2.5 -2.5	53.3	25.4	10.1
3	3000	13	.48	1.8	-1.9	25.4	15.2	10.1
4	4000	15	.23	2.7	-2.9	38.1	0	0
5	2000	10	1.12	1.2	-1.4	22.8	15.2	10.1
6 DOUBLE LAYER SINGLE LAYER	1600 3000 3000	6[1] 26[2] 12	.79[1] .56[2] .48	2.2 1.7 1.7	-2.3 -1.9 -1.9	22.8	15.2	10.1
7 DOUBLE LAYER SINGLE LAYER	1600 4000 4000	5[1] 22[2] 11	.56[1] .69[2] .30	2.0 1.6 1.6	-1.9 -2.3 -2.3	17.8	19.0	10.1
8	4000	15	.25	2.7	-2.4	10.1	0	0
9	2000	10	1.17	1.2	-1.3	22.8	17.8	12.7
10	4000	12	.30	1.9	-2.6	44.7	22.8	7.6
11	3000	10	.56	1.5	-1.8	30.5	17.8	12.7
12	4000	14	.25	2.9	-3.1	22.8	17.8	7.6
13	2000	7	1.17	.8	-1.6	22.8	17.8	12.7
14	3000	9	.70	1.2	-1.1	30.5	17.8	12.7
15	4000	9	.41	1.3	-1.6	15.3	0	0
16		15	.25	2.6	-2.8	31.8	31.8	31.8

[1] OUTER LAYER OF DOUBLE LAYER LINING
[2] INNER LAYER OF DOUBLE LAYER LINING

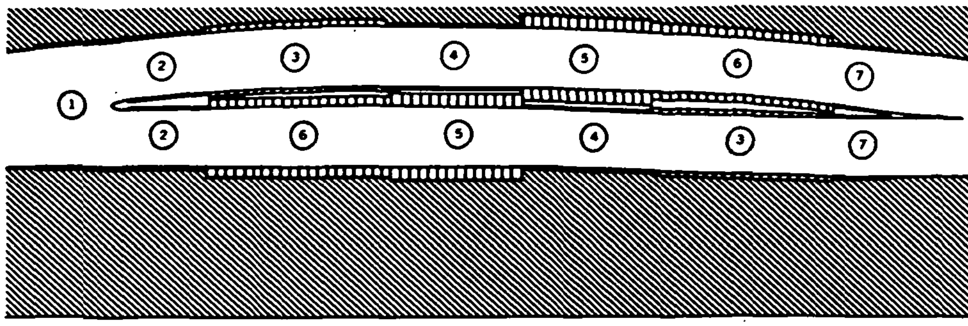


PREDICTED INLET LINING ATTENUATION SPECTRA AT 60% FAN SPEED – QUIET FAN NACELLE

FIGURE 49



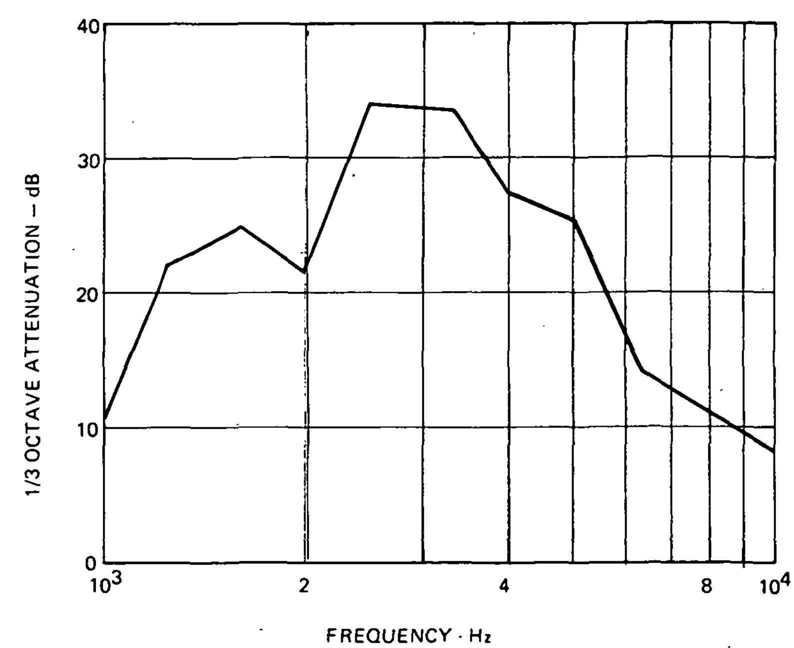
QUIET FAN NACELLE INLET
FIGURE 50



LOCATION OF FAN DUCT LININGS – QUIET FAN NACELLE
FIGURE 51

TABLE XI
CHARACTERISITCS OF QUIET FAN NACELLE FAN DUCT LINING

LINING SEGMENT	TUNED FREQUENCY (Hz)	NUMBER OF PLIES	CAVITY DEPTH (CM)	AVERAGE IMPEDANCE		LINING LENGTH (CM)		
				R/ρc	X/ρc	MAX.	10 PNdB	5 PNdB
①		12	.23	2.5	-2	25.4	25.4	25.4
②	4500	7	.48	1.2	-.9	22.8	22.8	15.2
③	3500	6	1.12	.9	-.6	53.3	22.8	15.2
④	5000	8	.48	1.3	-.9	38.1	0	0
⑤	1500	4	4.92	.5	-.1	38.1	22.8	15.2
⑥	2700	6	1.85	.8	-.4	53.3	22.8	7.6
⑦	5000	8	.48	1.3	-.9	15.2	15.2	0



PREDICTED FAN DUCT LINING
ATTENUATION SPECTRUM AT 90% FAN SPEED – QUIET FAN NACELLE
FIGURE 52

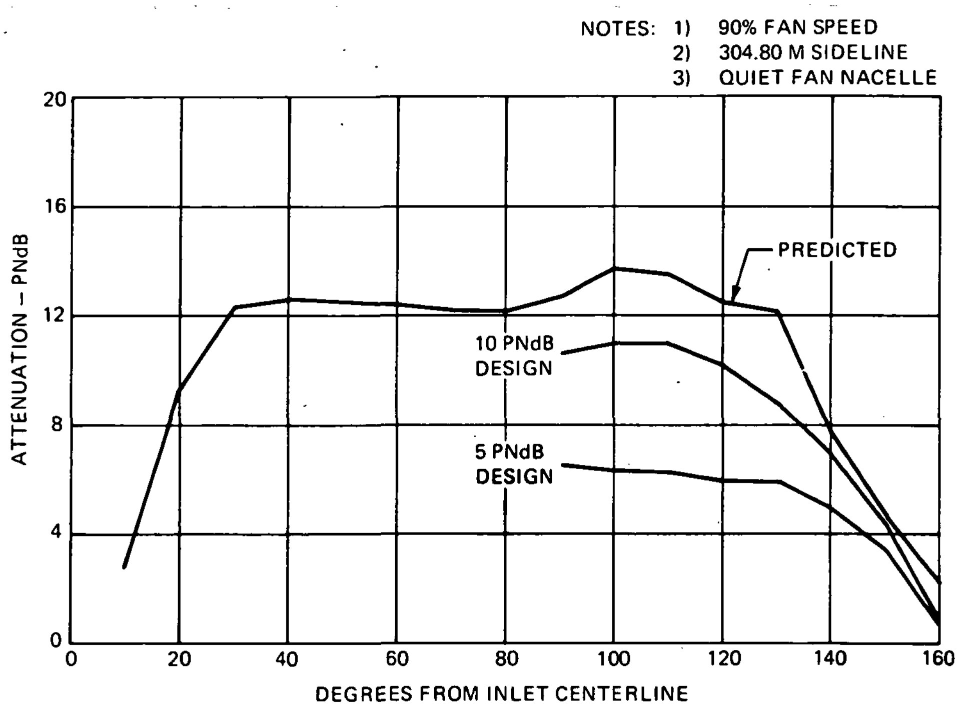
Estimated performance.– The predicted attenuation at 90 percent fan speed for the quiet fan with the acoustically treated nacelle is shown in Figure 53. The predictions are for a 304.8 m (1000 ft) sideline in 10° intervals from 10° to 160° from the inlet centerline. The predicted attenuations in the inlet quadrant exceed 12 PNdB at angles from 30° to 90°. The maximum reduction is 12.6 PNdB, which occurs 40° from the inlet centerline. Attenuations in the exhaust quadrant peak at 100° from the inlet centerline, where the predicted reduction in perceived noise is 13.7 PNdB. The attenuations decrease rapidly at angles greater than 130° where jet noise is the dominant source. Predicted aft quadrant attenuations due to reduced fan duct treated areas are also shown in Figure 53.

The predicted performance of the nacelle at 60 percent fan speed is given in Figure 54. The results show expected reductions in perceived noise level along a 112.72 m (370 ft) sideline. The peak attenuation in the inlet quadrant is predicted to be 13.9 PNdB at 30 degrees from the inlet centerline. The maximum attenuation in the exhaust quadrant is expected to be 11.1 PNdB at 110° from the inlet centerline. The attenuations expected after selectively reducing the inlet treated area are also shown for the future comparison with measured data.

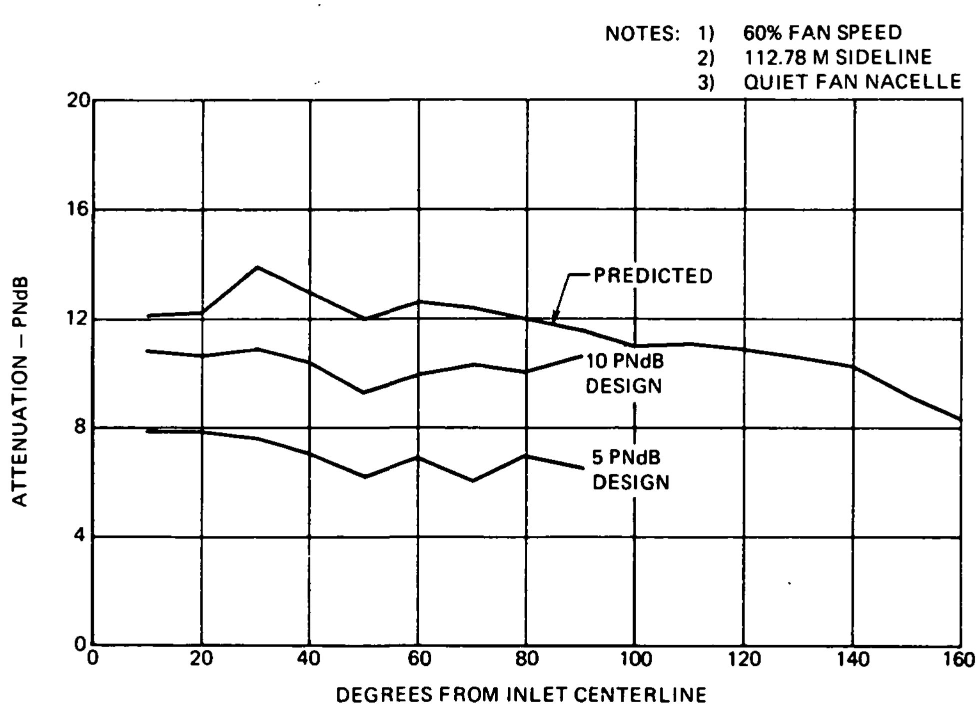
Nacelle weight.– Total weight of the quiet fan nacelle is 1107.7 kg, neglecting the weight of the inlet bellmouth. This weight includes 891.7 kg due to acoustic treatment with the balance due to support structure and other nontreated surfaces. The weight distribution of the acoustic linings by location is given in Table XII.

TABLE XII
WEIGHT OF QUIET FAN NACELLE ACOUSTIC LININGS

ITEM		Weight – kg	Treated Area – sq m
INLET	Cowl	98.9	8.45
	Outer Ring	129.7	10.13
	Mid-Ring	93.4	7.34
	Inner Ring	64.4	5.11
	Centerbody	16.8	2.04
	TOTAL	403.2	33.07
FAN DUCT	Outer Cowl	176.9	14.59
	Splitter	239.0	20.07
	Inner Cowl	72.6	8.36
	TOTAL	488.5	43.02
TOTAL NACELLE		891.7	76.09



PREDICTED ATTENUATION AT 90 PERCENT FAN SPEED – QUIET FAN NACELLE
FIGURE 53



PREDICTED ATTENUATION AT 60 PERCENT FAN SPEED – QUIET FAN NACELLE
FIGURE 54

DISCUSSION OF RESULTS

This research program has demonstrated use of an analytical procedure for design of acoustically treated nacelles for high bypass turbofan engines. Integration of the nacelle aerodynamic and acoustic design processes results in a nacelle which satisfies acoustic attenuation requirements while minimizing internal pressure losses due to addition of acoustically treated rings and cowlings. Locating rings on streamlines and controlling the internal area progression to avoid flow separation can reduce internal losses until skin friction is the dominant loss mechanism.

The acoustic lining design procedure summarized in this report has been successfully used to select lining configurations, identify properties of the acoustic linings, and predict acoustic performance of the selected linings. Acoustic flow duct tests have been performed on typical inlet and fan duct lining configurations with flow velocities equal to those expected during engine and fan testing. Results of these tests have confirmed that the linings perform as predicted.

Performance estimates made for the quiet engine nacelle show peak sideline noise reductions of 10.3 to 12.8 PNdB in the inlet quadrant. Peak reductions in the exhaust quadrant are estimated to be 6 to 9.4 PNdB. The larger reduction is achieved at approach power in both cases. Additional reductions are limited by jet noise and turbine noise from the engine which is predominant in the exhaust quadrant. The thrust penalty due to addition of acoustic linings is estimated to be 5.0 percent at takeoff power and 6.4 percent at a 0.82 Mach cruise condition at 10,670 m altitude.

The quiet fan nacelle is expected to reduce peak inlet noise 12.6 to 13.9 PNdB at distances typical of takeoff and approach flight profiles, respectively. Peak reductions in aft radiated noise are estimated to be 13.7 to 11.1 PNdB at 60 and 90 percent fan speeds.

Future research should be devoted to attenuating jet and turbine noise which are dominant when the quiet engine nacelle is installed.

CONCLUSIONS

The following conclusions are based on the design analyses and laboratory testing conducted during development of acoustically treated nacelles for the General Electric/NASA quiet engine and the NASA quiet fan:

- A three-ring inlet, one ring fan duct design provides the best aeroacoustic performance of the configurations considered.
- Broadband acoustic lining designs are required for this class of fans to give the required attenuation.
- The acoustic design goal of 15 PNdB fan noise reduction cannot be observed during quiet engine testing because of jet and turbine noise floors. Estimates of peak attenuation are 12.8 and 9.4 PNdB in the inlet and fan duct radiated noise, respectively.
- The acoustic design goal of 15 PNdB will probably be achieved with the quiet fan nacelle as conservative predictions are peak reductions of 13.7 and 13.9 in inlet and fan duct radiated noise, respectively.
- Flow duct test results confirm that the design procedure developed results in linings which satisfy acoustic requirements.
- Multi-layered linings can be used to achieve broadband noise reduction.
- The effects of sheared flow on inlet lining designs are significant and must be considered in the design process.

SYMBOLS

c	Speed of sound in fluid, centimeters per second
℄	Centerline
dB	Decibels referenced to .0002 dynes/cm^2
EPNdB	Units of effective perceived noise level, decibels
EPNL	Effective perceived noise level, EPNdB
f	Sound frequency, Hertz (Hz)
H	Distance between acoustically lined walls, centimeters
L	Length of acoustic lining, centimeters
PNdB	Units of perceived noise level, decibels
PNL	Perceived noise level, PNdB
R	Resistive impedance of acoustic lining, gm/(cm^2sec)
SPL	Sound pressure level, dB
t	Ring thickness
TSFC	Thrust specific fuel consumption
X	Reactive impedance of acoustic lining, gm/(cm^2sec)
θ	Inlet diffusion angle
ρ	Density of fluid, gm/cm^3
ϕ	Weighting function proportional to area of acoustic treatment

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