NASA CONTRACTOR REPORT

NASA CR-1711

STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN-COMPRESSOR NOISE RADIATION

Volume I - Program Summary

Prepared by
THE BOEING COMPANY
Seattle, Wash. 98124
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1971

1. Report No. NASA CR-1711	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN–COMPRESSOR NOISE RADIATION. VOLUME I – PROGRAM SUMMARY.		5. Report Date January 1971
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address The Boeing Company Seattle, Wash. 98124		11. Contract or Grant No. NAS 1-7129
		13. Type of Report and Period Covered Contractor Report, May 1, 1967 to Nov. 1, 1969
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract This report summarizes the results of a flight evaluation of an acoustically treated nacelle installed on the Pratt and Whitney JT3D turbofan engines on a Boeing 707-320C airplane and reviews the economic impact of this installation. The work was accomplished by The Boeing Company under Contract NAS 1-7129 with the National Aeronautics and Space Administration. The program objective was a PNL reduction of 15 PNdB to landing approach noise which was accomplished by installing two acoustically treated rings in the engine inlet and by acoustically treating an extended length fan duct configuration. The acoustic treatment consisted of a polyimide-fiberglass sandwich material. A detail description of the nacelle is presented and a summary of the acoustic and performance results of the flight evaluation are presented. In addition, the structural-mechanical aspects and the impact on operational factors are reviewed. Both operating costs and impact on airline operations based on retrofit of these nacelles are reviewed in the economic analysis. The appendix reviews the total program, of which the flight evaluation is only a part. Highlights of results presented are:

Reduction of 15.5 EPNdB (16 PNdB) in landing approach noise

Reduction of 3.5 EPNdB in take-off noise

Reduction of 4.5 EPNdB in take-off with power cutback noise

Airplane capacity payload range reduction of 200 n. mi.

Nacelle retrofit costs of $1 million per airplane

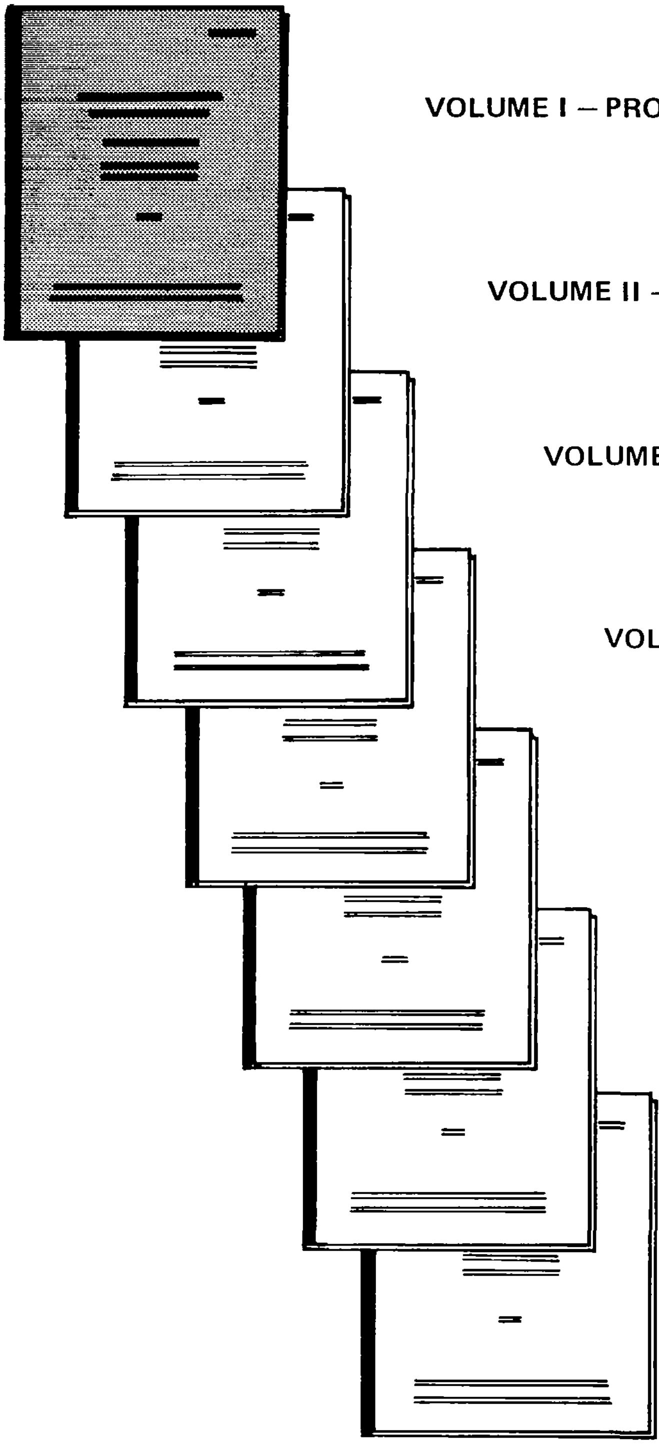
A direct operating cost increase for the treated airplane of 9.2 percent for international operations and 9.6 percent for domestic operations

17. Key Words (Suggested by Author(s)) 707 Airplane; Noise/aircraft; Acoustically treated nacelles; Economics; Flight tests		18. Distribution Statement Unclassified - Unlimited; 1, Aircraft noise	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 38	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN-COMPRESSOR NOISE RADIATION

OVERALL REPORT ORGANIZATION



VOLUME I – PROGRAM SUMMARY

VOLUME II – ACOUSTIC LINING DEVELOPMENT

VOLUME III – CONCEPT STUDIES AND GROUND TESTS

VOLUME IV – FLIGHTWORTHY NACELLE DEVELOPMENT

VOLUME V – SONIC INLET DEVELOPMENT

VOLUME VI – ECONOMIC STUDIES

VOLUME VII – SUBJECTIVE EVALUATION TESTS

CONTENTS

TABLE

FIGURES

FIGURES—Concluded

STUDY AND DEVELOPMENT OF TURBOFAN NACELLE MODIFICATIONS TO MINIMIZE FAN-COMPRESSOR NOISE RADIATION

VOLUME I

PROGRAM SUMMARY

The Boeing Company
Seattle, Washington

INTRODUCTION

Late in 1966, the National Aeronautics and Space Administration issued a request for proposal for a program to study and develop engine nacelle modifications to minimize fan-compressor noise radiation in turbofan engines. Based on its response to the request for proposal, The Boeing Company was awarded Contract NAS 1-7129 on May 1, 1967, to study and develop sonic inlets and acoustically treated long fan ducts on the JT3D turbofan engine. In April 1968, the contract was changed to require that acoustically treated inlets rather than sonic inlets be developed for the flightworthy nacelles. The Boeing contract was parallel to Contract NAS 1-7130 awarded to the Douglas Aircraft Division of the McDonnell-Douglas Corporation to study and develop acoustically treated inlets and short fan ducts on a JT3D engine.

The Boeing contract stipulated a four-phase program: Materials and Concepts, Models, Boilerplate/Prototype Components, and Flightworthy Nacelles. The program objective was to develop effective fan noise reduction concepts for the inlet and fan discharge duct of the JT3D engine as installed on the Boeing 707-320B series airplane. These concepts were to be applied as nacelle modifications and were aimed at achieving the following goals:

- A reduction in perceived noise level (PNL) of 15 PNdB during landing approach with no adverse affect on takeoff and climbout noise
- No compromise in flight safety nor increase in crew workload
- Retention of an economically viable transport

As executed by Boeing, the program consisted of material development, conceptual studies, design and fabrication of test parts, model tests, ground tests, and flight tests. Flight testing was conducted on a JT3D-7 powered 707-320C airplane during takeoff, climb, cruise, descent, and landing approach conditions. Sufficient data were recorded to permit acoustic, performance, structural-mechanical, operational, and economic analyses. A more detailed review of the total program is contained in the appendix to this volume.

The results of the flight evaluation of the finally selected treated nacelle configuration and an economic evaluation of this installation are summarized in this Program Summary volume of the final report. All aspects of the program are reported in detail in other volumes of the report as noted on page iii.

OBJECTIVES AND DESIGN CONSTRAINTS

The program objective of developing effective fan-compressor noise reduction concepts for turbofan engines was based on the known noise characteristics of this type engine. The program goal of 15-PNdB noise reduction of the JT3D engine at landing approach power was defined through evaluation of the noise characteristics of the JT3D engine in particular. It was determined that a strong fan noise component exists and that the fan-generated noise radiated from the inlet and the fan discharge ducts is almost solely responsible for the maximum perceived noise levels during airplane landing approach (fig. 1). This fan noise component also contributes significantly to the maximum perceived noise levels at the high thrust conditions of takeoff and climbout. The fan noise (whine) during landing approach is considered to be responsible for a large percentage of the noise complaints received at many major metropolitan airports. For these reasons, the program was aimed at reducing the discrete frequency components of the fan-generated noise spectra. The program goal of 15-PNdB reduction during landing approach was established on the basis of the relationship between fan and jet noise levels at landing approach thrust conditions. The 15-PNdB represents the major portion of the difference between the total airplane flyover noise (jet plus fan) and the jet efflux noise (fig. 1). No direct attempt was made in this program to reduce the jet noise.

In proceeding with the development of effective fan noise reduction concepts, an eight-segment sonic inlet and a treated long fan discharge duct evolved. The sonic inlet was initially selected to ensure adequate inlet noise suppression to supplement the fan duct suppression and provide the 15-PNdB overall noise reduction program goal. Data available at that time indicated it would be difficult to achieve the necessary inlet noise suppression through application of acoustic lining. Subsequent tests conducted by the Douglas Aircraft Division, under their contract with NASA, showed that an acceptable amount of attenuation could be obtained from treated inlets. The Boeing flightworthy nacelle development was therefore redirected from the sonic inlet to a two-ring treated inlet. The results of the sonic inlet development work are presented in volume V of this report. Development of the treated inlet in conjunction with the treated long fan duct then progressed through the development and testing of flightworthy articles. This development did not include a thrust reverser for the secondary exhaust; however, space provisions for one were provided.

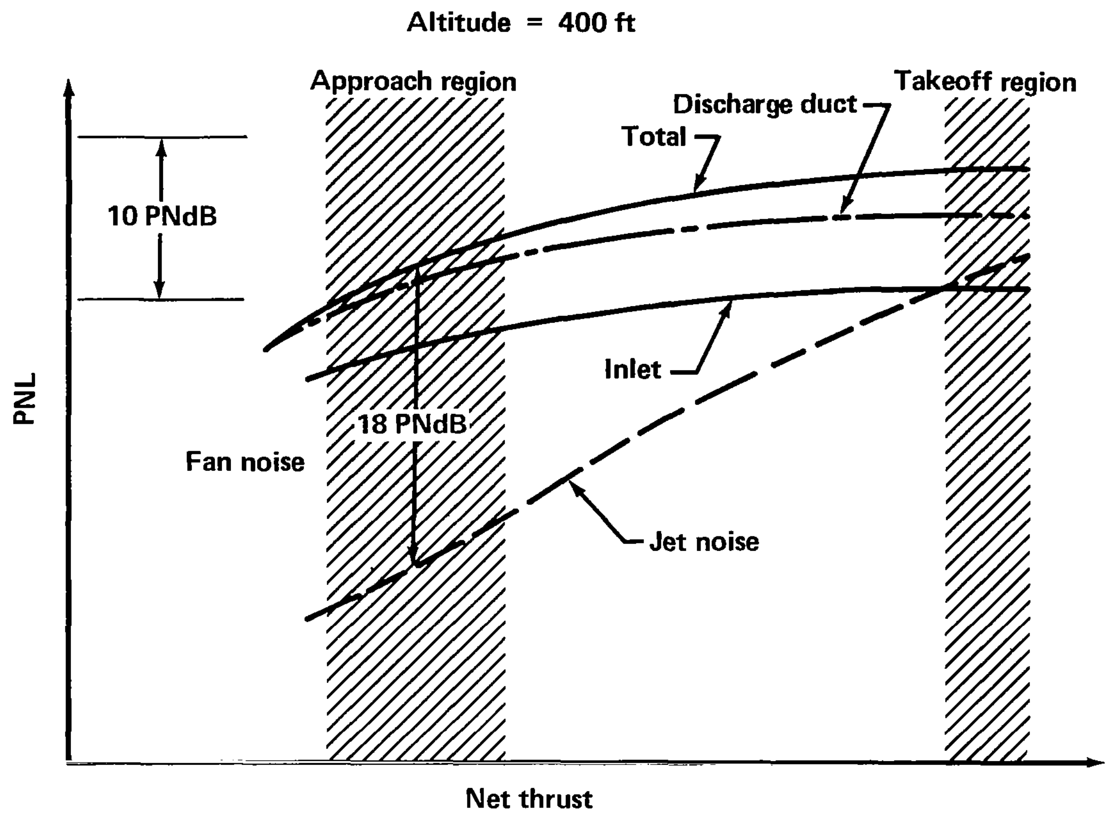


FIGURE 1.—JT3D NOISE CHARACTERISTICS

To ensure the proper application of acoustic treatment in the inlet and the fan duct, development of acoustic materials and lining technology became a prime goal of the program. Requirements placed on the acoustic material were that it (1) be acoustically effective, (2) have flexibility of design and application to provide for use under various environmental conditions, (3) be light in weight, (4) be reasonable in cost, and (5) create minimum loss of propulsion performance. In establishing the nacelle configuration, impact on engine operation, airplane performance, and cost were all primary considerations. However, in design of the full-scale test hardware, ease of manufacture and cost were considered ahead of weight. While this philosophy resulted in expediency and satisfactory test articles, the final nacelle weight was not representative of production articles. For the economic analysis, an estimated production weight was used. It is emphasized that the economic study presented in this report is largely theoretical. The fleet operation assumed is hypothetical. A JT3D-3B engine was assumed rather than the JT3D-7 engine used with the test nacelles. Costs were predicted for the year 1972.

SYMBOLS

C_D	drag coefficient
EPNL	effective perceived noise level, EPNdB
EPNdB	unit of effective perceived noise level
M	Mach number
P	pressure, pounds/inch^2
PNdB	unit of PNL
PNL	perceived noise level, PNdB
PNLM	maximum perceived noise level, PNdB
W	gross weight of aircraft, pounds
δ	pressure ratio, P/P_o

Subscript:

o	sea level standard

TREATED NACELLE DESCRIPTION

The nacelle selected for flight evaluation was acoustically treated in both the inlet and fan exhaust duct as shown in figure 2. The inlet was extended approximately 9 in. over the existing 707 airplane inlet and the blow-in doors were eliminated. The fan duct was redesigned and extended the full length of the nacelle so that its nozzle exit and that of the primary jet occur at essentially the same plane. Acoustic material consisted of polyimide-impregnated fiberglass sandwich panels for both inlet and fan duct. Flight test airplane modification consisted of replacing the existing inlet and short fan duct with the treated nacelle after locally modifying the nacelle struts to add attachment provisions. The modified flight test airplane is shown in figure 3.

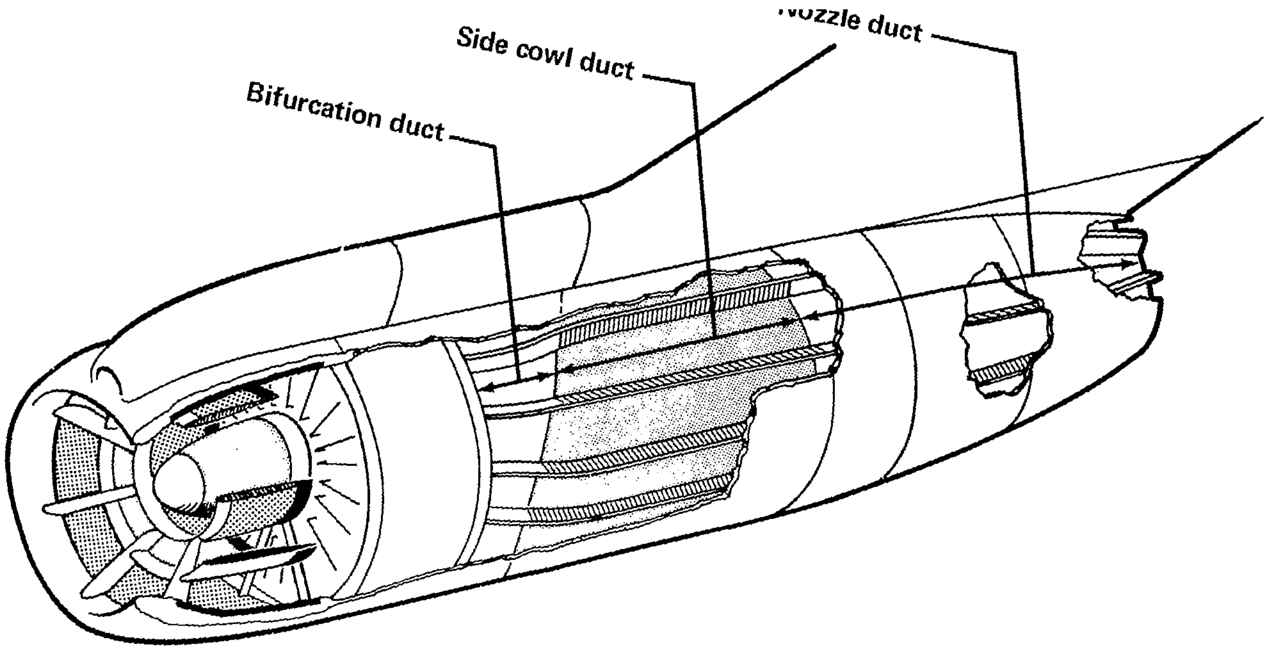


FIGURE 2.–TREATED NACELLE

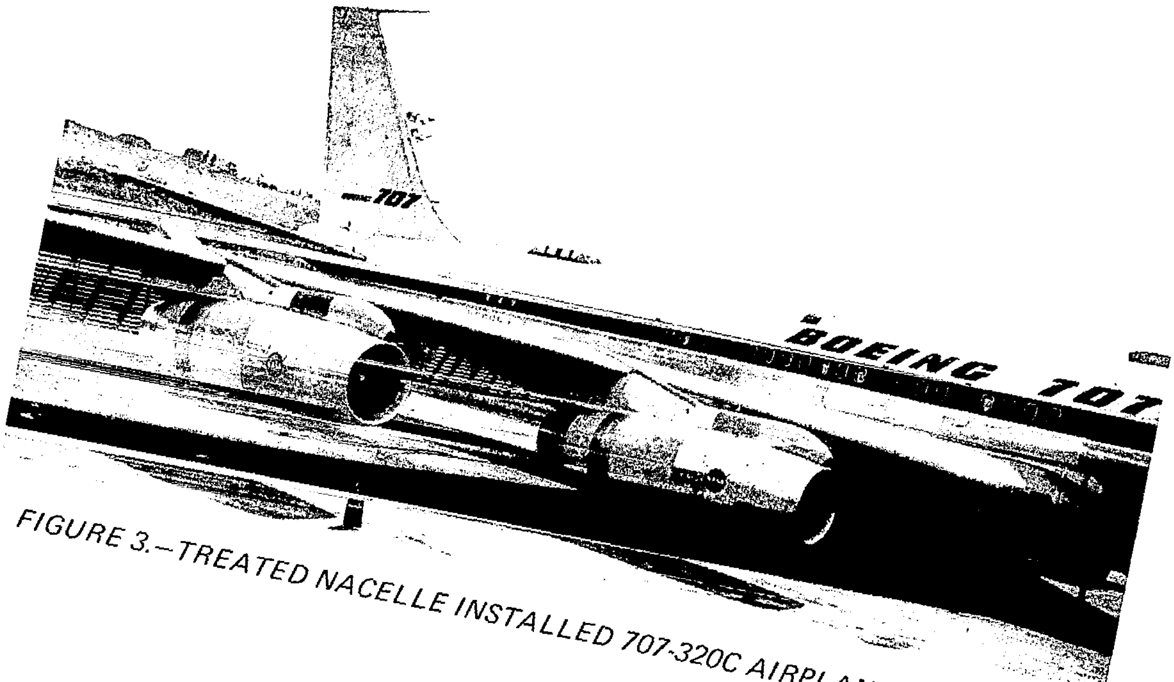


FIGURE 3.–TREATED NACELLE INSTALLED 707-320C AIRPLANE, SIDE VIEW

Treated Inlet

The treated inlet had two acoustically treated annular rings supported by struts at eight radial intervals, as shown in figure 4. These rings divided the inlet into three annular airflow channels of nearly equal height. This configuration was selected since it permitted adequate acoustic treatment to achieve attenuation goals with a minimum performance loss. The ring support strut configuration was designed to minimize engine fan blade excitation. The centerbody and cowl wall were also acoustically treated, giving a total inlet treatment area of 71 ft^2.

Aerodynamic as well as acoustic requirements were considered in defining the internal inlet geometry to achieve the best possible pressure recovery and thereby the best inlet performance. The inlet length was selected so that the rate of air diffusion controlled by the cowl wall angle would be small to avoid flow separation and attendant performance losses. The cowl lip, centerbody, leading edges of the acoustic rings, and struts were anti-iced by engine bleed air.

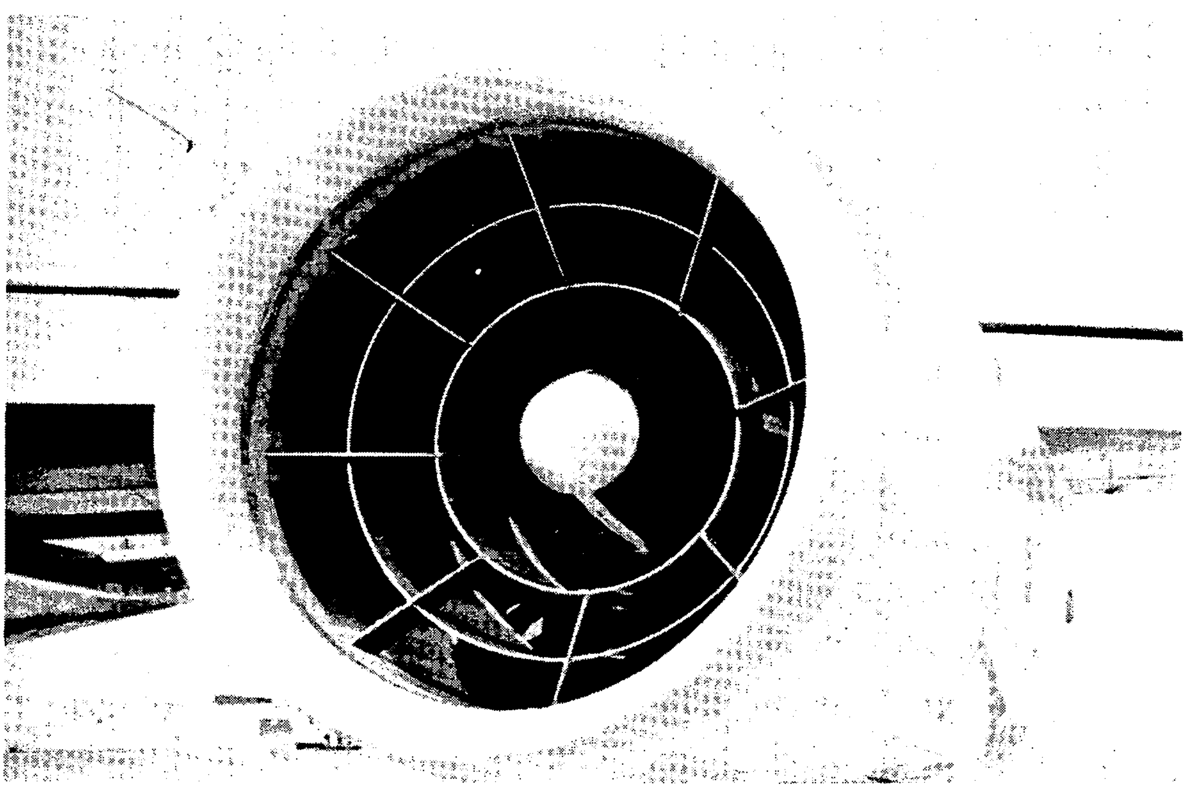


FIGURE 4.—TREATED NACELLE INSTALLED ON 707-320C AIRPLANE, FRONT VIEW

Treated Fan Exhaust Duct

The treated fan exhaust duct consisted of three major components as shown in figure 2: the bifurcation duct, side cowl duct, and nozzle duct. The duct contours in the side cowl, nozzle section, and exit-plane areas are shown in figure 5. The cross section of the side cowl duct shown in figure 5 is constant over its entire length. The nozzle section duct was continually reduced in area through its length, with the duct halves reuniting and terminating in an annular nozzle in the vicinity of the primary nozzle. Duct internal contours were designed to minimize aerodynamic losses. The duct was closely fitted to the engine contours for minimum cross-section area. Duct entry and exit area transitions were designed to minimize airflow losses. This configuration was selected from those studied because together with the treated inlet it showed the ability to meet the 15-PNdB noise attenuation goal and exhibited the least airplane range penalty.

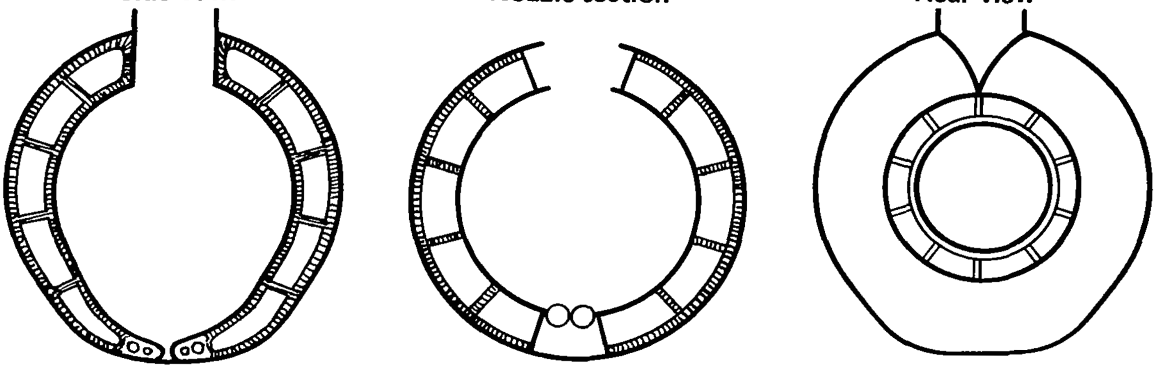


FIGURE 5.–DUCT CONTOURS

The duct acoustic treatment served as primary duct structure. The main body of treatment was located in the side cowl duct. It was 69 in. long and included 216 ft^2 of effective area. Both inner and outer duct walls were of acoustic sandwich construction. Figures 2 and 5 show the radial splitters that divided each duct half into five longitudinal flow channels. The splitters (1) minimized airflow turning losses, (2) contained the structural fasteners that join the duct walls together, and (3) were acoustically treated on both surfaces.

A secondary treatment area of 51 ft^2 was included in the nozzle duct. This additional area was intended to satisfy possible contingencies due to manufacturing deviations or differences between actual and predicted requirements. Acoustic data from static tests of the boilerplate/prototype nacelle indicated that the attenuation goal could be met by the main treatment area alone. However, to ensure attainment of the program objectives, this area remained treated for all flight testing.

Acoustic Treatment

All the acoustic treatment was in the form of structural sandwich panels that consisted of three basic elements: (1) a porous face sheet, (2) a honeycomb core, and (3) a nonporous backing sheet (fig. 6). In use, the panels are arranged with their porous skins facing the noise environment. This type of panel performs acoustically as a broadband resistive resonator. Both the honeycomb core and face skins were of polyimide resin-impregnated fiberglass cloth material. Adhesives used in bonding panel elements together were also polyimide resin compounds. In addition to good acoustic properties, polyimide-fiberglass material selection was based on physical properties such as (1) structural capability, (2) resistance to high temperatures, (3) resistance to contaminants, (4) resistance to sonic fatigue, and (5) maintainability. Other important considerations for selection of polyimide-fiberglass acoustic panels were that they can be readily fabricated into complex curved surfaces with close-tolerance control of acoustic porosity in the face sheet. They can also provide variation in porosity with length, thus offering optimized acoustic attenuation.

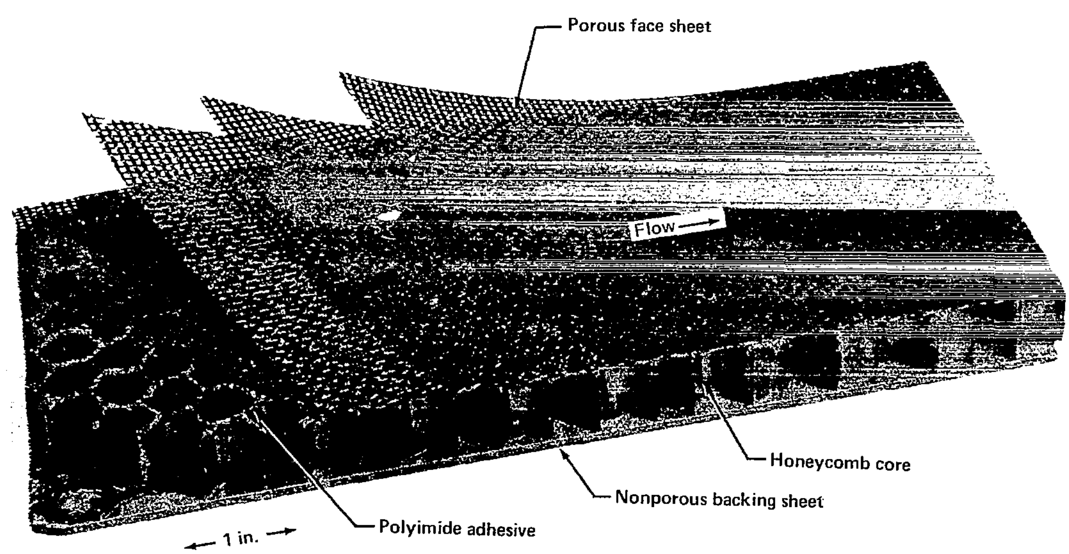


FIGURE 6.—POLYIMIDE-FIBERGLASS SANDWICH PANEL

FLIGHT EVALUATION

Flight tests were conducted to evaluate the acoustic and operational performance of a 707-320C airplane equipped with four of the acoustically treated nacelles described in the preceding section. The performance was evaluated by comparing data obtained from flight tests of the treated nacelles with that obtained from flight tests of the untreated nacelles. A summary of the acoustic and operational performance is presented in table I. After completion of the performance flight tests, subjective evaluation tests were conducted using the acoustically treated airplane and a second, untreated 707-320B airplane. The contractor's acoustic test range, installed at the Grant County Airport, Moses Lake, Washington, was used for acquisition of the acoustic data.

Acoustic Results

Measured evaluation.—Acoustic lining technology developed during this contract was applied to treat four JT3D-7 engine nacelles. These four nacelles were first tested on an engine test stand to define performance and noise reduction during static operation and then were finally evaluated by flight testing. Noise measurements were made under the flightpath during landing approach, takeoff, takeoff with power cutback, and 400-ft-altitude level flyovers at various power settings. Noise levels were also recorded 1500 ft to the side of the flightpath during takeoffs.

The landing approach noise levels measured 1 n. mi. from threshold are shown in figure 7 for both the existing and treated airplanes. The noise reduction achieved was 15.5 EPNdB at the approach power setting of 5000 lb and 14.5 EPNdB at the landing approach power setting of 6000 lb. The equivalent noise reductions on the PNL scale are 16 and 14.5 PNdB, respectively. Practically all of this noise reduction is due to the elimination of the fan whine at the higher frequencies. The reduction in landing approach noise in the vicinity of an airport is shown by the difference in the ground noise contours in figure 8. The noise levels inside the corresponding contours are 100 EPNdB or higher. It is estimated that the land area enclosed by the 100-EPNdB contour for the treated airplane is only about 15 percent of that for the existing airplane.

Although the primary goal of this program was the reduction of landing approach noise, it was found that the absorption of fan tones by the acoustic linings at takeoff power settings reduced the total takeoff noise by measurable amounts. The noise reduction achieved under the takeoff flightpath, 3.5 n. mi. from brake release, was 3.5 EPNdB, as shown in figure 9. These results have taken into account a climb performance loss for the treated nacelle airplane of 120-ft altitude at the 3.5 n. mi. point, which is equivalent to approximately 1-EPNdB loss in noise reduction. The equivalent ground noise contours are shown in figure 10 for nominal 260 000-lb gross-weight airplanes having a typical range of 2500 n. mi. It is estimated that the land area enclosed by the 100-EPNdB contour for the treated airplane is only 45 percent of that for the existing airplane.

TABLE I.—FLIGHT EVALUATION AND ECONOMIC ANALYSIS—SIGNIFICANT RESULTS

Acoustic	
Landing approach reduction (1 n. mi. from threshold), EPNdB	15.5 (16 PNdB)
Takeoff reduction (3.5 n. mi. from brake release), EPNdB	3.5
Max. gross weight takeoff with cutback at 3.5 n. mi. reduction, EPNdB	4.5
Takeoff sideline reduction (1500 ft to side of runway), EPNdB	4.5
Performance	
Capacity payload range reduction, n. mi.	200
Takeoff thrust loss	
Static condition, percent	0.25
100 kn, percent	1.5
Max.gross weight takeoff distance to 35-ft altitude increase, percent	1.6
Max. gross weight climbout altitude loss (3.5 n. mi. from brake release), ft	120
Structural-Mechanical	
Treated nacelle—airplane compatibility	Satisfactory
Test airplane polyimide-fiberglass acoustic lining material	Satisfactory
Economic	
Estimated operating weight empty increase, lb	3140
Retrofit cost per airplane	$1 million
First retrofit kit available (test article), months after go-ahead	19
Direct operating cost increase	
International operations, percent	9.2
Domestic operations, percent	9.6
Indirect operating cost increase	Negligible
Total operating cost increase, percent	4.3

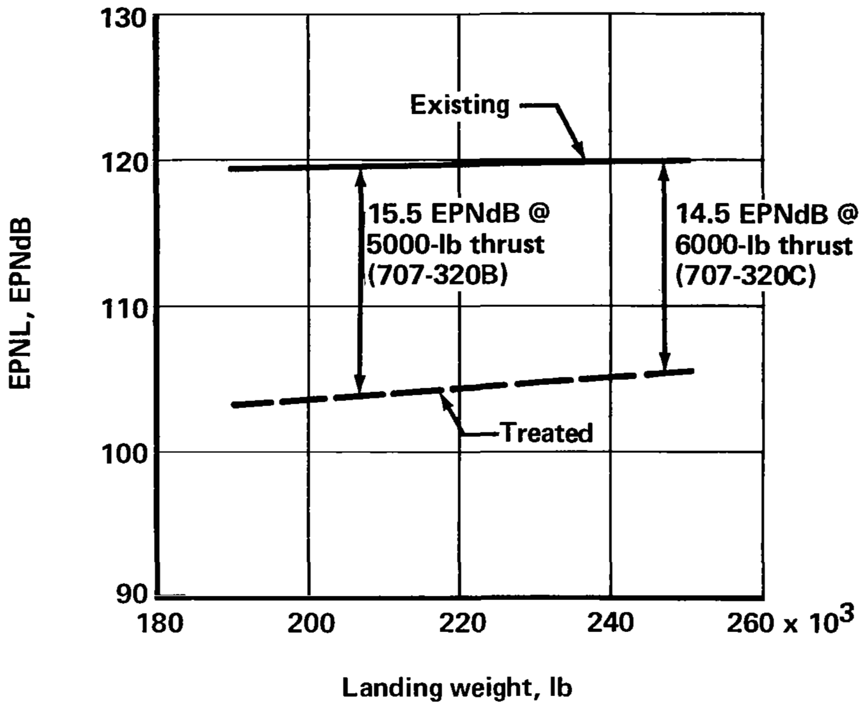


FIGURE 7.—LANDING APPROACH NOISE, 1 N. MI. FROM THRESHOLD, 50° FLAPS

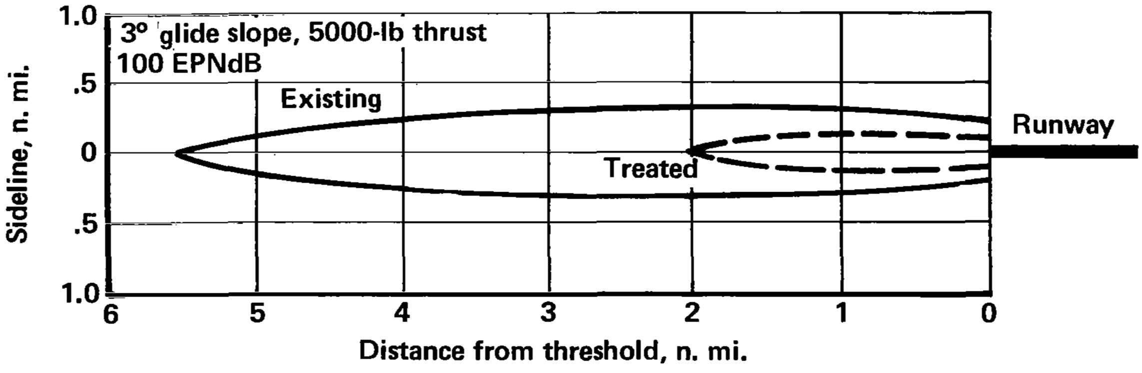


FIGURE 8.—LANDING APPROACH NOISE CONTOURS

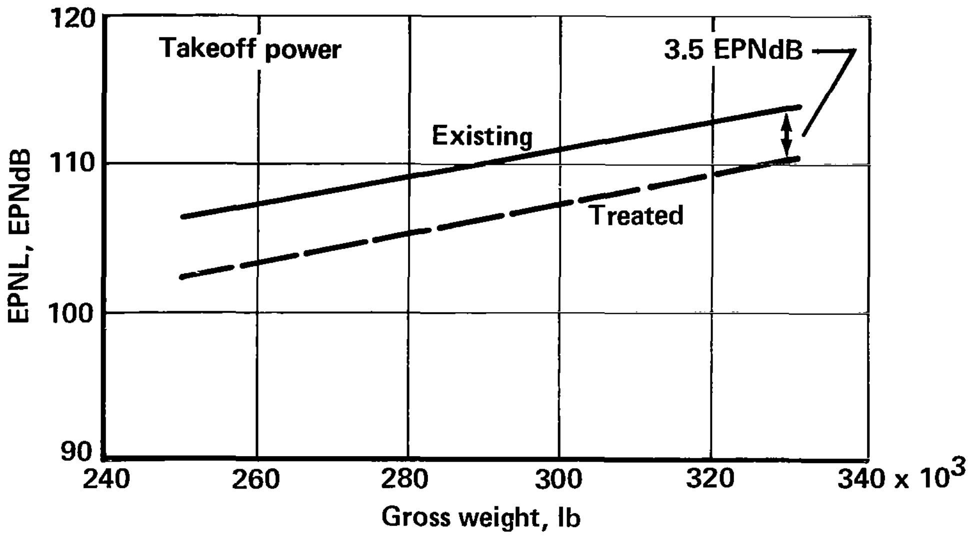


FIGURE 9.—TAKEOFF NOISE, 3.5 N. MI. FROM BRAKE RELEASE

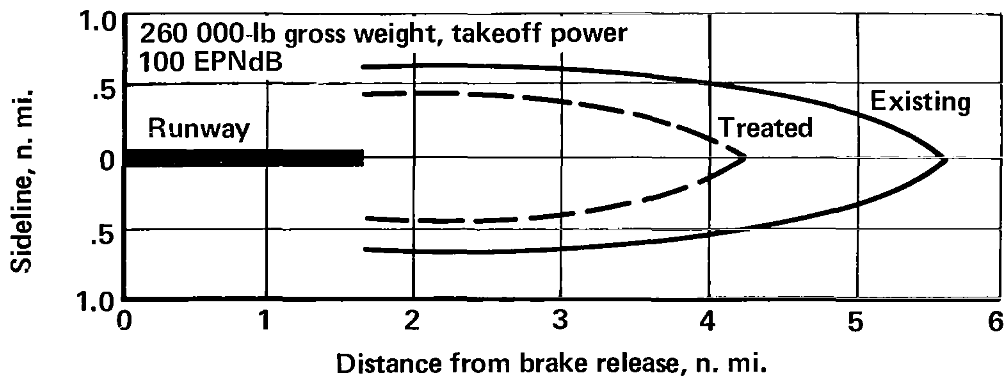


FIGURE 10.—TAKEOFF NOISE CONTOURS

Similarly, for takeoffs with power cutback initiated just prior to the 3.5 n. mi. point, it was found that the noise had been reduced by 4.5 EPNdB at the maximum certified takeoff weight, as shown in figure 11. A lower cutback power setting corresponding to a gross weight of 250 000 lb gave a noise reduction of 6.5 EPNdB.

The results of sideline noise measurements made 1500 ft from the flightpath are shown in figure 12. It was found that the maximum sideline noise during takeoff was reduced by about 4.5 EPNdB for the treated nacelle airplane and that the maximum noise levels occurred when the airplanes were at a height of approximately 1000 ft during climbout.

Prior to the flight test program, flyover noise levels for the two airplanes were estimated from noise data taken during ground tests on the engine test stand. It can be seen in figure 13 that for the engines and airplane configuration used in this study, test stand data properly taken and corrected provided reasonably accurate predictions of flyover noise.

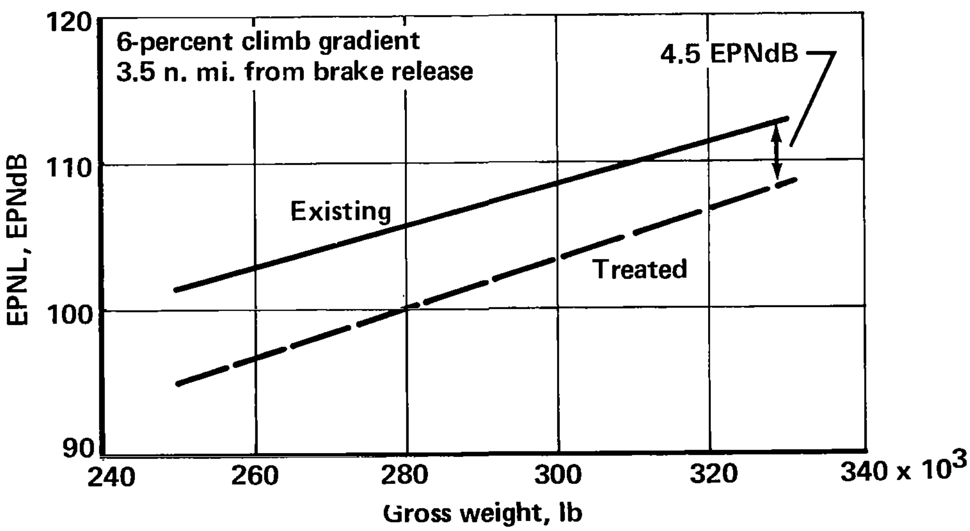


FIGURE 11.—TAKEOFF NOISE, POWER CUTBACK

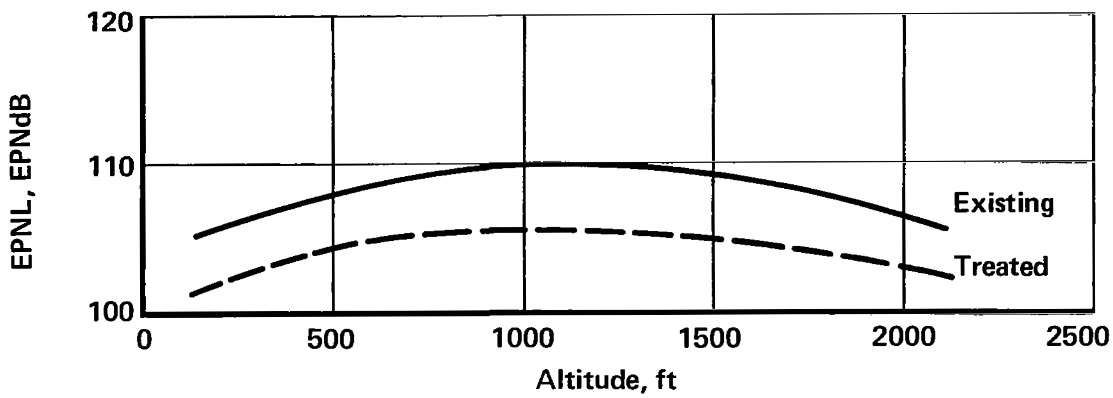


FIGURE 12.–TAKEOFF NOISE, 1500 FT TO SIDE OF RUNWAY

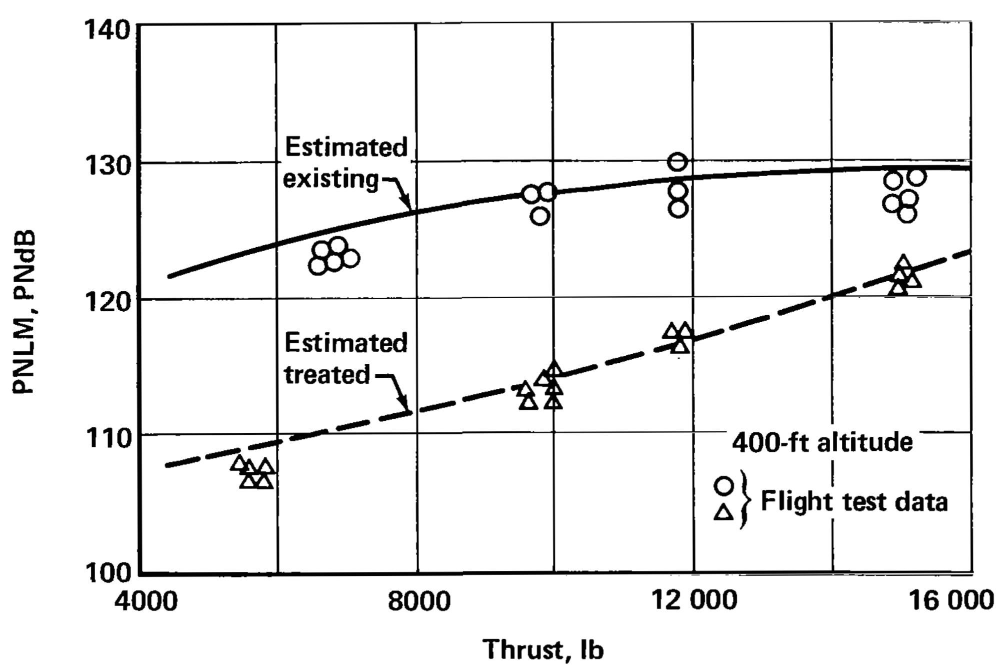


FIGURE 13.–ESTIMATED AND FLIGHT TEST RESULTS

Subjective evaluation.—The primary purpose of the subjective evaluation tests was to relate the measured noise reduction to the noise reduction judged by a sample of persons from the community. Judgments of the relative annoyance of noise from aircraft flyovers and loudspeaker noise were made by 180 persons, equally divided among six listening positions. Assignment of the 30 persons to each listening position was based on the results of an annoyance questionnaire, thereby ensuring that the groups were equal in their noise sensitivity, mean age, and education. Figure 14 illustrates the arrangement of the six listening positions, three of which were located indoors (trailer).

The people were first exposed to a loudspeaker noise and told that the sound had a noisiness score of 10 and to use that sound as a standard for judging each succeeding sound. Judgments of flyover noises from an untreated 707-320B airplane and the treated airplane, as well as loudspeaker noise, were made during sessions of approximately 2 hr each on two consecutive days. Judgments of aircraft routinely using the airport were also obtained. Recordings of all sounds judged at each listening position were made. Sound-pressure spectra from these recordings were reduced to subjective units using 18 engineering calculation procedures, one of which was the FAA noise certification unit, EPNL (effective perceived noise level). The variation of annoyance judgments as a function of EPNL is shown in figure 15 and is typical of the data obtained.

The 18 calculation procedures were variants of perceived noise level (PNL) and perceived loudness level (PLL) involving tone and duration corrections. The relationship between the judges' annoyance ratings and the various subjective units was established in terms of rates of change of annoyance and the product-moment coefficients of correlation. The results indicate that, while all 18 engineering calculation procedures adequately relate the measured noise to the judged noise, PNL had a slightly higher linear relationship to the judges' ratings of the flyover noise. The basic calculation procedures, PNL and PLL, are equally applicable as evaluation methods for the flyover noise of the untreated and treated airplanes and accurately reflect the measured noise reduction. The product-moment coefficients of correlation relating the judgments to the calculation procedures were satisfactorily high; for session I, the correlation was 0.94 for PNL and 0.93 for PLL. Since the relationship between the judges' ratings and the calculation procedures was high, it is concluded that the measured noise reduction was perceived by the sample of persons from the community.

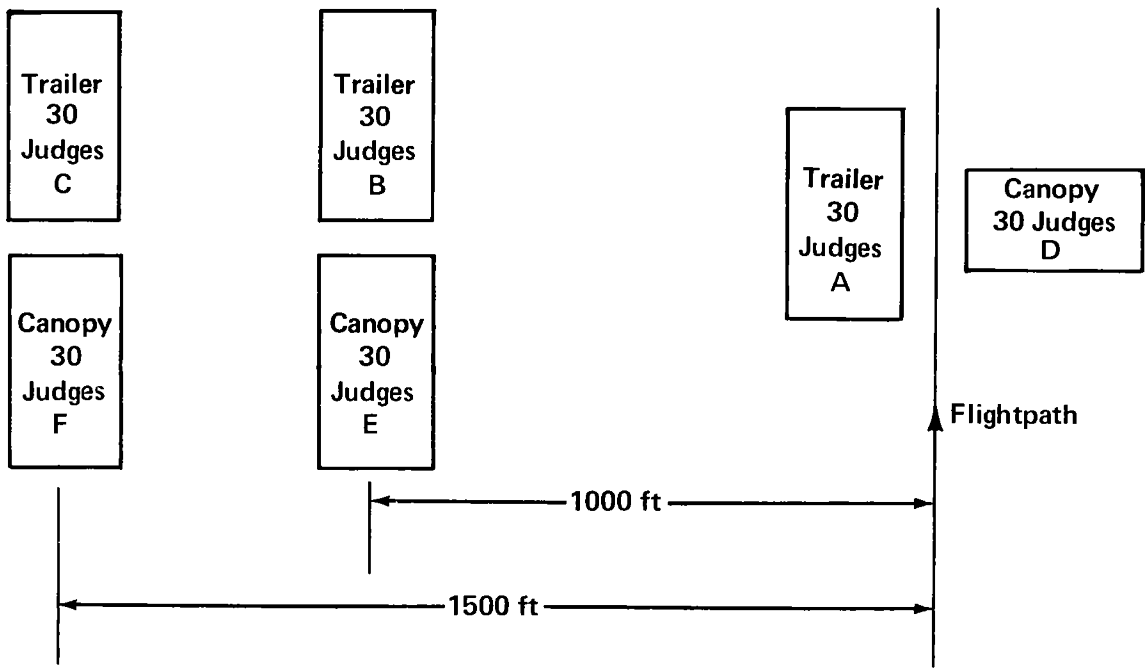


FIGURE 14.–JURY LOCATIONS 1 MILE FROM RUNWAY THRESHOLD

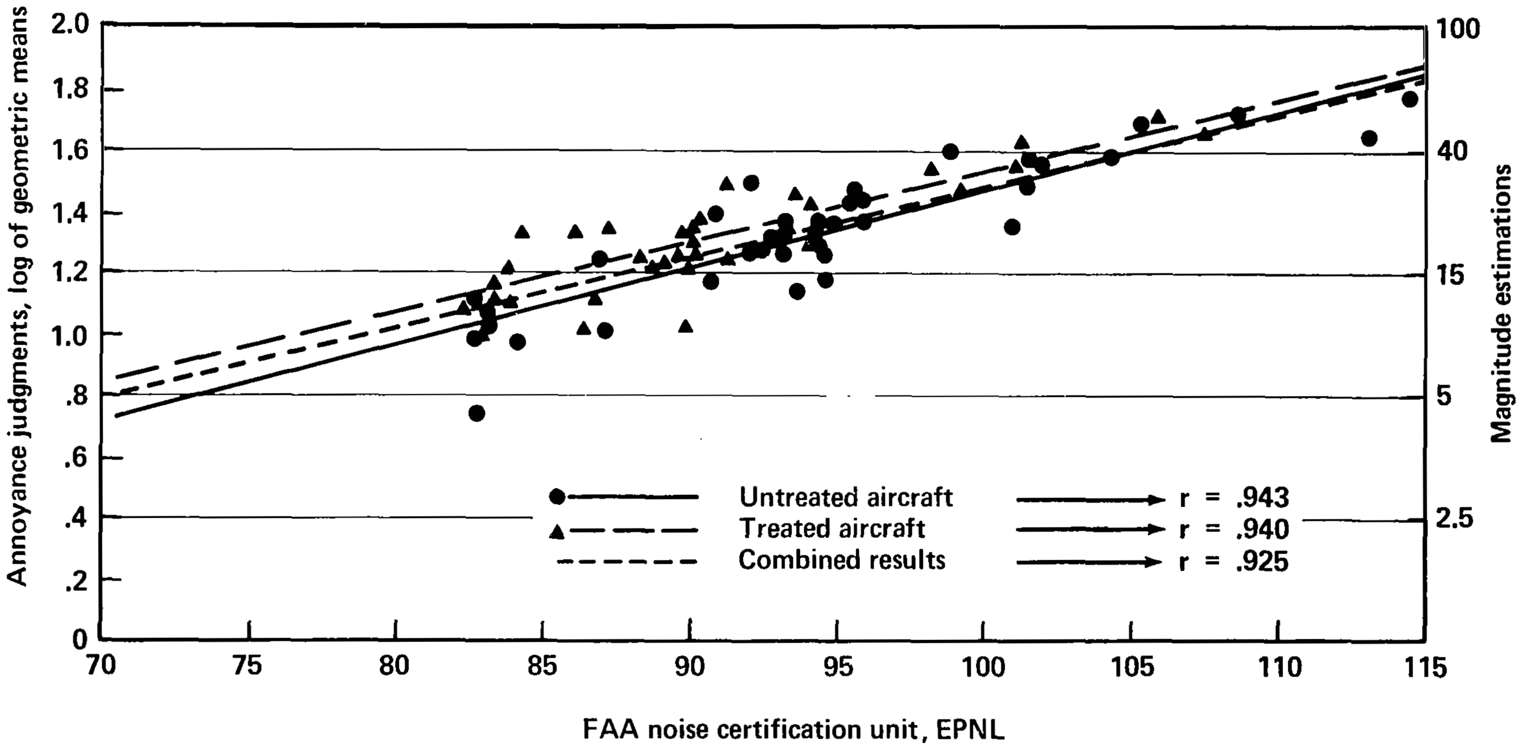


FIGURE 15.—ANNOYANCE JUDGMENT OF AIRPLANE FLYOVER NOISE AS A FUNCTION OF EFFECTIVE PERCEIVED NOISE LEVEL (EPNL) MEASUREMENT APPROACH (SESSION I)

Performance Results

The major effect of the treated nacelles on airplane performance was approximately a 200 n. mi. reduction of capacity payload range. This reduction was primarily due to the estimated 3140-lb loss of available fuel displaced by the increased operating empty weight of the airplane. Other airplane performance changes are presented below.

Takeoff.—At static takeoff conditions, thrust loss attributed to the treated inlet (about 1 percent relative to the existing inlet) is partially compensated for by improved fan duct performance. The net thrust produced with the treated nacelle at static takeoff conditions was approximately 0.25 percent less than that with the existing nacelle. During airplane takeoff, as the forward speed increases, inlet pressure recovery of the existing nacelle improved more rapidly than that of the treated nacelle, and at 100-kn forward velocity, approximately 1.5 percent less thrust was produced with the treated nacelle. Although only a limited number of measured takeoffs were made, a slight increase of take-off distances was apparent. The increase of takeoff distance to a 35-ft height was 2.6 percent at 260 000-lb gross weight and 1.6 percent at 330 000-lb gross weight.

Climbout.—The combined effect of a slightly longer takeoff distance and a reduced climbout gradient led to a loss of height during the climbout. This is obviously pertinent to any assessment of noise generation under the takeoff path. Over a point 3.5 n. mi. from brake release, the height loss was 90 ft at 260 000-lb gross weight and 120 ft at 330 000-lb gross weight. This height loss would be somewhat less, however, on a JT3D-3B powered airplane.

Cruise.—Measured normalized fuel mileage is shown in figure 16 for each configuration. These results reflect both the decrease in thrust specific fuel consumption and the increase in drag of the treated configuration; they show a reduction in fuel mileage due to the nacelle modification of between 0.7 and 2.1 percent over the representative range of W/δ and Mach number 0.80 to 0.83.

The scrubbing drag associated with the short existing fan duct is a significant portion of the net thrust loss presently accrued at cruise. By eliminating the scrubbing drag, the long treated duct provided about 3.2 percent more fan thrust for the same fan-pressure ratio. At the nominal cruise condition of Mach number 0.8 and 17 000-lb corrected net thrust, the combined effect of the inlet and fan duct resulted in the estimated specific fuel consumption being 2 percent less for the completely treated nacelle than for the existing nacelle. At higher power settings, the inlet pressure recovery decreased. This affects the treated nacelle more than the existing nacelle. As a result, the specific fuel consumption at maximum cruise thrust was approximately the same for both configurations. Drag for the cruise configurations is shown in figure 17. These estimates were obtained directly from a computation of in-flight thrust, which was estimated to be accurate within ±2.5 percent. The trend indicates that the treated nacelle drag is greater than that of the existing nacelle and that the increment increases with Mach number.

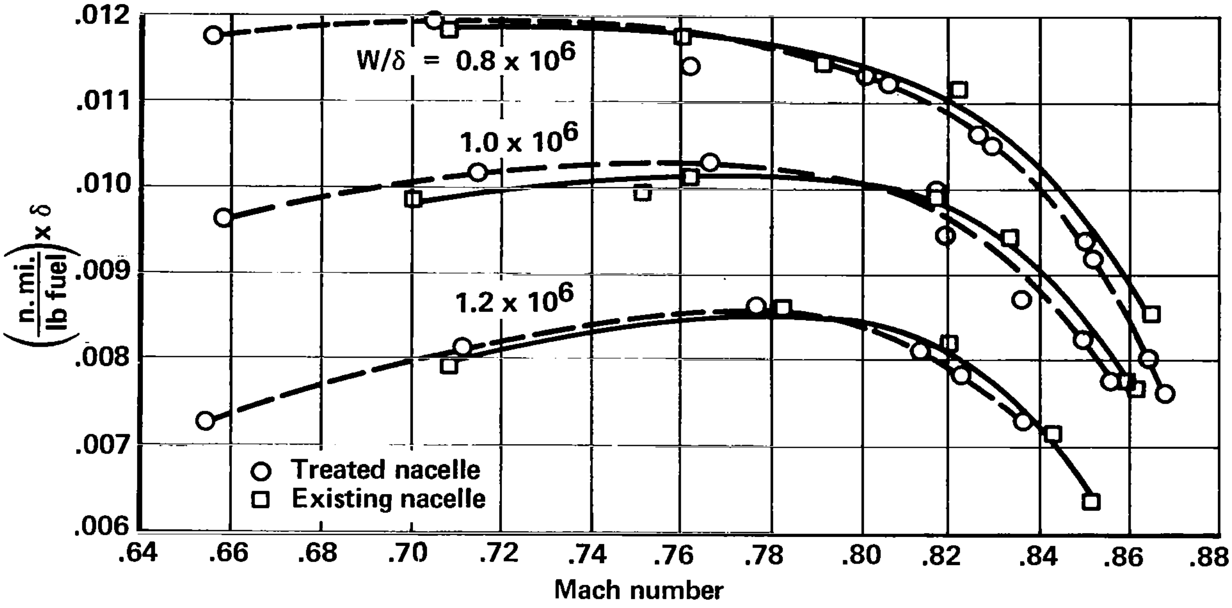


FIGURE 16.—FUEL MILEAGE COMPARISON

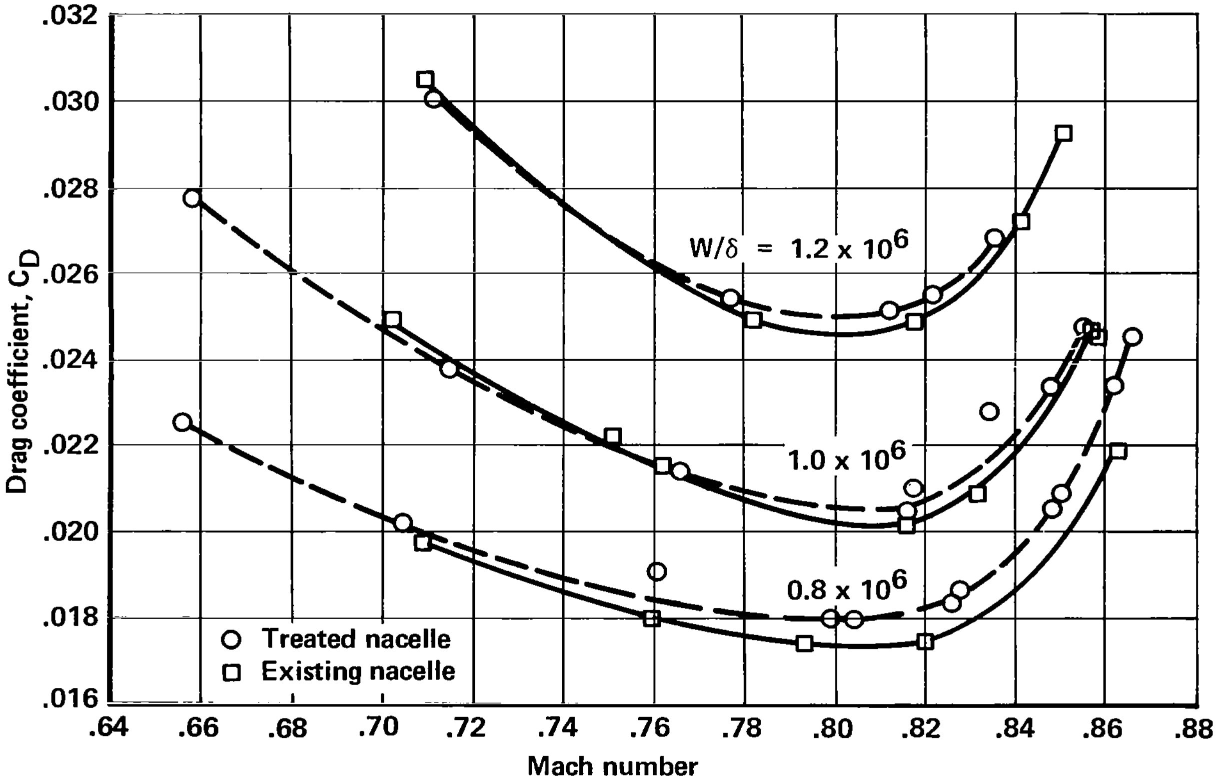


FIGURE 17.—CRUISE DRAG COMPARISON

Payload range.—A production version of the treated nacelle, including a thrust reverser, is estimated to increase the airplane operating empty weight by 3140 lb. The resultant displacement of available fuel contributed the major part of the loss of capacity payload range. Figure 18 shows the effect on payload range for international reserves and long-range cruise techniques (M = 0.80). The overall reductions of capacity payload range are summarized as follows.

Fuel reserve	Cruise technique	Loss of range, n. mi.
Domestic	Maximum range	200
	Minimum cost	225
International	Maximum range	200
	Minimum cost	225

Figure 18 also shows that the maximum allowable payload is not affected by the increase in operating empty weight. Since the extra weight of the nacelles is distributed across the wing-span, a corresponding increase in maximum zero fuel weight was determined to be permissible without exceeding airplane structural limitations.

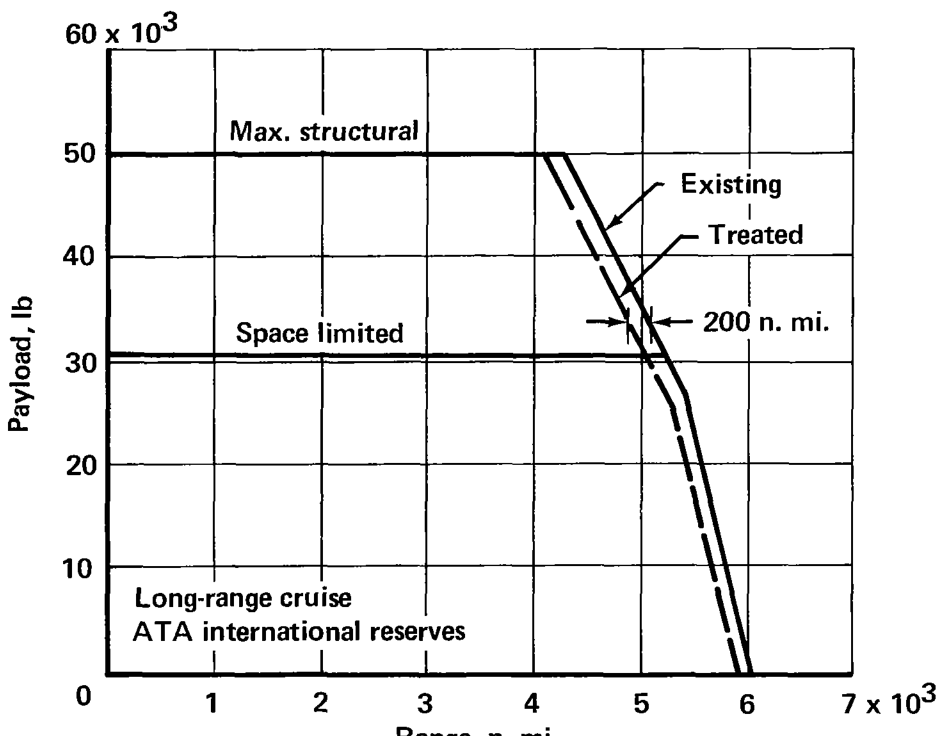


FIGURE 18.—PAYLOAD RANGE

Structural-Mechanical Results

Airplane flutter tests were conducted early in the flight evaluation program to ensure that changes in nacelle weight and center of gravity did not affect flight safety. Flutter response was completely satisfactory. Flight evaluation of the oil cooling systems for the alternator constant speed drive and the cabin air turbocompressors, as well as the air cooling systems for engine accessories, showed temperature well within allowable limits. The inlet anti-icing system was operated in flight under icing conditions with satisfactory results.

Following completion of the flight program, all inlets and fan ducts were removed for complete inspection. No structural problems were found. The polyimide-fiberglass acoustical/structural lining material in the inlets and ducts was in excellent condition, showing no delamination, wear, breakage or appreciable contamination. Duct joint seals showed some abrasion and torn areas, indicating need for improved design.

Impact On Operational Factors

Information obtained during a flight safety check of the modified airplane and during the test program indicated that no deviations in the normal flight operating procedures would be required and that the work load of the flight crew would be unchanged. Small changes in airplane performance, discussed under "Performance Results," were determined that will affect fleet operational planning. Maximum permissible payloads on long-range flights will be reduced by increased takeoff distance, reduction of climb gradient, and reduced specific range. Reduced noise levels at takeoff and approach may permit some increased operational freedom relative to specific airport noise restrictions.

ECONOMIC ANALYSIS

Retrofit Program

A 1972 treated nacelle retrofit price has been estimated by Boeing to be $1 million per airplane including installation based on a production run of not less than 300 airplane sets. A feasible production schedule is shown in figure 19, which reflects a manufacturing rate of approximately 16 airplane sets per month. It is considered that retrofit could be achieved during major overhaul periods without incurring any additional airplane out-of-service time. Accordingly, the production schedule is based on the requirement to have sufficient sets available to facilitate retrofit at major overhaul periods assumed to occur at approximately 3-yr intervals. This schedule requires 19 mo from program initiation to availability of the first kit, 27 mo to 707-320B/C airplane certification with the treated nacelles, 39 mo to the availability of 200 airplane sets, and 52 mo to the availability of 400 airplane sets. Over 420 707-320B/C airplanes are currently in service or on order.

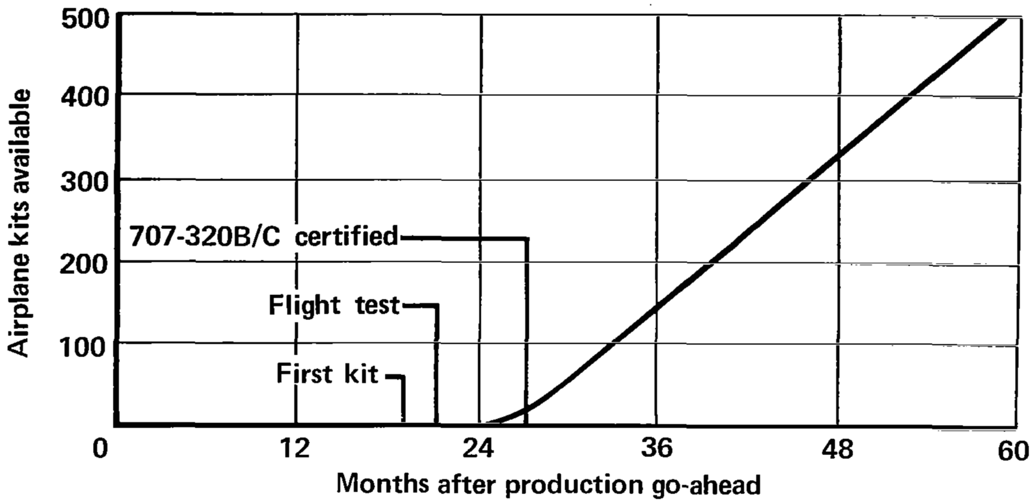


FIGURE 19.–RETROFIT KIT PRODUCTION SCHEDULE

Operating Costs

The effect of the nacelle modifications on both direct and indirect operating costs was estimated for the year 1972. The airplane considered was the 707-320B powered by JT3D-3B engines.

The direct operating costs were estimated on the basis of the Air Transport Association's method published in 1967. Appropriate modifications were made to this method to cover the special case of a nacelle retrofit in 1972. The direct operating cost (DOC) was estimated to increase by 9.2 percent for international operations and 9.6 percent for domestic operations over most of the usable airplane range (fig. 20). It is noted, however, that a reduction of capacity payload range of approximately 200 n. mi. (due mainly to the available fuel displaced by the increased operating empty weight with the treated nacelles) leads to greater percentage increases of DOC than noted above at the long-range extreme for both international and domestic operations. Approximately 85 percent of the DOC increase is estimated to be due to the increase of depreciation costs. The retrofit price, the period of depreciation for the treated nacelles (assumed to be 5 yr), and the spares provisioning for the treated nacelles (assumed to be 20 percent) are therefore the factors that most affect DOC increase.

Indirect operating costs were examined, particularly those items concerning aircraft servicing and ground equipment. Tentative estimates were made of the additional costs due to additional or modified ground equipment made necessary by the nacelle modifications. When the additional costs were distributed over a fleet operation of 5-yr duration, it was

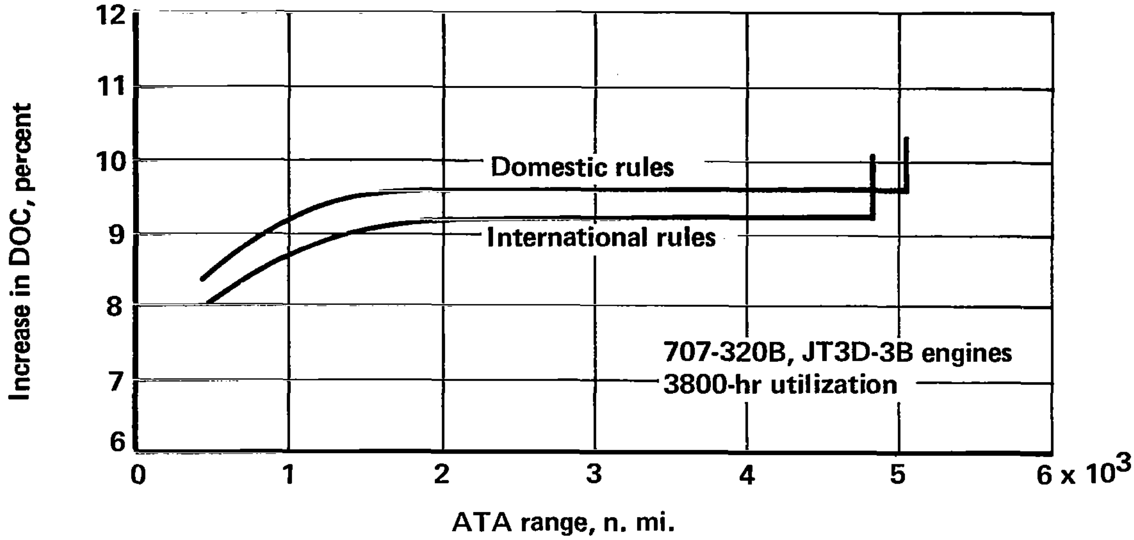


FIGURE 20.—INCREASE OF DIRECT OPERATING COSTS DUE TO NACELLE TREATMENT

found that they were equivalent to less than $1 per trip. According to a calculation method devised by Boeing and Lockheed and revised by Boeing in 1967, typical indirect operating costs for an international trip would be approximately $4000.

Airline Operations

A theoretical evaluation of the operation of 115 707-320B airplanes with and without the retrofit and powered by JT3D-3B engines over a hypothetical route network was made. This network included U.S. to Hawaii, transatlantic and beyond to the Far East and central Africa, and the internal U.S. through routings associated with both. Passenger demand, trip frequencies, and load factors were representative of the year 1968. These assumptions led to an annual average utilization approximately the same as that assumed in the DOC study (3800 hr).

With the use of a special computer program designed to model a fleet operation, passenger demand and airfield temperature were described in statistical terms. In this way, passenger denials, and thus the effects of any performance changes brought about by the nacelle modification, were simulated satisfactorily. No payload other than passengers was considered. Passenger revenue only was assumed, and fare yields were assumed as per 1968 levels.

The study showed a small loss of passenger revenue-earning capacity of 0.10 percent due to the nacelle modifications. This was caused by a slight increase in the number of passenger denials made necessary by the nacelle modifications. The additional passenger denials occurred on five of the long-range westbound flights.

Total operating costs (direct plus indirect) increased by 4.3 percent; this increase is due almost entirely to the increased depreciation costs. The net result of these revenue and operating cost changes was to reduce the return on passenger revenue by 4.3 percent.

In interpreting these results, two points are emphasized. First, the maximum stage length for the route system studied falls in the range from 4500 to 4750 n. mi. The fleet operation of this hypothetical study was not greatly affected by the reduction of capacity payload range due to the treated nacelles. A system with a higher content of long-range routes would demonstrate a greater sensitivity to the nacelle modifications and would undoubtedly show a greater economic penalty. Second, for the purpose of estimating operating costs for the year 1972, the assumption has been made that the complete fleet of 115 airplanes will be retrofitted. The price estimate for retrofit has assumed that the retrofit will occur concurrently with normal overhaul periods in order to minimize airplane out-of-service time. Consequently, retrofit operations would actually be spread over a period of time greater than 1 yr. The production schedule of figure 19 also indicates that only a minority of all Boeing 707-320B/C models could be retrofitted by the end of 1972. The cost implications of a slide in retrofit schedules beyond 1972 should be evaluated by each airline for their own particular case.

The simulated fleet operation was also used to investigate the frequency of noise level experience at the takeoff and landing approach measurement points proposed by reference 1. Because of the narrow range of landing weights involved, 100 percent of the landing noise levels were found to shift from about the 118-EPNdB level to about 103 EPNdB. However, the takeoff levels, which assumed thrust cutback to 6-percent climb gradient, were spread over a wide range because of the large spread of takeoff weights employed in the fleet operation. The frequency of experiences for takeoff noise levels above 100 EPNdB was determined to be reduced from 40 percent of the total flights to 13 percent.

IMPLICATIONS OF RESULTS

During this program, an acoustic technology was developed for suppressing the discrete frequency noise generated in the fan section of the turbofan engines. The basic approach followed in the study was the treatment of the engine inlets and fan ducts with acoustically absorbent liners. Application of this technology to a JT3D engine resulted in a noise reduction of 15.5 EPNdB during the landing approach condition. The acoustic lining selected, a polyimide-impregnated fiberglass sandwich panel, provided a trouble-free nacelle installation on the experimental flight test airplane. In addition, the operating procedures of the test airplane, a 707-320C, were not appreciably affected by the nacelle modifications. The following implications are noted.

Acoustic Lining Technology

The acoustic lining technology developed during this program should provide a firm base for future use of acoustic linings in turbofan or turbojet engines. It was found that a number of variables can affect the results obtained when applying this technology. Four of the major variables are (1) the material selected, (2) the liner design, (3) the nacelle geometry, and (4) the engine noise characteristics. The technology developed provides information for design methodology in which most of these variables can be evaluated. However, there still remains considerable work to ensure that all factors have been properly considered and that the design methodology provides an optimum liner for each application.

Material and Lining Development

A number of metallic and nonmetallic materials and linings were examined during this program. The final selection of a polyimide-fiberglass material was based on a number of considerations. In addition to its acoustic qualities, the selected material was judged on properties such as structural strength, weight, maintainability, fatigue life, and ability to withstand the engine/airplane environment. The selection of polyimide fiberglass was not meant to indicate that this is the material best suited for all such applications. Changes in one or more of the above conditions may result in the need for a different material. In addition, as new materials or improvements in presently available materials are developed, the choice of material may possibly change. At the present time, no material has been evaluated to the extent required to provide an in-service treated nacelle. Such extensive evaluation might lead to a selection of another type of acoustic material or panel. At the present time, fatigue life and the problems associated with contamination of materials and liners are two important factors requiring further study.

Engine Application

This program focused its work on the JT3D engine. Examination of the noise characteristics of this engine indicated that a 15-PNdB reduction in engine noise was possible through suppression of the fan noise only. The suppression available through application of acoustic liners to other turbofan or turbojet engines cannot be established from the results of this program. Each engine type must be properly evaluated to establish all the noise-generating mechanisms and the absolute noise levels over the range of engine operating conditions of concern. Little, if any, benefit can be gained in suppressing compressor or fan noise if the jet noise is dominant, or nearly so. On the other hand, if inlet fan noise is quite strong, more elaborate suppression devices may be needed in the inlet. Another suppression technique (i.e., sonic throat) may be required. The engine noise characteristics will be strongly influenced by the engine bypass ratio and the fan design.

Airplane Application

The 707-320C airplane was used in the application of the acoustically treated nacelles developed in this program. The penalties incurred by this airplane due to installation of these developmental nacelles should be considered as unique. That is, each airplane/engine configuration must be evaluated separately to define any problems resulting from modification of the engine nacelles for noise suppression. A study of 707-120B and 720B airplanes, for instance, indicates that severe flutter problems will result if these treated nacelles are installed on the existing struts. New struts providing relocation of the outboard engines would be required to maintain the desired airplane performance.

The potential noise suppression for airplanes using other engine types (i.e., 720, 727, 737, DC-9, BAC 111) cannot be inferred from the results obtained in this program. Engine design and engine installation will dictate the type of noise-suppression devices needed on these airplanes and their corresponding penalties.

In view of the cost penalties associated with retrofitting present engine/airplane configurations, consideration should be given in future nacelle studies to a more cost-effective approach with possibly less emphasis on performance losses. Where possible, consideration should be given to nacelle acoustic lining requirements during basic engine/airplane development. Integration of noise suppression with engine/airplane design considerations will provide the maximum noise reduction along with the least cost and least loss in engine/airplane performance.

The Boeing Company
Commercial Airplane Group
Seattle, Washington, September 1969

APPENDIX

PROGRAM REVIEW

The Contract NAS 1-7129 tasks were subdivided into four major phases: Materials and Concepts, Models, Boilerplate/Prototype Components, and Flightworthy Nacelles. The events of each phase are reviewed with the materials activities and the concepts activities reviewed separately and the model activity included as a part of the conceptual development activity. The schedule to which all of these tasks were performed is shown in figure A1.

Material Development

Prior to Contract NAS 1-7129, a search for metallic and nonmetallic acoustic attenuation materials, suitable for lining fan engine discharge ducts, was initiated and the potential of a polyimide-fiberglass laminate identified. Throughout the search, which continued for more than a year after receipt of the contract, a methodology was employed in testing newly identified materials. All potential materials were tested for flow resistance and normal acoustic impedance. Materials showing promise during these tests were further evaluated for acoustic attenuation characteristics. The most promising nonmetallic material (polyimide-fiberglass) and the most promising metallic material (a commercially available product) were then subjected to further testing. This included additional measurement of acoustic properties, aerodynamic flow property measurements (skin drag), environmental and physical properties tests, and full-scale engine tests.

Based on the results of the various tests conducted on candidate materials, polyimide-fiberglass was selected in design of boilerplate/prototype fan ducts. Further specialized tests were then conducted on the material. They included additional acoustic attenuation measurements with various noise sources, sonic fatigue tests, flow-resistance measurements of the laminate with honeycomb attached as well as thick laminate (1/4 in.) only, and tests to determine internal wall transmission losses. Acoustic attenuation tests were also made of the simulated boilerplate/prototype fan duct lining configuration and the flightworthy nacelle fan duct and inlet treatment configurations. Further tests of Boeing-developed polyimide-fiberglass specimens were conducted by Pratt & Whitney Aircraft Division of United Aircraft Corporation. Test panels required for this testing were fabricated by Boeing. This helped to identify detailed fabrication techniques and quality control procedures for polyimide-fiberglass laminate.

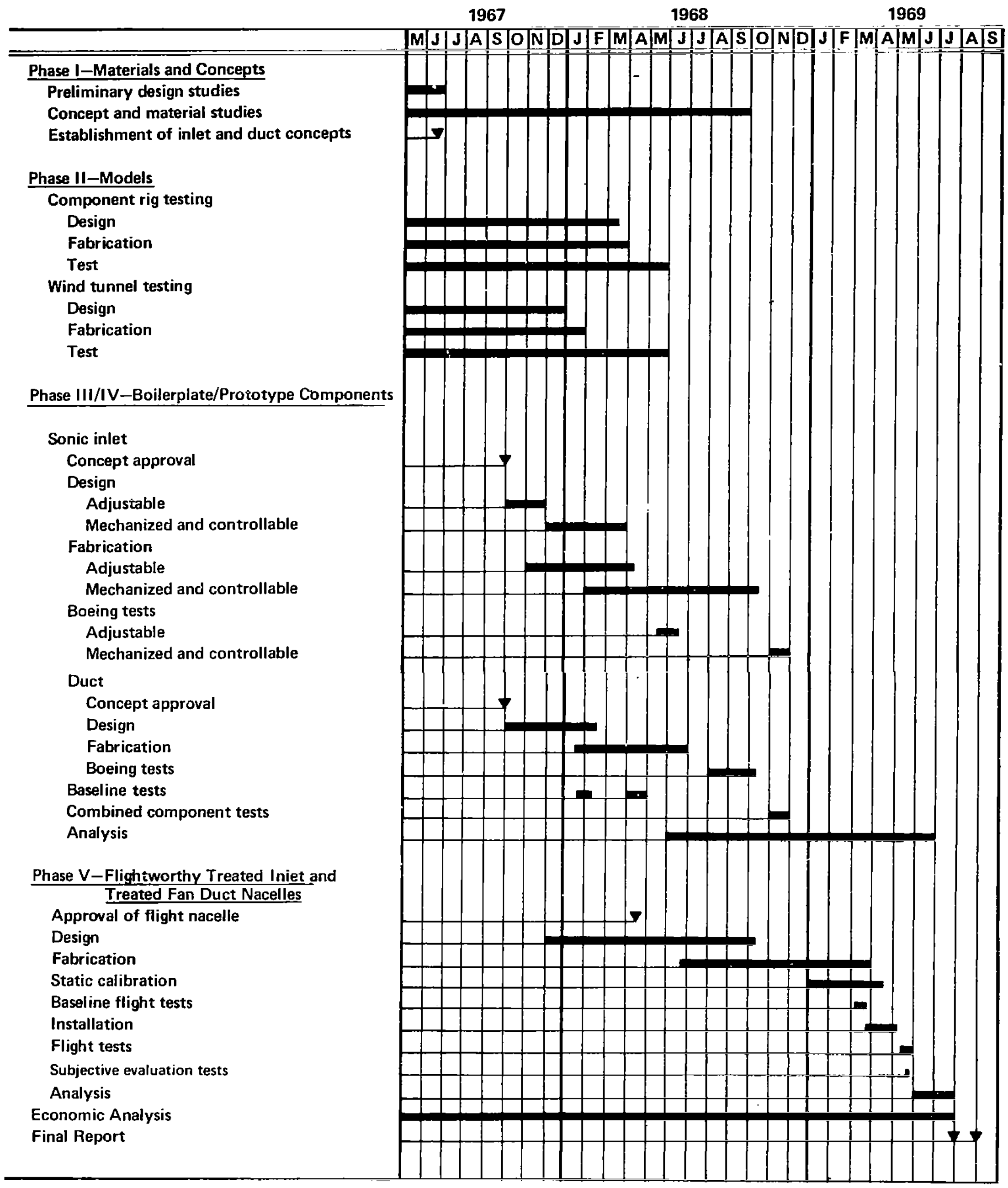


FIGURE A1.—MASTER SCHEDULE

Throughout testing, theoretical and empirical studies were conducted relative to the prediction of the acoustic attenuation of a given material specimen. The validity of these studies was checked throughout the tests, and, upon conclusion, lining technology guidelines were developed for design purposes.

Three supplemental studies conducted during this period consisted of a Boeing study of turbine noise, a Pratt & Whitney study on impedance tube tests with flow velocity, and a Pratt & Whitney study on development of a theoretical method for predicting sound attenuation in rectangular ducts (see ref. 2 for details on the later two studies).

Conceptual Studies

Sonic inlets.—Initial sonic inlet work consisted of preliminary design studies on a wide range of configurations. They were supported by analytical potential flow and boundary layer studies, water table tests, experimental scale-model tests, and full-scale tests of a five-door configuration that had been designed and fabricated prior to the contract. The number of candidate configurations was progressively reduced until an eight-segment contracting cowl configuration with blowing boundary layer control (BLC) in the diffuser was identified for further development in the boilerplate/prototype phase.

Once the concept decision was made, further analytical, water table, scale-model (1/9 scale) and full-scale studies were conducted to support development of the boilerplate/prototype hardware. The BLC investigations and JT3D engine compatibility checks were facilitated by fabrication of a full-scale nonadjustable model of the selected configuration.

Treated fan ducts.—Initial fan duct work also consisted of preliminary design studies on several configurations with the studies supported by scale-model tests. Both acoustic and performance characteristics were considered in the conceptual studies. The configurations included a short duct with sliding sleeve, a 3/4-long duct, a 7/8-long duct, and a full-length duct. The configuration selection process also was a progressive reduction in the candidate configurations until the full-length configuration with coplanar annular fan, primary exit nozzles, and kidney-shaped 900-in^2 internal flow area was selected for further development in the boilerplate/prototype phase. The selection process included consideration of acoustic and propulsion performance, with both internal and external performance characteristics considered.

Following the choice of concept, additional scale-model (1/5 scale) tests were conducted. Both boilerplate/prototype and Pratt & Whitney short fan duct (baseline) configurations were tested.

Treated inlets.—Following the decision to change from a sonic inlet to a treated inlet for the flightworthy nacelles, a brief configuration-verification study was conducted before initiating the detail design. In addition, a wind tunnel test of the wake of a simulated outer ring was conducted, and studies were made to determine optimum locations for placement of acoustic-attenuation material.

Boilerplate/Protytype Components

Five-door sonic inlet.—Prior to receipt of Contract NAS 1-7129, a full-scale five-door sonic inlet was designed and fabricated. Performance testing on a JT3D engine test rig was undertaken as an initial part of the contract to determine the best way to obtain inlet choke without engine surge. Acoustic testing followed at Boeing's Tulalip test facility on a JT3D engine test stand.

Adjustable eight-segment sonic inlet.—After selecting an eight-segment concept for boilerplate/prototype development, a manually adjustable configuration was designed and fabricated. Aerodynamic and acoustic tests then were performed on the JT3D engine test stand, using 750-, 900-, and 1570-in^2 throat areas at various inlet centerline Mach numbers and with various blowing BLC slot locations.

Mechanized and controllable eight-segment sonic inlet.—Concurrent with testing of the adjustable eight-segment sonic inlet, studies were conducted to determine optimum means of mechanizing and remotely controlling the inlet. Included were studies of control and actuation systems as well as water table tests to predict loads and torques. Subsequently, a mechanized and controllable inlet configuration was designed. Following design completion, proof tests were conducted and parts fabricated and assembled. Testing followed on the test stand.

Treated fan duct.—After selecting a full-length concept for boilerplate/prototype development, preliminary design studies were undertaken, resulting in a decision to use polyimide-fiberglass laminate in both acoustic and structural applications. On this basis a final design was executed and parts were fabricated. To facilitate the design, an existing full-scale production nacelle mockup was modified and used. In addition, sonic fatigue and structural tests were conducted. The duct was then installed on the test stand, and both performance and acoustic tests were performed. Tests were conducted on the duct alone and on the duct with the mechanized and controllable eight-segment sonic inlet. Acoustic testing was accomplished with the total designed acoustic treatment and with the aft 30 in. of the designed treatment blanked off as well as with and without an inlet noise directionalizer. Tests of the existing (707 production) duct also were made.

Treated inlet.—No full-scale boilerplate/prototype development efforts were undertaken by Boeing on the treated inlet. Conceptual studies and boilerplate/prototype development of a single-ring treated inlet were conducted by the Douglas Aircraft Division of McDonnell Douglas Corporation under a separate contract with NASA.

Flightworthy Nacelles

Early flightworthy nacelle effort was directed primarily toward development of a control system for a sonic inlet. After a short period, Boeing's efforts were changed to a two-ring treated inlet to be used in conjunction with a full-length treated fan duct. The schedule for the changed configuration was also accelerated 4 mo. Detailed design of the treated inlet, the full-length treated fan duct, and the engine/nacelle modifications required to accommodate these components was then executed, and four nacelle sets of hardware were fabricated.

Static calibration.—Each of the four nacelle hardware sets was installed on a JT3D-7 engine mounted on the test stand and static calibrated. Static calibration was performed to check both the acoustic and propulsion performance of the nacelles, to confirm their structural integrity, to check out the subsystems, and to measure ground static thrust for comparison with calculated in-flight thrust. Tests were performed on the treated inlet with a calibrated Pratt & Whitney reference long duct, on the treated duct with a Pratt & Whitney bellmouth inlet, and on the total nacelle. Baseline tests of the standard JT3D-7 engine nacelle also were performed.

Flight tests.—Concurrent with static calibration testing, performance and acoustic baseline flight tests were conducted on a 707-320C airplane. The acoustic tests were conducted over the Boeing Acoustic Test Range at Grant County Airport, Moses Lake, Washington, and included noise measurements during ground, takeoff, climbout, and landing approach operations. After testing, the standard JT3D-7 engine cowling was removed, and acoustically treated hardware was installed. Ground taxi tests first were run to check out the new installation and were followed by flight tests of the safety, flutter, inlet performance, engine performance, airplane performance, acoustic, and nacelle cooling aspects of the treated nacelles. Acoustic tests were again conducted over the Boeing Acoustic Test Range. At completion of these tests, the 707-320C treated airplane and a production 707-320C airplane flew a series of simulated takeoff and landing conditions over the airport. During these conditions, 180 people subjectively evaluated the extent of noise reduction. Observations were made directly under the flightpath and at sideline positions from both indoor and outdoor listening posts. These tests completed the test program. The treated nacelles then were removed from the test airplane, and the airplane refurbished to its original condition.

REFERENCES

1. Federal Aviation Administration, Department of Transportation: Noise Standards, Aircraft Type Certification (Notice of Proposed Rule Making 69-1). Federal Register (34 F.R.453) Jan. 11, 1969.

2. Pratt & Whitney Aircraft Division: Analytical and Experimental Studies for Predicting Noise Attenuation in Acoustically Treated Ducts for Turbofan Engines. NASA CR-1373, Sept. 1969.

NASA-Langley, 1970 —— 2 CR-1711