NASA SP-220

NASA ACOUSTICALLY TREATED NACELLE PROGRAM

A conference held at
LANGLEY RESEARCH CENTER
Hampton, Virginia
October 15, 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1969
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

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PREFACE

This document contains final results of the NASA acoustically treated nacelle program. The program was conducted by The Boeing Company and McDonnell Douglas Corporation under contract to NASA. Interim results on the acoustically treated nacelle program were included in the Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft held on October 8-10, 1968, at the Langley Research Center and reported in NASA SP-189.

The material contained in the papers of the present conference held at the Langley Research Center on October 15, 1969, reflect information obtained during flight tests made since the previous conference.

Additional detailed information obtained during the contractors' studies will be reported in future Contractor Reports.

A list of attendees is included.

CONTENTS

1. OPENING REMARKS

By Robert W. Boswinkle, Jr.

NASA Langley Research Center

NASA ACOUSTICS RESEARCH

The NASA noise research program goes back many years, some 40 years at the Langley Research Center, and is very broad in scope. It includes fundamentals of noise generation and propagation from aircraft components, structural response, the effects of noise on people, and sonic boom. In regard to reducing aircraft engine noise, it includes at least three approaches: reduction of noise generation, absorption of generated noise, and modification of the aircraft flight operational procedure. The second approach, absorption of generated noise, is the one that was pursued in the program which is the subject of this present conference.

These NASA research efforts are part of an integrated national program. NASA has associations with many organizations in coordinating and conducting acoustics research. These associations extend throughout industry, the universities, the professional societies, and the government. For example, the Aircraft Noise Abatement Program, under the chairmanship of the Department of Transportation, has representation of all applicable Government agencies and is the cognizant coordinating body for work such as is to be discussed at this conference.

NASA CONFERENCES

One way of reporting the results of NASA research is through technical conferences. In 1968, for example, the first NASA conference devoted exclusively to noise research was held. The $2\frac{1}{2}$-day conference was entitled "Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft." Various NASA Centers and their contractors presented papers in sessions entitled Nacelle Acoustic Treatment Technology, Nacelle Acoustic Treatment Application, Noise Generation and Reduction at the Source, Operational and Environmental Considerations, and Subjective Reaction.

The acoustic treatment and application sessions of the 1968 conference dealt largely with the early results of the NASA Acoustically Treated Nacelle Program. In this effort two companies under contract to NASA, McDonnell Douglas and Boeing, studied means of minimizing the radiation of fan noise from turbofan engines. The contracts are nearly completed now and most of the final results will be presented in the present conference.

DOCUMENTATION

It may be helpful to describe the various reports, other than those included in the present compilation, that have come about as a result of the McDonnell Douglas and Boeing studies. At the present time, the best source of the technology of nacelle acoustic treatment is included in the compilation of the papers presented at last year's conference (ref. 1).

The following reports are in preparation by the two contractors. These reports will present a final account of the studies and are much more detailed than reference 1 or the present compilation.

The McDonnell Douglas final report is entitled "Investigation of DC-8 Nacelle Modifications to Reduce Fan-Compressor Noise in Airport Communities" and includes

Part I	Summary of Program Results
Part II	Design Studies and Duct-Lining Investigations
Part III	Static Tests of Noise Suppressor Configurations
Part IV	Flight Acoustical and Performance Evaluations
Part V	Economic Implications of Retrofit
Part VI	Psycho-Acoustical Evaluation

The Boeing final report is entitled "Study and Development of Turbofan Nacelle Modifications to Minimize Fan-Compressor Noise Radiation" and includes

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 of Treated Nacelle Noise Reduction

Reference 2 is a recent report which was prepared as part of the Nacelle Acoustic Treatment Program. The work was done by Pratt and Whitney Division of United Aircraft Corporation under NASA contract NAS 1-7129. It deals with noise attenuation in acoustically treated ducts.

One other group of documents is of interest. As part of the contractual arrangement with McDonnell Douglas and Boeing, the two companies agreed to make available to NASA, for distribution to industry, the results of all of their previous work pertaining to aircraft noise alleviation. The documents were reviewed by NASA and those considered of interest to others, some 44 of them, were announced in reference 3. Abstracts of the documents, copied from reference 3, are included herein as an appendix. These documents may be obtained from:

Clearinghouse for Federal Scientific and Technical Information (CFSTI)
Springfield, Virginia 22151

The availability of these documents in hard copy form (HC), at a cost of $3.00 apiece, or in microfiche (MC), at a cost of $0.65 apiece, is indicated for each report. Additional documents from the two companies are being reviewed and will be announced in future issues of "Scientific and Technical Aerospace Reports" (STAR), which is an NASA abstract journal available in many technical libraries. References 1 and 2 are also available from CFSTI.

REFERENCES

1. Anon.: Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft. NASA SP-189, Conference held at Langley Research Center, Oct. 8-10, 1968.
2. Feder, Ernest; and Dean, Lee Wallace III: Analytical and Experimental Studies for Predicting Noise Attenuation in Acoustically Treated Ducts for Turbofan Engines. NASA CR-1373, 1969.
3. Scientific and Technical Aerospace Reports, Vol. 6, No. 20, Oct. 23, 1968, pp. 3395-3401.

APPENDIX

McDonnell Douglas and Boeing Reports

pertaining to

Aircraft Noise Alleviation

Copied from Oct. 23, 1968 (vol. 6, no. 20) issue of

Scientific and Technical Aerospace Reports

(STAR)

02 AIRCRAFT

Includes fixed-wing airplanes, helicopters, gliders, balloons, ornithopters, etc; and specific types of complete aircraft (e.g., ground effect machines, STOL, and VTOL); flight tests; operating problems (e.g., sonic boom); safety and safety devices; economics; and stability and control. For basic research see: 01 Aerodynamics. For related information see also: 31 Space Vehicles; and 32 Structural Mechanics.

N68-32190# Boeing Co., Renton, Wash. Commercial Airplane Div.
THE REDUCTION OF FAN NOISE IN TURBO-FAN ENGINES BY USE OF ACOUSTICAL LININGS. VOLUME 1: SUMMARY OF THEORETICAL AND EXPERIMENTAL DATA
A. O. Andersson, A. J. Bohn, and R. A. Mangiarotty 24 Oct. 1967 111 p refs Previously X68-18469
(D6-17100, V. 1) CFSTI: $3.00

Initial results and conclusions are presented on a program to develop theoretical methods and experimental techniques leading to a better understanding of the technology for acoustical treatment of engine fan ducts. Theoretical prediction methods are being used for lining optimization studies, and sufficient experimental data have been acquired to compile acoustical design criteria for treating engine fan ducts. Some correlation has been obtained between laboratory flow duct and full scale engine duct acoustical performance. Existing acoustical materials are being evaluated, and an analog computer technique has been developed for determining the desirable characteristics of lining materials. A new nonmetallic lining material, polyimide resin glass fiber, is being developed and some evaluation has been completed. Author

N68-32191# Boeing Co., Renton, Wash. Commerical Airplane Div.
THE REDUCTION OF FAN NOISE IN TURBO-FAN ENGINES BY USE OF ACOUSTICAL LININGS. VOLUME 2: DETAILED THEORETICAL AND EXPERIMENTAL DATA
A. O. Andersson, A. J. Bohn, and R. A. Mangiarotty 24 Oct. 1967 152 p refs Previously X68-18452
(D6-17100, V. 2) CFSTI: HC$3.00/MF$0.65

This volume consists of the appendices to N68-32190. The data presented were analyzed and reduced from the bulk of the test data in the experiments and theoretical analyses. Author

N68-32192# Boeing Co., Renton, Wash. Commercial Airplane Div.
ACOUSTIC AND THRUST CHARACTERISTICS OF THE SUBSONIC JET EFFLUX FROM MODEL SCALE SOUND SUPPRESSORS. PART 1: UNHEATED JETS, VOLUME 2
R. A. Mangiarott and D. Elizabeth Cuadra 27 Dec. 1967 141 p refs
(D6-15071, V. 2) CFSTI: $3.00

Acoustic near and far field data and thrust characteristics are presented for four model nozzle configurations. A smooth-walled conical nozzle serves as a reference model; comparison models include a rough-walled conical nozzle, the Boeing 21-tube suppressor nozzle, and a 12-fluted nozzle. Using unheated air, these nominally tenth-scale (6 square-inch exit area) nozzles were tested for their noise generation characteristics for exit Mach numbers $0.5 < M_j < 0.9$ and for their thrust characteristics for exit Mach numbers $0.2 < M_j < 0.8$. (See Volume 1, N68-32196.) Author

N68-32193# Boeing Co., Renton, Wash. Airplane Div.
INTERIM PREDICTION METHOD FOR THE ACOUSTIC FAR FIELD OF EJECTORS
D. Elizabeth Cuadra 2 Aug. 1966 39 p refs
(D6-17093TN)

A far field acoustic prediction method is recommended for the broadband jet noise of ejectors for the cases of fully mixed flows and unmixed flows, together with shroud length criteria for complete mixing. The beginning of a method for partially mixed flows is also indicated, but additional knowledge, on both mean flow properties and turbulence properties is needed to make it workable. Author

N68-32194# Boeing Co., Renton, Wash. Airplane Div.
LIMITED COMPRESSOR NOISE SURVEY: ANALYSIS OF TEST RESULTS
J. A. Crim and R. E. Russell 25 May 1966 48 p refs
(D6-11226TN) CFSTI: HC$3.00/MF$0.65

An exploratory research program was carried out to investigate possible causes of fan and compressor noise. Several ideas had been advanced with respect to the source of this noise. The experiments, carried out on a 5.3-inch diameter fan, were aimed at quickly testing these theories, and at finding promising methods of reducing the noise. The results are not quantitatively applicable to a full size fan. However, there is reason to believe that the qualitative trends will be present in larger fans. The following five basic areas of noise generation were investigated: (1) upstream turbulence, (2) rotor tip flow field, (3) rotor loading (4) rotor/inlet guide vane spacing, and (5) inlet guide wave treatment. The two most promising means of reducing fan noise are rotor unloading and injecting air out the trailing edge of the inlet guide vanes. Author

N68-32195# Boeing Co., Renton, Wash. Airplane Div.
INTERNAL SUPPRESSION OF COMPRESSOR NOISE OF THE JT3D-3B ENGINE WITH 3/4 LENGTH FAN DUCTS
A. J. Bohn 6 May 1966 63 p Revised
(T6-3498, Rev. A) CFSTI: $3.00

Acoustic treatment of internal surfaces of the inlet and 3/4 length fan ducts of the JT3D-3B engine were tested. Effects of variations in treatment design, length of treated section, areas of treatment and depth of backing space within the fan ducts were studied. The treatment design tested in the inlet duct had no measurable effect on engine noise. Treated 3/4 length fan ducts reduced peak flyover noise (calculated for 200 foot altitude) by from one PNdb at 4000 lbs static thrust up to 7 PMdb at 15,000 lbs static thrust, and by 4 PNdb at maximum static thrusts. The effectiveness of a unit area of treatment in the fan duct varied nonuniformly with its location within the duct. Consequently, no reliable measure of attenuation in terms of a nondimensional ratio such as L/d (length of treatment over depth or diameter of duct) could be deduced for application to other engines. Author

N68-32196# Boeing Co., Renton, Wash. Airplane Div.
VELOCITY AND SHEAR PROFILES IN THE SUBSONIC JET EFFLUX FROM MODEL SCALE SOUND SUPPRESSORS. PART 1: UNHEATED JETS, VOLUME 1
James A. Ranner and D. Elizabeth Cuadra 14 Mar. 1966 111 p refs
(D6-15071, V. 1) CFSTI: $3.00

Mean velocity and shear patterns throughout the major noise generating regions of the jet efflux from four nozzle configurations are described. A smooth-walled conical nozzle serves as a reference model; comparison models include a rough-walled conical nozzle, the Boeing 21-tube suppressor nozzle, and a slotted nozzle based on the Rolls-Royce suppressor. Using unheated air, these nominally tenth scale (6 square-inch exit area) nozzles were tested for exit Mach numbers ranging from 0.1 to 1.75. Implications regarding the sound generation are discussed. (See Volume 2, N68-32192.) Author

N68-32197# Boeing Co., Renton, Wash. Airplane Div.
PNDB GROUND CONTOUR DETERMINATION FOR JET AIRCRAFT
J. V. O'Keefe 18 Mar. 1966 37 p refs Revised
(D6-15082TN, Rev. A) CFSTI: $3.00

Procedures are outlined for determining maximum jet noise levels for ground static and flight conditions. A method for defining ground contour iso-PNdB lines for a specific engine airplane match and an assigned flight profile is provided. Jet noise level predictions are in terms of full octave band sound pressure levels of ground-to-ground sideline noise or air-to-ground sideline or fly-over noise. These values may be converted to overall sound pressure levels (OA-SPL) or a subjective rating of perceived noise levels (PNdB). Author

N68-32198# Boeing Co., Renton, Wash. Airplane Div.
PROCEDURES FOR JET NOISE PREDICTION
M. B. Mc Kaig, R. H. Sawhill, and John B. Large 11 Mar. 1965 29 p refs Revised
(D6-2357TN, Rev. A) CFSTI: $3.00

Calculation procedures are provided for predicting maximum flyby noise from jet aircraft exhausts. Three types of engine exhausts are considered: turbojet with standard circular nozzle; turbojet with nonstandard nozzle; and turbofan or bypass engine with unmixed exhausts or completely mixed exhausts. Noise predictions are in terms of octave-band sound pressure levels of maximum air-to-ground flyby noise or of maximum ground-to-ground sideline noise. These levels may be converted to an overall sound pressure level or to a subjective rating such as perceived noise level. Author

N68-32199# Boeing Co., Renton, Wash. Airplane Div.
FAN-DISCHARGE NOISE SUPPRESSOR TEST JT8D ENGINE
M. B. Mc Kaig 28 Oct. 1964 47 p
(T6-3166) CFSTI: $3.00

To determine if suppression of fan-discharge noise is feasible in the high-velocity duct system of a turbofan engine, an acoustically treated extension of the fan discharge duct of a JT8D engine was tested. Engine thrusts ranged from 4000 to 13,500 pounds (maximum static). More than 20 db attenuation of discrete-frequency spike noise was obtained. White noise between spikes also was reduced as much as 8 db. It is concluded that acoustic lining in high-velocity air ducts can give useful amounts of attenuation, and that application of the technique to turbofan engines is promising because of the large proportion of high-frequency noise discharged from the fan duct. Author

N68-32200# Boeing Co., Renton, Wash. Transport Div.
J-75 INLET NOISE SUPPRESSION TEST
M. B. Mc Kaig 27 Oct. 1964 60 p
(T6-3173) CFSTI: $3.00

Three devices were tested on a J-75 turbojet engine for reducing compressor or fan noise radiated from the inlet: (1) sonic throat, (2) absorbent inlet lining, and (3) absorbent inlet guide vanes. The basic inlet design simulated a supersonic inlet with expandable spike. The first device, the sonic throat, was formed by setting the spike in its fully expanded, supersonic-cruise position, and then advancing the throttle until choking occurred. The absorbent inlet lining consisted of acoustic material extending along the inside of the barrel for a length of about one diameter. The absorbent guide vanes, 20 in number, were placed directly upstream of the engine's fixed inlet guide vanes. The most effective single device was the choked inlet, delivering 10 to 15 PNdB. Conflicting results were obtained as to the relative merits of the inlet lining and inlet guide vanes, but they were probably about equally effective, giving around 3 PNdB. Author

N68-32201# Boeing Co., Renton, Wash. Airplane Div.
ATTENUATION OF AUXILIARY POWER UNIT (APU) EXHAUST NOISE BY STACK INSERT DEVICES
V. E. Callaway 12 Aug. 1964 18 p
(T6-3160) CFSTI: HC $3.00/MF $0.65

Attenuation of 727 auxiliary power unit exhaust noise provided by stack insert devices are presented. The combination of an in-line flow-through muffler and an exhaust deflector was found to be the most effective method of reducing this noise. These two devices complement each other in their attenuation properties; the deflector devices reduce levels in frequencies below 300 cps by 2 to 7 dB, while the muffler reduces speech interference level frequencies (600 4800 cps) by 4 to 8 dB. Author

N68-32202# Boeing Co., Renton, Wash. Airplane Div.
AIRCRAFT ACOUSTICS: COMMUNITY NOISE PREDICTION
K. Fukushima 2 Jul. 1964 70 p refs
(D6-4219TN) CFSTI: $3.00

A computer program was written specifically to determine the following: (1) The community noise level expected at an airport, given the take-off (normal and power cutback) or landing path of the aircraft, its engine noise level and parameter governing attenuation of the radiated engine noise. (2) The geographical plot of ground noise level, varying time, the point of the aircraft's break release and the chosen flight path. Author

N68-32203# Boeing Co., Renton, Wash. Transport Div.
COMMUNITY NOISE LEVELS FOR VARIOUS AIRCRAFT DURING TAKE-OFF AND LANDING
R. D. Hulsey 5 Feb. 1964 21 p refs
(D6-9375TN) CFSTI: $3.00

Data from many sources were gathered and processed to obtain noise as a function of altitude for the take-off and landing approaches of various airplanes. The purpose here is to present, in one central document, material that can be used for aircraft noise comparisons at a later date and thus eliminate the confusion that usually arises from multiple sources of information. Author

N68-32204# Boeing Co., Renton, Wash. Transport Div.
PROCEDURE FOR ANALYZING DATA FROM UNCONTROLLED FLY-BY TESTS
M. B. McKaig 1 Oct. 1963 37 p
(D6-9815TN) CFSTI: $3.00

Analysis of acoustic data from fly-by tests offers special difficulties when the basic flight conditions are uncontrolled; from test to test there may be variations of speed, altitude, flight path, and weather conditions. The effects of these variables on the recorded sound may make direct comparison of results very misleading. A procedure is set forth for reducing these effects, by referring recorded sounds to the airplane's orientation with respect to the observer at the time the sounds originated; the sound levels are then corrected to standard conditions of distance and weather. Author

N68-32205# Boeing Co., Renton, Wash. Transport Div.
GRAPHICAL DETERMINATION OF COMMUNITY–NOISE CONTOUR COORDINATES
Merle B. McKaig 28 Jun. 1963 28 p
(D6-9582TN) CFSTI: $3.00

A graphical method is presented for determining the location in a community of the peak-noise contour lines expected from operation of a given type of aircraft from a nearby airport. Two variations of the method are included: how to show the effects of cut-back, and how to determine the peak level to be expected at a given ground location. Steps in the presentation are given in enough detail that users of the method need not have extensive technical training. Author

N68-32206# Boeing Co., Renton, Wash. Transport Div.
THE DESIGN AND CONSTRUCTION OF AN ANNOYANCE SCALE FOR JET ENGINE NOISE
Stanley J. Rule 23 Jan. 1963 62 p refs
(D6-4348) CFSTI: $3.00

A research program is described on the development of a human reaction scale for airplane noise. Such a scale is useful in determining the relative effects of noise reduction procedures on human comfort. The annoyance scale has been found to be applicable in the SPL range 60 to 100 db to broadband noises which do not contain discrete components. A scaling relationship has been developed which permits an annoyance equivalence to be established between broadband noise and impulse noise. Author

N68-32207# General Applied Science Labs., Inc., Westbury, N. Y.
INLET NOISE
Simon Slutsky Renton, Wash. Boeing Co. 25 Oct. 1962 55 p
Prepared for Boeing Co., Renton, Wash.
(D6-4241) CFSTI: $3.00

Three mechanisms have been found to be of importance in inlet attenuation or transmission. The first involves the phenomenon of wave propagation cut-off frequencies experienced by spiral progressive waves below which rapid attenuation occurs. The second is the generation of waves as a result of interference of the rotor and stator blades. The third mechanism involves a technique of acoustic noise attenuation based on the use of thin porous diaphragms instead of the usual thick absorptive materials. An analysis of the far field of the inlet for the engine at rest is described. Author

N68-32208# Boeing Co., Renton, Wash. Transport Div.
ACOUSTIC ENERGY GENERATION AS A FUNCTION OF TURBOFAN ENGINE DESIGN
Harry Garmanian 21 Jun. 1962 92 p
(D6-9045) CFSTI: HC$3.00/MF$0.65

A program was initiated to cover experimental and analytical investigation of the performance of the variable exhaust geometry in a bypass engine in terms of jet noise attenuation and engine design criteria. The experimental portion of the program, a series of scale-model tests simulating exhaust flow conditions of a coplanar and partially mixed discharge configuration of the JT3D-1 and JT8D-1 turbofan engines, was conducted in the Model Jet Facility. The analytical part of the program was confined to a prediction of the acoustic potential of a fully-mixed discharge configuration of the tested engine. Author

N68-32209# Boeing Co., Renton, Wash. Transport Div.
EXTERIOR SOUND CHARACTERISTICS OF THE 707–320B AIRPLANE
D. L. Bryan 11 Jun. 1962 44 p refs
(T6-2418) CFSTI: $3.00

Acoustics tests were conducted so that the exterior sound characteristics of the Model 320B airplane during various in-flight and ground operations could be determined. The airplane tested was a production Model 320B powered by Pratt and Whitney Model JT3D-3 engines. Sound levels were measured under the flight path of the airplane as it was flying over in level flight. Tests were also conducted during ground-static operation of a single engine at which time sound levels were measured on the ground around the engine. Sound characteristics are presented in the form of sound level tables, frequency-spectrum plots, subjective noise curves, and directivity plots. The maximum sound pressure level at a point on the ground 800 feet below the take-off flight path of the airplane operating at maximum take-off power is estimated to be 109 dB. The corresponding loudness level and perceived noise level would be 117 phons and 120 PNdB, respectively. Author

N68-32210# Boeing Co., Renton, Wash. Transport Div.
MEASUREMENT OF NOISE CONTAINING DISCRETE FREQUENCY COMPONENTS IN THE PRESENCE OF RANDOM NOISE SIGNALS
H. H. Taniguchi 18 Apr. 1962 32 p refs
(D6-8786) CFSTI: $3.00

The measurements of discrete frequency noise and the method of interpreting the data were studied. The study was initiated for the purpose of obtaining a greater understanding of noise measurements made when intense discrete frequency components are present in the noise spectrum. The emphasis is placed on measurements of noise originating from jet engines during ground (static) operations and on measurements taken on the ground during aircraft fly-over (transient) conditions. Special measurement techniques are required for determining the time-average value of a discrete frequency signal. These techniques can be classified as (1) sampling process, whereby the rectified signal is integrated over a fixed time period, and (2) continuous process, whereby the rectified signal is continuously smoothed (with a low-pass filter) and the resultant level displayed on a level-recording device. Author

N68-32211# Boeing Co., Renton, Wash. Transport Div.
PARAMETRIC STUDY OF COMMUNITY NOISE LEVELS FOR VARIOUS ENGINE CYCLES AND WEIGHT FLOWS
Heinz E. Schoernich 20 Feb. 1962 149 p refs
(D6-8147) CFSTI: $3.00

Community noise levels are calculated for airplanes equipped with four power plants, either turbojet or turbofan. A comparison of the perceived noise levels of various weight flows and engine types reveals that the perceived noise level (1) increases with an increase in total weight flow for each engine type, (2) decreases with higher bypass ratios for the same total weight flow, (3) decreases with reduction in power for any engine and any weight flow, and (4) decreases with increase in altitude for any engine and any weight flow. The perceived noise levels presented cover a wide range of total weight flow and engine cycles and should suffice as first approximations for many future airplane configurations. In short, the results of the study can be used to determine the community noise levels for various airplane configurations. Airplane–power plant-matching, aerodynamic, and other studies will yield the altitudes above a community for various airplanes. These altitudes, together with the engine cycle and the engine size, will determine the community noise levels for the airplane to be studied so that the optimum configuration as far as the community noise is concerned can be found. Author

N68-32212# Boeing Co., Renton, Wash. Transport Div.
THE TRANSMISSION OF SOUND INSIDE ABSORBING DUCTS
Heinz E. Schoernich 22 Jan. 1962 80 p refs Previously X65-80645
(D6-8087) CFSTI: $3.00

Theoretical formulas and graphs are derived which can be used to calculate the attenuation in db per foot of duct length. Rectangular, cylindrical, and square ducts with one, two, or four absorbing walls are considered. Since the equations and graphs are cumbersome to use, approximations for the formulas are derived. It is shown that the perimeter for a given area must be as large as possible if maximum attenuation is to be obtained; therefore, a rectangular duct is more favorable than a circular duct. It is also shown that attenuation is increased when duct width is decreased.

Diminishing wall impedance, maximum possible theoretical attenuation, and a method for simplifying the Morse attenuation charts are also discussed. All modifications necessary for the calculation are made so that effective attenuation constants can be calculated for flows over an absorbing liner. Author

N68-32213# Boeing Co., Renton, Wash. Transport Div.
A METHOD OF PREDICTING STATIC TURBOFAN FAR FIELD NOISE
Peh Sun Ku 4 Dec. 1961 64 p refs Previously N64-82461
(D6-7859) CFSTI: $3.00

The jet noise, the fan noise, and the compressor noise were first estimated separately. The resultant spectrum contributed by these three types of noise was obtained by superposition of the respective levels in the appropriate octave bands. As an illustration, the predicted static results for the CJ 805-23 engine indicated good agreement with the measured static results. The maximum deviation from the measured results was 6 db in the octave band levels while the agreement with measured CJ 805-23 data for over-all SPL was ±2 db. Considering the maximum estimated error of measurement of ±2 db, the method is believed to be reliable for qualitative estimating purposes. Author

N68-32214# Boeing Co., Renton, Wash. Transport Div.
COMPARATIVE EVALUATION OF ACOUSTICAL PERFORMANCE OF BASIC AND HUSH KIT VERSIONS OF PRATT AND WHITNEY JT3D-1 TURBOFAN ENGINES
A. M. MirSepasy 29 Sep. 1961 26 p refs
(T6-2111) CFSTI: $3.00

Acoustics tests were conducted so that the acoustical characteristics of the Pratt and Whitney modified JT3D-1 turbofan engine could be evaluated. The test airplane, a 720B, was equipped in turn with (1) Pratt and Whitney Aircraft basic JT3D-1 engines, and (2) Hush Kit modified version of the JT3D-1 engine. The maximum sound pressure level attenuation at a point on the ground 800 feet below the airplane's takeoff flight path, with engines at takeoff power, was 1 db. At the 3400 pound thrust condition, the modified engine afforded attenuations of up to 6 PNdb during the pre-overhead (approach) position of the airplane and at a flight altitude near 400 feet. The Hush Kit modification produced little or no octave band SPL attenuation in the directions of fan discharge noise propagation (approximately 130° from inlet axis), and the normal to the engine axis. Author

N68-32215# Boeing Co., Renton, Wash. Transport Div.
WHINE NOISE IN FAN DUCTS
J. H. Prindle 21 Jul. 1961 48 p Previously X65-80742
(D6-7538) CFSTI: $3.00

The form of the acoustic field developed in a duct by a whining fan is investigated. A basic result is that the modes which will be excited can be predicted by supposing the stator blades are the noise sources. The effects of sound—absorptive walls and of flow in the duct are discussed. Application of the results to the JT8D-1 engine leads to the prediction that lining one foot of the inlet duct should suppress inlet whine at least four or five decibels. Author

N68-32216# Boeing Co., Renton, Wash. Transport Div.
THE DESIGN AND EVALUATION OF AN AERODYNAMIC INLET NOISE SUPPRESSOR
L. Maestrello 12 Dec. 1960 39 p
(D6-5980) CFSTI: $3.00

An inlet model noise suppressor has been designed and successfully tested. The inlet consists mainly of a cylindrical duct with central movable plug. The plug controls the throat area ratio and, as a consequence, induces pressure, density, and velocity jumps across a section of the inlet; this discontinuity suppresses the sound radiated upstream from the compressor. The tests reveal that for an inlet Mach number below 0.5, the noise radiated along the inlet was propagated without attenuation; but as the Mach number increased, the noise decreased; it finally disappeared when the inlet Mach number reached 0.90. The total pressure losses for the scale model varied from 1 to 1.5 inches of mercury, depending on the operating inlet total pressure. Author

N68-32217# Boeing Co., Seattle, Wash.
THE ACOUSTIC NEAR FIELD OF A MODEL AIR JET SIMULATING VERTICAL TAKE-OFF
Stanley Oas 28 Jan. 1958 32 p refs
(D2-2463) CFSTI: $3.00

Detailed measurements were made in the acoustic near field of a supersonic cold air jet exhausting vertically downward onto a ground plane. In the free field, the distribution and power spectrum shape of the model noise field matched very closely that of a 130,000 lb thrust rocket motor, although the power and frequency scale factors did not agree with those based on scaling methods in use. The distortion of the sound field by the ground plane showed the combined effects of sound reflection and the 90° deflection of the jet stream. At close proximity to the ground plane, a 4 db reduction of total radiated acoustic power was measured. The noise spectrum shape differed from the free field shape for all positions of the jet above ground up to and including 32 nozzle diameters. Author

N68-32218# Boeing Co., Seattle, Washington.
PROPAGATION AND MEASUREMENT OF JET NOISE
A. A. Evenson and N. M. Barr 20 Dec. 1957 46 p refs
(D6-2820) CFSTI: $3.00

To obtain consistent data with which to describe the noise fields of jet aircraft, it is shown that very stable conditions are prevalent just after dawn when winds are light and a temperature inversion exists. Three separate tests, conducted under such conditions, gave satisfactory results. Far-field noise measurements are often meaningless unless referred to a standard meteorological condition. Present knowledge does not permit normalization of data acquired under different meteorological conditions. Consistent data may be acquired under a narrow range of meteorological conditions which may be forecast and identified by a professional meteorologist. Author

N68-32219# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.
AERODYNAMIC LOSSES CAUSED BY POROUS FIBERMETAL
S. P. Patel May 1967 82 p
(DAC-33722) CFSTI: HC$3.00/MF $0.65

Tests to determine the aerodynamic losses caused by porous fibermetal were conducted in the low speed tunnel. Two fibermetal plates with different porosities (25-Rayl and 10-Rayl material) with 0.75 inch-deep air-cavity backing were tested. For comparison, a smooth solid plate was also tested. When the backing was an air cavity, the momentum-thickness ratios were minimum for zero pressure gradient across the plate. When various types of backings were used in the cavity, the momentum-thickness ratios had the same values as those for the zero pressure gradient. These minimum values were 1.3 for the 25-Rayl fibermetal and 1.6 for the 10-Rayl fibermetal. The high momentum losses for the fibermetals with air-cavity backing are due to the crossflow through the porous surface. Author

N68-32220# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.

SONIC FATIGUE DESIGN STUDIES OF NACELLE ACOUSTICAL TREATMENTS. STUDIES CONDUCTED BETWEEN MARCH 1966 AND MARCH 1967
R. L. Frasca May 1967 102 p refs
(DAC-33770) CFSTI: HC$3.00/MF$0.65

A series of sonic fatigue tests on acoustically-treated panel designs were conducted using the Douglas high intensity sound system. These tests were conducted in support of a program directed toward the study of turbofan engine nacelle modifications to minimize fan-compressor noise radiation. The results of these tests aided in evaluating the relative acoustic fatigue strength of the panel designs tested, and served as guidelines for designing similar structure to resist acoustically induced fatigue. Author

N68-32221# Douglas Aircraft Co., Inc., Long Beach, Calif. Structural Mechanics Section.
FLYOVER NOISE DURING TAKEOFF AND LANDING OF THE DC-9-30 AIRCRAFT
E. B. Fish May 1967 19 p
(DAC-33753 CFSTI: $3.00

Data are presented on measured noise levels and measured aerodynamic performance which are necessary to determine takeoff and landing flyover noise levels for airport communities during operation of the DC-9-30. Takeoff noise levels can be determined for full takeoff thrust departures and for departures with a special noise abatement thrust reduction. Noise levels below the landing flight path can be determined for a given landing gross weight for a given distance from touchdown. Author

N68-32222# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.
MEASURED FLYOVER NOISE LEVELS OF THE DC-8-62 POWERED BY JT3D-3B ENGINES WITH LONG FAN-DISCHARGE DUCTS
B. B. Adams Mar. 1967 56 p refs
(DAC-33676) CFSTI: HC$3.00/MF$0.65

The results of a program to measure flyover noise of the DC-8-62 powered by JT3D–3B engines with long duct pods are presented. The data are also applicable to the DC-8-63 equipped with the same engines. A description of the testing procedures, data analysis, and the final results are included. With the data presented, one can determine the noise levels on the ground below the aircraft for virtually any thrust condition which may be encountered in either takeoff or landing operations. Included are brief discussions of the test equipment, measurement procedures, and data reduction procedures, as well as a discussion of the techniques used to normalize the measured data points. Author

N68-32223# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.
MEASURED FLYOVER NOISE LEVELS OF THE DC-8 POWERED BY JT3D-3B ENGINES WITH SHORT FAN–DISCHARGE DUCTS
B. B. Adams 16 Dec. 1966 81 p refs
(DAC-33523) CFSTI: $3.00

The results of a program to measure the flyover noise of the DC-8 powered by JT3D–3B engines with short duct pods are presented. The data are applicable to the Series 55 and the Series 61 DC-8's. A description of the testing procedures, data analysis, and the final results are included. With the data presented, one can determine the noise levels on the ground below the aircraft for virtually any thrust condition which may be encountered in either takeoff or landing operations Author

N68-32224# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.
MEASURED FLYOVER NOISE LEVELS OF THE DC-8 POWERED BY JJ3D-3B ENGINES WITH SHORT FAN-DISCHARGE DUCTS AND PROTOTYPE FAN-DISCHARGE DUCT SUPPRESSORS
B. B. Adams 16 Dec. 1966 90 p refs
(DAC-33524) CFSTI: $3.00

As a part of the program to reduce airport neighborhood noise levels a flyable prototype noise suppression system was developed for the JT3D-3B turbofan engine with short-duct engine pods. The noise suppression system consists essentially of the installation of sound absorbent surfaces in the fan-discharge ducts of the engine in place of the production surfaces of sheet aluminum. A brief discussion of the amount of noise reduction achieved by the suppressor is included. Author

N68-32225# Douglas Aircraft Co., Inc., Long Beach, Calif. Engineering Div.
FLYOVER NOISE DURING TAKEOFF AND LANDING OF THE DC-8-61 AIRCRAFT
13 Dec. 1966 37 p Revised
(DAC-33379, Rev.) CFSTI: $3.00

Data are presented on the measured noise levels and measured aerodynamic performance necessary to determine noise levels in communities near airports during operation of the aircraft. Because there are very few differences between the −55 and −61 DC-8s, all of the data presented will be applicable to both versions of the aircraft unless indicated. The drag of the DC-8-61 on the approach configuration is significantly less than that of the DC-8-55 as measured during flight. Thus, despite an increase in landing gross weight, the approach noise of the DC-8-61 will be about the same as for the DC-8-55 due to the lower engine thrust required to follow a three degree glide slope. Author

N68-32226# Douglas Aircraft Co., Inc., Long Beach, Calif.
A METHOD FOR THE DETERMINATION OF THE NOISE RADIATED FROM TURBOJET AIRCRAFT DURING TAKEOFF
Michel Kobrynski 23 Nov. 1966 72 p refs Transl. into ENGLISH from ONERA Tech. Note No. 81, 1965
(DAC-33481) CFSTI: HC$3.00/MF$0.65

A general calculation method is proposed which is applicable to airplanes on a test stand, during the takeoff roll and in subsonic flight. The calculation method rests on Lighthill's law of the variation of the acoustic power with SV_j^8 and involves the amplification of the sound intensity through the convection factor (for either stationary or moving jets) and a reduction factor given by an aerodynamic effect and the Doppler attenuation effect. An important result is the evidence of an aerodynamic effect on the turbulence of the jet, a function of $(1 + V_e/V_j)^2$ which causes a change to the emitted frequencies and a reduction of the sound intensity by the factor $(1 + M \cos \Theta_M)^4$ Author

N68-32227# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.
METHOD OF CALCULATING NOISE PRODUCED BY JET AIRPLANES DURING TAKEOFF
Michel Kobrynski 6 Sep. 1966 26 p refs Transl. into ENGLISH from ONERA Tech. Paper No. 249 (France), 1965 and La Rech. Aerospatiale (France), No. 105, Mar./Apr. 1965
(DAC-33359) CFSTI: HC$3.00/MF$0.65

A calculation method based on the sound emission laws for stationary and flying jets and on the directional characteristics of the noise has been established. Relations between the noise levels and the characteristics of the jet are defined and verified by a large number of experimental data. This work leads to a unique calculation method for airplanes in flight and on the ground. The application of the method is simplified with the use of design charts. The method is applicable for future airplanes, now in the design stage, whose engines have predicted jet exhaust velocities exceeding those of present-day engines. The investigation of a generalized spectrum, common to all cases, clearly shows the effect of entrainment by the jet in flight on the emitted frequencies. Author

N68-32228# Douglas Aircraft Co., Inc., Long Beach, Calif. Acoustics Section.

FLYOVER NOISE DURING TAKE-OFF AND LANDING OF THE SERIES 50 DC-8 WITH P and WA JT30-1 TURBOFAN ENGINES

A. L. Mc Pike and A. H. Marsh 20 Jul. 1961 34 p refs
(LB-30637) CFSTI: $3.00

The jet exhaust noise of the JT3D-1 engine is considerably lower than that of an equivalent turbojet engine; however, the pure tone whine of the JT3D-1 is greater in magnitude than that of the turbojet and has different directional characteristics. A series of tests were conducted to determine the noise levels under the flight path during takeoff and landing operations of the DC-8 powered by JT3D-1 engines without the Pratt and Whitney Hush Kits. The noise levels as determined by these tests are presented to show what noise levels can be expected in airport communities during takeoff and landing operations. Author

N68-32229# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.

FLY-OVER NOISE DURING TAKE OFF OF THE DC-8 WITH JT3C-6 ENGINES

A. L. Mc Pike 22 Mar. 1961 70 p refs Revised
(SM-23641, Rev.) CFSTI: HC$3.00/MF$0.65

A series of tests were run to determine the noise levels under the flight path of the DC-8 during takeoff. The purpose was to show the perceived noise level which can be expected from the DC-8 under various operating conditions during takeoff and to explain how acceptable noise levels can be achieved by the selection of suitable runways and the use of engine power reductions. The data presented show that runways with adequate distance from start of takeoff roll to heavily populated areas must be used and appropriate engine power reductions during takeoff must be considered in relation to airplane loading if the 112 PNdB requirement of the Port of New York Authority is to be satisfied by the DC-8. Author

N68-32230# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.

FLY-OVER NOISE DURING TAKE OFF OF THE DC-8 WITH JT4A-9 ENGINES

A. L. Mc Pike 17 Dec. 1959 29 p refs
(SM-23787) CFSTI: $3.00

A series of tests was conducted to determine the noise levels during takeoff under the flight path of the DC-8 with JT4A-9 engines and Daisy-Ejector suppressors. The purpose was to show the perceived noise level which can be expected from the DC-8 under various operating conditions during takeoff, and to explain how acceptable noise levels can be achieved by the selection of suitable runways and the use of engine power reductions. The data presented show that runways with adequate distance from start of takeoff roll to heavily populated areas must be used and appropriate engine power reductions during takeoff must be considered in relation to airplane loading if the 112 PNdB requirement of the Port of New York Authority is to be satisfied by the DC-8. Author

N68-32231# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.

SIMILARITY CONSIDERATIONS OF NOISE PRODUCTION FROM TURBULENT JETS, BOTH STATIC AND MOVING

Alan Powell 1 Jul. 1958 23 p refs Previously N63-84105
(SM-23246) CFSTI: $3.00

Once a suitable fundamental equation is chosen, similarity arguments may be applied to the question of noise source distribution in turbulent jets in regions adjacent to the potential cone and far downstream. Certain modifications to the analysis are made in the light of certain experimental data. Similarity analyses then yield the following conclusions. The intensity of source distribution along the jet seems to be nearly constant, perhaps rising slightly, from the exit to some point just beyond the end of the potential cone, after which it falls off rapidly. The high frequency part of the spectrum, arising from regions adjacent to the potential cone, depends on the jet exit velocity raised to the ninth power, or a little greater, and upon f-2, or somewhat steeper. The assumption that the downstream region of the jet is responsible for the low frequency part of the spectrum results in a spectrum level depending on about the fifth power of the exit velocity with a slope of f^2. These results are in moderate agreement with such experimental data as are available. Author

N68-32232# Douglas Aircraft Co., Inc., Long Beach, Calif. Aircraft Div.

GENERALIZED PERFORMANCE OF CYLINDRICAL AND CONICAL AIRCRAFT EJECTORS

R. W. Mc Jones, J. A. Sain, and J. R. Flores 28 Dec. 1956 42 p refs
(LB-25320) CFSTI: $3.00

The available NACA theoretical and experimental studies of cylindrical and conical ejectors have been generalized and combined into working charts for use in estimating the pumping and thrust characteristics of a wide range of aircraft jet-exhaust ejectors. In general, theoretical treatments are limited to ejectors with cylindrical shrouds; however, both cylindrical and conical ejector performance may be correlated against the parameters suggested by cylindrical theory, and the minor variations in performance may be handled by empirical corrections. The most important difference between cylindrical and conical ejectors is a serious thrust loss of the latter type under certain conditions. Author

N68-32233# Douglas Aircraft Co., Inc., Santa Monica, Calif.

THE PUMPING CHARACTERISTICS OF LONG MIXING SECTION JET PUMPS

N. L. Fox 5 Sep. 1952 43 p refs Revised
(SM-14385, Rev.) CFSTI: $3.00

Two theoretical analyses are presented for the pumping characteristics of a jet pump, both of which assume complete mixing in a constant area mixing section which is not choked, and neglected friction. The first analysis, which neglects compressibility, yields an equation sufficiently simple for engineering use. The second analysis, which considers compressibility, leads to a better understanding of the system, but is tedious for calculation. Correction factors, based on experimental data and supported by the compressible analysis, are applied to the incompressible analysis to yield results sufficiently accurate for most engineering use. Author

2. PROGRAM SCOPE AND DEFINITIONS

By John G. Lowry

NASA Langley Research Center

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INTRODUCTION

The purpose of this paper is to review briefly the objectives and history of the NASA Acoustically Treated Nacelle Program and provide a background for the contractors' presentations of the final results of their studies.

The main objective of the program was to identify promising nacelle modifications for current four-engine turbofan-powered transports that would reduce the noise under the approach path by 15 PNdB. Another equally important objective was to develop acoustic treatment technology that would be applicable to other turbofan engines including the newer high-bypass-ratio engines. Certain design constraints were placed on the modifications since they were to be considered for application to commercial transports. Although it was anticipated that the devices would provide relief during take-off and climbout, under no conditions should the modifications increase the already undesirably high take-off noise. It goes without saying that there should be no compromise in flight safety. There should be no increase in crew workload during the critical approach phase of flight because the safety of operations would be affected. Last but not least, the modified airplane must retain its economic viability. The problem then was one of designing a modification to the nacelle that was practical, that could reduce the approach noise by a substantial amount, that would have as small performance penalties as possible, and one that could be manufactured and installed at a reasonable cost.

DISCUSSION

The procedure followed by the contractors in developing the modifications was to develop the several concepts through basic experiments of acoustic materials, component test of treatment concepts, and inlet and duct design. As a result of these studies, the more promising concepts were to be tested by use of the ground runup technique to evaluate or substantiate the acoustic and engine performance of the modified nacelle within the actual engine environment. The most desirable of these concepts, from both an acoustic and economic point of view, would be selected for flight testing on a transport airplane since the desired information is the noise measured under an actual airplane in flight. In addition, this procedure allowed for measurements of performance with the modified nacelles installed on the airplane. Each of the contractors was required, in addition to taking physical measurements of the noise reduction, to obtain data on the subjective reaction of people to the nacelle modification.

The project was started in May 1966 as part of the NASA's contribution to the Interagency Aircraft Noise Abatement Program. It should be pointed out that this project is only a small part of the overall NASA acoustical research program. A request for proposal was sent to industry in September 1966. After reviewing the proposals submitted, negotiations were started with The Boeing Company and the McDonnell Douglas Corporation; as a result, contracts were signed with the two companies in May 1967. The studies were to be conducted in such a manner that the data would, in addition to defining nacelle modifications applicable to the current four-engine transports powered by JT3D turbofan engines, provide technology that would be applicable to other turbofan engines. In October 1968, a status report on these studies was presented to industry as part of NASA's progress report of research related to noise alleviation of large subsonic jet aircraft. The papers presented at that time were published in NASA SP 189 (ref. 1). At that time they reported in detail on the results of their studies including the results of the full-scale ground runup tests of promising concepts on a JT3D engine. They also presented a description of the treated nacelles selected for flight testing. Since that time, they have each fabricated four treated nacelles, installed them on test airplanes, and performed the flight tests necessary to obtain the acoustic and performance characteristics of the modified airplanes. The flight tests of the treated airplanes were made during March and May, 1969. The results of the flight tests have been analyzed and papers 3 to 13 herein present a summary report on the final results of the contractors' $2\frac{1}{2}$-year effort.

Figures 1 to 3 are presented to indicate the noise sources and their relative strengths and to indicate why the program was directed toward the approach noise. Figure 1 indicates the sources of noise radiated from a turbofan engine. The fan noise is radiated forward through the inlet and aft through the fan discharge duct. The jet noise is generated from the turbulance aft of the discharge nozzle. The main source of jet noise is that emitted from the primary nozzle. Because of the sound intensities generated and the various directivity patterns developed by these noise sources, the total noise heard at any point under an airplane flight path is a complex combination of both fan and jet noise. The effort of this program was limited to reducing the fan noise radiated from the inlet and fan discharge ducts.

Figure 2 shows the relative contribution of each of the noise sources to the total noise as heard by an observer during an airplane flyover and illustrates one of the reasons that the program was directed toward reducing the fan noise. The perceived noise level (PNL) under the flight path of a four-engine transport is presented as a function of the thrust. It can be seen that at the higher thrusts, associated with take-off operations, the fan noise emitted from the fan discharge duct is the controlling factor and would have to be reduced if any reduction in take-off noise is to be obtained. At thrusts associated with landing approach, the fan noise is about 18 PNdB above the jet noise. This analysis indicated that a noise suppression goal of 15 PNdB was feasible by suppression of fan noise only, less reduction being needed in the inlet noise than in the fan discharge noise. Because many of the complaints around airports occur in this landing phase of operation, substantial benefits for the airport neighbor appeared possible through attenuation of the fan noise in the approach power region.

The type of noise spectrum under consideration is illustrated in figure 3, which is a plot of sound pressure level (SPL) in dB as a function of frequency in hertz. This spectrum is typical for the JT3D engine during landing approach. Not only is the fan noise level of higher intensity than the jet noise, but it also occurs in a higher frequency region. The characteristic high-pitched whine associated with the turbofan engine at landing thrust is indicated by the spikes at about 2500 Hz and higher. Suppression of these high-frequency spikes would reduce the overall noise level as well as alleviate the undesirable fan whine. On the basis of this possibility of noise reduction, the program was directed toward reduction of fan noise during landing approach.

During the negotiations of the contracts with Boeing and McDonnell Douglas, it was decided that the overall value of the program could be enhanced by having the two contractors take different approaches to the problem and have different goals of attenuation. The McDonnell Douglas approach was limited to configurations using treated inlets. At that time it was felt that the use of treated inlets would limit the attenuation to about 7 to 10 PNdB and, as a result, the McDonnell Douglas goal was set at that value. In order to match the fan discharge duct with the inlet, they were also restricted to short fan discharge ducts. Figure 4 is a photograph of the McDonnell Douglas treated nacelle. Some of the treatment in the inlet can be seen and the fan nozzle is located about halfway back on the nacelle. The term short fan discharge duct means that the duct ends well ahead of the jet nozzle. Details of the nacelle configuration and the acoustic treatment are given in paper 3 herein. In addition to the physical measurements of noise, provisions were made to obtain additional noise tapes during the flight tests that could be used in the laboratory to study the subjective response of a jury of college students to the noise of the airplane before and after the installation of the treated nacelles. The modification selected for flight test was to be installed on a Douglas DC-8 airplane.

The original noise reduction goal of 15 PNdB was retained for the Boeing portion of the overall program. To obtain this amount of attenuation, it was believed that the more effective sonic or near-sonic inlet concept would be required to reduce the inlet noise to the desired level. The operation of a sonic inlet is described in detail in paper No. 13 of reference 1. To obtain the higher attenuation, Boeing was required to develop a long fan discharge duct in order to get the required amount of acoustic treatment and thus reduce the aft radiated fan noise by 15 PNdB. During the first year's effort, McDonnell Douglas's work on the treated inlet concept indicated substantially greater noise reduction than at first thought possible. Because of these promising results and Boeing's success with the long duct, the Boeing contract was modified to defer flight testing of the sonic inlet and substitute flight tests of a treated inlet. Figure 5 is a photograph of the Boeing treated nacelle. As in figure 4, a little of the treatment in the inlet is shown and the fan discharge is located at the aft end of the nacelle, almost coplanar with the jet exhaust nozzle. Details of the configuration and the acoustic treatment are given in paper 6 herein. Since the fan ducts extend to the aft end of the nacelle, they are referred to as long ducts. The change was made from a sonic to a treated inlet to make the data available on a more timely basis and to get results on a mechanically simpler inlet. As in the Douglas program, Boeing was to obtain subjective evaluations of the modification as well as physical measurements of the noise. For their subjective program, Boeing obtained the data in the field by having a jury of about 190 people, under and to the side of the flight path, make their judgments based on actual airplane flights. The noises were recorded so that laboratory studies could also be made at a later date if desirable. Boeing was to use a Boeing 707-320B airplane for the flight tests required to evaluate the treated nacelle.

In order to complete the reporting of the Boeing program, a few remarks on the work done on the sonic inlet since the conference of a year ago seems to be in order. Boeing completed the fabrication of the inlet equipped with the automatic control device that adjusted the inlet area, and thus the Mach number in the inlet, as a function of the fan rotational speed. This device was tested in conjunction with the treated long fan discharge duct to obtain the acoustic characteristics of the combination. In addition, tests were run to evaluate the relatively simple control device and determine how well it would operate under rather severe engine accelerations, in cross winds, and under normal throttle movements. It is expected that the final results of the Boeing contract will be obtained in the early part of 1970. It is sufficient to say that the results indicate that the sonic or near-sonic inlet could be made into a satisfactory inlet for a subsonic transport.

The contractor presentations will refer to several noise terms that need to be defined. Sound pressure level (SPL) is the term generally used to define the level of noise and is expressed in decibels (dB) and is referred to the conventional value of 0.0002 dynes/cm^2. A decibel is a logarithmic unit and represents the smallest perceptible change in amplitude of a sound. A 6-dB change represents a factor of 2 in sound pressure. One of the subjective measurements of noise that has wide acceptance is that of perceived noisiness. Perceived noise level (PNL) is a function of the sound pressure level plus a spectrum shape factor that reflects the reaction of people to noise. This shape factor weights the various frequencies much the same as your ear does in determining the noisiness of a sound. The unit used to indicate PNL is PNdB. The concept of effective perceived noise level (EPNL) is an extension of the PNL concept to include the effects of tone and duration. EPNL is a modification of PNL to include a tone weighting factor and a duration factor. The tone weighting factor varies both as a function of the tone amplitude and its frequency. The duration factor indicates that the longer a sound is heard the noisier it is. The unit used to indicate EPNL is EPNdB.

Figure 6 defines the points under the flight path where both contractors present much of their noise results. These reference points are the same as those agreed upon by the FAA in their proposed noise certification rule for new aircraft. During approach the reference point is 1 nautical mile from the 50-foot obstacle under a 3° glide slope. For take-off, the reference point under the flight path has been selected as 3.5 nautical miles from brake release. Although these points are the reference points, acoustic data were obtained along the flight path up to distances of about 4 miles from the end of the runway. In addition, data were taken to the side of the flight path to obtain better coverage of the noise field near the flight path. During take-off, measurements were taken at a side-line distance of 1500 feet to establish the reduction in side-line noise associated with the modification.

CONCLUDING REMARKS

The following papers will report on how successful the contractors have been in realizing the goal and objectives of the program. The contractor final reports will, in addition to the summary papers (papers 3 to 13) presented herein, also present detailed data that can be used in evaluating modifications to other engines on other airplanes. Information will also be presented that will provide a better understanding of acoustic materials and their application to noise problems.

REFERENCE

1. Anon.: Progress of NASA Research Related to Noise Alleviation of Large Subsonic Jet Aircraft. NASA SP-189, 1968.

TURBOFAN-ENGINE NOISE EMISSION

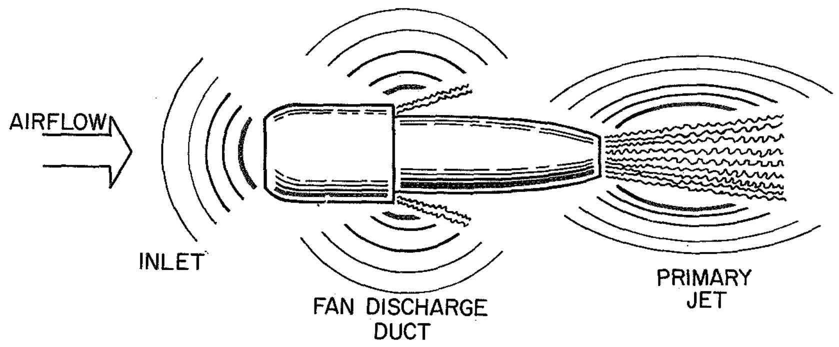

Figure 1

JT3D NOISE CHARACTERISTICS

ALTITUDE = 400 ft

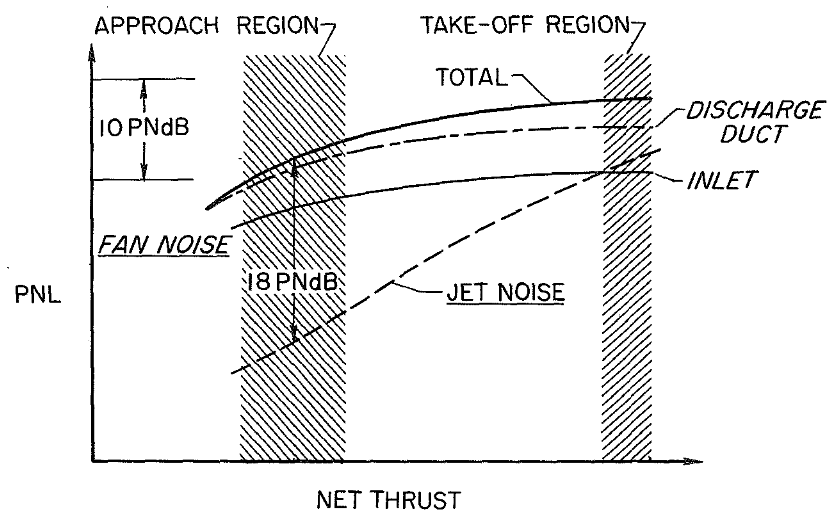

Figure 2

ENGINE NOISE SPECTRUM

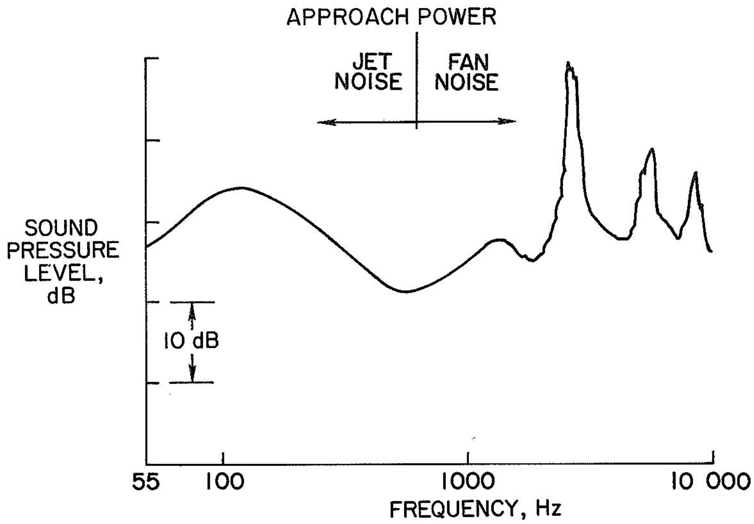

Figure 3

McDONNELL DOUGLAS TREATED NACELLE

Figure 4

BOEING TREATED NACELLE

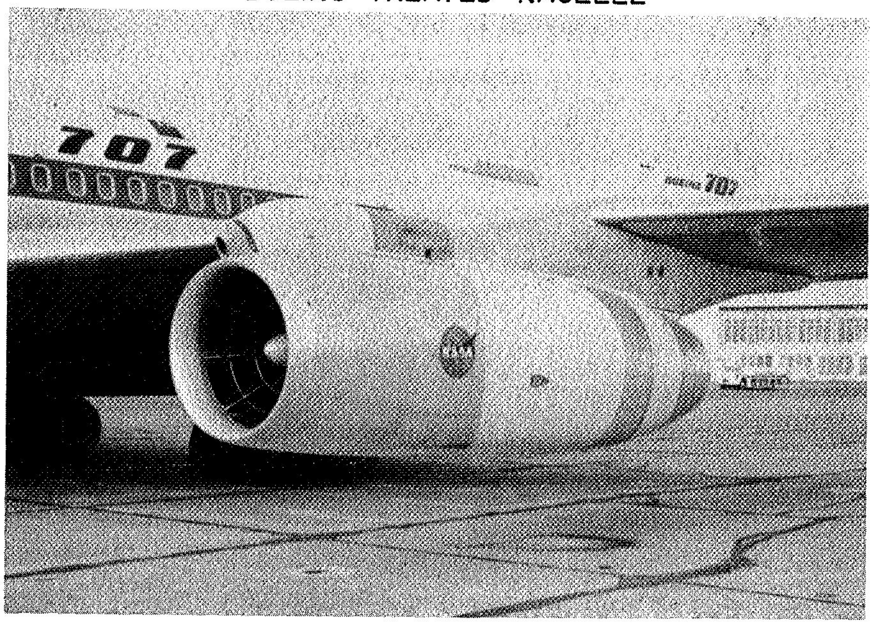

Figure 5

NOISE REFERENCE POINTS

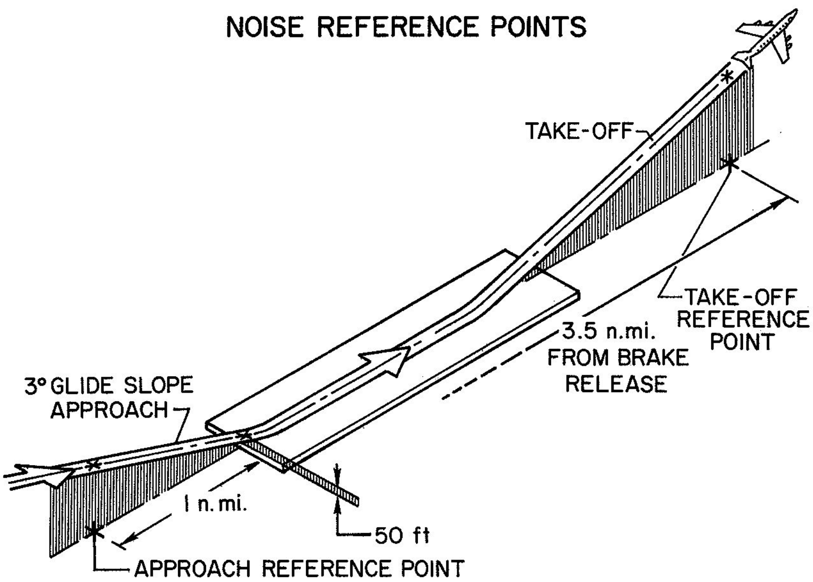

Figure 6

3. INTRODUCTION TO McDONNELL DOUGLAS PROGRAM

By Robert E. Pendley

McDonnell Douglas Corporation

The McDonnell Douglas Corporation part of the NASA treated-nacelle program was performed for the Langley Research Center under Contract NAS 1-7130 in five phases: (1) nacelle design studies and duct lining investigations, (2) ground static tests of noise suppressor configurations, (3) flight tests of a selected nacelle modification design, (4) studies of economic implications of retrofit, and (5) an evaluation of human response to the flyover noise of the modified nacelles.

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Results of the flight test program are summarized by David K. Gordon in paper no. 4 and Alan H. Marsh in paper no. 5. Performance and operational changes are described by Gordon and the effects of the treated nacelles on flyover noise are described by Marsh. Economic implications of modifying the existing short-duct nacelles of DC-8 airplanes to the treated nacelle configuration are discussed in paper no. 6 by H. D. Whallon. A status report of the investigation of human response to the flyover noise of the modified nacelles is presented in paper no. 12 by Lawrence E. Langdon and Richard F. Gabriel.

It is the purpose of this introductory paper to describe the nacelle design selected for the flight test program and to summarize the background work that resulted in the selection of the design.

DESCRIPTION OF SELECTED NACELLE DESIGN

A photograph of one of the four nacelles built for the flight test program is shown as figure 1. The inlet contained a total of 64 square feet of acoustically absorptive linings located on the inlet duct inner surface, the center body, and on the inner and outer surfaces of a concentric ring vane. The ring vane was supported by struts located in the vertical and horizontal planes. The design of the struts provided for passages through which compressor bleed air could be ducted for anti-icing of the leading edges of the struts and the ring vane. However, the experimental flight nacelles were not equipped with an operable anti-icing system since such a system was unnecessary to evaluate the acoustic and aerodynamic effects of the acoustically treated inlet.

The fan discharge ducts were 24 inches longer than those of the existing short-duct nacelles of the DC-8 series 50 and model 61 airplanes and contained a total of approximately 70 square feet of acoustically absorptive duct linings. The nacelle overall length and cross section and the primary nozzle and thrust reverser were not altered by the modification. External nacelle contours were changed slightly from the inlet lip aft to the primary thrust reverser. The changes were needed to accommodate the revised design for the fan discharge ducts and nozzles. No change was required in the contours at the nacelle-pylon junction or in any of the mechanical or subsystem interfaces at this junction.

The acoustic treatment used in the inlets and fan discharge ducts is illustrated in figure 2. The porous facing sheet, which replaces the aluminum skins in the existing inlet and discharge ducts, is in grazing contact with the duct aerodynamic flow. The facing sheets were made of sintered fine stainless-steel fibers. These sheets, together with an impervious solid backing sheet, were bonded to a honeycomb core made from phenolic-resin-coated fiber-glass cloth. The bonding agent was an aluminum-filled modified epoxy adhesive. The drainage slots prevent the accumulation of water or other nacelle fluids within the honeycomb cells.

SELECTION OF TREATED-NACELLE DESIGN

The design of the modified nacelle was selected on the basis of the work of the first two phases of the program. An initial step in the development of the design was the definition of the suppression requirements of the fan inlet and discharge ducts as shown in figure 3. Previous work had shown that the maximum perceived noise level radiated from the JT3D inlet is approximately 3 PNdB less than that radiated from the fan exit. Therefore, to achieve an overall reduction of 10 PNdB, the perceived noise levels from the inlet and fan exit ducts must be reduced by 7 PNdB and 10 PNdB, respectively.

The meager information on acoustical duct lining absorptivity available at the beginning of the program was reviewed to develop a tentative design chart for estimating the amount and location of lining materials required to accomplish the required noise reductions. This estimate indicated that 48-inch-long discharge ducts, as shown in figure 4, would satisfy the requirement if acoustical linings were provided on all inner duct walls and on both sides of four longitudinal splitters that divide each discharge duct into five channels. The design required a new fan thrust reverser located 24 inches farther downstream than the existing reversers. A new target-type reverser design consisting of a single pivoting bucket on each side of the nacelle was evolved to fit within the reduced space between the engine casing and the nacelle skin in the farther downstream location. (See fig. 4.) As for the anti-icing system, a functioning fan thrust reverser was not needed to achieve the program goals and was therefore not provided in the flight test nacelles.

Another approach to the reduction of noise radiated from the fan discharge ducts was evaluated in the design studies phase of the program. This approach, as illustrated in figure 5, was intended to provide the required acoustical lining area with minimum changes to existing nacelle equipment. The treated fan discharge ducts had the same length and nozzle shape as the existing production discharge ducts. The supplementary panels augmented the treated area that could be provided within the 24-inch-long ducts, since it was estimated that the treated area within the ducts would be insufficient to achieve the required noise reduction. The panels would normally be stowed flush on the cowl sides forward of the fan exit nozzles. When noise suppression is required, they would be translated rearward to the position shown in figure 5. Estimates of the increase in direct operating costs due to the two designs indicated lower costs for the 48-inch duct design. Furthermore, the supplementary panels would tend to degrade safety, since failure of one of them to retract would make reverse thrust unavailable from the affected nacelle. For these reasons, the 48-inch duct design was selected for further investigation in the succeeding ground test program.

The selected ring-vane inlet design, which is shown in figure 6, was a derivative of one of a number of inlet configurations investigated in the nacelle design studies phase. Two of the study configurations were investigated in the ground test program.

One of the configurations, which is shown in figure 7, was acoustically identical to the selected design except that it contained a second concentric ring vane located between the ring vane shown in figure 6 and the center body. In the horizontal plane, the internal shape and location of the inlet duct, the center body, and the outer ring vane of the two designs (figs. 6 and 7) were identical downstream of the throat of the inlet. The ring vanes provided additional acoustically absorptive surface area without elongation of the inlet. They also reduced the spacing between treated surfaces, which is believed to improve the absorptivity of the acoustical materials. The second configuration was a basically different type illustrated in figure 8. Additional acoustically treated area was provided in the lightbulb inlet by elongation of the inlet and enlargement of the center body. The larger center-body diameter, in addition to providing more acoustically treated area, was thought to offer the potential of some additional noise reduction through partially obstructing the direct path of the noise propagating forward from the fan inlet.

Figures 7 and 8 illustrate the two-ring and lightbulb inlet designs as they were tested on an outdoor JT3D engine test stand. External inlet contours were simulated only as far aft as was required for satisfactory flow over the inlet lip, and the inlets were built axisymmetrically in the interests of test economy.

The tests indicated that the lightbulb configuration achieved slightly more noise reduction than the two-ring inlet. Also, tests with the inner ring removed from the two-ring inlet indicated that the required noise reduction was achieved with only the outer ring installed. Since this single-ring configuration met the noise reduction requirement at the least estimated cost in weight, drag, and thrust loss, it was selected for the flight test program.

The full-scale tests of the treated-inlet configuration were made with the existing production short fan discharge ducts installed and with a large enclosure completely surrounding the engine aft of the treated inlet. The function of the enclosure was to suppress the fan exit noise and thereby permit evaluation of the noise reduction achieved individually by the treated inlets. The inner surfaces of the three walls and ceiling of the enclosure were covered with 4-inch-thick fiber-glass batts. Similarly, a ground test model of the treated 48-inch fan discharge duct configuration was tested with a large enclosure fitted to the inlet. Details of the enclosures and the test techniques used are presented in reference 1. Sound pressure levels were measured along an arc of 150-foot radius centered on the primary exhaust nozzle. Estimates of flyover noise were calculated by a technique that utilized these ground test measurements. These estimates indicated that the treated single-ring inlet and the treated 48-inch discharge ducts would achieve landing noise reductions of 8 and 11 PNdB, respectively, which are slightly in excess of the requirements of 7 and 10 PNdB. A final test of the inlet and exit ducts was made with these components installed simultaneously and the suppressor enclosures removed. The results indicated a landing noise reduction of 11 PNdB, in confirmation of the results obtained with the components tested individually.

An explanation of weight changes that would result from converting existing nacelles to treated nacelles will help in understanding the performance and economic effects discussed by Gordon (paper no. 4) and Whallon (paper no. 6).

Five major new components are required to convert existing nacelles: a treated inlet, treated fan discharge ducts (left and right), and fan thrust reversers (left and right). As indicated in figure 9, the new acoustically treated inlet and exit ducts would weigh a total of 370 pounds more per nacelle than the existing components they replace. The new target-type thrust reversers, however, would weigh 287 pounds less than the existing cascade type they replace. The weight of all other additional new nacelle components would approximately equal the weight of the components they replaced. The net weight change due to the modification would therefore amount to 83 pounds per nacelle or 332 pounds per airplane. The reduction in fan thrust reverser weight is made possible by the use of target-type thrust reversers rather than the heavier cascade-type reversers now in service. Although reverse-thrust levels of target-type reversers are somewhat less than that of cascade types, thrust reverser development programs subsequent to the design of DC-8 short-duct nacelles have shown that satisfactory levels may be achieved through proper design of the target-type reverser.

The total scope of the nacelle modification may be indicated by relating the weight of the new components to the total nacelle weight. The weight of all nacelle components (excluding the engines) presently in service totals 10 188 pounds per airplane. Of these components, 5156 pounds would be removed and replaced by 5488 pounds of the new components. Measured in this manner, retrofit of acoustically treated ducts would affect approximately half of the nacelle components on an airplane.

CONCLUDING REMARKS

The present program dealt with the application of acoustic duct lining technology to DC-8 airplanes equipped with short-duct nacelles, that is, to the series 50 and model 61 airplanes. Although the principles used in developing the present design are believed to be generally applicable to other turbofan-engine installations, it must be remembered that the acoustic, performance, operational, and economic data discussed in the McDonnell Douglas papers apply strictly to the specific airplane models studied.

The existing short-duct design was committed to production engineering in November 1959. Advancements in nacelle mechanical and aerodynamic design subsequent to that time were applied to the acoustically treated nacelle design developed in this program. The reduced weight of the fan thrust reversers for the acoustically treated nacelle is an example. In more recently designed turbofan nacelles, such as those of the DC-8 models 62 and 63 airplanes, these advancements have already largely been applied and, therefore, cannot offset to any significant extent the added weight and internal aerodynamic friction due to retroactive installation of acoustical lining materials. Separate studies would be required to define the design and the acoustic, performance, and economic effects of applying duct lining technology to the nacelles of these airplanes or to the nacelles of airplanes powered by other engines.

REFERENCE

1. Marsh, Alan H.; Zwieback, E. L.; and Thompson, J. D.: Ground-Runup Tests of Acoustically Treated Inlets and Fan Ducts. Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968, pp. 131-162.

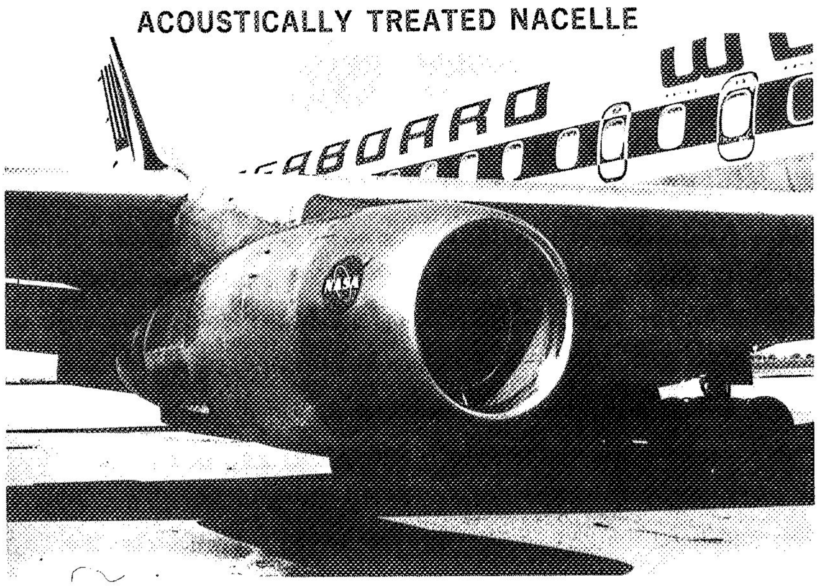


Figure 1

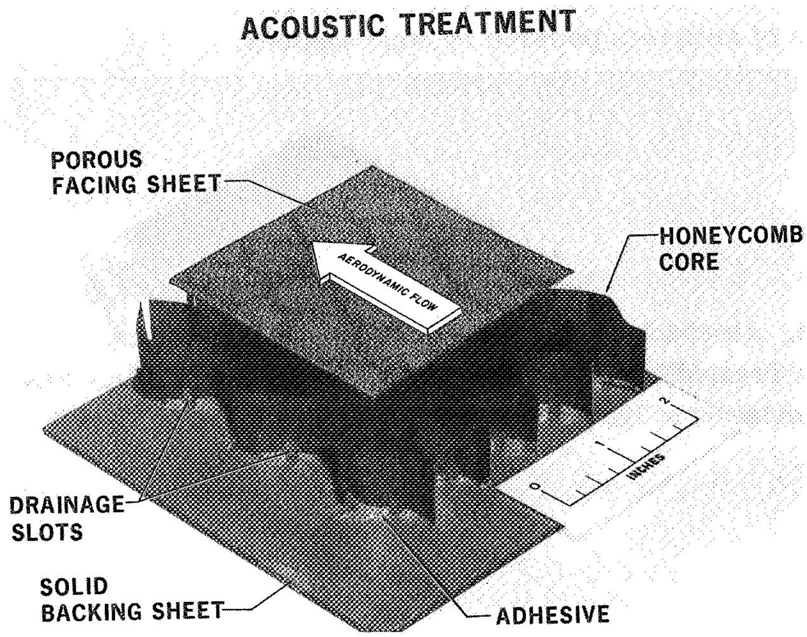


Figure 2

NOISE-REDUCTION GOALS
LANDING APPROACH POWER

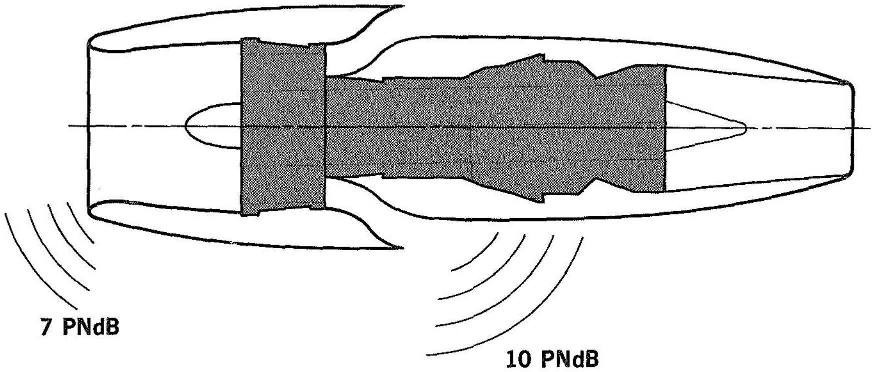


Figure 3

48-INCH TREATED FAN DISCHARGE DUCTS

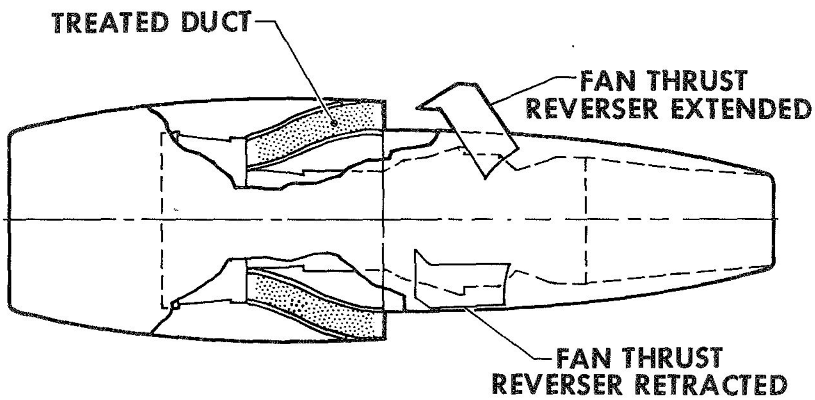


Figure 4

24-INCH TREATED FAN DISCHARGE DUCTS WITH SUPPLEMENTARY PANELS

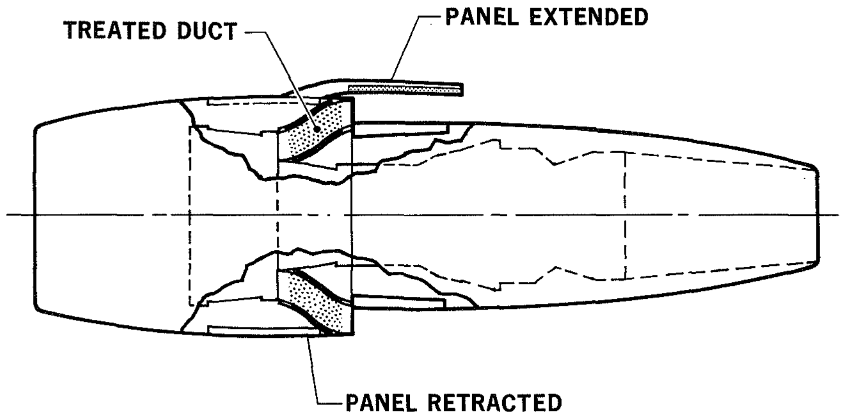


Figure 5

TREATED RING-VANE INLET

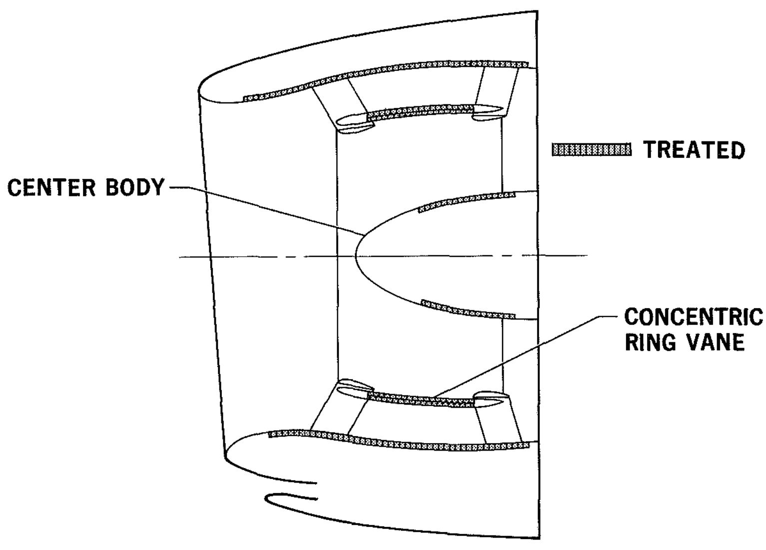


Figure 6

TREATED TWO-RING INLET

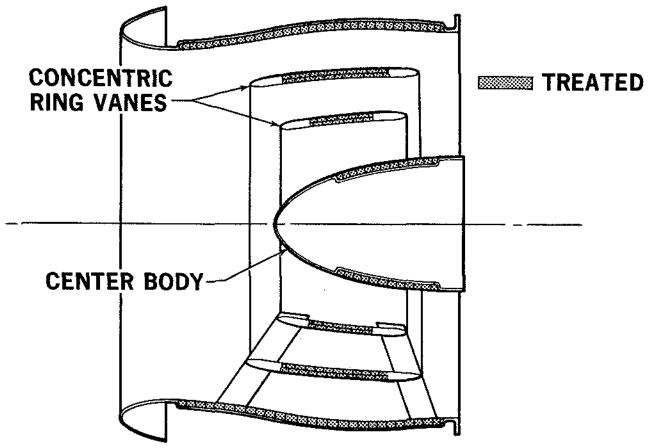


Figure 7

TREATED LIGHTBULB INLET

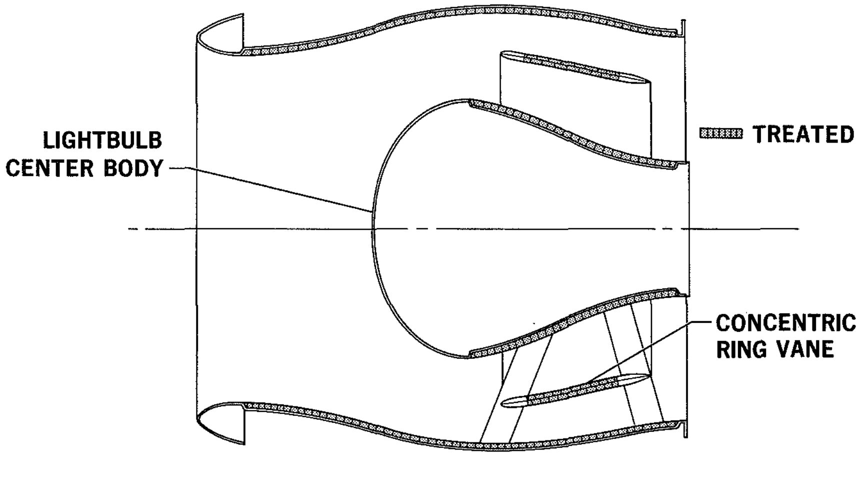
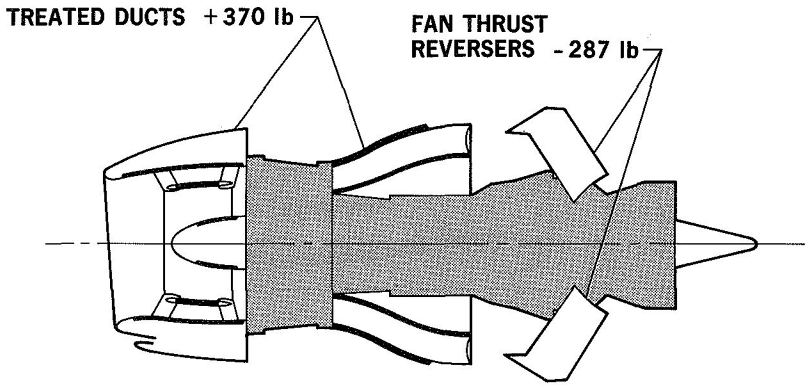


Figure 8

WEIGHT CHANGES



OTHER NACELLE COMPONENTS +0

	WEIGHT, lb/AIRPLANE
REPLACED COMPONENTS	-5156
NEW COMPONENTS	+5488
△ OWE	+ 332

Figure 9

4. PERFORMANCE AND OPERATIONS OF THE DC-8-55 AIRPLANE WITH ACOUSTICALLY TREATED NACELLES

By David K. Gordon

McDonnell Douglas Corporation

SUMMARY

This paper describes the performance and operational characteristics of a model DC-8-55 airplane retrofitted with acoustically treated nacelles. The changes in airplane and engine performance due to the treated-nacelle installation were determined by analysis of the results of DC-8-55 flight tests and engine static tests.

The results of the analysis showed that the maximum range capability of the airplane with treated nacelles was improved by approximately 3.0 percent. Changes in take-off field length and block time were minimal. The initial cruise altitude capability was calculated to be reduced approximately 500 feet. The approved speed-altitude operating envelope and load-factor limitations for the airplane were unaffected by the installation of the treated nacelles.

Flight tests conducted by McDonnell Douglas Corporation and static tests conducted by the engine manufacturer showed that the treated nacelles did not affect compressor surge susceptibility. No surges were experienced during the flight-test program, or during static tests for power conditions from idle to take-off in simulated 90° cross winds up to 35 knots. Static and inflight engine starting were also unaffected by the installation of the acoustically treated nacelles.

Engine compressor air-bleed requirements for inlet anti-icing would be increased by about 30 percent for a retrofit installation of treated nacelles on DC-8 airplanes with short fan ducts. However, this additional bleed will not result in a reduction in allowable take-off thrust at sea level. At 8000 feet, the thrust loss at take-off power due to inlet anti-icing would be approximately 0.6 percent.

The serviceability of various acoustical materials exposed to the environment of actual airline operation is currently under investigation. Twelve test samples of fiber metal installed in the fan-discharge ducts of Western Airlines 720B and American Airlines 707 airplanes have accumulated up to 1200 hours of test time. No cleaning or repair of the samples has been required in this time.

INTRODUCTION

Ground static and flight tests were conducted to evaluate the aerodynamic performance and operational characteristics of a short-duct DC-8 airplane equipped with acoustically treated nacelles. The portion of the test program relating to aerodynamic performance and operational characteristics is the subject of this paper. The results of the flyover noise tests are presented in paper no. 5 by Marsh. The aerodynamic performance reported herein was subsequently used in a study of the economic effects of an assumed treated-nacelle retrofit program for all models of the DC-8 series 50 airplanes and the DC-8-61.

The nacelle design selected for the test program included acoustically treated inlet and fan-discharge ducts. The inlet had acoustical treatment on the surface of the inlet duct and center body and on both surfaces of a concentric ring vane. The fan-discharge ducts were twice as long (48 inches) as ducts in current production and had acoustical treatment applied to the walls of the ducts and the four duct splitters. A more detailed description of the treated nacelle is included in paper no. 3 by Pendley.

The flight-test airplane was a DC-8-55 airplane furnished by Seaboard World Airlines. The performance and operational effects shown herein were determined for a passenger version of the airplane.

ENGINE AND AIRPLANE PERFORMANCE

The McDonnell Douglas performance test program consisted of ground static tests and flight tests. The structural integrity of the treated nacelle and the compatibility of the nacelle with the engine were evaluated from the results of the static tests. The effect of the treated nacelles on static engine performance and on thrust at rated engine power was also determined. The results of the flight-test program were used to determine airplane specific range. The results of both the static-test and flight-test programs were used to calculate the effect of the treated nacelles on airplane take-off, climb, and payload-range performance.

Static tests were conducted by Pratt & Whitney Aircraft (P&WA) to evaluate the effect of the acoustical treatment on engine operation, thrust ratings, and compressor surge susceptibility in simulated cross winds.

Static Tests

An existing nacelle and a treated nacelle were tested statically by McDonnell Douglas with the same JT3D engine to determine the change in engine performance due to the modification. Figure 1 shows a treated nacelle on the calibrated test stand located at

Edwards Air Force Base. The engine controls and data readout system were located in a nearby test-control center. A nonmetric afterbody shield isolated the fan jet from the gas-generator cowling and prevented the scrubbing drag caused by the fan-discharge flow from being included in the thrust measurement. The test-stand thrust results therefore included only the effects of internal flow on engine performance. The change in scrubbing drag due to the more rearward location of the fan-discharge nozzles was calculated by analysis to be 0.4 percent at take-off power.

Figure 2 shows that the change in thrust caused by the treated nacelle at indicated engine pressure ratios (EPR) corresponding to high engine powers is less than 1 percent at constant values of EPR. The results also showed less than 0.5 percent change in fuel flow and rotor speeds at constant EPR.

A treated nacelle was tested by P&WA at their facility in East Hartford, Connecticut. Data obtained in these tests were used to determine the thrust ratings that would permit operation of the treated nacelle with existing engine warranties. The following average thrust reductions, relative to the performance of the existing installation, resulted from the revised thrust ratings:

Rated take-off thrust. 2.5%
Rated maximum climb thrust 2.9%
Rated maximum cruise thrust 3.1%

Flight Tests

The airplane flight-test program was conducted first with the existing nacelles. The test schedule was then repeated with the treated nacelles installed. The same engines were used for both tests.

The airplane performance test results were used to evaluate the airplane range factor in nautical miles at three values of referred airplane gross weight (W/δ) over a range of cruise Mach numbers. Figure 3 shows the results of the range-factor evaluation for the lowest and highest values of W/δ (where W represents airplane weight in pounds and δ is the ratio of ambient pressure at altitude to sea-level standard pressure). Range factor is defined as the product of airspeed in knots and airplane referred weight in pounds divided by the rate of fuel flow in pounds per hour. An improvement in range factor varying from approximately 1.3 percent at high values of gross weight to 4.4 percent at low values was indicated at Mach number 0.82 for the airplane with treated nacelles. The average improvement at that Mach number was 3.0 percent for the gross weights tested. At higher Mach numbers and at high values of airplane gross weight, the treated-nacelle installation caused a decrease in range factor. However, an airplane with high gross weight is not normally operated at high Mach numbers because this combination is relatively uneconomical.

The flight-test program was limited to the determination of airplane range factor. Test instrumentation and procedures did not provide for the separate measurement of thrust. The reason for the range-factor changes are not, therefore, directly indicated. On the basis of the improved range factor, however, it was inferred that the drag of the treated airplane was approximately 3 percent less than that of the existing airplane. The drag reduction was probably related to the change in the flow field in the region of the wing, pylon, and nacelle caused by the lengthened fan-discharge duct.

Airplane Performance

Figure 4 shows the effect of the treated nacelles on specific range for three values of airplane gross weight at an altitude of 30 000 feet. Specific range was calculated by dividing the range factor by the airplane weight. Specific range is a measure of the range flown per pound of fuel burned. The effect of the previously mentioned 3.1 percent reduction in maximum cruise thrust on maximum cruise Mach number is also indicated in figure 4 for standard conditions and standard plus 10° C. The reduction in rated cruise thrust would not preclude operating the airplane at Mach numbers typically used at these temperatures, even at high airplane weights.

The effect of the treated nacelles on the payload-range characteristics is shown in figure 5. The improvement in specific range shown in figure 4 is reflected in figure 5 by the improvement in range, approximately 3 percent, shown for operation at the 325 000-pound maximum take-off gross weight. The performance is shown for a reference payload consisting of 135 passengers, their baggage, and 2500 pounds of cargo. Figure 5 also shows that the weight-limited payload is the same for both the treated and existing airplanes. Because the 332-pound increase in airplane operating weight empty described by Pendley in paper no. 3 is small, and because the added weight acts as a relieving wing bending moment, no change in weight-limited payload was necessary.

Figure 6 shows the effect of the performance changes on take-off field length requirements. Required field lengths corresponding to ranges less than 2500 nautical miles are slightly longer for the treated airplane than for the existing airplane, whereas field lengths for longer ranges are slightly shorter. For ranges less than 2500 nautical miles, the improvement in specific range (fig. 4) and the resulting reduction in fuel load for the treated airplane were not sufficient to compensate for the reduction in take-off thrust. The take-off field length required for short ranges was therefore greater for the treated airplane. At long ranges, the reduction in fuel load for the treated airplane more than compensated for the reduction in take-off thrust, and the required take-off field length was therefore less.

Thrust for calculating airplane climb performance was based on the results of the ground static tests which showed that the treated nacelle would cause a reduction in rated climb thrust of 2.9 percent. This reduction is essentially equal to the 3-percent inferred average reduction in airplane drag. Since the lowest test Mach number during the flight-test program was 0.65, the effect of the treated nacelles on airplane range factor, and therefore on inferred drag, at Mach numbers lower than 0.65 was not known. During typical climb operations, a Mach number of 0.65 is attained at approximately 20 000 feet. Therefore, at altitudes above 20 000 feet, the reduction in rated climb thrust would approximately equal the average reduction in inferred drag, and the rate of climb would be unaffected. At lower altitudes, where the beneficial drag reduction may not be present, but where the rate of climb is high, the effect of the thrust reduction on climb performance would be small. A small increase in total time to climb to cruising altitude would be expected.

Calculations indicated that the treated-nacelle installation will affect the maximum initial cruise altitude capability. The maximum initial cruise altitude of the DC-8-55 for all actual gross weights occurs at a W/δ of 1,100,000 pounds. The cruise data at this W/δ and a Mach number of 0.82 show an apparent drag reduction of 1.2 percent. This reduction in drag is more than offset by the 3-percent loss in thrust due to the reduction in rated maximum cruise EPR. The resultant loss of 1.8 percent in the thrust-minus-drag margin is estimated to produce a 500-foot decrement in maximum initial cruise altitude. This decrement would not affect range capability at long-range cruise and would cause no more than a 5-mile range reduction for cruise at a Mach number of 0.82.

As previously noted, the cruise Mach number is unchanged by the treated-nacelle installation. It was estimated that the increase in block time would be less than 1 minute, for a range of 850 nautical miles, because of the small increase in time to climb.

The performance of the treated airplane indicated that the approved altitude-speed envelope for the DC-8-55 would be unchanged by the installation of the treated nacelles. Flutter and strength analyses showed that the load-factor limitations would be unaffected.

OPERATIONS

Engine Operation

The static tests of the treated nacelle conducted by P&WA indicated that the nacelle modification did not cause an increase in compressor surge susceptibility in simulated 35-knot cross winds. No compressor surges occurred during the flight-test program.

Both the static-test and flight-test programs showed that the engine starting envelope would be unaffected by the treated nacelle.

Ice Protection

The design of the inlet included provisions for anti-icing the ring vane and the supporting struts by the use of compressor bleed air (as in the existing cowl system). The bleed airflow required was calculated to be 30 percent more than the inlet anti-icing air bleed required for the existing nacelle.

The engine may be overboosted at take-off power to compensate for the thrust decrement caused by bleeding up to 1 percent of engine airflow for inlet anti-icing. The air bleed required to anti-ice the inlet of the treated nacelle was less than 1 percent of engine airflow at sea level. Therefore, no additional thrust penalty due to inlet anti-icing would be incurred during take-off at sea level. At 8000 feet, the additional thrust penalty would be approximately 0.6 percent.

The results of the operational considerations on performance are summarized as follows:

Altitude-speed envelope . . . . No change

Load-factor limitations . . . . No change

Compressor surge susceptibility . . . . No change

Engine starting capability (static and inflight) . . . . No change

Take-off thrust change due to inlet anti-icing at –
  Sea level. . . . . No change
  8000 ft . . . . 0.6% less

Maintenance

Estimates of the maintenance costs of acoustically treated ducts are uncertain at this time because of the limited service experience with such materials. Specimens of acoustical material are being exposed to the nacelle environment in routine service in order to determine the useful life of such materials, the manner in which deterioration occurs, the rate at which porous materials become clogged, and the effectiveness of alternative methods for cleaning contaminated specimens.

Several different kinds of materials are presently in service in the fan-discharge ducts of Boeing 707 and 720B and Douglas DC-8-63 airplanes.

Figure 7 illustrates the components of an installation of two specimens in existing screw-mounted panels located in the fan-discharge ducts of Boeing 720B nacelles. These specimens, 8 inches in diameter, are constructed of fiber metal bonded to fiber-glass honeycomb. The specimen in the right side of the panel is shown in position just prior to the installation of its mounting screws. In the left side of the panel is a specimen with the acoustical material removed.

All specimens are assembled in the receptacle shown on the upper right. The receptacle has large perforations to permit flow-resistance tests of the specimens when they are removed from time to time for inspection. Impervious cover plates (one of which is shown in the upper middle of fig. 7) are used to seal the perforations when the specimens are installed.

Twelve specimens have been introduced into aircraft operated by American Airlines and by Western Airlines. As of September 1969, these specimens have accumulated a total exposure time of 8440 hours. Of the specimens that have been returned for inspection, the high-time specimen has experienced 1166 hours of flight exposure. Two specimens have experienced minor foreign-object damage which did not require repair, and all specimens have shown evidence of oil and dust contamination. However, the contamination was not sufficient to affect the flow resistance measurably and, therefore, cleaning was not required.

The bonded construction described above was selected in 1967 for the acoustical materials used in the present program. Since that time, studies of other materials assembled in other ways have been continued, and specimens of the newer materials will also be tested in the Boeing 720B installation. Specimens of integrally woven fiber-glass fabrics, impregnated with polyimide resins, will soon be introduced.

In a second program, another type of acoustical material has been incorporated into two removable sections of the long fan-discharge ducts of a DC-8-63 airplane (fig. 8) operated by Flying Tigers Airlines. This material was installed throughout the internal surfaces of the duct section shown. This installation consists of an adhesively bonded aluminum sandwich. The honeycomb core was bonded between a perforated facing sheet and a solid backing sheet. Four circular receptacles were incorporated into the basic material installation to permit periodic removals and inspection of small specimens. The duct sections were recently introduced into service, and they have accumulated approximately 200 hours exposure at this time. No problems with the duct sections have been reported by the operator, and the results of the first laboratory inspection of the small specimens will soon be available.

CONCLUDING REMARKS

The modification of the nacelles of DC-8 aircraft having short fan-discharge ducts required to install acoustical treatment results in a significant improvement in airplane payload-range capability and essentially no change in take-off field length and block time. Initial cruise altitude capability would be reduced approximately 500 feet.

The approved airplane performance envelopes and load-factor limitations are unchanged by the modification.

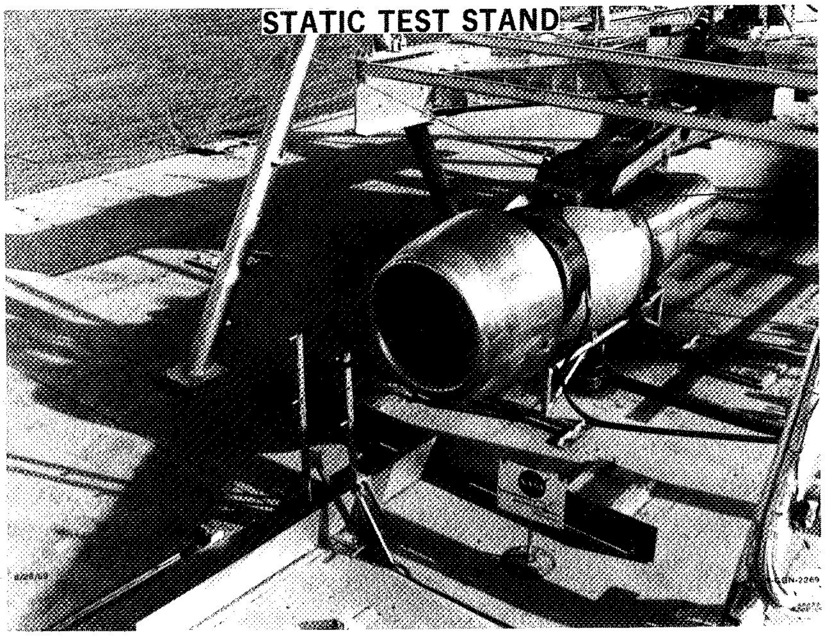


Figure 1

JT3D STATIC-TEST RESULTS

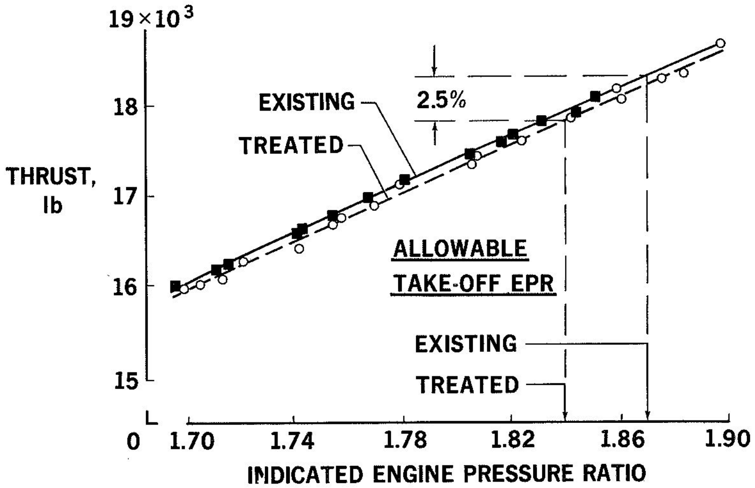


Figure 2

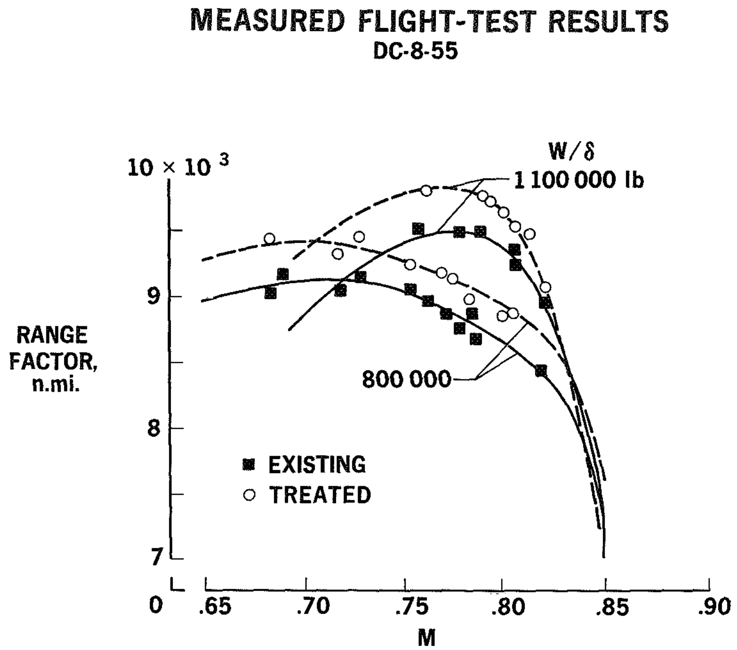


Figure 3

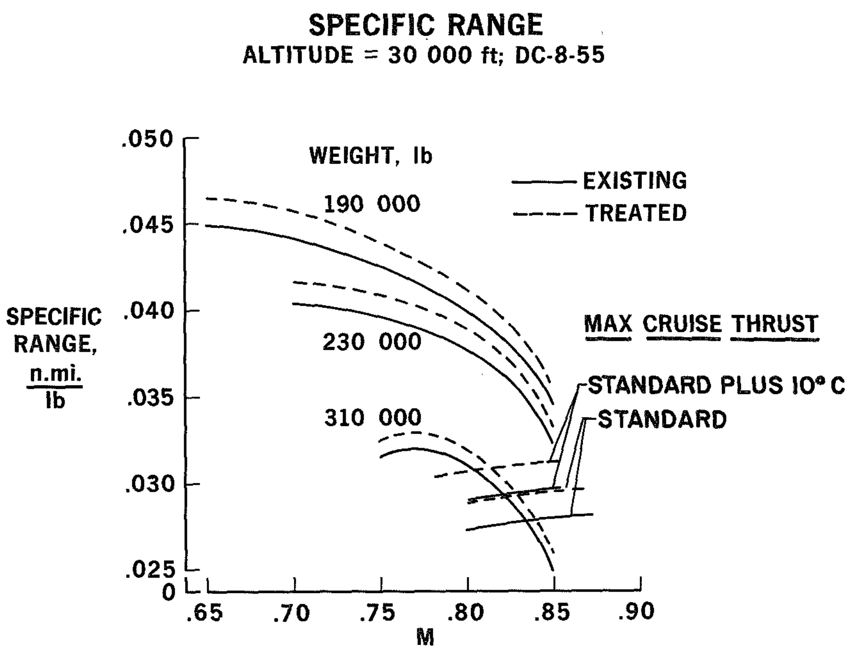


Figure 4

PAYLOAD-RANGE CHARACTERISTICS
INTERNATIONAL OPERATING RULES; STANDARD DAY
DC-8-55

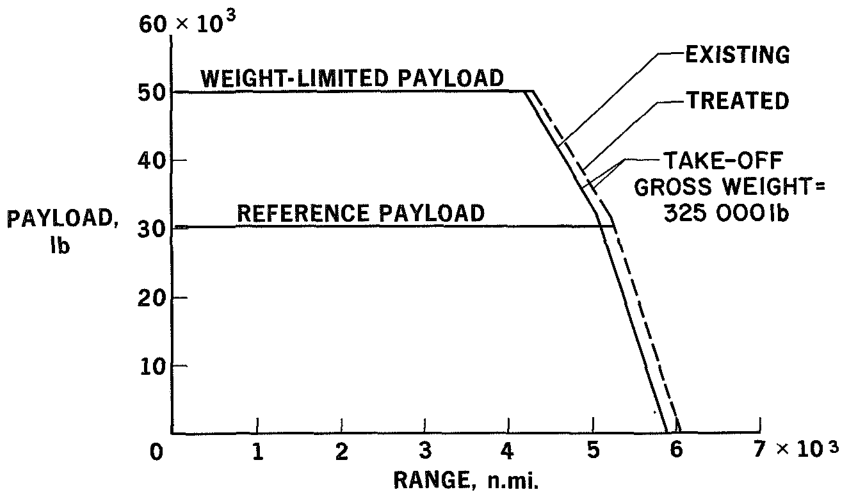


Figure 5

CALCULATED FIELD LENGTH REQUIREMENTS
STANDARD DAY; SEA LEVEL
REFERENCE PAYLOAD; DC-8-55

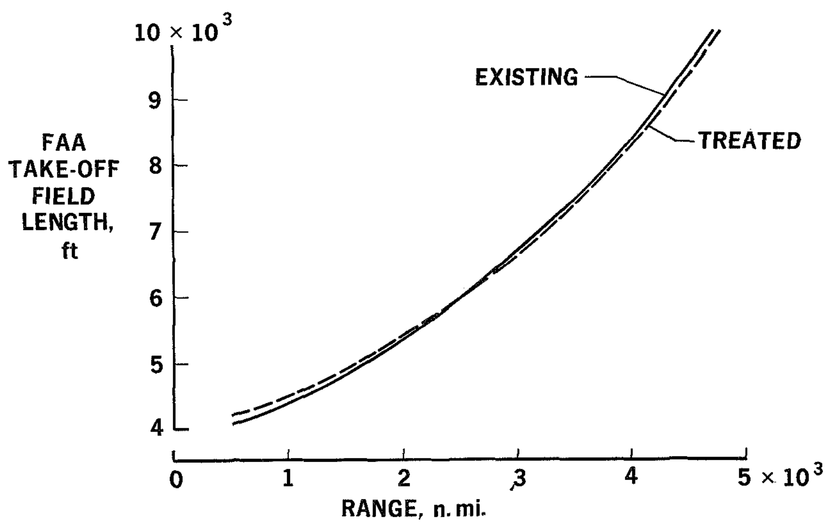


Figure 6

SERVICE-TEST SPECIMEN FOR SHORT-DUCT INSTALLATION
BOEING 720B

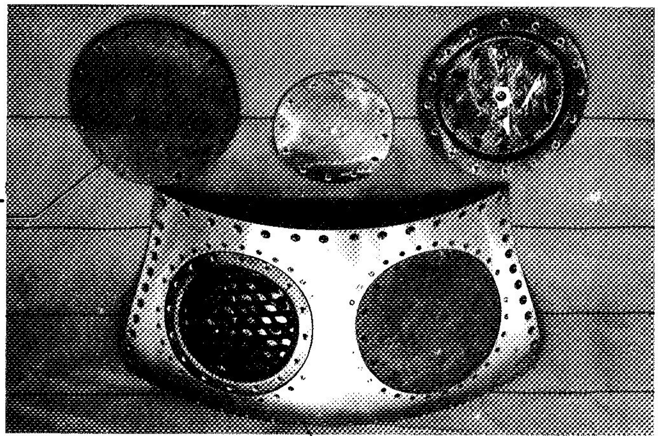


Figure 7

SERVICE-TEST SPECIMEN FOR LONG-DUCT INSTALLATION
DC-8-63

Figure 8

5. FLYOVER NOISE LEVELS OF DC-8-55 AIRPLANES WITH ACOUSTICALLY TREATED NACELLES

By Alan H. Marsh

McDonnell Douglas Corporation

SUMMARY

Flyover-noise tests were conducted with a DC-8-55 test airplane equipped first with existing and then with treated nacelles. Tests were conducted in February and March 1969 in the vicinity of Fresno Air Terminal, Fresno, California. Effective perceived-noise levels were derived from 1/3-octave-band sound-pressure levels measured at several stations under the landing and take-off flight paths. Effective perceived-noise levels, with units of effective perceived-noise decibels (EPNdB), were used to evaluate the acoustical effectiveness of the treated nacelles as installed on short-duct DC-8-55 airplanes powered by four JT3D-3B engines.

Reductions in effective perceived-noise level were achieved at locations under both the landing-approach and the initial-climb take-off flight paths. Under a 3° landing-approach flight path at a distance of 1 nautical mile from threshold, an airplane with treated nacelles and the maximum landing gross weight of 240 000 pounds would produce 10.5 EPNdB lower noise levels than an airplane with existing nacelles.

At a point beneath the initial-climb path and 3.5 nautical miles from brake release with the airplane climbing at 10 knots above the FAA take-off safety speed and maintaining rated take-off thrust, the treated nacelles on an airplane with the maximum 325 000-pound take-off gross weight would reduce the effective perceived-noise level by 3.5 EPNdB. Airplanes with lighter take-off weights would achieve less noise reduction. Along a line 1500 feet to the side of the take-off flight path, the treated nacelles would reduce the maximum effective perceived-noise level of the 325 000-pound airplane, at rated take-off thrust, by approximately 3 EPNdB.

By using a reduced-thrust initial-climb procedure in which rated take-off thrust is decreased at 1500 feet before the 3.5-nautical-mile point to the thrust required to maintain a 6-percent climb gradient, the treated nacelles on an airplane weighing 325 000 pounds at take-off would reduce the effective perceived-noise level by 5.5 EPNdB at the 3.5-nautical-mile point. Airplanes dispatched at lighter weights for flights with shorter ranges would achieve larger noise reductions over the 3.5-nautical-mile point than the airplane with the 325 000-pound take-off weight.

Estimates of flyover noise levels made on the basis of sound-pressure levels measured around an engine test stand were compared with measurements obtained during the flyover-noise tests. Reasonably good agreement was found for the treated nacelles in terms of the magnitude and the spectrum of the 1/3-octave-band sound-pressure levels at the instant of maximum perceived-noise level. Good agreement was also obtained between the measured and the predicted variation with time of perceived-noise level during a flyover.

INTRODUCTION

The October 1968 conference on progress in noise-alleviation research described the results of the McDonnell Douglas ground static tests that led to the choice of the treated nacelle selected for flight testing (ref. 1). Since the October 1968 conference, four sets of treated nacelles have been fabricated and flight tested on a DC-8-55 airplane – as reported by Robert E. Pendley in paper no. 3. Flight tests were conducted with the test airplane equipped first with existing and then with treated nacelles. The airplane was powered by four Pratt & Whitney Aircraft JT3D-3B turbofan engines. The flight-test program determined changes in engine and airplane performance and changes in flyover noise levels.

The present paper describes the flyover-noise tests that were conducted and discusses the results that were obtained. Evaluations of the effects of the treated nacelles on flyover noise levels are presented in terms of effective perceived-noise level (EPNL) in units of effective perceived-noise decibels (EPNdB). A comparison is also given between measured and estimated perceived-noise levels (PNL) and between measured and estimated 1/3-octave-band sound-pressure levels (SPL). The values of SPL are in decibels referenced to a pressure of 0.0002 dyne per square centimeter.

SYMBOLS AND ABBREVIATIONS

EPNL effective perceived-noise level, effective perceived-noise decibels (EPNdB)

ΔEPNL difference between values of EPNL obtained with an airplane equipped with existing nacelles and those obtained with an airplane equipped with acoustically treated nacelles, EPNdB

F_n installed net thrust, lb

F_n/δ_{am} referred installed net thrust, lb

N_1	low-pressure rotor speed, rpm
$N_1/\sqrt{\theta_{t_2}}$	referred low-pressure rotor speed, rpm
p_{am}	ambient pressure, lb/ft^2
$p_{am,sl}$	ambient pressure at sea level, 2116 lb/ft^2
PNL	instantaneous perceived-noise level, perceived-noise decibels (PNdB)
PNLM	maximum value of instantaneous perceived-noise level, PNdB
PNLT	tone-corrected instantaneous perceived-noise level, PNdB
PNLTM	maximum value of tone-corrected instantaneous perceived-noise level, PNdB
SPL	sound-pressure level (ref. 0.0002 $dyne/cm^2$), decibels (dB)
$T_{am,std}$	standard-day ambient temperature, 518.7° Rankine
T_{t_2}	total air temperature at inlet-guide-vane station, degrees Rankine
V_2	FAA take-off safety speed, knots (kn)
VHF	very high frequency
δ_{am}	ratio of p_{am} to $p_{am,sl}$
θ_{t_2}	ratio of T_{t_2} to $T_{am,std}$

FLYOVER-NOISE TESTS

All flyover-noise testing was accomplished in February and March 1969 in the vicinity of Fresno Air Terminal, Fresno, California. The airport had a 9200-foot-long main runway and a 2.5° Instrument Landing System. The ground beneath the flight paths was relatively flat with an elevation of 335 ± 15 feet. There were no large obstacles near any sound-recording stations. This section describes some of the general features of the test procedures and the acoustical data reduction.

Test Program

The flyover-noise test program consisted of a series of tests at 12 conditions that were repeated on three different test days for the existing as well as the treated airplane. Table I lists the 12 test conditions and the nominal airplane gross weights that were included in the flyover-noise tests. All airplane weights stated in this paper are gross weights. Figure 1 shows the test airplane with the existing nacelles.

Test Procedures

Figure 2 shows typical locations for the mobile sound-recording stations used for the flyover-noise measurements. All tests were conducted under low-wind conditions permitting downwind take-offs. Most of the recordings were made with the airplane flying over microphones located along the extended center line of the runway. Four microphones were located along a line 1500 feet to the side of the runway to obtain measurements of sideline noise during take-off at the heaviest take-off weight.

For the full-power take-offs (items 1, 5, and 9 of table I), rated take-off engine-pressure ratio was maintained to an altitude of 5000 feet or for 5 minutes, whichever occurred first. The reduced-thrust simulated take-offs (items 2, 3, 6, 7, 10, and 11 of table I) were started from level flight along the center line of the runway at a height of about 300 feet. On arriving at a selected point over the runway, the power levers were adjusted to provide a specified rotor speed and the airplane climbed out at a prescribed airspeed. For the landing approaches (items 4, 8, and 12 of table I), the rotor speed was maintained at selected values throughout the approach to minimize fan-noise variations and to obtain comparable noise recordings of airplanes with the existing and treated nacelles on each test day. The average measured values of airspeed and low-pressure rotor speed are given in table II.

Flyover-noise measurements were made at 10 mobile recording stations that were moved about as required. Figure 3 shows a typical noise-recording station with its portable battery-powered equipment. The microphone and sound-level meter were mounted on a tripod with the microphone 5 feet above the ground and oriented for grazing incidence. Photographs were taken when the airplane was over or opposite a station to supplement the time-correlated onboard space-positioning system. The space-positioning system was used to determine the location of the airplane in space relative to the sound being recorded. A portable VHF transceiver was used to transmit a synchronizing signal to the airplane when it passed over the station. The area where most of the recordings were made was used principally for agriculture, as indicated by the grapevines in the background. At each station, the microphones were located so as to avoid any interference or unusual absorption from adjacent vegetation.

Ambient noise levels at the test sites due to ground-vehicle traffic, farming equipment, and wind were acceptably low except in the 1/3-octave bands at and above 5000 Hz. The ambient levels in these high-frequency bands introduced some data-reduction problems for recordings of the noise propagated through long distances. Figure 4 shows the range of ambient sound-pressure levels that were measured. The value of PNL corresponding to the maximum ambient sound-pressure levels was 73 PNdB; the average ambient PNL was approximately 55 PNdB.

Both surface and low-altitude weather conditions were measured. All surface weather measurements at the test sites were made at approximately the 5-foot microphone height. The measurements consisted of wind speed, wind direction, and wet- and dry-bulb air temperatures. For the tests with the existing nacelles (conducted in February 1969), the ambient air temperatures ranged from 48° to 65° F with corresponding relative humidities of 84 to 40 percent. For the tests with the treated nacelles (conducted in March 1969), the corresponding temperature and relative-humidity values were 43° to 57° F and 81 to 53 percent, respectively. The surface absolute humidity ranged from 5.8 to 7.5 grams per cubic meter. Vertical weather soundings were obtained by an instrumented lightweight airplane. The general results of the vertical soundings are presented in figures 5 and 6. The weather conditions were comparable for the tests of the existing nacelles and the treated nacelles on the DC-8-55 airplane.

Data Reduction

The flyover-noise recordings obtained were reduced into 1/3-octave-band sound-pressure levels by using an analog-to-digital data-reduction system. The 1/3-octave-band SPL data consisted of the spectral and temporal variations of the SPL during each flyover-noise recording. The values of SPL provided the fundamental information needed to evaluate the noise-suppression system and also were used to derive instantaneous perceived-noise levels (PNL), tone-corrected instantaneous perceived-noise levels (PNLT), and effective perceived-noise levels (EPNL). Calculation of these psychoacoustic measures for estimating human annoyance was based on the procedures of reference 2. The PNL calculations used the mathematical formulations of the noy tables given in reference 3.

For each flyover-noise recording, the data-reduction procedure yielded the time variation of the SPL in each of the twenty-four 1/3-octave bands with center frequencies between 50 and 10 000 Hz. The indicated SPL data, system-frequency-response correction factors, and microphone-pressure-response correction factors for each flyover-noise recording for the airplanes with existing and treated nacelles were processed by a digital computer to determine PNL, PNLT, and duration correction factors.

In programing the digital computer to carry out the calculations required for an evaluation in terms of EPNL, the following details were specified for determining duration correction factors:

- Duration correction factors were computed by the integration method.
- The constants in the integration method were adjusted to account for the 0.25-second interval used in sampling the flyover-noise recordings.
- The duration time was determined from the calculated values of PNLT as a function of time during a flyover. The duration time was defined by the points that were 10 PNdB less than the maximum value of PNLT. If a 10-PNdB-down point did not coincide with a calculated value, then the duration time was taken as the difference between the initial and final times for which PNLT was nearest to the value of PNLTM minus 10 PNdB. For those cases with more than one PNLT peak, the applicable limits for the duration time were chosen so as to yield the largest possible duration time.

A sample of the EPNL test results for landing-approach power settings is presented in figure 7 as a function of height above the microphones. The treated nacelles produced substantial noise reductions over the range of heights. The variation of the individual EPNL values from a mean line drawn through the data points was ±1 to ±1.5 EPNdB. From an analysis of the results at other engine power settings, it was found that the variation at the take-off thrust setting was similar to that observed at the landing thrust setting. For the simulated take-offs with reduced thrust, the scatter was larger and on the order of ±2 to ±3 EPNdB.

The flyover-noise measurements were analyzed to yield generalized results of PNLM and EPNL as a function of distance and thrust. With these generalized results, it was possible to account for the effects of the treated nacelles on the noise levels as well as on the airplane performance. Furthermore, the specific test results might be related in this way to operational conditions of wide interest. Appropriate values of installed net thrust for the test results were determined from the thrust—rotor-speed relationship given in figure 8 for Mach numbers ranging from 0 to 0.4.

All the estimates of airport-community noise levels presented in this paper were based on sound-pressure levels corresponding to the test-day atmospheric conditions. Because the weather conditions were comparable for the tests on the existing and the treated nacelles, the noise reductions determined for comparable airplane weights and engine power settings should be correct under the test-day atmospheric conditions.

COMMUNITY NOISE LEVELS

In this paper, noise levels in communities in the vicinity of airports are presented principally for the maximum landing gross weight and the maximum take-off gross weight; for the DC-8-55 airplane, these weights are 240 000 and 325 000 pounds, respectively. These weights and the three-point noise-measuring system (landing, take-off, and sideline noise) were selected because they were proposed in reference 4 for use in certifying the flyover noise levels of jet transports.

Landing-Approach Noise

Figure 9 shows EPNL under a 3° landing-approach flight path for the 240 000-pound landing weight. The required thrust level was 5500 pounds per engine. Directly below the flight path at 1 nautical mile from threshold, the treated airplane reduced the EPNL by 10.5 EPNdB (from 117.5 to 107 EPNdB). The noise reduction below the flight path was approximately constant to nearly 5 nautical miles from threshold, and then it slowly decreased.

The substantial noise reduction achieved by the nacelle treatment was caused by the significant change in the spectral content of the sounds of the two airplanes, as shown in figure 10. The two spectra show the sound-pressure levels occurring at the instant of the maximum value of the PNL (that is, at PNLM) at a location 1 nautical mile from threshold where the airplane is at a height of 370 feet. In the frequency region above 1000 Hz, which contains the combination tones and the fan-blade-passage frequencies, the treated nacelles substantially reduced the values of SPL. Essentially no change occurred to the portion of the spectrum below 800 Hz, which is controlled by jet-exhaust noise.

Additional information on landing-noise levels at a location 1 nautical mile from threshold is presented in figure 11 for an operational range of landing weights from 180 000 to 240 000 pounds. The noise reductions were greater for the lighter weights because of the smaller contribution of jet-exhaust noise. For example, for airplanes with a 180 000-pound landing weight, the noise reduction was approximately 12 EPNdB.

Take-Off Noise

The values of EPNL at locations under the take-off flight path are shown in figure 12 for airplanes with 325 000-pound take-off weights and climbing with a speed of $V_2 + 10$ knots. The speed of $V_2 + 10$ knots is equivalent to a speed of 174 knots at this weight for an air temperature of 59° F and a take-off flap setting of 25°. At 3.5 nautical miles from brake release, the treated nacelles reduced the EPNL of the airplanes by

3.5 EPNdB (from 115 to 111.5 EPNdB). Airplanes with lower take-off weights would achieve less noise reduction at rated take-off power settings. For example, at a take-off weight of 240 000 pounds, representative of a transcontinental range of 2500 nautical miles, the noise reduction would be 2 EPNdB (from 105.5 to 103.5 EPNdB). The values of EPNL are considerably lower at this weight because of the better climb capability of the 240 000-pound airplane compared with that of the 325 000-pound airplane.

The noise reductions achieved at the take-off power setting are smaller than those at the landing power setting because of the increased intensity of the low-frequency jet-exhaust noise. Figure 13 shows the SPL spectra at the time of PNLM at a location 3.5 nautical miles from brake release. The approximate heights of the airplanes were 975 feet for the airplane with the existing nacelles and 930 feet for the airplane with the treated nacelles. This difference in heights reflects the loss in rated take-off thrust due to the treatment. Although the blade-passage tones were significantly reduced at this rated take-off thrust setting, the relatively more intense jet-exhaust noise determines the PNL of the treated nacelles.

If the thrust can be reduced during the initial climb after lift-off, then lower values of EPNL and larger noise reductions can be achieved at the 3.5-nautical-mile point. For comparison purposes, it was assumed that the thrust could be reduced to that required to maintain a 6-percent climb gradient with a rate of climb of approximately 1000 feet per minute and an airspeed of $V_2 + 10$ knots. The climb procedure assumed a thrust reduction from rated take-off power at a point 1500 feet before the 3.5-nautical-mile point. Figure 14 shows the resultant noise levels. With the 325 000-pound take-off weight, use of this thrust-reduction procedure yielded a noise reduction of approximately 5.5 EPNdB. With a take-off weight of 240 000 pounds, the corresponding noise reduction was approximately 8 EPNdB. Larger noise reductions were achieved with the lighter take-off weights because of the lower thrusts required to maintain the 6-percent climb gradient at these weights. At the distances considered, the contribution of jet-exhaust noise to the PNL decreases as the thrust is reduced on the JT3D-3B engine.

Sideline Noise

The noise levels along the 1500-foot sideline are shown in figure 15 as a function of distance from brake release for airplanes with a 325 000-pound take-off weight and climbing with rated take-off thrust. The difference between the maximum value of EPNL for the existing nacelle and that for the treated nacelle was approximately 3 EPNdB and occurred at 3.5 to 4 nautical miles from brake release. The maximum values of 109 and 106 EPNdB occurred when the airplanes with the existing and treated nacelles were at heights of approximately 900 feet and 1100 feet, respectively. Airplanes with lighter take-off weights (for example, 240 000 pounds) would achieve the same amount of noise reduction.

Estimated EPNL Contours

The approximate extent of the changes in the noise-exposed areas around an airport are indicated in figures 16 and 17. The estimated contours of equal EPNL are drawn at a representative 100-EPNdB level for the existing and the treated airplanes. The scale of the contours is in nautical miles and is the same in both directions. For the landing-noise contours in figure 16, the scale is relative to the threshold end of the runway. For the take-off-noise contours in figure 17, the scale is relative to the brake release point.

During the landing approach (fig. 16), the estimated contour lines indicated that the treated nacelles would produce a substantial reduction in the area exposed to levels of 100 EPNdB or higher. The change in the area exposed to noise levels of 100 EPNdB or higher was much less for take-off (fig. 17) than for landing (fig. 16).

ESTIMATED AND MEASURED NOISE LEVELS

The flyover-noise data obtained in this program afforded an opportunity to validate the flyover-noise estimation method that was described in reference 1. Figure 18 shows comparisons of measured and estimated values of PNL. A comparison of the estimated and measured SPL at the time of PNLM is shown in figure 19 for the airplane equipped with treated nacelles. The comparisons in both figures are shown for a selected landing power setting and for a height overhead of approximately 400 feet.

The predictions were based on SPL measurements at a distance of 150 feet around an engine test stand. The estimated values (dashed lines) were adjusted to the engine conditions of the measurements. The measured data in figure 18 (solid lines) are not representative of the average difference between the noise level of airplanes with the existing and the treated nacelles.

The agreement between the measured and estimated values of PNL and SPL is encouraging, especially because of the considerable difference between the SPL spectra of the existing and treated nacelles. The differences between the measured and estimated values of PNL in figure 18 at times away from the peak values would result in a negligible difference in the integrated duration correction factor in EPNL calculations. It is anticipated that these encouraging results will stimulate further efforts to develop a general prediction technique applicable to engines other than the JT3D-3B and to nacelle treatments other than that used in this program.

CONCLUDING REMARKS

Evaluation of the flyover-noise test results has shown that installation of acoustically treated nacelles on a DC-8-55 airplane achieved noise reductions under both the landing-approach and the take-off flight paths. Estimates of the flyover noise levels at locations under the landing-approach flight path were made based on sound-pressure-level measurements around an engine test stand. Comparison with flyover-noise measurements indicated reasonably good agreement for both perceived-noise levels and 1/3-octave-band sound-pressure levels. Tables III and IV summarize the principal results, which are as follows:

- Under the landing-approach path, at 1 nautical mile from threshold, the treated nacelles reduced the EPNL by 10.5 EPNdB for an airplane with a 240 000-pound landing weight and by 12 EPNdB for an airplane with a 180 000-pound landing weight.
- Under the initial-climb flight path, at a point 3.5 nautical miles from brake release, a 325 000-pound airplane with treated nacelles achieved a 3.5-EPNdB noise reduction and a 240 000-pound airplane with treated nacelles achieved a 2-EPNdB reduction when climbing with rated take-off thrust. With the thrust reduced to that required to maintain a 6-percent climb gradient, the noise reductions achieved were 5.5 EPNdB for an airplane with a 325 000-pound take-off weight and 8 EPNdB for an airplane with a 240 000-pound take-off weight.
- Along a line 1500 feet to the side of the take-off flight path, the treated nacelles reduced the maximum EPNL by approximately 3 EPNdB for airplanes with take-off weights of 325 000 and 240 000 pounds and climbing at rated take-off thrust.

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3. Anon.: Definitions and Procedures for Computing the Perceived Noise Level of Aircraft Noise. ARP 865, Soc. Automot. Eng., Nov. 15, 1964.
4. Anon.: Noise Standards: Aircraft Type Certification. Notice of Proposed Rule Making. Department of Transportation, Federal Aviation Administration, [14 CFR Parts 21 and 36] [Docket No. 9337; Notice No. 69-1]. (As published in the Federal Register [34 F.R. 453], Jan. 11, 1969.)

TABLE I.- FLIGHT CONDITIONS FOR FLYOVER-NOISE TESTS

Test item	Flight operation	Nominal gross weight, lb
1	Take-off	300 000
2	Simulated take-off	295 000
3	Simulated take-off	245 000
4	Landing	240 000
5	Take-off	235 000
6	Simulated take-off	230 000
7	Simulated take-off	225 000
8	Landing	205 000
9	Take-off	200 000
10	Simulated take-off	195 000
11	Simulated take-off	190 000
12	Landing	185 000

TABLE II.- AVERAGE AIRSPEEDS AND ROTOR SPEEDS DURING FLYOVER-NOISE TESTS

Test item	True airspeed, kn		Referred low-pressure rotor speed, rpm	
	Existing-nacelle tests	Treated-nacelle tests	Existing-nacelle tests	Treated-nacelle tests
1	Static to 220	Static to 220	6540	6420
5	Static to 200	Static to 200	6570	6440
9	Static to 195	Static to 195	6590	6460
2	245	245	5900	5890
6	215	210	5860	5930
10	190	190	5880	5930
3	225	225	5520	5540
7	205	205	5500	5550
11	185	185	5510	5570
4	155	160	4705	4730
8	140	150	4500	4400
12	131	135	4290	4150

TABLE III.- LANDING NOISE REDUCTIONS AT 1 NAUTICAL MILE FROM THRESHOLD

Landing weight, lb	ΔEPNL, EPNdB
240 000	10.5
180 000	12

TABLE IV.- TAKE-OFF NOISE REDUCTIONS

Take-off weight, lb	Noise reduction under flight path at 3.5 n. mi. from brake release, ΔEPNL, EPNdB		Reduction in maximum EPNL along 1500-ft sideline, EPNdB
	Rated take-off thrust	Thrust for 6-percent climb gradient	
325 000	3.5	5.5	3
240 000	2	8	3

FLIGHT-TEST AIRPLANE

Figure 1

FLYOVER-NOISE STATIONS

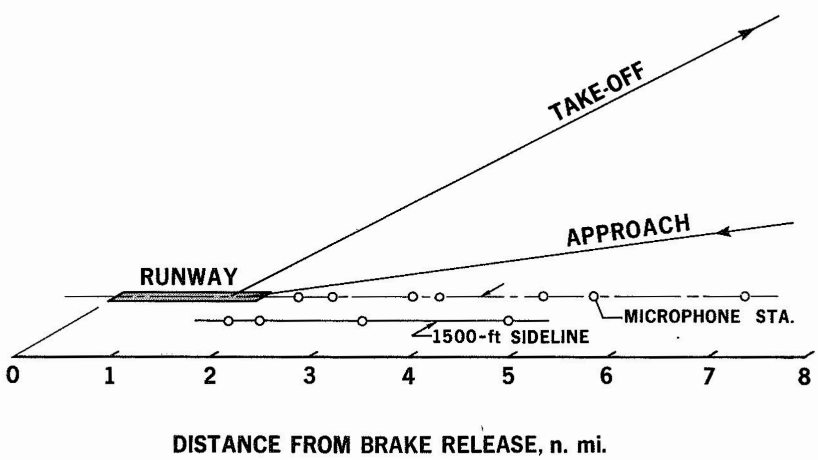


Figure 2

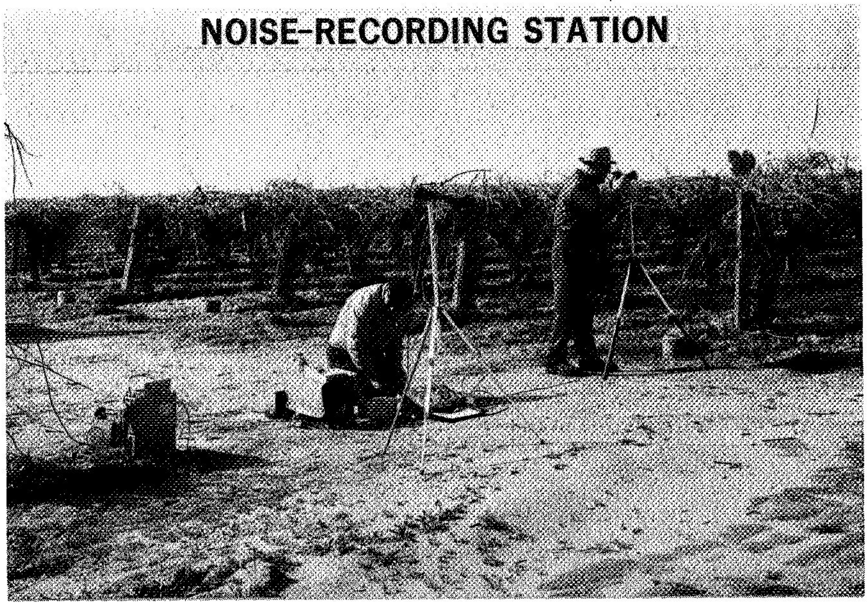


Figure 3

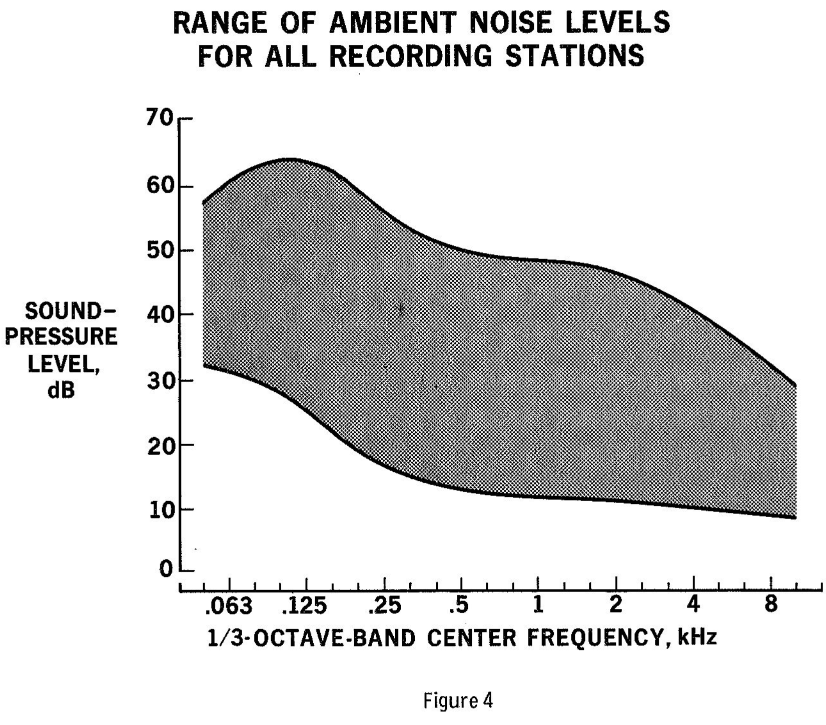


Figure 4

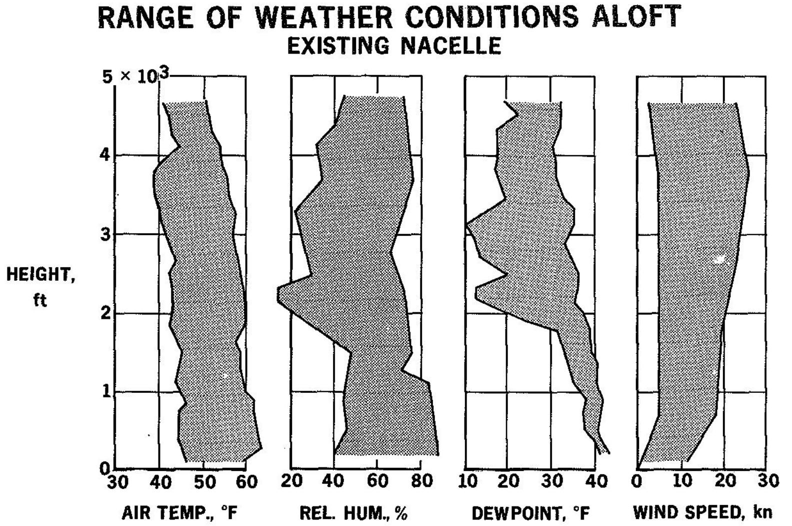


Figure 5

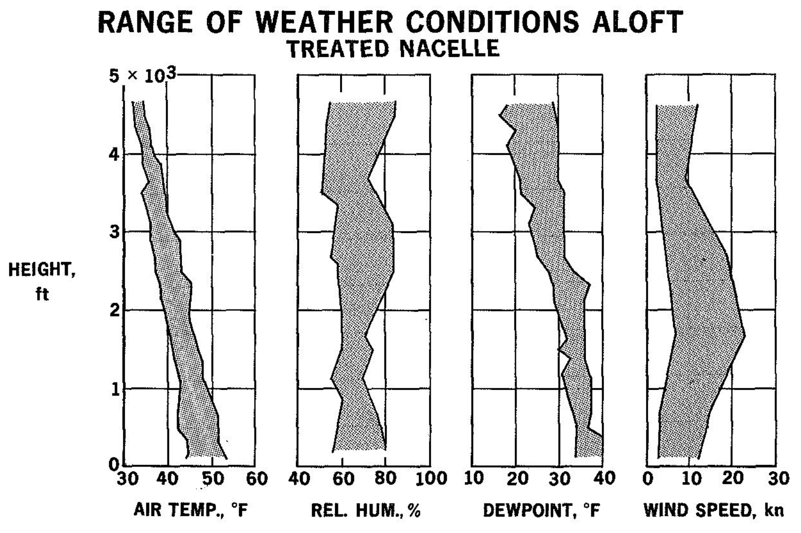


Figure 6

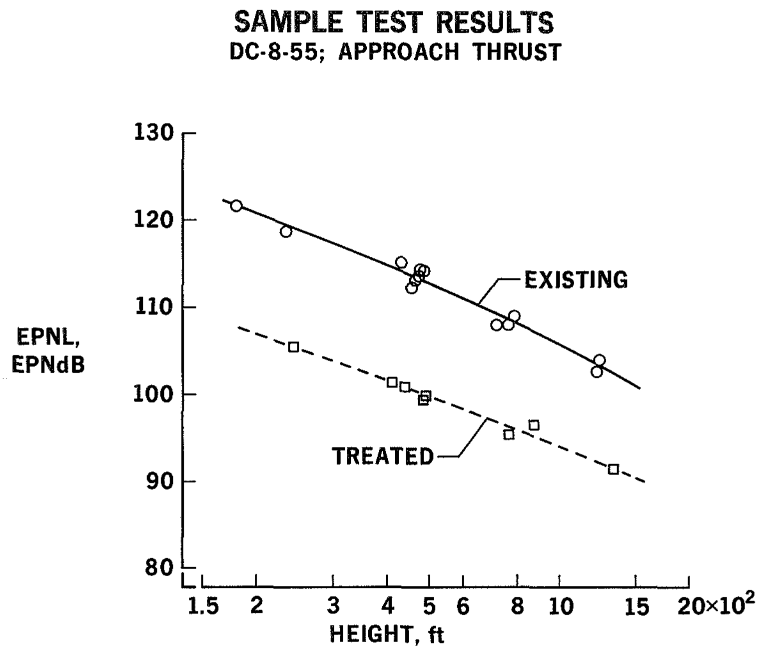


Figure 7

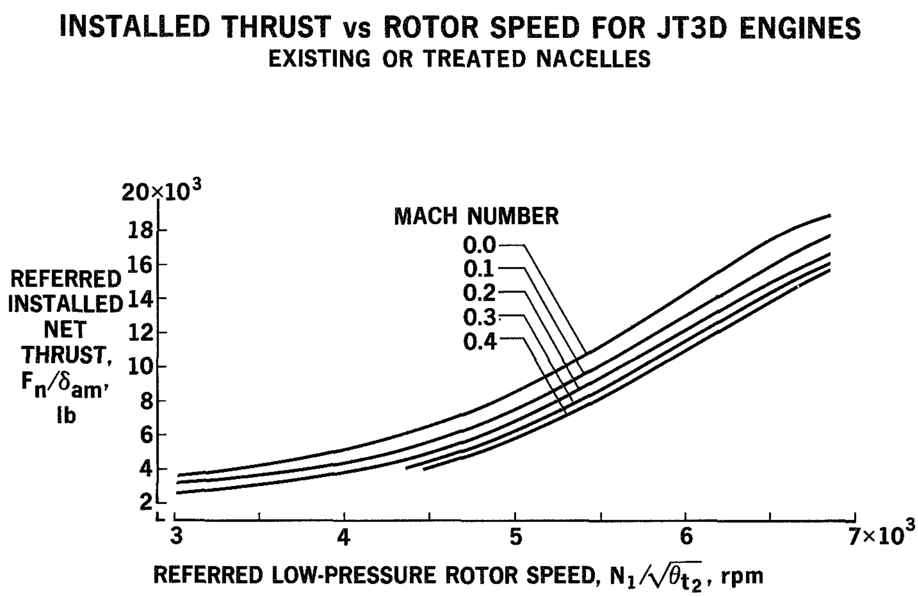


Figure 8

LANDING-APPROACH NOISE LEVELS
240 000-lb LANDING WEIGHT

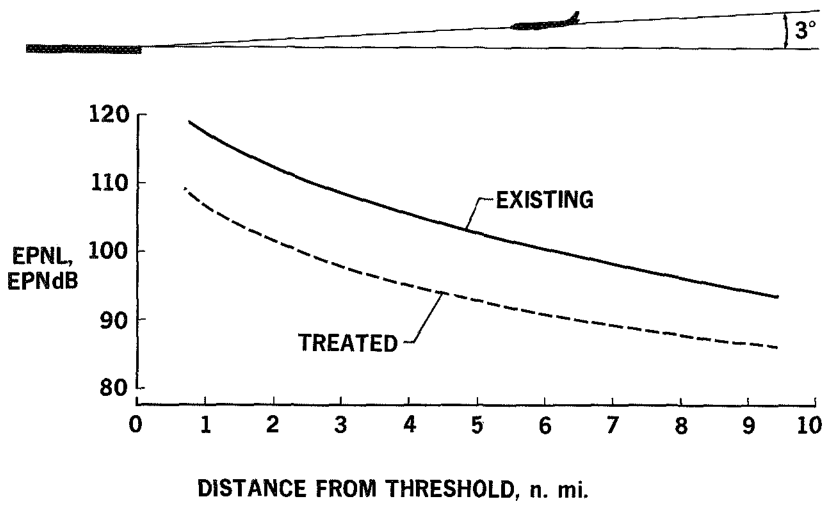


Figure 9

SPL SPECTRA AT TIME OF MAXIMUM PNL
1 n. mi. FROM THRESHOLD; 240 000-lb LANDING WEIGHT

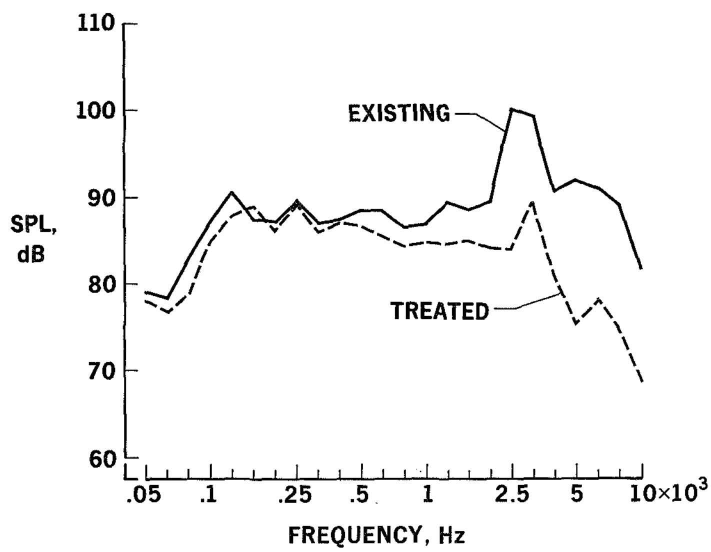


Figure 10

EPNL AT 1 N.MI. FROM THRESHOLD
3° APPROACH FLIGHT PATH

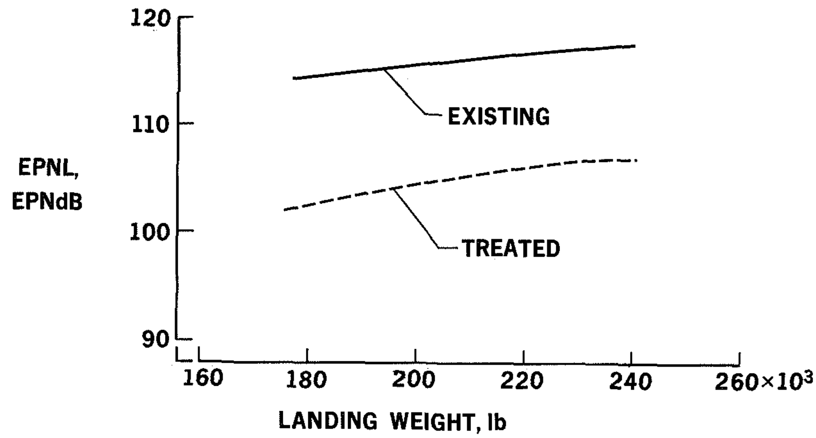


Figure 11

TAKE-OFF NOISE LEVELS
325 000-lb TAKE-OFF WEIGHT; V_2 + 10 knot CLIMB SPEED

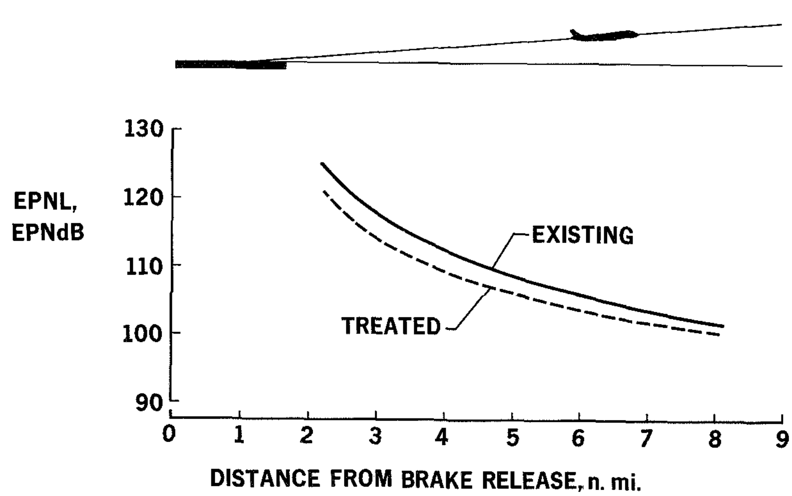


Figure 12

SPL SPECTRA AT TIME OF MAXIMUM PNL
3.5 n. mi. FROM BRAKE RELEASE
325 000-lb TAKE-OFF WEIGHT; V_2 + 10 knot CLIMB SPEED

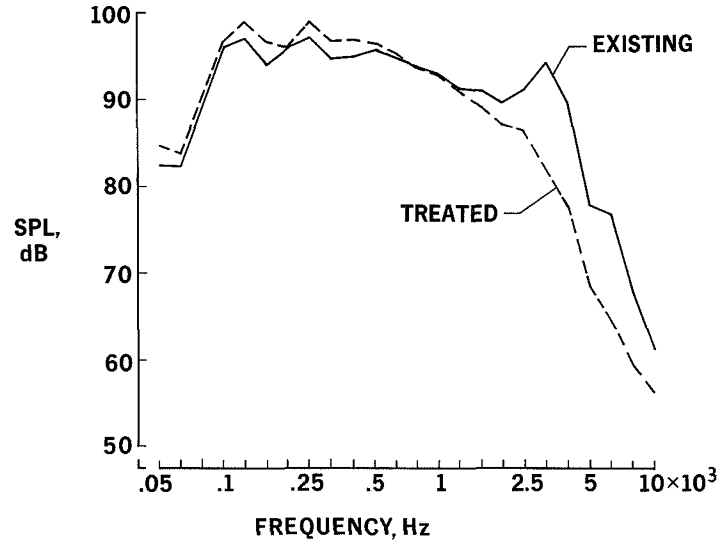


Figure 13

EPNL AT 3.5 N. MI. FROM BRAKE RELEASE
6% CLIMB GRADIENT; V_2 + 10 knot CLIMB SPEED

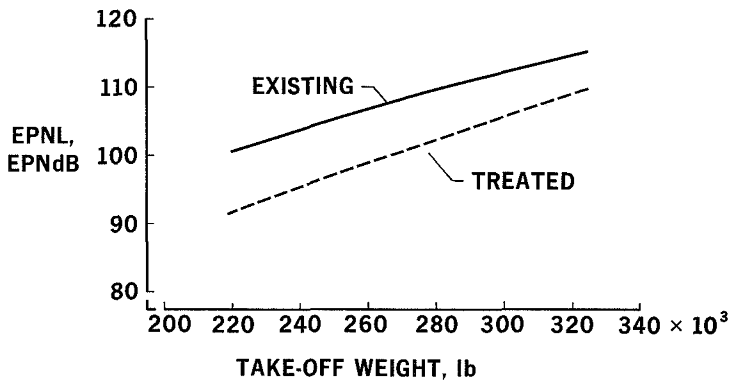
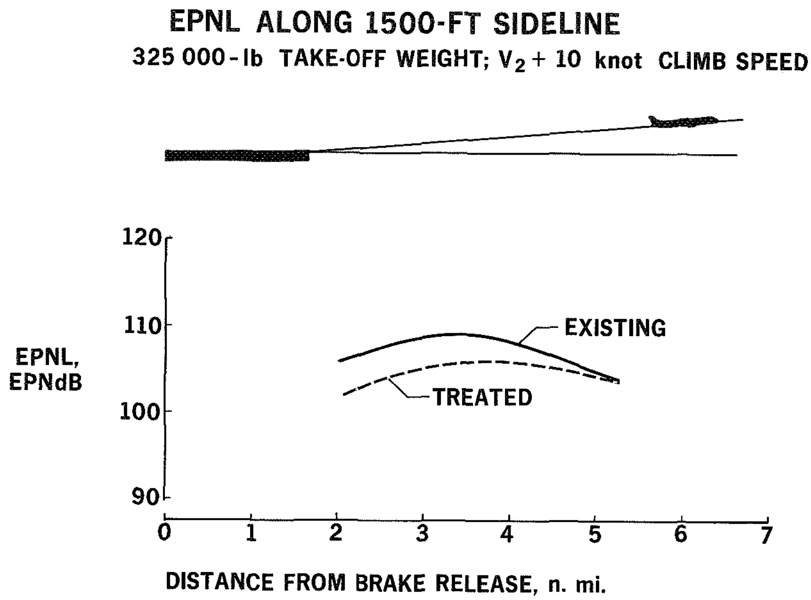


Figure 14



EPNL ALONG 1500-FT SIDELINE
325 000-lb TAKE-OFF WEIGHT; V2 + 10 knot CLIMB SPEED
EPNL, EPNdB
120
110
100
90
EXISTING
TREATED
0
1
2
3
4
5
6
7
DISTANCE FROM BRAKE RELEASE, n. mi.

Figure 15

ESTIMATED 100-EPNdB CONTOURS
240 000-lb LANDING WEIGHT; 3° APPROACH PATH

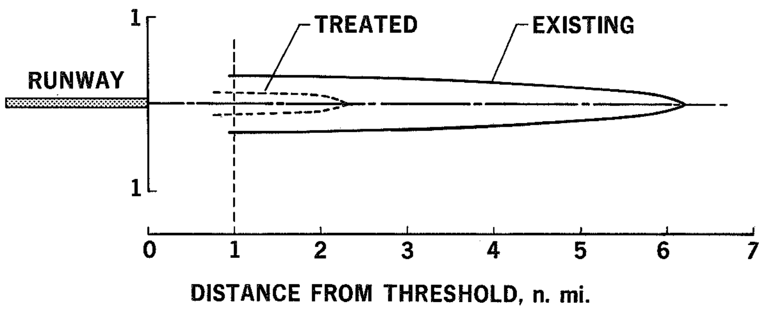


Figure 16

ESTIMATED 100-EPNdB CONTOURS
325 000-lb TAKE-OFF WEIGHT; V_2 + 10 knot CLIMB SPEED

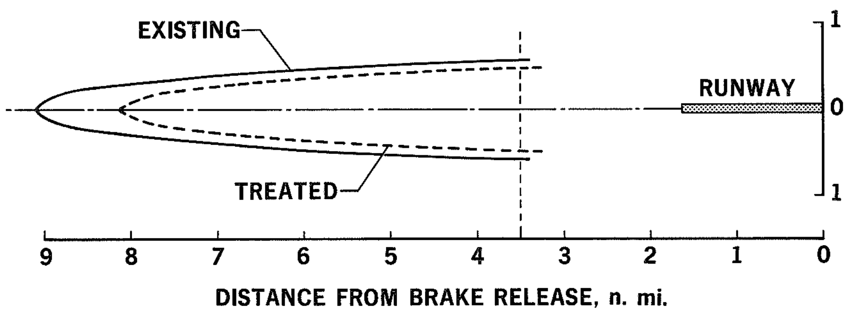


Figure 17

MEASURED AND ESTIMATED PNL

HEIGHT ≈ 400 ft; APPROACH THRUST ≈ 4200 lb/eng

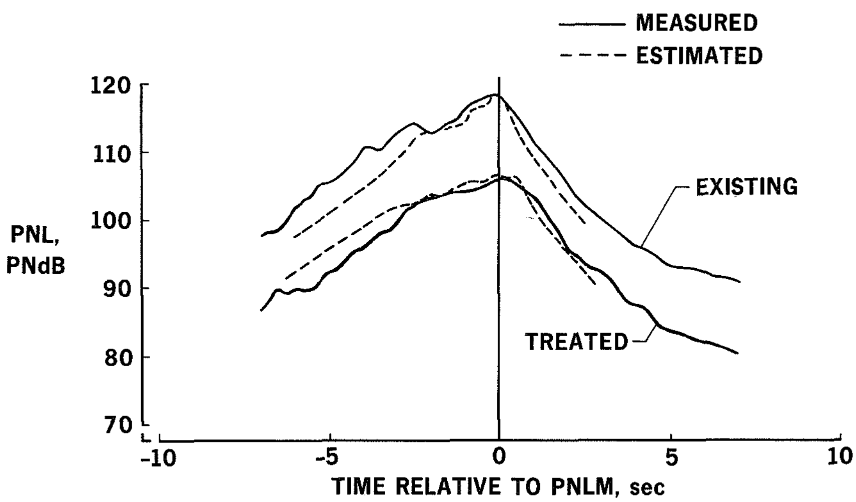


Figure 18

SPL SPECTRA AT TIME OF PNLM FOR TREATED NACELLES

HEIGHT≈ 400 ft; THRUST ≈ 4200 lb/eng

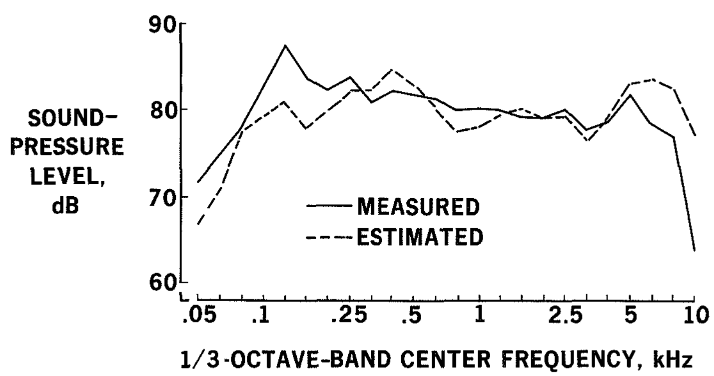


Figure 19

6. ECONOMIC IMPLICATIONS OF RETROFITTING SHORT-DUCT DC-8 AIRPLANES WITH ACOUSTICALLY TREATED NACELLES

By H. D. Whallon

McDonnell Douglas Corporation

SUMMARY

An investigation was conducted to determine the economic implications of retrofitting short-duct DC-8 airplanes with acoustically treated nacelles. The study compared each existing and modified model in terms of (1) annual profit and loss criteria, including taxes and profit after taxes, (2) investment, and (3) return on airplane investment. Estimates of the costs of developing, producing, and installing the treated nacelles were used as a basis for these comparisons. The effects on direct operating cost of the expected airplane performance changes and of amortization of the modification costs were also included in these estimates.

The study indicated that direct operating cost would be increased between 4 and 5 percent, assuming a 5-year amortization of the retrofit cost and modification of all short-duct DC-8 airplanes. The increase in direct operating cost would be due almost entirely to amortization of the costs of modification. On the assumption that operating revenues would be the same for the existing and treated airplanes, calculation indicated that profit after taxes and Federal income taxes would be reduced 10.1 percent for 5 years, the investment book value of airplane inventory would be increased 18.5 percent, and the discounted cash flow rate of return on airplane investment would be reduced 8.2 percentage points, about a one-quarter reduction from the existing level.

INTRODUCTION

This paper is part of a presentation of the results of an investigation performed under Contract NAS 1-7130 for the Langley Research Center by the McDonnell Douglas Corporation of DC-8 nacelle modifications to reduce fan compressor noise in airport communities. In this paper are examined the economic implications of retrofitting a fleet of DC-8 series 50 and model 61 airplanes with acoustically treated nacelles. These airplanes are equipped with JT3D engines and short-duct nacelles and constitute about 50 percent of the total DC-8 airplane fleet.

Studies were made of (1) a program schedule for a fleet retrofit, (2) the initial prices of retrofit kits needed to accomplish the modifications, (3) the changes in direct operating costs due to the modifications, and (4) the effects of retrofitted-fleet operations on profit and loss criteria, investment, and return on airplane investment. In order to perform these studies, it was necessary to make a number of assumptions regarding basic factors that are uncertain at this time. Ultimately, each operator should assess the assumptions and make such adjustments as are necessary to fit the particular circumstances of his operations.

DISCUSSION

Assumed Retrofit Program Schedule

The assumed retrofit program schedule is outlined in figure 1. A 5-year overall program was assumed. The 5-year program shown would provide for retrofit installation of the modified nacelles on airplanes during scheduled engine or airplane overhauls and, thus, would require no out-of-service time for installation. The first 2 years of the program are necessary for development, tooling, and certification. The third through the fifth years of the program encompass retrofit kit production and installation.

Retrofit Price

About 250 short-duct DC-8 airplanes are expected to be in service in the early 1970's. Retrofit prices were estimated on the basis of 300 airplane kits to be produced in the years 1972 through 1974, which assumes retrofit of the total 250 airplanes and includes a 20-percent allowance for spares. The elements of the price estimate are indicated in table I. Values were initially estimated on the basis of current rates and were then escalated 4 percent per year to 1972. The estimated 1972 values would have to be adjusted if the number of kits, the time period, or the escalation factor differed from the foregoing assumptions.

Development and tooling represent estimated non-recurring or fixed costs, whereas manufacturing represents the estimated recurring or variable per-kit cost of production at the 300-unit level of production. The total price per kit installed was estimated to be $546 000. With 20 percent spares, the total price per airplane would be $655 000.

Figure 2 illustrates the variation of kit unit price with the number of airplane kits to be produced. The larger the base over which the non-recurring costs are allocated, the lower the per-unit price of the airplane kit. The curve also reflects some economies of scale and improvements in production efficiency with quantity.

Direct Operating Cost

Another element to be assessed is the effect of the modification on the operating costs of the airplane. This effect was determined by comparing the direct operating costs (DOC) of the existing airplane with those of the same airplane after nacelle modification.

The change in the DOC of the airplane which would result from the retrofit was calculated on the basis of the retrofit price discussed in the previous section, the changes in airplane performance described in paper no. 4 by David K. Gordon, and some basic assumptions as indicated in table II. The standard 1967 Air Transport Association (ATA) method was used as the basis for calculating direct operating costs (ref. 1). However, certain modifications in the method were made and certain values were assumed to reflect the specific nature of the retrofit program.

Installed price of the retrofit modification was $546 000 per airplane (without spares). The price of the existing airplane would be increased by the price of the retrofit kit installed. Standard spares factors of 10 and 40 percent, respectively, were used for airframe and engines; a nonstandard 20 percent spares factor was introduced for the nacelle parts, corresponding with spares practice on quick engine change components. The standard depreciation period of 12 years was used for the airplane; the added price of the nacelle modifications, however, was depreciated over a 5-year period. This implies the assumptions that the airplane is retrofitted at the end of its seventh year of service and that depreciation of the additional investment in the retrofit nacelles coincides with the last 5 years of airplane service life. Fixed, rather than variable, utilization of 3800 hours was used. A typical mixed-class interior configuration of 135 seats was assumed for the DC-8-55 airplane. Only this assumption is peculiar to the model 55 airplane, as shown in table II, and it illustrates that a representative domestic passenger configuration was assumed for each short-duct DC-8 model. Zero downtime was assumed for retrofit-kit installation, in the expectation that installation could be phased with normally scheduled downtime for maintenance. Finally, the change in nacelle maintenance cost due to the modification was estimated by task analysis, although the basic existing nacelle maintenance costs were calculated by the ATA method.

Based on the airplane modification costs and the approach and assumptions discussed, the DOC of the existing and treated DC-8-55 airplanes would be as shown in figure 3. The direct operating cost is in terms of cents per seat nautical mile, and the range is given in nautical miles. The solid-line curve is the DOC of the existing unmodified airplane; the dash-line curve is the DOC of the same airplane with treated nacelles.

The modification increases the airplane's DOC between 4 and 5 percent in the customary operating ranges below the discontinuities of the DOC curves. The 3-percent increased range of the airplane with treated nacelle, discussed in paper no. 4, is reflected by the greater range at which the discontinuity occurs for the modified airplane.

Table III shows a breakdown of the elements that constitute the change in DOC shown in figure 3. The change in each element is shown as a percent of DOC. The example shown is for domestic passenger service at an 850-nautical-mile range and a 5-year depreciation of the retrofit. Crew cost did not change, since block time was not perceptibly changed by the modification. Insurance increased; this reflected the increased book value of the airplane after the modification. Fuel cost decreased; this reflected the improved cruise fuel consumption of the modified airplane.

Maintenance was estimated by task analysis to increase about 1 dollar per flight hour, or about one-tenth of 1 percent of DOC. This preliminary estimate is subject to change when additional experience is accumulated on the service life, inspection and repair costs, and cleaning costs associated with the acoustic materials that would be used. The changes in insurance, maintenance, and fuel cost approximately cancel each other.

The change in depreciation, which is due to amortization of the added cost of the modification, was found to be the dominant element of the overall net change in DOC.

Economic Analysis

DC-8-55 airplane.- To evaluate the financial aspects of the retrofit, comparisons were made between the existing and treated airplanes as though each were operating under the same average service conditions and assumptions. Preliminary studies indicated that profit and loss calculations based on an average range of 850 nautical miles resulted in average operating revenues, costs, and profits and in valid economic comparisons between the two airplanes. Particular assumptions used in the economic analysis are listed in table IV.

The revenue-earning capability of the airplane with treated nacelle was assumed to be the same as that of the existing untreated airplane. (See paper no. 4.) Not evaluated were the increased payload-range capability or the possibilities of earlier retirement, changes in route structure, and changes in airplane task assignment. Both airplanes were assumed to perform the same service task and to earn the same revenue. Revenue calculations were based on published air fares as of May 1969. Although it is recognized that fares might be increased to accommodate the increased operating costs of the modified airplane, this factor was not treated in the study.

Both airplanes were in passenger service, both operated at a 50-percent load factor, and both had the same indirect operating costs, calculated at 42 percent of revenue. The cost of the retrofit was treated as an increase in capital investment rather than as an expense. The same 48-percent corporate income tax rate was applied to the operations of both airplanes, and the investment tax credit was treated as zero in synthesizing each airplane's profit and loss status.

Table V shows the changes resulting from the modification in 1 year's profit and loss criteria. Revenue was not changed and operating expenses, except for depreciation, were likewise unchanged. Depreciation increased to amortize the cost of the modification, and the increase in depreciation was the only perceptible change in operating expenses, as previously noted. The increased depreciation caused an equivalent reduction in profit before taxes. Of the reduction in profit before taxes, 48 percent was absorbed by a decrease in income taxes paid and the balance came out of profit after taxes. In effect, the Government absorbed 48 percent of the cost of retrofit, and operations bore 52 percent of the cost. Annual cash flow, which is the sum of depreciation and profit after taxes, increased since the increase in depreciation was greater than the decrease in profit after taxes.

Table VI shows the changes in airplane investment and return on airplane investment. Investment was calculated to be the depreciated value of the airplane at the time of retrofit, which was assumed to be at the end of the seventh year. Investment was increased by $655 000, the cost of the retrofit plus spares.

Return on airplane investment was calculated to be the discounted cash flow rate of return on airplane investment over the economic life of the investment, which in this study is 5 years. Return on airplane investment was reduced 6 percentage points. The investment increased relatively more than did the cash flow, which decreased the rate of return.

DC-8 short-duct fleet.- The operational service analysis in the preceding section dealt with only one of the six short-duct DC-8 models. A similar analysis was performed on each of the other five models. The results for the six models were combined to evaluate the effect of the total fleet retrofit.

Table VII shows the estimated composition of the short-duct DC-8 fleet at the start of 1972. About 250 short-duct DC-8 airplanes are estimated to be in service on January 1, 1972. The model 61 is the only short-duct DC-8 airplane presently in production, and deliveries by the start of 1972 may differ from the estimate of 101 shown. Attrition and retirement are additional unpredictable factors that make the total of 250 airplanes a working estimate only.

The economic effects were different for each model. Generally, the economic impact was the least severe for the largest and most profitable model, the extended-fuselage DC-8-61. Table VIII summarizes the overall economic impact of retrofitting the entire mixed fleet of 250 short-duct DC-8 airplanes. Profit after taxes was reduced 10.1 percent, investment book value of airplane inventory was increased 18.5 percent, and the rate of return on airplane investment was reduced by 8.2 percentage points, about a one-quarter reduction from the rate of return of the existing unmodified fleet.

CONCLUDING REMARKS

The economic effects of retrofitting DC-8 short-duct airplanes with acoustically treated nacelles were examined in this paper. The cost of retrofitting 250 airplanes was estimated to be $655 000 per airplane. Direct operating cost would be increased 4 to 5 percent.

On the basis of the assumptions that the retrofit program would not affect revenues, scheduling, utilization, route and traffic assignment, or remaining economic life and retirement plans for the airplanes, it was estimated for the total short-duct DC-8 fleet that profits (and Federal income taxes) would be reduced 10.1 percent for 5 years, investment book value of aircraft inventory would be increased 18.5 percent, and the discounted cash flow rate of return on aircraft investment would be reduced 8.2 percentage points, a one-quarter reduction from the existing level.

The economic effects determined in this program apply only to DC-8 airplanes with short-duct nacelles. The total DC-8 fleet in 1972 is expected to include not only the 250 short-duct DC-8 airplanes discussed but also an approximately equal number of other DC-8 models, including turbojet engines and long-duct nacelle installations to which these study results do not apply.

The economic impact on individual operators and on the industry as a whole as a result of retrofitting existing airplanes with acoustically treated nacelles warrants further study in which consideration can be given to factors such as fleet reequipment plans, possible changes in airplane traffic and route assignments, possible changes in fares, and future local, federal, and international noise regulations.

REFERENCE

1. Anon.: Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes. Air Transp. Assoc. Amer., Dec. 1967.

TABLE I

RETROFIT-KIT PRICE

[BASIS: 300 AIRPLANE KITS FOR 250 AIRPLANES]

ELEMENT	PRICE, 1972 DOLLARS
DEVELOPMENT	52 000
TOOLING	11 000
MANUFACTURING	480 000
INSTALLATION	3 000
SUBTOTAL (PER AIRPLANE KIT)	546 000
SPARES	109 000
TOTAL (PER AIRPLANE)	655 000

TABLE II

ASSUMPTIONS USED IN DOC CALCULATIONS

[DC-8-55]

PRICE OF RETROFIT LESS SPARES, 1972 DOLLARS	546 000
SPARES FACTOR, PERCENT	
AIRFRAME	10
ENGINES	40
RETROFIT-KIT	20
DEPRECIATION PERIOD, YEARS	
AIRFRAME	12
NACELLE MODIFICATIONS	5
UTILIZATION, HOURS/YEAR	3 800
SEATS	135
DOWNTIME, HOURS	0
NACELLE MAINTENANCE INCREMENT	TASK ANALYSIS

TABLE III

DIRECT OPERATING COST CHANGES

[DC-8-55; DOMESTIC RULES; 850 n. mi. RANGE]

ELEMENT	DOC, PERCENT
CREW	0.0
INSURANCE	+0.3
FUEL	-0.5
MAINTENANCE	+0.1
DEPRECIATION	+4.3
NET CHANGE	+4.2

TABLE IV

ASSUMPTIONS USED IN ECONOMIC ANALYSIS

ITEM	ASSUMED VALUE
REVENUE	UNCHANGED
SERVICE	PASSENGER
LOAD FACTOR, PERCENT	50
INDIRECT OPERATING COST, PERCENT OF REVENUE	42
FINANCIAL TREATMENT OF RETROFIT COST	INVESTMENT
CORPORATE TAX RATE, PERCENT	48
INVESTMENT TAX CREDIT, PERCENT	0

TABLE V

PROFIT AND LOSS
[DC-8-55; DOMESTIC RULES; 850 n. mi. RANGE]

	ANNUAL CHANGES PER AIRPLANE
OPERATING REVENUE	NONE
OPERATING EXPENSES LESS DEPRECIATION	NONE
DEPRECIATION	$ +131 000
PROFIT BEFORE TAXES	-131 000
INCOME TAXES	-63 000
PROFIT AFTER TAXES	-68 000
CASH FLOW	+63 000

TABLE VI

RETURN ON AIRPLANE INVESTMENT
[DC-8-55; DOMESTIC RULES; 850 n. mi. RANGE]

	EXISTING	TREATED	CHANGE
INVESTMENT	$3 590 000	$4 245 000	$655 000
RETURN ON AIRPLANE INVESTMENT	18 PERCENT	12 PERCENT	-6 PERCENTAGE POINTS

TABLE VII

ESTIMATED FLEET COMPOSITION
[SHORT-DUCT DC-8 AIRPLANES, JAN. 1, 1972]

DC-8 MODEL	QUANTITY
51	34
52	27
53	27
54	28
55	33
61	101
TOTAL	250

TABLE VIII

FIVE-YEAR IMPACT ON OPERATIONS OF TOTAL FLEET RETROFIT
[250 AIRPLANES]

CRITERIA	CHANGE
PROFIT AFTER TAXES, PERCENT	-10.1
INVESTMENT, PERCENT	+18.5
DISCOUNTED CASH FLOW RATE OF RETURN ON AIRPLANE INVESTMENT OVER THE 5-YEAR PERIOD, PERCENTAGE POINTS	-8.2

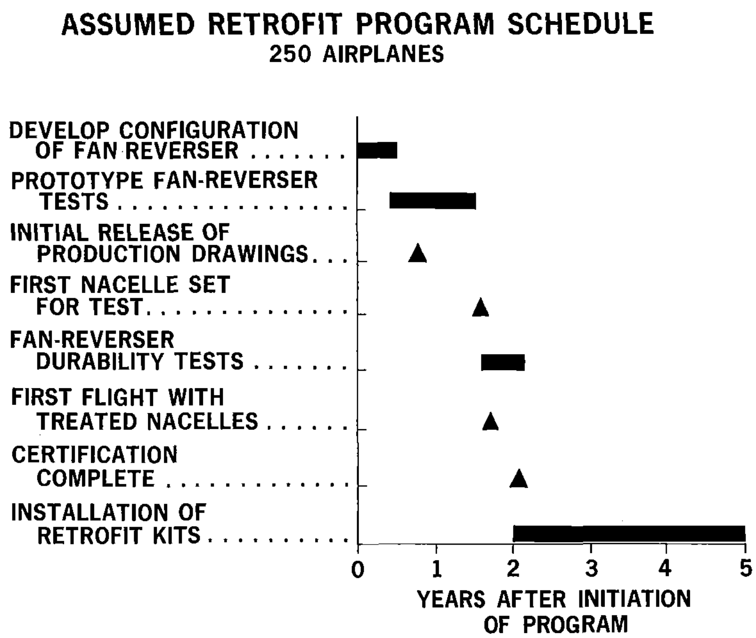


Figure 1

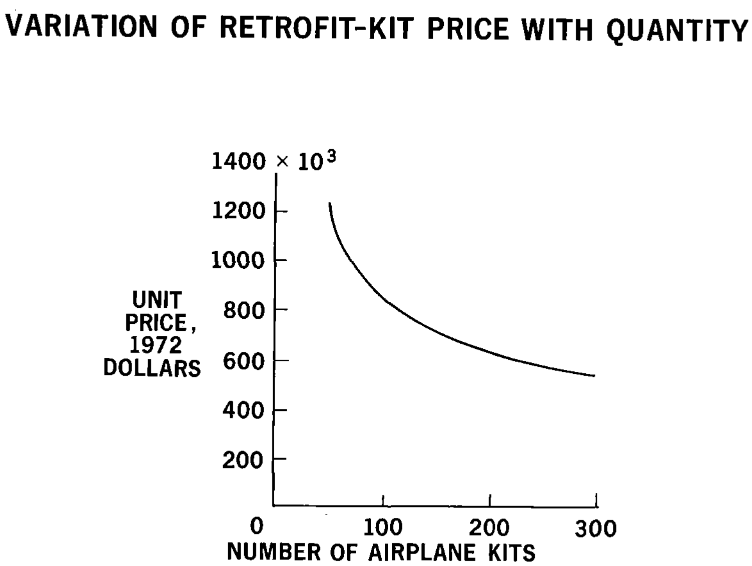


Figure 2

DIRECT OPERATING COST
DC-8-55; DOMESTIC RULES

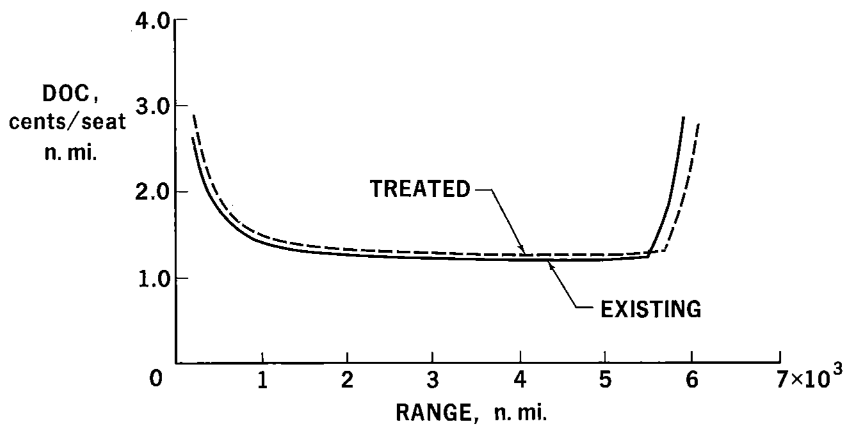


Figure 3

7. INTRODUCTION TO THE BOEING PROGRAM

By Robert H. Sawhill

The Boeing Company

INTRODUCTION

The Boeing Company, under NASA Contract NAS 1-7129, has developed and tested an acoustically treated engine-nacelle concept on the JT3D low-bypass turbofan engine. This treated nacelle was designed to reduce the fan noise components of the turbofan-engine noise. The primary goal of the program was a reduction of perceived noise level of 15 PNdB during landing approach. The basic approach applied in the development of the treated nacelle was the absorption of the fan-generated engine noise by acoustic lining material. A program of analysis, model test, full-scale ground test, and subsequent full-scale flight test on a 707-320B airplane was followed in the development and testing of this nacelle. The acoustic and performance results obtained during testing of the final flightworthy nacelle as well as an economic analysis are discussed in papers 8, 9, and 10. The purpose of this paper is to provide a background of the program studies leading to the final testing. This paper will describe the acoustic material used, the nacelle configuration selected, and the final airplane/nacelle installation.

ACOUSTIC MATERIAL SELECTION

The noise-suppression technique applied in this program was based on the principle of sound absorption in acoustically lined ducts. This approach proved feasible because of the nature of fan-generated noise in turbofan engines. First, the fan noise propagates through the inlet and duct passages before it radiates from the engine. Second, the fan noise consists of discrete high frequency components that are amenable to absorption with acoustical lining. The studies that were conducted to develop an acoustic lining technology for fan noise suppression and the material development part of this program were covered in detail at the NASA conference held in October, 1968. Those studies will not be detailed in this paper. However, one important result from those studies needs to be emphasized to provide a complete story on the acoustic material selection efforts. That is, the acoustic test results on porous surface materials indicated that similar acoustic performance could be obtained from a number of the materials examined, provided the materials were properly selected. Hence, final selection of the material for use as an acoustic duct lining was determined as much by structural qualities as by acoustic characteristics. To aid in this selection, sandwich panels were subjected to high sonic environment tests, aerodynamic flow property measurements, environmental tests, and weight analysis. Ease of fabrication analysis and maintainability evaluation were carried out as well. The latter evaluation included such items as durability, ease of cleaning, susceptibility to damage from foreign objects entering the inlet cowl, and repair.

The final acoustic material selected by Boeing for application to the JT3D engine was a polyimide fiberglass sandwich consisting of a polyimide-porous fiberglass laminate face sheet, a honeycomb core, and a nonporous laminate backing sheet. (See fig. 1.) This material was developed by Boeing for application as acoustic lining. The porous fiberglass laminate consists of several layers of fibercloth arranged to provide proper acoustic porosity, strength, and minimum surface roughness. The honeycomb core consists of nonporous fiberglass cloth joined to the porous and nonporous laminates with polyimide adhesive. Cell depth of the honeycomb was determined primarily by acoustic considerations. In applying this material to the nacelle, single layer linings were selected for all walls. Attenuation over the required frequency range was achieved by varying the honeycomb cell depth.

Following material selection, further evaluation tests were conducted. Additional sonic environment tests were run with panels subjected to noise levels as high as 160 dB for 25 hours. No fatigue failure or degradation of material properties was evident during these tests. The panels were also subjected to cyclic tests simulating environmental conditions encountered in normal flight. Test parameters included temperature and pressure, moisture, airflow, and noise. There was no measurable change in weight or material properties. In addition, sandwich panels were subjected to water and then frozen. As anticipated, the bond between the porous laminate and the core was broken. However, in order to achieve a panel failure, the core had to be completely filled with water. Moreover, the only way the sandwich could be completely filled was by complete submersion of the specimen in a vacuum chamber.

Although all the items described above were studied in sufficient detail to ensure a successful ground-test and flight-test program, the studies were not extended to develop an acoustic liner for in-service operation. Considerable work is still required in many areas to provide a material and liner for this use. However, acoustic panel service testing is proceeding at Boeing with various material types. To date, polyimide fiberglass panels, a sample of which is shown in figure 2, have been subjected to over 200 hours of operation in the fan duct of JT8D turbofan engines which have been used in both ground and flight operations. Some small bond separations have occurred in the bond line between the acoustic skin and the potted core. Contamination has been very slight. These same panels have experienced no change in acoustic performance.

NACELLE CONFIGURATION SELECTION

After the material was selected, methods of applying the material to the JT3D engine were studied. The existing engine and nacelle are shown in figure 3. Examination of the existing Boeing nacelle on a JT3D engine indicated that substantial changes would be required to achieve the program noise suppression goal. This nacelle has a relatively short inlet with blow-in doors and a very short fan duct that provides little area for acoustic linings. Modifications to this nacelle for noise reduction were investigated. The final treated nacelle configuration selected following a number of conceptual studies is shown in figure 4.

Inlet modifications include a 10-inch extension from inlet lip to compressor face, removal of the blow-in-doors, and acoustic treatment on the inner cowl wall and long inlet centerbody. Two treated concentric rings have been added. These rings are treated on both sides and equally spaced between inlet surfaces. Insertion of the rings divided the inlet into a series of channels or ducts, thus allowing for more effective use of acoustic linings. Unlined ring support struts are located at eight radial positions in the inlet. The treatment lengths in the rings, cowl, and centerbody were selected to provide a uniform noise field across the inlet. The total area treated in the inlet was 71 square feet. This configuration resulted from conceptual studies that included acoustic as well as performance analysis. Of the various designs studied, the concentric ring design provided the best engine performance characteristics for a given noise attenuation.

Fan duct modifications included a full-long extension to the existing nacelle fan ducts. That is, the fan duct was extended to become essentially coplanar with the primary exhaust duct. The acoustically treated areas are located in two separate parts of the duct. The forward section has double-wall lining plus four lined splitters in each duct half. The aft section has outer wall lining only, plus four treated splitters. The duct contour progresses from an elongated kidney design in the forward section to a full annular configuration at the tailpipe. (See fig. 4.) This design provides for minimum duct height, which aids in sound absorption and provides for maximum area for acoustic treatment. Total area treated was 267 square feet. A section of duct between the two acoustically treated sections has been left untreated. This area represents the possible location of a new secondary thrust reverser, made necessary by the redesign of the forward section of the fan duct. The primary jet-thrust reverser is located in the same area as on the existing nacelle. It has been assumed that, by making the double wall nozzle section translatable as is done with the existing single wall nacelle, the primary reverser would require a minimum of rework to remain compatible with the treated nacelle.

The duct design was evaluated for both aerodynamic and acoustic performance. The two-ring inlet and full-long duct provided proper balance of noise suppression for inlet and fan-duct noise. An additional advantage of long ducts uncovered during preliminary testing was that the jet noise was redirected to provide noise reduction at landing-approach power. Ground-test results obtained on a boilerplate nacelle indicated that the acoustical treatment in the nozzle section did not reduce the noise levels below the levels obtained with the treatment in the forward section only. Nevertheless, a decision was made to treat this area on the flightworthy nacelle in the event that the suppression afforded by the completely treated nacelle as measured in flight might be less than that measured on the ground. The additional nozzle treatment also provided a cushion in case contamination of the treatment might result in loss of acoustic efficiency. Since neither of these events occurred, it is believed that this treatment could be removed without affecting the overall noise reductions afforded by the treated nacelle.

AIRPLANE/NACELLE CONFIGURATION

The nacelle described herein was subjected to both a ground-test and flight-test program. The flight-test portion of the program was conducted on a Boeing 707-320B airplane powered by JT3D turbofan engines. The nacelle installation is shown in figures 5 and 6. An anti-icing system was included for all surfaces in the inlet to aid in evaluating the viability of the treated configuration. This system was ground tested and met all the basic requirements. In addition, positive water drainage was provided from each acoustic panel by circumferential grooves in the core surface. All treatment material in both the inlet and fan duct was frame-mounted and of load-carrying construction. No major strut modifications were required. The treated nacelle did not incorporate thrust reversers. However, as stated previously, space was allotted for their inclusion. No problems were encountered with the nacelle or the acoustic material during the 40 hours of flight testing.

The estimated nacelle weight change required for a potential retrofit version of the treated nacelle, including thrust reversers, is shown in figure 7. Weight increase of the nacelle, including thrust reversers, is estimated to be 3140 pounds per airplane. Although the two-ring inlet and the full-long, full-annular duct provided a flightworthy test nacelle for the JT3D engine installed on the 707-320B airplane, it is not necessarily an optimum retrofit design, nor does it represent a standard design for all turbofan engines. Each engine/airframe type has unique acoustic, installation, and performance problems that must be considered in design of an acoustically treated nacelle for in-service operation. Examination of the 720B and 707-120B airplanes, for instance, revealed that installation of the treated nacelle described herein would require that the outboard nacelle be relocated approximately 15 inches aft and extended downward approximately 4 inches to prevent flutter problems. A new strut would therefore be required.

The acoustic lining technology developed in this program is applicable not only to the JT3D engines, but other turboflow engines as well. However, the noise suppression achieved through application of the acoustic lining technology will be a function of the noise-generating characteristics of the engine and the duct geometry. These will both change significantly with change in engine bypass ratio and/or fan design.

The subject airplane-engine configuration was tested during conditions of static ground operations, ground roll, take-off, climbout, cruise, and landing approach. The evaluation of acoustics, performance, and economics obtained from these tests is presented in papers 8, 9, and 10.

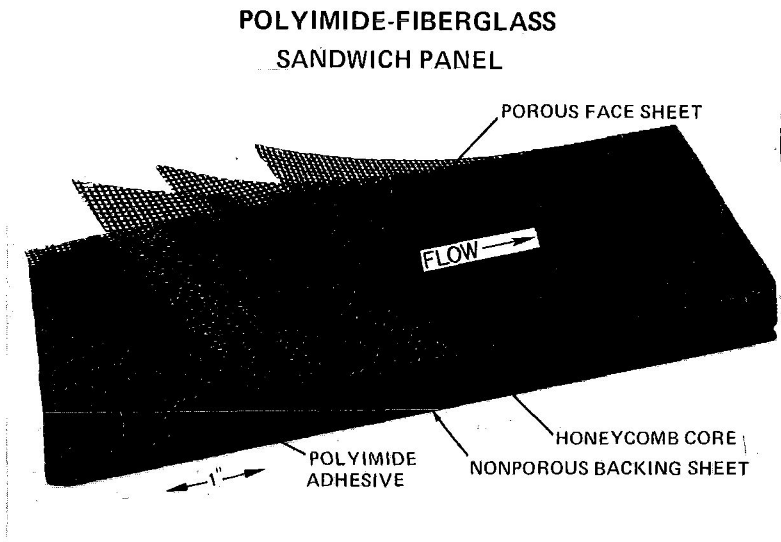


Figure 1.- Acoustic lining for JT3D inlet and fan duct.

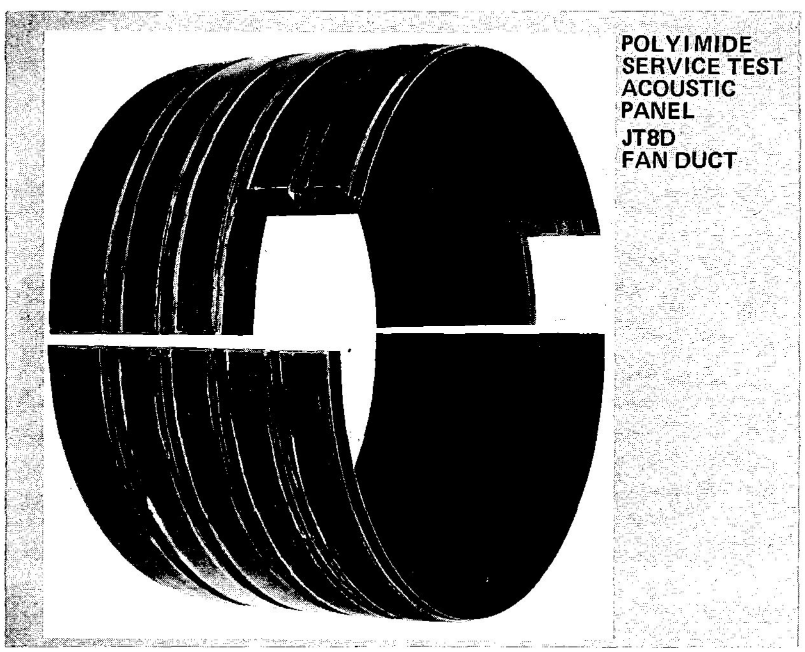


Figure 2.- Environmental test panel for acoustic lining evaluation studies.

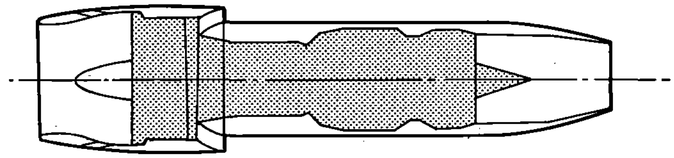


Figure 3.- Existing Boeing nacelle for JT3D engine.

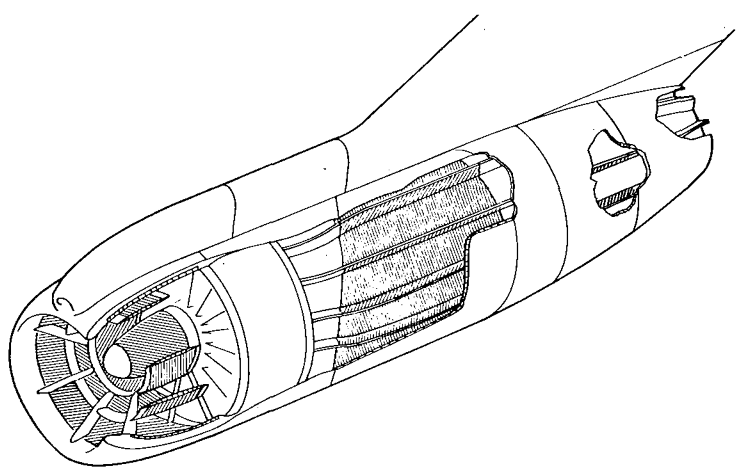


Figure 4.- Boeing JT3D treated nacelle concept.

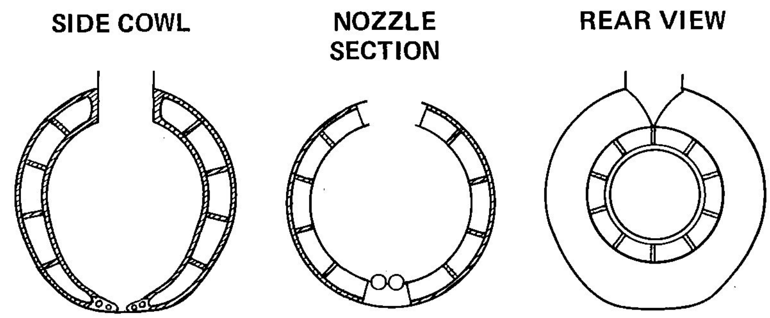


Figure 5.- Treated nacelle duct design.

Figure 6.- JT3D engine/nacelle installation.

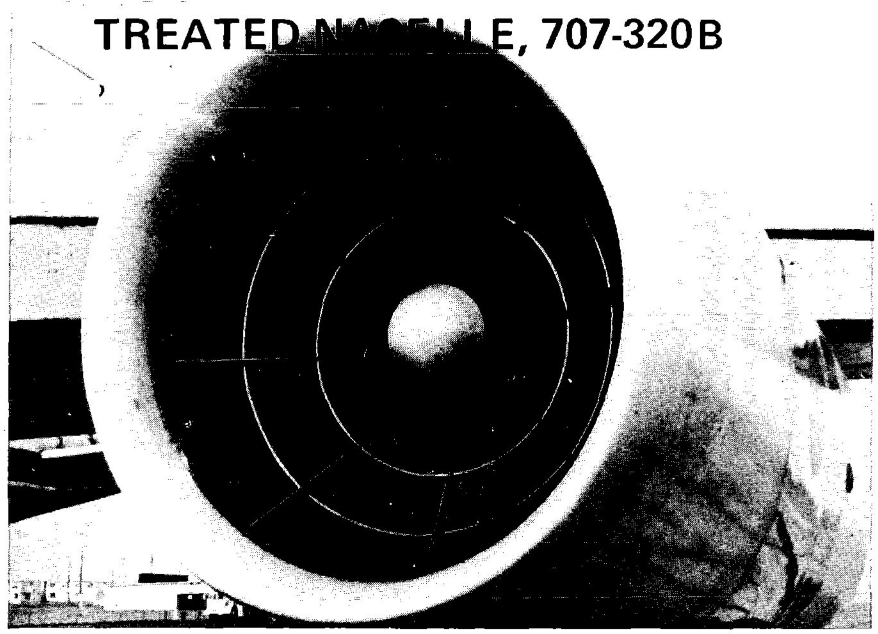


Figure 7.- Acoustically treated JT3D inlet installation.

NACELLE WEIGHT
FOUR NACELLES MINUS ENGINES

EXISTING	7768 lb
REMOVED	3888 lb
ADDED	7028 lb
TREATED	10,908 lb
Δ WEIGHT	3140 lb

Figure 8.- Nacelle weight changes required to provide JT3D acoustically treated nacelle.

8. PERFORMANCE OF THE 707-320B AIRPLANE WITH ACOUSTICALLY TREATED NACELLES

By Ralph B. McCormick

The Boeing Company

SUMMARY

The major performance effect of the Boeing designed acoustically treated nacelle on a Boeing 707-320B airplane powered by Pratt and Whitney JT3D-7 engines is a reduction in capacity-payload range of approximately 200 n. mi. The reduction is primarily due to the 3140-pound loss of available fuel displaced by the increased operating empty weight of the airplane. Details of airplane performance changes along with a description of the flight test program used to obtain the performance effects are included.

INTRODUCTION

The development of the Boeing treated nacelles and the acoustic results are presented by Sawhill (paper 7 herein) and Atvars, Mangiarotty, and Walker (paper 9 herein). The purpose of this paper is to present the effects of the nacelle modification on the performance of a Boeing 707-320B airplane powered by Pratt and Whitney JT3D-7 engines. The nacelle configuration changes and the relation of the changes to airplane performance are described. The flight test program used to evaluate acoustic results and airplane performance is outlined. Performance effects are evaluated by comparing measured take-off distances, cruise performance, and effect on payload range of an airplane with the modified nacelles to an airplane with the existing nacelles.

CONFIGURATIONS

Figure 1 shows the existing nacelle used on current 707 airplanes. The nacelle was developed to provide low weight and minimum cruise drag. The relatively short inlet has an 18-percent contraction from the highlight area to the throat area. The small contraction was selected for low cruise drag and requires the use of blow-in doors to provide the high-pressure recovery at the compressor face required for maximum thrust at take-off conditions. The short fan exhaust duct has small internal losses and allows the aft nacelle cowl to be very tightly fitted to the engine. Location of the nacelle forward of the wing, combined with the small cross-sectional area of the nacelle, results in minimum wing-nacelle interference drag. The forward location of the fan exhaust nozzle results in some thrust and specific fuel-consumption penalties as a result of the scrubbing drag caused by the relatively high-velocity fan exhaust air blowing over the aft nacelle cowl.

It was necessary to alter substantially the existing nacelle design to accommodate the amount of acoustic material required to obtain the desired noise attenuation. The treated-nacelle configuration is shown in figure 2. The addition of 71 sq ft of acoustic treatment in the inlet and 267 sq ft of treatment in the fan exhaust duct requires an increase in the size and weight of the nacelle. These changes make it difficult not to incur a significant loss in airplane performance with the treated nacelles installed. The acoustic treatment in the inlet is located in the cowl wall, in two concentric rings, and in the centerbody. The inlet length was increased from 36 to 45 inches to accommodate the acoustic treatment with a minimum effect on inlet-pressure recovery. A large contraction ratio of 1.25 was used to simplify the design and provide adequate take-off performance without the use of blow-in doors. These changes contributed to some deterioration in inlet performance. A full-length fan duct with an annular nozzle was selected to provide adequate treatment surface. The relatively large flow area through the duct, designed to provide a low velocity over the acoustic lining and reduce internal losses, increased the diameter of the aft nacelle. The larger nacelle results in increased wing-interference drag. These losses are partly compensated for by the reduction in scrubbing drag with the long-duct configuration.

FLIGHT TEST PROGRAM

The performance of the treated nacelles was evaluated from measurements made during a flight test program. Tests were made to compare airplane performance with the existing nacelles to the performance of the same airplane equipped with the treated nacelles. Figure 3 shows the test airplane with the treated nacelles installed. The airplane was basically a Boeing 707-320B, a long-range, heavyweight version of the 707 series. Pratt and Whitney JT3D-7 calibrated engines were used. The airplane contained several minor modifications, including wing-tip changes and radar antennas on the upper aft portion of the fuselage that were used for other tests. These changes had a small effect on the overall airplane performance; however, since the configuration was the same for both sets of nacelles, there was no measurable effect on the incremental performance between the existing and the treated nacelles. The calibrated airplane contained instrumentation to measure both airplane performance and engine characteristics. When the treated nacelles were installed, instrumentation was included to evaluate the internal flow in one of the nacelles.

Prior to the performance flight tests of the treated nacelles, tests were conducted to insure the flight safety of the modified airplane. In-flight checks of flutter characteristics, compressor surge, nacelle and oil cooling performance, and engine operation were made. The possibility of compressor surge was investigated during conditions of maximum sideslip, power-on and power-off stalls, engine acceleration, and during an overrotation at take-off conditions. Ground tests with simulated crosswinds up to 15 knots at 90° to the inlet were also conducted. During the safety checks and during the entire flight test program, no adverse effects were observed, and no deviations from the normal flight operating procedures were required.

The flight test program included a ground run-up and a series of flight tests at take-off, climb, approach, fly-by, and cruise conditions. Ground tests were made at power settings up to maximum take-off thrust to obtain acoustic and engine performance data. Take-offs were made at airplane gross weights of approximately 330 000 pounds and 260 000 pounds. Maximum power settings were used, and climb-out was made at velocities equivalent to $V_2 + 10$ knots where V_2 is the minimum climb speed. Runway distances and airplane altitude were measured with airplane-mounted theodolite cameras. Acoustic data, recorded by using the acoustic test range, were also obtained for tests in which the take-off power was cut back to the power required to maintain a 6-percent climb gradient when the aircraft reached an altitude of 700 feet. Approach conditions were run by using a 3° glide slope and by maintaining constant thrust settings of 4900 or 6800 pounds. Noise data for fly-by conditions were obtained for thrust settings corresponding to approach, maximum take-off, and cutback power. The airplane was flown at an altitude of 400 feet at approximately 160 knots for all fly-by conditions. Details and results of the acoustic tests are presented by Atvars, Mangiarotty, and Walker (paper 9 herein).

Airplane cruise drag tests were conducted at constant values of airplane weight divided by the ambient-pressure ratio (W/δ). Tests for values of W/δ equal to 0.8×10^6, 1.0×10^6, and 1.2×10^6 were made at Mach numbers from 0.65 to 0.88. The values of W/δ selected are representative of normal long-range cruise conditions. The largest value corresponds to the optimum high-altitude conditions. Propulsion cruise performance tests to obtain engine performance characteristics were made at an altitude of 35 000 feet at Mach numbers of 0.7 and 0.8. The engine power setting was varied on two engines while the other two engines were used to maintain test conditions.

PERFORMANCE EFFECTS

The measured ground distance required for the airplane to reach an altitude of 35 feet is shown in figure 4 as a function of airplane gross weight. The treated-nacelle configuration required about 2.6 percent more distance for 260 000 pounds gross weight and 1.6 percent for 330 000 pounds. The data were corrected to zero-wind, standard-day conditions at sea level. The measurements are consistent with test-stand data which indicated the static take-off thrust of the treated nacelle would be about 0.25 percent less than that of the existing nacelle. During take-off, as the airplane velocity increases, the relative inlet performance of the treated nacelle decreases, and at about 100 knots forward velocity, approximately 1.5 percent less thrust is produced by the treated nacelle. The combined effects of a slightly longer take-off distance and a reduced climb gradient lead to a loss of height during climb-out. Figure 5 indicates that at a point 3.5 n. mi. from brake release, the height loss was 90 feet at 260 000 pounds gross weight and 125 feet at 330 000 pounds. The values shown were obtained from measurements made with an airplane equipped with JT3D-7 engines. If JT3D-3B engines had been used, the height loss for 330 000 pounds gross weight would have been about 90 feet.

The thrust specific fuel consumption (designated TSFC in the figure) measured during the propulsion cruise tests is plotted against net thrust (F_N/δ) in figure 6 for Mach numbers (designated M in figures) of 0.7 and 0.8. When the propulsion performance of the two nacelles is compared, the scrubbing drag associated with the existing nacelles was considered as a loss in thrust because the scrubbing drag is closely related to the fan-duct performance. Figure 6 indicates that at cruise conditions the reduction in scrubbing drag has compensated for the increased inlet and fan-duct losses and results in a 2-percent improvement in specific fuel consumption at the lower thrust settings. At the higher thrusts, the inlet losses for the treated nacelle increase and the specific fuel consumption increases to values similar to those of the existing nacelles. The airplane drag coefficients based on calculated thrust values are illustrated in figure 7 for various Mach numbers and two values of W/δ. As expected, the drag of the larger treated nacelle is greater. The increase at a Mach number of 0.8 is about 1.5 percent for a value of W/δ equal to 1.2×10^6 and 3.4 percent for a value of W/δ equal to 0.8×10^6.

The changes in specific fuel consumption and airplane drag combine to give the normalized specific range shown in figure 8. The treated-nacelle configuration shows an increase in specific range at low Mach numbers, but at normal cruise speeds a reduction is indicated. The loss is about 0.7 percent at a Mach number of 0.8 and 2.1 percent at a Mach number of 0.83 for the representative values of W/δ.

The effects of the modified nacelle on the payload-range characteristics of the airplane are defined in figure 9. A potential retrofit version of the treated nacelles, including thrust reversers, is estimated to increase the operating empty weight of the airplane by 3140 pounds. The resulting displacement of available fuel contributes the major part of the loss of 200 n. mi. in capacity-payload range. About 25 percent of the range loss is caused by the change in specific range. The curve shown is for international fuel reserves and long-range cruise techniques. The increased operating empty weight has not affected the maximum permissible payload because the distribution of the extra weight of the treated nacelles across the wing span allows a corresponding increase in maximum zero-fuel weight. The long-range cruise technique is associated with cruise at a Mach number of 0.8. If a minimum-cost cruise technique is used, where the cruise Mach number is about 0.83, the reduced specific range at this Mach number increases the loss of capacity-payload range to 225 n. mi. If domestic fuel reserves are considered, the range loss is increased an additional 25 n. mi.

CONCLUSIONS

The changes in measured performance obtained with the Boeing designed, acoustically treated nacelles installed on a Boeing 707-320B airplane are summarized as follows:

1. The major performance effect of the treated nacelle is that the capacity-payload range is reduced approximately 200 n. mi. The reduction is primarily due to the 3140-pound loss of available fuel displaced by the increased operating empty weight of the airplane.

2. During take-off the height at a distance of 3.5 n. mi. from brake release is reduced 125 feet for an airplane of 330 000 pounds gross weight.

3. At cruise conditions, the specific range is reduced by 0.7 to 2.1 percent.

4. No change is required in flight operating procedures with the modified airplane.

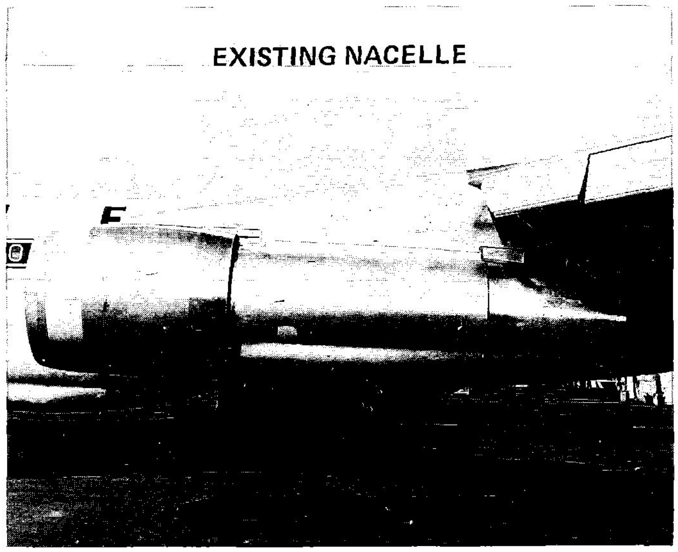


Figure 1

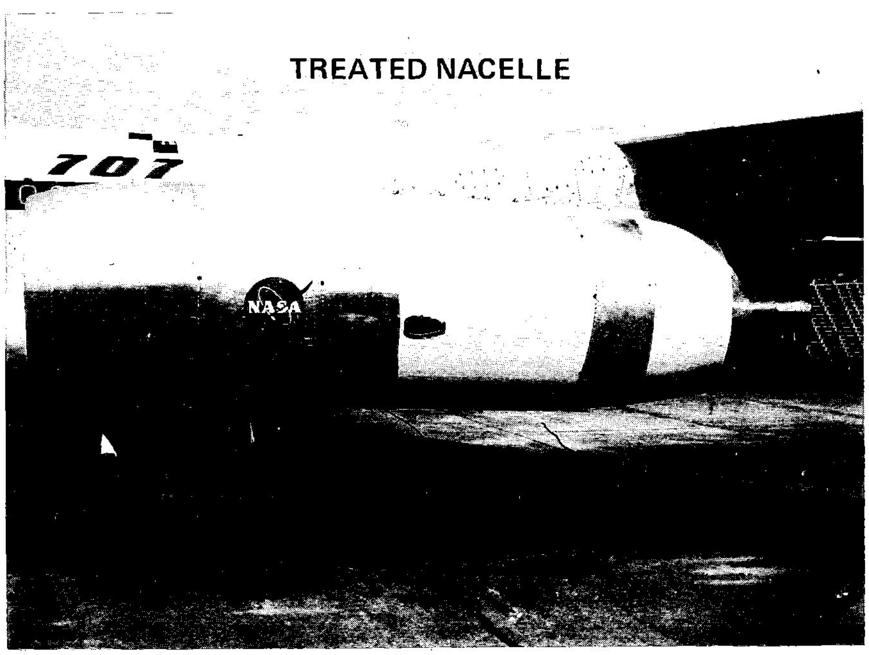


Figure 2

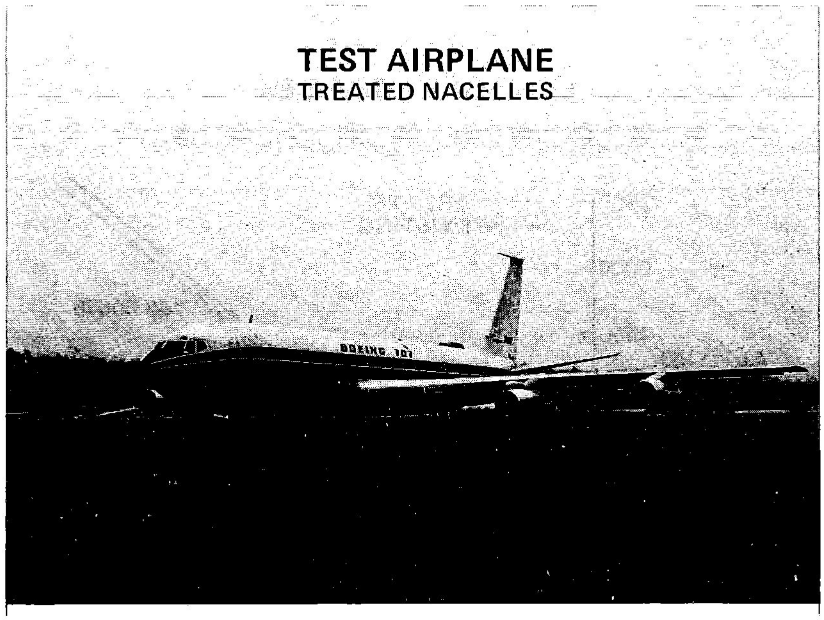
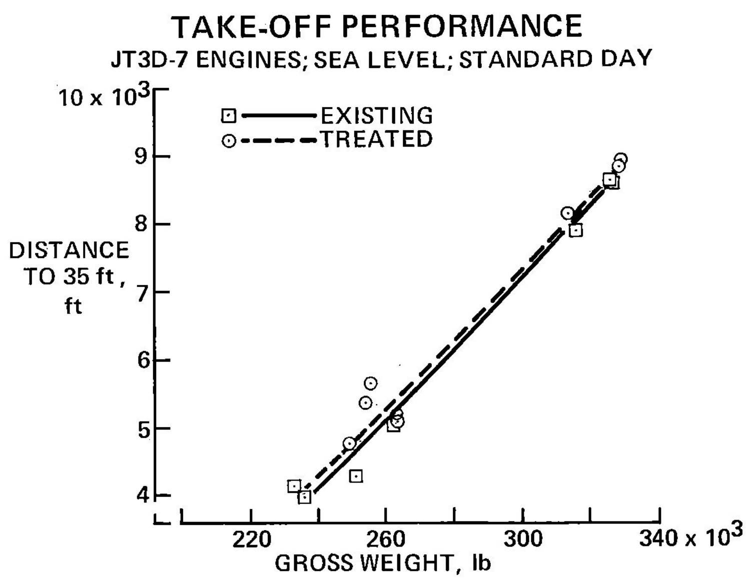


Figure 3



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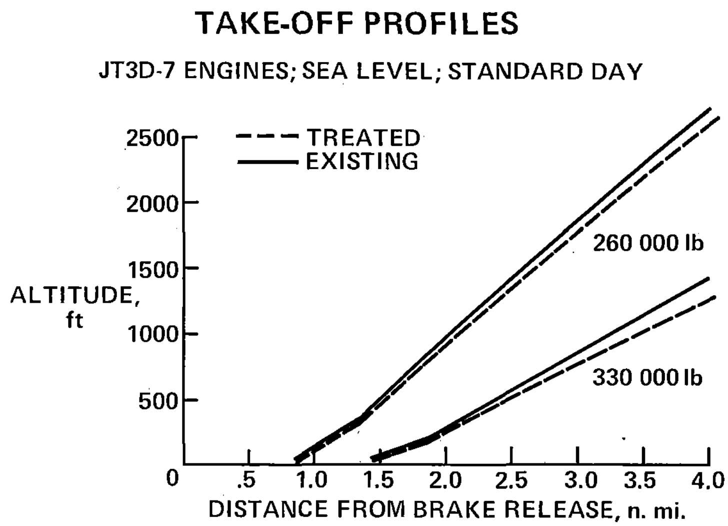

Figure 5

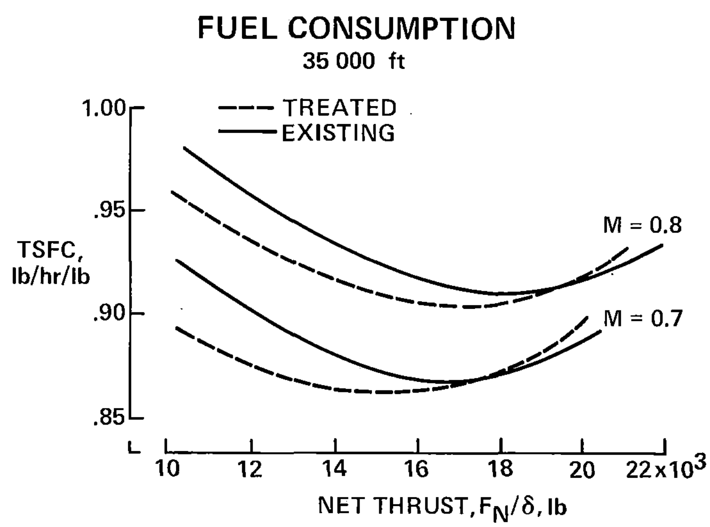

Figure 6

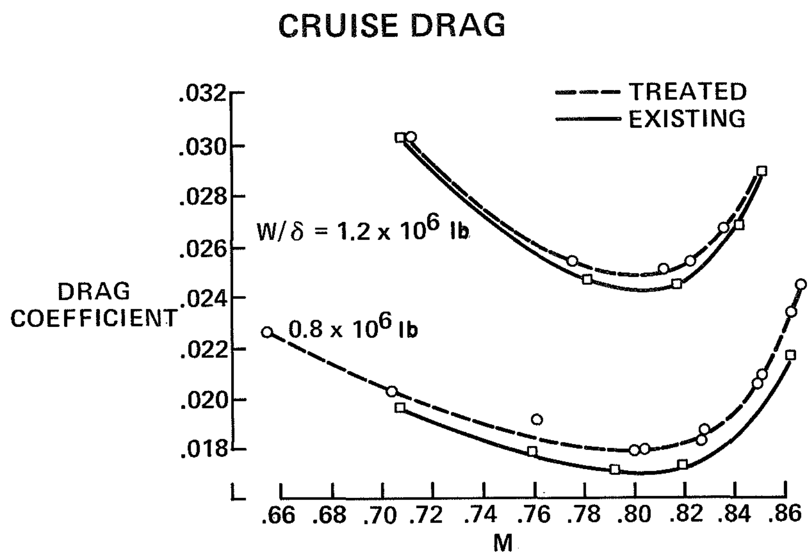

Figure 7

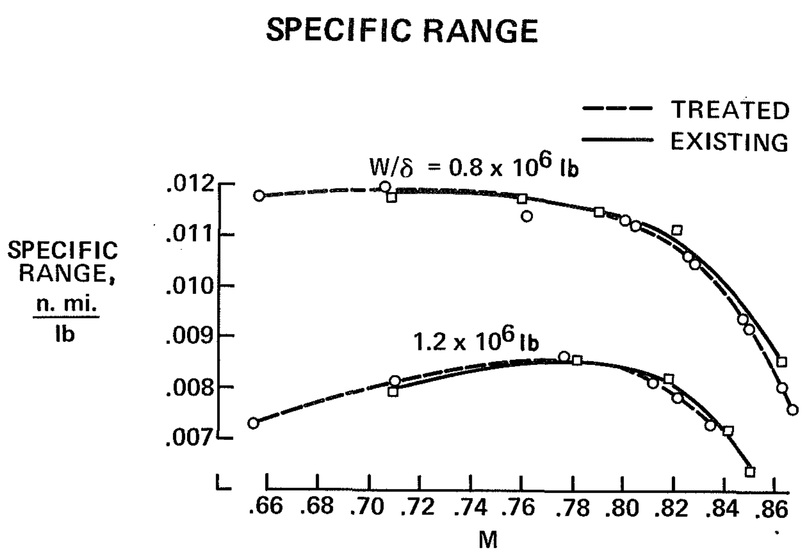

Figure 8

PAYLOAD RANGE

LONG-RANGE CRUISE ; ATA INTERNATIONAL RESERVES

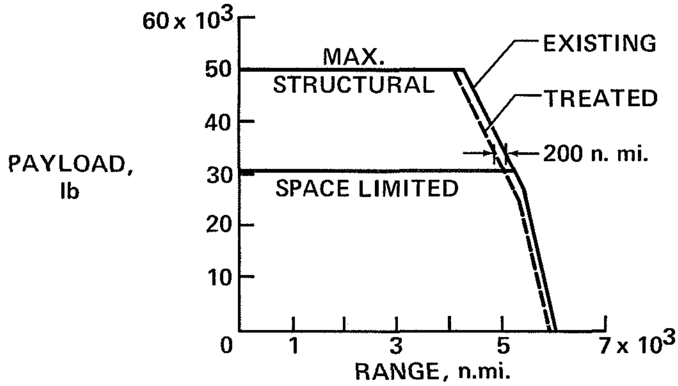

Figure 9

9. ACOUSTIC RESULTS OF 707-320B AIRPLANES WITH ACOUSTICALLY TREATED NACELLES

By Janis Atvars, R. A. Mangiarotty,
and David Q. Walker

The Boeing Company

SUMMARY

This paper summarizes the acoustic results from the test program carried out on the acoustically treated nacelles developed by The Boeing Company under Contract NAS 1-7129. The test airplane was a Boeing 707-320B powered by JT3D-7 engines. The effective perceived noise level reductions achieved, as demonstrated by the flight tests, were 15.5 EPNdB on landing approach, 3 EPNdB during take-off, 5.5 EPNdB during take-off with power cutback, and 3.5 EPNdB in sideline noise.

INTRODUCTION

Presentations at the NASA technical conference in October 1968 (ref. 1) summarized the development of acoustic lining technology applicable to engine nacelle treatment for reducing fan generated noise. This technology has been applied to treat four JT3D-7 engine nacelles. These four flightworthy nacelles were first tested on an engine test stand to ensure that adequate noise reduction was achieved, and then were evaluated by flight testing.

Static ground test results were evaluated in terms of the perceived noise level (PNL) scale. All flight test results were evaluated in terms of effective perceived noise level (EPNL) to account for time and tone correction factors. The principal results of the acoustic tests are presented in this paper.

ABBREVIATIONS

PNL	perceived noise level
PNLM	maximum perceived noise level
PNdB	unit of PNL
EPNL	effective perceived noise level
EPNdB	unit of EPNL
SPL	sound pressure level, dB re 2×10^{-4} microbar

9

TEST ENGINE CONFIGURATIONS

The two nacelles tested on the basic JT3D-7 engine are shown in figure 1. The existing short duct JT3D-7 nacelle was used as the untreated base line. The acoustically treated test nacelle has an extended inlet incorporating lining materials in the outside wall, two concentric rings, and the centerbody. The fan exhaust duct of the treated nacelle is extended to be almost coplanar with the primary nozzle and is acoustically lined in the areas shown.

ACOUSTIC TEST PROGRAM

The acoustic test program consisted of both ground tests and flight tests. During ground testing, noise measurements were made for the existing and treated nacelles to determine the effectiveness of the acoustic treatment. The flyover noise levels of the airplanes with the existing and treated nacelles were estimated from these test-stand results prior to the flight tests.

During flight testing, noise measurements were made under the airplane flight path during landing approach, take-off, take-off with power cutback, and 400-foot-altitude level flyovers at various power settings. Noise levels were also recorded 1500 feet to the side of the flight path during take-offs.

ACOUSTIC GROUND TEST RANGE

The acoustic ground test range is shown schematically in figure 2. Noise measurements were made in the acoustic far field by two microphone arrays centered on the engine test stand. Measurements in the vertical plane were taken primarily to evaluate the ground effects on noise recordings in the horizontal plane, which contained the principal microphone array. The microphone angular positions were measured relative to the engine inlet center line.

Ground tests with the treated flight nacelles were conducted for two main reasons: (1) to determine if the noise suppression was as predicted from earlier boilerplate tests, as a prior step to flight testing, and (2) to establish the similarity of noise reduction characteristics between the four flight nacelles.

GROUND TEST RESULTS

Noise spectra measured in the test stand 110° from the inlet axis are shown in figure 3. The variation in SPL for the four treated nacelles, as shown by the shaded area, is approximately 4 decibels, except in the 500-hertz band because of ground reflection effects. Comparison of the treated nacelles with the previously tested boilerplate and existing nacelles indicated that adequate fan noise reduction has been achieved to meet the program goal.

Prior to conducting the flight test of the treated nacelles, flyover noise levels were estimated from ground test results by using the procedure summarized in figure 4. This method converts ground test data measured at a constant radius on a polar array of microphones around an engine test stand to flyover noise at a required altitude; thus, it provides preliminary information for treated nacelle in-flight noise characteristics.

Test-stand data are corrected for ground reflection effects, temperature, and humidity to standard day conditions. (See ref. 2.) The polar measurements are extrapolated to linear conditions taking into account the inverse square law and atmospheric absorption. Perceived noise levels are calculated for the required altitude for each angular position measured on the ground. (See ref. 3.) By superimposing an airplane velocity on the results, PNL time histories and maximum PNL's are predicted.

The estimated maximum PNL's obtained from test-stand data using this method are shown in figure 5 for an altitude of 400 feet. The estimated noise reduction obtained by the treated-nacelle airplane at the landing approach power setting is shown to be 15 PNdB. Evaluation of these results with flight test data will be made after discussion of the actual flight test results.

ACOUSTIC FLIGHT TEST RANGE

Flight tests were conducted with a 707-320B experimental airplane using the existing nacelles, followed by tests with the acoustically treated nacelles. These tests were conducted over the acoustic test range shown schematically in figure 6. The test range consisted of 20 microphone stations located as shown to measure noise under the airplane flight path during landings and take-offs, and sideline noise 1500 feet from the center line. The position of the test airplane was monitored continuously by means of a radar tracking station. Weather conditions were monitored on the ground as well as up to flight altitudes by using weather balloons and an instrumented light aircraft at regular intervals during the test period.

Acoustic tests were conducted within the following weather restrictions to minimize effects on the noise measurements:

(a) No rain or other precipitation

(b) Relative humidity between 30 and 90 percent

(c) Wind below 10 kn at 10 m above ground

(d) Ambient temperature below ISA + 15° C

The acoustic results presented herein have been analyzed and corrected to standard weather conditions, chosen for this contract to be 70 percent relative humidity and 59° F.

FLIGHT TEST RESULTS

All the test results for a given flight condition and power setting were plotted versus airplane altitude and averaged by drawing a best-fit curve through all the data points as shown in figure 7. The data scatter shown is typical for all the landing approach and level flyover tests and is considered to be satisfactory for the purpose of obtaining reliable average noise levels.

LANDING APPROACH NOISE

The landing approach noise levels measured 1 nautical mile from threshold are shown in figure 8 for both existing and treated airplanes. The noise reduction achieved at this point was 15.5 EPNdB. The equivalent noise reduction on the PNL scale was 16 PNdB. The way this noise reduction has been achieved is shown in detail in figure 9. The difference in the maximum noise spectra between the two airplanes represents the noise reduction. Practically all of the noise reduction is due to the elimination of the fan whine at the higher frequencies. The small reduction shown at the jet noise frequencies is mainly due to the change in directivity of the treated nacelle jet noise because of the coplanar jet nozzles and contributes very little to the over-all EPNL reduction.

Reduction in landing approach noise in the vicinity of an airport is shown in the form of ground noise contours for treated nacelles in figure 10. The land area exposed to noise levels of 100 EPNdB or higher for the treated-nacelle airplane, as shown by the contours in this figure, is only 15 percent of that for the existing airplane.

TAKE-OFF NOISE

Although the primary effort in this program was directed toward reducing landing approach noise, it was found that the reduction of fan noise at take-off power settings reduced the total take-off noise by measurable amounts. The noise reduction achieved under the flight path, 3.5 nautical miles from brake release, was 3 EPNdB, as shown in figure 11. These results have taken into account a climb performance loss for the treated-nacelle airplane of 125 feet at the 3.5-nautical-mile point; this is equivalent to approximately 1 EPNdB loss in noise reduction. The equivalent ground noise contours are shown in figure 12 for a nominal 260 000-pound-gross-weight airplane having a typical range of 2500 nautical miles. The difference in gross weight of 3140 pounds between the airplanes with the treated and existing nacelles has negligible effect on the ground noise contours shown. It is estimated that the land area exposed to noise levels of 100 EPNdB or higher has been reduced by 55 percent for the treated-nacelle airplane.

Similarly, for take-offs with power cutback initiated just prior to the 3.5-nautical-mile point, it was found that the noise had been reduced by 5.5 EPNdB, as shown in figure 13. The corresponding ground noise contours for a 260 000-pound-gross-weight airplane (fig. 14) show that the land area exposed to noise levels of 100 EPNdB or higher has been reduced by approximately 50 percent for the treated-nacelle airplane.

The results of sideline noise measurements taken 1500 feet from the flight path are shown in figure 15. It was found that sideline noise during take-off was reduced by about 3.5 EPNdB for the airplane with treated nacelles and that the maximum sideline noise levels occurred when the airplanes were at a height of 1000 feet during climbout.

COMPARISON OF ESTIMATED FLIGHT TEST RESULTS

Finally, the flyover noise estimation method was evaluated by comparing the results with flight test data in figure 16. It was found that for this particular airplane configuration and for constant altitude flyovers, the noise levels could be estimated with reasonable accuracy from test-stand data taken during ground run-ups.

CONCLUSIONS

The results of the flight test program on the acoustically treated nacelle show that landing approach noise at the 1-nautical-mile point has been reduced by 15.5 EPNdB. On the equivalent PNL scale, the original contract target noise reduction of 15 PNdB was exceeded by 1 PNdB.

The treated nacelles also showed a noise reduction of 3 EPNdB during take-off and 5.5 EPNdB during take-off with power cutback.

It has been shown that for the engines and airplane configuration used in this contract, test-stand data properly taken and corrected provide reasonably accurate predictions of flyover noise.

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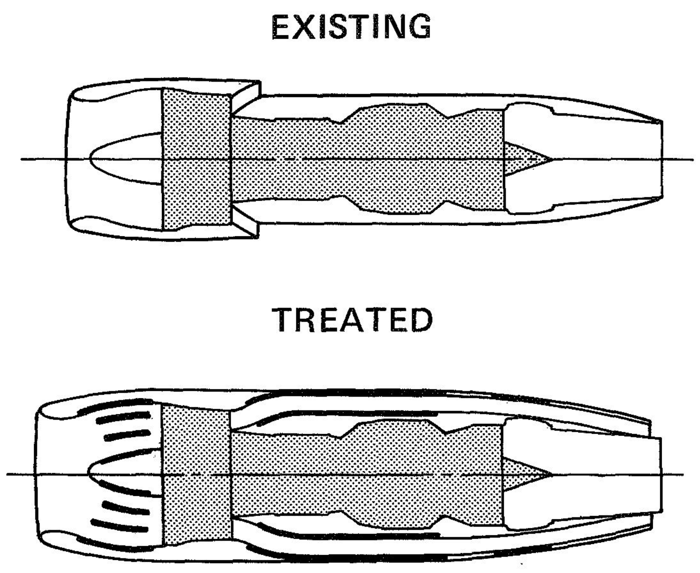

Figure 1

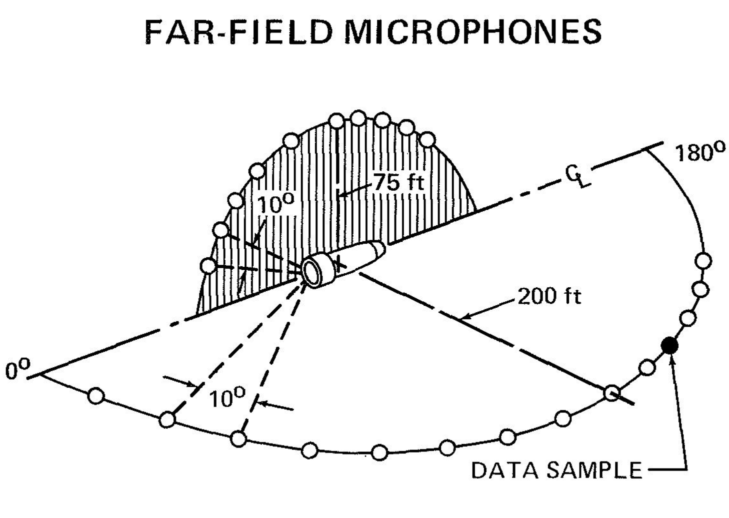

Figure 2

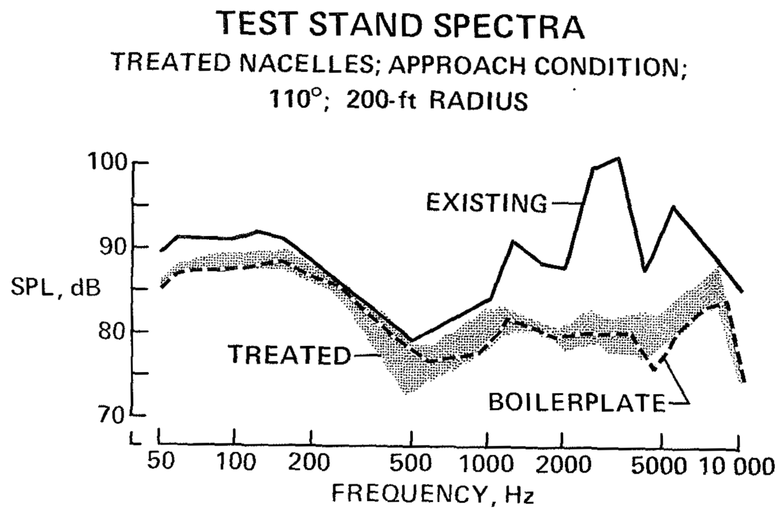

Figure 3

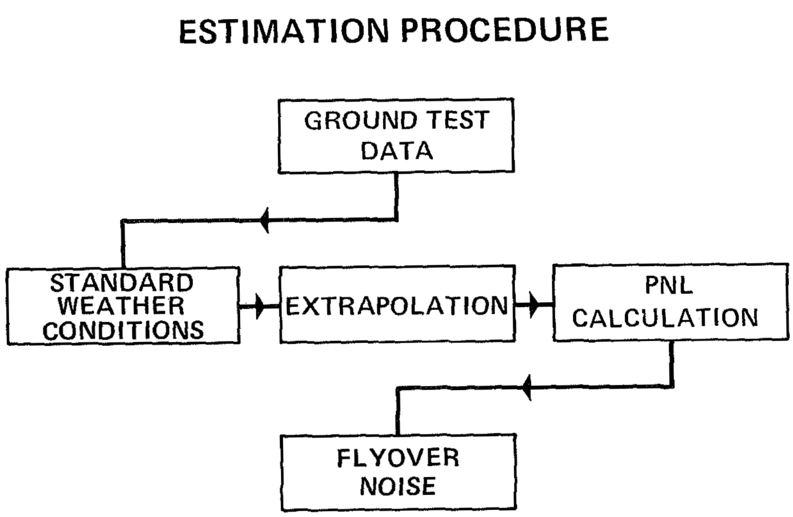

Figure 4

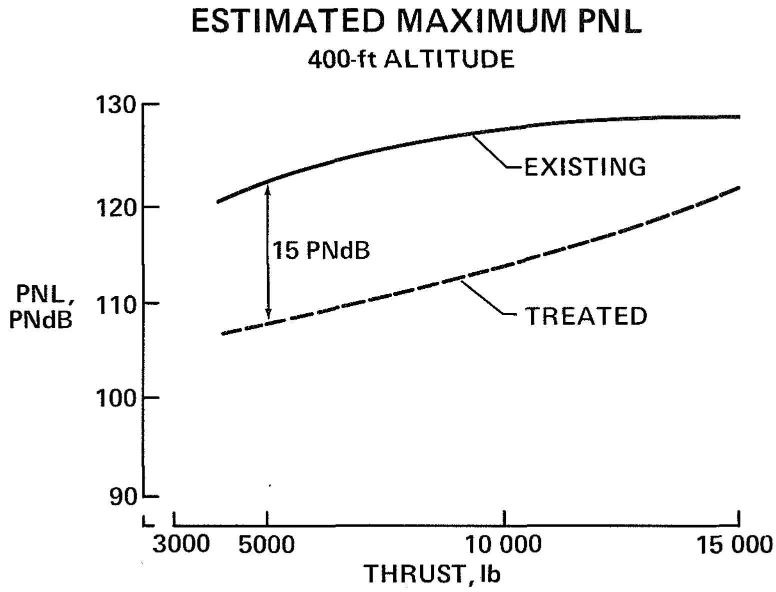

Figure 5

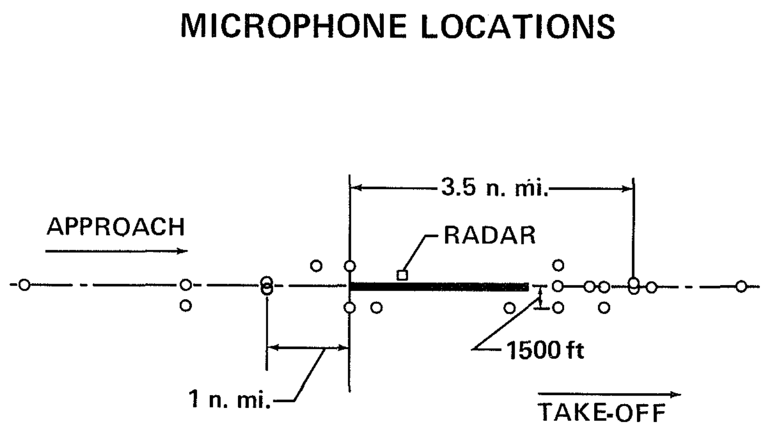

Figure 6

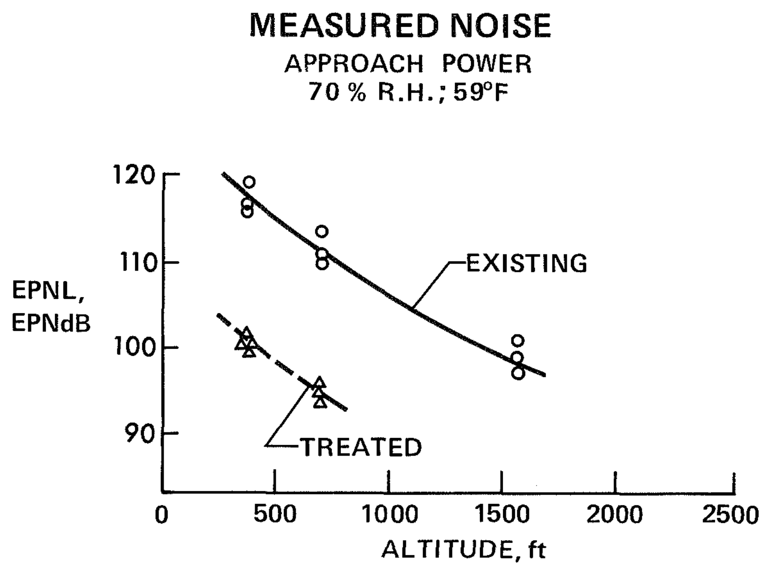

Figure 7

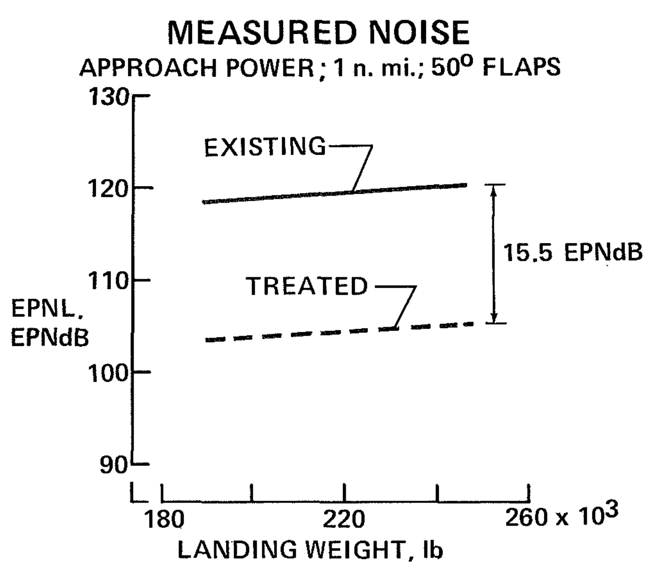

Figure 8

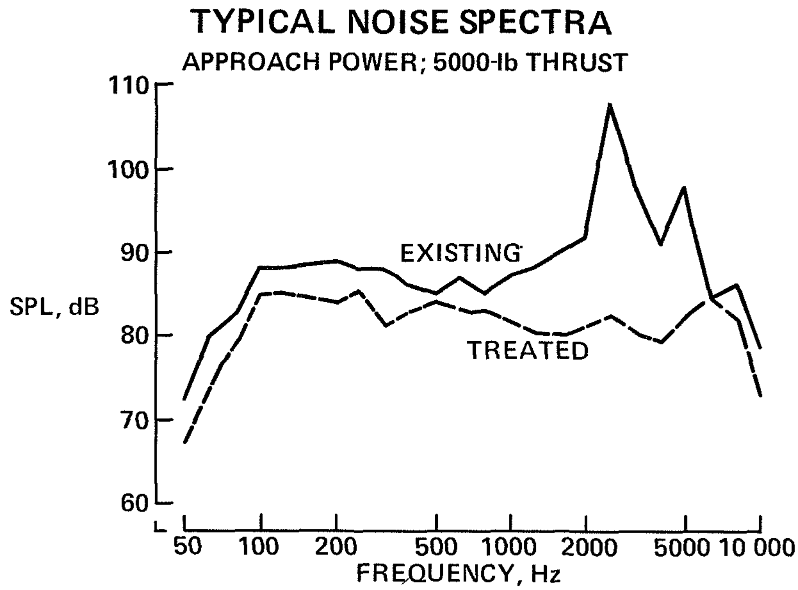

Figure 9

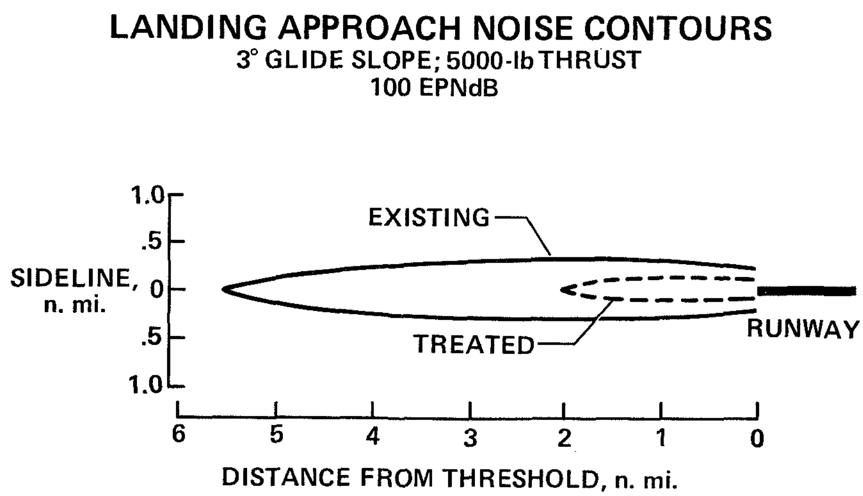

Figure 10

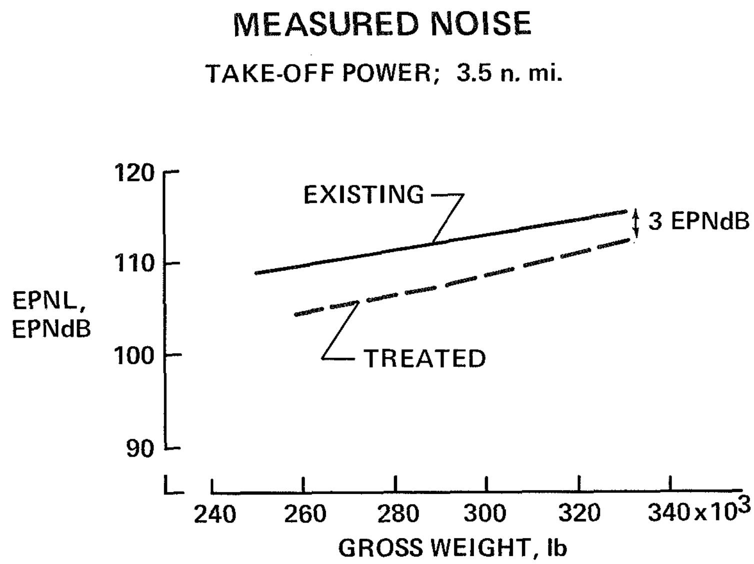

Figure 11

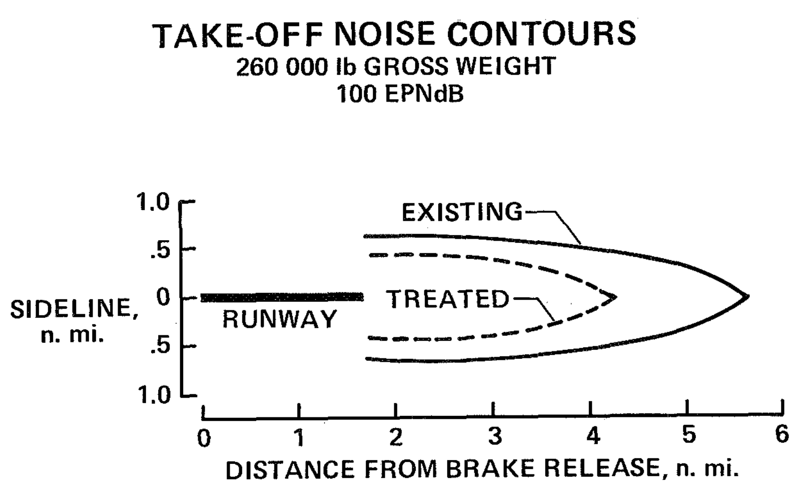

Figure 12

MEASURED NOISE

CUTBACK POWER ; 6% CLIMB GRADIENT; 3.5 n. mi.

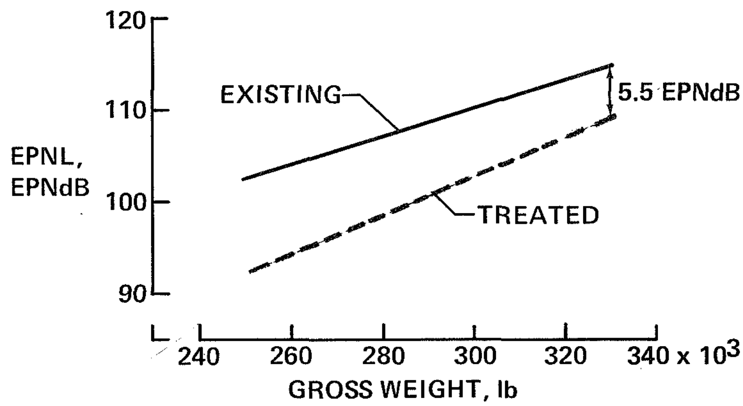

Figure 13

TAKE-OFF NOISE CONTOURS

260 000 lb GROSS WEIGHT; POWER CUTBACK AT 3.5 n. mi.;
100 EPNdB

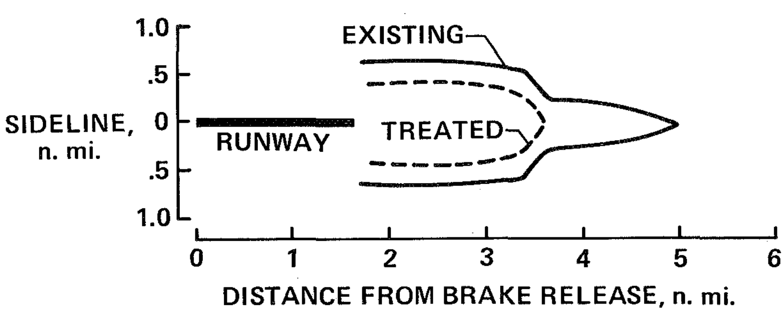

Figure 14

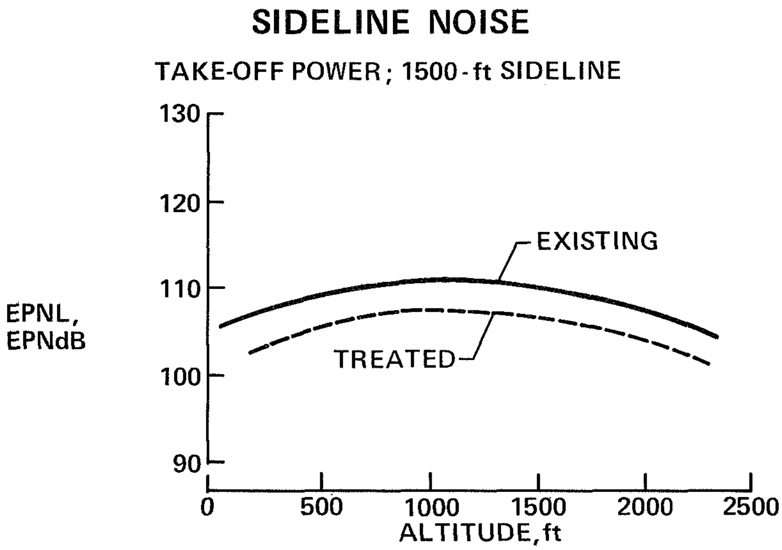

Figure 15

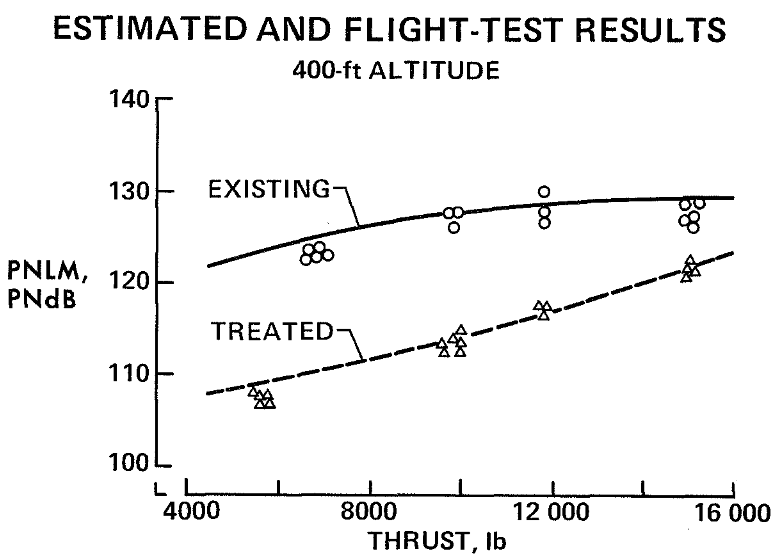

Figure 16

10. ECONOMIC IMPLICATIONS OF RETROFITTING 707-320B AIRPLANES WITH ACOUSTICALLY TREATED NACELLES

By James Fletcher

The Boeing Company

SUMMARY

This paper presents the results of a theoretical economic study that compares two fleets of Boeing 707-320B airplanes, one with and one without acoustically treated nacelles described in earlier papers. The treated nacelle includes a two-ring treated inlet and a full-length treated fan duct. The study included evaluation of a hypothetical airline 707-320B route network operating with a representative passenger fare yield structure. The results of this study are applicable only to the route structure assumed. Any specific airline having a significantly larger proportion of long-range routes, higher passenger load factors, or inclusion of cargo would be more severely affected by the treated nacelle. The results of this study show that the 1972 direct operating costs (DOC) will increase by about 9.2 percent and that this increase is almost entirely due to the depreciation cost of the retrofit itself.

It was found that when operating both airplane fleets at the current maximum gross take-off weight of 327 000 lb, the airplane with the treated nacelle presented some operational restrictions that produced a small reduction of revenue earning capacity. The major factor in economic return was the increase in DOC. This resulted in a reduction in return on revenue of 4.4 percent. This 4.4 percent reduction for the hypothetical carrier assumed may appear small. However, in a narrow-margin industry, a nominal cost increase can produce a drastic impact on return on investment. In the final analysis, a detailed assessment of the economic effect of a treated nacelle retrofit must be made by each of the affected airlines.

INTRODUCTION

The development and performance of a nacelle with a two-ring treated inlet and a full-length treated fan duct have been described. (See figs. 1 and 2.) The program demonstrated noise level reductions of 15.5 EPNdB at the landing-approach power condition, 3 EPNdB at take-off power, and 5.5 EPNdB at cutback power. Although these results are based on tests made on an airplane powered with Pratt & Whitney JT3D-7 engines, the results are directly applicable to the 707-320B powered with Pratt & Whitney JT3D-3B engines, when proper account is made for the performance differences between the two engines.

The economic impact of the nacelle modifications on all the airline operations has been studied in two separate stages. First, the increased DOC for the 707-320B powered with P&W JT3D-3B engines has been assessed. Second, the economic effect on a hypothetical airline operation has been studied. The study is theoretical and necessarily limited in its scope. It does not attempt to answer important questions such as whether the airlines can absorb the cost of such a program without attendant increases in income. McCormick (paper no. 8) has shown that the major performance effect due to the nacelle treatment was a loss of capacity payload range of approximately 200 nautical miles. This loss in range was due mainly to the fuel displaced by the increased operating empty weight of 3140 lb.

DIRECT OPERATING COST

The DOC was estimated according to the 1967 Air Transport Association (ATA) cost formula with specific modifications to cover the special case of a treated nacelle retrofit. The changes concern costs due to maintenance, depreciation, and airplane utilization. The costs used in this study are intended to be representative of the year 1972. For this reason, maintenance labor rate was assumed to be $5 per hour (a 25 percent increase over the ATA formula), and material costs were assumed to be increased by 20 percent over the ATA formula. A theoretical analysis has been made of the maintenance costs for a production version of the nacelle including a thrust reverser installation. When the additional costs due to inspecting, cleaning, repairing the treated areas, and the increased handling problem (extra weight) were taken into account, the estimates showed that the nacelle maintenance cost would be increased from $2.70 per nacelle per flight hour for the existing nacelle to $3.02 for the treated nacelle (1972 prices).

While the assumed airplane depreciation conformed with the ATA method, the modified nacelles were depreciated over a 5-year period. This period was chosen to reflect the fact that by 1972 the airplanes will be partially depreciated. No residual value was assumed for the existing nacelles. Spares provisioning for the treated nacelles was taken to be 20 percent to reflect the current lack of operational experience with treated nacelles. The ATA formulas state a 10 percent provision for the airframe including the nacelles and 40 percent for the engines. An airplane utilization of 3800 hours per year was considered to be a representative figure for the route systems commonly flown by the 707-320B/C type airplanes.

There are uncertainties in estimating retrofit cost, mainly with respect to production techniques for the polyimide fiberglass acoustic material, date of go-ahead, number of kits produced, the production rate, and method of performing the installation. However, on the basis of an assumed total of 400 airplane sets manufactured to the production schedule given in figure 3, the current estimate for a 1972 price is $1 000 000 per airplane including installation (fig. 4). Retrofit installation is assumed to be concurrent with normal major overhaul periods. If this assumption is proved to be incorrect, additional costs for airplanes out of service will have to be included. Table 1 lists some of the important assumptions. All others not listed were as prescribed by the 1967 ATA formulas.

Figure 5 shows DOC for international operations, both for the current production airplane and the treated-nacelle airplane. These data are based on a Mach number of 0.83, which is the Mach number currently used for minimum-cost cruise, except at the long-range extreme, where a cruise Mach number of 0.80 is used. Figure 6 shows the percent increase of DOC for both international and domestic operations due to the incorporation of the nacelle modifications. The increases are about 9.2 and 9.6 percent for the international and domestic rules, respectively.

Figure 7 shows how the various elements of cost contribute to the total cost at CAB distances of 2500 nautical miles. Although insurance, maintenance, and fuel contribute increases, 84.5 percent of the total increase stems from the depreciation cost of the treated nacelle. The following table gives the elements of DOC increase for a CAB distance of 2500 nautical miles:

	Percent of total increase
Crew pay	0
Fuel	8.9
Insurance	4.8
Maintenance	1.8
Depreciation	84.5
	100.0

Thus, the retrofit price and period of depreciation for the nacelle are of primary concern.

AIRLINE ECONOMIC STUDY

Basic Methodology and Assumptions

The operation of a fleet of Boeing 707-320B airplanes was simulated over the hypothetical route network shown in figure 8. This network includes U.S. to Hawaii, Transatlantic and beyond to the Far East, and domestic through routings from both. Passenger demand, trip frequencies, and load factors for each segment of the route system are representative of the period 1967-1968. The load factors are as follows:

Route sector	Load factor, percent	
	Summer	Winter
U.S. to Hawaii	61.0	50.2
U.S. through flights from Hawaii	61.0	50.2
U.S. through flights from Transatlantic	55.1	41.0
Transatlantic and beyond	64.6	64.9
Fifth freedom	43.0	31.0

The assumption of a fleet of 115 airplanes resulted in an average annual utilization for the existing airplane of 3785 hours. Note that the utilization is approximately the same as that used in the DOC study. The slight difference is due to the requirement to have a whole number of airplanes in the fleet study. As in the DOC study, minimum-cost techniques were assumed throughout, that is, a cruise Mach number of 0.83, except where range considerations were found to be critical. In this event, a long-range cruise Mach number of 0.80 was assumed.

Indirect operating costs (IOC) were calculated for the existing airplane by a method devised by Boeing and Lockheed and updated by Boeing in 1967. The individual items considered by the method are as follows:

1. Passenger service
2. Passenger and baggage handling
3. Aircraft servicing
4. Aircraft control
5. Servicing administration
6. Reservations and sales
7. Advertising and publicity
8. Maintenance burden – ground equipment
9. Depreciation – ground equipment
10. General and administrative

Each item was studied individually to estimate the increase, if any, due to the retrofit of the treated nacelle. Emphasis was placed on the maintenance and aircraft servicing and the depreciation of additional ground equipment. However, the total increase of indirect operating cost, when apportioned over an assumed 5-year period for the entire fleet, was found to be a small percentage of the total IOC.

With the use of a special computer program designed to model an operation, passenger demand and airfield temperature were described in statistical terms. Occasionally peak demands would occur simultaneously with high airfield temperatures; consequently, passenger denials for certain long range flights were necessary. The unrestricted maximum gross take-off weight used was 327 000 lb for both airplane fleets. The maximum landing weight was 207 000 lb.

Pertinent CAB passenger-yield data were analyzed to derive the curves shown in figure 9. These were used together with the operating costs estimated for 1972 to determine the change in profit margin for the airplanes with the treated nacelles.

Results

Figure 10 shows the CAB distance percentage distribution resulting from the route-system and passenger-demand assumptions made in the study. Other operational quantities resulting from the simulated fleet operation are summarized in table 2. In particular, it will be noted that for a given number of trips, the airplane maintains substantially the same service level for the route system under study. In fact, the reduction of passengers carried is 0.05 percent. The increase of passenger denials occurs on three of the long-range westbound flights. A comparison of the related economic quantities for the two fleets is presented in table 3. The revenue earned is reduced by 0.10 percent. Direct operating costs increase by 9.6 percent and total operating costs by 4.4 percent. Essentially the whole of the operating cost increase is attributable to the increase of DOC. The net result of these revenue and operating-cost changes is to reduce the return on revenue, based on passenger yield only, by 4.4 percent.

In interpreting these results, two points need to be emphasized. First, the maximum stage length for the route system studied falls in the range from 4500 to 4750 nautical miles. 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 times. Consequently, retrofit operations will be spread over a period of time greater than 1 year. The production schedule of figure 3 also indicated that it will not be possible to retrofit all Boeing 707-320B/C models by the end of 1972. The cost implications of a slide in retrofit scheduled beyond 1972 must be evaluated by each airline.

Noise Level Distribution

For the fleet operation studied, frequency distribution of noise levels experienced during take-off and landing approach can be estimated. This is shown in figure 11 for the landing approach and figure 12 for take-off climbout. It can be seen that the treated nacelle shifts the landing noise from the 118-121 EPNdB band to the 103-106 EPNdB band at a point 1 nautical mile from the landing threshold.

Because of the wide spread of take-off weights, the take-off noise levels are distributed over a range of EPNL. No estimates are shown below 85 dB because of the lack of test data at the low EPNdB levels. These data, as measured on P&W JT3D-7 engines, have been assumed to be applicable to the P&W JT3D-3B engine of this study. This has been confirmed by other Boeing flight-test measurements. Figure 12 shows that the frequency of noise level experienced at the 3.5 nautical mile point above 100 EPNdB, for instance, is reduced from 31 percent of the total number of flights to 14 percent.

CONCLUDING REMARKS

The economic impact of nacelle modifications to reduce airplane noise have been studied for the Boeing 707-320B powered with Pratt & Whitney JT3D-3B engines. The modifications comprise a two-ring treated inlet and a full-length treated fan duct. The increase of airplane operating empty weight would be 3140 lb and this leads to the major effect on performance, that is, a capacity payload range loss of approximately 200 nautical miles due to the available fuel displaced. The major economic effects of the above changes are as follows:

(1) A total installed retrofit cost of $1 000 000 based on a production run of 400 airplane sets.

(2) An increase of international direct operating cost of 9.2 percent, due mainly to the treated-nacelle depreciation costs. In this study, the depreciation period of the treated nacelle has been assumed to be 5 years.

(3) Small reduction of revenue earning capacity for the airline route structure and stage-length distribution assumed in this study. The revenue loss would increase for a route structure with a higher content of long-range stages.

(4) A reduction in return on revenue of 4.4 percent for the case considered.

Further work is necessary in the following areas:

(1) Validation of retrofit price estimates, particularly as affected by design and production techniques for polyimide fiberglass acoustic panels.

(2) Validation of in-service performance of the acoustic panels and the associated maintenance cost.

(3) Consideration of the cost effects of a retrofit schedule extending beyond 1972.

(4) Consideration of the case of an airline route system with a higher content of very long-range stages.

TABLE 1.- ASSUMPTIONS FOR DOC STUDY

Airplane:	
Airframe	Boeing 320B
Engines	P&W JT3D-3B
Seats	149
Maximum gross take-off weight, lb	327 000
Flight operations:	
Cruise altitude, ft	31 000, 35 000, and 39 000
Cruise technique	Step climb where applicable
Cruise Mach number:	
Minimum cost	0.83
Long-range extreme	0.80
Utilization, hours/year	3800
Maintenance:	
Labor rate, dollars/hour	5
Operating empty weight, lb, for -	
Existing airplane	145 100
Airplane with treated nacelles	148 240
Material costs	ATA plus 20%
Nacelle maintenance cost, dollars per flight hour per nacelle, for -	
Existing airplane	2.70
Airplane with treated nacelles	3.02
Downtime penalty for retrofit	0 (accomplished during base maintenance)
Depreciation:	
Period for airframe, years	12
Period for treated nacelle, years	5
Spares provisioning for treated nacelles	20%
Retrofit price, dollars	1 000 000

TABLE 2.- OPERATIONAL COMPARISONS

Operational quantity	Airplanes with –	
	Existing nacelles	Treated nacelles
Average trips per week	1753	1753
Utilization hours per year	3785	3786
Average number of passengers per week . . .	127 963	127 895
Average load factor, percent	48.99	48.97

TABLE 3.- ECONOMIC COMPARISONS

[Based on annual total figures]

Economic quantity	Percent change after retrofit
Passenger revenue	-0.10
Direct operating costs	+9.6
Indirect operating costs	Negligible
Total operating costs	+4.4
Reduction in return on passenger revenue	-4.4

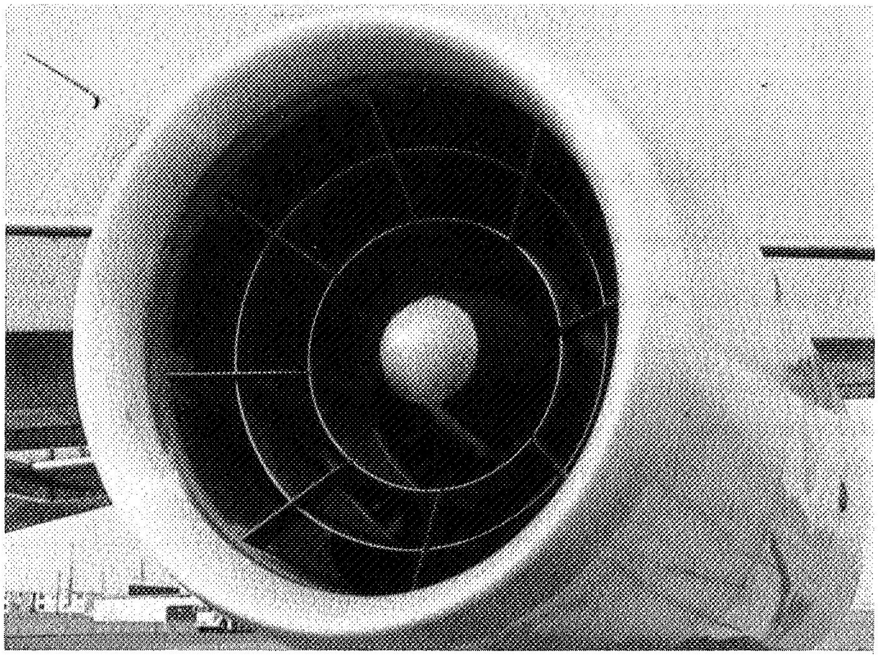

Figure 1.- Treated nacelle installed on 707-320B airplane, front view.

Figure 2.- Treated nacelle installed on 707-320B airplane, side view.

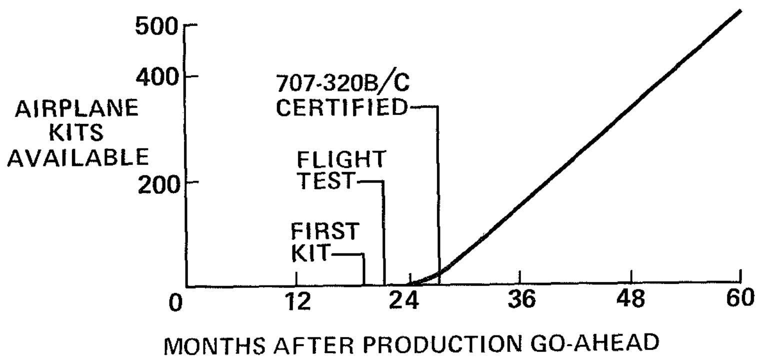

Figure 3.- Retrofit kit production schedule.

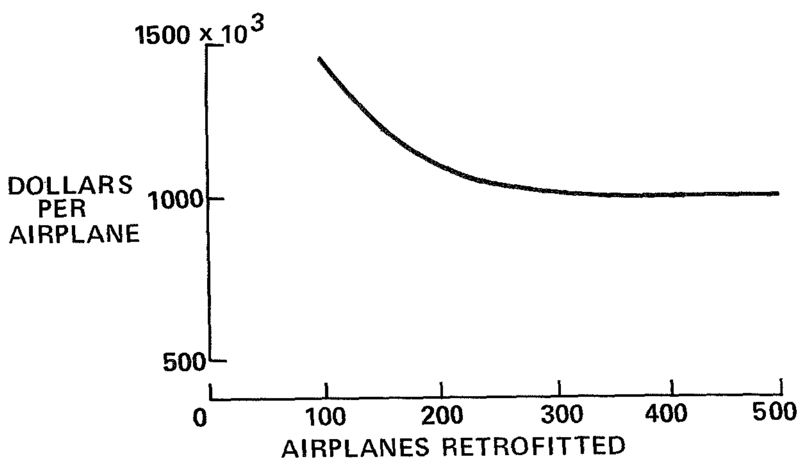

Figure 4.- Retrofit price.

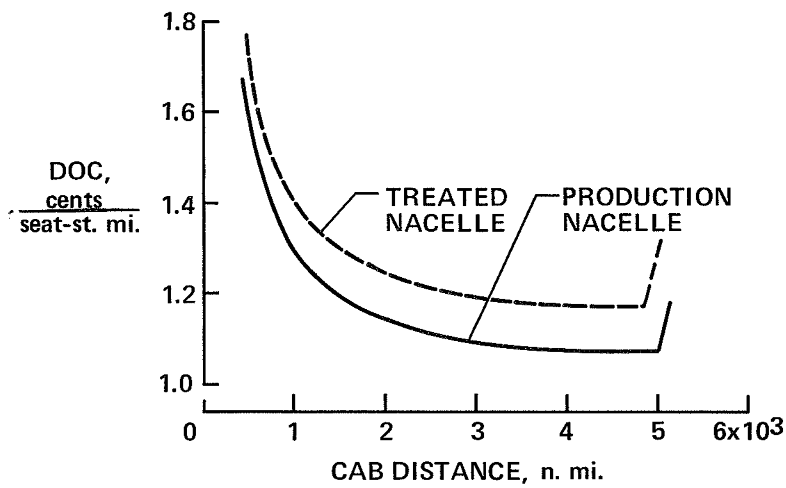

Figure 5.- Direct operating costs for 707-320B with P&W JT3D-3B engines. ATA international operations.

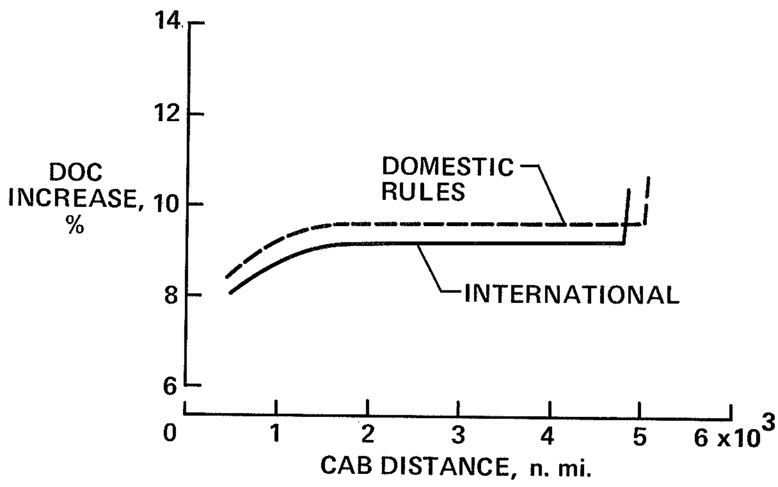

Figure 6.- Increase of direct operating cost due to nacelle treatment.

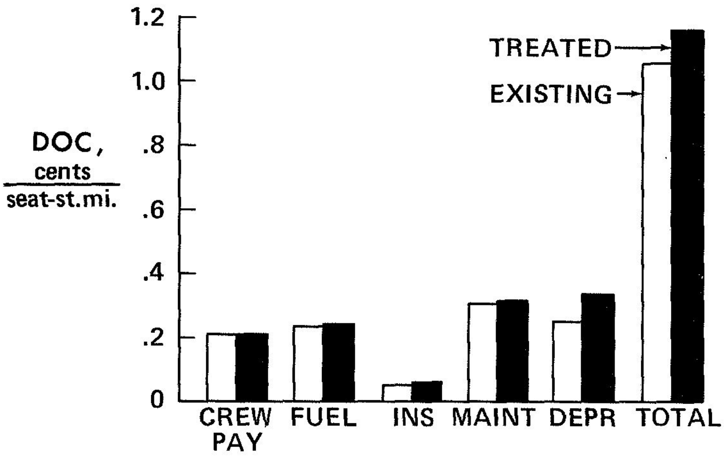

Figure 7.- DOC elements. CAB distance, 2500 nautical miles.

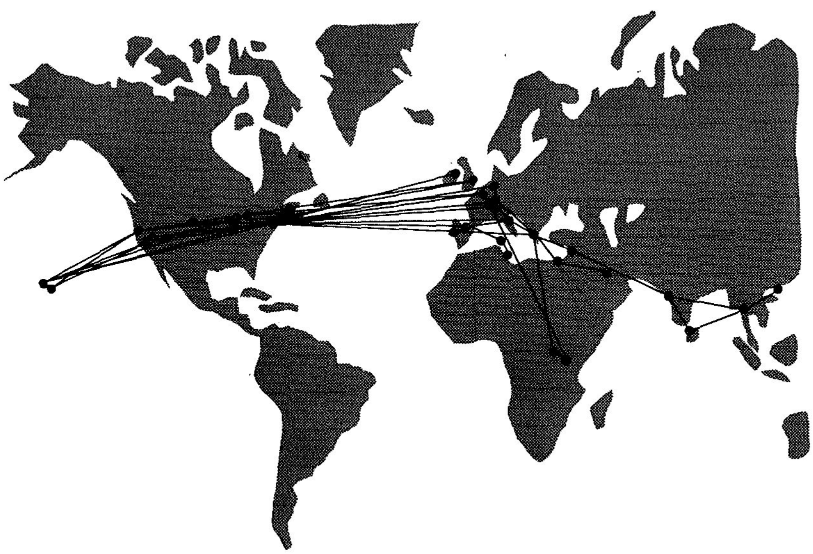

Figure 8.- Airline route system.

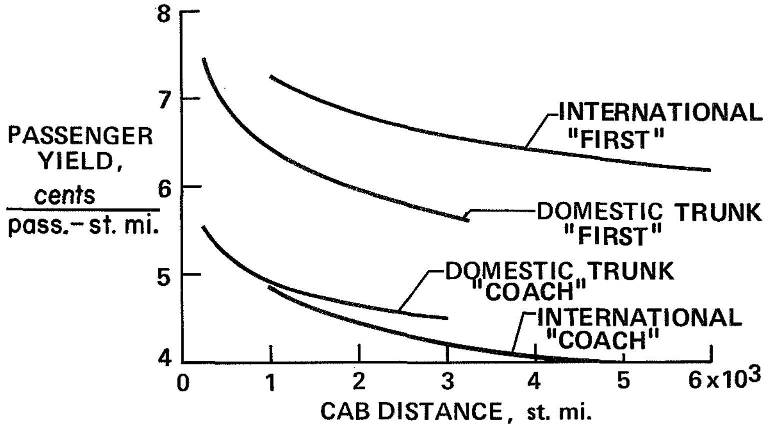

Figure 9.- Passenger fare yield.

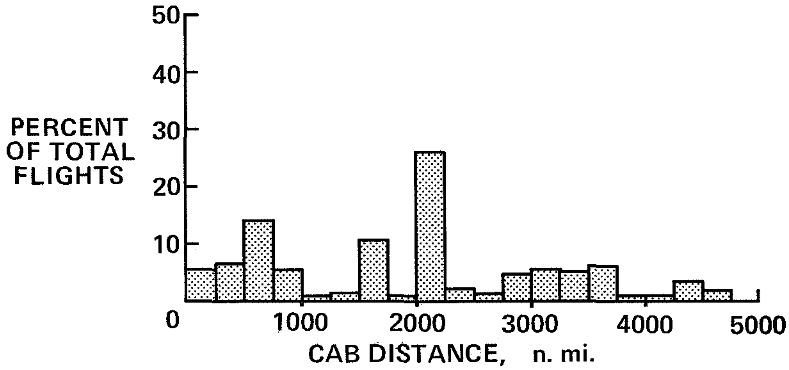

Figure 10.- Distribution of CAB distance.

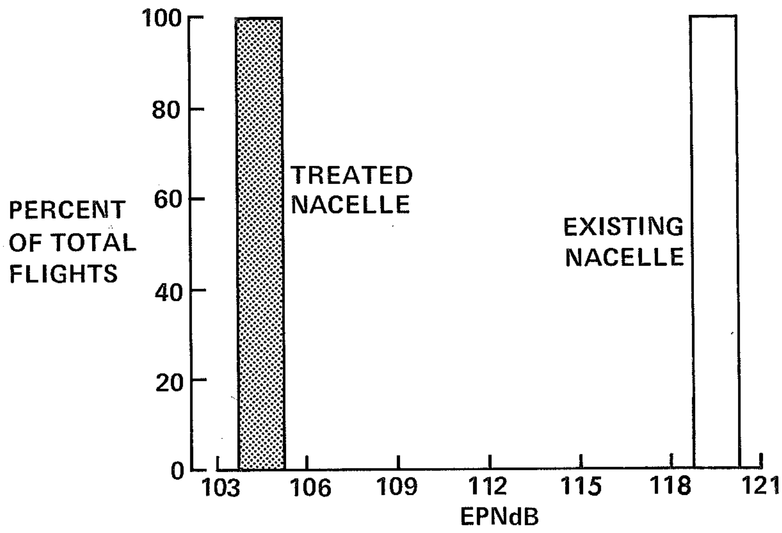

Figure 11.- Approach noise level distribution at 1 nautical mile from landing threshold. 707-320B; P&W JT3D-3B engines.

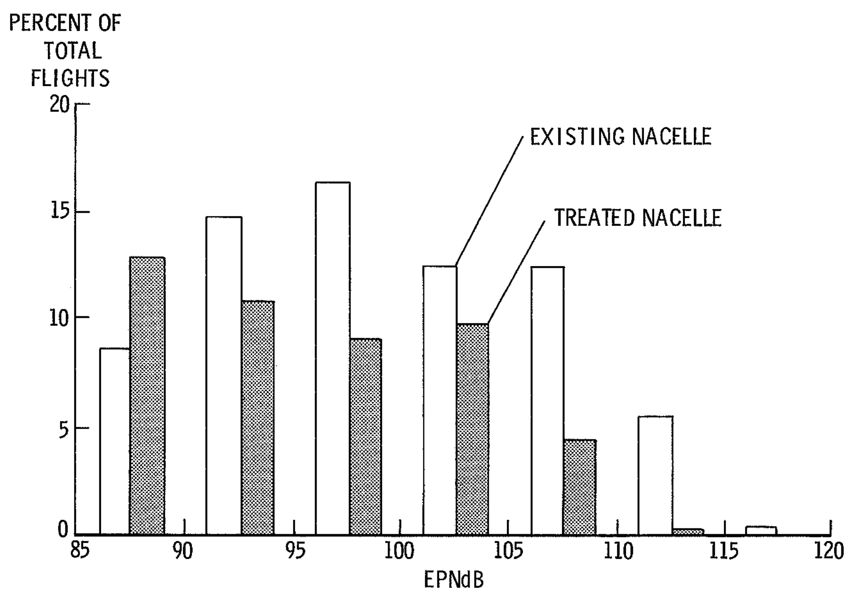

Figure 12.- Take-off noise level distribution at 3.5 nautical miles from start of take-off roll. 707-320B; P&W JT3D-3B engines.

11. STUDIES OF ATMOSPHERIC ATTENUATION OF NOISE

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and Raymond E. Panko

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INTRODUCTION

Everyone who works with outdoor sound measurements quickly becomes aware that the atmosphere is a very unsatisfactory propagation medium. It greatly attenuates sound at high frequencies, with coefficients varying widely from hour to hour and day to day. The atmosphere is almost always in motion and is characterized by turbulence, stratified layers, gradients, and inhomogeneities especially near the ground surface. The velocity of sound in air is temperature sensitive and slow enough that Doppler shifts due to winds, engine-generated airflow, and vehicle motion cannot be neglected.

To study atmospheric effects on sound propagation, it is necessary to start with simplifications and gradually approach a more realistic model. It should not be surprising that the classical assumption of a homogeneous, stationary atmosphere does not give an entirely satisfactory result. Yet it is on such an assumption that reference 1, the Society of Automotive Engineers standard on atmospheric absorption corrections, Aerospace Recommended Practice 866 (ARP 866), is largely based.

It has become popular to criticize ARP 866. The large corrections it calls for at high frequencies seem to be unreasonable, and when they are applied to much of the fly-over data, they lead to absurdities, such as a noise level which increases as the airplane gets more remote. Such results have led to restrictions on the range of temperature and humidity within which experimental data are acceptable. These restrictions in turn cause extra complications in flight-test scheduling and frequently cause delay and added expense. As a result, The Boeing Company, in conjunction with NASA, has undertaken to find answers to questions like the following:

(1) Is ARP 866 based on sufficiently well-established theoretical grounds?

(2) Does ARP 866 fit reasonably well with experimental results?

(3) Are there other measurement factors which can account for the unsatisfactory results which are often obtained?

(4) Can the accuracy of data be improved and the range over which measurements taken be increased, either by modifying ARP 866 or by changing instrumentation and/or data processing?

DISCUSSION

ARP 866 is based on the work of recognized authorities in the field, particularly Kneser and Harris. (See refs. 2 and 3, respectively.) In the words of the ARP document (ref. 1), "The experimental results of Harris were obtained for a single temperature of 20^{o} C (68^{o} F). Essentially, these data were used, and curves based on Kneser's theory were 'modified' to fit them." More recently, Harris has extended his laboratory experiments to include a range of temperature, but these results have not been incorporated into ARP 866.

Atmospheric absorption is caused by several mechanisms which convert sound into heat. Within the audible frequency range, however, by far the largest portion of the absorption is caused by the resonant vibration of the oxygen molecules, which is in turn strongly influenced by the presence of water molecules. As a result atmospheric absorption is strongly dependent on humidity. The maximum attenuation which can occur at any frequency, as calculated from Kneser's work (ref. 2), agrees very well with experimental data from various observers. Measurements of the humidity values at which maximum attenuation is obtained and of the attenuation curve for other humidity values have also been made by a great many observers. They show a very wide spread and none agree particularly well with Kneser's theory.

No one has yet been able to explain this discrepancy. The procedure in developing ARP 866 was simply to shift Kneser's theoretical curve to make a reasonable fit with experimental results, most of which were obtained by Harris, whose work is the most extensive and most recent of the laboratory studies. (See ref. 3.) As Harris points out, the measurements are very sensitive to small errors and to boundary losses in the measurement chamber. He has attempted to control these carefully, but the issue will scarcely be settled until either a new measuring procedure results in better agreement with theory or modifications are developed to the theory to bring it in line with present data. The differences are considerable at humidities above those which give maximum absorption, with values according to ARP 866 running to four times the theoretical values in extreme cases. Therefore, the answer to the first question, "Is ARP 866 based on sufficiently well-established theoretical grounds?," must be a rather qualified "yes."

Data from outdoor acoustic measurements almost without exception lead to attenuation values far greater than those from the Kneser theory and, in some instances, larger than values from ARP 866. Data from The Boeing Co., Douglas Aircraft Co., and Rolls-Royce, Ltd., obtained prior to 1962, were considered in the development of ARP 866 and were shown to be reasonably consistent with it. Comparison of more recent data by these three companies plus data from British Aircraft Corp., Ltd., General Electric, and the British National Physical Laboratory shows a rather wide scatter around the ARP 866 values.

Actually, it should not be expected that outdoor measurements, which include atmospheric attenuation and turbulent scatter, will correspond to ARP 866 predictions, which are in theory based on atmospheric absorption only. Most outdoor data include a variety of interference effects and ground absorption phenomena as well as shadowing from thermal and wind gradients. No complete analysis has yet been developed to compensate for all these factors, and it is hard to imagine an adequate array of meteorological sensors to provide a systematic description of the entire path over which the sound from an airplane is propagated. At best, statistically significant data are all that can be hoped for, and inclusion of a wide range of atmospheric conditions is necessary.

TEST PROGRAM DESCRIPTION

Since large amounts of noise data are being collected in Boeing flight tests at the acoustic range at Grant County Airport, Moses Lake, Washington, a procedure has been devised for comparing data from various microphones at different distances, but at a uniform angle with respect to the engine center line. The computer program, after adjusting for spherical divergence, automatically plots differences in sound level between pairs of microphones and draws the best fit straight line through the values. The slope of the line gives the attenuation coefficient.

The data used in the present analysis were obtained during a flight test program conducted during February through May, 1969, at Moses Lake and over Puget Sound near Seattle. The purpose of the program was to compare the acoustic and operational performance of a 707-320B airplane equipped with acoustically treated nacelles with that of the same aircraft with production nacelles installed.

The flight program consisted of several series of tests including take-offs, landings, and level fly-bys for both the treated and existing nacelle configurations. (See table I.) Acoustic data were recorded from an array of microphones along the center line and to the side of the runway. (See fig. 1.) Tracking radar provided time-correlated aircraft-space-position data during the acoustic test series. From this information, accurate space position of the aircraft was obtained.

Surface temperature, relative humidity, and wind were measured at a central location near the midpoint of the main runway. In addition, conditions were monitored at points near the approach and take-off ends of the runway. Table II shows the range of weather conditions sampled during the various test series, including the level fly-bys over Moses Lake and Puget Sound and the subjective tests at Moses Lake on May 24 and 25, 1969. Some of the flights provide information on the effects of winds above 10 knots and relative humidity below 30 percent, the usual cut-off conditions for accurate testing.

In addition, soundings of temperature, humidity, and wind were made to a height of 3000 feet at intervals during some of the series of flights. Testing was scheduled to take advantage of the higher relative humidity prevailing in the early morning; however, analysis of the radiosonde data shows that the surface measurements may not be representative of the entire atmospheric layer between the aircraft and microphone. A comparison can be made of attenuation coefficients obtained from surface weather measurements with those obtained by using the radiosonde data.

ANALYSIS

The basic problem of aircraft-noise evaluation is obtaining valid measurements. Of equal importance is the availability of accurate normalizing procedures for comparing measurements taken at other distances and conditions.

The present study is concerned with atmospheric attenuation but first considers some of the sources of error and their effects on measurement, analysis, and normalization of noise data.

Figure 2 shows the more important sources of error and distortion in fly-over-noise measurements. The typical jet-engine spectrum as measured in free field between about 45 and 11 000 hertz can be expected to have a rather uniform, smoothly rounded shape reaching a maximum in the vicinity of 1 kilohertz and perhaps falling off by 20 decibels or so at the extremes. Many engines have discrete line spectra or narrow-band noise peaks related to fan, compressor, or other rotating components.

Propagation through the atmosphere selectively attenuates the high frequencies, with absorption values according to ARP 866 of more than 35 decibels per 1000 feet at 8 or 10 kilohertz on a moderately dry day. Since the propagation path may be 5000 feet or more, a spectrum at the ground where the 8-kilohertz level may be as much as 170 decibels below that at 1 kilohertz can be anticipated.

Microphones near the surface also pick up ambient noise from other sources, such as traffic, insects, birds, and so on; this noise sets a noise-floor limit below which the signal cannot normally be detected. On a broad-band basis, this floor is not likely to be lower than 40 to 50 decibels in most outdoor locations. On a 1/3-octave-band basis, centered at 8 or 10 kilohertz, the value could be expected to be perhaps 10 to 15 decibels lower. In practice, it is doubtful if aircraft noise measurements have usually reached this acoustic noise floor because of electrical noise pickup in the input circuits and dynamic range limitations in recording and analyzer components. Thus, it is evident that even with care, it is probably impossible to maintain a dynamic range at the microphone input much in excess of 70 decibels. As shall be seen later, this is usually reduced by other parts of the measurement system.

Another distortion of the input signal is caused by the frequency-selective multipath interference between direct and ground-reflected signals. This interference pattern is considerably modified by the complex impedance and propagation constants of the surface in the case of a porous medium like sod, sand, or gravel. It affects primarily the lower frequency ($<\approx 1$ kilohertz) components in the case of overflight measurements.

All electronic components introduce some electrical noise, and since they also have an overload distortion level, they have a restricted dynamic range. The magnetic-tape recorder, for example, usually has a potential range of about 48 decibels for broad-band signals. For 1/3-octave-band analysis in the higher frequencies, this range can be increased to about 60 decibels. The analyzer currently in use has a dynamic range of only 40 decibels, but this can be improved by repeating the analysis with a different gain setting or by using other equipment.

In summary, instrumentation usually limits the dynamic range and even with careful attention to equipment use, the dynamic range is at best about 70 decibels. The difference between this dynamic range and the 170-decibel range from atmospheric attenuation explains the unreasonable results that are often observed. Even if the values in ARP 866 are an exact representation of the atmospheric attenuation, application of them to data below or near the noise floor is meaningless. In spite of these restrictions on the accuracy of available data, it is worthwhile to pursue the present analysis with a view to quantifying more precisely the magnitude of uncertainty.

Figure 3 is an example of the type of results produced by the present work to describe attenuation coefficients for various frequencies. The slope of the line of best fit gives the attenuation coefficient for that frequency. In this example the attenuation is 17 decibels per 1000 feet. An attenuation value of 14 decibels per 1000 feet is derived from ARP 866 for the ambient surface temperature (T) and relative humidity (RH) and is shown by the dashed line. Adjustment of the ambient conditions to account for differences between surface and radiosonde measurements results in an ARP 866 derived attenuation of approximately 17 decibels per 1000 feet.

From attenuation values obtained for each 1/3-octave band, a curve of attenuation versus frequency can be plotted for each flight. Figure 4 shows the data for all frequencies above 1000 hertz for the same flight (example 1) as illustrated in figure 3. The attenuation curve from ARP 866 for ambient surface conditions is shown by the dashed line. When adjusted to average temperature and humidity for the entire propagation path, the curve nearly coincides with the measured values between 1000 and 5000 hertz. Above that frequency the effect of the noise floor is distinctively evident.

A similar plot of attenuation using Boeing data from another flight (example 2) is shown in figure 5. The effect of the equipment noise floor begins to be evident at frequencies above 6300 hertz. The difference between the measured and predicted attenuation at lower frequencies is unexplained at this time.

Data for all temperatures and humidities can be compared with the ARP 866 (Harris) curve for normalized attenuation (α/α_{max}) versus normalized absolute humidity (h/h_{max}). Figure 6 shows the preliminary results obtained from the two flights discussed previously.

CONCLUDING REMARKS

While results presented herein are preliminary, answers to the questions originally posed can be suggested.

The answer to the first question, "Is ARP 866 based on sufficiently well-established theoretical grounds?," is a qualified "yes."

The second question was "Does ARP 866 fit reasonably well with experimental results?" Although this analysis is far from complete at the present time, the indications are that the absorption coefficients which have been determined agree well with ARP 866 values. In fact, it has become evident that a majority of unsatisfactory experimental data cannot be blamed on errors in ARP 866. However, the third question must be answered before a firm conclusion can be reached on the second question, especially at the higher frequencies and for weather conditions much different from the acoustical standard day ($T = 59^{\circ}$ F, RH = 70 percent). Identification of major limitations in the dynamic range provided by current procedures for using conventional equipment have been made. This obstacle must be overcome if ARP 866 is to be validated or revised. There is no technical reason why this cannot be done, but it will not be done without a very substantial and expensive effort.

Studies are now underway to determine a reasonable way to implement atmospheric corrections without exaggerating noise-floor effects. A technique has been developed to determine the absorption from data which are above the noise floor. It is hoped that the data determined by this technique can be extrapolated to replace values which are below the noise floor. Only portions of the data which are obviously unreasonable would need to be discarded, and absorption values would be based on measurements over the real path through which the sound travels. This path must be determined and measurement of its meteorological properties must be made possible. The only assumptions are that (1) the atmospheric path during the overflight remains reasonably constant, and (2) the acoustic output of the aircraft is statistically uniform during the overflight. Some difficulties are appearing in the extrapolation procedure, particularly for large aircraft where reflections from the wings may substantially modify the directional pattern of the engine.

This complicates not only the noise-floor extrapolation but also the atmospheric attenuation computation and the computation of overflight noise characteristics from static test data. It is believed that this problem can be solved, and, consequently, it should be possible to get acceptable noise measurements over a much broader range.

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3. Harris, Cyril M.: Absorption of Sound in Air in the Audio-Frequency Range. J. Acoust. Soc. Amer., vol. 35, no. 1, Jan. 1963, pp. 11-17.

TABLE I.- AIRCRAFT OPERATIONS SUMMARY

Flight condition	Objective tests for –		Subject tests for existing and treated nacelles	Total
	Existing nacelle	Treated nacelle		
Take-off	12	27	---	39
Landing	6	10	7	23
Level fly-by at				
Moses Lake	12	24	36	72
Puget Sound	12	12	---	24
Total	42	73	43	158

TABLE II.- RANGE OF ACTUAL WEATHER CONDITIONS

Weather conditions	Objective tests for –				Subjective tests for existing and treated nacelles at Moses Lake
	Existing nacelle at –		Treated nacelle at –		
	Moses Lake	Puget Sound	Moses Lake	Puget Sound	
Wind speed, knots	2 to 9	--	1 to 9	7 to 8	1 to 18
Temperature, ^{o}F	46 to 59	48	48 to 67	59 to 61	64 to 85
Relative humidity, percent	33 to 60	76	27 to 89	75 to 85	28 to 44

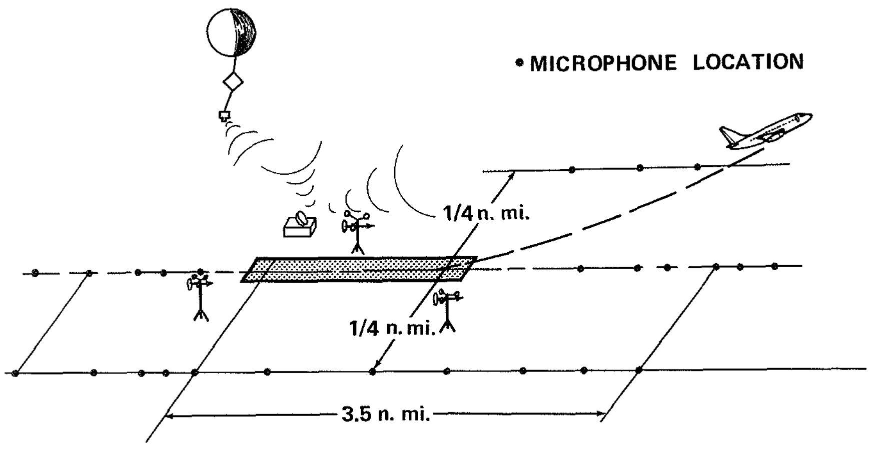

Figure 1.- Test site.

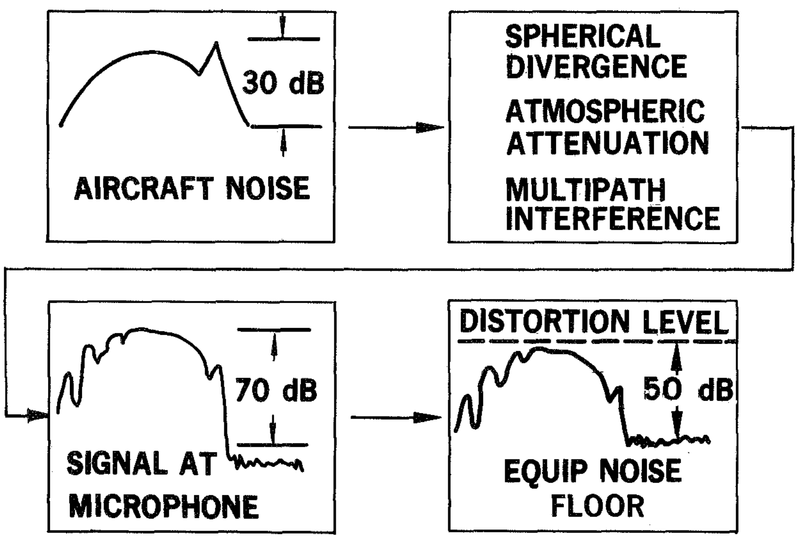

Figure 2.- Sources of error and distortion in aircraft noise measurements.

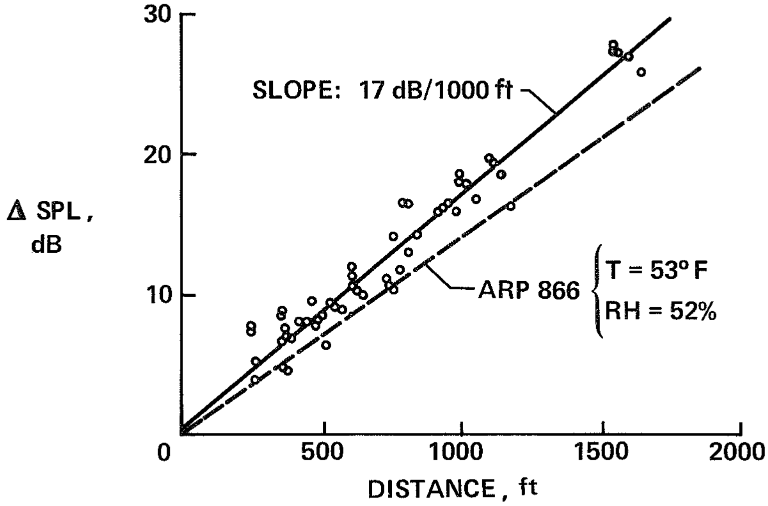

Figure 3.- Attenuation at a given frequency of 5000 hertz.

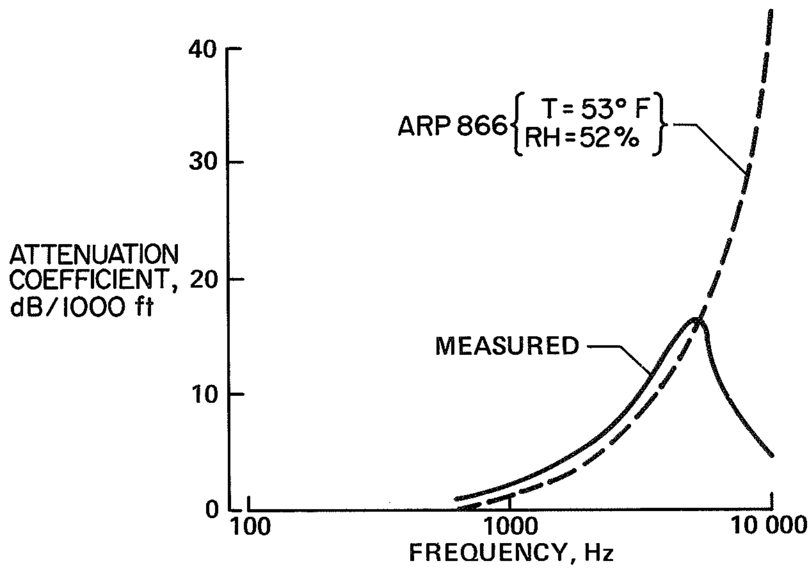

Figure 4.- Measured versus predicted attenuation for example 1.

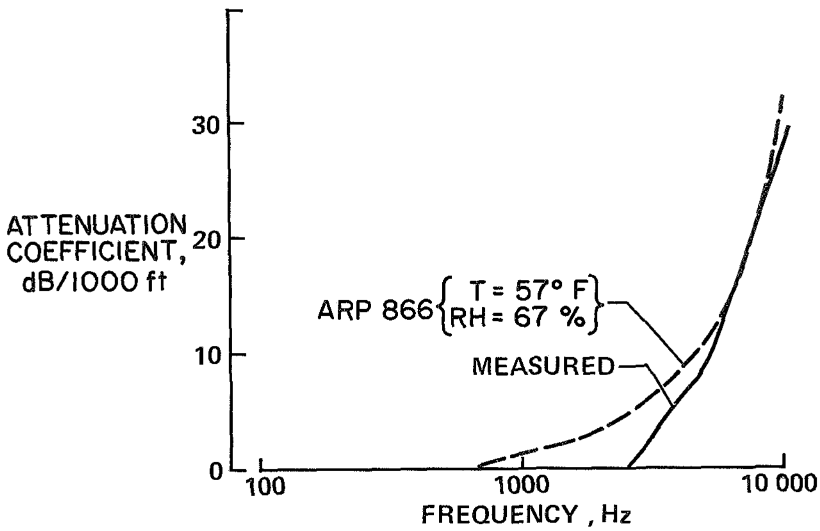

Figure 5.- Measured versus predicted attenuation for example 2.

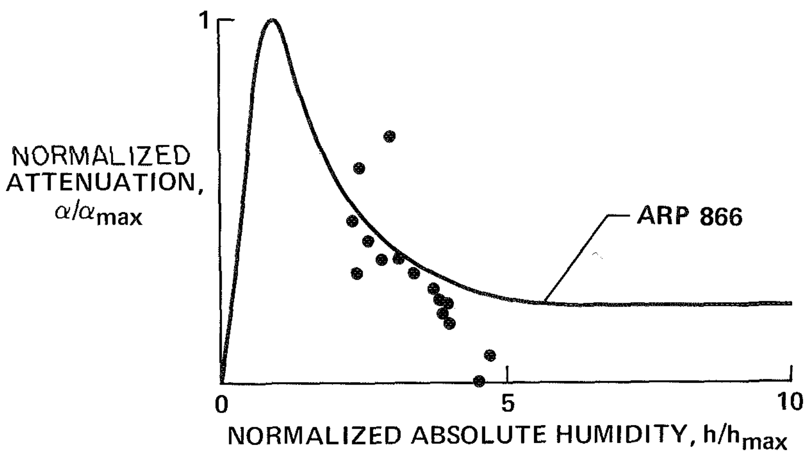

Figure 6.- Normalized attenuation.

12. TECHNIQUES USED IN McDONNELL DOUGLAS SUBJECTIVE NOISE-RATING STUDIES

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SUMMARY

Recordings of DC-8-55 flyovers with both treated and existing nacelle configurations are being used in a psychoacoustic test. The results will be used to provide an empirical evaluation of the subjective effects of the nacelle treatment and an evaluation of existing noise-rating scales in terms of their accuracy in predicting the results of this particular change in noise spectra.

Outdoor recordings were selected to represent all combinations of three nominal thrust levels (15 000, 10 000, and 5000 lb) and three heights (500, 1000, and 2500 ft) for both the treated and existing nacelle configurations. Indoor recordings of treated and existing nacelle configurations were selected for the three thrust conditions for one location. Pair-comparison tests in an anechoic chamber using 40 college-age subjects are currently in progress, all subjects having normal hearing. Pairs of noise test stimuli were constructed to provide four comparisons $\left(\pm 1\frac{1}{2} \text{ and } \pm 4 \text{ dB}\right)$ for each condition. Pairs were chosen to equate for order effects and existing or treated as standard. Pairs of noise stimuli are being presented to the subjects in a random order.

Results will be analyzed to provide a statistical statement concerning the accuracy of the prediction of various existing scales such as EPNL, PNL, dB(A), and others.

INTRODUCTION

The usefulness of a body of knowledge generally increases as a function of the degree that mathematical formulations may be validly applied. Most, if not all the time, this usefulness requires quantitative data in the form of scalar information. Measurement seems to come naturally to the physical sciences but it was only a relatively short time ago that what is now called an inch was the length of the first joint of a king's index finger. Naturally, this length varied from king to king; consequently, its value was limited. However, as soon as a standard, although arbitrary, unit was established, order could be and was established.

A scale by itself has little value but a valid scale increases the accuracy of prediction and allows one to quantify and generalize from one situation to another in a convenient manner. A valid and reliable psychoacoustic scale of annoyance resulting from noise would be of significant value in aiding aircraft designers and operators to reduce airport noise. Such a scale is mandatory for the establishment of equitable noise levels.

During the past several decades, a number of noise-rating scales have been developed. (See table I.) Original work was primarily concerned with quantifying loudness. Later work attempted to account for other factors in annoyance, such as pure tones or duration of the sound. The introduction of jet aircraft and helicopters into general use has further complicated the situation since the resulting noises make it necessary to consider additional noise variables. Each major engine development suggests the need for a new scale because of significant changes in the spectrum.

The development of a valid psychoacoustic scale for an essentially aesthetic judgment is not easy. Among the factors which complicate this task are

(1) The many attributes of the stimulus

(2) The wide variance of the observer characteristics

(3) Consideration of environmental factors

(4) Difficulty in specifying a precise stimulus

(5) Difficulty of control, even if the stimulus is adequately specified

Table II lists some of the factors which may contribute to scaling error.

These factors do not negate the use of psychoacoustic scales, they simply suggest caution. The DC-8-55 nacelle treatment has resulted in an important change in engine noise spectra. The pure-tone content associated with compressors has been significantly reduced. It was therefore judged important to conduct a psychoacoustic study to determine which of the existing scales most accurately predicts the human response of rating the effect of the nacelle treatment. Furthermore, since house attenuation influences the high-frequency segment of the spectra, as does the nacelle treatment, it was considered advisable to evaluate the accuracy of predicting indoor as well as outdoor spectra.

METHOD

Forty college students with normal hearing (within ±5 dB of the American Medical Association standard) are being used as subjects. Approximately 20 of the subjects are female and the remainder are male.

Recordings of flyover noise were obtained during the DC-8-55 flyover test program described by Marsh (paper no. 5). Representative samples of these recordings were provided to Dr. K. Kryter of Stanford Research Institute who is performing the study. All combinations of the following outdoor conditions are being evaluated:

(1) Thrust: takeoff (15 000 lb), takeoff with cutback (10 000 lb), and landing (5000 lb)

(2) Height: 500 ft, 1000 ft, and 2500 ft

(3) Nacelle treatment: existing and treated

Recordings were obtained within a house located under the flight path for thrusts of 5000, 10 000, and 15 000 lb which corresponded to altitudes of 400, 2000, and 1500 ft, respectively. Both treated- and existing-nacelle recordings were obtained for these conditions.

These recordings were used to prepare test tapes which consisted of stimuli paired to provide a standard stimulus adjacent to a comparison stimulus for each condition noted above. This technique is commonly known as "pair comparisons," or the method of constant-stimulus differences. Treated- and existing-nacelle engine noises were used as both standard and comparison sounds. The standard sound was compared with each of four comparison sounds. The level of the comparison sounds was changed so the standard was bracketed by comparison stimuli at $\pm 1\frac{1}{2}$ and ± 4 dB. The duration of the sound was determined by the 15-dB-down points of the respective noises. Stimulus pairs were randomly ordered.

All subjects are rating all the sounds. Instructions are to rate the sounds in terms of annoyance "if heard 20 to 30 times a day in your home" and other similar words to provide a global mental set. Ten subjects at a time are rating noises in an anechoic chamber. Listening positions have been calibrated and a spectrum shaper has been used to insure an accurate representation of flyover spectra at the subjects' ears. The chamber is rectangular with two adjacent speakers on one wall to provide total coverage.

DATA ANALYSIS TECHNIQUES

The data were being collected as this paper was written. Thus, definitive results cannot be presented at this time. The methods, however, to be used in analyzing the data will be discussed.

This experiment is attempting to answer several questions. These questions may be expressed as follows:

(1) Which scale best predicts obtained values and how accurate is it?

(2) How accurate is EPNL, and is it significantly worse than the best scale?

(3) How much reduction in perceived noise actually was obtained as a result of the nacelle treatment under various operationally meaningful conditions?

(4) Are there differences between the accuracy of prediction for indoor data as opposed to that for outdoor data?

The error variance of each of the scales studied in predicting points of subjective equality will be calculated. Estimates of the accuracy of the experiment in predicting these variance values will then be determined. In addition, the means and standard deviations of the error scores will be calculated to provide insight into any existing scaling errors. It will then be possible to determine which scale proved most valid in predicting the test data and the accuracy to be expected from that scale. Graphs and charts will be provided to permit inspection of the data in order to determine any systematic or otherwise important sources of scaling error.

Thus, the most important immediate result will be a measure of the accuracy of EPNL data reported on the nacelle treatment in predicting annoyance ratings. Secondly, a judgment can be made about the value of presenting these results in terms of another scale. Finally, specific sources of error in prediction will be isolated.

DISCUSSION

It was noted in the Introduction that scales, though inaccurate, may be useful. It was also noted that the greater the accuracy, the greater their value. The methodology commonly used in annoyance scaling and represented in most aspects by this study provides a maximum amount of control of many potentially important, confounding elements. It is limited, however, by its artificiality and lack of consideration for many important variables existing in the actual situation. To be highly accurate, an annoyance scale must consider such factors as those outlined in table II. Emphasis to date has been devoted primarily to the stimulus characteristics.

It may be true that humans can generate a mental set which provides judgments which are almost perfectly correlated with those that would be obtained in the actual situation. Data exist which indicate that speech interference is most frequently cited as the most annoying characteristic of aircraft noise (ref. 1). Kryter (ref. 2) has conducted a study which suggests that annoyance ratings correlate well with speech interference. Research to date, however, is only suggestive.

CONCLUDING REMARKS

The ultimate application of scaling techniques is to produce a tool to be utilized for such purposes as land-use planning, aircraft design, and operational constraints. As such, it must be remembered that present scales are measures of relative annoyance value of noise as measured at the ear and do not contain any practical implementation factors. Furthermore, there are a number of factors, such as those listed in table II, which may have important but as yet unmeasured effects upon the annoyance resulting from noise and which suggest the importance of continuing research. Nevertheless, the present scaling techniques can be considered state-of-the-art approximations of human response and can be utilized with reasonable confidence.

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TABLE I.- SOME EXISTING NOISE-RATING SCALES

Scale	Variables considered	Comment
dB(A)	Frequency and amplitude	Single-frequency weighting per scale for all amplitudes
dB(B)	Frequency and amplitude	
dB(C)	Frequency and amplitude	
dB(D)	Frequency and amplitude	
LL	Frequency and amplitude	Separate curves for several amplitudes
PNL	Frequency and amplitude	
PNLT	Frequency, amplitude, and tone	
EPNL	Frequency, amplitude, tone, and duration	

TABLE II.- POTENTIAL FACTORS INVOLVED IN ANNOYANCE RATINGS

Stimulus characteristics	Amplitude Frequency (Hz) Duration Frequency of occurrence Change over time
Environmental characteristics	Ambient noise General nature of neighborhood Characteristics of the structure (attenuation) Weather conditions Others
Observer characteristics	Socioeconomic class Adaptation level Personal interests Tasks content Physiological characteristics
Other	Community attitudes Municipal legislation

13. TECHNIQUES USED IN BOEING SUBJECTIVE NOISE-RATING STUDIES

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INTRODUCTION

For over a decade the effect of jet airplane noise on humans has been evaluated in terms of perceived noise level (PNL). Continued use of the PNL calculation procedure has not prevented further research directed toward obtaining more precise relationships between the physical parameters of the flyover noise and man's response. Corrections to the PNL calculation procedure have resulted from this continuing research for both discrete frequencies (tone above background noise) and duration. However, from the standpoint of flyover-noise-reduction efforts, the most disconcerting finding is that, at times, the amount of noise reduction predicted by the PNL procedure is not matched by human perception. Results from both laboratory and field-test studies of man's response to flyover noise indicate that reductions of 13 to 16 PNdB are required for groups of judges to rate the lower-level noise as one-half the noisiness of the original noise (refs. 1 and 2). These results indicate that, if the aim is to reduce the noise by one-half, the reduction should be on the order of 15 PNdB instead of 10 PNdB, which was the value assumed in the development of the PNL calculation procedure. This inconsistency between subjects' judgments and the assumed rate of change of noisiness played a major role in the selection of the approach used to determine the noise reduction achieved in the National Aeronautics and Space Administration Treated-Nacelle Program.

APPROACH

General

A field-test approach was used, with the main noise stimuli being level flyovers of both an existing 707 airplane and a 707 airplane treated for noise reduction. Annoyance judgments were also obtained for routine airplane flyovers and for random noise presented over loudspeakers.

Six groups of 30 persons judged all the noises at six different listening positions. Three of the listening positions were inside trailers (one directly under the flight path and two at sidelines 1000 and 1500 feet from the flight path). The other three were outside listening positions adjacent to each of the three trailers. Figure 1 is a schematic drawing of the six positions.

Noises Judged

Judgments were obtained for the annoyance to four groups of stimuli. These four groups are designated as (1) pairs, (2) specials, (3) unscheduled traffic, and (4) loudspeaker noise. Table I shows the number of noise events judged in each of the four groups.

Pairs.- Pairs of level flyovers simulating landing and take-off conditions were used. Table II shows the pairs as planned for the two days of testing. For each condition, the existing airplane was flown repeatedly at a given altitude while the treated airplane was flown at three different altitudes so that the noise levels would be about 5 PNdB less than, equal to, and 5 PNdB greater than the level for the existing airplane. Each of the resulting four sets of three pairs in table II was to be flown twice. On one occasion, the subjects first judged the existing airplane and then the treated airplane, while on the other occasion, the order of presentation for the pair was reversed. One of the main reasons for using pairs of flyovers was to determine the extent of agreement between various engineering calculation procedures and the subjective evaluations, as discussed subsequently in the section "Analysis Techniques." Since it was not possible to complete all of the program for the second day, some of the pairs listed for that day were not flown.

Specials.- Individual flyovers of both the existing and treated airplanes were made at the same altitudes and power settings. These flyovers are referred to as specials.

Unscheduled traffic.- Subjective evaluations were obtained for jet-powered airplanes that routinely use the airport for crew training. This group of stimuli is referred to as unscheduled traffic.

Loudspeaker noise.- At the beginning of each listening session, a 4-second USASI noise at a level of 90 PNdB was presented via loud speakers at all six listening positions. This was the standard to which the subjects were to compare all noises for that session. (USASI noise is random noise with a frequency distribution that peaks at 250 Hz and falls off at -3dB/octave from this peak.) During the session, the 4-second USASI noise was again generated at six different levels during times when flyovers were not occurring. These levels were 70, 75, 80, 85, 90, and 95 PNdB for the inside listening positions and 80, 85, 90, 95, 100, and 105 PNdB for the outside listening positions. The three main reasons for asking the subjects to judge this artificial noise were the following:

(1) Judgment of the artificial noise was a means for determining that the subjects were adequately performing the task.

(2) Since it was not possible to present flyovers on a regular basis, making annoyance judgments of the artificial noise during slack periods kept the subjects at their task.

(3) Subjective evaluations of the same steady-state noise at different levels allowed assessment of the extent that noise-reduction approaches, based on a particular calculation procedure, match judges' ratings of the flyover noise.

Judges and Their Task

The 180 judges for the six listening positions were hired through a state employment agency. There was an equal number of males and females. Applicants were required to respond to a 40-item "Annoyance Questionnaire." Since there were ten items relating to noise in the questionnaire, it was possible to equate the six listening groups on the basis of their reported sensitivity to noise in general. The questionnaire was also used as a kind of screening device. Prior to employment, the questionnaires were examined for ability of the applicants to follow the simple instructions. It was presumed that anyone who could not understand the instructions for the "Annoyance Questionnaire" would also have difficulty in understanding the nature of the noise-judgment task.

The subjects made their judgments under the following instructions, which they were asked to read:

"We are asking you to help us solve a problem concerned with noise: How annoying or disturbing are various kinds of sound when heard in your home? You will be asked to give a score for each sound. First, we will produce a sound whose noisiness score is 10. Use that sound as a standard, and judge each succeeding sound in relation to that standard. For example, if a sound seems twice as noisy as the standard, you will write 20 in the appropriate box on the answer sheet. If it seems only one-quarter as noisy, write 2.5. If it seems three times as noisy, write 30, and so on. Please try to judge each sound carefully, and give it a score that tells how strong the annoyance seems to you. There are no right or wrong answers. The important thing is to say how you rate each of the sounds."

After the subjects had read the instructions, the test director made the following announcement over the loudspeaker systems: "Your rating should be only your own opinion. The test will begin in a moment. Here is the sound which has a noisiness score of 10. Listen to it carefully." To give an idea of the judges' task, the log for the noise judgments of session I is presented as table III.

ENGINEERING CALCULATION PROCEDURES TO BE EVALUATED

Eighteen separate calculation procedures are to be evaluated. The basis for nine of these procedures is the widely used PNL scale. The remaining nine are based on S. S. Stevens' Perceived Loudness Level (Mark VI) from which the PNL approach was originally derived. Each of the two basic engineering calculation procedures is to be evaluated without corrections. In addition, two different tone correction methods utilizing two different methods for identifying the tone will be applied to each basic procedure. Finally, all tone-corrected procedures will be corrected for duration. Thus, the procedures to be evaluated are the following:

(1) Perceived Noise Level (PNL)

(2) Perceived Loudness Level (Mark VI) (PLL)

(3) PNL with tone correction according to FAA Docket No. 9337, Notice No. 69-1

(4) PLL with tone correction according to FAA Docket No. 9337, Notice No. 69-1

(5) PNL with tone correction of Third Revised Draft of Proposed FAA Noise Certification Criteria (May 1, 1967)

(6) PLL with tone correction of Third Revised Draft of Proposed FAA Noise Certification Criteria (May 1, 1967)

(7), (8), (9), and (10) Same as (3), (4), (5), and (6), respectively, but with the tone identified by a four-band averaging technique

(11), (12), (13), (14), (15), (16), (17), and (18) Duration correction to FAA Docket No. 9337, Notice No. 69-1, applied to procedures (3) to (10)

Procedures (11) to (18) yield various forms of Effective Perceived Noise Level. Procedure (11) is recommended by the FAA in Docket No. 9337, Notice No. 69-1.

ANALYSIS TECHNIQUES

The data were collected in such a manner that two analysis approaches could be utilized. The two approaches are the method of constant-stimulus differences (sometimes referred to as the method of pair comparisons) and the method of direct magnitude estimation.

Constant-Stimulus Differences

The aim of this method is to determine the extent that the subjective evaluations agree with a particular calculation procedure. Figure 2 shows some expected results for pairs 4, 5, and 6 from judgments made at the positions directly under the flight path.

The premise and conclusion for this approach is that if two different sounds are judged equally annoying, an acceptable engineering calculation procedure assigns the identical real number to both sounds.

Figure 2 shows a case of good agreement between the subjective judgments and the calculation procedure since the discrepancy is less than 1 PNdB. All eighteen procedures are to be evaluated by using the available sets of pairs, and the procedure for which the agreement is best becomes a likely candidate for describing the amount of noise reduction achieved.

Direct Magnitude Estimation

The magnitude-estimation method, refined by S. S. Stevens of Harvard, has been used widely as a method of relating human response to a physical stimulus. Data from many studies indicate that sensation is a power function of the stimulus. Consequently, in log-log plots a linear equation is obtained for the relationship between the judgments and the physical evaluation of the noise.

Figure 3 shows a plot of one set of expected results. Note that the rate of change of annoyance for the airplane flyovers is less than that for the USASI noise. This prediction is made on the basis of the previously mentioned studies (refs. 1 and 2).

CONCLUDING REMARKS

The findings of this study must be analyzed by both the constant-stimulus-differences technique and the magnitude-estimation technique for each engineering calculation procedure. Subsequently, the results must be compared with previous relevant sets of similar data that describe human response to airplane flyover noise. It is naturally expected that good agreement will exist between the two analysis techniques since they both draw from the same pool of data. However, when subject variability is high or when the sounds being judged are unique enough to bias responses so that they are different than expected, the two methods may produce different findings.

At this time there seem to be two very distinct advantages to the described test method for field testing of subjects. First, there is the strong advantage that at least two different analysis techniques can be used on the same set of data. Second, the method has excellent practical advantages since a precise test format is not essential. Testing with aircraft in flight depends on having good weather and uninterrupted aircraft performance, neither of which can be guaranteed. The described method allows for test-plan deletions or additions at will with no significant loss in data if only a few conditions of a set are missed.

Finally, it must be remembered that most of the past work relating human response to aircraft noise has been done in laboratory studies, which are usually simpler and less expensive than field tests of the type described in this report. Thus, there is a natural concern that correlation be established between field and laboratory findings. All sounds judged in the present field test are stored on magnetic tape, and thus a source of stimulus material is provided for subsequent laboratory investigation.

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TABLE I.- NOISE EVENTS

Noise group	Number of noise events		
	First day	Second day	Total
Pairs	12	10	22
Specials	8	3	11
Unscheduled traffic	3	11	14
Loudspeaker noises:			
Standards*	1 + 5	1 + 5	2 + 10
Other levels	25	25	50

*The standard was identified for the subject only one time each day but was presented five more times.

TABLE II.- PAIRS OF EXISTING AND TREATED AIRPLANES

[E = Existing airplane; T = Treated airplane]

First day			Second day								
Simulated landings with 5000-lb thrust			Simulated landings with 5000-lb thrust			Simulated take-offs with maximum thrust			Simulated take-offs with cutback thrust		
Airplane	Altitude (ft)	PNL (PNdB)	Airplane	Altitude (ft)	PNL (PNdB)	Airplane	Altitude (ft)	PNL (PNdB)	Airplane	Altitude (ft)	PNL (PNdB)
E	2000	99	E	2000	99	E	2100	108	E	3400	98
T	1150	94	T	1150	94	T	2100	103	T	2100	93
T	850	99	T	700	99	T	1600	108	T	1600	98
T	650	104	T	450	104	T	1100	113	T	1100	103

TABLE III.- LOG FOR NOISE JUDGMENTS OF SESSION I

[E = Existing airplane; T = Treated airplane]

No.	Code (*)	Notes	Time	No.	Code (*)	Notes	Time
0	3u	Standard at 90 PNdB	2:40	27	5	E (altitude of 2040 ft)	3:20
1	3u	90 PNdB		28	5	T (altitude of 875 ft)	3:23
2	4u	95 PNdB		29	6u	105 PNdB	
3	1u	80 PNdB		30	2u	85 PNdB	
4	1u	80 PNdB		31	4u	95 PNdB	
5	(8)	E (special landing)	2:47	32	4u	95 PNdB	
6	1u	80 PNdB		33	1	T (altitude of 1255 ft)	3:36
7	DC-8	No recording	2:48	34	1	E (altitude of 1980 ft)	3:38
8	2u	85 PNdB		35	3u	90 PNdB	
9	6u	105 PNdB		36	1u	80 PNdB	
10	2	T (altitude of 870 ft)	2:49	37	1u	80 PNdB	
11	2	E (altitude of 2100 ft)	2:56	38	5u	100 PNdB	
12	4u	95 PNdB		39	6u	105 PNdB	
13	3u	90 PNdB		40	4	E (altitude of 2100 ft)	3:44
14	6u	105 PNdB		41	4	T (altitude of 1170 ft)	3:47
15	(7)	T (special landing)	2:59	42	3u	90 PNdB	
16	DC-8	Landing		43	5u	100 PNdB	
17	5u	100 PNdB		44	5u	100 PNdB	
18	2u	85 PNdB		45	3u	90 PNdB	
19	2u	85 PNdB		46	6	E (altitude of 2180 ft)	3:54
20	3	T (altitude of 640 ft)	3:11	47	6	T (altitude of 710 ft)	3:56
21	3	E (altitude of 2000 ft)	3:14	48	(9)	E } (1000-ft alt.; max.	4:02
22	DC-8	Landing	3:15	49	(10)	T } take-off thrust)	4:03
23	6u	105 PNdB		50	(11)	E } (1000-ft alt.;	4:11
24	5u	100 PNdB		51	(12)	T } cutback thrust)	4:13
25	4u	95 PNdB		52	(13)	E } (700-ft alt.;	4:19
26	2u	85 PNdB		53	(14)	T } actual landing)	4:20

*u refers to USASI noise; all USASI noise durations are 4 seconds.

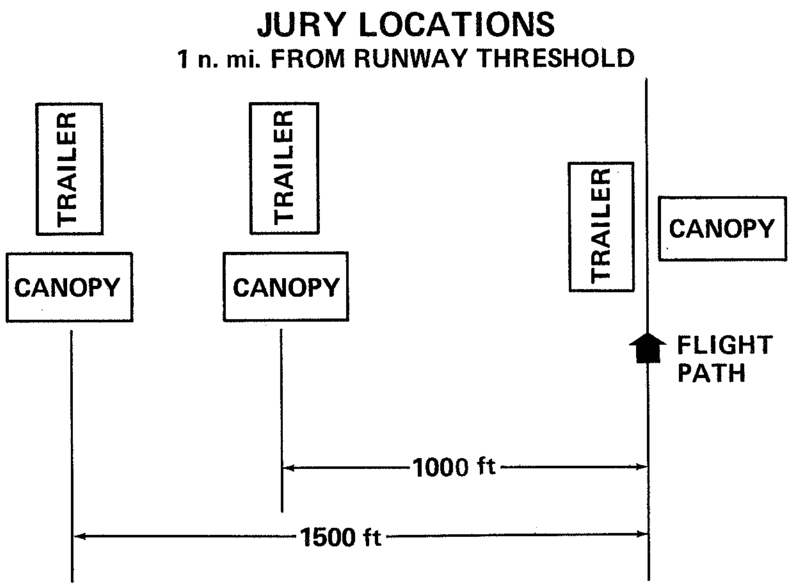

Figure 1

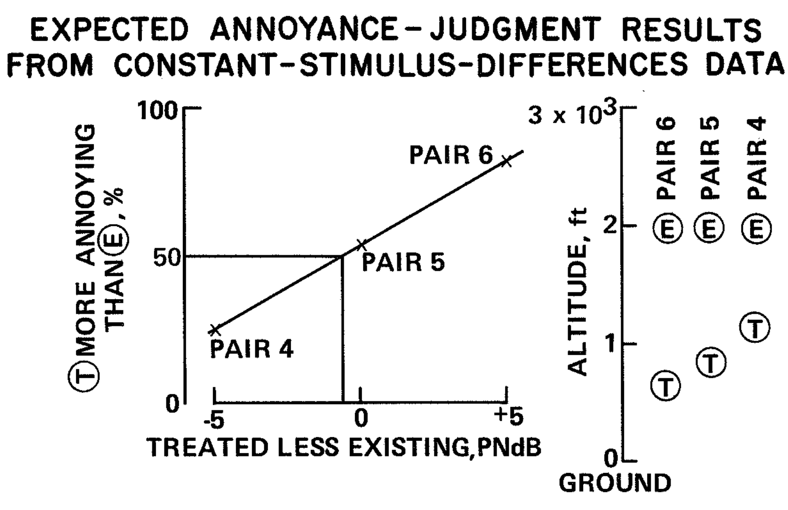

Figure 2

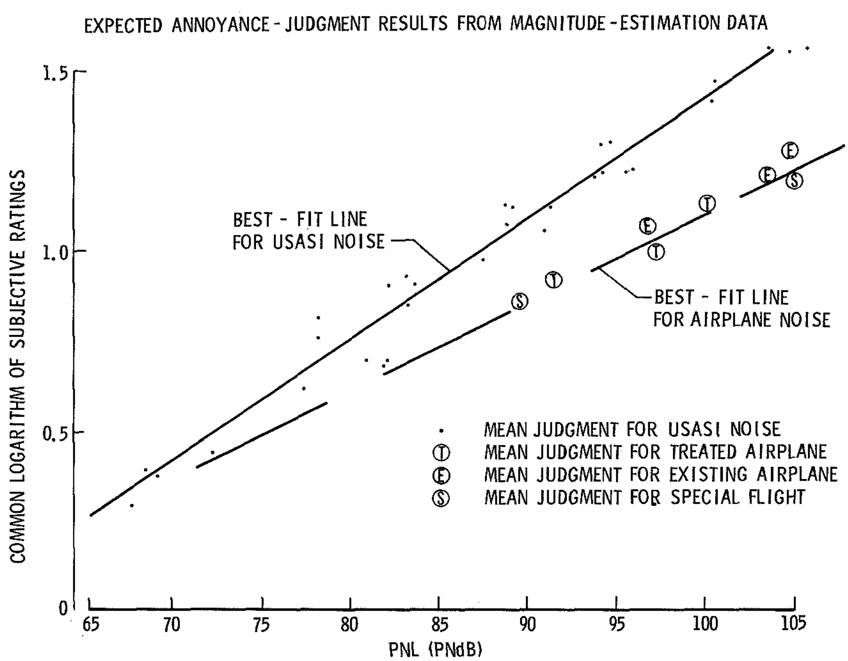
EXPECTED ANNOYANCE - JUDGMENT RESULTS FROM MAGNITUDE - ESTIMATION DATA
COMMON LOGARITHM OF SUBJECTIVE RATINGS
1.5
1.0
0.5
0
BEST - FIT LINE FOR USASI NOISE
BEST - FIT LINE FOR AIRPLANE NOISE
MEAN JUDGMENT FOR USASI NOISE
T MEAN JUDGMENT FOR TREATED AIRPLANE
E MEAN JUDGMENT FOR EXISTING AIRPLANE
S MEAN JUDGMENT FOR SPECIAL FLIGHT
65
70
75
80
85
90
95
100
105
PNL (PNdB)

Figure 3

14. CLOSING REMARKS

By Robert W. Boswinkle, Jr.
NASA Langley Research Center

RESULTS

Important results of the NASA Acoustically Treated Nacelle Program are illustrated in figure 1. The noise reduction with nacelle treatment during landing approach is shown as a function of percent change in direct operating cost (DOC). The coordinates for the McDonnell Douglas design are 10.5 EPNdB at a 4.2 percent DOC increase and for the Boeing design 15.5 EPNdB at a 9.2 percent DOC increase. These direct operating cost increases are largely due to the costs of retrofitting the airplanes considered and are not applicable to other situations where treatment may be incorporated during original production.

The curve in figure 1 merely connects the two principal data points obtained in the program and thus applies to the conditions of the study, which include retrofit, the JT3D engine, the specific airplanes used, the weight conditions tested, and so forth. Perhaps under certain conditions the curve would be somewhat different, perhaps even discontinuous; nevertheless, this simplified figure illustrates two important points: (1) substantial noise reductions are possible, and (2) the direct operating costs increase with increasing noise reductions.

MAJOR ACCOMPLISHMENTS

In the course of getting these two very valuable coordinates, many other accomplishments resulted. Some of these accomplishments follow:

(1) The noise reduction goals were met.

(2) The achievement of the noise-reduction goals provides optimism that similar design procedures may be valid for other installations.

(3) The successful estimate of flyover noise levels from engine ground tests provides optimism that flight tests will not always be required in future studies.

(4) The many analyses and laboratory studies of acoustic lining material have advanced substantially the technology of treatment application to engine nacelles.

(5) A number of metallic and nonmetallic materials have been identified as satisfactory, acoustically, for duct lining application, the choice depending largely on such factors as weight, strength, and cost.

(6) Valuable experience was gained which has improved the techniques of noise measurement.

(7) A successful ground test demonstration was made of a mechanized and controllable area inlet design which attenuates the emitted noise by fully or partially choking the entering flow.

(8) The subjective reaction studies have yet to be completed; however, it appears that much useful information will be forthcoming, including evaluation of effective perceived noise level (EPNL) and other parameters as noise annoyance indicators, and evaluation of the effectiveness of various test techniques involving juries.

REQUIRED ADDITIONAL MAINTENANCE STUDIES

Although the treated nacelles were successfully flight tested and although no maintenance-type problems were encountered, additional studies along this line would be required before a production type nacelle could be said to be available; these studies would include contamination of acoustic material during in-flight service, inservice life of acoustic material, and repairs and replacement of acoustic material.

CONTINUED RESEARCH

Although the two studies are approaching completion, Langley continues support of research in the area of jet aircraft noise alleviation. The attenuation of fan noise by means of acoustic treatment of the nacelle can be sufficiently effective so that the noise from the primary jet predominates, particularly during take-off. There is considerable interest, therefore, in attacking the primary jet noise, but no dramatic solution is yet in hand. The turbine and turbulence noise emitted from the engine in the primary jet may be amenable to acoustic treatment of the tailpipe and a study in this area is planned. The noise reduction potential of tailpipe treatment for the JT3D engine appears to be about 3 PNdB; however, probably more importantly the study will give us experience with acoustic treatment in the hot section of the engine.

CONCLUDING REMARKS

It should be kept in mind that despite the gains made by the McDonnell Douglas and Boeing studies in reducing noise, silent jet engines have not yet been attained. Rather, the present studies have indicated how only some of the airport community noise might be alleviated.

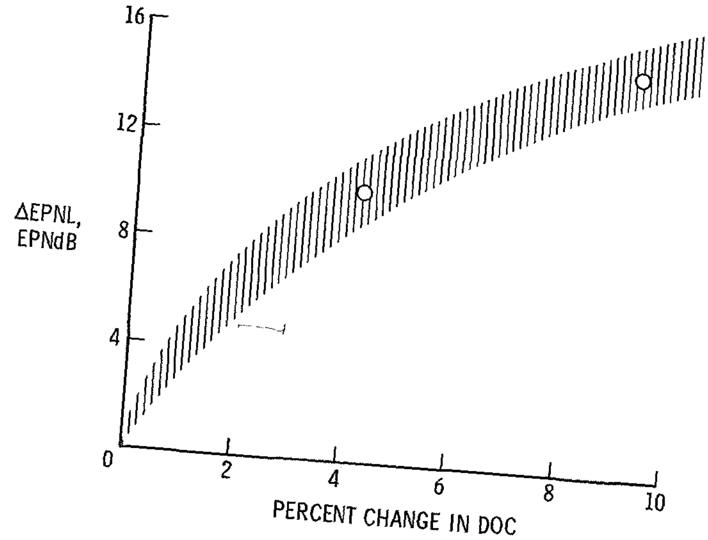

Figure 1.- Benefits and costs of retrofitted nacelles.

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