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INVESTIGATION OF DC-8 NACELLE MODIFICATIONS TO REDUCE FAN-COMPRESSOR NOISE IN AIRPORT COMMUNITIES

Part I – Summary of Program Results

by Robert E. Pendley and Alan H. Marsh

Prepared by
MCDONNELL DOUGLAS CORPORATION
Long Beach, Calif. 90801
for Langley Research Center

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16. Abstract

An investigation was conducted of methods to reduce fan-compressor noise from the JT3D-3B engines of DC-8 airplanes equipped with short duct nacelles. The purpose of the investigation was to define modifications that could be applied to the nacelles of operational airplanes and could reduce the perceived noise level by 7 to 10 PNdB under the landing-approach path without adverse effects on takeoff noise. The program included laboratory investigations, full-scale ground tests, and flight tests. This document presents a summary of the program results.

The modified-nacelle design that was selected incorporated revised fan inlet and exhaust ducts containing acoustically absorptive linings. Flyover noise evaluations were made in terms of perceived noise level (in units of PNdB) and effective perceived noise level (in units of EPNdB). The results of flight tests using a DC-8-55 airplane indicated that the modifications, on an airplane at maximum certified landing weight, would achieve a 10.5 EPNdB reduction in the noise outdoors at a point on the ground beneath a 3° landing-approach path one nautical mile from the runway threshold. Analysis of measurements made beneath the takeoff path indicated that the noise 3.5 nautical miles from brake release for maximum- gross-weight takeoffs would be reduced by 3.5 EPNdB if rated takeoff thrust were maintained and by 5 EPNdB if the thrust were reduced to that required for a 6-percent climb gradient. The maximum sideline noise (1500 ft from the runway centerline) during takeoff and initial climb would be reduced by approximately 3 EPNdB.

The nacelle modifications reduced the static takeoff-rated gross thrust by 2.5 percent. The flight-test data indicated that the modifications improved the cruise fuel consumption and therefore the maximum-range capability by approximately 3 percent. Airplane performance calculations indicated minor effects on takeoff field length and maximum initial cruise altitude, and a negligible effect on block speed.

Economic studies indicated that the initial cost of modifying the nacelles of airplanes in service would be $655 000 per airplane, if a fleet of 250 airplanes were retrofitted, and $863 000 per airplane, if 125 airplanes were retrofitted. With the assumption of an average depreciation period of 5 years for the retrofitted fleet of 250 airplanes, it was estimated that the modification would increase direct operating costs 4.4 percent and would reduce return on airplane investment 8.2 percentage points.

Flyover noise recordings obtained during the flight tests were reproduced in an anechoic chamber to obtain human judgments of the improvement achieved by the modified nacelles. Subjective judgment tests indicated slightly larger improvements in acceptability due to the nacelle modification than were calculated directly in terms of effective perceived noise level and several other noise-rating scales of current interest.

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CONTENTS

INVESTIGATION OF DC-8 NACELLE MODIFICATIONS TO REDUCE FAN-COMPRESSOR NOISE IN AIRPORT COMMUNITIES

PART I - SUMMARY OF PROGRAM RESULTS

By Robert E. Pendley and Alan H. Marsh

INTRODUCTION

Human annoyance caused by operations of commercial jet transports has increased with the growth of the air transportation industry and the number of people living in communities around airports. This increased annoyance has stimulated efforts to alleviate the problem through reducing the level of the noise radiated from the aircraft, through modifying aircraft operational procedures, and through achieving compatible usage of the land around airports. The alleviation efforts are being conducted as part of a coordinated industry-government research program.

In May 1967, the Langley Research Center of the NASA contracted with the McDonnell Douglas Corporation and The Boeing Company to investigate nacelle modifications for operational McDonnell Douglas and Boeing transports powered by four Pratt and Whitney Aircraft (P&WA) JT3D turbofan engines. The nacelle modifications were to achieve significant reductions in flyover noise levels in airport communities.

During landing approach, the perceived noisiness – and hence the annoyance caused by the sound from the JT3D engines – is attributed principally to the discrete-frequency tones radiated from the fan stages through the inlet and fan-exhaust ducts. Accordingly, the purpose of the McDonnell Douglas and the Boeing investigations was to develop methods of reducing fan noise. The McDonnell Douglas investigation was directed toward the determination of nacelle modifications that could reduce fan noise primarily through the use of fan-inlet ducts and short fan-exhaust ducts containing acoustically absorptive materials. The modifications were to be applicable to DC-8 airplanes equipped with short-duct nacelles, that is, to the Series 50 and the Model 61 airplanes.

The McDonnell Douglas goal was a 7 to 10 PNdB reduction in outdoor perceived noise level (PNL) under the landing approach path. The Boeing goal was 15 PNdB. Both programs required that the nacelle modifications be designed to satisfy the following requirements:

- No adverse effect on takeoff or climbout noise
- No compromise with flight safety
- No additional flight crew workload
- Retroactively modified airplanes to be economically viable.

In seeking economic viability, efforts were to be made to minimize changes in existing nacelle or pylon structure and equipment.

The McDonnell Douglas program was performed, and is reported, in five phases: (1) initial nacelle-modification design studies and duct-lining investigations (ref. 1); (2) ground static tests of suppressor configurations (ref. 2); (3) a flight investigation of the acoustical and performance effects of the selected design of modified nacelles on a DC-8-55 airplane (ref. 3); (4) a study of economic implications of retrofit of the selected design (ref. 4); and (5) an evaluation of human response to the flyover noise of the modified nacelles (ref. 5).

The purpose of this document is to summarize the results of the McDonnell Douglas program. The results of the Boeing program are summarized in reference 6.

DESCRIPTION OF NACELLE MODIFICATION

Existing Nacelle Design

The configuration of the short-duct nacelles of DC-8 Series 50 and Model 61 airplanes is illustrated in figure 1(a). The fan air-inlet ducts are provided with relatively thick inlet lips to produce high inlet pressure recovery (and therefore thrust) at takeoff conditions. As a result, there is a substantial space between the inlet duct skins and the exterior nose-cowl skins. This space is utilized for the installation of oil and pneumatic system heat exchangers, the nose-cowl ice-protection system, and related piping, valves, and ducting.

The fan-exhaust air is led through bifurcated ducts 24 inches long and discharged through two nozzles, one on each side of the nacelle. Cascade-type fan-air thrust reversers are located immediately downstream from the nozzles. The lower part of figure 1(a) illustrates the extended (reverse thrust) and stowed (forward thrust) positions of the reverser. The engine turbine exhaust is discharged through the primary nozzle. A thrust-reverser assembly for the turbine exhaust gas is incorporated inside the primary nozzle.

Modified Nacelle Design Suitable for Retrofit

A number of modifications to the existing nacelle design were studied in the first two phases of the program. The studies led to the selection of the modified design illustrated in figure 1(b). The inlet design provided for a total of approximately 64 square feet of acoustically absorptive materials on the inlet duct walls, on the centerbody, and on both surfaces of a concentric ring vane. The ring vane was supported by four pairs of struts located in the vertical and horizontal planes. In addition to providing structural support, the design of these struts provided for passages through which compressor-bleed air could be ducted for ring-vane anti-icing.

The fan-exhaust ducts were lengthened to 48 inches in order to provide enough acoustically absorptive surface area to meet the noise-reduction design goal. Approximately 70 square feet of acoustical materials were provided on the duct inner and outer walls and on both sides of the longitudinal splitters that divided each duct branch into five separate channels. The longer fan-exhaust ducts would restrict engine access if they were designed as fixed, integral components. Therefore, a joint was provided to separate fixed forward portions of the ducts from movable aft sections that may be pivoted outward about hinges at the top. The longer fan-exhaust ducts would also require new fan thrust reversers. As may be seen in figure 1(b), there is less space between the engine casing and the nacelle outer skin at the more downstream fan-nozzle location. Fan thrust reversers of a new design would be required to fit within that space. A design based on the concept of single-panel pivoting deflectors mounted on each side of the nacelle was found to be feasible. The extended and the stowed positions of the deflectors are illustrated in the lower part of figure 1(b).

In order to modify existing nacelles to this design, the existing inlets, fan-exhaust ducts, and fan thrust reversers would have to be replaced by the new components. In addition, the existing nacelle-access doors must be replaced by new doors to fit the acoustically treated inlet and fan-discharge ducts, and a number of internal nacelle components must be relocated or replaced by components compatible with the new duct shapes. The existing primary exhaust nozzle, primary thrust reverser, pylon, and pylon-nacelle interfaces would not be affected.

Estimated weight changes due to the modification are summarized below.

Component	Weight, pounds per nacelle		
	Existing	Modified	Increase
Inlet duct	244	390	146
Fan exhaust ducts	98	322	224
Fan thrust reversers	475	188	−287
Other affected components	472	472	0
Total of affected components	1289	1372	83

As the sum of the first two numbers in the third column indicates, the new acoustically treated ducts would weigh 370 pounds more than the existing components they replace. However, the new single-panel thrust reversers would weigh 287 pounds less than the existing cascade type they replace. The weight of all other new nacelle components would approximately equal the weight of the components they replace. The net weight change due to the modification would therefore amount to 83 pounds per nacelle. The thrust-reverser weight reduction, which largely offsets the weight increase due to the nacelle acoustical treatment, has been made available through the results of thrust-reverser development programs subsequent to the development of the existing thrust-reverser design. Although the reverse-thrust effectiveness of reversers of the single-panel type is somewhat less than that of the cascade type, recent thrust-reverser development programs have shown that satisfactory effectiveness can be obtained through proper design of the single-panel type.

Materials for acoustical duct linings were selected during the initial study phase of the program and are illustrated in figure 2. The porous facing sheets replaced the aluminum skins in the existing fan inlet and exhaust ducts and were therefore in grazing contact with the duct aerodynamic flow. The facing sheets were made of fine, sintered, stainless-steel fibers. Desired values of porosity were obtained through control of sheet thickness and surface density. The porous facing sheets and the solid (impervious) backing sheets of aluminum or titanium were bonded to a honeycomb core made from phenolic-resin-coated fiberglass cloth. The bonding agent was an aluminum-filled modified-epoxy adhesive. Drainage slots were provided in the honeycomb core to prevent the accumulation of water or other nacelle fluids within the core cells. Linings of this type absorb part of the incident noise through transforming acoustical energy into heat. Air particles within the porous material are vibrated by the incident noise; viscous resistance to the vibrating motion within the porous material results in the conversion of sound energy into heat.

Modified Nacelle Design Flight Tested

One of the four modified nacelles built for the flight-test program is shown in figure 3. These nacelles were designed to permit evaluation of the acoustic, aerodynamic, engine performance, and operational effects of the potential retrofit design described above. Certain features needed for operational versions of retrofitted nacelles were not essential to the accomplishment of flight-program objectives and were omitted from the experimental flight-test nacelles. The flight nacelles did not include operable fan-exhaust thrust reversers, operable inlet-duct ice-protection systems, or duct joints and access doors needed to permit rapid engine inspection and maintenance. In addition, the inlet-duct assemblies did not include oil or pneumatic-cooling-system components; the functions of these components were performed by simplified provisions within the engine accessory section. However, the nacelles were equipped with the acoustical duct-lining material illustrated in figure 2, and all inlet-duct, fan-exhaust-duct, and nacelle contours were identical to those of the retrofit nacelle design, in order to simulate the internal and external aerodynamic effects of the modification.

FLIGHT EVALUATION OF MODIFIED NACELLES

Description of Test Airplane

The airplane used for the flight evaluation was a McDonnell Douglas DC-8 Model 55 equipped with JT3D-3B engines in short-duct nacelles. A photograph of the test airplane with the existing nacelles is presented as figure 4. Basic characteristics of the airplane are as follows:

Fuselage length, feet	146.3
Wing span, feet	142.4
Maximum takeoff gross weight, pounds	325 000
Maximum landing gross weight, pounds	240 000
Operator's empty weight (international operating rules and 135-seat interior configuration), pounds	137 490

Basic uninstalled sea-level static thrust ratings of the JT3D-3B engine are as follows:

Takeoff thrust (flat-rated to 84°F), pounds	18 000
Maximum continuous thrust, pounds	16 400

Test Instrumentation and Methods

The test airplane was instrumented for measurements of (1) the flight path and the airplane and engine operating variables during flyover-noise tests and (2) the change in cruise performance due to the nacelle modifications. Tests of flyover noise and of cruise performance were made with the airplane equipped with the existing production short-duct nacelles and were then repeated after installation of the modified nacelles. In addition, observations were made during ground and flight tests of engine-operating characteristics, including engine starts, accelerations, and decelerations. The cruise-performance measurements were supplemented by tests of the existing nacelles and of the modified nacelles, on an instrumented static engine test stand, to determine the changes in noise level and basic propulsive characteristics due to the modified nacelles.

After the completion of the flyover-noise and cruise-performance tests, subjective-judgment tests of the improvement in the acceptability of the sound of aircraft flyovers were conducted by using flyover noise recordings obtained at various locations outdoors and at a location inside a house.

Flyover noise tests. – The noise tests were made during February and March 1969 in the vicinity of the Fresno Air Terminal in Fresno, California. Ten mobile sound stations were used to record the noise during the tests. Noise measurements were made during twelve different flight operations, comprising takeoffs using takeoff-rated thrust, simulated takeoffs using the thrust required for a reduced climb gradient, and landing approaches along the Instrument-Landing-System flight path.

During the rated-thrust takeoffs, noise levels were recorded at locations near the brake-release point, under the initial-climbout flight path, and along lines parallel to and 1500 feet from the runway centerline. During the tests at the other engine power settings, measurements were made only at locations under the flight path. The airplane was operated over a range of nominal gross weights from 185 000 to 300 000 pounds. The tests were repeated on each of three different days with both the existing and the modified nacelles.

Surface and low-altitude weather measurements were made at the test site to determine compliance with test criteria (ref. 3) and to provide the air temperature and relative-humidity data needed to correct the measured noise levels to reference atmospheric conditions. The surface weather measurements were made at 6 of the 10 sound stations. The low-altitude weather measurements (from the surface to a height of 5000 ft) were made by a specially instrumented small airplane.

The test criteria for surface weather conditions for acceptable sound recordings included limits on wind speed and on combinations of air temperature and relative humidity. A 10-knot limit was established for the steady wind speed. The desired temperature and relative humidity limits chosen were such that the maximum difference in the atmospheric absorption coefficients between those for the test-day atmospheric conditions and those for reference conditions (59°F and 70-percent relative humidity) would not exceed 5 dB/1000 feet at a 1/3-octave-band center frequency of 8000 Hz.

Flyover-noise measurements were occasionally permitted under conditions that were somewhat less than desirable, but not under conditions that indicated a difference of more than 9 dB/1000 feet at 8000 Hz between the absorption coefficients under test-day and reference conditions.

Judgment tests. – To assess the subjective effects of the change in flyover noise due to the nacelle modifications, 41 college students were asked to listen to several pairs of recorded flyover noises reproduced in an anechoic chamber. Each pair of sounds consisted of the flyover noise, for similar operational conditions, produced by the existing aircraft and by the modified aircraft. Had the pairs of sounds been presented at the true levels recorded during the flyovers, the subjects would have judged the modified airplane more acceptable for all operational conditions investigated. However, in order to obtain a quantitative measure of the improvement, the relative levels between the two sounds in the pairs were artifically varied in a predetermined manner. The relative increase in the noise level of the modified airplane that was found to be required for equal acceptability was designated the judged improvement.

Judged improvement was the basic dependent variable. The independent variables were the flight conditions of the selected flyover noise recordings. There were 18 recordings selected from those obtained outdoors and 6 recordings selected from those obtained indoors under the flight path during the flyover noise tests. These 24 recordings were used to make up the various pairs of sounds. The outdoor noise recordings consisted of nine recordings of the noise from the existing and nine from the modified aircraft at nominal heights overhead of 500, 1000, and 2500 feet for each of the three engine power settings of landing-approach thrust, takeoff thrust, and reduced-climb thrust. The indoor noise recordings consisted of three recordings of the noise from the existing and three from the modified aircraft at nominal heights of 500 feet for landing-approach thrust, 1500 feet for takeoff thrust, and 2500 feet for the reduced-climb thrust.

Judgments of the improvement in acceptability were compared to improvements calculated from sound pressure levels determined from the recordings. Comparisons were made between judged improvement and improvements indicated by eight noise-rating scales that have been used or proposed for use in evaluating aircraft flyover noise. Statistical analyses of the differences between judged improvements and improvements indicated by the rating scales were conducted to assess the ability of the scales to predict the judged improvements.

Cruise-performance tests. – Cruise-performance tests were made by measuring specific range (range in nautical miles flown per pound of fuel consumed) for several flight conditions. The tests covered speeds from 0.68 to 0.86 Mach, altitudes from 28 000 to 35 000 feet, and airplane gross weights from 220 000 to 280 000 pounds.

Results of Noise Measurements

The effect of the nacelle modification on the noise produced beneath the landing and the takeoff flight paths was evaluated in terms of (1) calculated measures in wide use and (2) subjective judgments of the improvement in acceptability.

Calculated measures. – The noise-reduction goals for the nacelle modification were initially stated in terms of the maximum instantaneous PNL (i.e., in terms of PNLM in units of PNdB), because that measure of the noisiness of aircraft noise was in wide use at the time. As the program proceeded, increasing interest developed in assessing the noise reduction in terms of effective perceived noise level (EPNL in units of EPNdB). The EPNL noise-rating scale was developed as an improvement relative to PNLM for evaluating the noise of turbofan-powered airplanes. The EPNL scale includes allowances for the additional noisiness of discrete-frequency tones in the noise spectra and for the duration of the noise. Both PNL and EPNL comparisons are presented in this report. Detailed definitions and computational procedures for both scales are given in reference 7.

Examples of the effect of the nacelle modification on the PNL history during a landing approach and during a takeoff with takeoff-rated thrust are shown in figures 5(a) and 5(b), respectively. The curves are plotted relative to the time of occurrence of the PNLM. The results shown in figure 5(a) indicate that the significant reduction in noise beneath the landing-approach flight path persisted throughout the flyover. Beneath the takeoff flight path, figure 5(b), there was little reduction in PNLM, although there were some significant reductions (in this sample) before and after the maximum values.

Samples of the 1/3-octave-band spectrum of the sounds corresponding to the PNLM values shown in figures 5(a) and 5(b) are compared in figures 6(a) and 6(b), respectively. The spectrum of the sound from the existing nacelles at the landing-approach power setting (fig. 6(a)) shows that the maximum 1/3-octave-band sound pressure level (SPL) occurred in the 1/3-octave band centered at a frequency of 2500 Hz. The SPL in this band represents the fundamental blade-passage frequency of the intense whine from the fan stages. The spectrum of the sound from the modified nacelles indicates that the nacelle modification reduced the amplitude of the whine by approximately 20 dB. The modification also significantly reduced the SPLs at other frequencies in the range from 800 to 10 000 Hz. These changes in SPL account for the change in PNLM. The SPLs in the spectrum below 800 Hz are produced by noise radiated from the jet-exhaust flow from the fan and primary exhaust nozzles. This part of the spectrum was not significantly affected because the jet-exhaust noise was not directly affected by the acoustical treatment of the fan-inlet and the fan-exhaust ducts.

As shown in figure 6(b), the SPLs from the jet-exhaust noise at the takeoff-thrust setting were substantially higher than those at the landing-approach power setting (fig. 6 (a)). The jet noise level at the takeoff thrust setting even exceeded the level of the fan whine, which at this power setting occurred in the 1/3-octave band centered at 3150 Hz. As at the landing-approach power setting, the nacelle modification did not appreciably affect the jet noise. Although the amplitude of the fan whine was reduced at the takeoff thrust setting, less noise reduction was achieved in the higher frequency bands than at the landing-approach thrust setting.

The data obtained in the flyover noise tests were analyzed in a generalized form in order to compare flyover noise levels beneath landing-approach and takeoff flight paths for a variety of assumed airplane operating procedures. The following discussion presents noise comparisons for a DC-8-55 airplane and takes into account the effects of the nacelle modification on airplane performance as well as on the noise radiated from the nacelles. For these comparisons, it was assumed that the air temperature was 59^{o}F and that the relative humidity was 70 percent, that there was no wind, that the runway was at sea level, and that the airplanes were carrying a reference payload weighing 30 175 pounds. This payload corresponds to a full load of passengers and baggage in a typical mixed-class seating configuration (135 seats) and an additional cargo load of 2500 pounds.

The noise produced by the existing airplanes and by the modified airplanes outdoors beneath a 3^{o} landing-approach flight path is shown in figure 7. The airplanes were assumed to be operating at maximum design landing weight (240 000 lb) and at the thrust required for fully deflected flaps. The results indicate that the modified nacelles would reduce the noise level directly below the flight path by approximately 10.5 EPNdB at a location 1 nautical mile from the runway threshold. The reduction would be approximately constant to a distance of 5 nautical miles from the threshold. A similar analysis for airplanes with 180 000-pound landing weights indicated that the noise reduction would be 12 EPNdB at the location 1 nautical mile from the threshold.

Noise levels are presented in figure 8 for locations outdoors beneath the initial-climb flight path of an airplane climbing with takeoff-rated thrust, a climb airspeed of V_2 + 10 knots, and a takeoff flap setting of 25°. Data are presented for takeoffs at maximum certified takeoff gross weight (325 000 lb) and for takeoff weights required for a flight of 2500 nautical miles. The takeoff weights of the existing airplanes and of the modified airplanes would differ slightly for flights of a specified range, because of the different propulsive performance of the two nacelle designs. Since the takeoff gross weight is usually less than the maximum certified weight, the data for the 2500-nautical-mile flights are more representative of typical operations.

Within the range of distances from brake release shown in figure 8, it is indicated that the modified nacelles would reduce the noise levels from 1.5 to 4 EPNdB. At a location 3.5 nautical miles from brake release, the nacelle modification would reduce the noise level of the 325 000-pound airplane by 3.5 EPNdB and that of the airplane flying 2500 nautical miles by 1.5 EPNdB. The reductions would be achieved despite the lower altitude at a given distance from brake release that results from the reduced takeoff thrust of the modified nacelles.

If the thrust can be reduced during the initial climb after liftoff, lower noise levels and larger noise reductions can be achieved at specified locations. Initial-climb flight paths were assumed for a reduced-thrust climb procedure that would reduce the noise level at the 3.5-nautical-mile point. At a point 1500 feet before the 3.5-nautical-mile point, the thrust was reduced to that required for a 6-percent climb gradient (i.e., a rate-of-climb of approximately 1000 ft/min).

Figures 9(a) and 9(b) present comparisons of the noise levels beneath the initial-climb flight paths. Figure 9(a) shows the effects of thrust reductions for airplanes with takeoff gross weights of 325 000 pounds. For the airplane with modified nacelles, reducing the thrust would reduce the noise at the 3.5-nautical-mile point 2 EPNdB below that produced at takeoff-rated thrust. For the airplane with the existing nacelles, however, the loss in altitude due to the reduced climb gradient would offset the noise reduction obtained by reducing the thrust. Therefore, the resultant noise reduction due to the nacelle modification, under conditions permitting thrust reductions during climb, would be the sum of the 2 EPNdB due to the thrust reduction and the 3.5 EPNdB reduction due to the nacelle modification, or a total of 5.5 EPNdB at the 3.5-nautical-mile point.

The results in figure 9(b) are presented for the respective takeoff weights required by the existing airplanes and by the modified airplanes for flights of 2500-nautical-mile range. At this weight (in contrast with the 325 000-lb case discussed above), the existing airplane can achieve lower noise levels at the 3.5-nautical-mile point with the use of the thrust-reduction procedure. Thus, comparison of the two cases for the reduced climb gradient shows that the nacelle modification would achieve a noise reduction of approximately 9 EPNdB at the 3.5-nautical-mile location.

Analysis of the noise measurements made along the line 1500 feet to the side of the takeoff and initial-climb flight path indicated that the nacelle modification on a DC-8 with a 325 000-pound takeoff gross weight, climbing with takeoff-rated thrust and an airspeed of $V_2 + 10$ knots, would reduce the maximum noise level by approximately 3 EPNdB. The maximum noise level was recorded when the airplane was approximately 1000 feet above the ground and at a distance of approximately 3.5 nautical miles from brake release. Airplanes with lighter takeoff gross weights would achieve the same noise reduction, but at locations closer to the brake-release point.

Tables I and II summarize the values of noise reduction achieved by the nacelle modification at locations outdoors under the landing-approach and initial-climb flight paths. The noise reductions achieved along the 1500-foot sideline are also listed.

Subjective judgments. – Judged improvements, in units of EPNdB, for the various flight conditions are presented in figure 10(a). The differences, in units of EPNdB, between the judged improvements and the improvements indicated by the EPNL noise-rating scale are presented in figure 10(b).

Over the range of heights from 450 to 2800 feet, the judged improvements in the acceptability of the sounds recorded outdoors (based on the faired lines in fig. 10(a)) varied from approximately 11 to 14 EPNdB at the landing-approach power setting, from approximately 4 to 13 EPNdB at the reduced-climb-gradient power setting, and from approximately 4 to 7 EPNdB at the takeoff power setting. For the indoor noise recordings, the judged improvement was approximately 8.5 EPNdB at the landing-approach power setting, approximately 5.5 EPNdB at the reduced-gradient power setting, and approximately 4.5 EPNdB at the takeoff power setting.

Figure 10(b) shows that the differences between the judged improvements and the improvements indicated by the EPNL noise-rating scale were on the order of 2 to 3 EPNdB, although differences ranging from –5 to +6 EPNdB were noted.

The statistical analyses of the eight noise-rating scales investigated indicated that none of the eight scales was significantly superior to the EPNL or the PNL scales in predicting the judged improvements.

Results of Performance Measurements

The basic performance data from the flight tests and the tests on the static engine test stand were used to calculate the effects of the modification on important performance characteristics of the DC-8 Series 50 and of the Model 61 airplanes. Since the effects of the modification were similar for all models studied, they are illustrated in this summary by the results for one model, the DC-8-55 airplane.

The flight test data indicated that the modification reduced the cruise fuel consumption an average of approximately 3 percent, depending upon cruise Mach number, weight, and altitude. It is believed that the external air flow in the region of the nacelle and pylon was improved by the more downstream location (24 in.) of the fan-exhaust nozzles of the modified nacelles. The resulting decrease in drag was more than enough to offset the increase in internal total-pressure losses due to the acoustically treated ducts. The static engine-test-stand data were analyzed to determine the effect of the modification on thrust ratings. This analysis indicated that the rated takeoff, maximum-continuous, and maximum-cruise thrust ratings would be reduced by 2.5, 2.9, and 3.1 percent, respectively. These reductions would result chiefly from the increased total-pressure losses of the acoustically treated inlet duct.

For long-range flights requiring large fuel loads, the improvement in cruise fuel consumption of the modified nacelles would result in appreciable reductions of trip fuel requirements and therefore in takeoff weight, which would tend to reduce the required takeoff field length. On the other hand, the reduced takeoff thrust would tend to increase the required takeoff field length. The resulting influence of these factors on takeoff field length requirements is shown in figure 11(a). Those parts of the curves to the left of the discontinuities represent takeoffs with a flap setting of 25° and cruise at a Mach number of 0.82. Under these conditions, the takeoff weight reduction is the predominant effect for long-range flights, and slightly smaller field lengths are required. For ranges less than approximately 3000 nautical miles, the effect of the reduced takeoff thrust predominates, and slightly increased field lengths are required.

The discontinuity in the curve for the existing airplane indicates the attainment of maximum certified takeoff weight. The horizontal distance spanned by the flat part of the curve represents the increase in range that would be achieved by reducing the cruise speed from Mach number 0.82 to the lower speeds of long-range cruise. The right-hand end of the curve thus denotes the maximum range capability with the 30 175-pound reference payload. The lower discontinuity in the curve for the modified airplane (at a field length of 10 400 ft) indicates the attainment of the maximum takeoff weight permitted for the modified airplane at a flap setting of 25°. This weight is determined by the second-segment climb gradient requirement and is less for the modified airplane because of its lower rated takeoff thrust. The increased takeoff weights required for ranges greater than that at the discontinuity (approximately 5000 n. mi.) requires a reduction in takeoff flap setting to 15°. This reduction in flap setting is represented by the vertical segment of the curve for the modified airplane. That part of the curve to the right of the vertical segment represents operations with a takeoff flap setting of 15°, and the horizontal part has the same significance that was discussed for the existing airplane. Thus, it is shown that, although the maximum-range capability would be increased by the nacelle modification, longer field lengths would be required to use the capability.

Climb performance would not be affected significantly by the nacelle modification. The airplane drag reduction implied by the improved cruise performance is believed to apply only at Mach numbers above approximately 0.6, which occur during the latter portion of the climb. Climb performance during that part of the climb, where most of the climb time is spent, would not be appreciably affected by the modification since the drag reduction is approximately equal to the reduction in climb thrust (maximum-continuous thrust for the JT3D-3B engine). At low altitudes and low speeds, where the drag advantage may not be present, the thrust-minus-drag margin, and hence the rate of climb, is high. Small drag differences during this part of the climb would have a negligible effect on the total time to climb.

It was estimated that the maximum initial cruise altitude capability, for an initial cruise speed of Mach 0.82, would be reduced approximately 500 feet by the nacelle modification. An analysis of the improvement in cruise fuel consumption measured in the flight test at the weight-altitude relationship corresponding to maximum initial cruise altitude indicated an apparent drag reduction of 1.2 percent. Since this improvement would not be sufficient to offset the 3.1-percent reduction in maximum cruise thrust, a lower maximum initial cruise altitude would result.

The measured 3-percent improvement in cruise fuel consumption would improve the maximum range capability. The improvement is reflected in the payload-range comparison shown in figure 11(b).

As was mentioned above, the modification would have a negligible effect on time to climb. Also, the reduction in maximum-cruise thrust would not prevent operations at cruise speeds currently used for either long-range or high-speed (Mach number 0.82) cruise. Therefore, no appreciable change in block speed would result from the modification.

Evaluation of Operational Characteristics

Observations of engine operational characteristics during the ground static tests and the flight tests indicated that the nacelle modifications had no effect, either on the ground or in flight, on engine starting, acceleration, deceleration, or compressor-surge characteristics. The pivoting single-panel type of fan thrust reverser required by the modification would be somewhat less effective than the type now in service. Longer landing distances may therefore be required on wet or icy runways. Increased compressor-bleed airflow would be required for anti-icing of the concentric-ring vane and its support struts in the inlet. The increased bleed flow would require thrust reductions at rated power settings. The required reduction in rated takeoff thrust would vary from zero at sea level to approximately 0.7 percent at an airfield pressure altitude of 8000 feet. The modified nacelles would require no change in cockpit controls or procedures.

The structural loads applied to the pylons and the wings by the modified nacelles would not be significantly different from those of the existing nacelles. The modification would therefore not affect the approved altitude-speed envelope or load-factor limitations.

ECONOMIC ANALYSIS OF RETROFIT

The economic implications of modifying the nacelles of DC-8 airplanes equipped with short-duct nacelles were considered. Estimates were made of (1) a schedule for a retrofit program, (2) initial costs of kits of parts needed to accomplish the modifications, (3) changes in direct operating costs due to the modifications, and (4) changes in cash flow, airplane investment, and return on investment resulting from retrofitted fleet operations. 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 airline operator must assess the assumptions made and make such adjustments as are necessary to conform with the circumstances peculiar to his operations.

Assumed Program Schedule

The retrofit program schedule assumed in this study is shown in figure 12. Initial development of the fan reverser configuration would be performed by tests of scale-model fan reversers in which the fan-exhaust flow would be simulated by an airflow source in the laboratory. The use of scaled models permits the investigation of alternative configurations or changes in a configuration faster than tests with full-scale reversers on an actual engine. The laboratory tests would indicate the reverser panel contours required to obtain sufficient reverse thrust effectiveness with an acceptable blockage of the fan-exhaust-duct flow at all panel positions from stowed to fully extended. Loads data for the structural design of the reverser panels and their support and actuating systems would also be obtained from the scale model tests.

Full-scale prototype fan reverser tests would use parts made from simplified tooling. These tests would verify the aerodynamic results of the model tests. Tests of configuration changes needed to correct deficiencies would be conducted as required.

The first nacelle set of parts built with production tooling would be available 18 months after program initiation. Critical pacing items in meeting this milestone are lead-time requirements for forgings and castings.

Fan-reverser durability tests would verify the loads and stress calculations made in design and would evaluate functional characteristics of the reverser and its actuating and control subsystems.

The flight test program would include (1) tests of the revised inlet ice-protection system; (2) verification of the functional and structural integrity of the modified ducts and fan thrust reversers under critical conditions within the flight envelope, including emergency high speed decelerations; (3) tests of fan reverser braking effectiveness during landing roll; and (4) flyover noise tests to verify the noise reduction achieved by the production design.

Overlap of key activities is provided in the schedule in order to permit the earliest practicable deliveries of certified retrofit kits. For example, design and fabrication of the prototype fan reversers would begin before completion of the scale model tests. The design of production tooling would begin well before complete release of production drawings, and before production manufacturing processes for the acoustical materials will have been completely defined. Overlaps of this nature are expected to require termination or redirection of some design and manufacturing approaches, but this risk would be necessary in order to meet the certification and installation dates shown in figure 12.

Installation of retrofit kits would begin shortly before certification. The kits would be installed during scheduled engine or airplane overhauls and would therefore require no out-of-service time for installation.

Retrofit Kit Price

An estimate was made of the engineering, tooling, manufacturing, and certification costs of producing modified nacelle kits. In order to relate these estimates to unit price (price per airplane kit), the total quantity of kits to be produced must be determined. The total must include kits both for installation and for the spares inventory.

As of 31 August 1969, 228 DC-8 airplanes with short-duct nacelles were in service. Additional Model 61 DC-8 airplanes are to be produced and will therefore increase the number of kits potentially required. However, two other factors will tend to reduce that number. First, the older short-duct DC-8 airplanes may be near the end of their economic lives at the time retrofit kits could be available. Operators may find it more desirable to retire these older airplanes from service than to invest in the new nacelles. Second, foreign operators may be able to continue service with unmodified airplanes. It is therefore believed that the maximum number of DC-8 short-duct airplanes that could be candidates for retrofit is approximately 250. On this basis, the estimated costs per airplane in 1972 dollars, including an allowance for installation, are as follows:

Number of airplanes in fleet	250
Total number of airplane kits produced	300
Cost of retrofit kit (4 nacelle sets)	\$543 000
Cost of 20-percent spare parts	109 000
Installation cost	3 000
Total cost including spares	\$655 000

In view of the uncertainty of the total production requirement, the unit price estimates are presented in figure 13 as a function of the number of kits to be produced. The unit price would be higher for smaller production programs, since nonrecurring costs would be amortized over a smaller number of units. For example, if a retrofit program were to involve only 125 airplanes, the total retrofit cost per airplane, including spares and installation, would be \$863 000.

An annual inflation rate of 4 percent was assumed in the cost calculations. The estimated unit costs are subject to revision if inflationary trends differ from those assumed, or if the kit production period is different from the 1972 to 1974 period assumed for this study.

Direct Operating Costs

The estimated kit costs and the changes in airplane performance discussed above were used to estimate changes in direct operating costs (DOC) due to the modified nacelles. The changes were estimated by calculating the DOC's of the existing airplane and of the modified airplanes by consistent rules. The standard 1967 Air Transport Association (ATA) method was used as the basis for the calculations.

Since the ATA method is designed to provide DOC estimates for new airplanes, a special treatment of the depreciation-expense element was needed to reflect the retrofit program of the modified airplane. The depreciation for the modified airplane was calculated as the depreciation of the existing airplane plus an additional amount calculated as the retrofit cost amortized over assumed depreciation periods. Because of the uncertainty of airplane retirement plans, the useful economic life of the modified nacelles is uncertain. For the purposes of this study, two depreciation periods were assumed: five years as an average for the total fleet of all DC-8 models with short-duct nacelles and ten years for the special case of the more recently delivered DC-8-61 airplanes.

Maintenance expense for the existing airplanes was calculated by the ATA method. The maintenance expense for the modified airplanes was estimated by analyzing the changes in maintenance tasks and materials expected as a result of the nacelle modification and by applying the estimated net cost of these changes to the maintenance expense of the existing airplane. Other assumptions and details of the DOC calculations are presented in reference 4.

The effects of the nacelle modification on DOC, based on a 5-year depreciation period and a retrofit cost of $655,000, are illustrated in figure 14(a) by the case of the DC-8-55 airplane. The curves were calculated for the reference mixed-class interior configuration providing 135 seats. The effects of the modification on the DOC of the DC-8-61 airplane are presented in figure 14(b). These curves were based on a 10-year depreciation period, a retrofit cost of $655 000, and a typical mixed-class DC-8-61 interior providing 198 seats. The knees in the curves (at ranges of approximately 5200 and 3600 n. mi. for the DC-8-55 and the DC-8-61, respectively) correspond to takeoffs at maximum certified gross weight. Flights at greater ranges require off-loading of passengers in favor of fuel and therefore result in economically undesirable operations that are normally avoided.

The increments between the curves of figure 14 are presented in figure 15 as percentage changes from existing levels of DOC. For ranges of normal operations, the modification would increase the DOC of the DC-8-55 by approximately 4 percent and the DOC of the DC-8-61 by approximately 2 percent. The increment for the DC-8-61 is smaller than that for the DC-8-55 primarily because of the longer assumed depreciation period. The DOC improvements indicated at the extreme ranges in figure 15 reflect the increased maximum range of the modified airplanes. These improvements are not likely to be important, however, since they represent improvements in the previously mentioned undesirable operations with partial passenger loads.

The elements of the DOC increments may be illustrated by the breakdown, shown in table III, of the increment for the DC-8-55 airplane at a range of 850 nautical miles, which corresponds approximately to the average range of present DC-8 service. As shown in table III, the DOC increment of 4.0 percent may be attributed almost entirely to the increased depreciation caused by the initial retrofit cost. The small increases in insurance and maintenance expenses would be essentially balanced by the decreased fuel expense of operations with the modified nacelles. Crew expense would be unaffected because block speed would be unaffected. The effect of the nacelle modifications may therefore be considered simply as an initial cost without further recurring costs.

Impact of Retrofit on Fleet Economics

An analysis was made of the overall economic implications of a retrofit program for an assumed fleet of 250 airplanes. The analysis was based on cost data discussed above and on an assumption that operating revenues would not be changed by the retrofit program. It is recognized that this assumption may be incorrect. The reduced noise and the changed performance characteristics could result in different route and traffic assignments, and fares might be adjusted to compensate for the increases in operating cost. These factors would be influenced by future local, federal, and international noise and tariff regulations. As these factors become defined, the data and methods of this study should be reapplied to reflect the impact of current circumstances.

It was assumed in the analysis that the modified fleet consisted of DC-8-51, -52, -53, -54, -55, and -61 airplanes. Calculations were based on operations of both the existing and the modified airplanes at the average range of 850 nautical miles with a fixed annual utilization of 3800 hours. Details of the analysis are presented in reference 4.

On the assumption of an average 5-year operating period for the modified airplanes, the results of the analysis for the composite fleet containing all models of DC-8 airplanes with short-duct nacelles are summarized as follows:

Number of airplanes in fleet	250
Increase in aircraft investment	$163 750 000
Increase in direct operating costs, percent	4.4
Decrease in federal income taxes paid	$ 78 600 000
Decrease in profit after taxes, percent	10.1
Decrease in discounted cash-flow rate of return on investment, percentage points	8.2

IMPLICATIONS OF RESULTS

Although the program discussed above considered the suppression of JT3D fan-compressor noise, it is believed that the principles used in the design of the lining installations will be useful in the design of installations for other engines. However, the magnitude of the noise reduction achievable and the economic impact of the lining installations will vary from case to case, owing to characteristics peculiar to the particular engine installation, such as:

1. The relative strength of the various noise sources.

2. The characteristics of the noise generated by the fan-compressor stages.

3. The sensitivity of the particular installation to changes in weight, duct friction, external drag, and aerodynamic distortion at the fan.

The present study considered the application of linings to the specific case of DC-8 airplanes with short-duct nacelles. Of the 343 JT3D-powered DC-8s in service as of 31 August 1969, 228 are equipped with the short-duct nacelles considered in this study, while 115 are equipped with long-duct nacelles. The design of the long-duct nacelles is basically different from that of short-duct nacelles: The nacelle maximum width and depth, and the length of the inlet ducts are smaller; the fan exhaust ducts extend the full length of the nacelle afterbody, discharging the fan exhaust flow in nearly the same plane as the primary exhaust flow; a single target-type reverser simultaneously reverses both the fan and primary exhaust flows; and the aerodynamic contours, structural interfaces, and subsystem interfaces at the nacelle-pylon juncture differ extensively. The technology developed during this program could be applied to acoustical treatment of long-duct nacelles. However, detailed studies would be needed to define the optimum design approach for acoustical lining installations in the fan inlet and exhaust ducts, the extent of the required nacelle modifications, and the effect of the modifications on noise, cost, and performance.

CONCLUDING REMARKS

An investigation has been conducted of methods to reduce fan-compressor noise from the JT3D-3B engines of DC-8 airplanes equipped with short duct nacelles. Laboratory, ground, and flight tests were performed in support of design studies and analyses. These efforts resulted in the definition of an aerodynamically, thermodynamically, and structurally practical means of reducing the noise by replacing the present fan-inlet and fan-exhaust ducts with acoustically treated ducts.

Flyover-noise measurements with a DC-8-55 test airplane indicated that the modification on an airplane at maximum certified landing weight would produce a 10.5-EPNdB reduction in the noise outdoors at a point on the ground beneath a 3° landing-approach path and 1 nautical mile from the runway threshold. Measurements beneath the takeoff flight path indicated that the noise 3.5 nautical miles from brake release, for takeoffs at maximum certified gross weight, would be reduced by 3.5 EPNdB if takeoff-rated thrust were maintained and by 5.5 EPNdB if the thrust were reduced to that required for a 6-percent climb gradient. The maximum sideline noise 1500 feet from the runway centerline, during takeoff and initial climb, would be reduced by approximately 3 EPNdB.

Over the range of heights (450 to 2800 ft) and engine power settings (landing-approach to takeoff-rated thrust) that were included in the psychoacoustic evaluation of the flyover noise levels, the judged improvement in the acceptability of the outdoor recorded noise of the DC-8-55 airplane equipped with acoustically treated nacelles ranged from approximately 4 to 14 EPNdB. For the three indoor-noise test conditions, the judged improvement in the acceptability of indoor recorded noise of the modified airplane was slightly less than the judged improvements noted for comparable outdoor noise recordings. It was also concluded that effective perceived noise level provided a reasonable method to evaluate the change in the acceptability of the sound of existing aircraft due to nacelle modifications.

Assuming kit production occurs during the period 1972 through 1974, the initial retrofit cost was estimated to be $655 000 per airplane if retrofit kits were to be produced for a fleet of 250 airplanes. An analysis was made of the economic impact of operating the retrofitted fleet for an assumed average remaining economic life of 5 years. The analysis was based on the foregoing retrofit cost, on estimated changes in direct operating costs due to the modified nacelles, and on the assumption that operating revenues would not be changed by a retrofit program. The results of the analysis are summarized as follows:

Number of airplanes in fleet	250
Increase in aircraft investment	$163 750 000
Increase in direct operating costs, percent	4.4
Decrease in federal income taxes paid	$ 78 600 000
Decrease in profit after taxes, percent	10.1
Decrease in discounted cash-flow rate of return on investment, percentage points	8.2

The economic impact on individual operators and on the industry as a whole warrants further investigation in which consideration can be given to factors not considered in the study conducted in this program. Three major factors that should be considered are: the effect of a retrofit program on (1) airplane route and traffic assignments, (2) fares, and (3) airplane retirement plans.

The noise reductions and economic effects determined in this program apply only to the specific JT3D engine and DC-8 short-duct nacelle design studied. Separate studies are required of the noise reductions and the economic effects of the application of duct-lining technology to other JT3D installations and to installations of other engines.

Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California February 1970

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TABLE I. – LANDING NOISE REDUCTIONS AT 370-FT HEIGHT UNDER A 3-DEGREE LANDING FLIGHT PATH

Landing weight, lb	Noise reduction, EPNdB
240 000	10.5
180 000	12

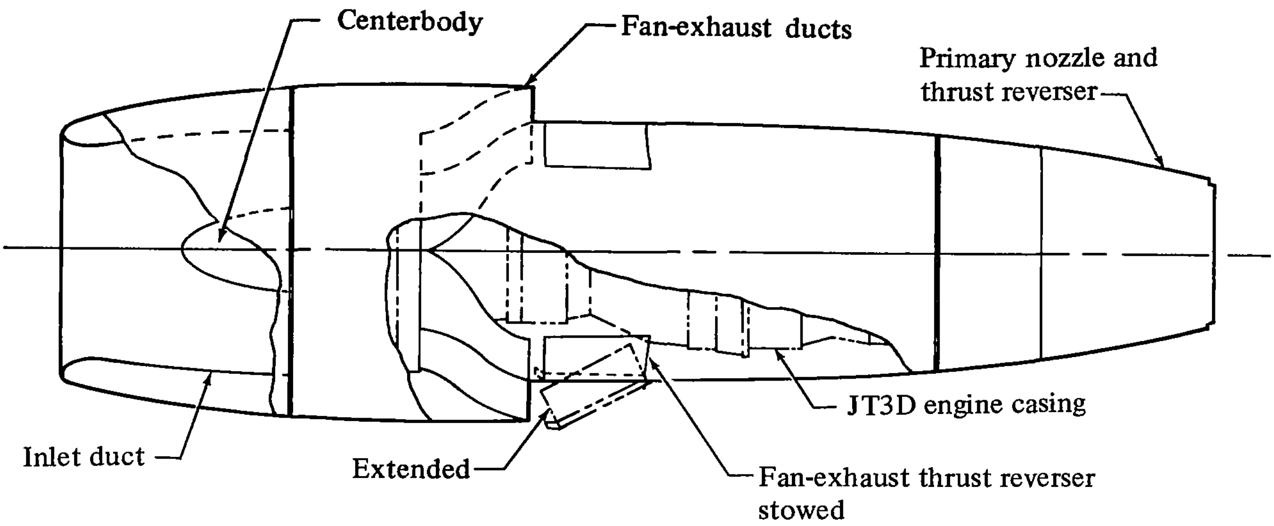
TABLE II. – TAKEOFF NOISE REDUCTIONS

Takeoff weight, lb	Noise reduction under flight path at 3.5 n. mi. from brake release, EPNdB		Reduction in maximum noise level along 1500-ft sideline, EPNdB
	Takeoff-rated thrust	Thrust for 6% climb gradient	
325 000	3.5	5.5	3
≈240 000 (2500 n. mi. range)	1.5	9	3

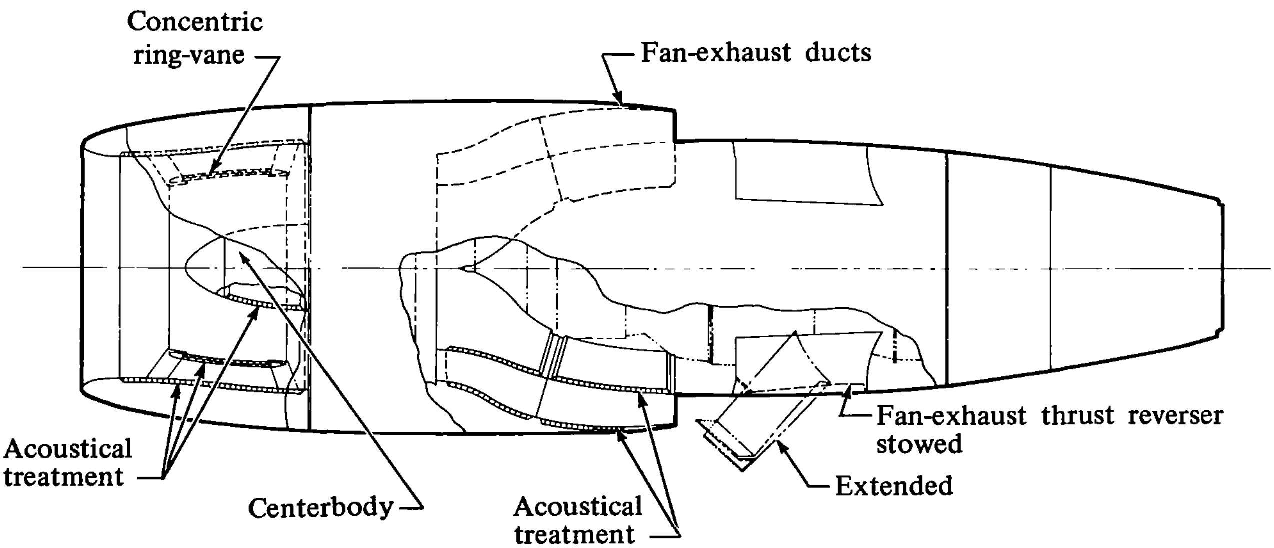
TABLE III. – CHANGES IN DIRECT OPERATING COSTS FOR DC-8-55 AT 850 N. MI. RANGE, INTERNATIONAL OPERATING RULES

Element	ΔDOC, percent
Crew	0.0
Insurance	0.3
Fuel	−0.6
Maintenance	0.1
Depreciation	4.1
Net change	4.0[a]

[a]Numbers do not add due to rounding.



(a) Existing nacelle.



(b) Modified potential-retrofit nacelle.

Figure 1. – Plan view of existing nacelle and of modified potential-retrofit nacelle.

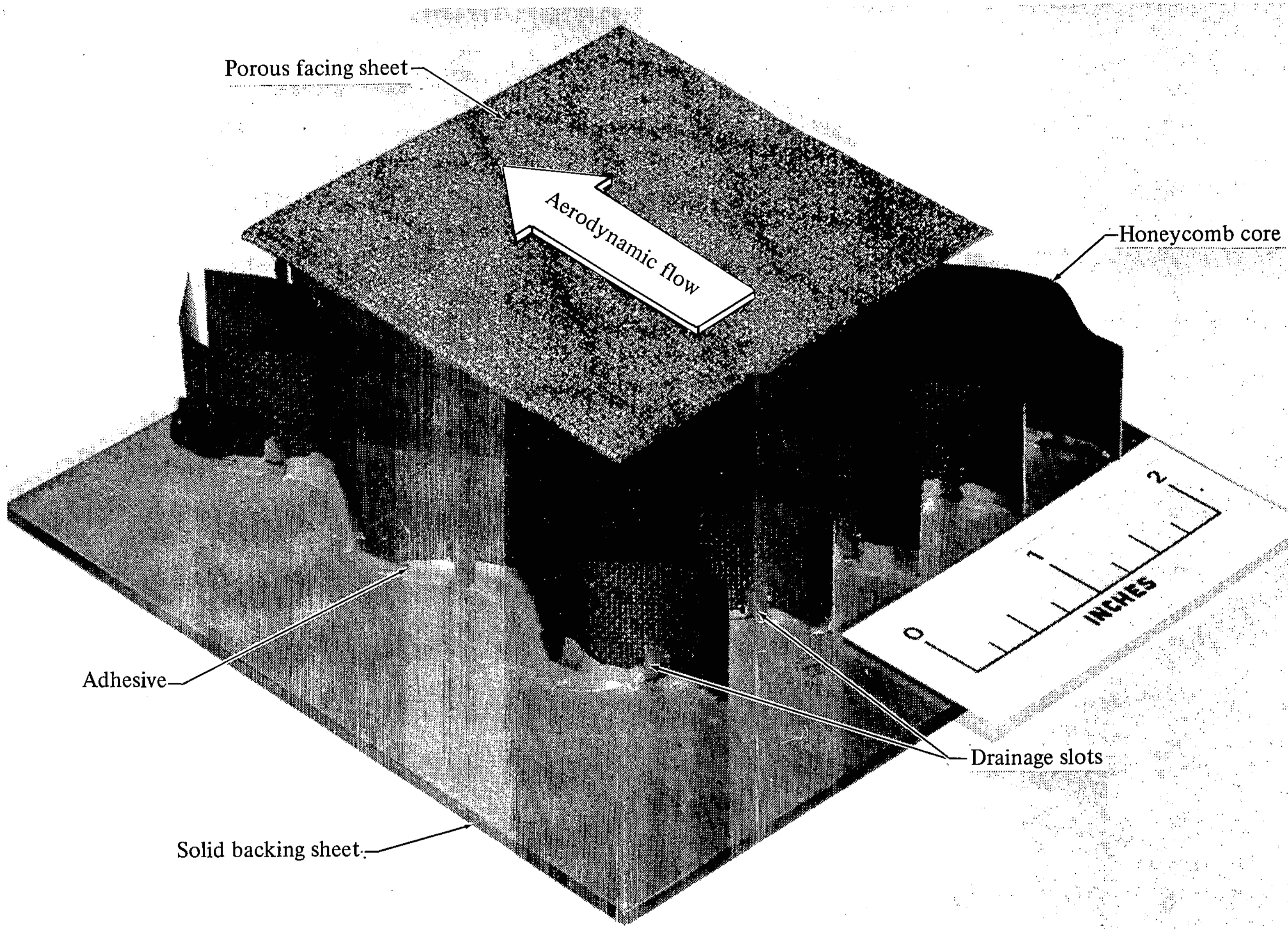
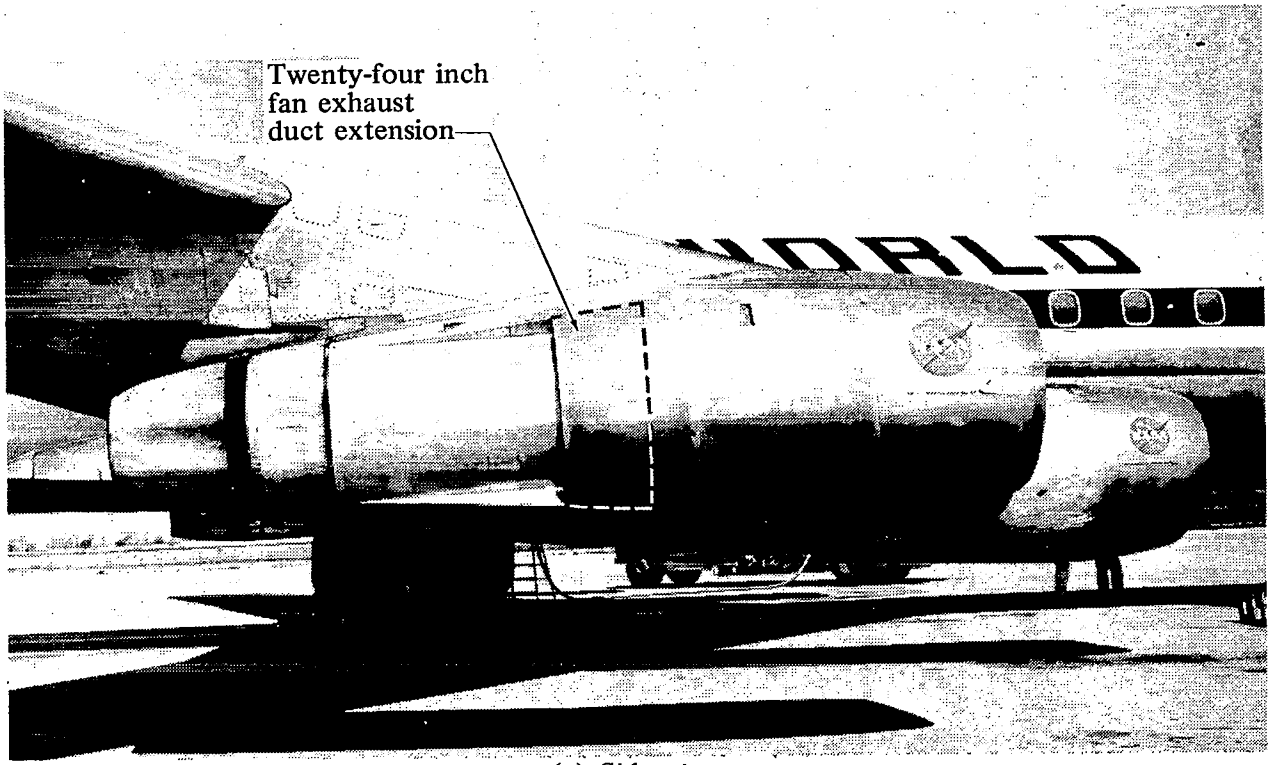
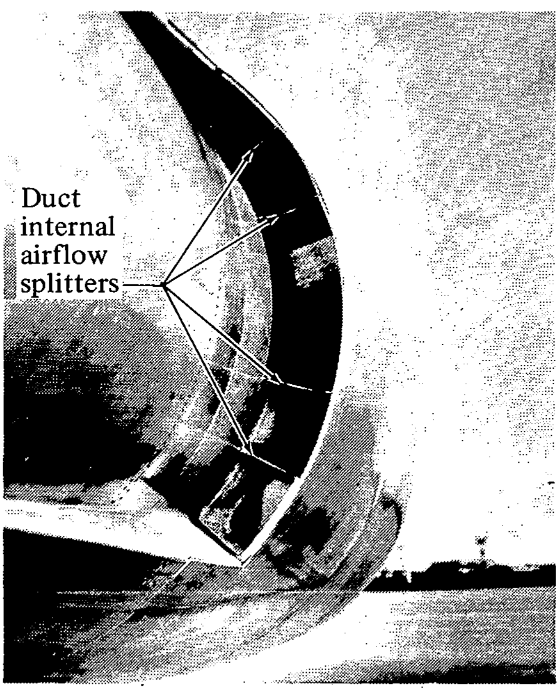


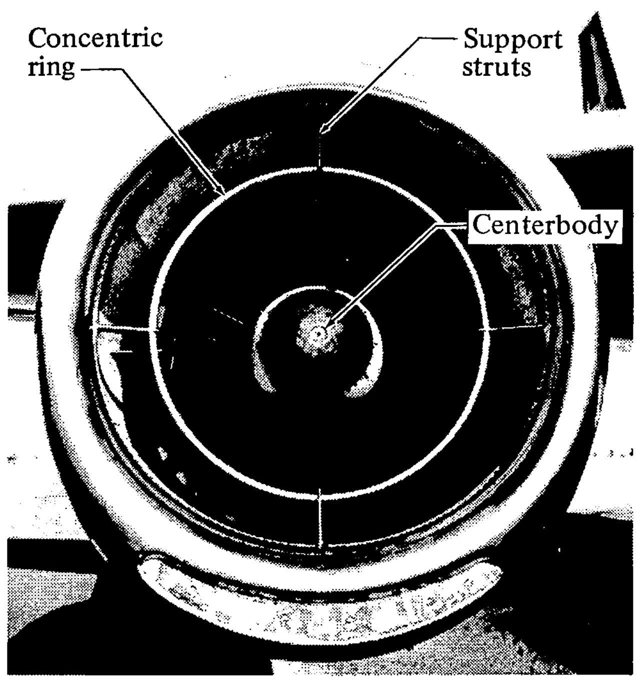
Figure 2. – Components of acoustical duct lining.



(a) Side view.



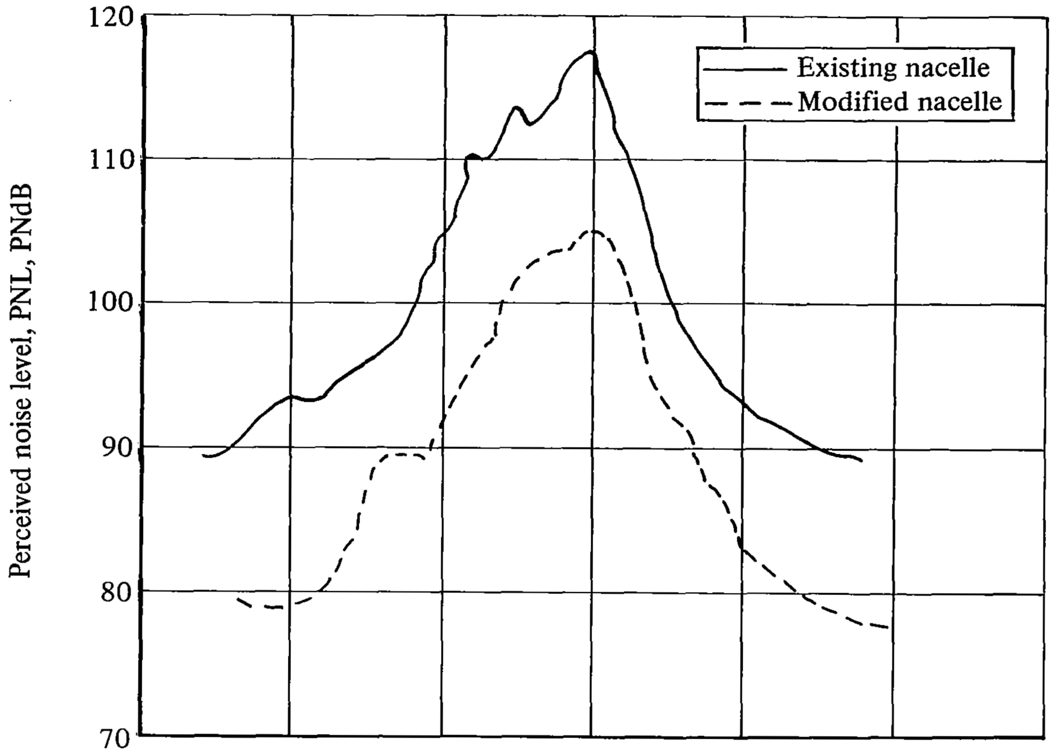
(b) Aft view of fan-exhaust duct.



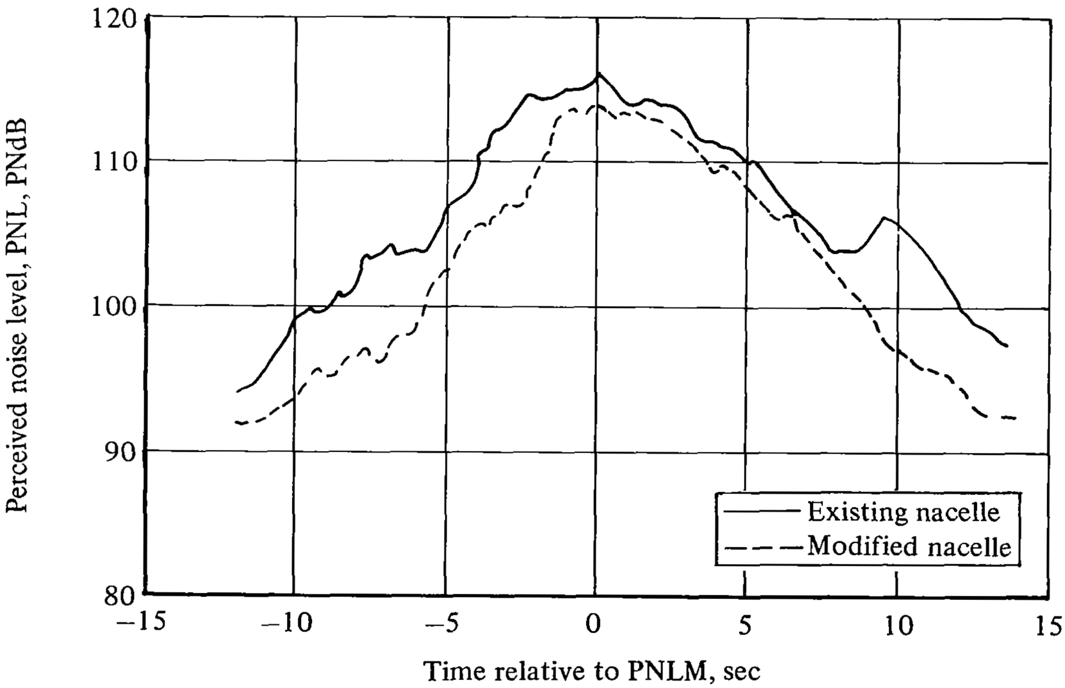
(c) Front view of inlet.

Figure 3. – Test nacelle installed on the DC-8-55 airplane.

Figure 4. – DC-8-55 test airplane.

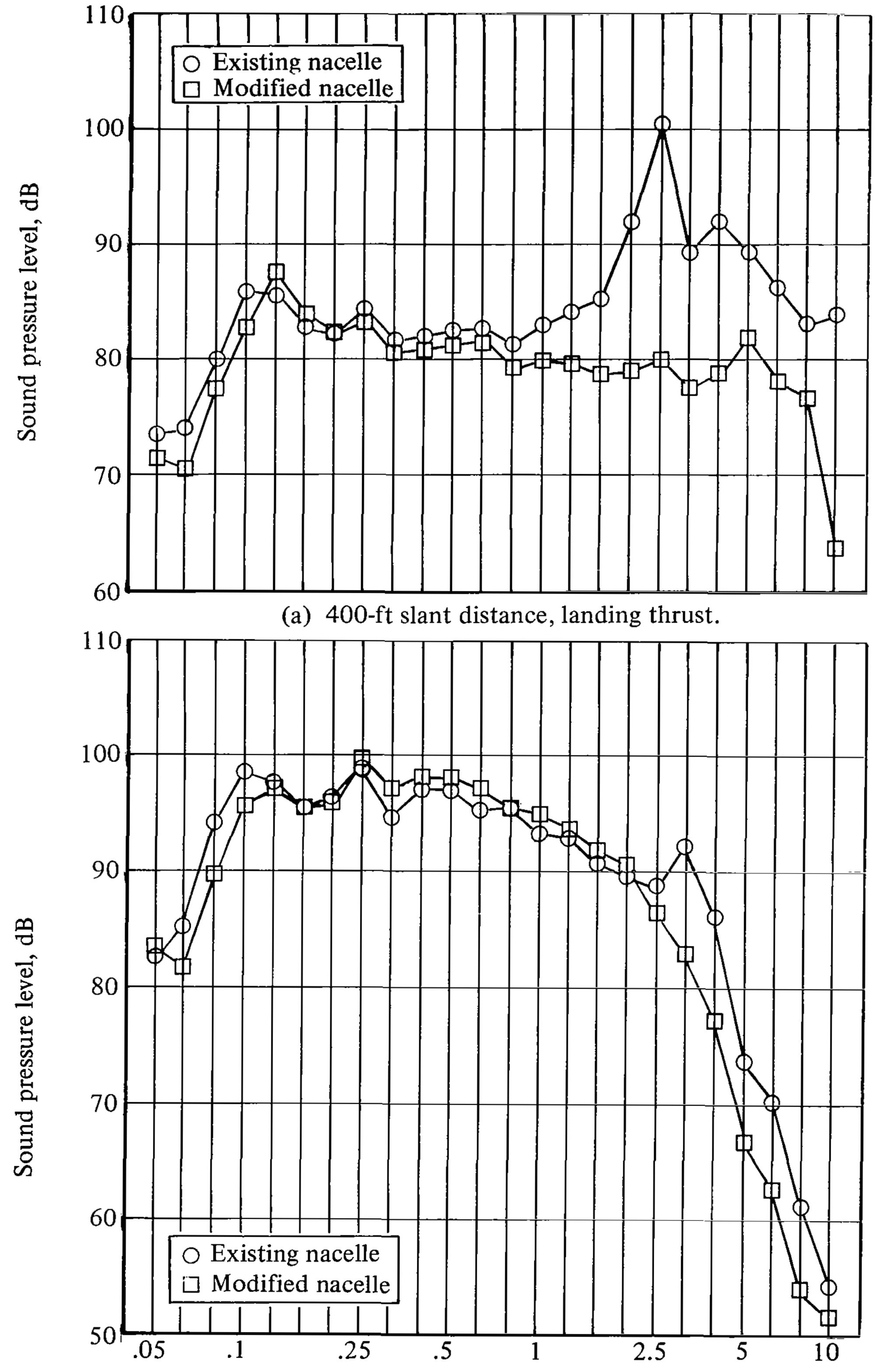


(a) 400-ft slant distance, landing thrust.



(b) 1000-ft slant distance, takeoff thrust.

Figure 5. – Variation of perceived noise level with time.



(a) 400-ft slant distance, landing thrust.

(b) 1000-ft slant distance, takeoff thrust.

Figure 6. – Sound pressure level spectra at time of PNLM.

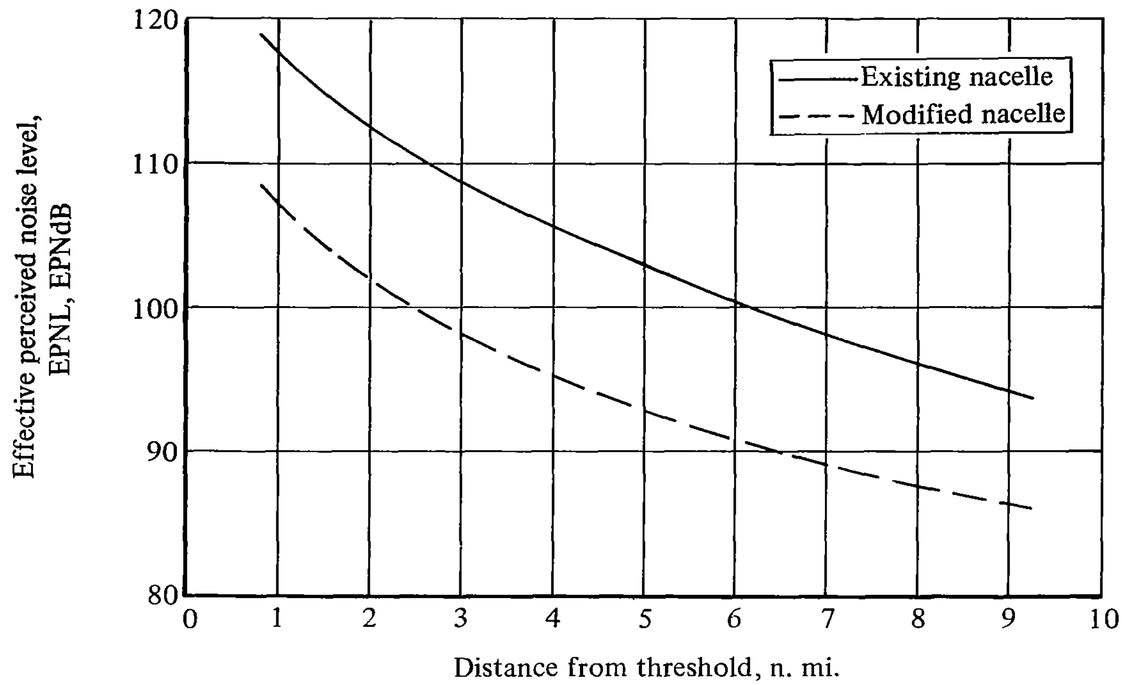


Figure 7. – EPNL under a 3-degree landing approach flight path. Landing weight 240 000 lb; flaps fully extended.

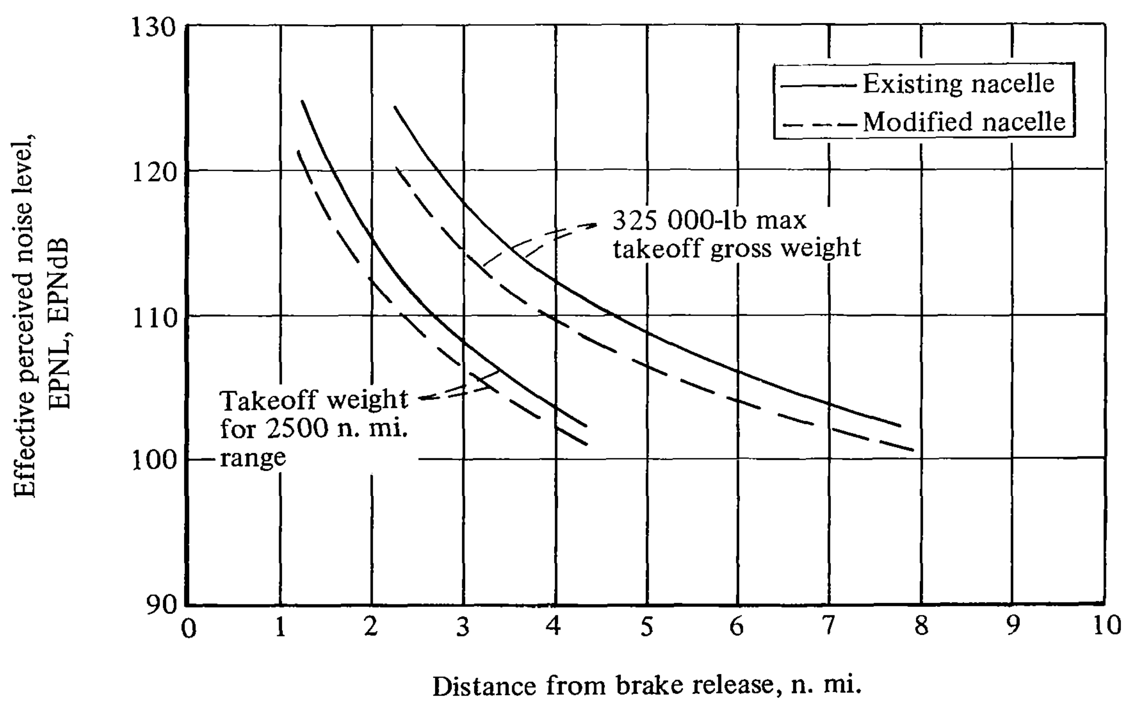
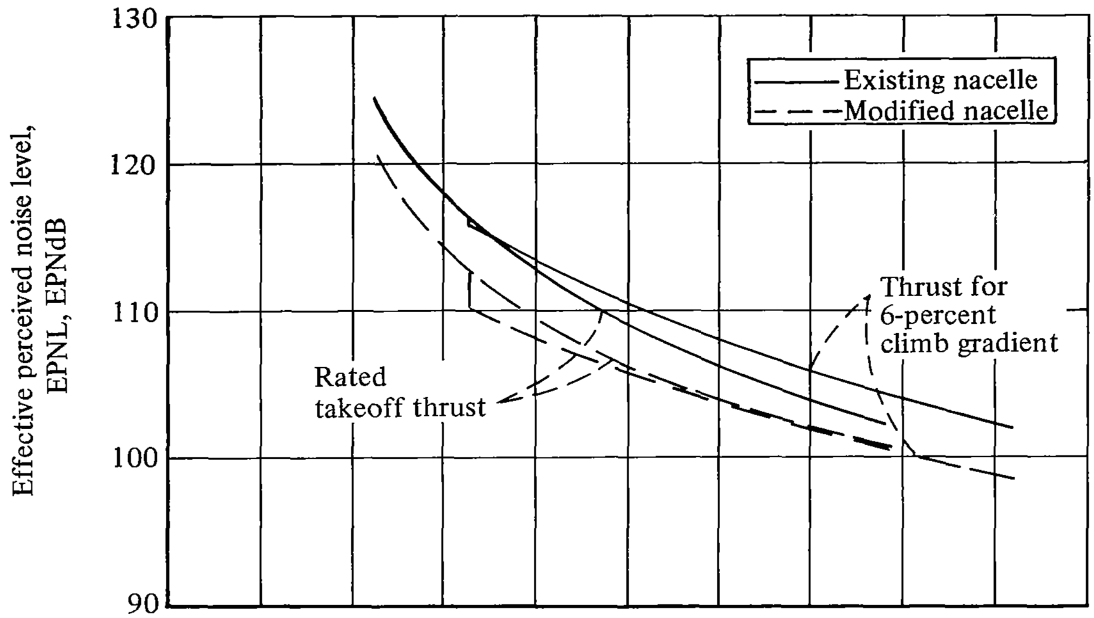
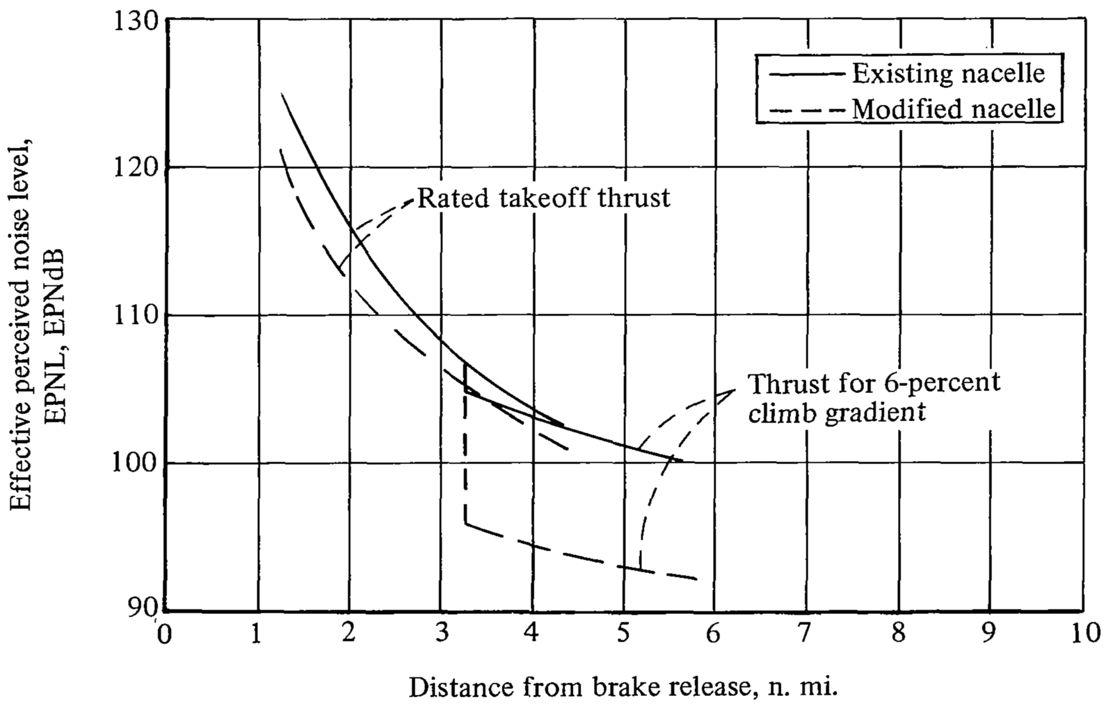


Figure 8. – EPNL under initial-climb flight paths.

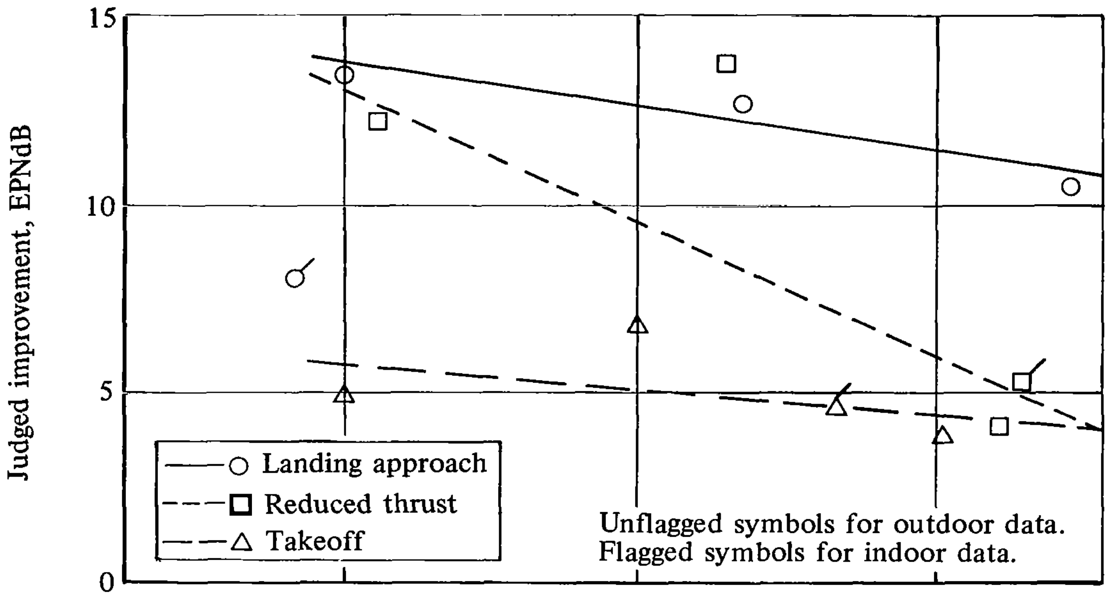


(a) 325 000-lb max takeoff gross weight.

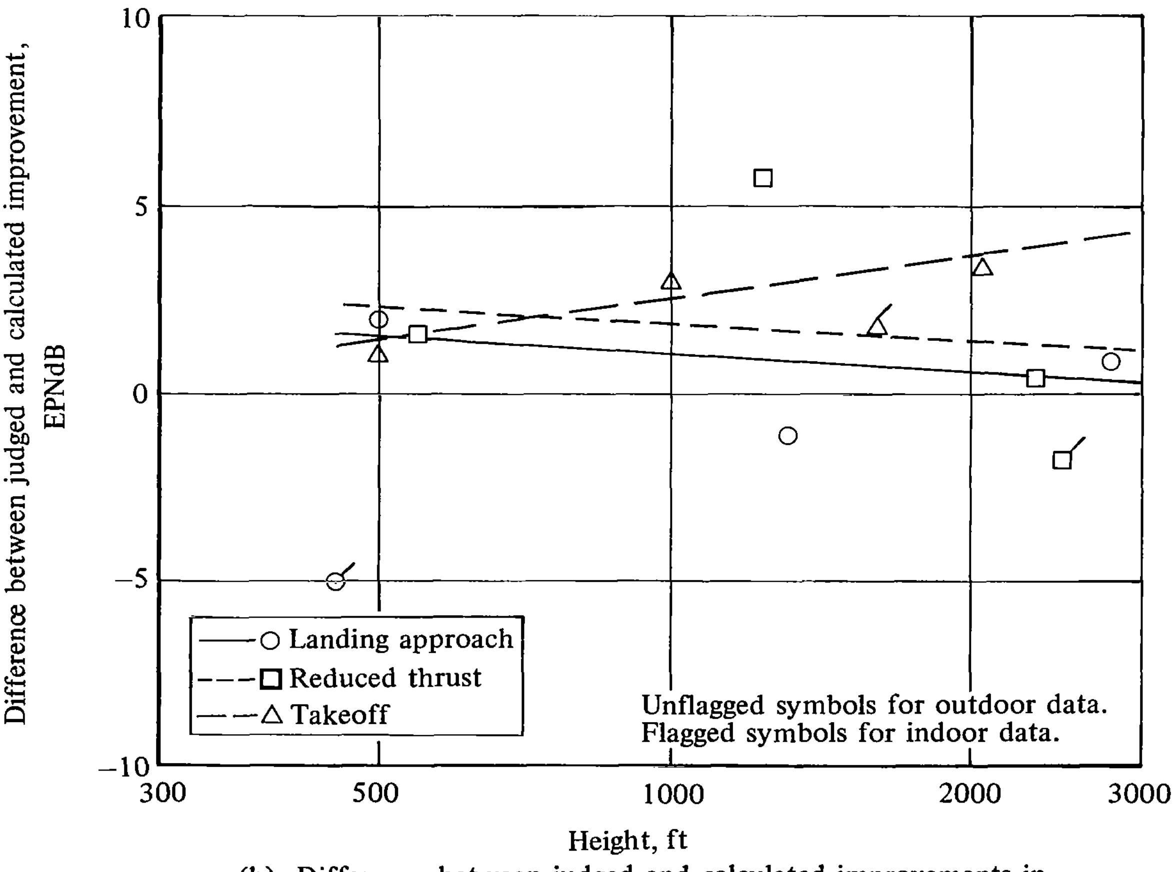


(b) Takeoff weights for 2500 n. mi. range.

Figure 9. – EPNLs under initial-climb flight paths; V_2 + 10 kn climb airspeed. (Takeoff-rated thrust maintained to 1500 ft before 3.5 n. mi. point, then reduced to that required for 6 percent climb gradient in cases noted.)

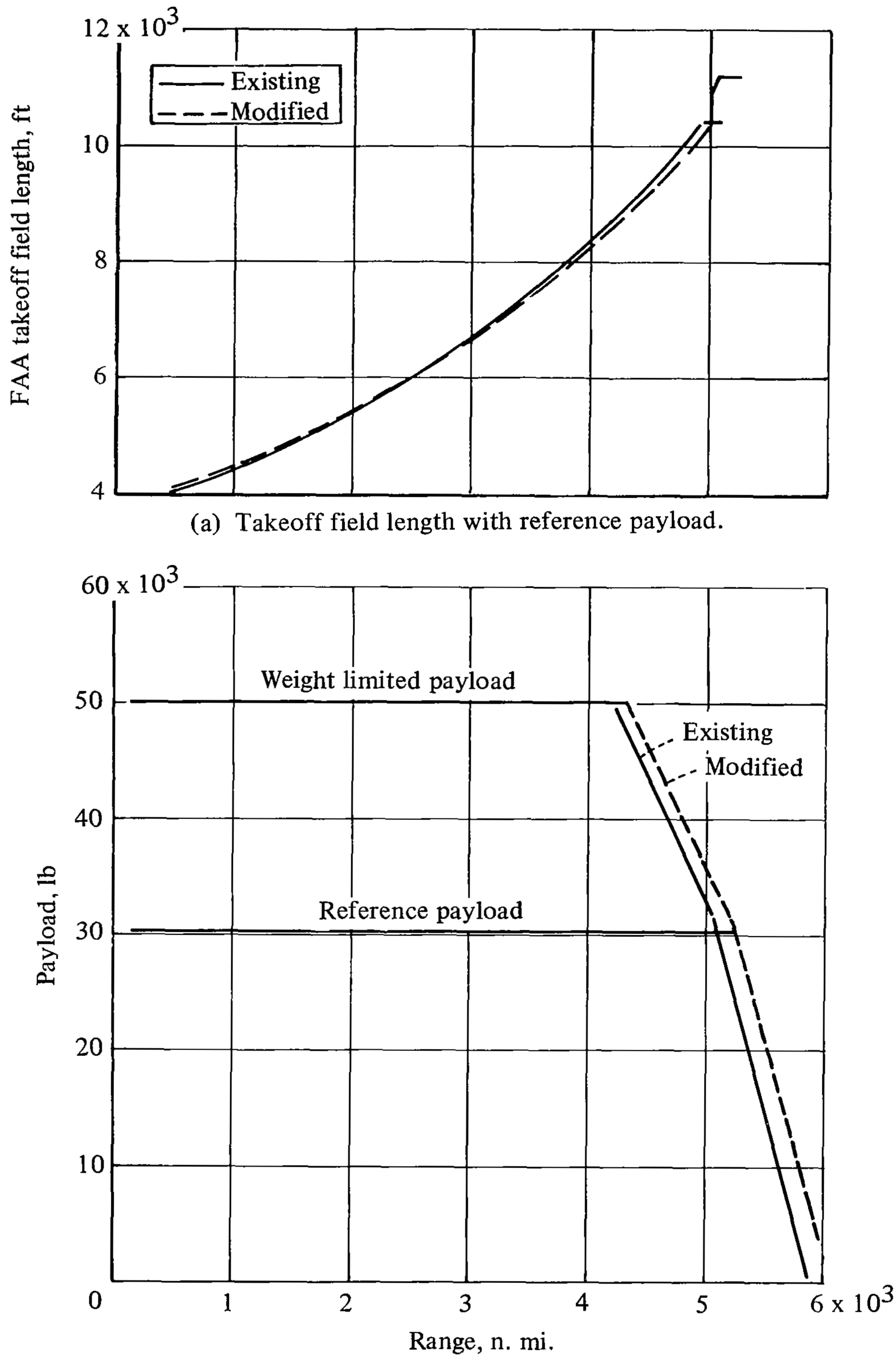


(a) Judged improvements in acceptability of flyover noise due to installation of acoustically treated nacelles.



(b) Difference between judged and calculated improvements in acceptability of flyover noise.

Figure 10. – Results of judgment tests of recordings of DC-8 flyover noise with existing and modified nacelles.



(a) Takeoff field length with reference payload.

(b) Payload-range characteristics.

Figure 11. – Effect of nacelle modifications on takeoff field length and payload range of DC-8-55 airplane. International operating rules. Sea-level runway and an ambient temperature of 84°F.

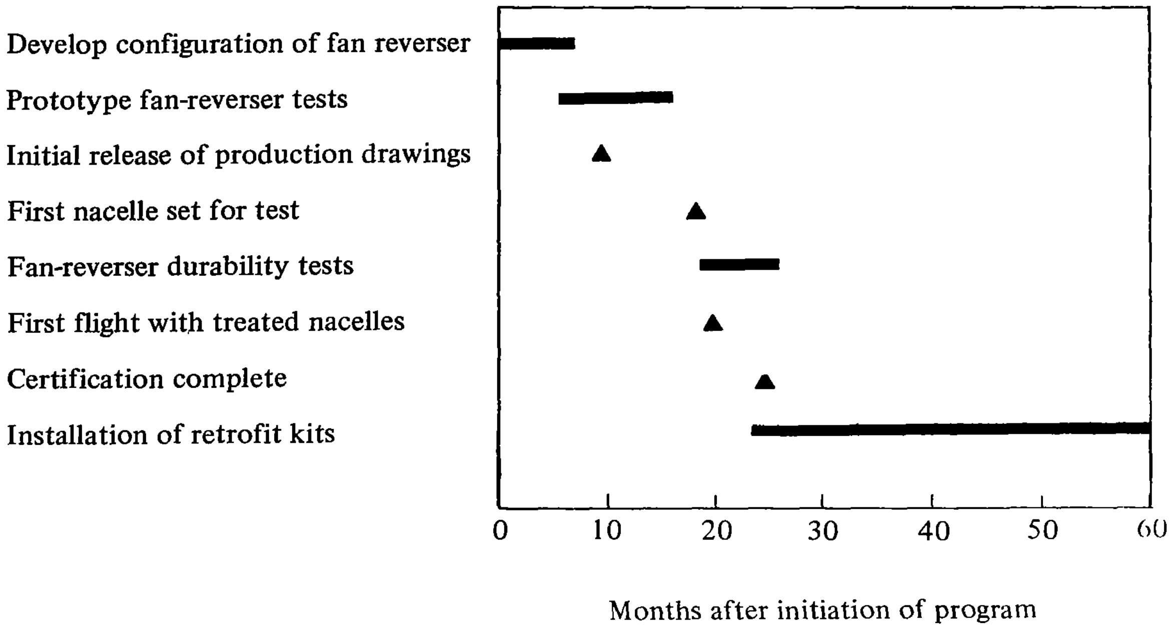


Figure 12. – Assumed retrofit program schedule.

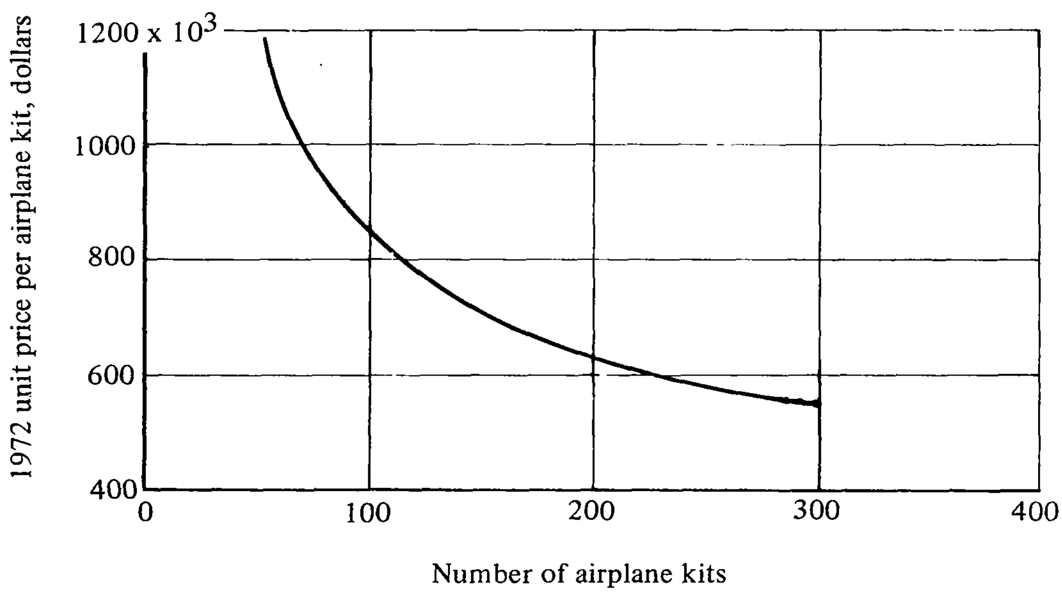
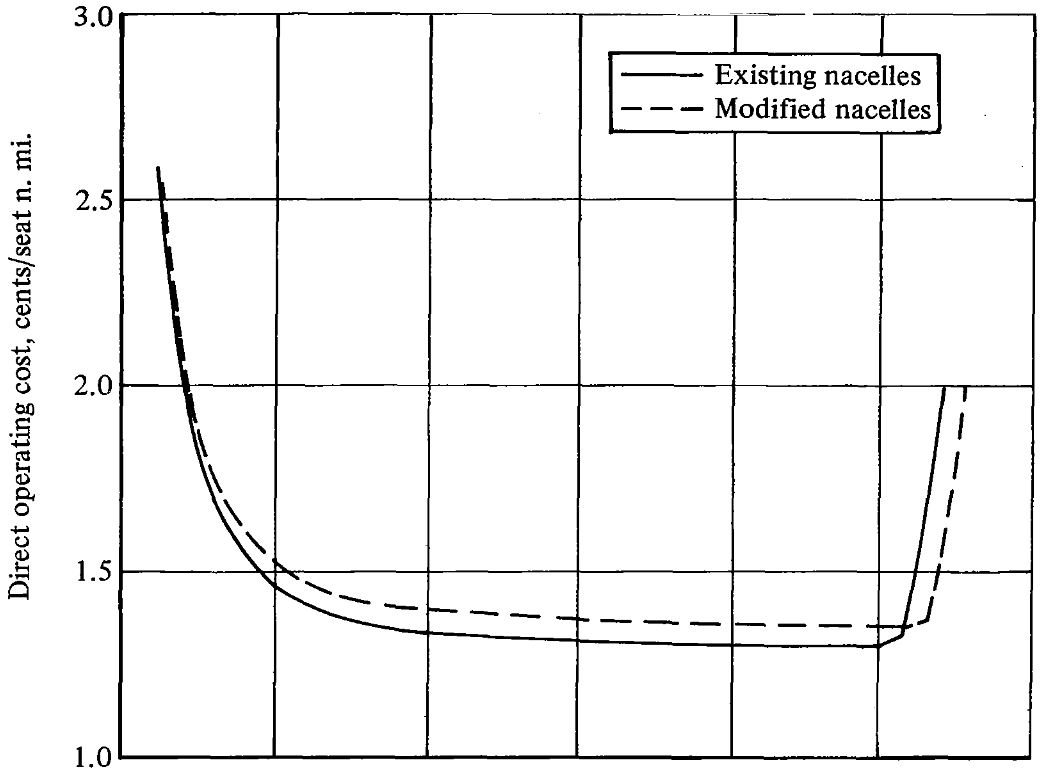
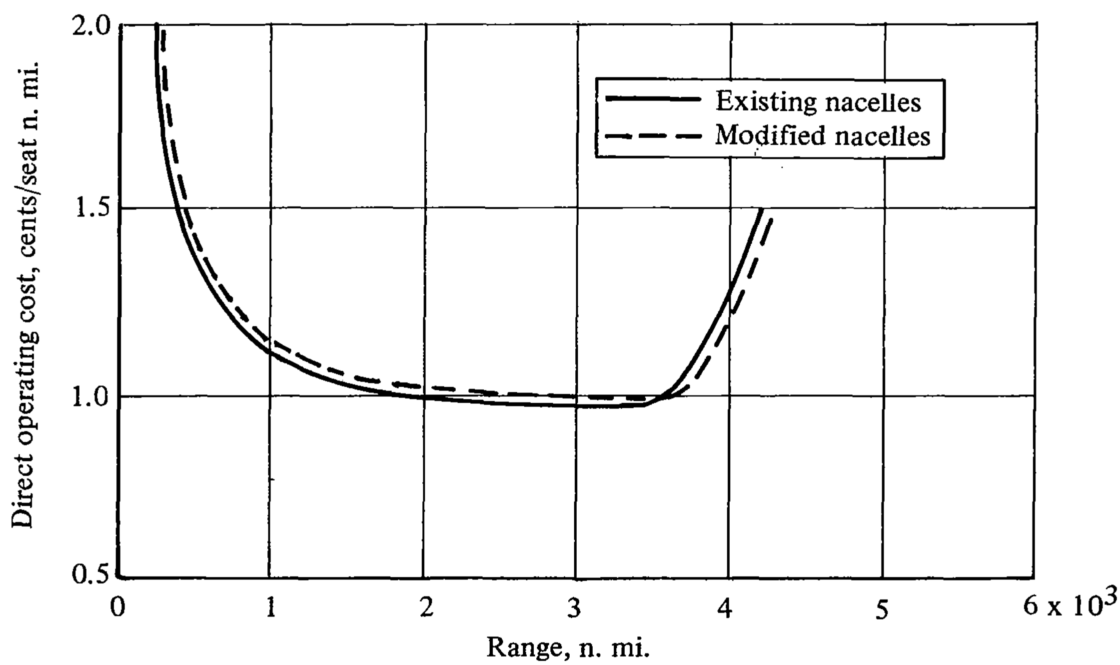


Figure 13. – Variation of retrofit kit price with quantity.



(a) Model DC-8-55 with 5-year depreciation period for modified nacelles.



(b) Model DC-8-61 with 10-year depreciation period for modified nacelles.

Figure 14. – Direct operating costs of DC-8-55 and DC-8-61 airplanes. International operating rules. Standard day.

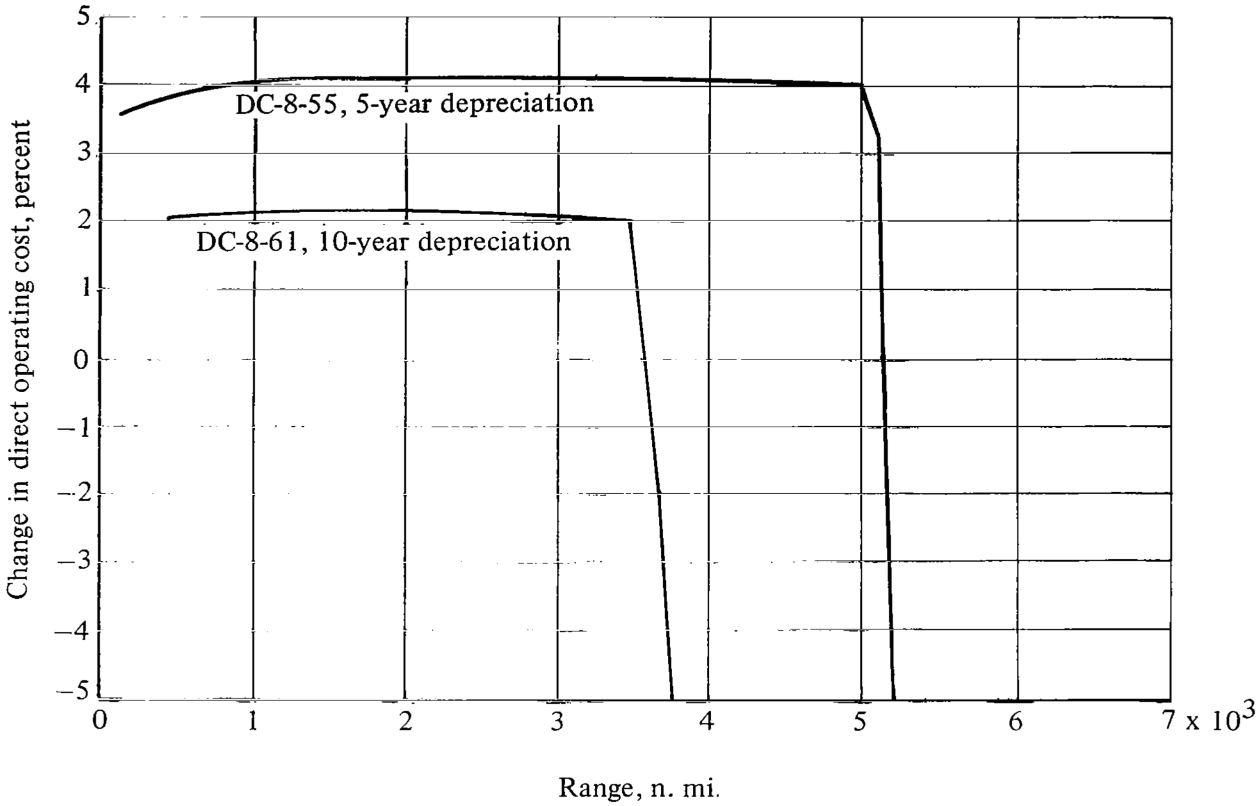


Figure 15. – Change in direct operating cost resulting from retrofit, international operating rules.