16. NOISE PREDICTIONS AND ECONOMIC EFFECTS OF BOEING NACELLE MODIFICATIONS

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SUMMARY

The features and requirements of an acoustically treated nacelle designed for JT3D turbofan-powered 707 airplanes are described. The acoustic features of this nacelle which make it different from the existing production configuration include (1) a two-ring treated inlet containing 87 square feet of acoustical material within the diffuser to reduce the fan-generated noise radiated forward and (2) a full-long fan duct lined with 267 square feet of sound absorbing material to reduce the aft radiated fan noise. It is predicted that this combination of inlet and fan duct treatment will reduce the fan noise to the level of the jet noise during landing approach. When this treatment is applied to the 707-320B airplane on a 3° glide slope, a reduction in peak flyover noise of approximately 13 to 16 PNdB is realized at a point 1 nautical mile from the runway threshold. In addition, the time of exposure to noise in excess of 100 PNdB is markedly reduced. The increase in jet noise level at take-off thrust settings limits the reductions in peak take-off flyover noise to approximately 5 to 7 PNdB at a point 3.5 nautical miles from brake release. If the airplane could cut back thrust to that required to maintain a 6-percent climb gradient, then a further reduction in flyover noise of 4 PNdB should be realized. Flight validation is required to substantiate that the predicted reductions can be achieved. Flight tests of the modified nacelle are scheduled for May and June 1969.

The nacelle modifications have been developed with the goal of maximizing the landing-approach noise reduction while minimizing the impact on airplane performance and economics. The loss of 180 nautical miles in maximum range capability is a result primarily of the 3360-pound total increase in nacelle weight. Although a slight reduction in take-off thrust is expected, its effects on field length and climbout are negligible.

The major factors affecting direct operating costs (DOC) for an airplane retrofitted with treated nacelles have been determined by using the 1967 Air Transport Association method. The resulting DOC increase of approximately 7 to 10 percent results from depreciating the estimated kit costs of $900,000 to $1,150,000 over a period of 5 years. The kit costs are based on 1972-1973 dollars and reflect the 46-month period, after production go-ahead, required to certify and produce retrofit kits for the six hundred 707 and 720 turbofan-powered airplanes that will be operating in the early 1970's.

INTRODUCTION

Details of the acoustically treated inlets and fan exhaust ducts being developed under NASA Contract NAS1-7129 are presented in references 1 and 2. The purpose of the present paper is to integrate these data in terms of the impact of acoustically treated nacelles on the JT3D-3B powered 707-320B airplane. Some of the characteristics of the basic-specification airplane selected for analysis are a maximum take-off gross weight of 327 000 pounds, 149 passenger seats with 15 percent first class and 85 percent tourist class, and a maximum landing weight of 207 000 pounds.

The effects of retrofitting the airplane with acoustically treated nacelles are considered in the following major areas:

(1) Noise reductions for landing-approach and take-off conditions

These noise-reduction predictions are based directly on Boeing and McDonnell Douglas ground-test results.

(2) Payload range and take-off performance

(3) Direct operating cost (DOC), and nacelle certification and retrofit kit production schedules

These cost and production data are based on a total fleet of six hundred 707 and 720 (including one hundred seventy 707-320B's) turbofan-powered airplanes expected to be operational during 1972-1973.

CONFIGURATION DESCRIPTION

The short-duct nacelle configuration (fig. 1), the design of which took place in 1959-1960, was carefully tailored to provide low weight and minimum cruise drag, The resulting inlet highlight diameter and the 18-percent throat contraction ratio selected required blow-in-doors to provide surge-free engine characteristics during low-speed operation. The large blow-in-doors shown in figure 1 illustrate a second iteration of the basic inlet with the intent of providing improved pressure recovery at the engine compressor face, and thus increased thrust during take-off and climbout. The short fan exhaust duct and the very tightly fitted cowl provide minimum nacelle cross-sectional area. Since the engine nacelle is also cantilevered as far forward of the wing as the structural design concept will permit, the combination effect provides minimum wing-nacelle interference drag. The fan nozzle location selected, however, results in some thrust and specific fuel consumption penalties as a consequence of scrubbing drag caused by the relatively high-velocity fan exhaust air blowing over the aft engine cowl. The manner in which these factors are related makes it difficult to change the nacelle configuration to obtain substantial noise attenuation and not incur a loss in airplane performance, a deterioration in airplane flutter characteristics, or some other adverse effect.

A number of significant changes from the baseline nacelle are required to accommodate the acoustic treatment needed to provide the desired noise attenuation. In the treated nacelle (fig. 2), the inlet design philosophy has been revised completely. The blow-in-doors have been eliminated and the inlet is longer and heavier. The highlight diameter has been increased, the throat contraction ratio has been changed to 25 percent to assure satisfactory low-speed operation, and 87 square feet of acoustic treatment have been provided within the diffuser. Further changes are evident in the installation of the larger diameter, full-long duct containing 267 square feet of acoustic treatment. It can be noted that the annular fan and primary nozzles are essentially "coplanar." These changes will add approximately 3360 pounds to the airplane operating empty weight and will also contribute to some deterioration in cruise performance. However, care has been taken in the detail design in an effort to minimize these adverse performance effects and yet meet the noise attenuation goals.

NOISE ATTENUATION

The noise attenuation attainable from the treated nacelle is very strongly influenced by power setting, as shown in figure 3. At the 707-320B maximum landing weight of 207 000 pounds, a net thrust of 5000 pounds per engine is required when the aircraft is on a 3° glide slope with gear down and landing flaps extended. The noise reduction shown of 9 to 16 PNdB at this power setting represents the extremes of the measurements obtained during ground test at the Boeing Company's Tulalip test facility corrected for flight and extrapolated to a 370-foot altitude and includes tolerances in measurement of both the baseline and the treated configurations. Spectral analysis clearly shows that the limiting noise source at this power setting is turbine-blade-generated noise.

At the 707-320B maximum take-off weight of 327 000 pounds, approximately 11 700 pounds of thrust per engine are required to maintain a 6-percent all engine climb gradient with take-off flaps extended and gear up. At this cutback power setting, the jet noise levels are relatively higher than those at approach thrusts. Therefore, the effectiveness of the treated rings, linings, and splitters of the inlet and duct in reducing fan noise cannot be fully exploited and the noise reduction is correspondingly reduced. At take-off thrust, the jet noise produced downstream of the primary nozzle becomes even more dominant and effectively limits the noise attenuation available to the values shown.

Figure 4 identifies the noise reference points currently proposed by the Federal Aviation Administration (FAA) and considered in this paper. The approach reference point is 1 nautical mile from the landing threshold and directly beneath the 3° glide-slope approach path, and the take-off reference point is 3.5 nautical miles from the start of the take-off roll and directly beneath the take-off flight path.

Estimated time histories of flyover noise at the approach reference point are presented in figure 5 for the baseline-nacelle airplane and a treated-nacelle airplane with a thrust per engine of 5000 pounds. The estimates use the limited ground-test data of figure 3 and represent the noise exposure that a ground observer at the approach reference point would receive. In addition, these noise time histories show a 13- to 16-PNdB reduction from the baseline-nacelle-airplane peak perceived noise level of 123 PNdB to the treated-nacelle-airplane peak perceived noise level of 107 to 110 PNdB. Therefore, on the basis of these data it may be observed that the time exposure to noise levels in excess of 100 PNdB will be substantially reduced.

Figure 6 identifies the effect of altitude and distance from the threshold on noise reduction during landing approach for a thrust per engine of 5000 pounds. Noise reduction and altitude are shown at various distances from the landing threshold during a 3° glide-slope approach. Note that the attenuation decreases approximately 1 PNdB per nautical mile from the threshold.

The flyover-noise signature at the take-off reference point is shown in figure 7(a) for the treated-nacelle airplane and the baseline-nacelle airplane. The variation in sound pressure level as a function of thrust measured during ground tests, when extrapolated to flight, results in an estimated 5- to 7-PNdB reduction in take-off noise from the baseline-nacelle-airplane peak perceived noise level of 118 PNdB to the treated-nacelle-airplane peak perceived noise level of 111 to 113 PNdB. The perceived noise levels of figure 7(a) are calculated for an altitude of approximately 900 feet, which is representative of the altitude attained by a maximum take-off gross weight 707-320B airplane at a point 3.5 nautical miles from the start of take-off roll.

Because the airplane with either nacelle configuration is at an altitude of less than 1000 feet, cutback thrust cannot be utilized as a noise abatement procedure under proposed **FAA** noise certification criteria. If take-off gross weights are less than approximately 320 000 pounds, altitudes at the take-off noise reference point will exceed 1000 feet. When cutback can be employed, the proposed FAA noise rule requires a minimum climb gradient of 6 percent. Figure 7(b) presents the baseline-nacelle and treated-nacelle flyover perceived noise levels estimated for the thrust setting required to maintain a 6-percent climb gradient. The results indicate that acoustic treatment will effect a further reduction of approximately 4 PNdB.

The noise variation with take-off gross weight is presented in figure 8 for the baseline-nacelle and treated-nacelle airplanes. Both configurations are assumed to employ an instantaneous cutback to a 6-percent climb gradient over the 3.5-nautical-mile point for take-off weights below 320 000 pounds. The take-off noise estimates shown in figure 8 therefore combine the effects of both the altitude increase at the noise reference point and the reduction in the thrust required to maintain climb as weight is reduced.

An interesting feature of the full-long-duct nacelle, which may contain a payoff of significant proportions, is that the annular "coplanar" fan and primary nozzles provide approximately 2- to 6-dB noise reduction from the baseline short-duct nacelle in the jet noise spectra. These reductions exist across the entire range of engine power settings and are believed to result from reduced shear velocity gradients in the primary nozzle mixing zone.

PERFORMANCE EFFECTS

Substantial engineering effort has been devoted to minimizing the adverse effects of the nacelle modifications on airplane performance. The principal nacelle change producing adverse performance effects is the full-long aft fan duct. The long-duct nacelle, compared with the existing short-duct production nacelle, results in a threefold increase in wetted area to be accounted for in drag calculations as well as an increase in the interference drag as a result of increased cross-sectional area adjacent to the wing. More important, the long duct, and the acoustic treatment that it contains, is responsible for an appreciable increase in nacelle weight.

The increase in airplane drag is estimated to be approximately 3.1 percent at Mach 0.80 and a 35 000-foot altitude, the conditions typical of long range cruise. The increase in skin-friction drag due to increased nacelle wetted area accounts for more than 80 percent of the total increase at Mach 0.80 and the increases in interference drag account for most of the rest of the penalty. These estimates contain a 10-percent allowance in skin friction to account for typical production surface roughness and excrescencies. The initial set of flight-test nacelles is not being fabricated with production tooling and the surfaces might not achieve the smoothness that would be demanded for airline equipment. Except for surface smoothness, it is believed that the estimated increases in drag are reasonably accurate. Some confirmation of these estimates is obtained from results of a wind-tunnel test of a generally similar sonic-throat-inlet nacelle model conducted under Contract NAS1-7129. The results of this test, when adjusted to account for configuration differences, bracket the estimated 3.1-percent increase. A long-duct—sonic-throat-inlet nacelle configuration and the existing short-duct production configuration were tested on an 0.068-scale half-model. The data obtained in this test are used to establish the drag rise characteristics. At the Mach 0.83 minimum DOC cruise condition, the added interference drag of the treated nacelles is estimated to result in an increase in drag of approximately 5.1 percent.

The installed engine performance at take-off and cruise has been estimated for the acoustically treated nacelle configuration. Engine performance changes resulting from estimated inlet pressure recovery losses, fan duct pressures (based on measurements obtained during ground tests), and fan exhaust nozzle velocity coefficients were applied to Pratt & Whitney specification engine performance. This analysis indicates that thrust increases of 3.1 percent and thrust specific fuel consumption (TSFC) improvements of 3.5 percent might be obtained for the Mach 0.80 long range cruise condition. This potential improvement results primarily from the elimination of the scrubbing of relatively high-velocity fan exhaust on the afterbody of the existing short-duct nacelle. This scrubbing drag is absorbed as an installed engine performance penalty of more than 4 percent of cruise thrust and TSFC so that its elimination can more than balance the inlet losses. The inlet pressure recovery losses are calculated on the basis of the estimated flat-plate skin-friction drag (with an allowance for the roughness) of the acoustic material and the ring-strut intersection drags. Duct and nozzle velocity coefficients are expected to change only a small amount in a favorable direction at cruise conditions.

At take-off, however, duct velocity coefficients change in an adverse manner by about 1/2 percent and contribute to the 70-pound reduction in take-off thrust that is estimated for a treated nacelle. At take-off, elimination of scrubbing drag, at best, represents an improvement of approximately 1.5 percent in thrust, about the same magnitude as the magnitude of the inlet losses which is also estimated to be about 1.5 percent and, thus, the inlet losses will balance the scrubbing-drag improvements.

Weight estimates indicate an increase in operating empty weight of 3360 pounds, 840 pounds for each nacelle, to account for acoustic material, increased length and diameters of the inlet cowls, long fan ducts, and new fan thrust reversers. These estimates are based on analysis of the weights of an assumed production configuration which would necessarily be different in many respects from the test configuration to be flown in this program.

Field lengths and take-off profiles were calculated for the existing production and acoustically treated nacelle airplanes by methods which account (empirically) for important parameters such as flare and rolling friction. The estimated effects on engine and airplane performance of the treated nacelle previously described are included in the calculation. The effect of the nacelle installation on take-off length and climbout profile is small. For a temperature of 77° F and for a 327 000-pound maximum take-off gross weight, the take-off field length of the airplane with treated nacelles is lengthened by 50 feet from a baseline of 10 710 feet and the altitude at 3.5 nautical miles from brake release is decreased by 15 feet from a baseline of 900 feet.

The effect of the treated nacelles on payload range is defined in figure 9 for domestic and international operations. Both long range cruise and minimum DOC cruise conditions are shown for the baseline 707-320B airplane and the treated-nacelle airplane. A step climb cruise procedure was used for long range cruise, whereas a constant altitude was utilized for minimum DOC cruise. Inasmuch as detailed differences exist between the basic-specification airplane selected for analysis and individual airlines' configurations, the performance shown in the figure can only be considered representative of airplane capability. The performance penalties ranging from 165 to 180 nautical miles for international and domestic long range cruise (fig. 9) are almost entirely due to the 3360-pound increase in operating empty weight because of the expectation that the drag increase of the treated-nacelle configuration will be balanced by an increase in installed engine performance at Mach 0.80 cruise. The domestic range penalty of 240 nautical miles at Mach 0.83 minimum DOC cruise is larger than the range penalty at long range cruise; this reflects the effect of the increase in interference drag with Mach number. The 1967 Air Transport Association (ATA) fuel reserve rules were applied. The difference in the fuel reserve requirements of these ground rules is responsible for the small differences in range penalties between the domestic and international performance shown in figure 9.

RETROFIT ECONOMICS

The economic consequences of the range penalties shown in figure 9, coupled with retrofit cost considerations, must be evaluated for each airline's route structure to determine how critical long range routes or take-off limited fields are affected and how these changes will affect the airline profit structure. A study of this magnitude is beyond the scope of this paper but considerable insight into the economic consequences of retrofitting treated nacelles into airline operations can be determined by analyzing changes caused in direct operating costs. For this purpose, direct operating costs have been calculated for airplanes equipped with baseline and treated nacelles by using the 1967 ATA method for domestic and international operations (except that actual maintenance estimates are used for the treated nacelles). Major DOC considerations are as follows:

Retrofit cost (including installation)	$900,000 to $1,150,000
Initial spares	20%
Depreciation period:	
Airframe	12 years
Nacelle	5 years
Airplane utilization	ATA curve
Passenger seats	149
First class	15%
Tourist class	85%
Airplane downtime	Assumed zero
Nacelle maintenance	Functional analysis

Two retrofit cost estimates are given, which correspond to the maximum and minimum estimates of the kit cost. This cost range represents the uncertainties in estimating production costs for the polyimide—glass-fiber acoustic construction currently being considered for this nacelle. The airplane kit costs of $900,000 to $1,150,000 are estimated for 1972-1973 dollars. A factor of considerable importance to the DOC estimate is the inclusion of a 20-percent initial spares allowance for the retrofit nacelle. This allowance is based on current experience with the existing short-duct production nacelles which are requiring from 13 to 24 percent spares for various major nacelle components. This allowance is in line with the ATA 1967 formula because the nacelle is built up of "airframe" components, for example, inlet and fan discharge duct cowlings (13 to 17 percent initial spares) and "engine" components, for example, thrust reversers and quick engine change items (15 to 24 percent initial spares). The ATA method's new airplane depreciation period of 12 years is assumed. The 5-year depreciation period for the treated nacelle is being used in other noise-alleviation studies sponsored by the Air Transport Association and Aerospace Industries Association. This depreciation period accounts to some degree for the fact that the average airplane being considered for retrofit has already been in service for some time and, therefore, has a limited useful life. Each airline has its own individual depreciation philosophy however, and these philosophies must be extended to this particular problem in each individual case. Downtime was not included as an economic factor on the basis of the assumption that retrofit would be accomplished concurrent with airplane overhaul. If this assumption should prove to be incorrect, additional airplane out of service costs would have to be included.

The calculated direct operating costs, based on the aforementioned ground rules, are presented as a function of ATA range in figure 10 and the data indicate an increase of approximately 7 to 10 percent in DOC as a result of retrofit for both domestic and international operations. The most significant factor causing this increase is the kit cost of $900,000 to $1,150,000 and the assumed 5-year depreciation period.

The significance of the change in value to be depreciated can be better understood by a comparison of depreciation, crew pay, insurance, maintenance, and fuel costs for the baseline-nacelle airplane and the treated-nacelle airplane. As can be seen in figure 11, retrofit causes an increase in depreciation from 26 percent to 31 percent of the DOC. Crew pay does not change, but insurance costs will increase slightly as a function of the retrofit kit cost. Fuel costs will increase by an amount about equal to the increase in insurance costs.

The baseline maintenance costs were also calculated by the 1967 ATA maintenance cost analysis procedure. If this ATA procedure had been used for the retrofit maintenance cost calculations, instead of actual estimates based on functional analysis of the proposed configuration, the value would be 0.344 cent per seat statute mile rather than

0.341 cent as shown in figure 11. Should the retrofit kit costs be written off over a different time period from the 5-year period assumed, then the depreciation costs can change substantially as shown in figure 12. In this figure the percentage increase in DOC is established for assumed depreciation periods ranging from 2 to 12 years. As can be seen, depending on the period assumed for depreciation, the impact of retrofit on DOC can be almost halved or doubled. Again, depending on the depreciation period, the spread in estimated kit costs could result in a change of from 2 to 4 percent in DOC.

Some insight into the implications of the timing of the treated-nacelle retrofit program can be gained from the possible production schedule shown in figure 13. Significant program events are identified with respect to an assumed production program go-ahead. The program schedule could vary somewhat from the estimated timing shown, depending on factors such as timing of production go-ahead, urgency of program, certification rule application, total production requirements and production rates. However, the program is believed to be quite representative considering current and proposed production capability and capacity. The first significant milestone occurs 14 months after production go-ahead when the first complete production kit is available for flight test. Precertification and certification flight testing leads to a certified retrofit for the 707-320B airplane 22 months after go-ahead. Delivery of kits to the airlines could begin at this time and, based on an assumed production rate of 25 kit shipments per month, production of kits for 600 airplanes, not including spares, would be completed approximately 4 years after production go-ahead.

It must be understood that use of DOC as a measure of airplane operating profitability for a massive retrofit program, such as that envisioned for the acoustically treated nacelle, extends the 1967 ATA method beyond its designed intent. Also, the DOC is only one measure of the impact of retrofit. Questions arise such as, Will an old airplane be retired and new equipment purchased? Or, Will the outlay of substantial monies for quiet nacelles preclude the purchase of much of the planned new equipment? Nearly $1 billion in financing must be arranged over a relatively short period. Will the public pay? How elastic is the market? These questions are not part of the contract with NASA, but these and other questions must be both asked and answered in the near future.

CONCLUDING REMARKS

An acoustically treated nacelle designed for the JTSD turbofan-powered 707 series airplanes is currently being constructed and is scheduled to be flight tested in May-June 1969. Although technology evolved during the development of this nacelle is applicable to other turbofan engines installed on other airplanes, the magnitudes of the noise reductions estimated for the acoustically treated JTSD nacelle are not applicable to any other type of turbofan engine, primarily because of the variation in the relative intensity of the individual noise sources within the engine. Similarly, performance and DOC penalties are not applicable to aircraft other than the 707-320B airplane used as an example. The most important results of this program to date are as follows:

1. Significant reductions in JT3D engine noise appear to be technically feasible. In the landing-approach configuration, maximum noise reductions of 13 to 16 PNdB are predicted. Maximum noise reductions of 5 to 7 PNdB are possible at take-off thrust and 9 to 11 PNdB at cutback thrust.

2. The range penalty at long range cruise conditions, 180 nautical miles for domestic ATA fuel reserves, is due almost entirely to the 3360-pound increase in operating empty weight.

3. Changes in take-off and climb performance are considered negligible.

4. The direct operating cost increase of 7 to 10 percent is a direct result of the $900,000 to $1,150,000 kit cost and 5-year depreciation period adopted and can change considerably if other assumptions are made.

5. Delivery of certified quiet nacelle kits to the airlines could start as early as 22 months from a production go-ahead. Manufacture of 600 airplane kits could be completed 2 years later.

A word of caution is necessary with regard to application of these predicted noise reductions and associated performance effects. First, these predictions are based upon extrapolation of limited model and full-scale ground-test data applied to a proposed retrofit treated-nacelle airplane and, second, the noise reductions and performance have yet to be validated by flight demonstrations. This paper is an interim status report only.

REFERENCES

1. Drakeley, George T.; and McCormick, Ralph B.: Treated Inlets. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 14 herein.)

2. McCormick, Ralph B.: Fan-Duct Development. Conference on Progress of NASA Research Relating to Noise Alleviation of Large Subsonic Jet Aircraft, NASA SP-189, 1968. (Paper No. 15 herein.)

BASELINE NACELLE

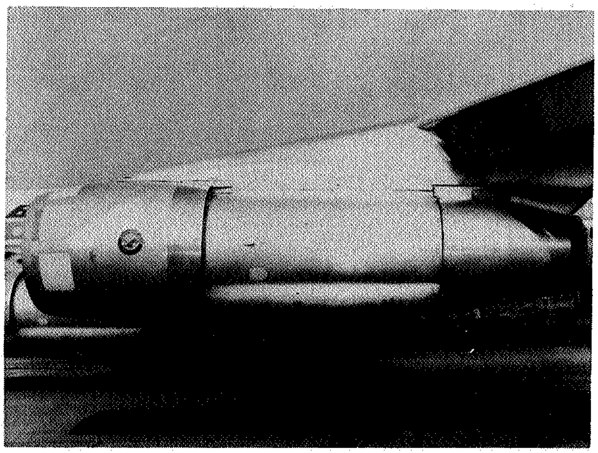

Figure 1

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TREATED NACELLE

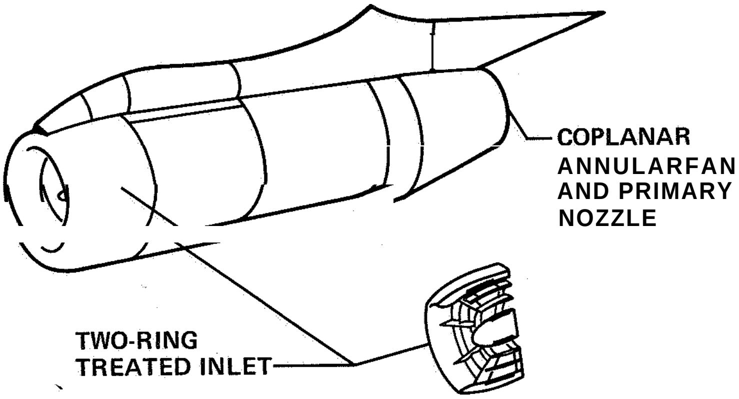


Figure 2

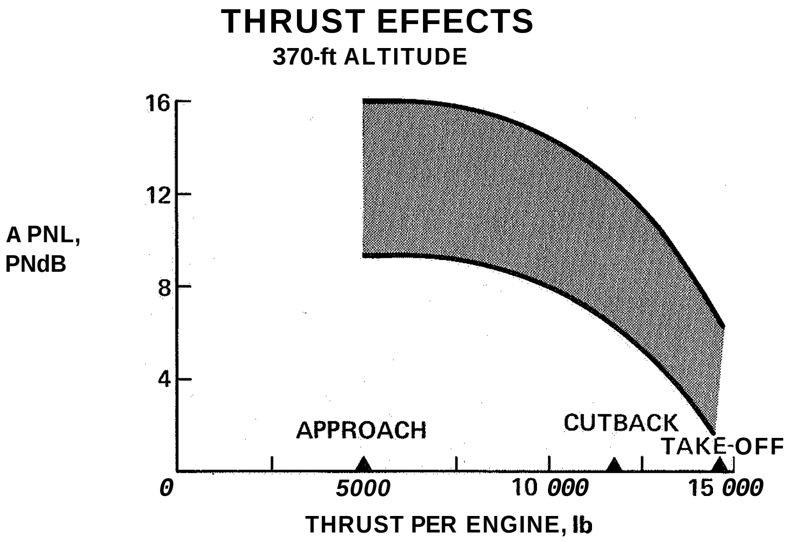


Figure 3

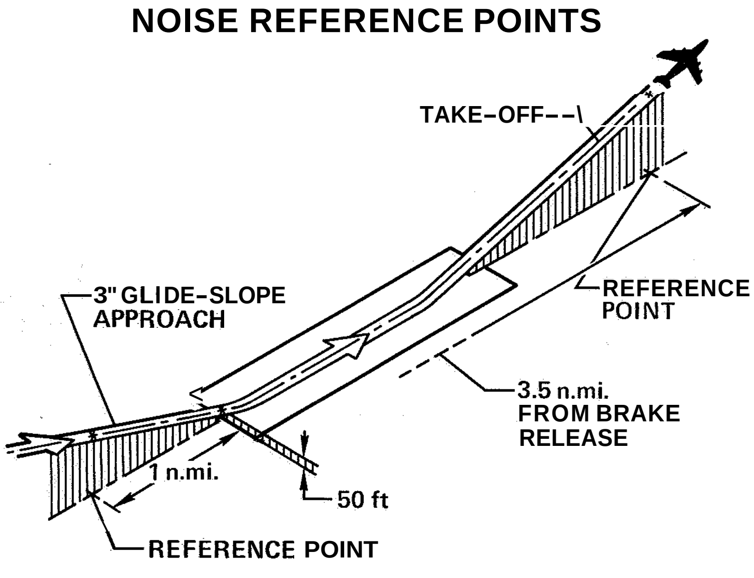


Figure 4

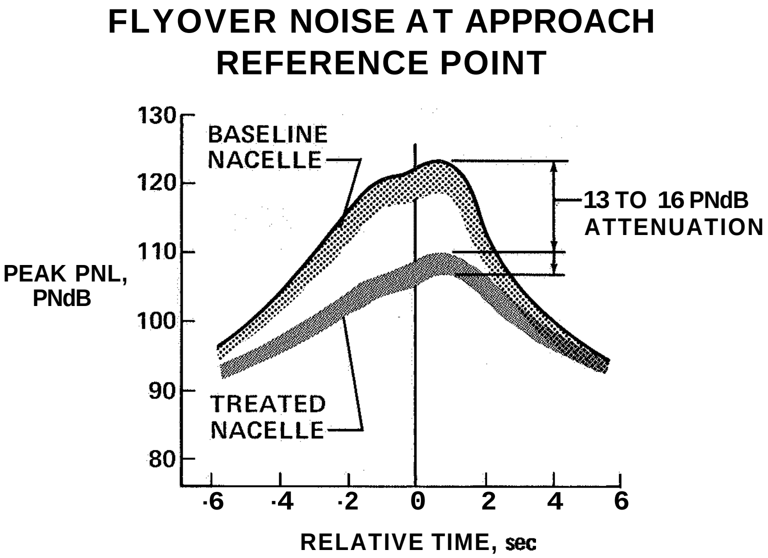


Figure 5

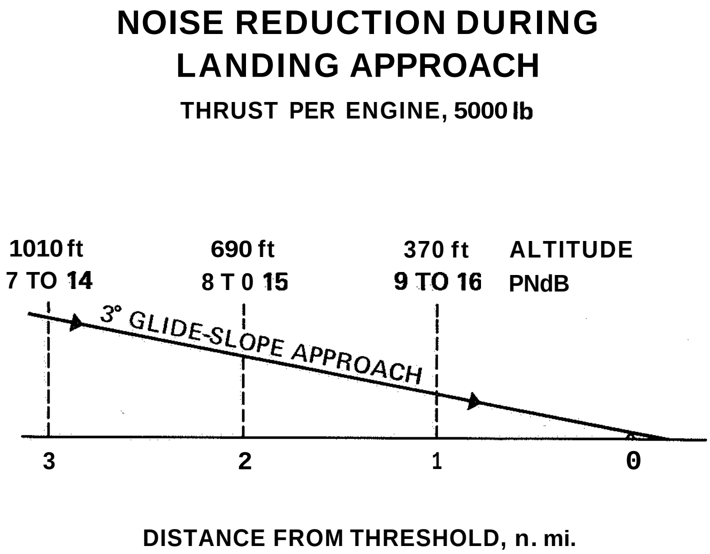
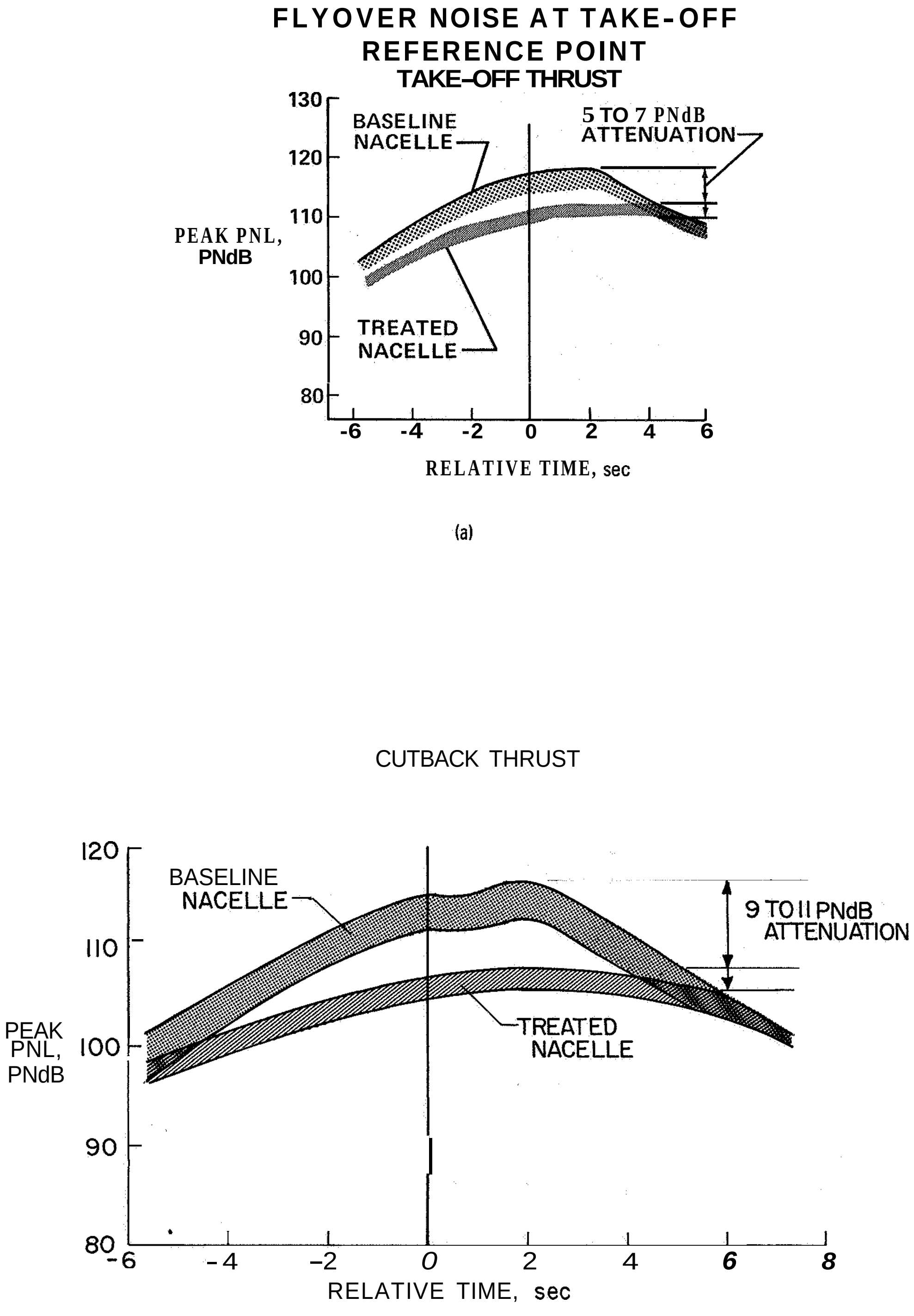


Figure 6


FLYOVER NOISE AT TAKE-OFF REFERENCE POINT
TAKE-OFF THRUST
PEAK PNL, PNdB
130
120
110
100
90
80
BASELINE NACELLE
TREATED NACELLE
5 TO 7 PNdB ATTENUATION
-6
-4
-2
0
2
4
6
RELATIVE TIME, sec
CUTBACK THRUST
PEAK PNL, PNdB
120
110
100
90
80
BASELINE NACELLE
TREATED NACELLE
9 TO 11 PNdB ATTENUATION
-6
-4
-2
0
2
4
6
8
RELATIVE TIME, sec

(a)

(b)

Figure 7

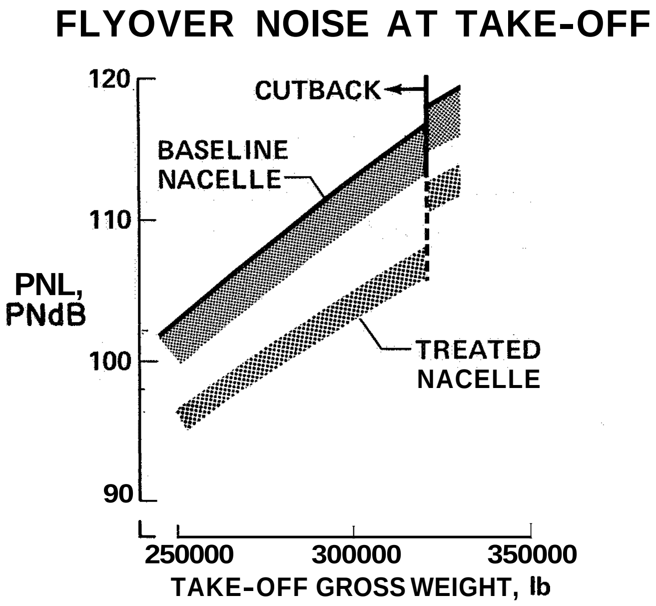


Figure 8

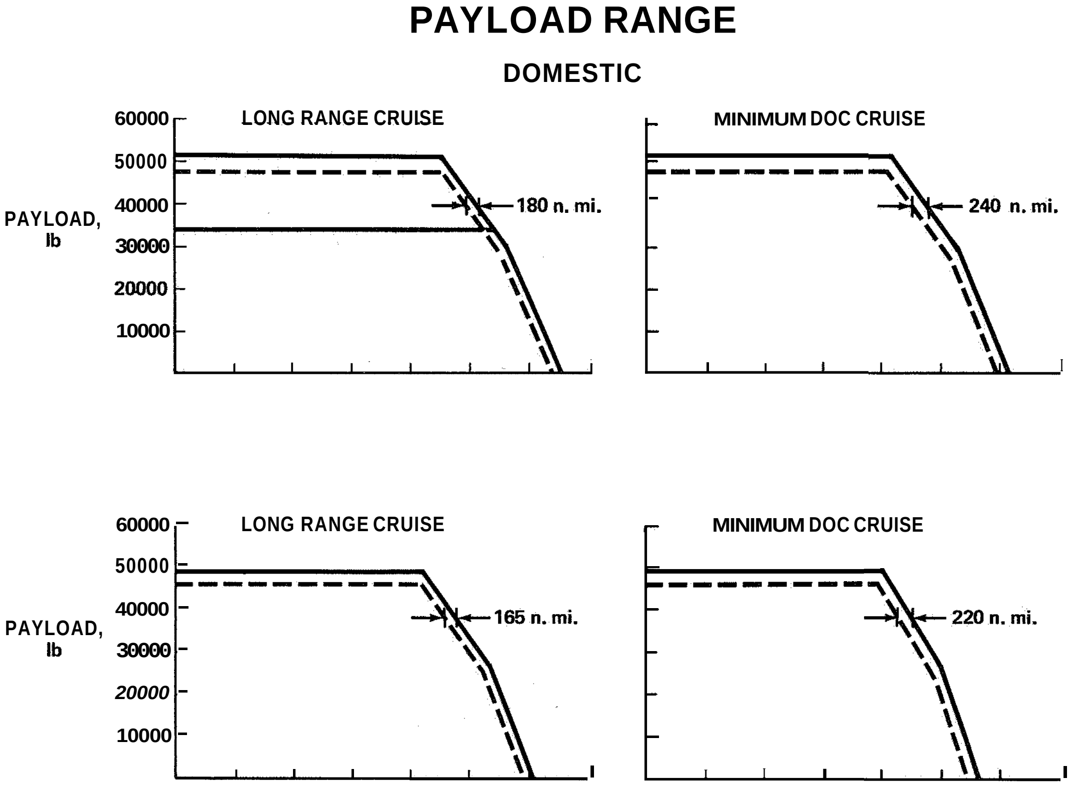
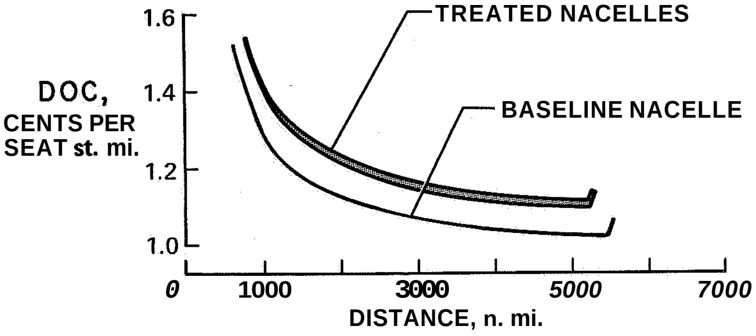


Figure 9

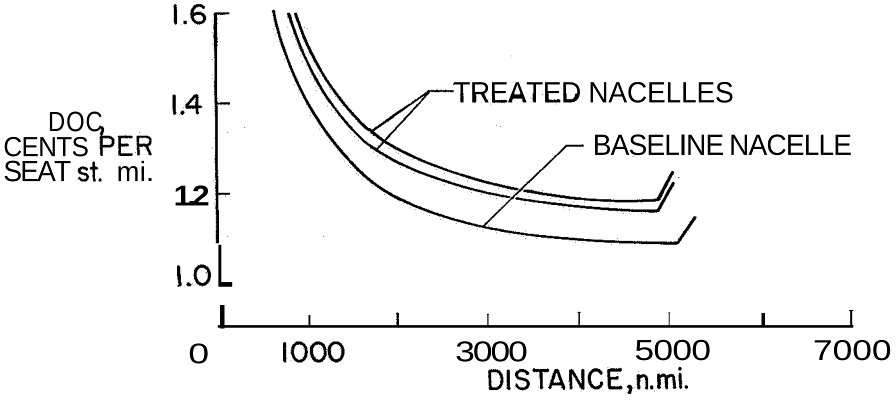
DIRECT OPERATING COST

DOMESTIC OPERATIONS



(a)

INTERNATIONAL OPERATIONS



(b)

Figure 10

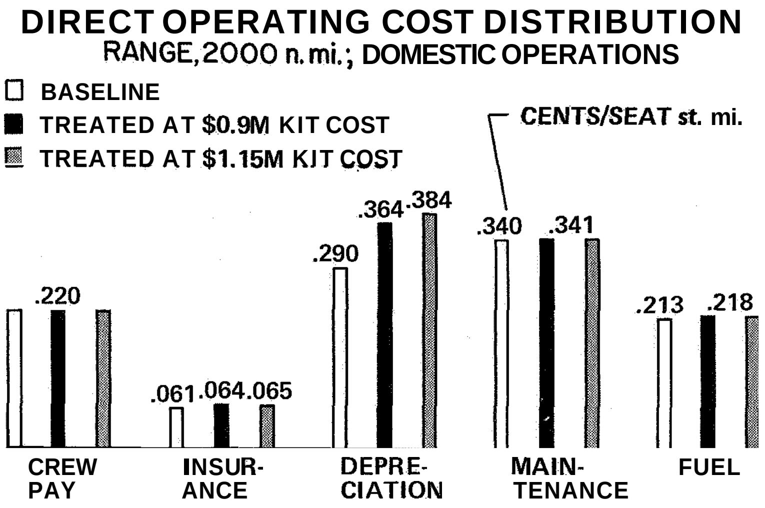


Figure 11

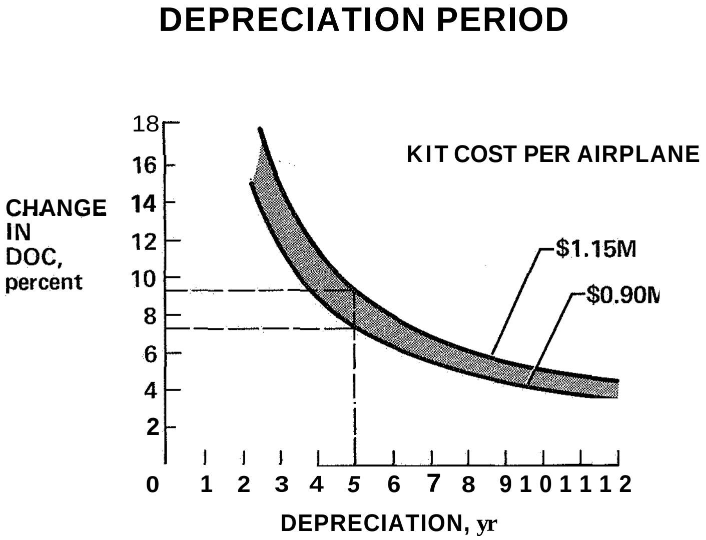


Figure 12

RETROFIT KIT PRODUCTION SCHEDULE

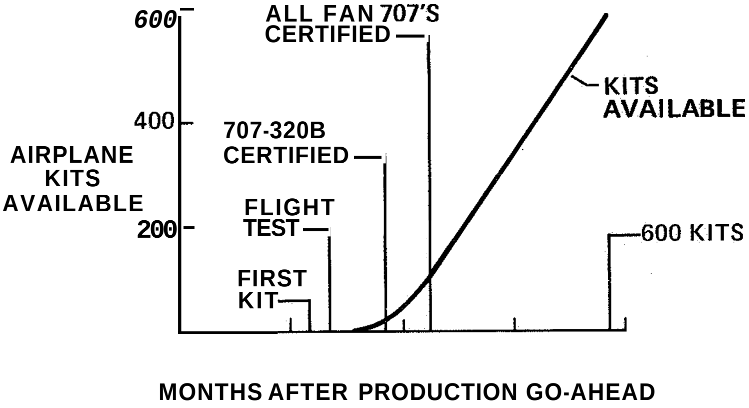


Figure 13