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**REDUCTION OF JT8D POWERED AIRCRAFT
NOISE BY ENGINE REFANNING**

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ABSTRACT

The purpose of the Refan Program is to establish the technical feasibility of substantially reducing the noise levels of existing JT8D powered aircraft. This would be accomplished by retrofitting the existing fleet with quieter refan engines and new acoustically treated nacelles. No major technical problems exist that preclude the development and installation of refanned engines on aircraft currently powered by the JT8D engine. The refan concept is technically feasible and provides calculated noise reductions of from 7 to 8 EPNdB for the B727-200 aircraft and from 10 to 12 EPNdB for the DC-9-32 aircraft at the FAR Part 36 measuring stations. These noise levels are lower than both the FAR Part 36 noise standards and the noise levels of the wide-body DC-10-10. Corresponding reductions in the 90 EPNdB footprint area are estimated to vary from about 70 percent for the DC-9 to about 80 percent for the B727. The refanned aircraft should perform typical range/payload missions with a negligible effect on block fuel. Production retrofit kits could be available in 1976 for the DC-9 at a unit cost of about \$1.0 million and in 1977 for the B727 at a unit cost of \$1.7 million.

INTRODUCTION

Aircraft noise is one of today's significant environmental problems. High aircraft noise levels have resulted in limitations of airport expansions, airport curfews, civil law suits, restrictions in aircraft operations, and a generally unfavorable reaction to airline operation at least by residents of property surrounding airports. All of these are costly to the airlines and their future growth.

The present airport noise environment is largely determined by the noise output of the narrow-body aircraft which comprise about 75 percent of the domestic fleet of 2400 aircraft. The narrow-bodied fleet is made up of aircraft powered by Pratt & Whitney (P&WA) JT3D and JT8D engines. These include about 600 B707 and DC-8's that utilize the JT3D and about 1200 B727, B737, and DC-9's with JT8D engines. The JT8D powered aircraft are newer and are still in production in large quantities. It has been estimated that the domestic fleet in 1985 will contain about 1600 JT8D powered aircraft and 400 JT3D powered aircrafts. Therefore, the reduction of the noise of these aircraft will have a major impact on the over-all aircraft noise problem.

Solutions to the problem of aircraft noise generally fall into two categories. The first category includes costly, long-range solutions that impose large economic burdens on the airlines and do nothing to provide a timely reduction in noise that will benefit all airport residents. The solutions in the first category include: replacement of existing narrow-bodied aircraft with new, quieter aircraft; replacement of the engines in existing narrow-bodied aircraft with new quieter engines; procurement of land surrounding existing airports and relocating the affected population; or abandoning existing airports bounded by populous areas and relocating new airports in remote unpopulated areas.

The second category of solutions involves modifications to existing narrow-body aircraft which can be achieved in a more timely and less expensive manner than those in the first category. Two approaches have been identified in this category. One approach is to apply current sound suppression technology to new nacelles for the JT3D and JT8D engines. The FAA has sponsored several programs directed to this approach that have demonstrated the feasibility of meeting current FAR Part 36 requirements for both JT3D and JT8D powered aircraft by the use of acoustically treated nacelles. Nacelle treatment, however, cannot reduce the exhaust jet noise created outside of the nacelles. The jet noise, therefore, provides a floor preventing any further reduction in noise.

In recognition of this limitation, the NASA, as part of the Joint DOT/NASA aircraft noise reduction effort, has initiated a second approach which consists of modifications of the JT3D and JT8D engines to reduce the jet velocity in addition to application of nacelle noise suppression. The engine modification consists fundamentally of replacing the fan with a design configuration that provides both an increase in engine bypass ratio and a reduction in fan source noise. This modification provides an opportunity to approach the noise characteristics of the popularly accepted wide-body aircraft (DC-10, B747, and L1011) without developing an entirely new engine. This latter program, called the Refan Program, is the subject of this paper.

REFAN PROGRAM OBJECTIVES, SCOPE, AND SCHEDULE

High interest was focused on an NASA Refan Program during late 1971 and early 1972 through joint discussions with NASA, FAA, DOT, engine and airplane manufacturers and several airlines. As a result of these discussions the Refan Program was officially initiated in August 1972 to modify and quiet both the JT3D and JT8D powered aircraft. The objective of the Refan Program is to establish the technical feasibility of providing a significant noise reduction for existing narrow-body aircraft to a level below FAR Part 36. As an example, noise levels for two of the most numerous JT8D powered aircraft (B727-200 and DC-9-32) are shown in figure 1 compared to both the FAR 36 noise standards and to the relatively quiet wide-body DC-10-10. The noise levels of the narrow-body aircraft are significantly higher than FAR 36 for takeoff and approach, and are higher than the heavier wide-body aircraft in all categories. It is de-

sirable to provide the same noise reduction below FAR 36 for the narrow-body jets as that provided by the wide-body aircraft. That is the goal of the Refan Program.

The scope of the Refan Program originally encompassed noise reduction for all five of the commercial narrow-body aircraft powered by the JT3D and JT8D engines (B707, DC-8, B727, B737, and DC-9). Phase I contracts were let for design and analysis of the engine and nacelle modifications with three major contractors: Pratt & Whitney Aircraft (a division of United Aircraft Corp.), The Boeing Commercial Airplane Company (a division of the Boeing Co.), and the Douglas Aircraft Company (a division of McDonnell Douglas Corp.). Contracts were also let with American Airlines and United Airlines for consulting work to assure that the modifications being considered incorporated as many of the user airlines' requirements as possible.

In January 1973, program funding curtailment forced limitation of the scope of the program to only one engine. The joint NASA/DOT/FAA decision was to proceed with the JT8D engine rather than the JT3D. This engine was selected since the aircraft it powers comprise about 60 percent of the domestic airline fleet and accounts for over 70 percent of the takeoffs and landings. These aircraft are more modern than the older JT3D fleet, and over 100 new aircraft are on order by the airlines. Reduction of the noise of this fleet of aircraft would, therefore, have the largest favorable impact on airport noise exposure in the 1980's.

There was no technical reason for discontinuing further work on the JT3D. The preliminary design work on the engine had been completed, and the refanned engine appeared to be a low technical risk development. Integration studies of the new engines on both the B707 and DC-8 had also been completed and revealed no significant problems in implementing a retrofit of these aircraft.

Budget constraints also required a reduction in the scope of the flight tests for the JT8D powered aircraft. The minimal changes required for the DC-9 airplane and its corresponding lower flight demonstration costs compared to the B727 and B737 aircraft, permitted negotiation of a contract culminating in a flight demonstration for the DC-9 in early 1975. Concurrently, ground test noise and performance evaluation for a refanned B727 side engine nacelle and a B727 center engine installation will be performed. While a ground test program at Boeing is not as desirable as a flight test program for the Boeing aircraft, this approach appears to be technically sound because of:

1. Similarity of the B727 side engine installation with that of the DC-9 for which both ground and flight test data will be obtained.
2. Extensive Boeing experience and statistical data to predict ground-to-flight noise levels and aircraft performance from ground tests.

The Refan Program is currently in Phase II of a two-phase program.

Phase I, concluded in July 1973, provided definition of engine, nacelle, and aircraft modifications, preliminary retrofit and economic analyses, and wind tunnel tests of the refanned DC-9, as shown in the schedule in figure 2. The current Phase II will complete the program which will include ground tests of the B727 side engine nacelle and center engine installation and a flight demonstration of a DC-9 with refanned engines and acoustic nacelles early in 1975. Most of the design effort has now been completed and a rather extensive model test program had been conducted at The Boeing Company in support of the refanned B727 aircraft. The first refanned JT8D-109 engine was run by P&WA at the end of February 1974. Engine acoustic and performance testing will continue throughout the current year. Aircraft modifications for the proposed DC-9 flight demonstrator have been designed and fabricated and are currently being installed on this aircraft on the production line. Nacelle components have also been designed for the DC-9 and B727 and fabrication has been initiated. Engineering mockups of the refanned JT8D-109 engine have been provided to both aircraft manufacturers by P&WA to assist in the design and installation of nacelle components and aircraft supplied subsystems.

TECHNICAL APPROACH

The overall approach to achieving lower engine noise is to replace the existing low-bypass-ratio engine two-stage fan with a larger single stage fan designed with low noise features. The hardware and general operating characteristics of the core engine are maintained while providing a new higher bypass ratio engine. The energy to drive the larger fan is extracted from the low pressure turbine which reduces both the jet velocity and jet noise. The increased tip speed of the fan required to maintain fan pressure ratio results in noise levels which will require effective fan and duct acoustic treatment. Since the engine features a full-length fan duct there is a favorable amount of surface area available for treatment. The inlet and tailpipe of the new nacelles provide additional surface area for sound treatment. The refanned engine with a higher bypass ratio provides an increase in takeoff thrust and a reduction in cruise TSFC for the uninstalled engine which helps offset the performance losses associated with the larger treated nacelles.

Engine and airframe modifications are limited to those changes that will make the engines quieter. For the engine, the changes will be limited to the fan (including fan stage and static parts), the fan-drive turbine, exhaust nozzles and engine nacelle with acoustic treatment. No modifications will be made to other engine or airframe components unless they can be shown to be necessary or to contribute directly and substantially to the reduction of noise. These limitations are required to minimize the cost of retrofit, and retain, to the largest extent possible, the proven reliability of the JT8D engine.

Engine Modifications

Engine modifications were determined as a result of extensive cycle studies conducted by Pratt & Whitney Aircraft for the JT8D engine. Figure 3 shows a comparison of the existing and refanned JT8D engines and table I compares the major performance characteristics of the two configurations. The two-stage fan, with closely spaced blade rows, is replaced by a single-stage fan with approximately two-chord spacing between blade rows, as shown in figure 3. The core engine pressure ratio and weight flow capabilities are maintained by the use of two super-charging stages in the core flow path in front of the low pressure compressor. These added stages restore the pressure rise that was lost by eliminating the second fan stage. Full-span IGV's are used and the stage is straddle-mounted with the IGV's supporting the front bearing. The IGV's are spaced several chord lengths forward of the rotor to reduce blade interaction noise and acoustic treatment is applied between the IGV's and the fan rotor. The fan diameter is increased about 8.7 inches, from 40.5 to 49.2 inches, and the bypass ratio is nearly doubled from 1.05 to 2.03.

The existing low and high pressure compressors and the high pressure turbine do not require modification. The three-stage low pressure turbine will not require any change in diameter or blade chord, but the last rotor blading is restaggered to permit increased work absorption while retaining essentially the same level of efficiency.

Design of the fan duct acoustic treatment (fig. 4) is based on an analytical procedure developed at P&WA. The acoustic treatment provided in the outer wall of the engine flowpath between the inlet guide vane and the fan was designed to attenuate tone noise which is present in the inlet noise spectra over most of the normal engine operating range. Also shown in figure 4 is the liberal use of acoustic treatment in the fan duct to reduce the levels of aft-propagating fan noise. The backing depth treatment was selected with a peak attenuation frequency in the 1/3 octave band below the blade passage frequency corresponding to approach power setting. In all cases, the treatment consists of aluminum perforated plate on aluminum honeycomb core.

The production JT8D has a full-length bypass duct with the core flow and bypass flow entering a common tailpipe (provided by the airframe manufacturer) to provide some natural mixing of the hot and cool streams. Performance tests of the production engine indicate that some mixing of the two streams is attained and thus there is a reduction in jet velocity and noise compared to an unmixed engine. The same tailpipe mixing effectiveness is assumed for the refanned engine so that the larger amount of cool bypass flow has a greater effect in reducing jet velocity than for the production engine. The mixed jet velocity at takeoff power is estimated to be reduced from 1470 to 1140 fps.

Nacelle Modifications

The JT8D-109 refan engine is 562 pounds heavier and 8.7 inches larger in diameter than the production JT8D-9 engine (table I). Therefore, the installation of the refan engine on either the DC-9 or B727 airplane requires completely new side-engine nacelles and a new center duct and engine installation on the B727. Figures 5 and 6 show a comparison of nacelles for side-mounted engines and figure 7 shows both the side and center installations on the B727.

Each side-engine nacelle requires a new nose cowl, new upper and lower main access doors, new tailpipe and new thrust reversers. The increased diameter of the side-engine nacelles (figs. 5 and 6) resulted from the increase in engine fan diameter. Increases in overall length resulted from the requirements for acoustic treatment as discussed in the following section on acoustic design. There is no restriction on either the inlet or tailpipe length on the side nacelle of the DC-9 aircraft. However, both the inlet and tailpipe length for the side engine nacelle on the B727 are limited. The inlet length is limited by access requirements for the existing galley service door as shown in figure 7. The tailpipe length is restricted both by access to the center engine and by ground clearance on the center engine during rotation at takeoff. These restrictions in length limit the surface area that is available for acoustic treatment on both the inlet diffuser and tailpipe walls. The acoustic design of the B727 side engine nacelle is, therefore, influenced by these length restrictions as will be discussed later. The existing nacelle subsystems are retained with little or no modifications to the components, but with extensive redevelopment of piping, ducting, and wiring.

The inlets are fixed geometry and sized to the flow requirements of the new engine. Inlet lip designs are based on recent wide-body aircraft experience and technology to provide high performance at low speed without flow separation and at cruise speed without incurring additive drag. These cowls feature thick inlet lips with contraction ratios near 1.3, low throat Mach numbers, and very low diffuser wall angles. The nacelles are designed to enclose the engine and accessories with the smallest nacelle size to minimize the nacelle friction drag at cruise. Boattail angles and the rates of curvature on the nacelle afterbody were selected to prevent the formation of shock waves or boundary layer separation at cruise speeds. Target-type thrust reversers are proposed for both aircraft. The new DC-9 reverser is the same type as that existing on the production aircraft but has been scaled-up to accommodate the increased engine flow rate. The thrust reverser on the B727 installation is changed from pneumatically actuated clamshells to hydraulically operated target doors. The new reverser is a scaled-up version of the successful design currently in use on the B737.

Nacelle Acoustic Design

The success of the refan concept relies to a great extent on the ability to design effective acoustic treatment in the nacelle such that the suppressed noise levels for the inlet and tailpipe are balanced and at the desired values.

DC-9 aircraft. - Definition of the detailed acoustic treatment in the inlet and tailpipe of the DC-9 nacelle is based on Douglas prediction methods and Pratt & Whitney Aircraft-supplied engine cycle parameters. An acoustic design chart, based on approach conditions, was used to select treatment lengths that provide a balanced configuration for equal inlet and aft fan flyover noise. The resulting acoustic treatment area for the DC-9 nacelle configuration is shown in figure 5. All inlet acoustic treatment is perforated aluminum sheet bonded to an aluminum honeycomb core. Welded steel and Inconel construction is used in the tailpipe. The details of the acoustic treatment were based on empirical data from DC-9 flyover noise tests, JT8D static engine tests, and laboratory flow duct transmission loss tests.

The length of the DC-9 refan inlet was selected to provide sufficient acoustic area to meet the noise goals without the need of a splitter ring or treated engine nose dome. The inlet treatment was designed to give maximum EPNL attenuation at the fan fundamental passage frequency (3150 Hz) at approach power setting. Multiple pure tone or buzzsaw noise caused by the high tip speeds of the refanned JT8D-109 engine was not considered by the inlet treatment design because sections of thick treatment between the IGV's and the rotor are tuned for buzzsaw noise and are supplied with the engine case (fig. 4). However, design provisions have been made to change the inlet acoustical treatment if subsequent testing shows that additional buzzsaw treatment is required.

Tailpipe length on the DC-9 nacelle was selected to provide sufficient acoustic treatment area to meet the noise goals. The tailpipe treatment was optimized with all of the treatment tuned to the second harmonic (6300 Hz) of the blade passage frequency at approach power setting.

B727 aircraft. - Treatment design parameters were obtained using lining design computer programs in which nacelle internal geometry, aerodynamic and acoustic parameters are input. The selected lining parameters were then used to predict the component attenuations achieved by the various lining design configurations using a noise-prediction program. The design point for the inlet, duct and tailpipe acoustic treatment is the approach condition and is aimed for maximum attenuation at the fan fundamental passage frequency.

Since the inlet length of the side engine nacelle is limited, additional surface area for acoustic treatment is provided by a long treated engine nose dome and a treated inlet ring as shown in figure 6. These surfaces are constructed of polyimide bonded fiberglass honeycomb, faced

with a porous woven skin and backed with a nonporous skin. The acoustic ring has a double-faced acoustic panel of polyimide construction. Three mounting struts support the ring and carry anti-icing air to the ring.

At this point in the program, there has not been a firm decision on whether the inlet ring is required in the refanned B727 inlet. For the B727 ground test program the inlet ring will be designed to be removable so that the acoustic benefits of the ring can be determined during ground tests. Buzzsaw treatment, other than that between the IGV's and the fan rotor, if required, could be installed in the inlet immediately upstream of the IGV to efficiently attenuate buzzsaw noise.

Since the tailpipe length of the side engine nacelle is limited, additional treatment area is provided by a long flow divider between the fan and core flow as shown in figure 6. The tailpipe treatment includes peripheral acoustic lining on the outer wall and on both surfaces of the primary/fan flow splitter. The splitter is fabricated of a layer of Inconel 625 honeycomb adjacent to the primary flow and a layer of titanium honeycomb adjacent to the fan duct. The tailpipe is also fabricated from titanium honeycomb. The outside surface of the splitter and the tailpipe periphery are lined for fan noise attenuation at the fan fundamental passage frequency at approach power setting. The inside surface of the splitter is lined for high-frequency turbine noise attenuation.

A description of the acoustic lining in the B727 center duct is provided in figure 8. The treatment configuration is perforated aluminum sheet over a honeycomb core of epoxy/fiberglass structure. Treatment areas near the engine (S-1 and S-2) are directed at reducing the buzzsaw noise while treatment area further forward (S-3 through S-5) reduces fan blade row interaction noise.

Aircraft Modifications

Changes to the basic airframe associated with installation of the larger and heavier nacelles consist of minor aerodynamic and structural modifications to the pylon and fuselage for the side engines of both the DC-9 and B727. New side engine mounts are required to accommodate the increased weight and nacelle diameter. The refan pylon for the DC-9 was reduced in span from 16.75 to 8.05 inches. For this airplane it was desirable to install the larger refan nacelle closer to the fuselage to minimize the effects on deep stall and engine out minimum control speeds.

Major modifications to the B727 airframe structure are associated with the installation of the enlarged S-duct and center engine (fig. 7). This rework will involve considerable alteration to several body bulkheads and frames to permit installation of the larger inlet duct. New engine mounts will be installed to accommodate the heavier and larger engine. New mount supports are required and local reinforcement added to distribute the load into the primary fin structure.

The major portion of the structural changes affect the aft body section of the airframe in the area of attachment of the new nacelles. There are no major changes to the forward body or wing structure except for minor reinforcement of body structure because of increased fuselage bending and installation of ballast to balance the added weight of the refan nacelle. The installation of the JT8D-109 refan engine results in an operational empty weight (OEW) increase of 2482 pounds for the DC-9 aircraft and 3660 pounds for the B727 aircraft.

PERFORMANCE PREDICTIONS

The JT8D refan program engine modifications are designed to reduce the jet noise by cycle changes which remove energy from the jet exhaust and transfer this work to the fan. Fan noise is then effectively suppressed by both engine case and nacelle acoustic treatment. Detailed noise estimates including spectra and flyover time histories have been made by the contractors. The results of these analyses were combined with estimated aircraft performance to determine noise levels at FAR Part 36 measuring stations and EPNL noise contours. In addition, engine and aircraft performance predictions were made.

Acoustic Performance

Perceived noise levels. - As indicated previously, the JT8D refan noise reduction strategy involves the reduction of the dominant jet and fan noise components. This is accomplished by the cycle change to reduce jet velocity and by fan design changes coupled with acoustic treatment. A summary of the aircraft manufacturer noise component analysis for current production and refanned aircraft is shown in figure 9(a) for the B727-200 and in figure 9(b) for the DC-9-32. These bar charts display the maximum tone corrected perceived noise levels, $PNLT_{max}$, contributed by each of five components (fan inlet, fan exhaust, low-frequency core, jet and high-frequency turbine) at the FAR 36 approach and takeoff measurement points. The total noise signature is also shown for each condition. Engine thrusts and aircraft altitudes for production and refan aircraft vary in a manner appropriate to the execution of an approach on a 3-degree glide slope and takeoff with a FAR 36 cutback certification profile.

For the B727 (fig. 9(a)), refanning and acoustic treatment substantially reduced the offending fan inlet and exhaust noise and the jet noise generated by the primary exhaust during both approach and takeoff. Low-frequency core noise is predicted to remain at roughly the same level as the production estimate and becomes the dominant source after refanning. High-frequency turbine noise does not contribute significantly for refan takeoff. Low-frequency core noise generation and transmission processes are poorly understood at present, and isolation of that component is difficult. Refan acoustic tests will emphasize core noise determination.

A qualitatively similar situation with respect to fan and jet com-

ponents is shown in figure 9(b) for the DC-9. However, estimated core levels do not dominate after refanning, and turbine noise is the largest contributor at approach.

Integration of the flyover noise histories based on the sum of the component analysis results in the predicted refan FAR 36 effective perceived noise levels (EPNL's) shown in figure 10. Refan levels are compared to the production aircraft levels, the corresponding FAR 36 standards, and the wide-body DC-10-10 data shown previously in figure 1. These noise estimates show that the refanned aircraft have a considerable potential for realizing significant reduction in community noise levels. The refanned B727-200 aircraft provides reductions of 7 to 8 EPNdB compared to the production aircraft, while corresponding reductions for the DC-9-32 are 10 to 12 EPNdB. In addition, the refan noise levels have been reduced below FAR Part 36 requirements by 5 to 11 EPNdB for the DC-9-32 and by 3 to 13 EPNdB for the B727-200. Compared to the relatively quiet wide-body DC-10-10, the refan aircraft are quieter by at least $3\frac{1}{2}$ EPNdB at all of the measuring points.

Noise contour area. - Noise contour areas provide a more complete indication of community exposure and the noise reduction benefits of refanning. EPNL noise contours have been calculated for the production and refanned aircraft. The resulting areas of these contours have been summarized as a function of EPNL contour level for the DC-9-32 and B727-200 aircraft in figures 11 and 12, respectively. These areas were calculated for a FAR 36 cutback certification takeoff profile and a single segment approach on a 3-degree glide slope. Estimates of DC-10-10 contour areas are also included for comparison. Note that a full power takeoff profile was used for the DC-10 to agree with the way the FAR 36 certification levels were measured for this aircraft.

The refanned aircraft provide substantial reductions in contour area compared to the production aircraft. For example, at the 90 EPNdB level, area reductions of about 70 and 80 percent are indicated for the DC-9 and B727, respectively. Both refanned aircraft expose smaller areas than the DC-10-10 for levels greater than 90 EPNdB.

Installed Engine Performance

The calculated performance of the JT8D-109 refan engine and the production JT8D-9 engine installed on both the DC-9-32 and B727-200 aircraft is compared in table II in terms of takeoff thrust and cruise thrust specific fuel consumption (TSFC). All performance estimates are based on data supplied by Pratt & Whitney Aircraft for a fuel lower heating value of 18 400 Btu/lb. Installation effects include those losses resulting from internal flow in the inlet and tailpipe and the effect of bleed and power extraction. External drag changes are considered in airplane performance calculations.

At takeoff, the installed takeoff thrust of the refan engine is about

5 percent higher than the production engine at a Mach number of 0.27. At cruise, the refan engine provides an improvement in uninstalled TSFC compared to the production engine. However, increased internal losses negate most of that gain so that the installed cruise TSFC's are all nearly equivalent for refan and production engines.

Airplane Performance

When compared to the existing airplane with production engines, the refanned aircraft would be expected to have the following characteristics: higher installed takeoff thrust; an increase in operating empty weight (OEW); small changes in installed cruise TSFC; and generally an increase in cruise drag resulting from the installation of a larger nacelle. All of these characteristics influence the performance of the aircraft over the entire mission (takeoff, climb, cruise, descent, and landing). Increased takeoff thrust can provide substantial improvements in takeoff field length and takeoff flight paths. However, refanned aircraft operating at baseline maximum gross weight with a full payload will suffer a loss in maximum range primarily due to the increase in OEW and the subsequent reduction in fuel load.

During the course of development of a new engine/nacelle installation, or a modification to an existing installation, much reliance is made on past experience and analytical analysis. However, some areas are not completely amenable to analytical analysis and require wind tunnel testing to determine design acceptability. In the case of installing refan nacelles on the DC-9 and B727 aircraft, these areas included determination of drag and stability at both high and low speeds.

DC-9-32 aircraft. - The payload/range curve for high speed cruise is shown in figure 13. For a full payload of 25 442 pounds there is a range loss of -190 nautical miles due primarily to the increase in OEW of +2482 pounds. The combined effect of installed cruise SFC and cruise drag of the refan aircraft provides a slight improvement in range. Wind tunnel tests at the NASA Ames 11-Foot Wind Tunnel for the JT8D-109 indicate that the refan nacelle installed on the DC-9 provides a favorable interference drag effect which was equal to and canceled the increased nacelle skin friction at the cruise Mach number of 0.78. This reduced drag resulted from a change in the wing pressure distribution due to the presence of the larger entering stream tube and the more forward location of the longer JT8D-109 inlet. The refan nacelle can, therefore, be installed without any increase in cruise drag.

The range loss at reduced payload (15 000 lb in fig. 13) is negligible because the small improvement in SFC and cruise drag nearly offsets the range loss due to increased empty weight.

A more meaningful comparison of the refan airplane performance compared to the baseline would be its ability to perform the same average or typical day-to-day mission with little or no change in the block fuel.

This comparison is shown in table III(a) for two ranges and two payloads at the DC-9 high speed cruise of Mach 0.78. All of these missions can be performed by the refan airplane with about one percent decrease in block fuel compared to the production airplane.

A low speed wind tunnel test was also conducted in the NASA Ames 12-Foot Wind Tunnel to assess the effects of the larger refan nacelles on the stability and control characteristics, with emphasis on the deep stall regime. Various pylons of reduced span were tested. Results indicate that deep stall recovery characteristics are nearly independent of pylon span and are acceptable with no additional design changes required.

B727-200 aircraft. - This aircraft, when refanned, also suffers a significant maximum range loss at full payload due primarily to the increase of operating empty weight (OEW). Table IV shows a range loss of 230 nautical miles for the production brake release gross weight of 172 500 pounds. Aircraft performance is also shown for four alternate gross weights to show the possible trades of range and field length. Because of the substantial increase in takeoff thrust for the refanned engine, a weight growth can be accommodated by this aircraft. This weight growth capability has already been certified for current production aircraft and is available in optional kit form to commercial operators. The baseline range can be recovered with a 177 900 pound aircraft with a slight reduction in takeoff field length. Increased range (+175 n. mi.) can be provided with essentially no loss in takeoff field length with the practical weight growth limit of 182 500 pounds.

The range/payload curves for the baseline and the growth refanned airplanes are shown in figure 14. The increased range occurs only with the full payload of 134 passengers. A slight range loss is noted at a reduced payload of 74 passengers.

Again, the more meaningful comparison of the refan airplane to the baseline would be its ability to perform typical B727 missions. This comparison is shown in table III(b) for four missions at the B727 high speed cruise Mach number of 0.84. The shorter missions (600 n. mi.) are performed with about a 1/2 percent increase in block fuel. The longer range missions can be flown with changes in block fuel from +0.31 to -1.30 percent. An alternate configuration for the B727 side engine nacelle is one without the inlet ring and with less acoustic treatment in the tailpipe. It has been estimated that this minimum treatment configuration would reduce the block fuel by about one percent compared to the configuration with an inlet ring.

B727 model tests. - A rather extensive model test program was conducted at the Boeing Company in support of the refanned B727 aircraft. Probably the most critical test program for the B727 was the center engine inlet and duct test. The refan of the JT8D increases the total airflow about 45 percent and requires a new center engine duct on the B727. The new duct configuration is constrained by the location of existing B727 airplane structure. An investigation was conducted in the Boeing

9' x 9' Low Speed Wind Tunnel to evaluate the pressure recovery and distortion characteristics of the refan center engine inlet and duct. An extensive test program was conducted which included an evaluation of many vortex generator and flow control device configurations. Excellent results in terms of pressure recovery and distortion were obtained. A vortex generator pattern was developed that results in greater control over airflow distortions at less pressure loss at all airplane operating conditions than previously experienced. At this time it would appear that there will be no center engine duct compatibility problems with the refan engine.

Flight control evaluations at low speed were conducted at Boeing Vertol and at the University of Washington Aero Lab. Results indicate that the airplane longitudinal characteristics with the refan nacelles are not significantly different from the production airplane. Some small reduction in directional stability was measured but rudder effectiveness was not affected.

A high speed configuration development test program was conducted in the CALSPAN Transonic Wind Tunnel. A nacelle shape was identified such that the inlet cowl, nose dome and side cowls can be interchangeable for left and right hand installations. Installation of the larger refan nacelles on the B727 resulted in a favorable interference drag at the cruise Mach number. The magnitude of this interference effect was equal to and offset the increased friction drag of the larger nacelles. The refanned nacelles can, therefore, be installed on this aircraft without any increase in cruise drag.

RETROFIT KIT COSTS

The costs of refanning the JT8D powered aircraft are estimated to be about \$1.0 million for the DC-9 and about \$1.7 million for the B727. These costs include the P&WA engine kit, new nacelles, new pylons, fuselage modifications, and installation charge. In addition to the kit costs, additional costs would be incurred for spares, crew training, and lost revenue over the period that the aircraft would be out of service. The DC-9 retrofit is relatively straight forward and out-of-service time is estimated to be about 16 days. The B727, with the more difficult center engine installation, would require about 21 days to retrofit. The impact of retrofit on cash trip costs (crew, fuel, insurance and maintenance) would be minor.

The total cost of retrofitting the entire domestic JT8D powered fleet is estimated at \$3.3 billion, which includes an initial investment of \$1.85 billion for the engine and airplane kits and their installation. To put the total cost in the perspective of airline revenue, it is equivalent to a one-percent increase in cost for domestic passengers and cargo applied over 8.5 years. If program go-ahead is assumed to be June 1975, first kit delivery could be in 1976 for the DC-9 and in 1977 for the B727. Program completion could be targeted for June 1980, assuming a retrofit of 395 domestic DC-9's and 669 B727 aircraft.

CONCLUDING REMARKS

The Refan Program is currently in its second and final phase. This phase will feature ground tests of the Boeing 727-200 side engine nacelle and center engine installation early in 1975. A flight demonstration of a Douglas DC-9 with refanned engines and nacelles will also be conducted early in 1975. At the present time no major technical problems have been identified that would preclude installation of the JT8D-109 refan engine on either the DC-9 or the B727 airplanes.

Substantial noise reduction using the refan concept is technically feasible and provides estimated noise reductions of from 7 to 8 EPNdB for the B727 and 10 to 12 EPNdB for the DC-9 at the FAR 36 measuring stations. These noise levels are lower than either the FAR-Part 36 noise standards or the noise levels of the wide-body DC-10-10. Corresponding reductions in the 90-EPNdB footprint area vary from about 70 percent for the DC-9 to about 80 percent for the B727.

Improvements in refanned engine performance can offset the losses in aircraft performance from nacelle treatment and added empty weight. Both the refanned DC-9 and B727 aircraft can perform typical range/payload missions with a negligible effect on block fuel compared to the production airplane.

The unit price of a refan kit for retrofit is estimated to be from about \$1 million for the DC-9 to \$1.7 million for the B727. Production kits could be available in 1976 for the DC-9 and in mid-1977 for the B727 aircraft. Finally, the increased thrust of the refan engine makes it a candidate for future production models of both the DC-9 and B727 aircraft.

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TABLE I. - COMPARISON OF PRODUCTION JT8D-9 AND
REFAN JT8D-109 ENGINES

Parameter	Production	Refan
Fan	2-stage	1-stage
Inlet guide vanes	Yes	Yes
Fan diameter, in.	40.5	49.2
Inlet diameter, in.	42.5	54.5
Length, in.	120	134
Engine weight (dry), lb	3218	3780
Total airflow, SLT0, lb/sec	319	467
Fan pressure ratio	1.97	1.67
Fan tip speed at T0, ft/sec	1420	1600
Bypass ratio	1.05	2.03
Cycle temperature, °F	1870	1863
Primary jet velocity, ft/sec	1766	1445
Mixed jet velocity, ft/sec	1470	1140
Uninstalled performance		
Thrust, SLS, lb	14 500	16 600
T.O. thrust (M = 0.27), lb	12 450	13 325
Maximum cruise thrust (M = 0.80 at 35 000 ft), lb	4540	4720
Maximum cruise TSFC (M = 0.80 at 35 000 ft), lb/hr/lb	0.802	0.770

TABLE II. - INSTALLED ENGINE PERFORMANCE

(a) Takeoff thrust, lb ($M = 0.27$ at sea level)

	DC-9-32		B727-200	
	Production	Refan	Production	Refan
Uninstalled thrust	12 450	13 325	12 450	13 325
Installed thrust	12 300	12 900	12 050	12 600

(b) Cruise TSFC, lb/hr/lb (Alt = 30 000 ft)

	DC-9-32 ($M = 0.78$ at $F_N = 3600$ lb)		B727-200 ($M = 0.84$ at $F_N = 4000$ lb)	
	Production	Refan	Production	Refan
Uninstalled TSFC	0.788	0.760	0.786	0.774
Installed TSFC	.806	.805	.813	.812

TABLE III. - FUEL COMPARISON - HIGH SPEED CRUISE

Range, n.mi.	Payload factor, percent	Production fuel, lb	Refan fuel, lb	$\frac{\Delta \text{fuel}}{\text{fuel}}$, percent
(a) DC-9-32 (M = 0.78 at 30 000 ft)				
375	65	6 249	6 197	-0.8
375	100	6 487	6 419	-1.0
840	65	12 264	12 137	-1.0
840	100	12 736	12 585	-1.2
(b) B727-200 (M = 0.84 at 35 000 ft)				
600	55	14 950	15 050	+0.67
600	100	16 100	16 150	+0.31
1000	55	22 480	22 550	+0.31
1000	100	24 520	24 200	-1.30

TABLE IV. - PERFORMANCE OPTIONS, B727-200 JT8D-109

ENGINE REFAN CONFIGURATION

WEIGHT VARIATIONS TO ACHIEVE:	BRGW (LB)	INCREMENT FROM BASELINE		
		Δ OEW (LB)	Δ RANGE (NMI)	Δ TAKEOFF FIELD LENGTH (FT)
BASELINE BRGW	172,500	+ 3,660	- 230	- 1,300
BASELINE T.O. FIELD LENGTH	181,000	+ 3,820	+ 135	0
BASELINE RANGE	177,900	+ 3,820	0	- 800
PRACTICAL WEIGHT GROWTH	182,000* (182,500)	+ 3,820	+ 175	+ 350
BASELINE BLOCK FUEL	177,000	+ 3,820	- 40	- 900

- BASELINE AIRPLANE: JT8D-9
MAX TAXI WT = 173,000 LB
MAX BR REL WT = 172,500 LB
OEW = 99,000 LB
MAX FUEL CAPACITY = 7,680 U.S. GAL
- BASELINE PERFORMANCE: ATA RANGE = 1,355 NMI
T.O. FIELD LENGTH = 8,370 FT
- TAKEOFF CONDITIONS: SEA LEVEL
84° F
A/C ON
- CRUISE CONDITIONS: M = .84 AT 30,000 FT
PAYLOAD = 134 PASS. (27,470 LB)
STANDARD DAY
ZERO WIND
ATA DOMESTIC RESERVES

NOTE: FUEL CAPACITY OF GROWTH OPTIONS IS INCREASED TO 7,780 U.S. GAL.

*FUEL CAPACITY LIMITED FOR THIS PAYLOAD

-6/-

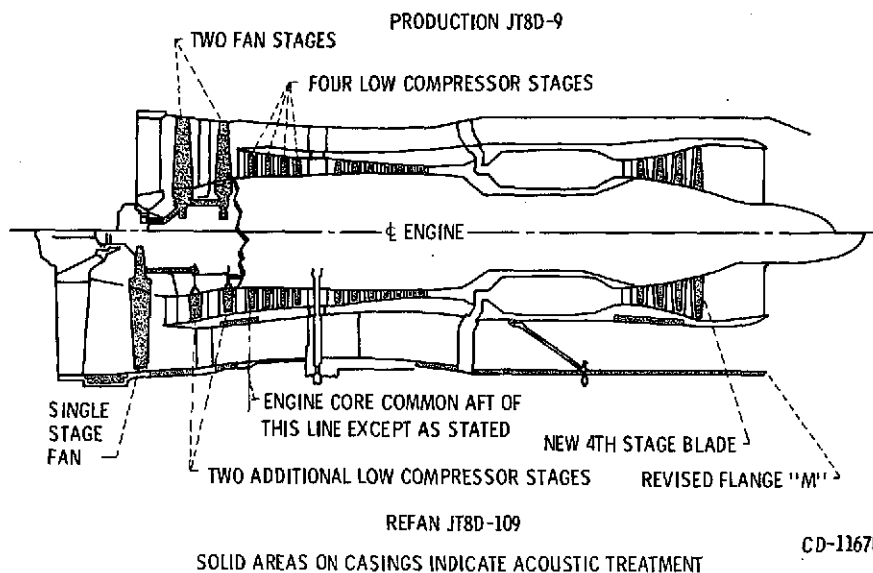


Figure 3. - Engine comparison.

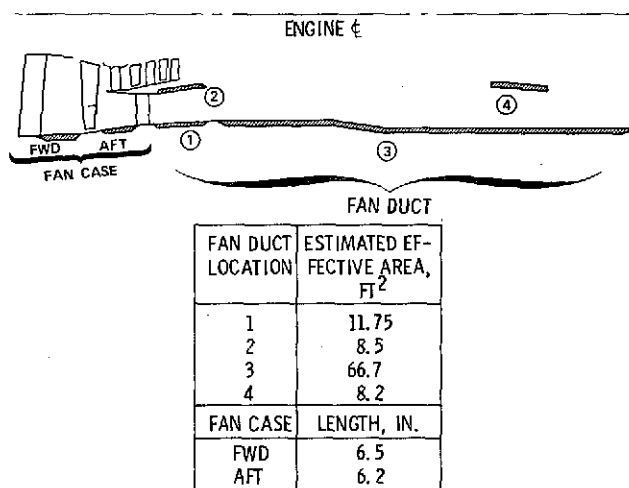


Figure 4. - P&WA supplied acoustic treatment.

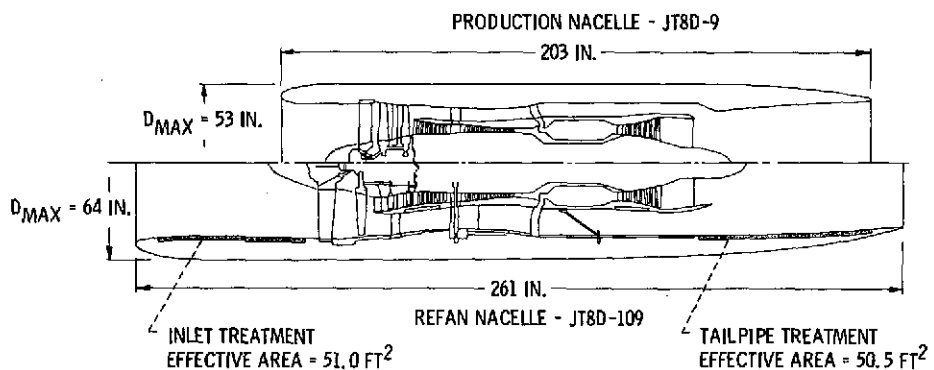


Figure 5. - Douglas DC-9 nacelle comparison.

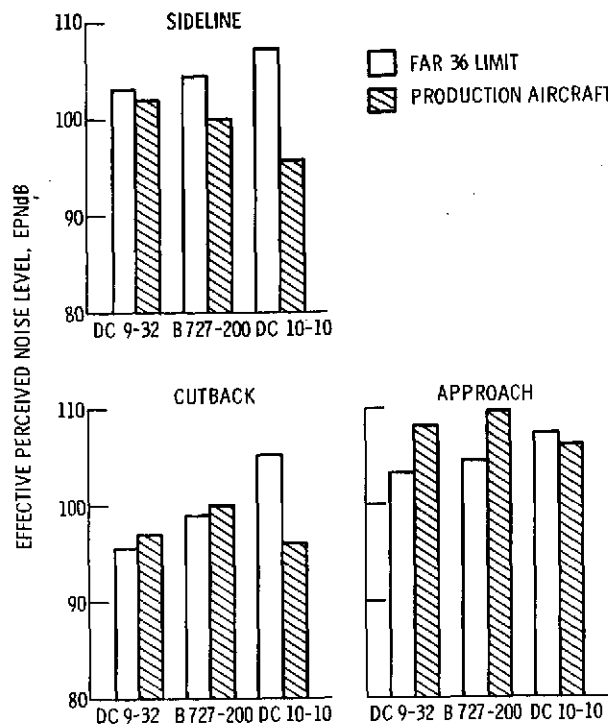


Figure 1. - Existing Far Part 36 noise levels for production aircraft.

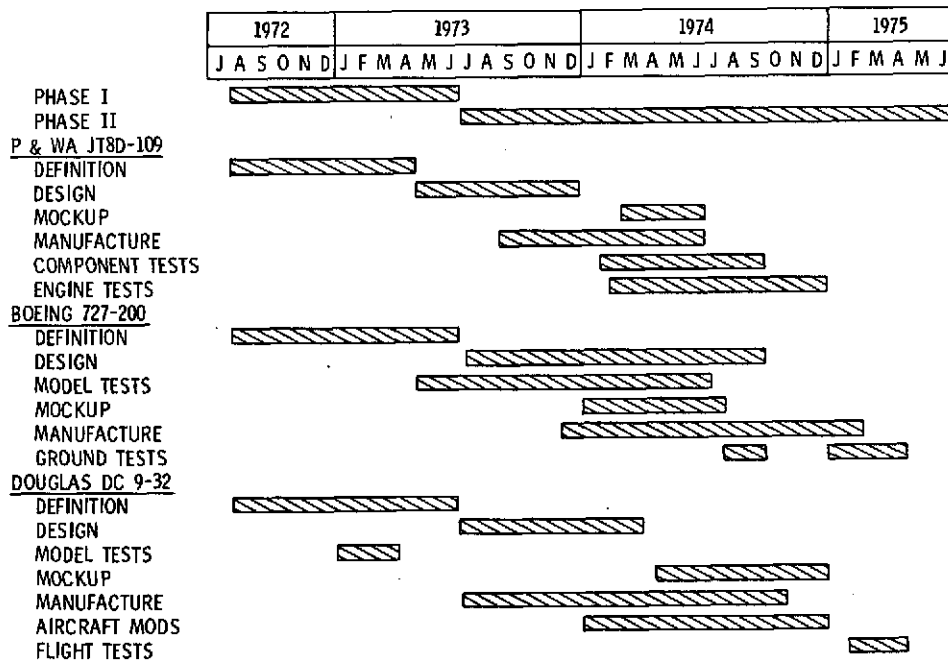


Figure 2. - JT8D refan program schedule.

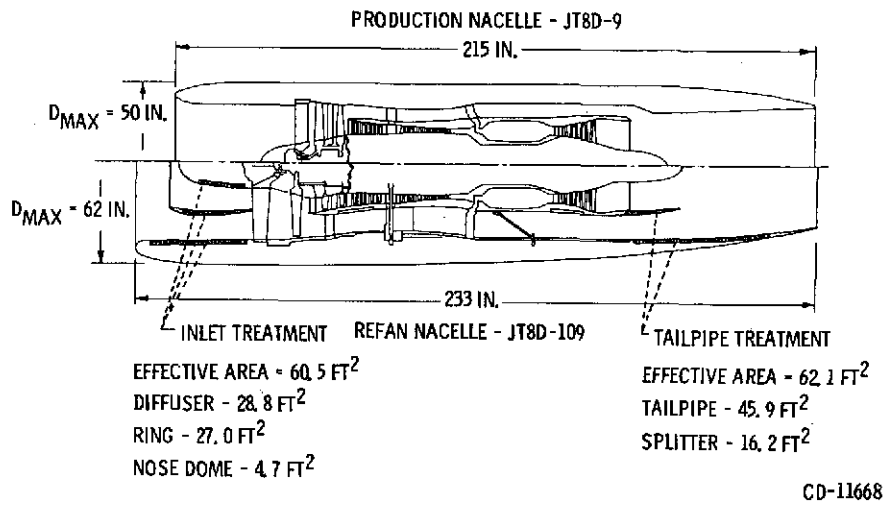


Figure 6. - Boeing 727 side-engine nacelle comparison.

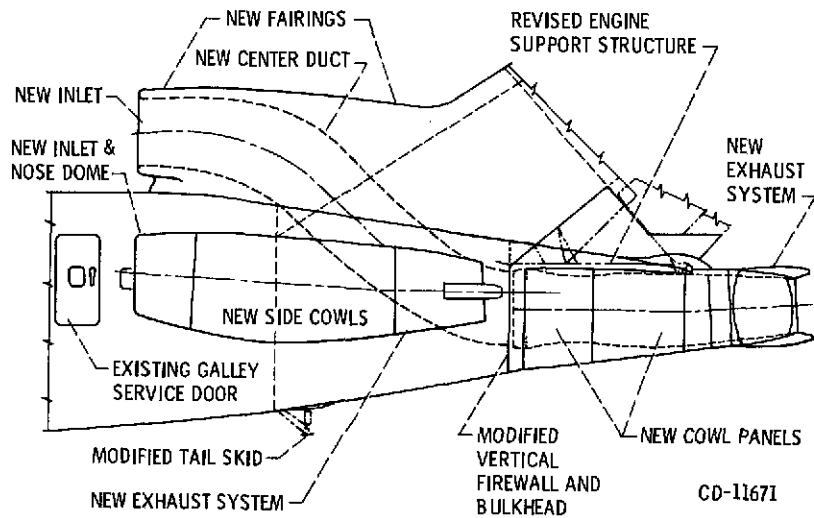


Figure 7. - JT8D-109 installation on B 727-200.

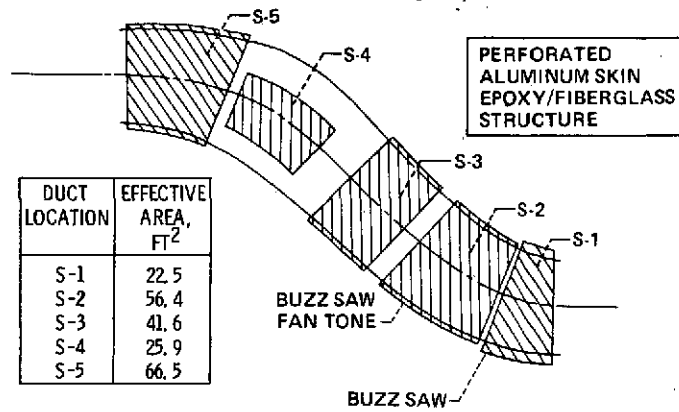


Figure 8. - B 727 acoustic lining description - center-engine inlet.

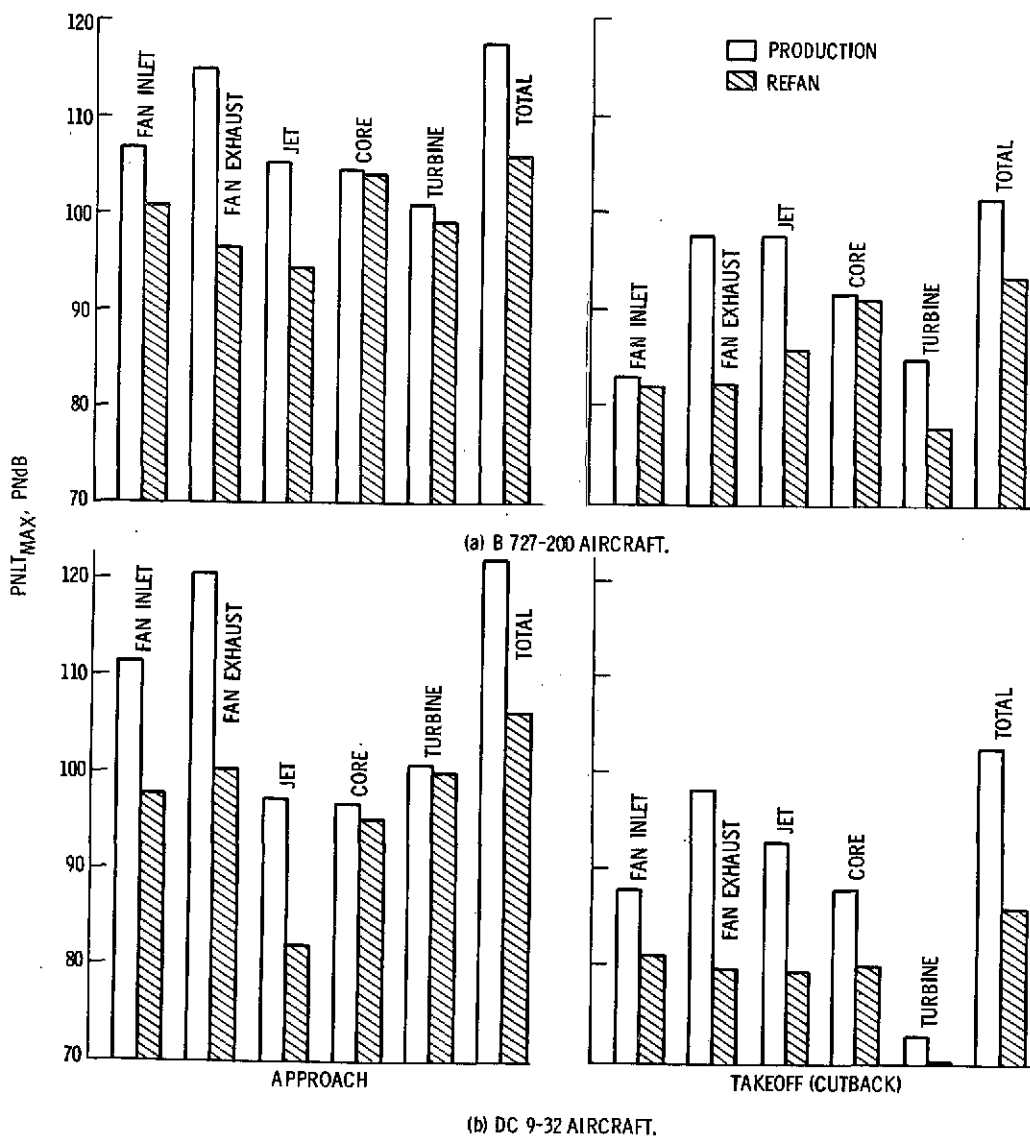


Figure 9. - Component noise levels at Far 36 measurement points.

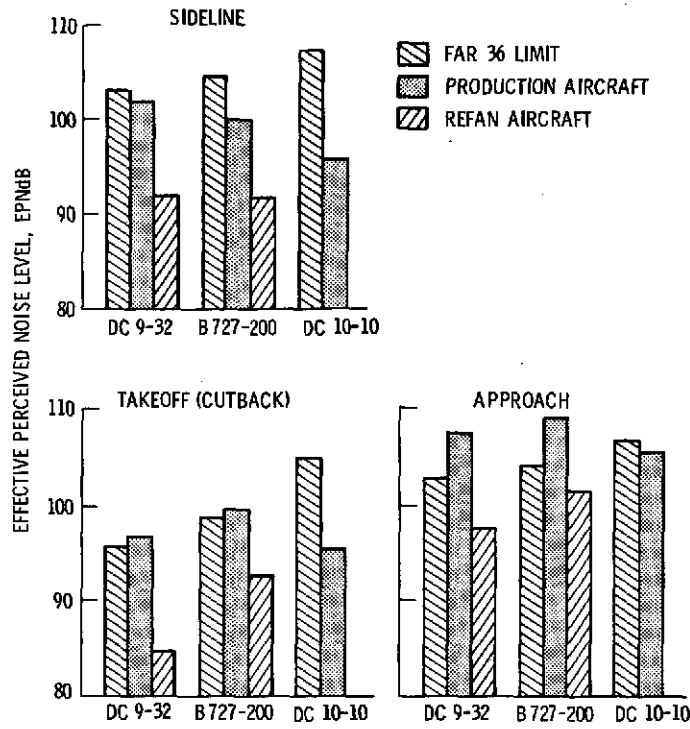


Figure 10. - Comparison of predicted refan noise levels with Far Part 36 and production aircraft.

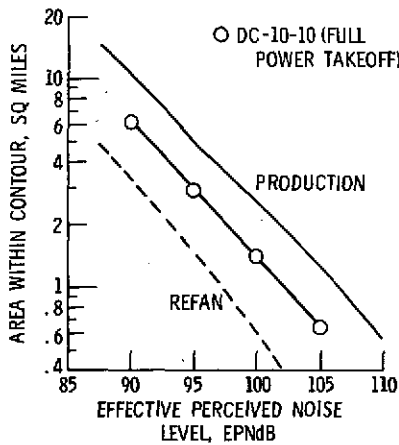


Figure 11. - DC-9-32 footprint contour areas. Cutback certification profile. Single segment approach.

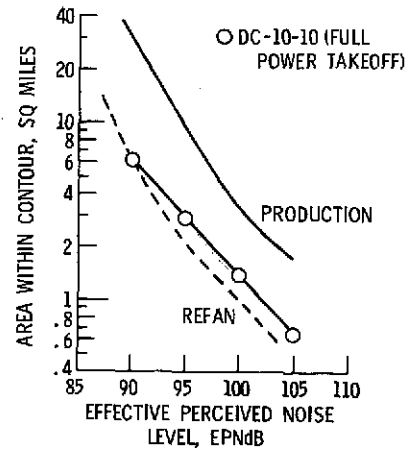


Figure 12. - B 727-200 footprint contour areas. Cutback certification profile. Single segment approach.

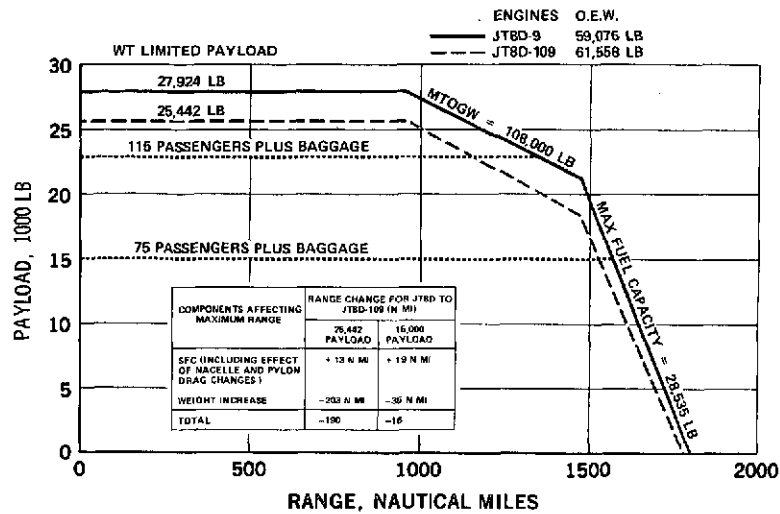


Figure 13. - DC-9-32 payload range. Q 78 Mach number, 30 000 ft.

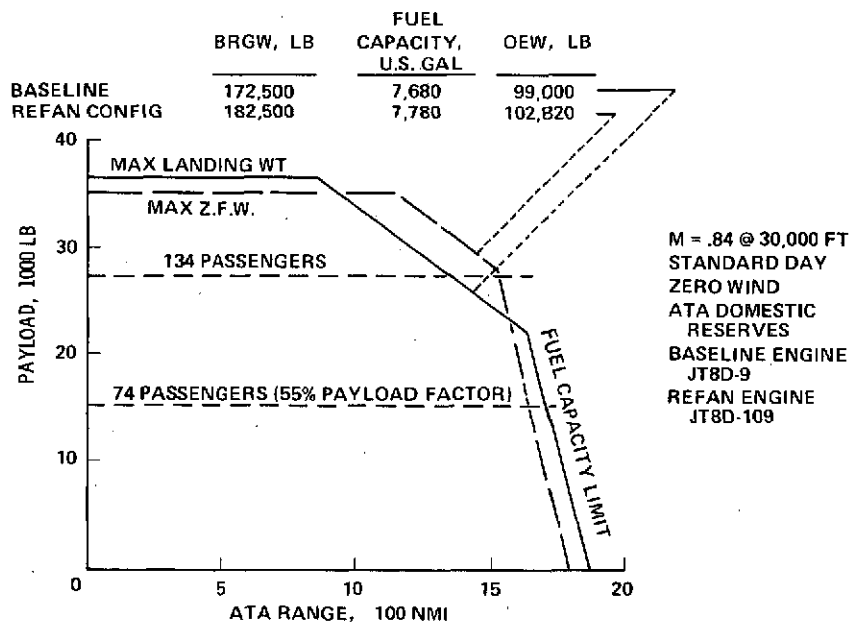


Figure 14. - B 727-200 payload range comparison.