LEVEL II

INTERNAL MIXER INVESTIGATION FOR

JT8D ENGINE JET NOISE REDUCTION

Volume I-Results

A.B. Packman and D.C. Eiler

December 1977

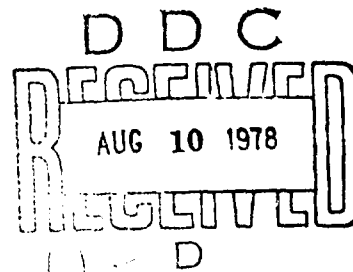## FINAL REPORT

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

Systems Research & Development Service

Washington, D.C. 20590

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2. Vol. II cannot get a
   letter copy

3. Table of content pages changed

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-77-132-I		

4. Title and Subtitle	5. Report Date
INTERNAL MIXER INVESTIGATION FOR JT8D ENGINE JET NOISE REDUCTION. Volume I - Results	December 1977
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
A. B. Packman and D. C. Eiler	PWA-5582-VOL-1

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
UNITED TECHNOLOGIES CORPORATION Pratt & Whitney Aircraft Group 400 Main Street (MSEB-2B) East Hartford, Connecticut 06108	
	11. Contract or Grant No.
	DOT-FA76WA-3899

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U. S. Department of Transportation Federal Aviation Administration Systems Research & Development Service Washington, D. C. 20590	Final Report, May 1976 through July 1977
	14. Sponsoring Agency Code

15. Supplementary Notes 112 p.

16. Abstract

A scale model experimental program was conducted to determine the noise reduction and the impact on propulsive performance that would result from installing a multi-lobed internal mixer on the JT8D engine. Long and short mixer designs were investigated. One-seventh scale mixer models, designed to permit lobe geometry variations, were fabricated and tested along with a model of the JT8D reference exhaust system.

The test results indicated that, in general, the long and short mixers produced 3-4 PNdB reduction in Peak Perceived Noise Level relative to the reference exhaust system. Exhaust system performance, in terms of improvement in cruise thrust specific fuel consumption (TSFC), and impact on takeoff thrust, was somewhat better for the long mixer than for the short mixer configurations. However, the short mixers offer significant advantages in terms of weight savings and minimized the hardware changes required for installation in the current JT8D engines. Based on the noise and performance test results in conjunction with the installation considerations, a short mixer design was recommended for evaluation in a full scale engine test.

17. Key Words	18. Distribution Statement
Acoustics Jet Noise Internal Exhaust Mixers Aircraft Noise Reduction	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	112	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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METRIC CONVERSION FACTORS

PREFACE

This Final Report describes the work conducted during the period May 1976 through September 1977, by the Commercial Products Division, Pratt & Whitney Aircraft Group of United Technologies Corporation under FAA Contract DOT-FA76WH-3809. This report presents the results obtained from experimental and analytical studies of mixers aimed at reducing noise levels in the JT8D engine.

Acknowledgements are given to Mr. Harold C. True, Program Manager for the Environmental Research Branch of the FAA, for his participation in guiding and monitoring the performance of the program.

This report submitted in December 1977, is in compliance with the report requirements of the contract schedule and was prepared under the Contractor's reference No., PWA 5582.

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OVERVIEW

SUMMARY

A major objective of this program was to define an internal mixer for the JT8D engine exhaust system that would produce a significant reduction in jet noise, be compatible with the JT8D engine mounting and structural limitations, be installed with minimum changes to Boeing 727 and 737 and Douglas DC-9 tailpipe hardware, provide satisfactory performance, and have an acceptably light weight. Two mixer concepts were studied, one designed to produce a relatively flat profile at the nozzle exit plane and one designed to provide partial inversion of the fan and primary exhaust streams. Models (one-seventh scale) of both mixers were designed, fabricated and tested under simulated JT8D engine exhaust flow conditions to evaluate noise and performance characteristics. Design studies were completed and scale model test results were analyzed to allow the characteristics of possible full scale designs to be estimated. Based on the results available at completion of contract work, two mixer options were defined as having potential for installation into the JT8D engine. These configurations have the following estimated characteristics:

	Long Mixer	Short Mixer
● Jet noise reduction	3 to 4 PNdB	3 to 4 PNdB
● Cruise thrust specific fuel consumption improvement	1.3%	0.5%
● Takeoff gross thrust loss	0	0.3%
● Weight increase	157 lbs.	105 lbs.

The Pratt & Whitney Aircraft analysis indicated that both mixers will be compatible with JT8D engine mounting and structural limitations. However, the long mixer will require a new rear engine case and a longer nacelle. The short mixer is expected to fit within the existing engine case and nacelles with only minor modifications. However, this analysis must be confirmed by the aircraft manufacturers. Based on the noise and performance test results in conjunction with the installation considerations, a short mixer design was recommended for evaluation in a full scale engine test. All characteristics of the final configuration appear to be compatible with use in airline service except for the loss in takeoff thrust, which could have an adverse impact on the operational characteristics of JT8D-powered airplanes as takeoff performance would be reduced.

A full scale engine flight and static test program is required to verify the estimated mixer characteristics and to establish that the selected configuration is suitable for airline use. Attention must be paid in the full scale design to elimination of a takeoff thrust loss. If the estimated loss of takeoff thrust is confirmed by full scale tests, a program may be required to correct the cause of the thrust losses.

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In addition to the Mixer Investigation work conducted, as required by contract DOT FA76 WA-3809, results from a concurrent Pratt & Whitney Aircraft in-house JT8D model program were made available at no cost to this contract to facilitate selection of the most effective design to be recommended for future full scale tests. The Pratt & Whitney Aircraft program addressed the characteristics of a shorter mixer of potentially lower performance, investigated the effects of details of the exhaust case hardware and flow-field that are peculiar to the JT8D engine family, and the effects of tailpipe length and 5 degrees of tailpipe "cant" on noise and performance for tailpipe geometries associated with specific airplane installations that differed materially from the reference tailpipe specified by the contract. Elements of the Pratt & Whitney Aircraft program are presented in this report along with results of the contract work in order to provide a complete presentation of all technical material used for mixer selection. Major results of both the contract work and the Pratt & Whitney Aircraft in-house program are presented in the following technical overview.

Under the contract work and the Pratt & Whitney Aircraft in-house studies, two basic mixer designs were selected to undergo tests to determine the noise, exit velocity profile, and thrust characteristics of the mixer installed in a one-seventh scale model JT8D exhaust nozzle. A series of modifications to the mixer lobe geometry then was tested to establish effects on thrust, noise and exhaust velocity profiles. An exhaust system patterned after that currently in use in the JT8D engine was also tested to establish reference noise and thrust levels.

MIXER DESIGN

Photographs of the basic model mixer designs tested during the programs are shown in Figure 1. The shorter mixer was used primarily for Pratt & Whitney Aircraft in-house tests. The schematics in Figure 2 present the engine flowpath as well as one modification of each mixer tested during the programs. The long mixer configuration has a gradual flowpath convergence that requires a modified outer case 16 inches longer than currently is used on the JT8D engine. The short mixer uses the current JT8D outer case extended approximately 8 inches AFT (Full Scale). The short mixer design was judged to be of a greater risk in terms of reducing nozzle performance, due to high predicted local flow diffusion rates that could result in local flow separation with accompanying increased pressure losses. However, the potential advantage of retaining the current outer exhaust case provided sufficient incentive for Pratt & Whitney Aircraft to investigate the shorter mixer design. In general, the extent to which aircraft nacelle, reverser, and exhaust case hardware modifications would be required would be greater with the longer mixer designs. Details of the mixer lobe trailing edge geometry modifications were established by the model test program.

ACOUSTIC AND PERFORMANCE TESTS

Acoustic tests were conducted at the Pratt & Whitney Aircraft Indoor Anechoic Jet Noise Facility. Exhaust system models were tested over a range of nozzle operating conditions simulating JT8D-15 operation at scaled thrust levels from approach to takeoff. Tailpipe exit plane pressure and temperature profiles were measured at maximum takeoff and cutback thrust conditions. Nozzle performance tests were performed at the FluiDyne Engineering Corporation's static thrust facility. A wide range of nozzle pressure ratios were tested with primary to fan stream temperature and pressure splits approximating those of JT8D-15 engine.

LONG FLOWPATH MIXER   SHORT FLOWPATH MIXER

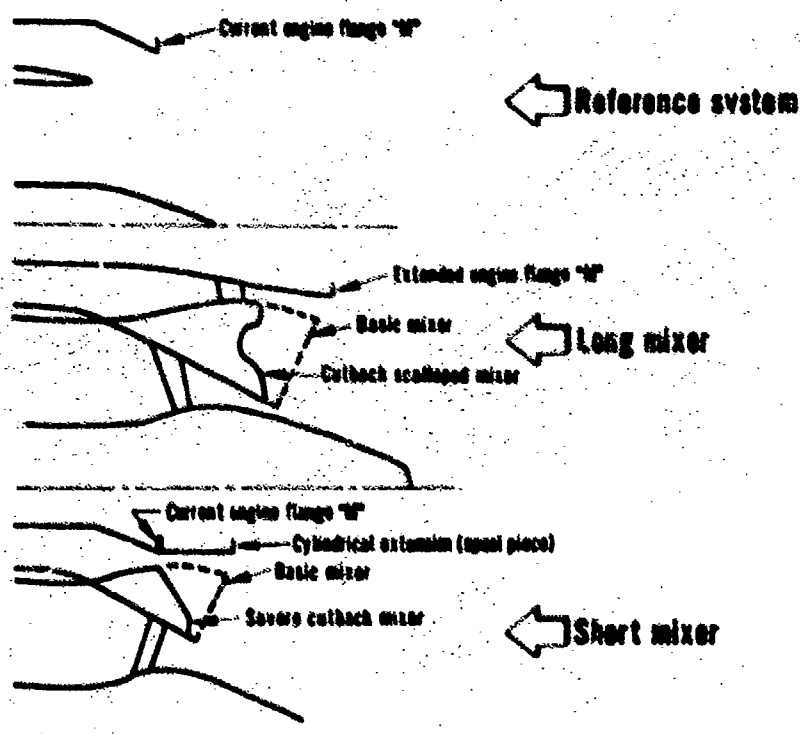Figure 1   Basic Long and Short Flowpath Mixers

Figure 2   Schematic of Reference Exhaust System and Long and Short Flowpath Mixers.

The acoustic characteristics of the representative long and short mixer configurations and the reference exhaust system, scaled to predict full scale jet noise, are shown in Figures 3 through 6. The peak perceived noise levels (PNL) are plotted versus estimated full scale JT8D engine static gross thrust in Figure 3. The reduction in peak PNL of both mixers relative to the reference exhaust system ranges from 3 to 4 PNdB in the thrust range of the engine normally used during takeoff operation (12,000 to 15,500 lbs.).

Perceived noise level directivity plots of the 3 exhaust systems are shown in Figure 4 at a typical cutback takeoff thrust of 12,800 lb. The directivity patterns for the two mixers are somewhat different, and can be related to the velocity profile of each mixer. In both cases, the largest noise reductions occur at the angle of maximum PNL for the reference exhaust system. These results are based on static tests. The effects of flight velocity on the jet noise of a mixer configuration must be determined by a flight test in order to determine the reductions in terms of effective perceived noise level (EPNL).

One-third octave band sound pressure level (SPL) spectra of the nozzle at 90 and 140 degrees are shown in Figures 5 and 6 at the 12,800 lb thrust condition. At both angles, the largest SPL reductions occur in the frequency range where the reference exhaust system spectra peak. At frequencies above 3000 Hz, the mixer configurations generated more noise than did the reference exhaust system. The spectral characteristics can be related to the nozzle exit velocity profiles in Figure 7 that show local velocity (normalized by the computed mixed velocity) as a function of exhaust nozzle radius, and averaged using values measured behind two mixer lobes. Both mixers produce substantial reductions in the peak flow velocity relative to the reference system to provide the low frequency noise reductions. The increase in velocity near the nozzle outer diameter due to the mixers would be expected to produce slightly higher levels of high frequency noise than the reference system. This is confirmed by the measured noise spectra.

Figure 3   Peak Perceived Noise Level Comparison of Reference Exhaust System with Long and Short Flowpath Mixers, with Engine Secondary Flow Simulation

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Figure 4 *Perceived Noise Level Directivity Comparison of Reference Exhaust System with Long and Short Flowpath Mixers at Cutback Thrust (with Engine Secondary Flow Simulation)*

Figure 5 *SPL Spectra At 90°, Comparison of Reference Exhaust System with Long and Short Flowpath Mixers (with Engine Secondary Flow Simulation)*
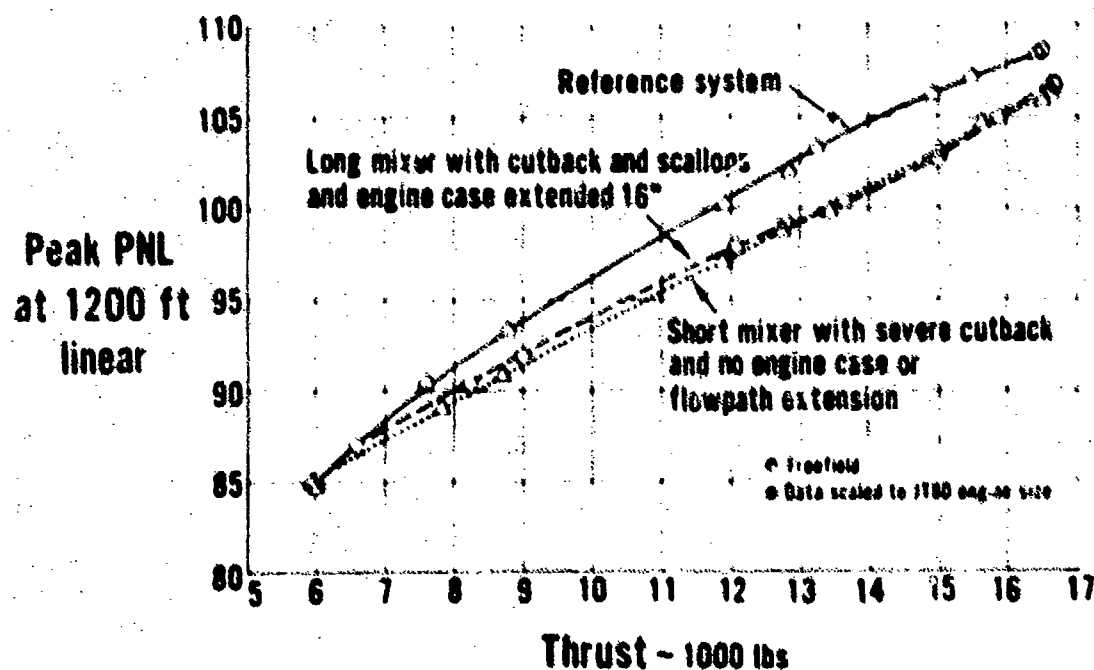
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Figure 6   SPL Spectra At 140°; Comparison of Reference Exhaust System with Long
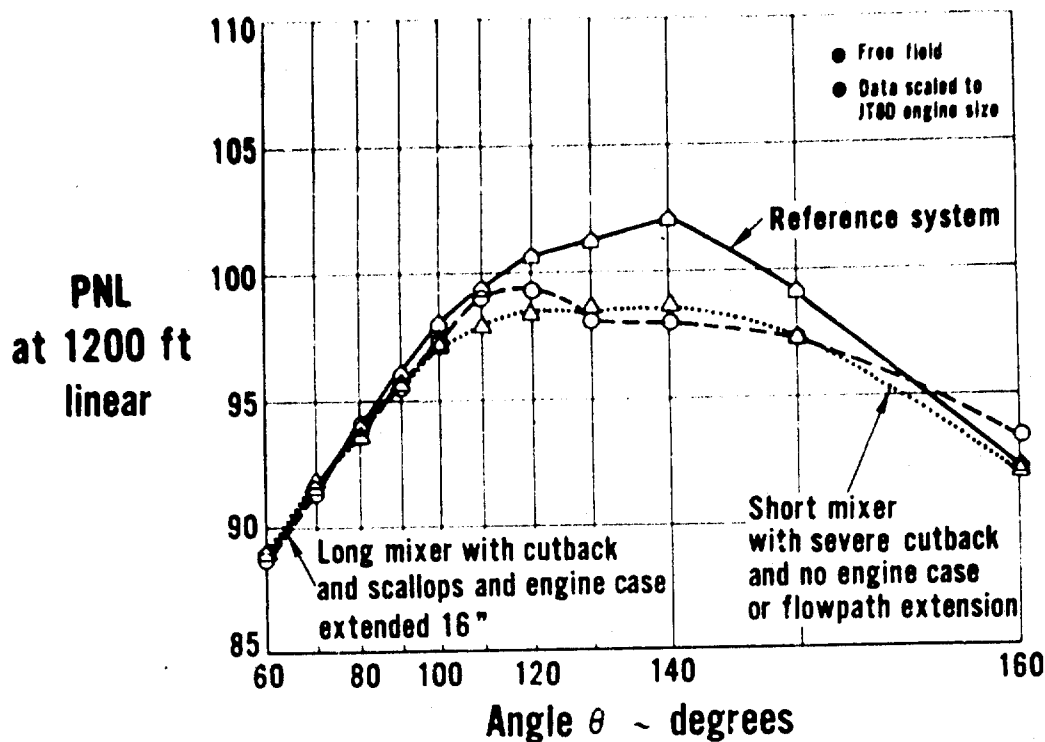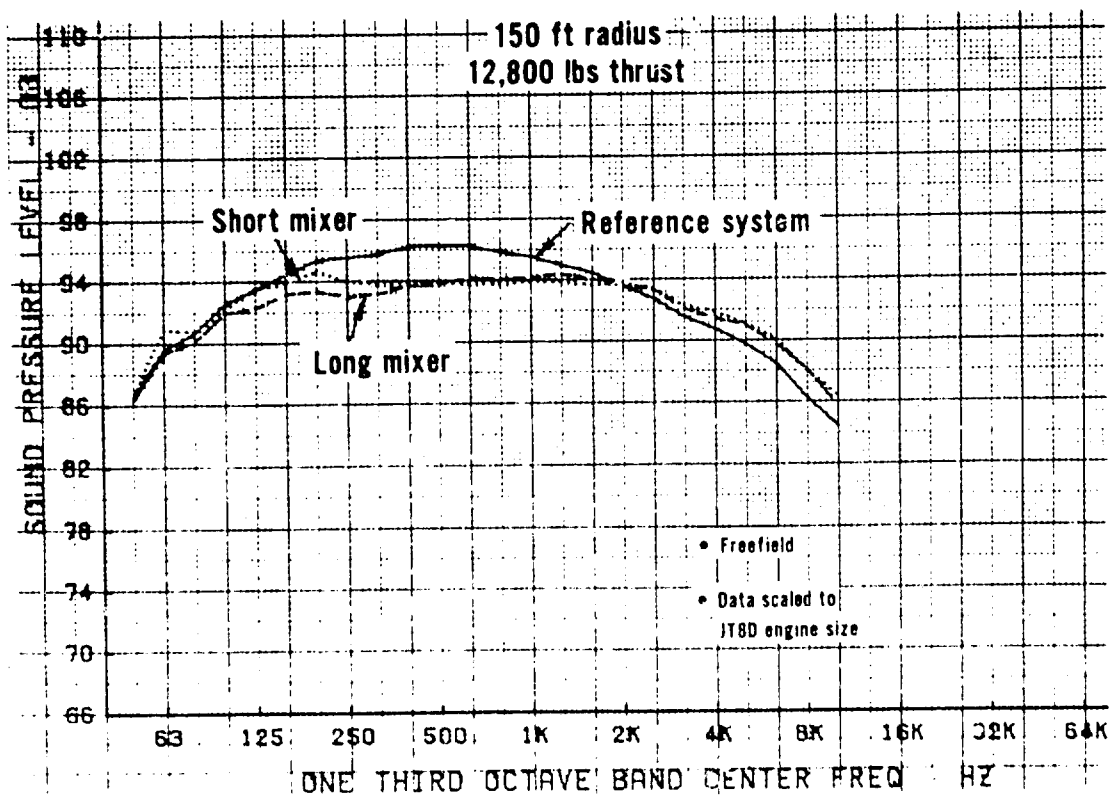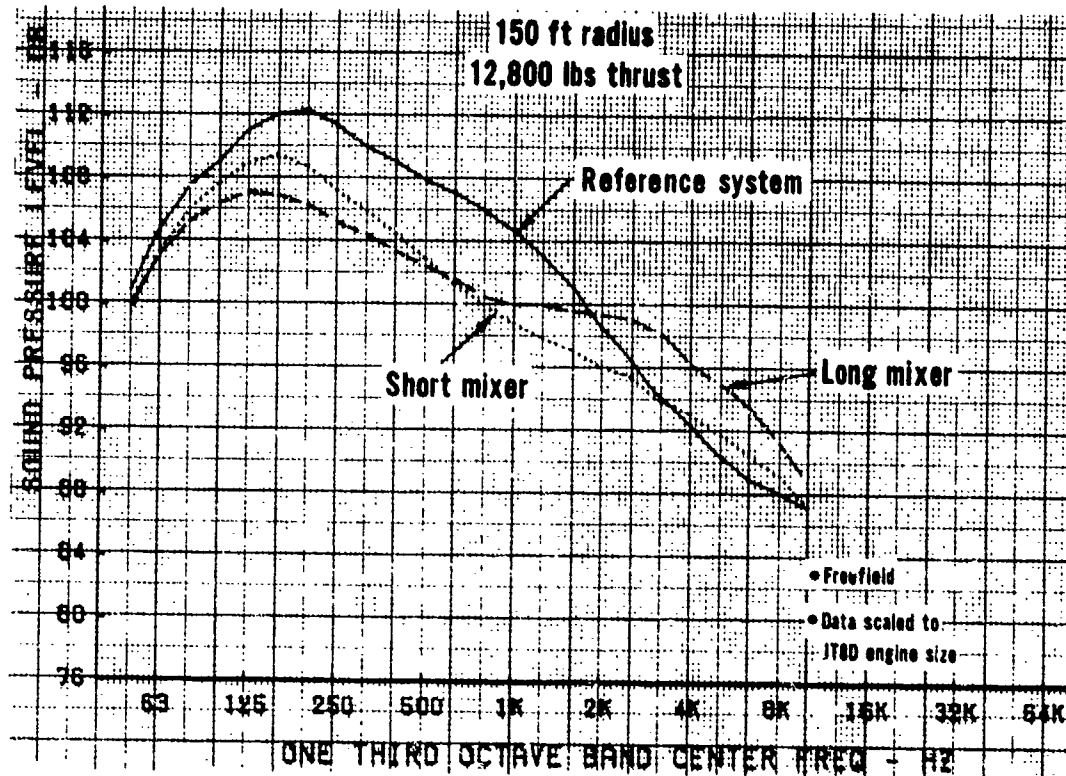and Short Flowpath Mixers (with Engine Secondary Flow Simulation)
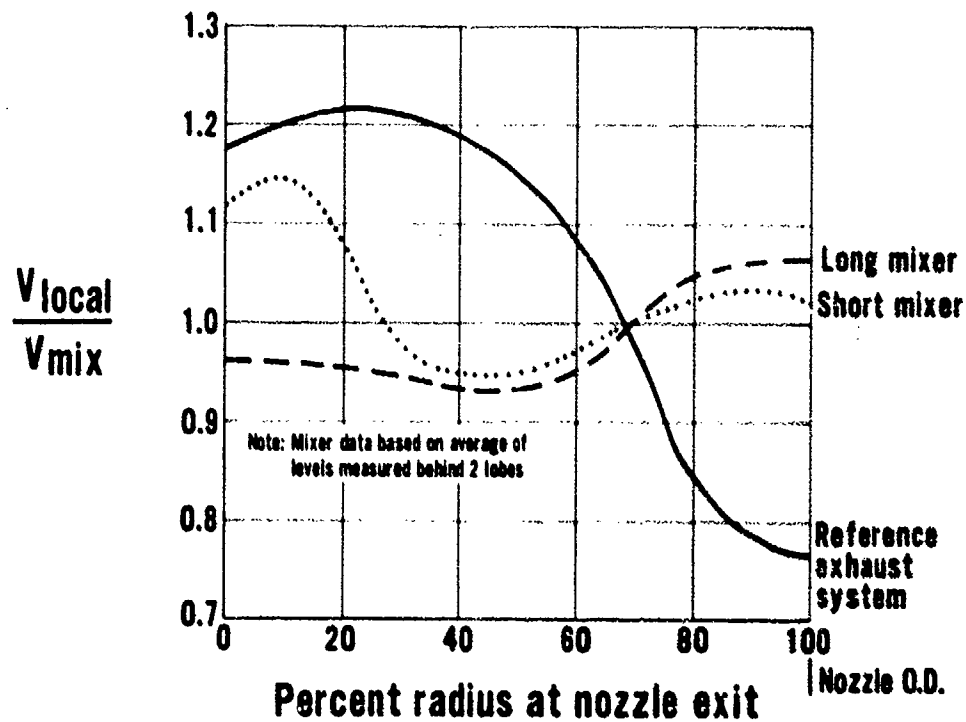

Figure 7   Tailpipe Exit Velocity Profiles; Comparison of Reference Exhaust System
with Long and Short Flowpath Mixers

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Performance results for the two mixers are summarized in Figure 8. The results are presented as a percent change in nozzle thrust coefficient (C_T) of the mixer with respect to the reference exhaust system. The long mixer produced a 0.7% increase (equivalent to a 1.3% improvement in cruise thrust specific fuel consumption, TSFC) with a negligible change in sea level takeoff thrust. The short mixer produced a 0.9% improvement in cruise TSFC, along with a 0.6% penalty in takeoff thrust.

A follow-on performance test program was conducted to investigate configuration changes to the cut-back short mixer which could reduce the deficit in takeoff thrust and also eliminate the need for the cylindrical extension between the engine case and the tailpipe. The most promising short mixer configuration tested demonstrated a 0.3% penalty in takeoff thrust and a 0.5% improvement in cruise thrust specific fuel consumption relative to the reference exhaust system as shown in Figure 8. Acoustic testing was not conducted with this configuration. However, since the design of this improved performance mixer was quite similar to the design of other short mixers tested, it was judged that the acoustic properties would, in general, also be similar to those measured for the other short mixers.

Figure 8   *Performance of Long and Short Flowpath Mixers Relative to Reference Exhaust System*

The acoustic and performance results described above were obtained during model testing in which "secondary" flow conditions of the JT8D engine were simulated by including the presence of turbine discharge swirl and fan stream pressure distortion as determined from full scale engine measurements in both primary and fan streams. Additional testing was conducted in the traditional manner of scale model jet noise testing, whereby the axial flow conditions in both the fan and primary streams are simulated, and non-uniform circumferential effects are ignored. The engine secondary flow simulation had an important impact on the acoustic results, as shown in Figure 9. With engine secondary flow simulation, the noise of the reference exhaust system was reduced by 2 PNdB at the takeoff thrust condition and by 1 PNdB at the cutback thrust condition. Conversely, the effect of the engine flow simulation on the noise with the mixers installed was small. The net result was to reduce the PNL suppression of the mixers relative to the reference system from values of 5 or greater without

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engine flow simulation to the values of 3 to 4 PNdB with engine flow simulation. Since the noise reductions of 3 to 4 PNdB described above are based on the results of tests conducted with engine secondary flow simulation, these results were used to estimate the noise reduction that could be obtained for the full-scale JT8D engine.

Figure 9   *Effect of Engine Secondary Flow Simulation on Reference Exhaust System Noise*

In contrast with the reduction in noise benefit due to the mixer when the secondary flow conditions were simulated, a positive thrust increment was obtained, associated primarily with removal of the residual turbine flow swirl present in the reference system. This effect was noted from the model test performance results in which the incremental improvement in mixer versus reference system performance increased by 0.10 to 0.25% when the models were tested with swirl struts and distortion. The magnitude of the improvement appeared to be associated with the specific mixer configuration. The incremental improvement of the mixer with simulated engine effects was used to estimate full scale engine performance because it is believed to be a more accurate indication of the improvement available.

Tests were conducted to evaluate the effect of a 5 degree canted tailpipe on the reference exhaust system and on one mixer. Figure 10 illustrates the effect of the 5 degree tailpipe cant on the peak PNL of the reference and the cutback scalloped long mixer at both takeoff thrust (15,500 lbs.) and cutback thrust (12,400 lbs.) The tailpipe was canted away from the microphone to simulate an overhead flyover. The effect of the 5 degree cant on the noise of the reference system was small, with no change at the higher thrust and a 0.5 PNdB decrease at the lower thrust. The noise of the mixer exhaust system with the canted tailpipe was 1 PNdB less at takeoff and 1.5 PNdB less at cutback thrust than the noise of the noncanted tailpipe mixer. Exhaust system performance was unaffected by tailpipe cant when thrust was evaluated using the resultant force vector.

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Figure 10   Effect of 5 Degree Tailpipe on Peak Perceived Noise Levels of Reference
Exhaust System and the Cutback Scalloped Long Flowpath Mixer (without
Engine Secondary Flow Simulation)

Results of tests with a long tailpipe showed that the reference exhaust system noise levels
were reduced by 0.5 PNdB and by 1 PNdB for the one mixer system tested relative to the
reference (standard length) tailpipe. The long tailpipe had only a slight effect on absolute
levels of performance and a negligible change in thrust of the mixer relative to the reference
system.

CONCLUSIONS

Based on encouraging acoustic and performance results and the minimum impact on engine
structure and installation, the shorter mixer is judged to be the design best suited for appli-
cation in the JT8D-15 engine, provided that the small loss in takeoff thrust can be corrected.

1.0 INTRODUCTION

1.1 BACKGROUND

The Pratt & Whitney Aircraft JT8D turbofan engine powers a large percentage of the world's short and medium range commercial jet aircraft fleet, including the Boeing 727 and 737 airplanes and the McDonnell Douglas DC-9 airplane. Although current production models of these airplanes meet noise certification requirements established under FAR part 36, the possibility exists of providing reductions in the jet noise through the use of an internal mixer exhaust system. The application of a mixer to the JT8D engine exhaust system was investigated under this contract.

The noise of the JT8D engine at cutback and takeoff power is dominated by jet noise which is related to and influenced by the jet velocity of the hot primary core exhaust at the tailpipe exit. One approach for reducing the jet noise of the JT8D engine involves the concept of internally mixing the primary and fan streams within the common tailpipe. The potential noise reduction that may be achieved using this concept has been predicted to be on the order of 3-4 PNdB in Peak Perceived Noise Level (PNL) under static conditions. The effects of airplane forward velocity on the noise reduction due to internal mixing cannot be accurately predicted. Therefore the expected noise reduction due to internal mixing in terms of Effective Perceived Noise Level (EPNL) of a JT8D powered airplane during a flyover has not been established.

A major impediment to the practical application of an internal mixer to the JT8D engine has been the adverse impact on performance that was projected based on early mixer studies. Recent analytical and experimental programs conducted at Pratt & Whitney Aircraft including full scale engine mixer tests, have shown, however, that internal mixer technology has advanced to a state such that the incorporation of a mixer could provide performance improvements relative to the current JT8D engine.

Based on the desire for reducing the jet noise of the JT8D engine without major engine modification and the recent advances in internal mixer noise and performance technology, this program was formulated to define a mixer configuration that has potential for application to the JT8D engine.

1.2 PROGRAM DESCRIPTION

The basic objectives of the program were to develop a mixer design that would provide reductions on the order of 3 to 4 PNdB in peak PNL without impairing engine performance. The mixer design was to be consistent with full scale JT8D engine structural limitations and also had to be practical in the sense that the modifications to the engine and nacelle should be minimized. In addition to the contract work completed, Pratt & Whitney Aircraft conducted company-sponsored tests of scale model JT8D mixers that complemented the tests conducted under this contract. Test results obtained from the Pratt & Whitney Aircraft program are reported along with the contract results. Specific activities completed under each program are summarized below.

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1.2.1 Contract Activities

JT8D Mixer Design Study

Design studies were conducted of concepts applicable to the JT8D engine, and compatibility with tailpipe hardware was investigated for JT8D-powered airplanes. A series of mixer flowpaths was designed requiring engine case extensions of up to 21 inches. It was concluded, based on the design studies, that a mixer which would provide satisfactory noise and performance would require a new engine outer case that lengthened the engine by 16 inches to provide lower rates of diffusion of the flow through the mixer, and therefore minimize performance losses due to possible regions of local flow separation. Although such a design would require an extended nacelle, it would still be compatible with existing DC-9, 727, and 737 tailpipe and reverser hardware. This design was supplied to the airframe manufacturers for review early in the study.

Scale Model Nozzle Design and Fabrication

Based on the above studies, one-seventh scale model mixers were designed and three sets fabricated to allow modifications during the test program as required to produce a relatively flat profile at the nozzle exit plane. Also, an one-seventh scale reference exhaust system was designed and fabricated. A reference tailpipe was fabricated that was representative of the length and flowpath lines used for 727 and DC-9 installations.

Scale Model Acoustic Tests

Noise and exit velocity profile characteristics were measured on mixed and reference model hardware tested with individually controlled fan and primary stream airflow pressures and temperatures to simulate operating conditions of a JT8D engine. The acoustic test facility provided an anechoic environment above frequencies of about 150 Hz to allow the measurement of free-field jet noise over a range of angles of interest. Tests were conducted of each model exhaust system over a range of at least 10 conditions simulating JT8D sea level operation, including approach, takeoff and cutback operation. Nozzle discharge traverse tests were conducted at two operating conditions for each exhaust system. The reference system was tested with both streams at the same conditions to define the noise characteristics of a 100% mixed flow. Data were scaled to simulate a full size JT8D engine under static conditions and extrapolated to 150 foot radius and from 400 to 6000 foot linear distances.

Although it would be desirable to present results in terms of Effective Perceived Noise Level (EPNL), which is the noise parameter used for airplane noise certification, information concerning the effect of airplane forward velocity on the jet noise is required to permit a meaningful value of EPNL to be calculated. Since flight effect information for the mixer configurations tested in this program is not available, the results are presented in terms of Static Perceived Noise Level (PNL). A flight test is necessary to determine the EPNL reductions due to a mixer.

Analytical Support and Data Analysis

The noise reduction potential of the various mixer configurations was established by comparison with the 100% mixed flow condition and by comparing the results of the mixers with the reference configuration.

Inverted Profile Mixer

One model mixer was modified by cutting back the lobe scarf angle to direct more primary air to the nozzle outer diameter and thus "invert" the flow relative to the normal co-axial exhaust where the hot primary flow is in the center. The nozzle was tested using the same procedures as were used for mixer nozzles, and the noise reductions were compared with results from other configurations.

Scale Model Performance Tests

Two mixers and the reference system were tested by the FluiDyne Engineering Corporation to provide accurate measures of thrusts and flows at conditions that simulate JT8D operation at takeoff and cruise. Cold flow tests also were conducted to evaluate pressure losses of the mixer systems to provide an additional basis for performance assessment.

1.2.2 In-House Program Activities

Design Study

Although the design of a mixer that could be contained within the existing JT8D-powered airplane hardware was judged to be outside the limits of current technology due to predicted excessively large pressure gradients and possible flow separation, there are several obvious installation benefits for such a design. Accordingly, Pratt & Whitney Aircraft initiated an in-house design study to evaluate "short" mixer designs that were outside of the range of experience but would minimize changes to engine case hardware. A series of mixer flow-paths was designed to fit within the current JT8D engine outer case. "Spool piece" extensions to attach the mixer to the engine were designed with lengths that ranged form 0 (i.e., no extension) up to 10 inches, with the zero length extension most desirable for ease of installation, but having the greatest risk of unacceptable performance. The candidate designs were consistent with JT8D engine structural and mounting limitations, and all allowed the retention of existing tailpipe/thrust reversers currently used on Boeing 727, 737 and Douglas DC-9 airplanes.

Model Nozzle Design and Fabrication

Scale models in one-seventh size were fabricated of the short mixer designs. Also, additional hardware was fabricated to simulate the 737 tailpipe, which is significantly longer than the reference tailpipe that simulated the length of 727 and DC-9 tailpipes used for the contract studies and a 5 degree canted tailpipe (engine and tailpipe centerlines intersect at a 5 degree angle) of 727 and DC-9 length to allow evaluation of this effect, which is relevant to 727 and DC-9 installations.

Scale Model Acoustic and Performance Tests

Tests of Pratt & Whitney Aircraft's in-house models were conducted using the same facilities and procedures used for the contract testing. In addition, as part of the in-house program, the effects on noise of fan and turbine case struts and residual swirl flow in the primary flow were evaluated for both baseline and mixer configurations. It was found that these features

produced a noise benefit for the baseline exhaust system, but the effect of struts and swirl on the noise of the mixer configurations was not significant.

1.3 RECOMMENDED FULL SCALE MIXER DESIGN

A final mixer configuration was selected and evaluated under the contract. Results of the Pratt & Whitney Aircraft in-house program were made available for this selection along with contract results and provided increased confidence in predicted performance and noise characteristics of a full scale device. Weight, structural durability, and installation compatibility estimates were based on design study results. The characteristics of the recommended full scale design are discussed in Section 6.0.

1.4 TECHNICAL DISCUSSION

Significant technical results from these programs are presented in the following sections. The results of both the contract program and the in-house program are presented, as required, to provide technical clarity.

Various elements of the program are reported in the following Sections:

Section 2.0 contains a description of the Mixer Design Studies, and presents the rationale for the selection of the basic mixer design as well as a definition of the test hardware.

Section 3.0 describes the Acoustic and Exit Traverse Test program, and provides a description of the test facility, the acoustic and profile data acquisition and processing systems, and presents the operating condition matrix used for the tests.

Section 4.0 contains a description of the Nozzle Performance Test Program. The FluiDyne Thrust Facility is described briefly. (A complete description is included in Appendix D.) The performance parameters are described and the operating condition matrix used for the tests is defined.

Section 5.0 contains a presentation and discussion of the acoustic, profile and nozzle performance results obtained during testing. Included in this section are results obtained during in-house testing, which have importance in applying the results of this program to select a mixer design for a full scale JT8D engine.

Section 6.0 presents the mixer design selected for application to the JT8D engine and summarizes the projected noise reduction, nozzle performance, weight and the impact on the engine and nacelle of incorporating this mixer design in the full scale engine.

Section 7.0 contains the conclusions derived from the efforts of this program.

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2.0 MIXER DESIGN STUDY

2.1 AERODYNAMIC DESIGN

The primary consideration in the aerodynamic design of an exhaust mixer for the JT8D engine was the exhaust discharge plane velocity profiles required to achieve both acceptable acoustic properties and engine performance. Fortunately, exhaust profile requirements for noise and performance both are best served by a relatively flat velocity profile at the exhaust plane. In addition, pressure loss, weight and existing engine dimensional constraints must be considered. The aerodynamic design of the JT8D mixer flowpath was, to a large extent, predicated on experience developed through tests of other engine models and, in particular, from experience with refanned derivative JT8D mixer configurations. This experience guided the establishment of basic criteria for the convoluted mixer flowpath design. Referring to Figure 2-1, these design considerations are:

a) Determination of the required total annulus area at the discharge of the mixer. Enlarging this area reduces the local Mach number which may be related analytically to a reduction in momentum pressure loss. Existing fan case dimensions, external drag and installation constraints will limit the diameter of this outer case.

b) Lobe coverage, which defines the circumferential separation of the lobes and therefore the number of lobes, is derived from empirical information relating the degree of mixing and pressure loss to the coverage.

c) Lobe penetration, which defines the height of the mixer lobe in relation to the total annulus height, also is determined empirically.

d) Mixer-plug gap, which is defined by the ratio of annulus area between the mixer and the plug to the total primary stream area at the mixing plane, is chosen to eliminate large regions of hot gas at the inner radius of the stream.

An additional engine match-related restriction is that the static pressure of the engine and fan streams be equal at the discharge of the mixer. This requires that the ratio of the areas at the mixing plane of the two streams be selected such that the Mach numbers (and hence the static to total pressure ratio) of the two streams compensate for any difference between total pressures that may exist. Failure to establish the proper pressure balance could result in a mismatch of the compressor and turbine systems with possible undesirable effects on engine operation or performance.

The area ratio, in conjunction with lobe coverage, penetration gap and the total annulus area at the mixer discharge, essentially defines the mixer configuration with exception to the basic geometric shape of the mixer lobes. Parallel, radial, and curved wall mixer designs have been investigated in the past. For the JT8D engine, a radial wall design is desirable because of the increased fan stream flow area in the innermost portion of the lobe trough that this design provides.

Mixer lines upstream of the discharge plane are determined primarily on the basis of achieving an acceptable gradual change in local and stream average turning and diffusion rates to discourage local flow separation.
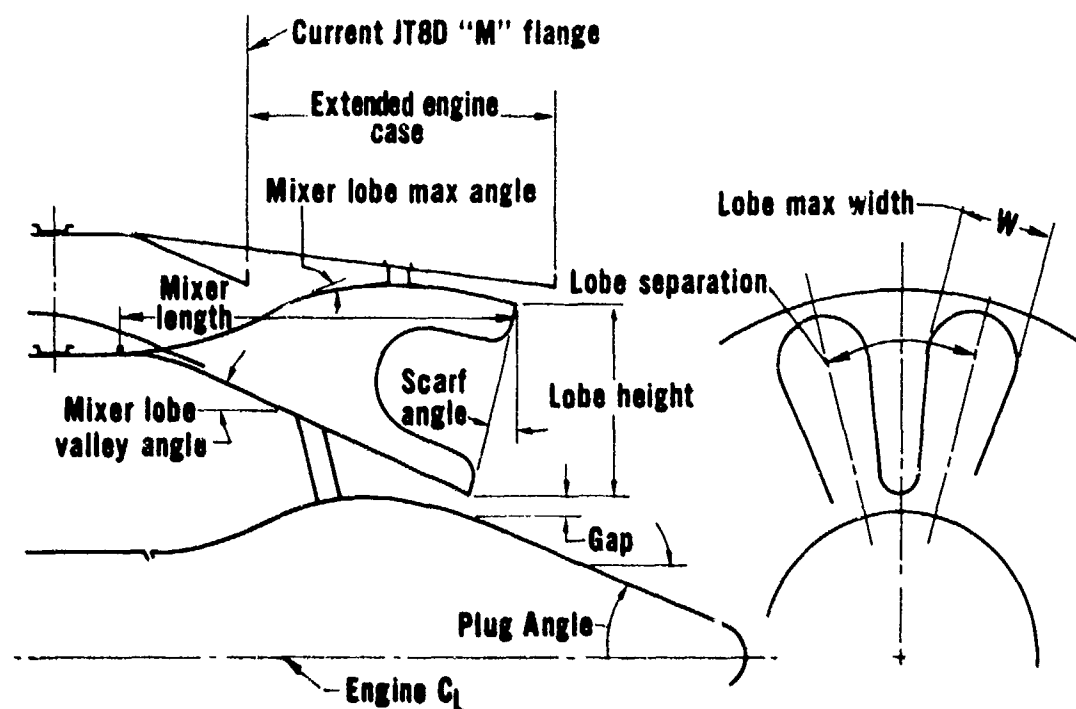
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Figure 2-1   Mixer Flowpath Design Parameters

A 12-lobe convoluted mixer, shown in Figure 2-2, was designed for the FAA JT8D program in accordance with the aforementioned criteria, aimed at achieving a flat velocity profile at the tailpipe discharge, and having conservative aerodynamic lines to avoid excessive pressure loss. This mixer flowpath required that the outer exhaust case be modified to a more gradual convergence slope and extended 16 inches axially rearward in order to achieve the desired diffusion rates. The shorter mixer, which required a 7.6 inch case extension, was generated for a Pratt & Whitney Aircraft funded test program. This shorter mixer design was undertaken in an attempt to reduce the impact of the mixer on the aircraft installation and, in particular, the requirements for extensive nacelle and reverser modifications.

The potential for separation (and accompanying high pressure loss) was evaluated analytically for the fan flow in the region between the mixer lobes. Flow properties in this region were evaluated by analytically creating an annular duct whose inner radius matched the mixer flowpath in the valley and whose outer radius yielded a duct cross-sectional area equivalent to the area on the fan stream side of the mixer (Figure 2-3). This duct was then evaluated as an annular diffuser. Prediction of boundary layer thickness and shape was related to skin friction coefficient (C_f) which, in turn, indicates a potential for separation if it approaches a value of zero. A comparison of C_f values for the 16 inch and 7.6 inch extension mixers (Figures 2-3(a and b) indicate that the increased potential for flow separation was inherent in the shorter mixer design.
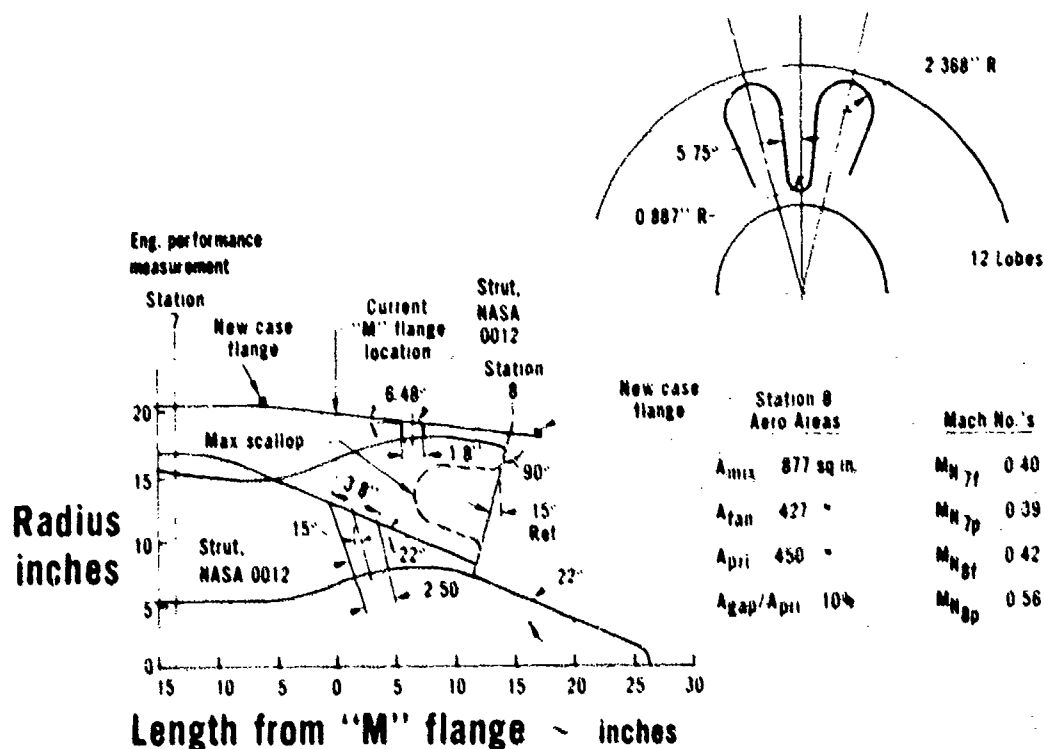
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Figure 2.2   Full Size JT8D Mixer Design with 16 inch Engine Case Extension

The basic design of each mixer considered the possibility of scalloping the mixer lobes by removing nonstructural wall sections. Scalloping has been shown to increase mixing by as much as 10% with an insignificant increase in pressure loss with mixer model configurations for other higher bypass ratio engine models. Scalloping provides two benefits: (1) it increases the flow interface perimeter at the mixer discharge plane, and (2) the remaining lobe extensions act as lifting airfoils and create tip vortices that promote mixing.

The angle of the lobes at the mixer discharge plane is also determined empirically. Refanned derivative JT8D model test experience has shown that overturning the engine flow radially inward will promote mixing due to impingement of the engine flow on the portion of the fan flow that "fills" the trough between the mixer lobes. The derivative experience indicated that overturning angles of 12 to 15 degrees provide optimum mixing. The detailed scalloping and lobe angle for a "best" mixer for the JT8D engine would be determined during the testing.

Thus, a mixer design was evolved for the contract based on producing a high degree of mixing with flow surfaces consistent with producing little chance of flow separation.
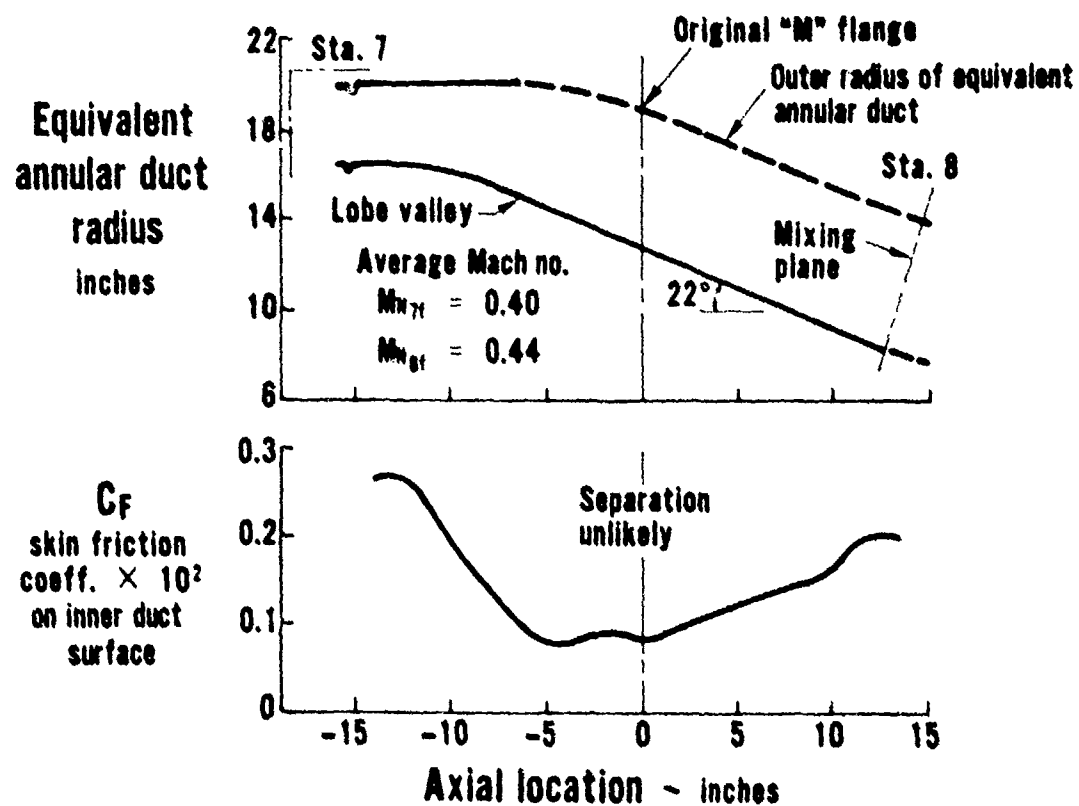
Figure 2-3,a) Estimated Aerodynamics of JT8D Mixer with 16 Inch Case Extension
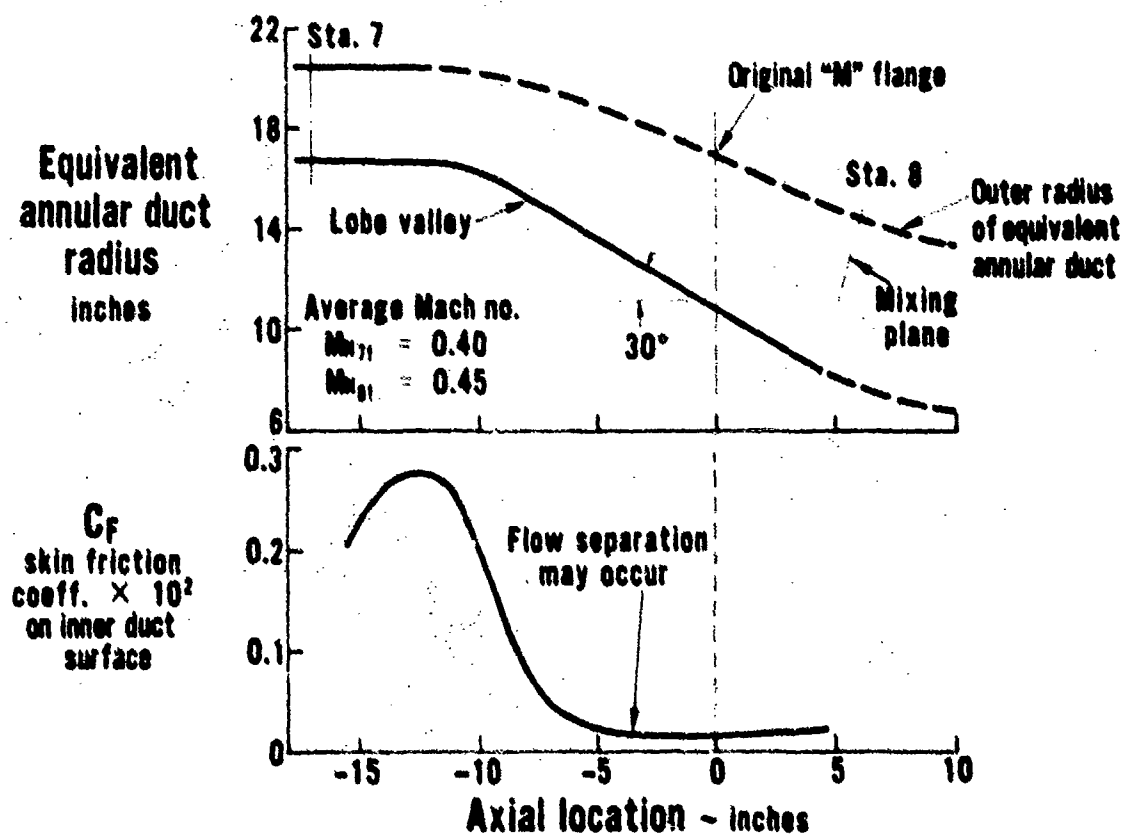

Figure 2-3,b) Estimated Aerodynamics of JT8D Mixer with 7.6 Inch Engine Spoolpiece

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2.2 ACOUSTIC CONSIDERATIONS

Achieving a flat velocity profile at the nozzle exit was considered a primary design goal for a mixer that would provide effective noise reduction for the JT8D engine. Since a flat profile would be achieved with complete mixing, the aerodynamic design criteria discussed in the previous section are consistent with an effective mixer for noise reduction purposes. Previous mixer investigations at Pratt & Whitney Aircraft have indicated that velocity profile having maximum local velocities on the order of 10% or less above the ideal mixed value produce noise reductions on the same order as completely flat profiles. Also, previous results have indicated that velocity profiles having inverted characteristics, i.e., having maximum local velocities at the outer perimeter of the tailpipe, sometimes have produced noise reductions greater than those achieved with an exhaust having a flat profile. One task of this program was to determine if an inverted velocity profile would produce additional noise reductions for the JT8D cycle.

Inverted flow could be produced with the mixer evolved from the design study by a relatively simple modification to the lobe geometry. The exact modification would be determined using the velocity profile results obtained during the initial testing.

2.3 JT8D COMPATIBILITY

Conceptual studies of the mechanical structure of the 16 inch engine outer case extension mixer were conducted to verify the practicality of the desired flowpath. Throughout this analysis it was assumed that the turbine case would remain unchanged from the current design. Loading requirements dictated that the entire mixer and plug should be supported by the outer case with loads transmitted through aerodynamic struts. Fairings and slip joints would be required at the turbine inner and outer diameter to avoid steps in the flowpath and to compensate for differential thermal expansion caused by temperature differences between the fan and primary stream.

As these design studies were being conducted, contact was established with The Boeing Company and Douglas Aircraft Corporation to solicit their judgements on the impact of the revised engine external lines on aircraft hardware and operation. Both airframe companies responded based on the results of cursory analyses and stressed the importance of attempting to develop mixers which require minimum change of the engine lines. Recognizing the problems associated with establishing an acceptable mixer flowpath within the existing tailpipe constraints, some estimates of impact on the installation were made. Estimated modifications to the nacelle and reverser were considerable, and it was noted that extensions in excess of 16 inches could impact aircraft takeoff rotation angle on certain aircraft, thus necessitating a longer takeoff roll.

2.4 SCALE MODEL HARDWARE

One-seventh scale models of the mixer and reference splitter exhaust system, were designed and fabricated at Pratt & Whitney Aircraft and FluiDyne Engineering Corporation. A photograph of the basic hardware is shown in Figure 2-4. The scale chosen was based on

past experience with airflow and heat addition capabilities at the FluiDyne force measurement and Pratt & Whitney Aircraft acoustic test facilities. A typical mixer installation, including adapting hardware, is shown in Figure 2-5. All model hardware was designed for operation at temperatures up to 1200°F and fabricated from steel. Allowances were made for differential thermal growth so that proper allignment would be achieved at the desired operating conditions.
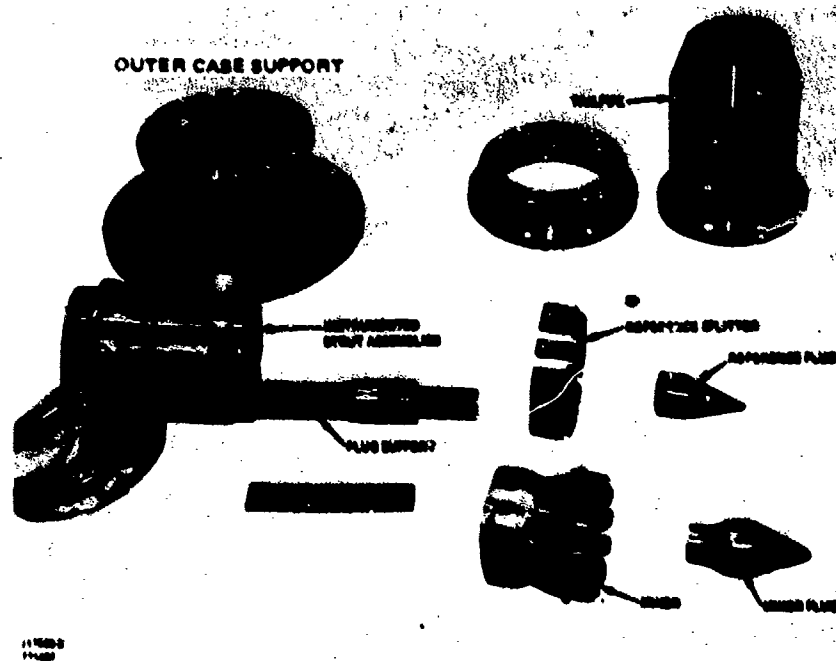

Figure 2-4   One-Seventh Scale Model Hardware for JT8D Reference and Mixer Exhaust Systems
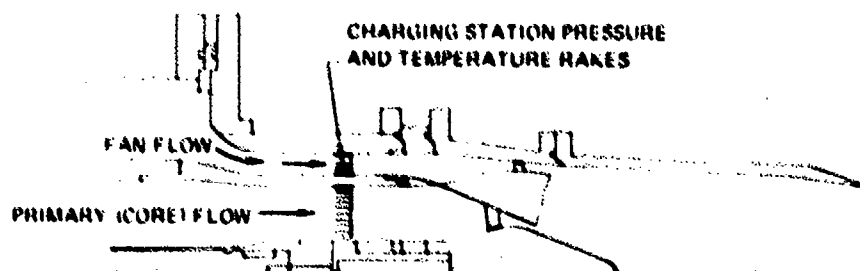

Figure 2-5   Schematic of JT8D Mixer Exhaust System Model

The model exhaust systems simulated the D-1 to D-17 versions of the JT8D engine. A reference tailpipe was selected to provide a compromise between the lengths and flowpaths of the Douglas DC-9 and Boeing 727 installations.

The bulk of testing was conducted with flat pressure and temperature profiles in each stream at the "charging station" location upstream of the nozzle where gas flow properties are measured. However, previous JT8D derivative engine model tests had indicated performance effects due to an interaction of turbine flow residual swirl with turbine case struts and/or fan pressure radial distortion. These "secondary" flow effects were simulated for portions of the test program. Swirl vanes were fabricated and inserted along with simulated JT8D exhaust case struts to simulate the JT8D turbine discharge swirl determined from full scale engine testing. A radial pressure profile was created in the fan stream by the insertion of perforated plates to simulate the full scale fan discharge pressure profile and boundary layer development in the fan duct.

Three separate models of the long mixer configuration were fabricated. This was done to accommodate simultaneous testing at Pratt & Whitney Aircraft and FluiDyne, to allow for variations in mixer schemes that were investigated to optimize mixing and pressure loss and to investigate the effects of partial inversion of the nozzle velocity profile.

Instrumentation for the model included total temperature and total pressure rakes installed at axial stations which approximate the measuring stations in the full scale engine. These measuring stations are identified in Figure 2-5, and were defined as the charging stations for this series of model tests. Pressure at each probe head was measured individually to facilitate mass averaging of flows with distorted pressure profiles.

Detailed drawings of all model hardware are provided in the FluiDyne Report, Appendix D.

3.0 ACOUSTIC AND EXIT TRAVERSE TEST PROGRAM

3.1 JET NOISE TEST FACILITY (X-206 STAND)

The Pratt & Whitney Aircraft Anechoic Jet Noise Facility, X-206 stand, was used to obtain both acoustic and exit velocity profile measurements required for the program. This facility, located at the Andrew Willgoos Turbine Laboratory, was specially designed to provide an accurate simulation of jet engine exhaust nozzle characteristics using scale model nozzles.

3.1.1 Test Chamber

The test chamber, illustrated in Figure 3-1, with a volume of approximately 12,000 cubic feet, is lined on all surfaces with specially constructed anechoic wedges to provide an anechoic environment for frequencies above 150 Hz. The walls are constructed with an air passage between the concrete block outer wall and a perforated sheet inner wall. Blowers are used to provide a slight inflow of air through the perforated wall in order to eliminate secondary air currents induced within conventional test chambers by the flow from the test nozzle. A honeycomb exhaust silencer further reduces the potential for secondary air currents as well as eliminating the transmission of outdoor noise sources into the stand. Chamber temperature, relative humidity and pressure are recorded for each test point.

The test nozzle is situated in a vertical position directly beneath the exhaust stack. Laboratory compressors provide the two air streams to the coannular test nozzle. The two flows are individually controlled for pressure, temperature and flow. The flows are heated by natural gas fired heater burners with a maximum capability of 1500°F at nozzle pressure ratios up to 4.0. A schematic of the air supply system is shown in Figure 3-2. Accurate weight flow measurements are provided by calibrated choked flow venturis. Test nozzle pressures and temperatures are measured by multiple probe rakes located at the nozzle charging station as illustrated by the rig scheamtic in Figure 3-3.

3.1.2 Acoustic Data System

3.1.2.1 Acoustic Data Acquisition

Acoustic signals are detected by a polar array of 0.250 inch diameter Bruell and Kjaer microphones (#4135) positioned at normal incidence to the centerline of the test nozzle exit plane at a distance of 15 feet. Microphones were located every 10 degrees from 60 to 160 degrees relative to the upstream jet axis. This array was shown in Figure 3-1.

The signals are transmitted to the control room and recorded on magnetic tape with a Honeywell system 96, 14 channel Wide Band Group II tape recorder. During the test, selected acoustic data are monitored on-line by a B&K #2107 one-third octave band sound analyzer. All microphones were calibrated prior to the tests by a procedure traceable to the National Bureau of Standards. Daily calibrations were performed by a B&K #4220 Pistonphone. The frequency response of the entire data acquisition system is essentially flat up to 80,000 Hz.
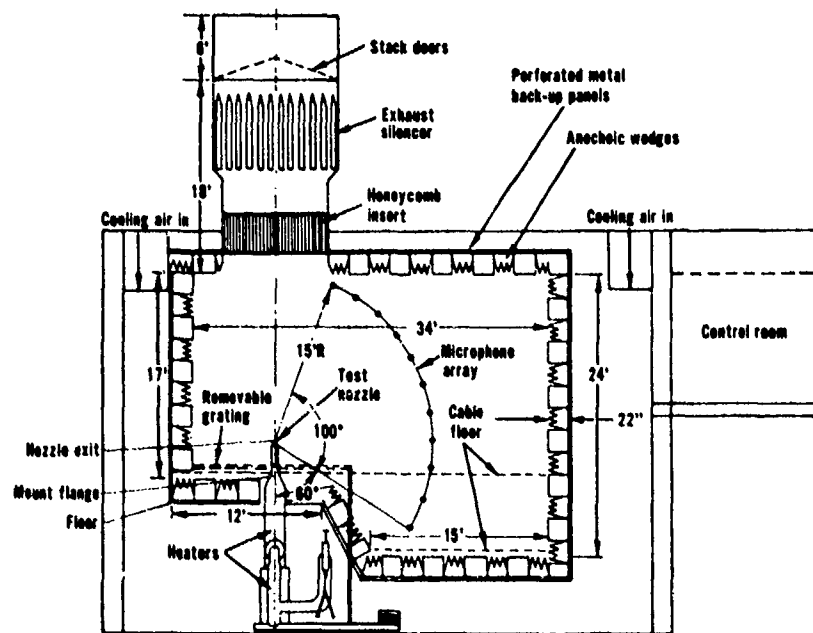
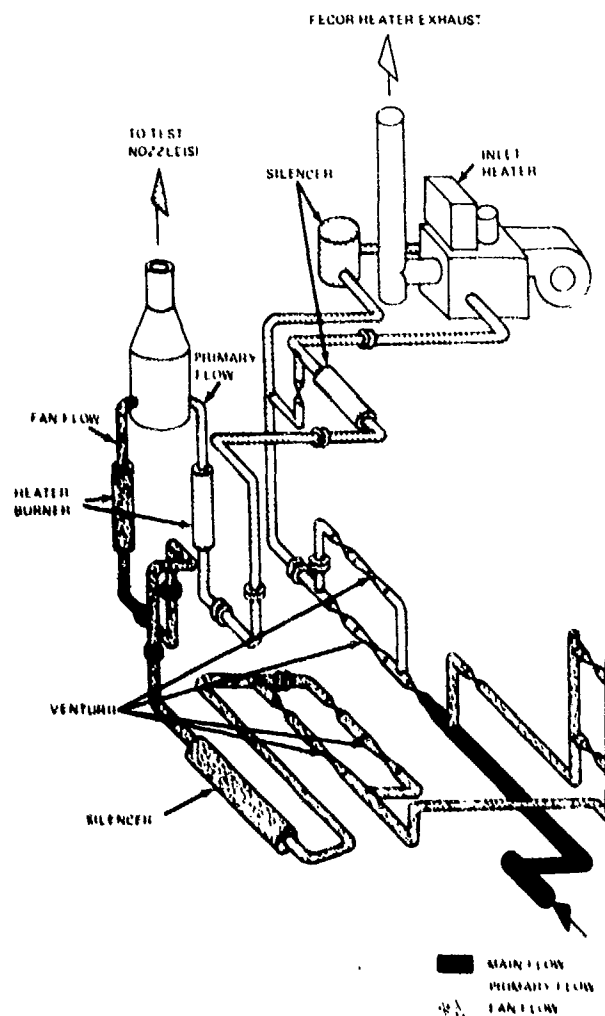Figure 3-1   Anechoic Jet Noise Test Facility, X206 Stand

Figure 3-2   Schematic of Air Supply Heating and Silencing Facilities for X206 Stand
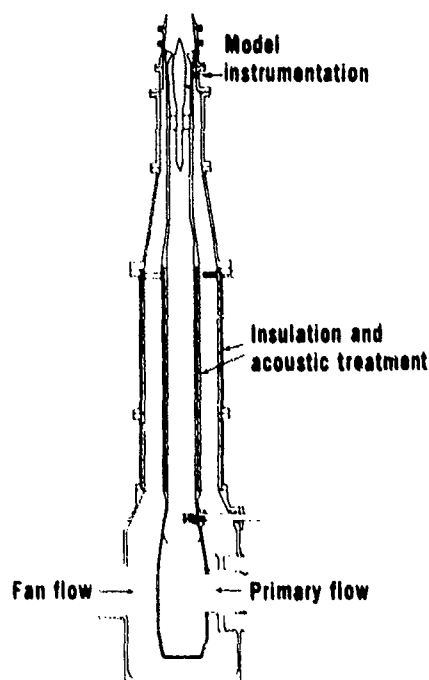
Figure 3-3   Exhaust System Test Installation

3.1.2.2   Acoustic Data Processing

The tape recorded data are processed in the Data Reduction Center on a General Radio 1920, one-third octave band analyzer, and the raw data are recorded on digital incremental tape. The incremental tape is then processed by an IBM 370 computer. In the computer processing, cable and microphone response calibration values are added. Atmospheric attenuation corrections are applied in order to adjust acoustic data to a standard FAA day ($77°F$, 70% relative humidity). Data in this form are contained in Appendix B. The data are then scaled for size and extrapolated to the desired distance to predict the free field jet noise of a full size JT8D engine using the standard scaling and extrapolation procedures. Extra ground attenuation corrections were not applied to the data. The data scaled to predict JT8D full scale engine noise for all test configurations also are contained in Appendix B.

Both the model and scaled data include one-third octave band sound pressure level (SPL) spectra at all measured angles. Also provided on each data sheet are the overall sound pressure level (OASPL) at each angle, integrated sound power level (PWL) spectra (model data only) and overall power level (OAPWL) (model data only). The scaled data also contain the PNL at each angle at linear distances of 400, 1200, 2000, 4000 and 6000 feet.

Each data sheet also contains a complete tabulation of all pertinent exhaust system operating parameters.

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3.1.3 Exit Traverse Data System

A diagnostic tool used to provide a direct determination of the amount of radial or circumferential mixing was the result of spatial traverses of pressures and temperatures in the exhaust plume directly behind the nozzle discharge. Data acquired from these traverses are used to calculate velocity profiles that can be used to guide geometric modifications required to achieve desired profile shapes and to relate acoustic and performance data trends to the nozzle discharge profiles.

The integrated pressure and temperature traversing system installed in the Anechoic Jet Noise Facility is illustrated in Figure 3-4. A probe head (Figure 3-5), which senses total and static pressure and total temperature, is automatically positioned to 148 locations in the nozzle exit plane (Figure 3-6). These locations are prescribed on a punched paper tape that is read by a console located in the control room. Measured probe radial and angular coordinates are also obtained at each sampling location.

3.1.3.1 Traverse Data Acquisition

A portable data unit is utilized to read out and record on magnetic tape all readings of traverse instrumentation as well as the probe location at each sampling point. The magnetic tapes are processed on a Xerox SIGMA 8 computer that converts raw millivolt data acquired from pressure transducers and thermocouples to engineering units and applies appropriate calibrations to the pressure data. The SIGMA 8 generates a hard copy printout of the data in raw millivolts and engineering units, data validity information and punch cards containing the calibrated data in engineering units.
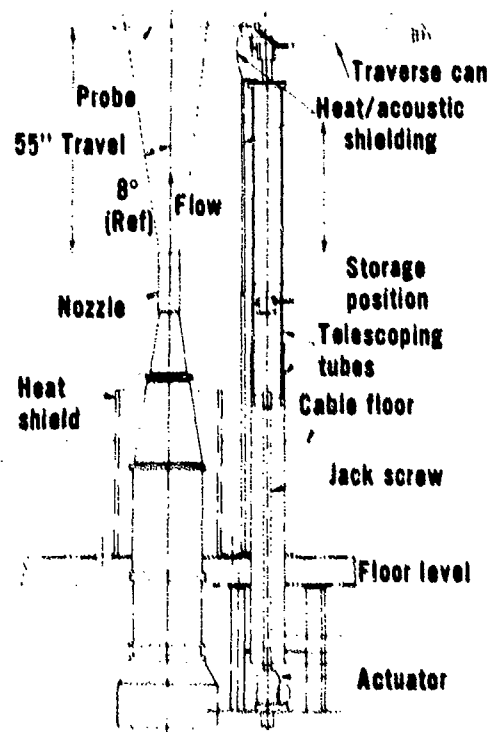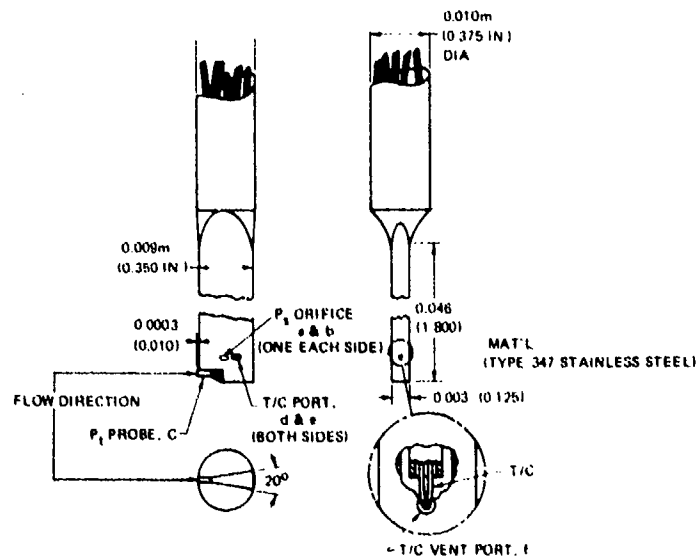

Figure 3-4   Exit Profile Traverse Rig

Figure 3-5   Traverse Probe for Measurement of Static Pressure, Total Pressure and Total Temperature
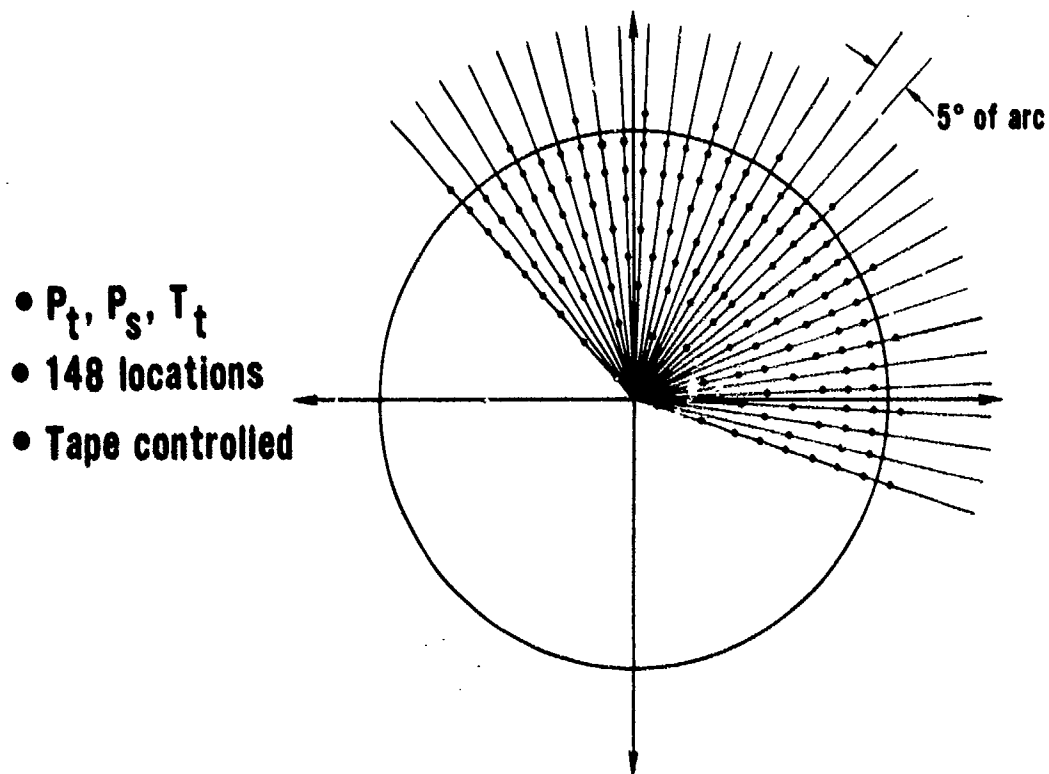

- P_t, P_s, T_t
- 148 locations
- Tape controlled

5° of arc

Figure 3-6   JT8D Mixer Model Profile Measurement Traverse Array

3.1.3.2 Traverse Data Processing

The punch cards are loaded into an IBM 370 computer that is linked to remote interactive graphic terminals where pressure and temperature data from the traversing are edited and used to generate contour plots of exit plane stream properties. A fully expanded velocity is calculated from the measured total pressure and temperature at the exit plane and the static pressure in the test cell. Curves of the circumferential and radial average values of pressure, temperature, and velocity are also plotted.

Overall averages of the parameters measured by the fixed instrumentation are calculated and used to determine the average mass flows, pressure and temperature splits, and expansion ratios that existed in each stream during the traverse. The average temperatures, pressures, and flows are used to calculate the ideal fully mixed pressure, temperature, and velocity which serve to normalize the traverse results for each configuration and account for slight differences in upstream flow conditions.

3.2 ACOUSTIC AND TRAVERSE TEST CONDITIONS

Each model configuration was tested at ten exhaust system operating conditions selected to duplicate those of the JT8D-15 engine sea level static operating line on a 77°F day. These conditions are defined in Table 3-1. Pressures and temperatures at the model charging station represent the fan and primary stream properties at the inlet to the splitter in the full scale reference configuration. The pressure ratio presented in this table is engine total pressure at the charging station divided by ambient pressure. The jet velocities are based on the JT8D-15 engine simulation customer computer deck and take into account measured engine performance characteristics.

Exit profile measurements were performed for points C and F, which represent the JT8D-15 takeoff (sideline) and cutback (overhead) thrust levels, respectively.

The reference and mixer nozzle were tested at the above operating conditions. On the basis of noise and profile results of the mixer, the lobe discharge geometry was modified three times to produce various degrees of profile flatness. Each modification was subsequently tested at the same ten operating conditions. A further lobe modification, which would provide a partially inverted flow profile, was also tested at the same conditions.

Mixed temperatures and velocities were also calculated for each point, and the reference exhaust system with those conditions in both the primary and fan stream flows in order to provide reference noise characteristics for an ideally mixed jet.

TABLE 3-1

NOZZLE OPERATING CONDITIONS FOR ACOUSTIC TESTS

	Condition	Thrust (1000 lbs) (full scale)	Primary			Fan				Mixed streams	
			P_{tp}/P_{amb}	T_t (°k)	V (fps)	P_{tp}/P_{amb}	T_t (°R)	V (fps)	Bypass Ratio	V (fps)	T_t (R°)
	A	16.4	2.16	1615	1990	2.01	700	1240	0.97	1620	1164
	B	16.0	2.13	1610	1970	1.99	700	1230	1.00	1600	1155
Takeoff	C	15.5	2.08	1570	1917	1.96	690	1209	1.02	1559	1130
	D	14.5	2.00	1525	1800	1.89	685	1170	1.06	1476	1093
	E	13.0	1.87	1470	1710	1.79	670	1115	1.12	1396	1047
Cutback	F	12.4	1.81	1440	1650	1.75	665	1090	1.16	1349	1021
	G	11.5	1.74	1410	1584	1.70	655	1051	1.20	1293	995
	H	8.5	1.49	1320	1330	1.51	625	920	1.33	1096	926
Approach	I	7.8	1.44	1300	1270	1.47	620	885	1.36	1048	908
	J	6.0	1.32	1260	1076	1.36	600	792	1.45	900	868

4.0 NOZZLE PERFORMANCE TEST PROGRAM

The impact of various mixer schemes on exhaust system performance was determined by measurement of exhaust nozzle forces at simulated JT8D nozzle operating conditions at the FluiDyne Engineering Corporation Medicine Lake Aerodynamics Laboatory. This facility was selected because it provides the high degree of accuracy and repeatability required for determining the relatively small differences in performance between the mixer and reference exhaust systems. All work was performed under subcontract to Pratt & Whitney Aircraft.

4.1 EXHAUST NOZZLE THRUST FACILITY

The FluiDyne Channel 11 facility, which is illustrated in Figure 4-1, is a static thrust stand capable of simultaneously testing two streams operating at different temperatures. For the JT8D installation both streams were ducted through concentric flow passages that fed the mixer or reference splitter and discharged through a common tailpipe. A typical mixer model installation is shown in Figure 2-5. Nozzle forces and mass flow rates, temperatures and pressures for each stream were measured at the facility.
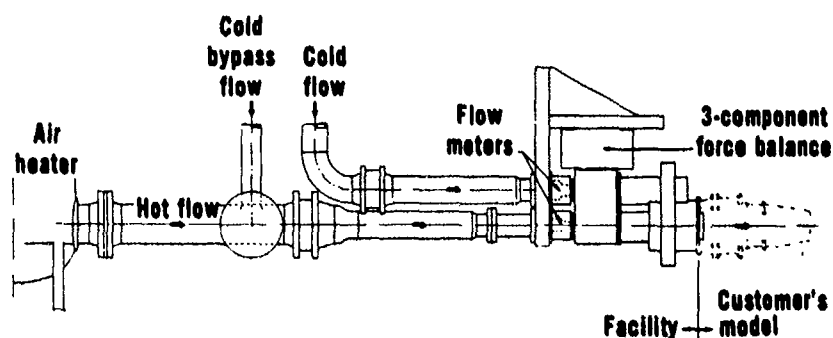

Figure 4-1   FluiDyne Engineering Corporation Channel 11 Dual Flow Exhaust Model Test Facility

An in depth description of the FluiDyne Facility, the force data corrections, and data processing is contained in Appendix D.

4.2 PERFORMANCE PARAMETERS

Of primary concern in the FluiDyne testing was the determination of the gross thrust output of the various exhaust systems investigated. Every effort was made to run each model configuration at exactly the same charging station operating condition to facilitate comparison of thrust performance. Nondimensional thrust coefficients were calculated to allow a valid comparison of force output. Exhaust system performance is assessed at the pressure and temperature measuring station upstream of the mixer instead of at the nozzle discharge plane. Therefore, internal pressure loss and skin friction drag and mixing are included within the nozzle coefficients. Thus, this method provides an evaluation of total exhaust system performance.

4.2.1 Thrust Coefficients

Thrust coefficient is defined as the ratio of the measured thrust to the sum of ideal thrusts obtained by isentropically expanding separate fan and primary streams to the static pressure surrounding the exhaust nozzle:

$$C_T = \frac{H}{F_{p_i} + F_{f_i}}$$

Since the ideal thrust defined here assumed no mixing and a thrust increase due to mixing does occur within the exhaust system, thrust coefficients of greater than unity are possible. A detailed discussion of nozzle thrust coefficient calculation procedures is contained in Section 4.5 of Appendix D.

4.2.2 Discharge Coefficient

Nozzle discharge is defined as the ratio of the actual gas flow through a nozzle to the ideal flow at the same temperature and nozzle pressure ratio. In order to determine a discharge coefficient for two streams discharging through a common nozzle, ideal flow per unit areas is calcualted for each stream and the sum of the two values is proportioned to the total measured flow divided by the measured exhaust nozzle area :

$$C_D = \frac{\left(\dfrac{W_7 + W_8}{A}\right)_{\text{meas.}}}{\left(\dfrac{W_7}{A_7} + \dfrac{W_8}{A_8}\right)_{\text{IDEAL}}}$$

A detailed description of discharge coefficient calculation procedures is presented in Section 4.3 of Appendix D.

4.2.3 Determination of Mixing and Pressure Loss

A technique has been devised for separating the thrust gain due to mixing from the thrust loss due to the additional pressure loss that results from the presence of the mixer. Because the sensitivity of engine performance to these two parameters varies as a function of flight condition and engine power setting, this determination is necessary to allow performance predictions over a range of conditions. The technique requires separate tests of the exhaust system; first with both streams at the same temeprature (cold test), and then with the streams at simulated engine operation temperatures (hot test). With both streams at the same temperature, the velocity difference (due only to the pressure split difference) is very small, as is the potential thrust gain due to mixing. Because the cold test stream Mach numbers approximate those of the desired operating conditions, the pressure losses tend to approximate those that occur during running with streams at different temperatures. A comparison of thrust and discharge coefficient measured from cold flow tests of a mixer configuration with those for the reference exhaust system will allow the mixer pressure loss to be determined.

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The cold test results are used in conjunction with hot flow results to establish percent mixing achieved by the mixer. To determine the degree of mixing achieved by a specific configuration an incremental change in thrust coefficient due to the pressure difference between the two cold streams is determined analytically (a small effect). This increment is combined with the ideal mixing thrust gain calculated for the temperature and pressure split of the hot flow test. The total increment is then applied to the adjusted cold flow baseline to establish a theoretical thrust coefficient level for 100% assumed mixing with hot flow. The differences between the thrust coefficients measured by hot flow tests and adjusted cold flow baseline thrust coefficients, divided by the ideal thrust coefficient change due to mixing, is then defined as the percent mixing. This concept is illustrated in Figure 4-2.

Figure 4-2   Definition of Percent Mixing for Dual Stream Exhaust System

4.3 NOZZLE PERFORMANCE TEST CONDITIONS

The reference exhaust system, the mixer and the mixer/inverter exhaust systems were tested for thrust performance so that increments between the mixer and reference exhaust system could be established. Test conditions were selected to simulate JT8D-15 engine operation at takeoff and cruise. In addition, a range of test points was selected for the reference and a mixer exhaust system that permitted thrust performance estimates to be made for a range of performance points that apply to the JT8D-15, -17, and -17R engines.

The hot and cold flow nozzle operating conditions tested are listed in Table 4-1. Each test point is defined with a fan to primary total pressure ratio and total temperature ratio and a primary to ambient total pressure ratio. The hot flow test points simulate JT8D engine flow

properties in the fan and primary streams at the engine measuring station. These properties are measured at comparable locations in the model hardware. Cold flow tests are included in the test schedule in order to determine the pressure loss of the mixer and mixer/inverter relative to the reference configuration.

Flow measurement and thrust measurement accuracy and repeatability were verified using a standard ASME nozzle. Test points were selected to have flow properties similar to those included in the test matrix.

TABLE 4-1

NOZZLE OPERATING CONDITIONS FOR MODEL PERFORMANCE TESTS

	① P_{Tp}/P_{Amb}	P_{Tf}/P_{Tp}	T_{Tf}/T_{Tp}	No. of Points/ Config.	Total Points
Ref. exhaust system & scalloped mixer exhaust system	1.6, 2.2	1.0000	1.000	2	
			0.470	2	
			0.440		14
	2.7 (2)	1.0	0.44	1 hot	
		1.0	0.47	1 hot	
	1.6, 2.2 2.7, 3.2	0.930	1.000	4 cold	
		0.930	0.470	4 hot	32
		0.930	0.440		
		0.930	0.415		
	1.8 (3)	93	44	1 hot	
	2.7, 3.2	0.880	1.000	2 cold	13
		0.880	0.440	2 hot	
		0.880	0.415		
Cutback scalloped mixer exhaust system	1.6, 1.8, 2.2, 2.7, 3.2	0.930	1.000	5 cold	10
		0.930	0.440	5 hot	
					69

Notes 1 Each pressure and temperature ratio is tested with each P_{Tp}/P_{amb} ratio.
2 Scalloped mixer exhaust system only
3 Ref. exhaust system only

5.0 RESULTS AND DISCUSSION

The experimental data obtained during the test program are of three basic types: acoustic, traverse, and performance. The acoustic data are characterized by various parameters. The parameters discussed in this section are:

- One-third octave band spectra at 150 ft. radius

- Perceived Noise Level (PNL) at 1200 ft. linear distance

- Peak Perceived Noise Level at 1200 ft. linear distance

The acoustic results presented in this section are based on model data scaled to predict full-size JT8D engine jet noise. All data are free field and, therefore, do not include ground reflection or ground attenuation effects that would be present in full-scale engine noise measurements made in the presence of a ground plane. Perceived Noise Levels (PNL) were calculated for the scaled data extrapolated to linear distances of 400, 1200, 2000, 4000, and 6000 feet. The PNLs of an internal mixer decrease more rapidly with distance than those of the reference exhaust system due to spectral differences and the effect of atmospheric absorption on noise. Thus, the PNL reductions due to a mixer increase with distance. The PNLs and the ΔPNLs presented in this report are those calculated for the 1200 ft. distance as this is a typical minimum airplane-to-microphone distance that would be present during JT8D powered airplane certification tests. To determine the jet noise PNL reductions at other distances, the PNL/distance tabulations contained in Appendix B should be used.

Traverse data were used to calculate velocity profiles that are presented in three ways: (1) 150 degrees of arc contour maps with lines of constant velocity; (2) lobe and valley radial velocity profiles; and (3) velocity distribution as a function of cumulative mass flow. Performance is presented in terms of nozzle thrust coefficients (C_f), thrust specific fuel consumption (TSFC), nozzle total pressure loss ($\Delta P_t/P_t$), and percent mixing. These parameters are defined in Section 4.0

Exhaust system test results are presented in the following order. Section 5.1 contains the acoustic, profile and performance results of the JT8D reference exhaust system. This is followed by results of the long mixer tests in Section 5.2, including the effects of various mixer lobe modifications. Pertinent results obtained from the Pratt & Whitney Aircraft in-house program on mixers for the JT8D engine are presented in subsequent sections. These sections include the test results from a short mixer design as well as results on the important effect of providing real engine secondary flow effects in the model testing. Also included are results illustrating the effects of tailpipe cant and length on the reference and mixer exhaust systems.

In the following sections, the data will be presented as follows: The velocity profile data will be shown first, followed by the acoustic results, and then the performance characteristics.

5.1 REFERENCE JT8D EXHAUST SYSTEM

The current JT8D engine incorporates an aerodynamic splitter (free mixer) having an area ratio selected to provide proper compressor and turbine matching. Although this configuration was not designed specifically to mix the exhaust flow, the bluff base of the splitter, in combination with the relatively steep angle of the outer exhaust case, provides a moderate amount of mixing at a low level of pressure loss.

A contour plot showing nozzle discharge velocity at simulated takeoff conditions is presented in Figure 5-1. Local velocities, determined from measured total pressure and temperature by assuming isentropic expansion to test cell static pressure, are presented normalized by the calculated ideally mixed velocity. The steepness of the velocity profile is evidenced by the close spacing of velocity contour lines. To assist in interpreting these contour plots, two additional curves are provided. The radial velocity distribution provided by averaging traverse data measured downstream of two lobes is presented as a function of nozzle radius in Figure 5-2(a). The lack of distinct definition of the interface of the two streams indicates that some mixing is occurring. Velocities at the nozzle exit vary substantially, ranging from 25% below to 19% above the ideally mixed value.

Figure 5-1   Tailpipe Exit Velocity Contour Map of Reference Exhaust System (without Engine Secondary Flow Simulation)

The second curve (Figure 5-2(b)) presents the tailpipe velocity distribution on a cumulative mass flow basis. This curve was obtained by calculating local velocities and mass flows for each of the individual points in the nozzle traverse, ordering the velocities from lowest to highest and plotting these velocities against the cumulative total of calculated mass flows. For example, Figure 5-2(b) indicates that 63% of the flow of the reference exhaust system had velocities less than 10% below the average value. Conversely, the curve shows what percent of flow has velocities higher than a specified value. For example, 23% of the flow had velocities greater than 10% above the average value. Contour plots of constant pressure and temperature lines show trends similar to those of velocity. These plots are presented in Appendix C.

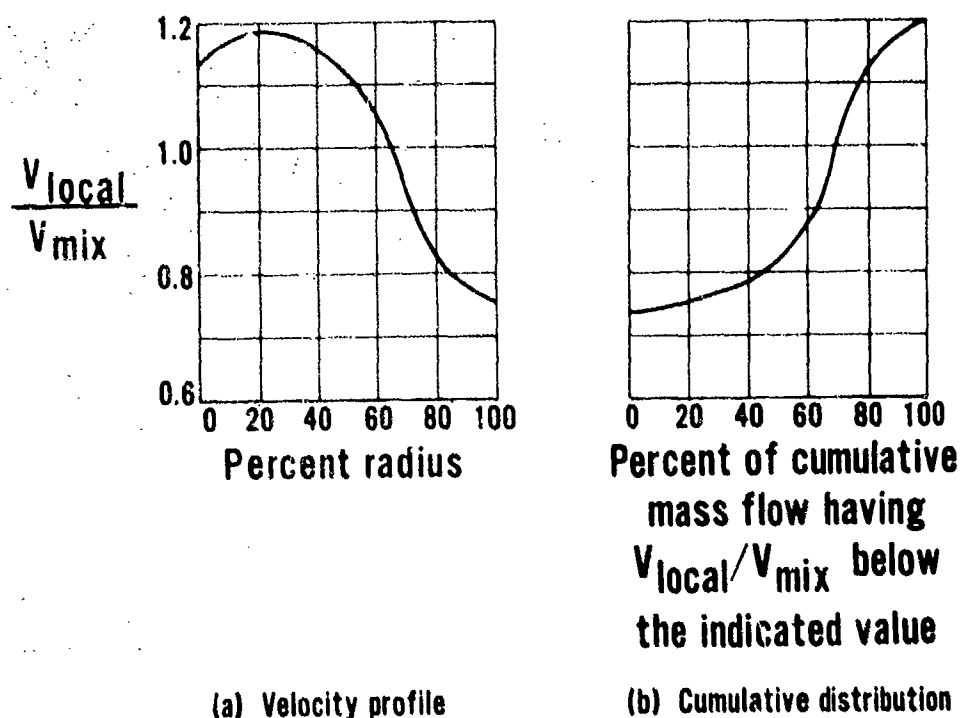(a) Velocity profile   (b) Cumulative distribution

Figure 5-2   Tailpipe Exit Velocity Profile and Cumulative Mass Flow Distribution of
Reference Exhaust System

The 1200 foot linear free field peak PNL, as a function of calculated equivalent full-scale engine thrust, is shown in Figure 5-3. Perceived Noise Level directivities at takeoff and cutback thrust levels are shown in Figure 5-4. Note that the angle of peak PNL is 140 degrees for both thrust conditions. The third octave band SPL spectra at the two thrust levels are shown at angles measured from the engine upstream jet centerline of $(\theta_j) = 90$ and 140 degrees in Figures 5-5(a) and 5-5(b). Typical of jet noise spectra, the 90 degree spectra is broader and has its peak SPL level at higher frequency than data at 140 degrees. The PNL and spectral data will be used in Section 5.2 to compare with the mixer nozzle results.

Thrust coefficient data for the desired JT8D stream temperature ratio (hot test) and for a temperature ratio of unity (cold test) are presented as a function of engine stream pressure ratio in Figure 5-6. The hot test data are used in later sections as the basis for performance comparisons between various mixer configurations and the current JT8D exhaust system. The calculated percent mixing for the reference configuration also is presented in Figure 5-6. As stated previously, this configuration provided a moderate amount of mixing (approximately 30%).

The data presented in this section were obtained for the JT8D reference exhaust system and were used as reference data against which some of the mixer data were compared. However, it should be noted that these data were generated by a so-called "clean" configuration that accurately modeled the flowpath and operating conditions of a JT8D engine exhaust system, but did not simulate the secondary flow effects introduced by the combined effects of turbine exit case swirl and struts and fan duct pressure distortion. In a later section, 5.3, the results obtained by testing the reference exhaust system and certain mixers with the real engine secondary flow simulation will be presented.

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Figure 5-3   Peak Perceived Noise Level of Reference Exhaust System (without Engine Secondary Flow Simulation)
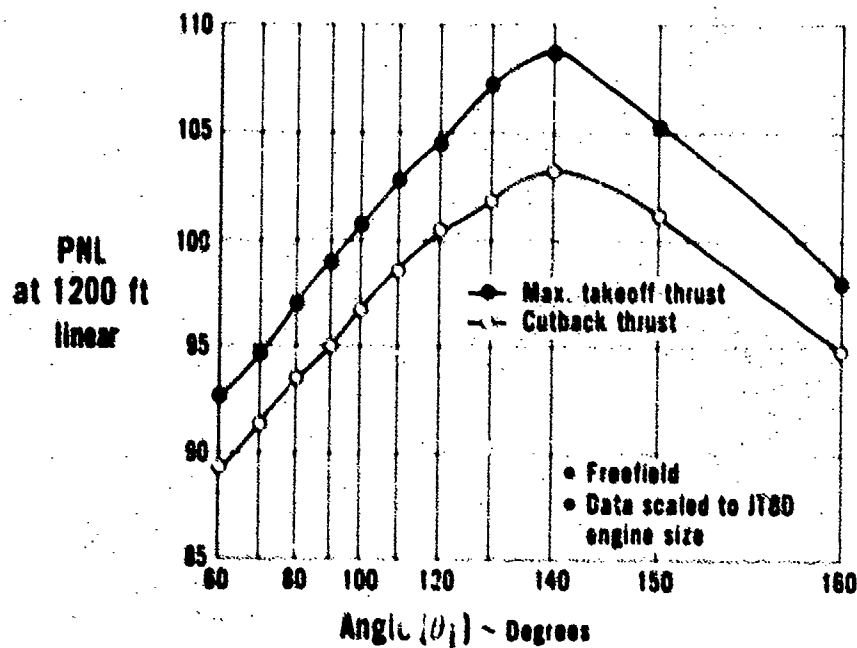

Figure 5-4   Perceived Noise Level Directivity of Reference Exhaust System (without Engine Secondary Flow Simulation)
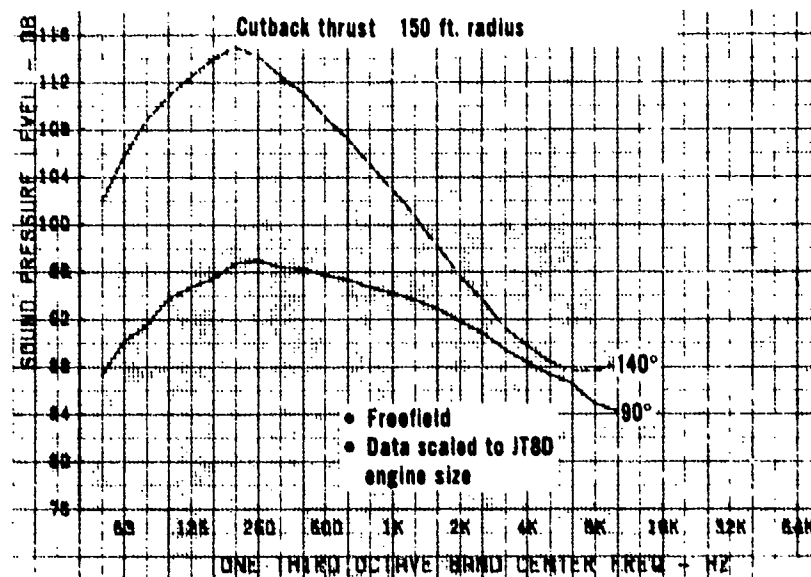
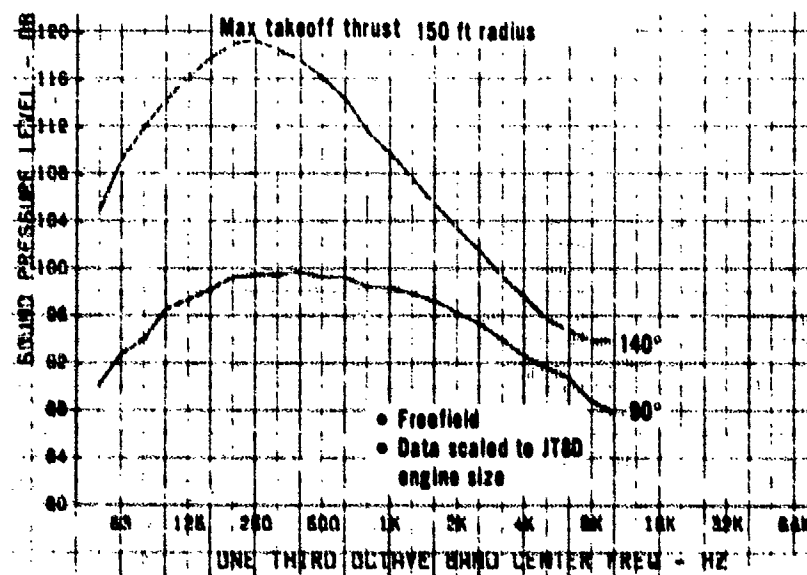Figure 5-5(a)   SPL Spectra Reference Nozzle (without Engine Secondary Flow Simulation)

Figure 5-5(b)   SPL Spectra of Reference Exhaust System (without Engine Secondary Flow Simulation)
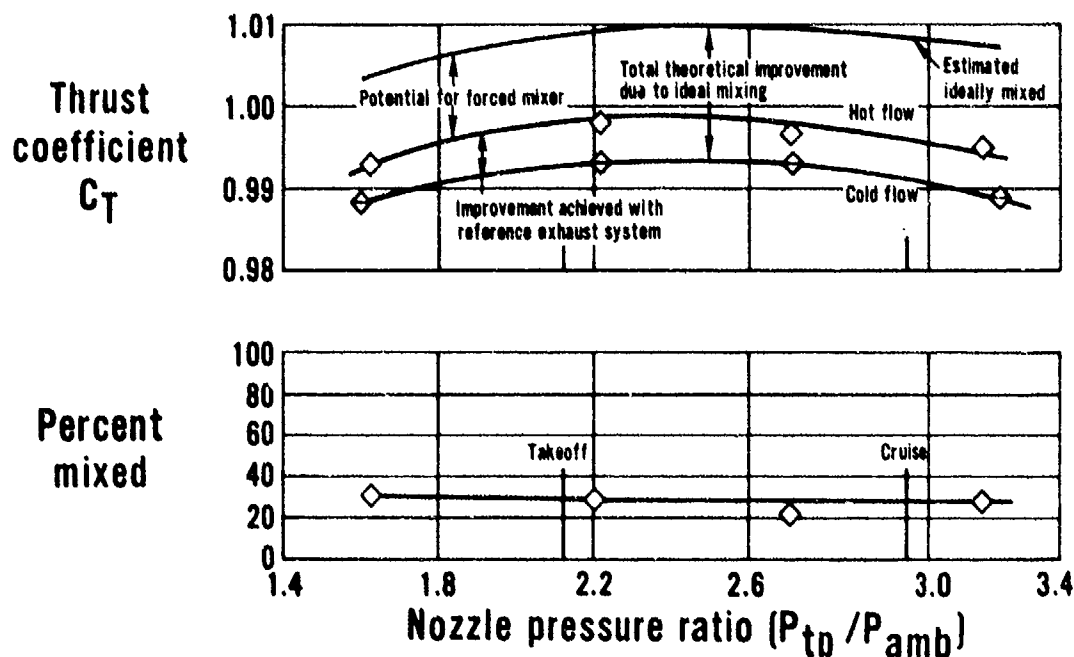
Figure 5-6   *Performance of Reference Exhaust System (without Engine Secondary Flow Simulation)*

5.2 LONG FLOWPATH MIXER

5.2.1 Basic Design

Design considerations for the long mixer were described earlier in Section 2.1. Since the basic intent of this design was to achieve a high degree of mixing with low pressure loss, mixer lines were gradual, resulting in a long mixer requiring a 16 inch extension to the exhaust case. The exhaust case upstream of the tailpipe attachment was also revised to a more gradual slope. A schematic of this mixer design is presented in Figure 5-7.

The contour plot of velocity (Figure 5-8) indicates a substantial flattening of the velocity profile due to the mixer compared to the reference exhaust system. However, pockets of residual high velocity can be seen indicating that the design objective to provide a flat profile was not achieved. Velocities ranged from 20% below to 11% above the theoretical ideally mixed velocity.

Velocity distributions for the basic long mixer and the reference exhaust system are compared in Figure 5-9. Both plots indicate that the mixer flattened the profile, with local peak velocities at the outer wall equalling those at the center of the stream. Local peaks cover only a small portion of the stream with only a few percent of the flow being more than 10% above the ideally mixed value. The minimum and maximum velocity values of the cumulative mass flow velocity curve do not agree exactly with those of the radial velocity profile plot since the former plot includes data from the entire 150 degree data of tailpipe are measured during the traverses, while the latter plot was generated from only the first two lobes and valleys.

40

"M" flange
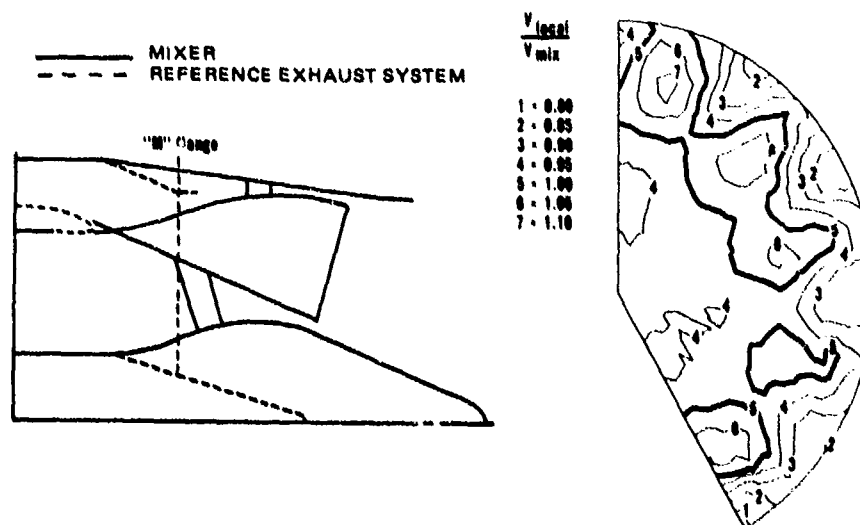

Figure 5-7   Schematic of Basic Long Flowpath Mixer Design

Figure 5-8   Tailpipe Exit Velocity Contour Map of Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)

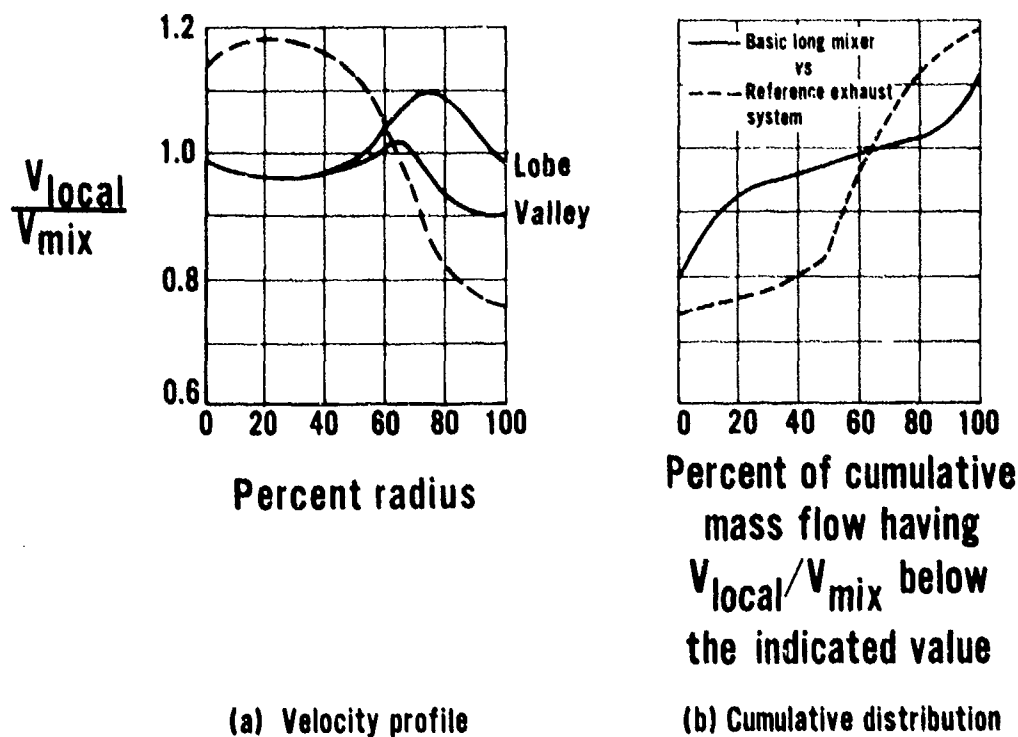**(a) Velocity profile** **(b) Cumulative distribution**

Figure 5-9   Tailpipe Exit Velocity Profile and Cumulative Mass Flow Distribution; Comparison of Reference Exhaust System and Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)

The acoustic results of the long mixer indicated a sizable noise reduction relative to the reference system. The peak PNL versus thrust plot of Figure 5-10 shows approximately a 5 PNdB reduction at maximum takeoff and cutback thrust levels. (It will be shown in Section 5.3 that the noise reduction for a JT8D engine is expected to be less than 5 PNdB, based on model results with JT8D secondary flow characteristics simulated). Comparisons of PNL directivity at maximum takeoff and cutback thrust conditions for the basic mixer and reference system are shown in Figure 5-11. At maximum takeoff, the noise reductions are significant from 120 to 140 degrees, while at cutback thrust the noise reductions are large for all angles aft of 120 degrees. The directivity shapes for the basic mixer will be seen in later sections to be generally characteristic of all the mixer configurations.

Comparisons of SPL spectra for both the basic mixer and reference nozzle at 90 and 140 degrees are shown in Figure 5-12(a and b). At 90 and 140 degrees, the basic mixer substantially reduced the noise at low frequencies at both thrust conditions. This result is consistent with the profile data that showed substantial mixing of the streams. At higher frequencies (1000-4000 Hz), however, the mixer generated slightly more noise than was present in the reference exhaust system spectra. This extra noise was believed to be due to the presence of high velocity "pockets" of primary exhaust flow behind the lobes which did not completely mix with the fan flow. It will be shown in a later section that, in these JT8D model tests, this extra noise decreases as the high velocity "pockets" in the velocity profile are "smoothed out" by modifications to the mixer.
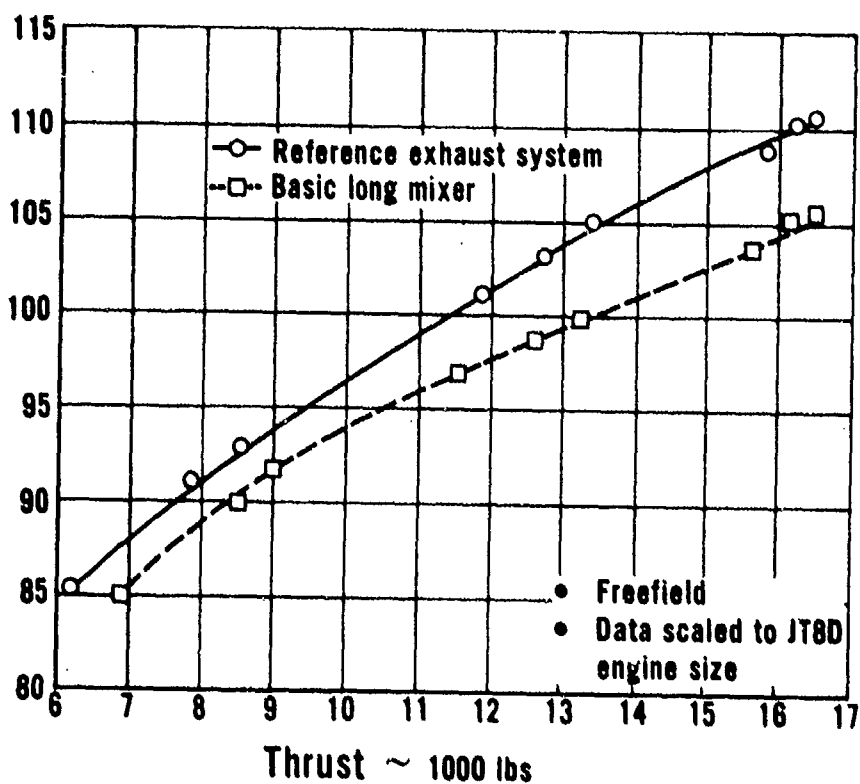
42

Figure 5-10   Peak Perceived Noise Level Comparison of Reference Exhaust System and
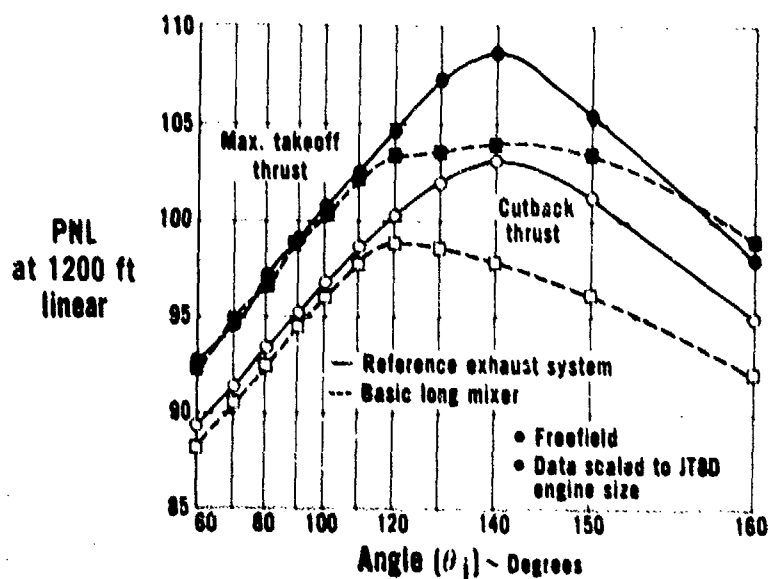Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)

Figure 5-11   Perceived Noise Level Directivity Comparison of Reference Exhaust System
and Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)
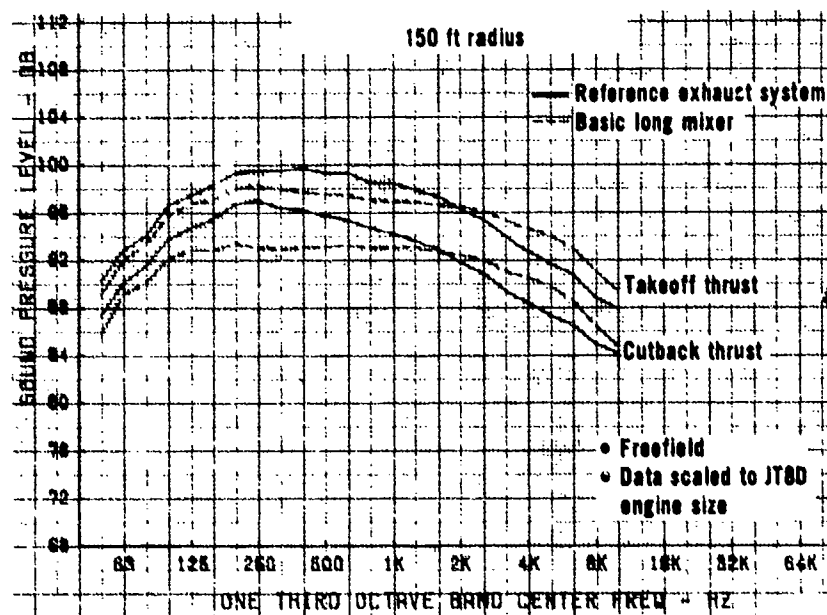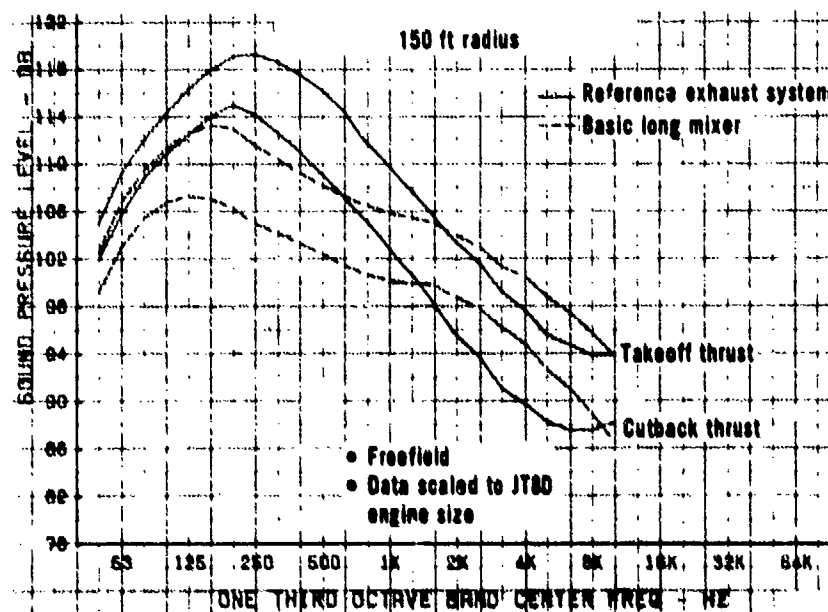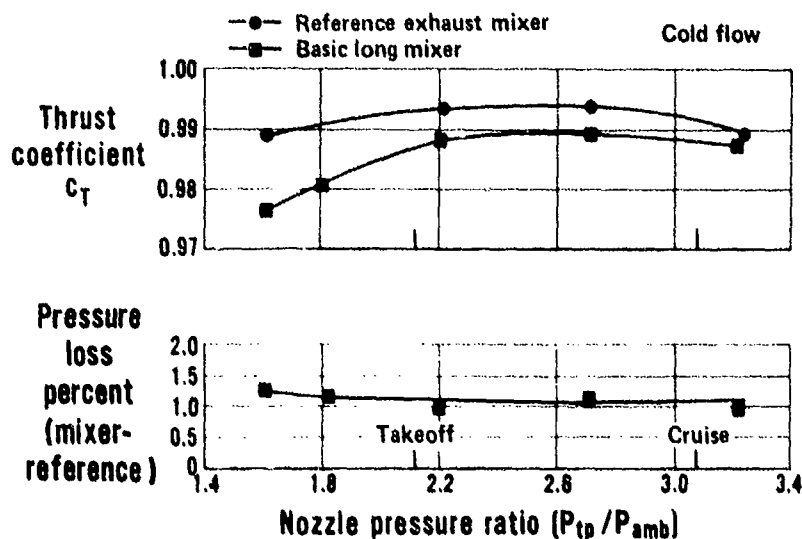
43

Figure 5-12(a)   SPL Spectra Comparison at 90 Degrees of Reference Exhaust System and
Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)

Figure 5-12(b)   SPL Spectra at 140 Degrees (without Engine Secondary Flow Simulation)

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Thrust coefficient data for cold testing of this configuration are compared with the reference exhaust system data in Figure 5-13. The additional pressure loss for the mixer, relative to the reference, was calculated to be 1.1% based on the thrust coefficient differences. Combination of the hot and cold flow data (Figure 5-14) resulted in calculated percent mixing ranging from 65% at takeoff to 80% at cruise. This result compares favorably with the 75% predicted for unscalloped mixer configurations. The net effect of increased mixing and pressure loss is shown in Figure 5-15 which compares the hot thrust coefficients of the basic long mixer and the reference exhaust system. Thrust coefficients at takeoff indicate a 0.25% loss in takeoff thrust with the mixer. Cruise performance indicates an increase of 0.65% in C_T, which equates to a 1.2% improvement in thrust specific fuel consumption (TSFC).

Thus, compared with the reference exhaust system, the basic long mixer provided significant noise reductions along with a cruise TSFC improvement and a small loss in takeoff thrust.

Figure 5-13   Pressure Loss Comparison of Reference Exhaust System and Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)
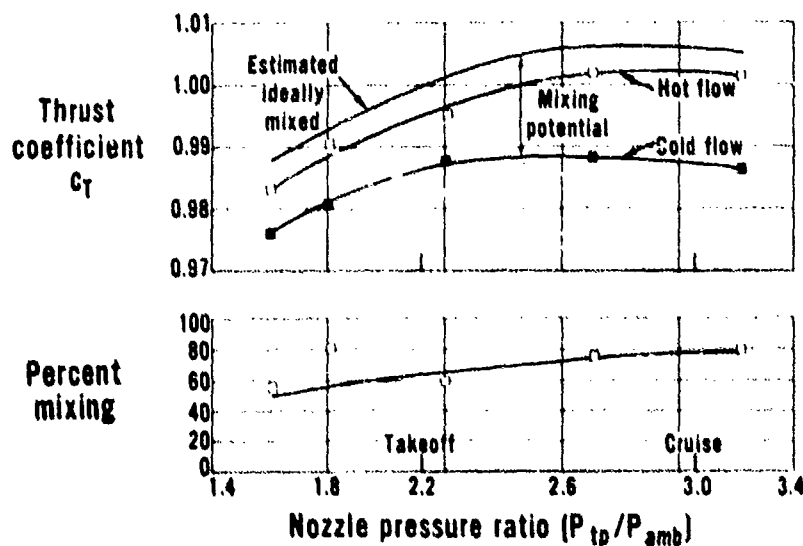

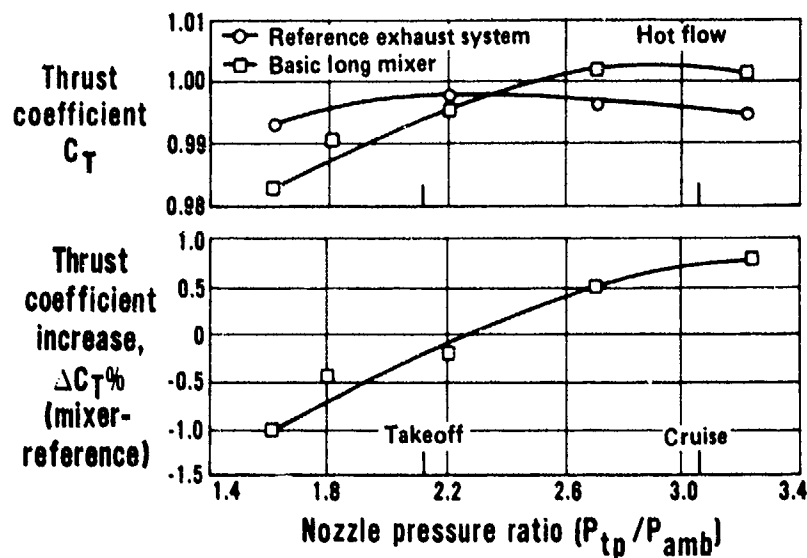Figure 5-14   Performance of Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)

45

Figure 5-15   *Performance Comparison of Reference Exhaust System and Basic Long Flowpath Mixer (without Engine Secondary Flow Simulation)*

5.2.2 Effect of Scalloping Mixer Lobes

Results of previous mixer exhaust system tests conducted by Pratt & Whitney Aircraft have indicated that improved mixing may be achieved by removing a portion of the lobe sidewalls, resulting in "scalloped" lobes. Therefore, based on the profiles of the basic mixer shown in the previous section, the mixer was modified by cutting scallops out of the lobe sidewalls, as shown in Figure 5-16.

Analysis of traverse data (Figures 5-17 and 5-18) for the scalloped and unscalloped schemes indicated that the peak values of velocity were slightly decreased and the location of the peak velocities moved inboard, compared with results from the unscalloped mixer. The peak-to-minimum velocity variation, however, actually increased over that for the unscalloped configuration indicating less overall mixing.

The effect of scalloping on peak PNL noise reduction varied with engine thrust, as shown in Figure 5-19. There was a 1 PNdB reduction in level at cutback thrust and no change at takeoff thrust relative to the unscalloped mixer. PNL directivity for the two thrust levels are shown in Figure 5-20. The scalloping produced little change in the takeoff thrust PNL directivity, but at cutback thrust, the scalloping reduced the noise at side and forward angles by 1 to 1½ PNdB. Spectral comparisons are shown in Figure 5-21(a and b). The scalloping reduced extra noise generated in the 1000 to 4000 Hz frequency range, which is consistent with the profile results. Scalloped mixer performance is compared with that of the unscalloped configuration in Figure 5-22   Performance data from the scalloped configuration indicated a decrease in mixing from 10% to 15% relative to the unscalloped mixer with a resultant decrease of 0.2% in takeoff thrust and an increase of 0.4% in cruise fuel consumption. Pressure loss remained at the same level as for the unscalloped mixer.
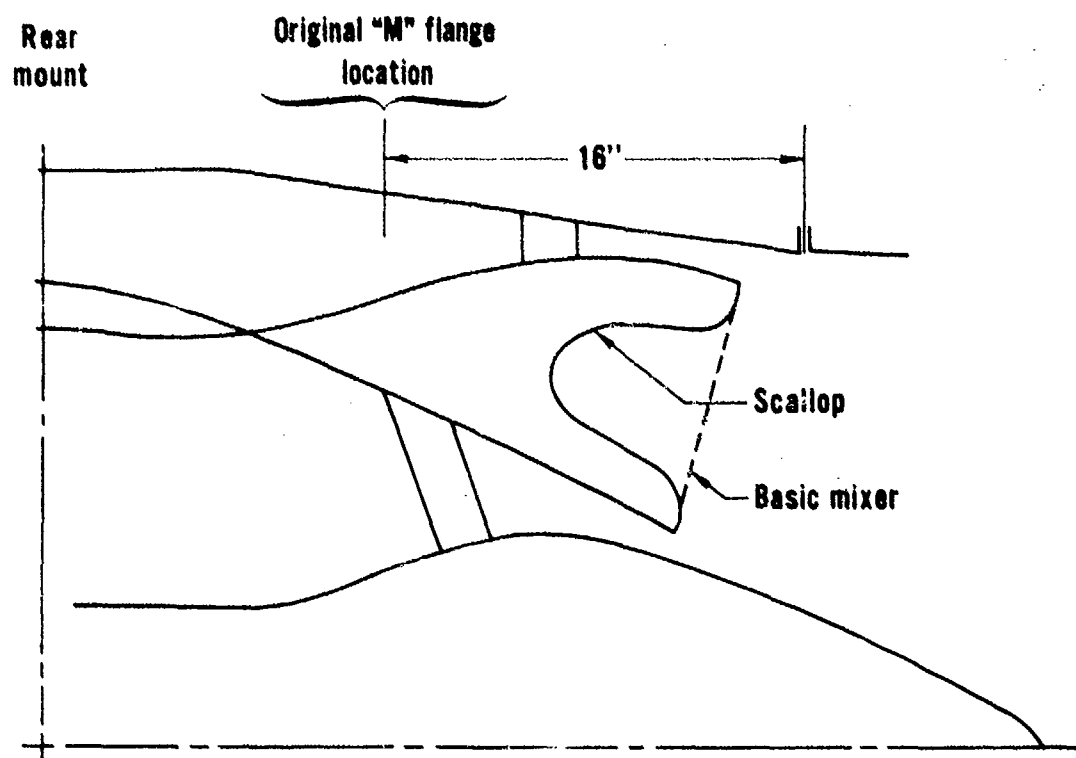
46

Figure 5-16   Schematic of Scalloped Long Flowpath Mixer

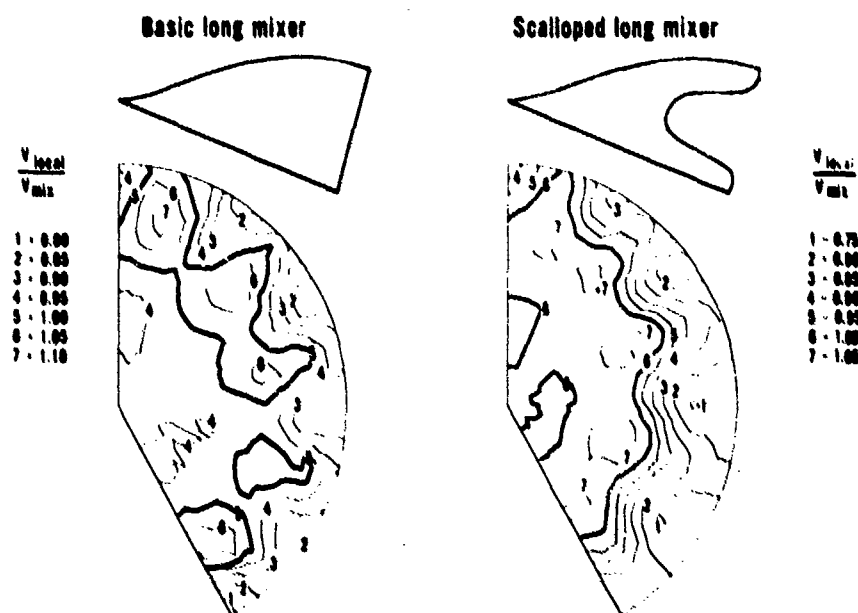Figure 5-17   Effect of Scalloping on the Tailpipe Exit Velocity Contour Map of Long Flowpath Mixer (without Engine Secondary Flow Simulation)

―――― Scalloped long mixer

――――― Basic long mixer
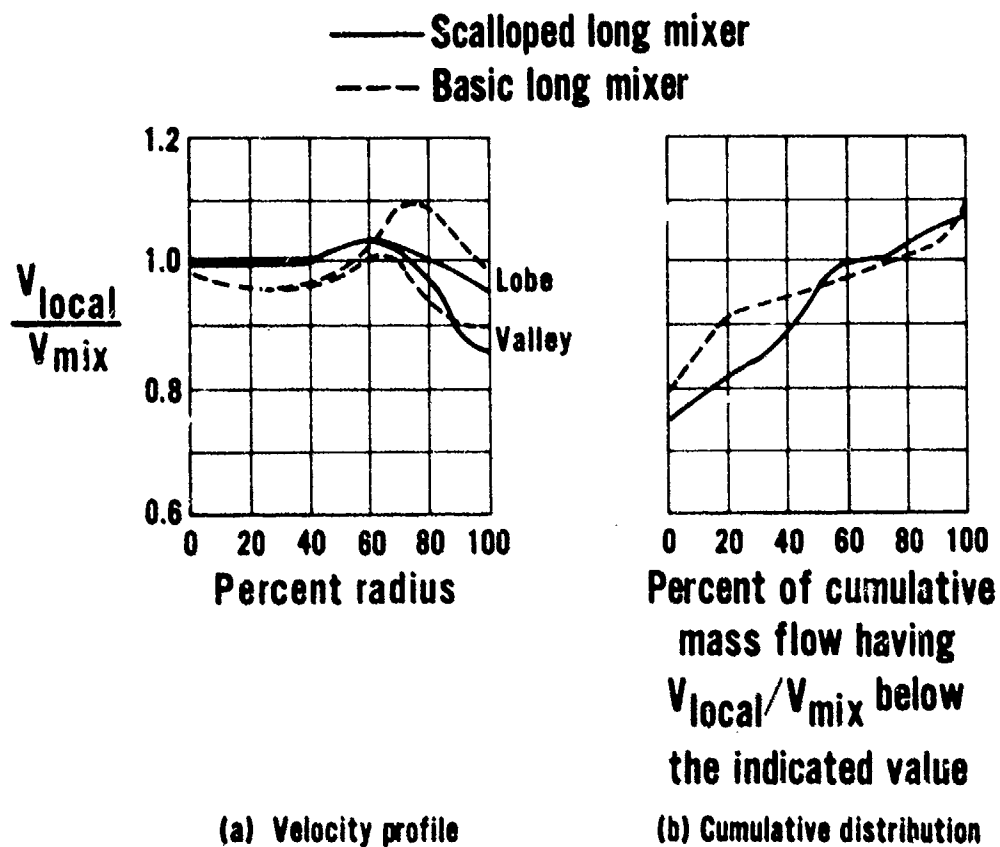

(a) Velocity profile

(b) Cumulative distribution

Figure 5-18   Effect of Scalloping on Tailpipe Exit Velocity Profile and Cumulative
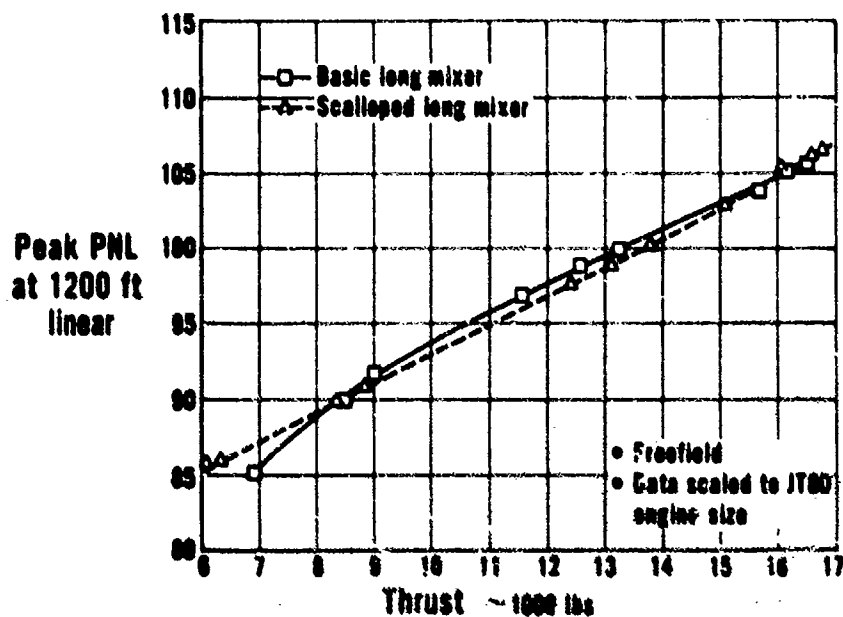Mass Flow Distribution of Long Flowpath Mixer (without Engine Secondary
Flow Simulation)

Figure 5-19   Effect of Scallops on Peak Perceived Noise Level of Long Flowpath Mixer
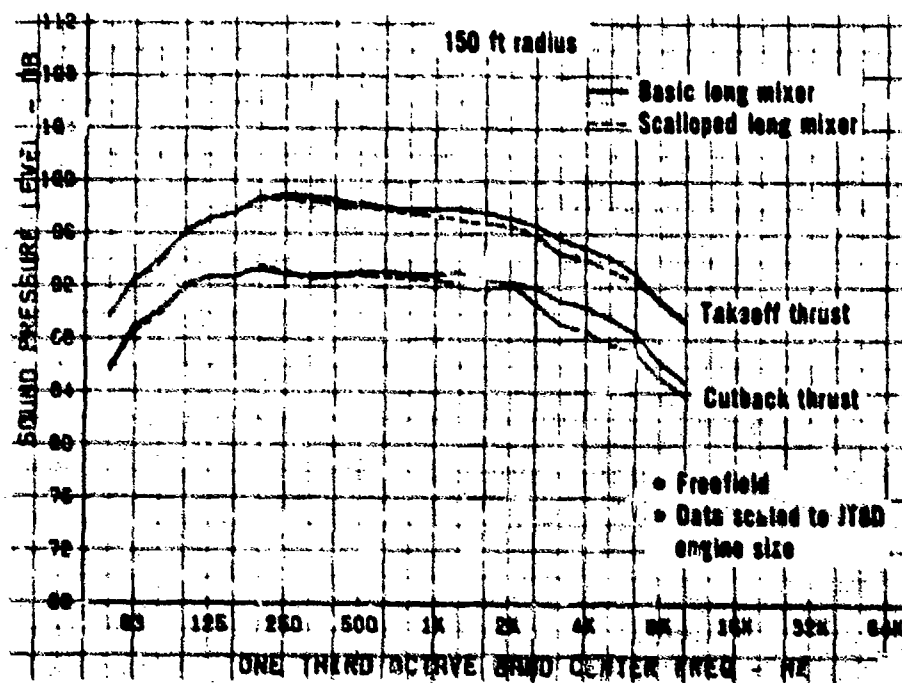(without Engine Secondary Flow Simulation)

48

Figure 5-20 Effect of Scallops on Perceived Noise Level Directivity of Long Flowpath Mixer (without Engine Secondary Flow Simulation)

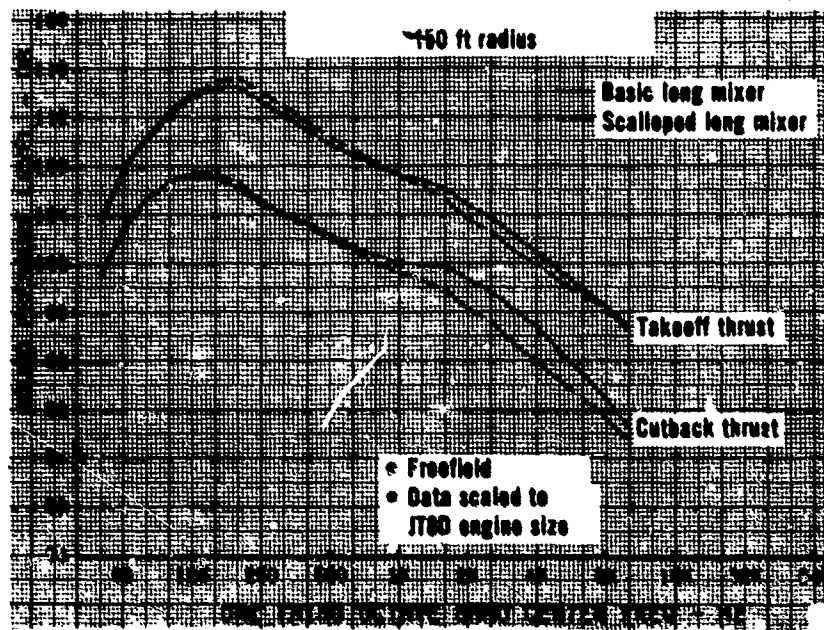Figure 5-21(a) SPL Spectra at 90 Degrees (without Engine Secondary Flow Simulation)

Figure 5-21(b) Effect of Scallops on SPL Spectra at 140 Degrees of Long Flowpath Mixer
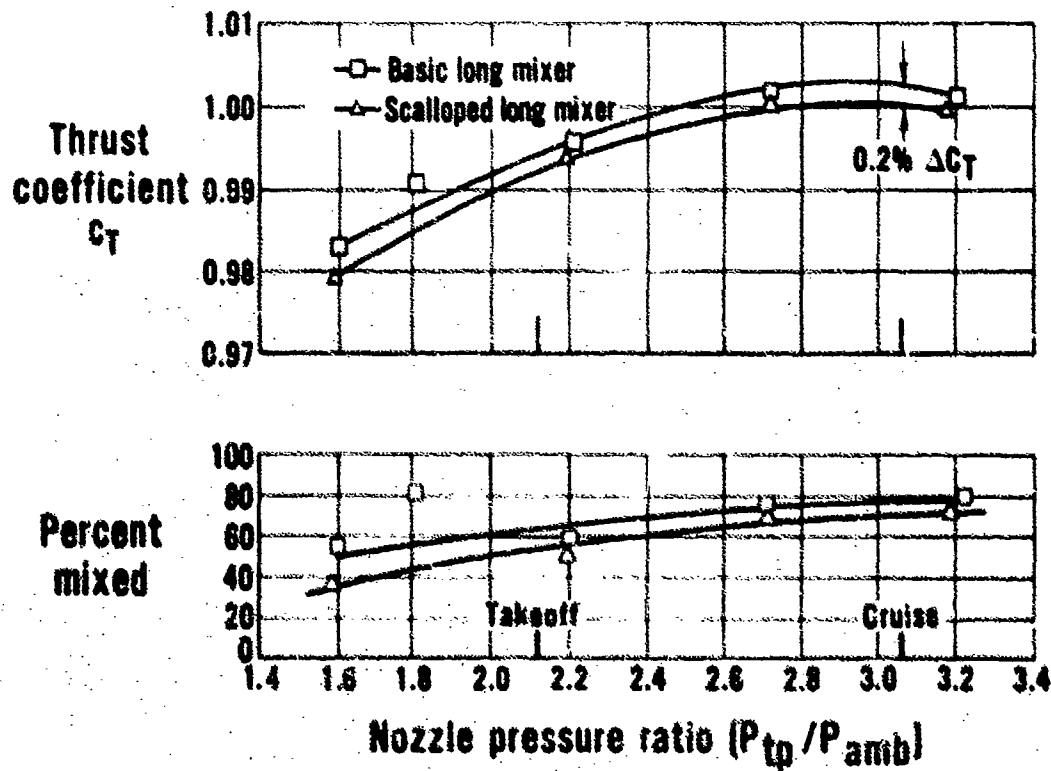(without Engine Secondary Flow Simulation)

Figure 5-22 Effect of Scallops on Performance of Long Flowpath Mixer (without
Engine Secondary Flow Simulation)

50

5.2.3 Effect of Cutting Back the Lobe Scarf Angle

The results shown in the previous section indicated that scalloping did not produce as flat a profile as was desired. Therefore, the lobe scarf angle was decreased in an attempt to reduce the radially inward turning of the engine flow exiting the mixer near the top of the lobe. The lobe scarf angle was modified to be slightly negative, as shown in Figure 5-23. Since model hardware used for the scallop testing was also used in this test, a shallow scallop remained in the cutback mixer lobes. This configuration is called the cutback, scalloped mixer.
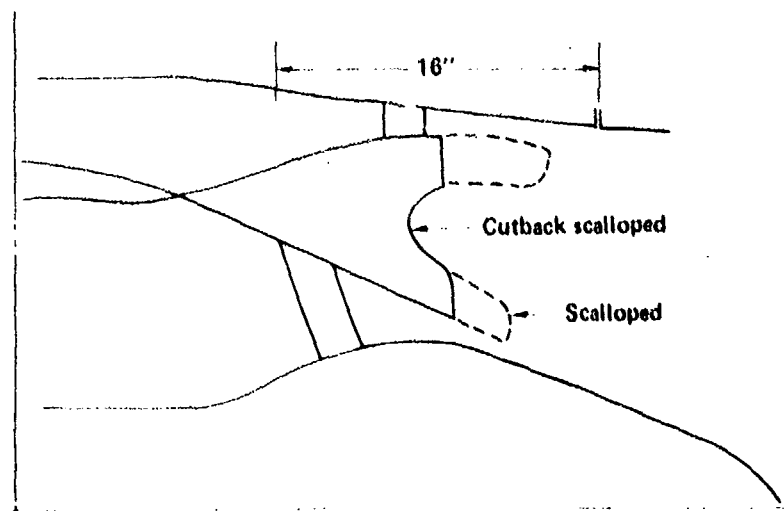

Figure 5-23   Schematic of Cutback Scalloped Long Flowpath Mixer

Contour plots (Figure 5-24) of velocity indicated that reducing the discharge angle provided a substantial improvement in redistributing energy between the two streams. This flattening of the velocity profile was accompanied by a slight inversion of the flow (Figure 5-25(a)) with the highest velocities appearing at the outer wall of the nozzle. Peak velocity was reduced to 7.5% above the calculated ideally mixed value, approximately the same level as that for the scalloped mixer without the cutback lobes. Overall variation in peak to minimum velocity was, however, reduced substantially with the cutback scalloped configuration (Figure 5-25(b)).

The effect of reduced lobe scarf angle on peak PNL was significant, as shown in Figure 5-26. The cutback mixer was up to 1 PNdB quieter at high thrusts (> 15,000 lbs) and up to 1 PNdB louder at lower thrusts. The PNL directivity shown in Figure 5-27 shows large differences. The large cutback angle tends to increase PNL at forward angles, and decrease PNL at aft angles. The shape of the directivity curves cause the crossover in peak PNL shown in the previous figure. At high thrust, the peak PNL is located at 140-150 degrees. The large reduction in noise at the aft angles thus decreased the PNL relative to the noncutback mixer. At the lower thrust value, however, the peak PNL is at a more forward angle. The increase of noise in the forward angles due to cutting back the mixer lobe caused the peak PNL to increase. The SPL spectra plots in Figure 5-28(a and b) show that at high thrust the reduction of noise in the lower frequencies is responsible for the peak PNL decrease, while at cutback thrust the increase in noise at higher frequencies is responsible for the increase in peak PNL. The data indicate that the moderately inverted profile of the cutback mixer is responsible for the decrease in low frequency noise and the increase in high frequency noise relative to the deep scalloped mixer. These spectral changes, in turn, cause the differences in peak PNL behavior of the two mixer configurations.
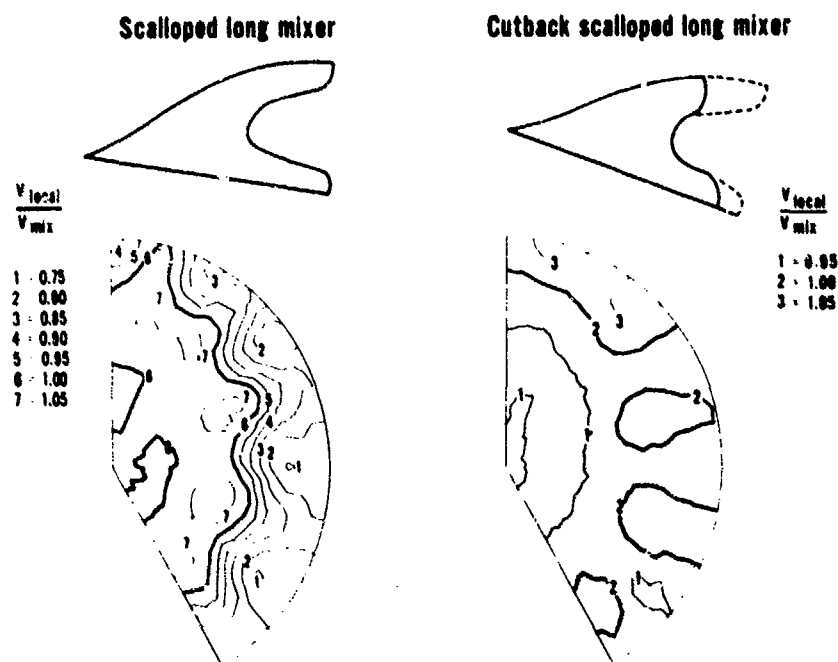
Scalloped long mixer

Cutback scalloped long mixer

$\dfrac{V_{local}}{V_{mix}}$

1 · 0.75
2 · 0.80
3 · 0.85
4 · 0.90
5 · 0.95
6 · 1.00
7 · 1.05

$\dfrac{V_{local}}{V_{mix}}$

1 · 0.95
2 · 1.00
3 · 1.05

Figure 5-24   Effect of Lobe Cutback on Tailpipe Exit Velocity Contour Map of Long
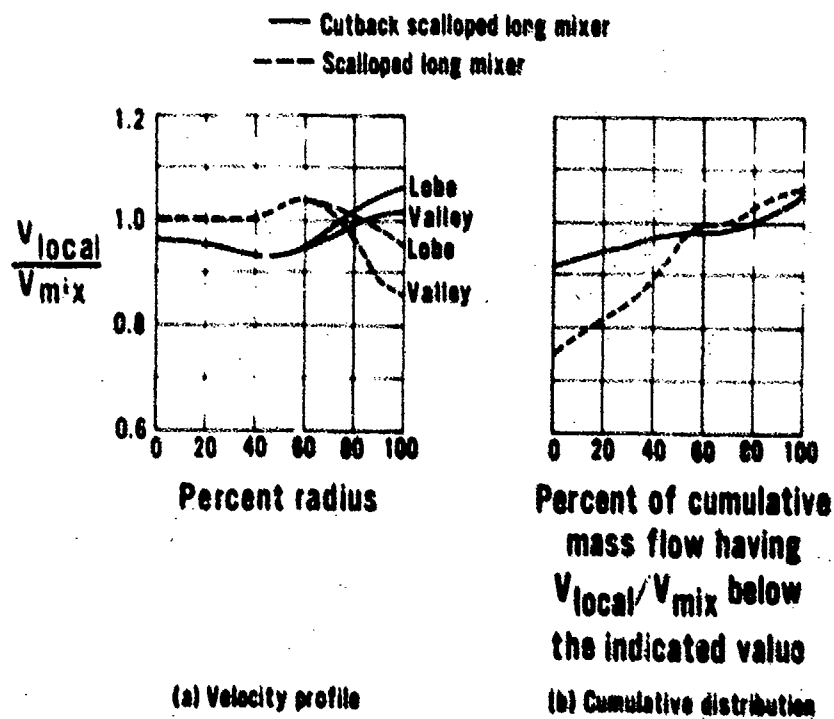Flowpath Mixer Scalloped (without Engine Secondary Flow Simulation)

—— Cutback scalloped long mixer
--- Scalloped long mixer

$\dfrac{V_{local}}{V_{mix}}$

Lobe
Valley
Lobe
Valley

Percent radius

Percent of cumulative
mass flow having
V_{local}/V_{mix} below
the indicated value

(a) Velocity profile

(b) Cumulative distribution

Figure 5-25   Effect of Lobe Cutback on Tailpipe Exit Velocity Profile and Cumulative
Mass Flow Distribution of Scalloped Long Flowpath Mixer (without
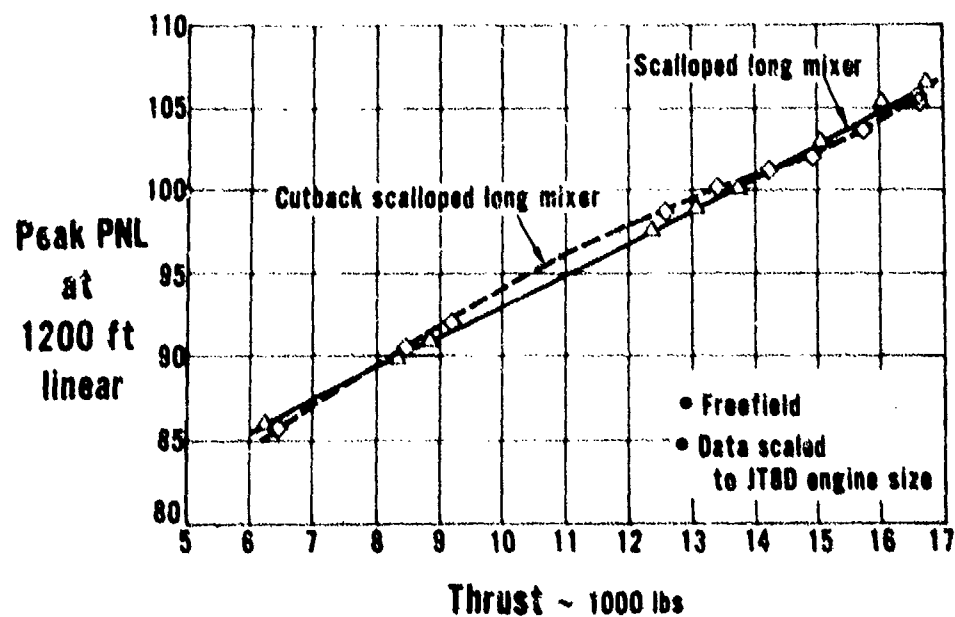Engine Secondary Flow Simulation)

52

Figure 5-26   Effect of Lobe Cutback on Peak Perceived Noise Level of Scalloped Long Flowpath Mixer (without Engine Flow Simulation)
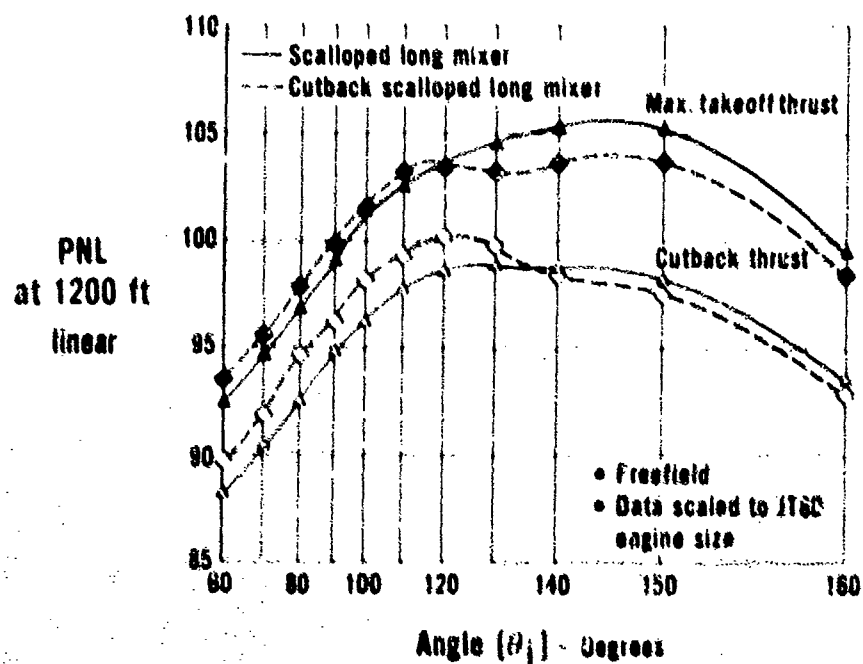

Figure 5-27   Effect of Lobe Cutback on Perceived Noise Level Directivity of Scalloped Long Flowpath Mixer (without Engine Secondary Flow Simulation)
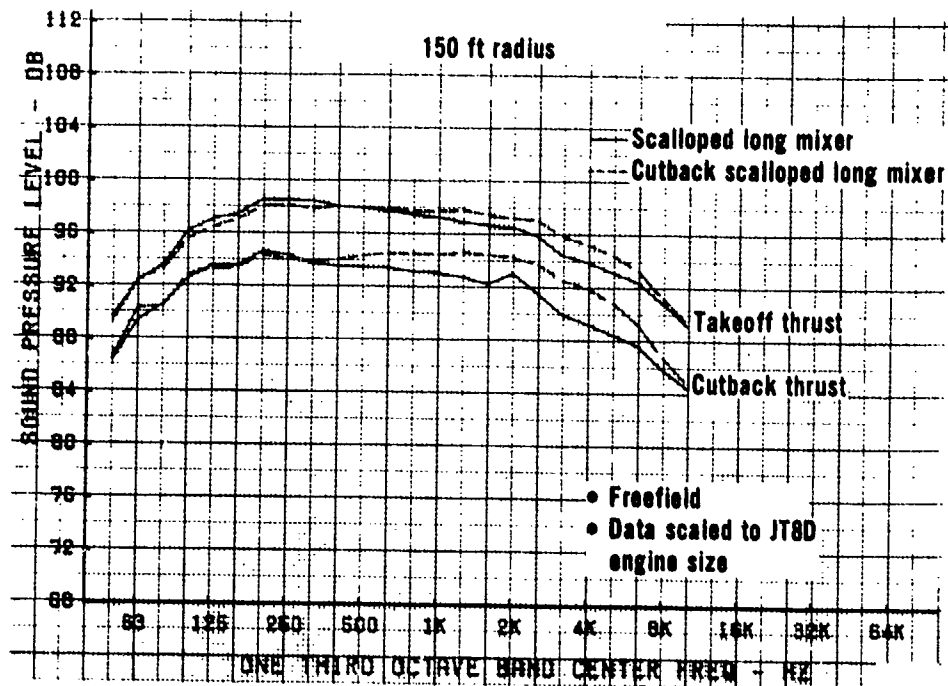
Figure 5-28(a)   Effect of Lobe Cutback on SPL Spectra at 90 Degrees of Scalloped Long Flowpath Mixer (without Engine Secondary Flow Simulation)
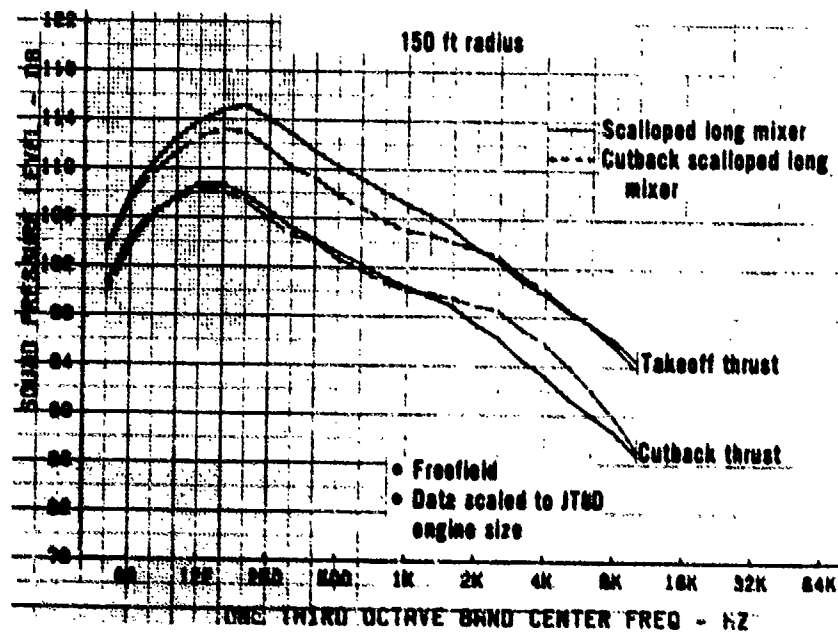

Figure 5-28(b)   SPL Spectra at 140 Degrees (without Engine Secondary Flow Simulation)

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Performance data for the cutback scalloped configuration indicated an increase in thrust coefficient due to improved mixing over the scalloped configuration. Thrust coefficient levels were essentially the same as the unscalloped, basic long mixer configuration discussed in Section 5.2.1.

Figure 5-29 compares the performance of the three basic mixer geometries. The basic mixer and cutback scalloped mixer achieved a cruise fuel consumption improvement of 1.2% with a 0.25 percent penalty in takeoff thrust, while the scalloped mixer with reduced mixing improved cruise performance by only 0.8% while suffering a 0.45% loss in takeoff thrust. Pressure loss for the three configurations was at the same level.
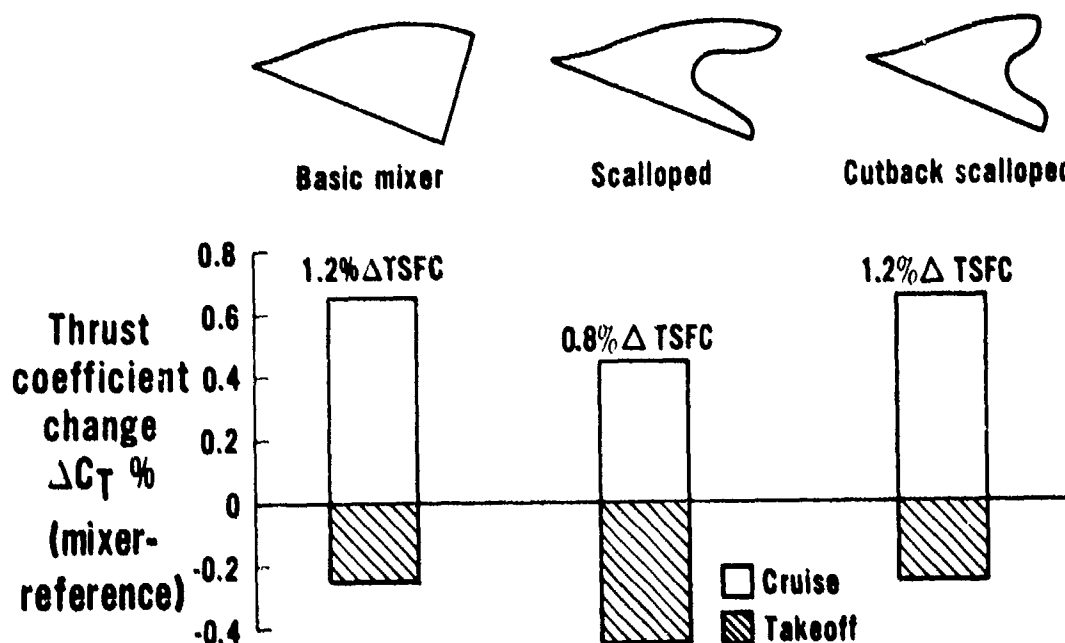
Basic mixer   Scalloped   Cutback scalloped

Thrust coefficient change ΔC_T % (mixer-reference)

Figure 5-29   *Summary of Long Flowpath Mixer Performance Relative to Reference Exhaust System at Cruise and Takeoff Conditions*

Thus, scalloping and cutting back the mixer lobes produced relatively small changes to the noise, profile and thrust performance characteristics relative to the basic mixer. It is important to note that these results were based on model tests that did not include the simulation of engine secondary flow effects such as turbine exit swirl, turbine and fan duct struts and fan flow distortion. The next section presents results where these JT8D engine secondary flow details were simulated on selected configurations.

5.3 EFFECTS OF ENGINE "SECONDARY" FLOW SIMULATION

The traditional method of conducting scale model jet engine exhaust nozzle noise tests has been to simulate the internal flowpath of the exhaust system starting at a position downstream of the turbine exhaust case. The models used in this program were designed to duplicate the nozzle flowpath in the traditional manner. However, limited test experience on refanned derivatives of the JT8D have indicated an effect of the distorted and swirling "secondary" flow characteristics on exhaust system performance. Based on these results the Pratt & Whitney Aircraft in-house program included testing to determine the impact of simulated actual engine secondary flow on noise and performance. These flow details included: (a) turbine exhaust case struts, (b) turbine discharge residual swirl, (c) fan case struts, and (d) fan stream radial pressure distortion. Devices were fabricated to simulate the fan stream distortion and turbine exit swirl levels which were determined from previous JT8D engine tests. Figure 5-30 illustrates the model hardware used to simulate flow details and Figure 5-31(a and b) presents the radial swirl and pressure profiles simulated by this hardware.

As will be shown in the following sections, the engine secondary flow simulation produced important effects on both the acoustic and nozzle performance characteristics.
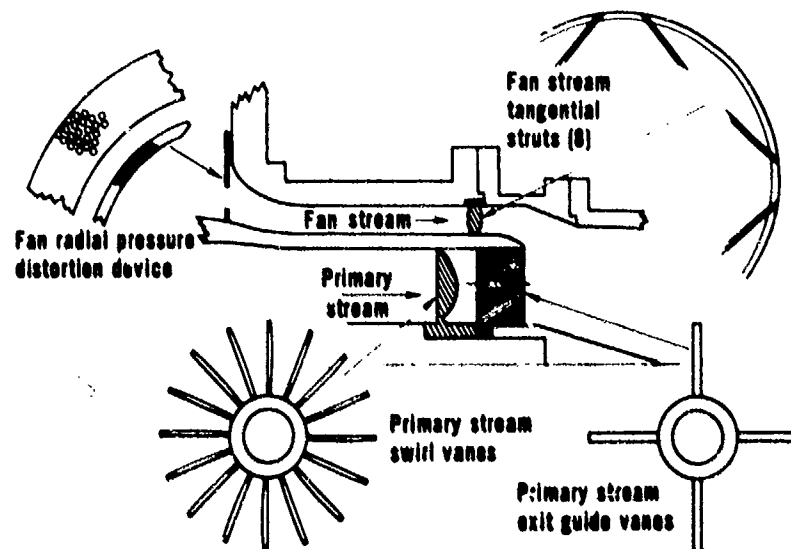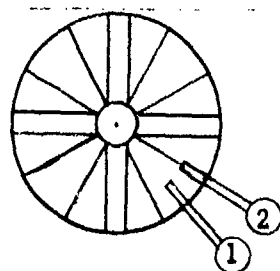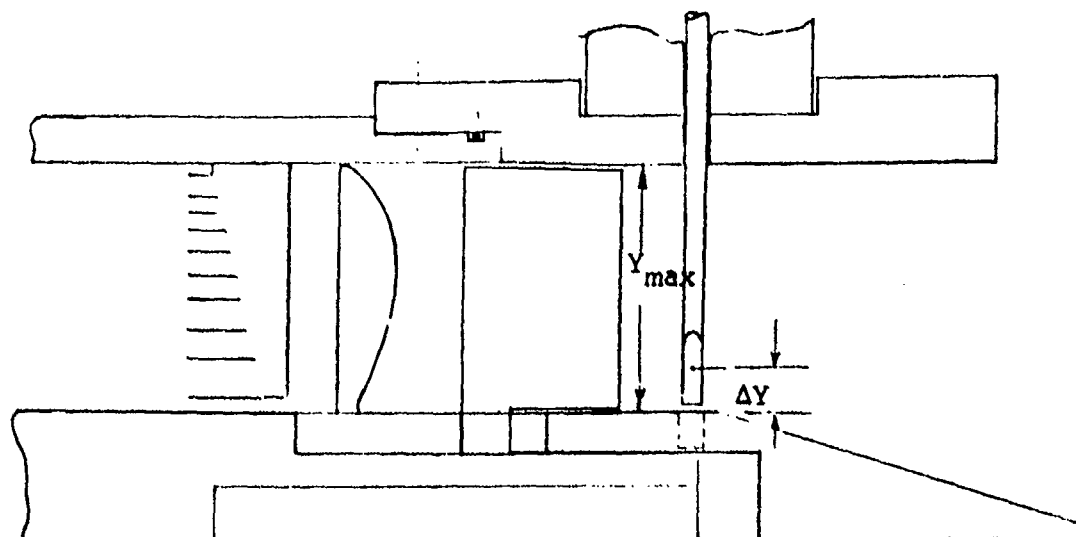

Figure 5-30   Schematic of Engine Secondary Flow Simulation Model Hardware

5.3.1 Traverse Results

Modest changes in nozzle discharge profiles occurred in both the reference splitter and mixer configurations. The most significant change was warping of the concentric ring pattern exhibited by the reference configuration into a diamond shaped pattern (Figure 5-32). Similar patterns have been observed in full scale JT8D engine traverses (Reference 1).

The effect of secondary flow effects on the mixer exhaust system profiles is illustrated in Figures 5-33 and 5-34 for the deep scallop and cutback scallop mixers, respectively. The changes to the profiles are relatively small for both mixers, although a slight improvement in mixing did occur.

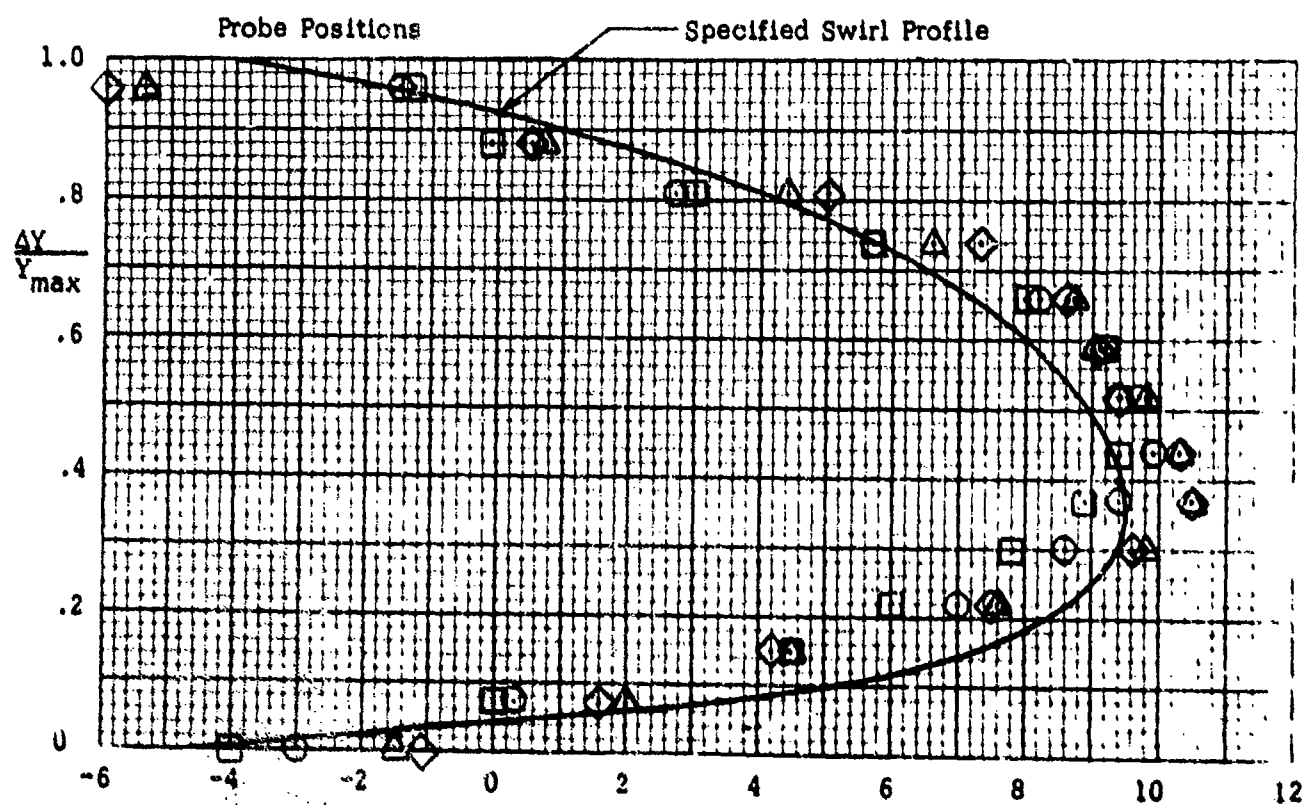| Symbol	Mach No.	Position
○	.3	1
□	.5	1
◇	.3	2
△	.5	2

Probe Positions — Specified Swirl Profile

Figure 5-3 1(a) Primary Stream Swirl Angle, Degrees (Counter Clockwise viewed aft looking upstream)

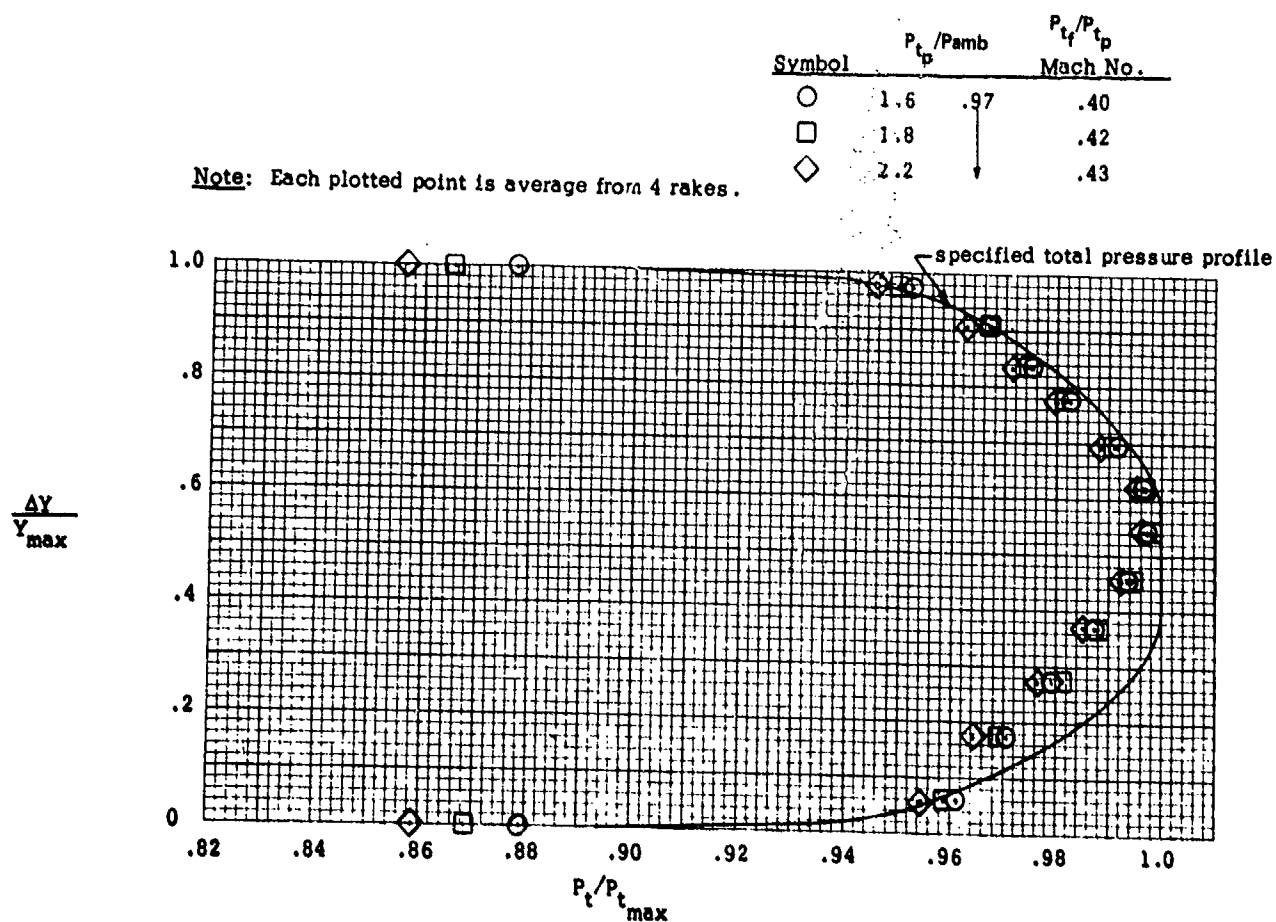**Note:** Each plotted point is average from 4 rakes.

Figure 5-31(b)   Fan Stream Total Pressure Profiles for Tests With Fan Stream Distortion
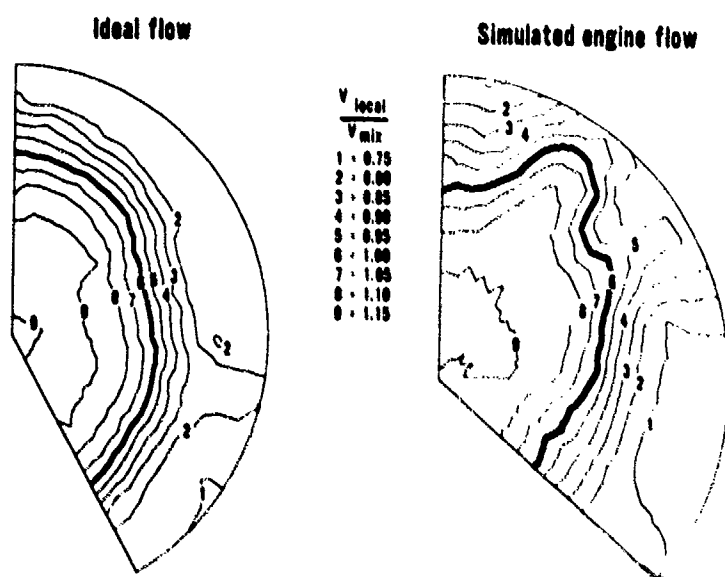

Figure 5-32   Effect of Engine Secondary Flow Simulation on Tailpipe Velocity Contour Map of Reference Exhaust System
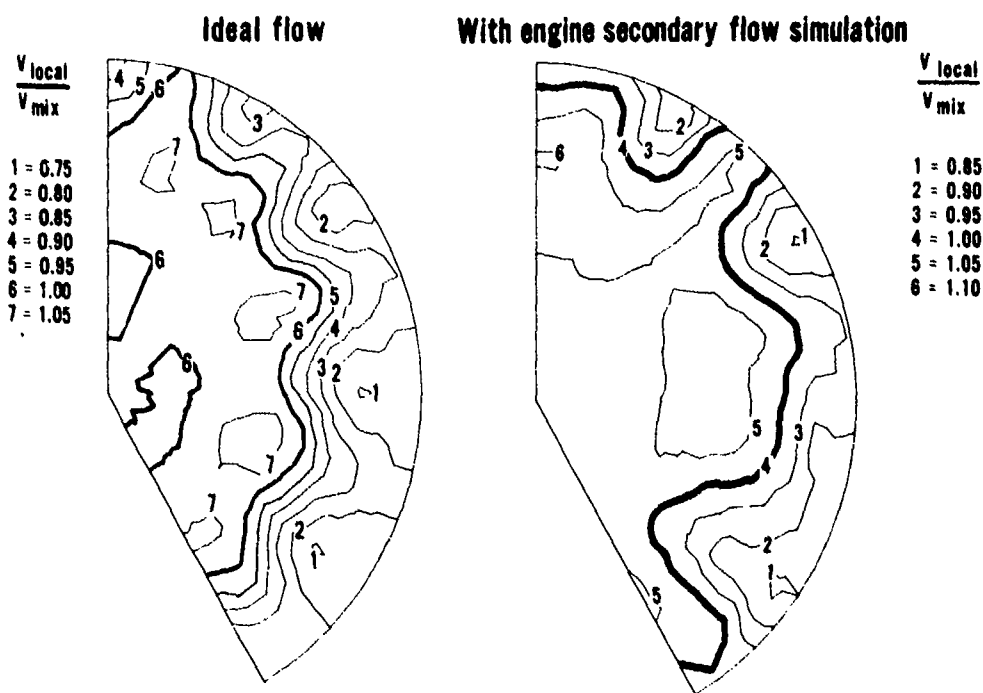
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Ideal flow   **With engine secondary flow simulation**

$\dfrac{V_{local}}{V_{mix}}$

1 = 0.75
2 = 0.80
3 = 0.85
4 = 0.90
5 = 0.95
6 = 1.00
7 = 1.05

$\dfrac{V_{local}}{V_{mix}}$

1 = 0.85
2 = 0.90
3 = 0.95
4 = 1.00
5 = 1.05
6 = 1.10

Figure 5-33   *Effect of Engine Secondary Flow Simulation on Tailpipe Exit Velocity Contour Map of Scalloped Long Flowpath Mixer*

Ideal flow $\dfrac{V_{local}}{V_{mix}}$ **With engine secondary flow simulation**
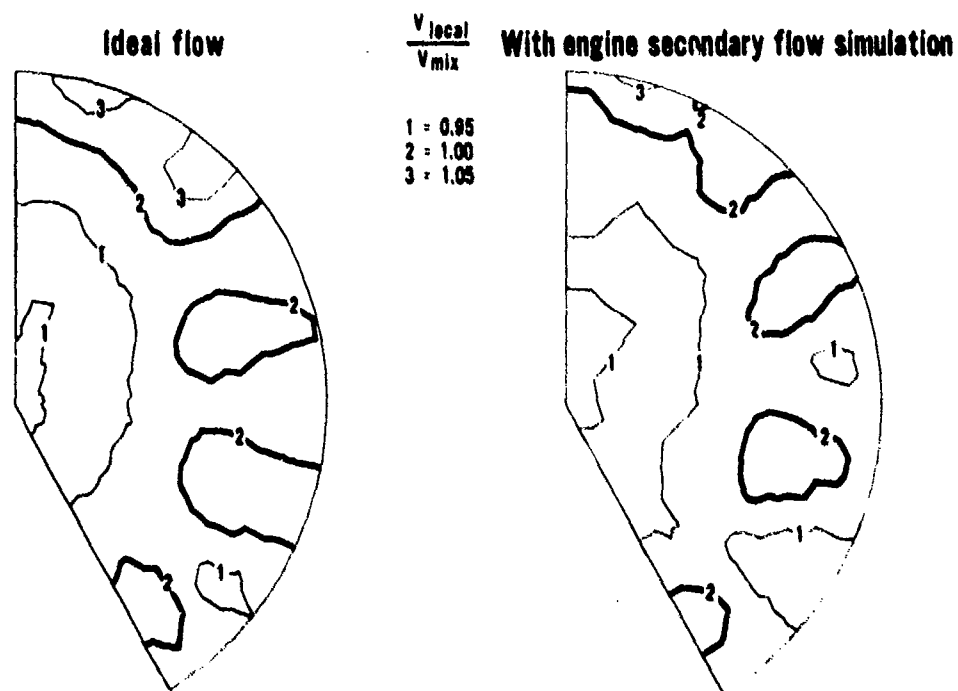
1 = 0.95
2 = 1.00
3 = 1.05

Figure 5-34   *Effect of Engine Secondary Flow Simulation on Tailpipe Exit Velocity Contour Map of Cutback Scalloped Long Flowpath Mixer*

5.3.2 Acoustic Results

The engine secondary flow simulation produced the largest effects on the reference exhaust system noise and had only small effects on the mixer results. The presentation and discussion of the acoustic results is divided into two parts. The reference nozzle results are presented in Section 5.3.2.1, followed by the mixer results in Section 5.3.2.2. Thrust performance results are presented in Section 5.3.3, followed by a discussion of the implications of engine secondary flow simulation in Section 5.3.4.

5.3.2.1 Reference Exhaust System

The effect of the engine secondary flow simulation on the peak PNL of the reference exhaust system is shown in Figure 5-35. The peak PNL is significantly reduced (up to 1.7 PNdB) relative to the same exhaust system without the engine flow simulation. The PNL directivity curves are shown in Figure 5-36 at the maximum and cutback takeoff thrusts. At both thrust conditions, the engine secondary flow simulation caused significant PNL reductions in the aft angles ($\theta_i > 130$ degree) and slight increases in the forward angle PNL levels.
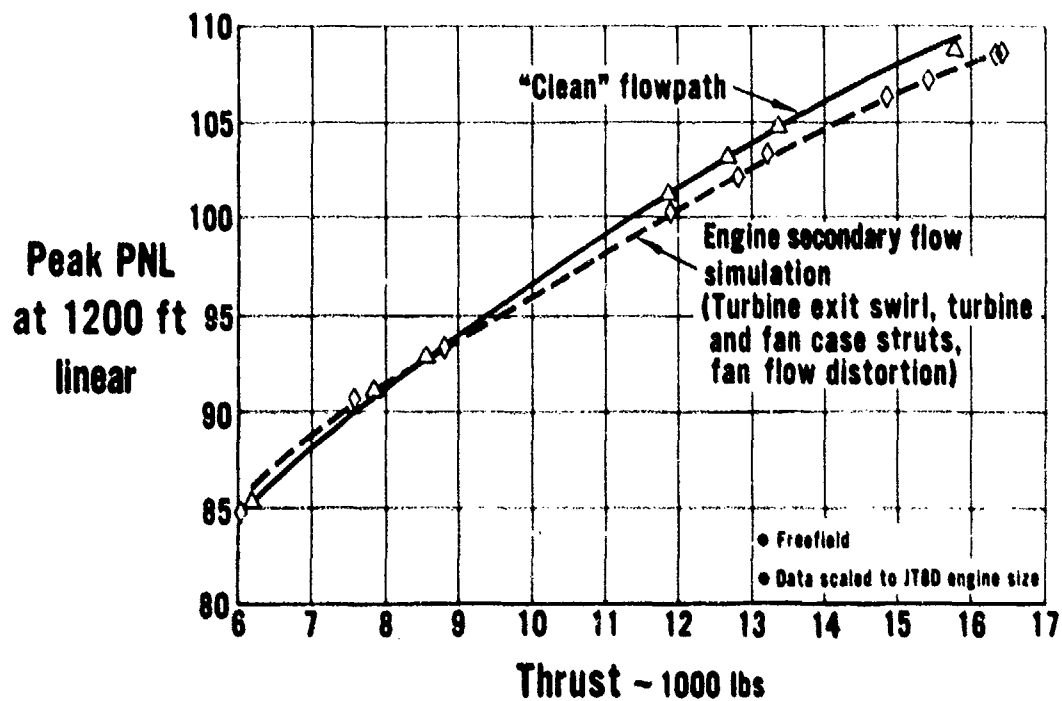

Figure 5-35   Effect of Engine Secondary Flow Simulation on Peak Perceived Noise Level of Reference Exhaust System
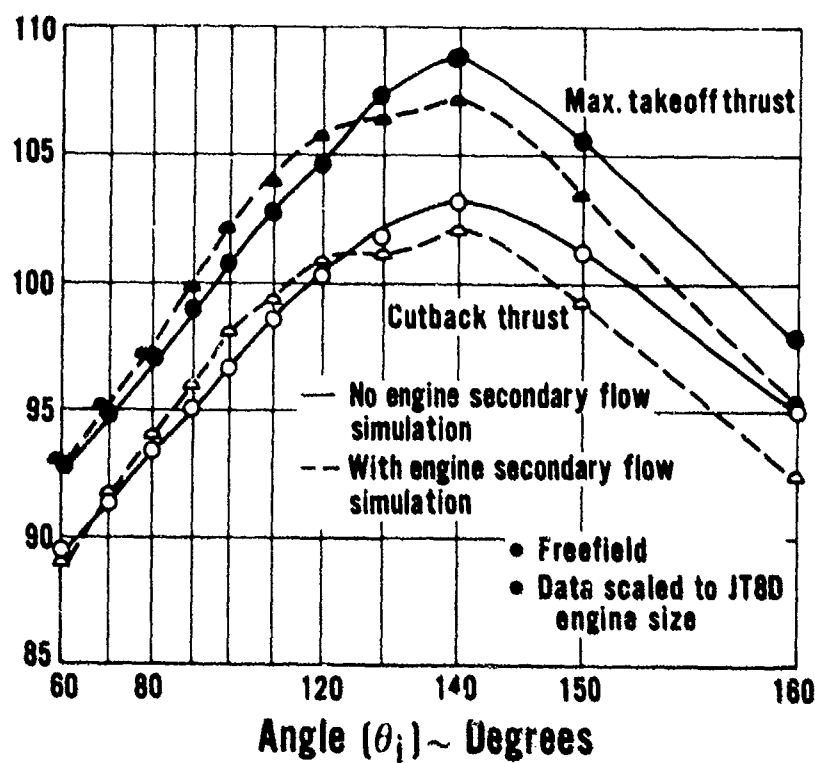
Figure 5-36   Effect of Engine Secondary Flow Simulation of Perceived Noise Level
Directivity of Reference Exhaust System

The SPL spectra at 90 and 140 degrees are shown in Figure 5-37(a and b). In each case, the noise
was reduced at low frequencies and increased at high frequencies. Since the aft angle PNL
levels are controlled by the noise at low frequencies, the spectra changes are consistent with
the reduced PNL's at the aft angles shown in the previous figure. At 90 degrees, since the PNL
is controlled by the noise levels at the higher frequencies, the spectral changes are consistent
with the increased PNL at forward angles shown in the previous figure.

Considering the spectral changes in relation to the velocity profile changes, it is possible to
postulate a possible mechanism of the noise reduction. First, the spectral changes are con-
sistent with the effects observed from the addition of an external multi-element daisy nozzle
jet noise suppressor on turbojets, which reduce low frequency noise at the expense of increased
noise at high frequencies. As was shown earlier in this section, the velocity profile produced
by the engine flow simulation was quite distorted. This type of profile is similar to the flow
downstream of a suppressor nozzle with four lobes. Thus, both the acoustic and profile results
suggest that the presence of the engine flow simulation produces a jet exhaust having external
daisy nozzle characteristics.

It is thought that the interaction of the swirl flow with the turbine exit case struts causes
strong secondary vortex flow patterns to be set up inside the tailpipe. These flow patterns
have also been observed in full scale JT8D engine tests (Reference 1). The vortex flows are
thought to be responsible for the distorted velocity profiles and the resulting noise reductions.
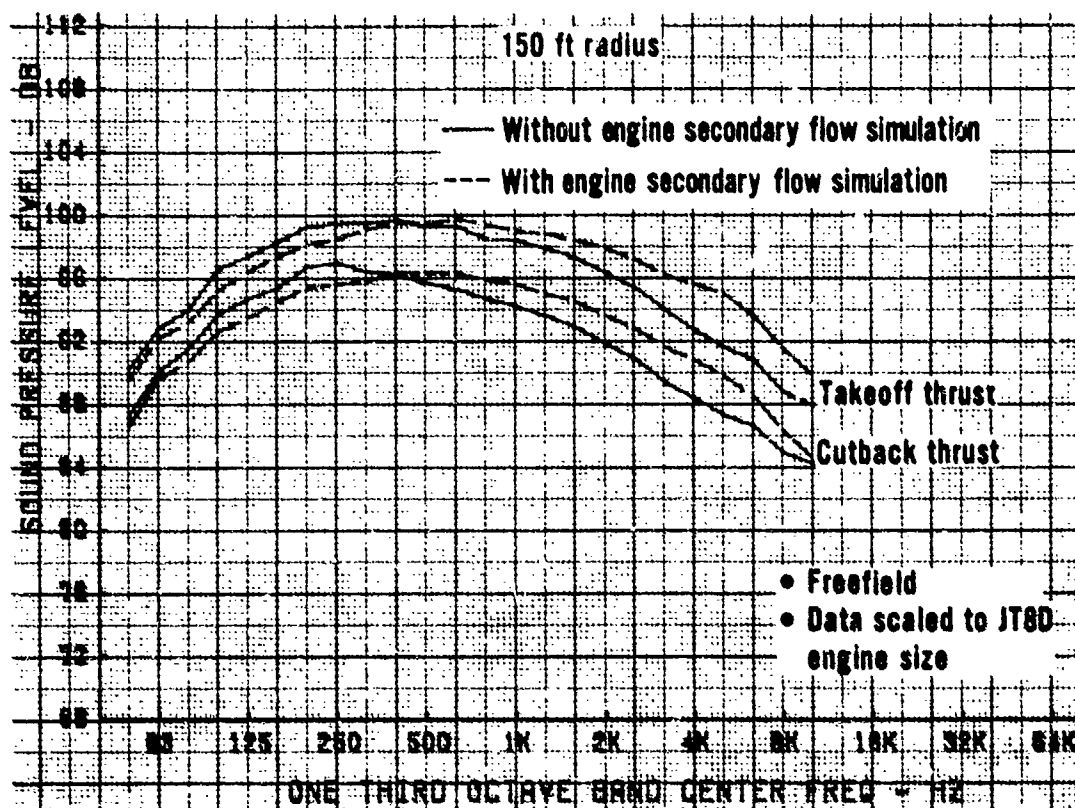
61

Figure 5-37(a)   Effect of Engine Secondary Flow Simulation on SPL Spectra at 90 Degrees of the Reference Exhaust System
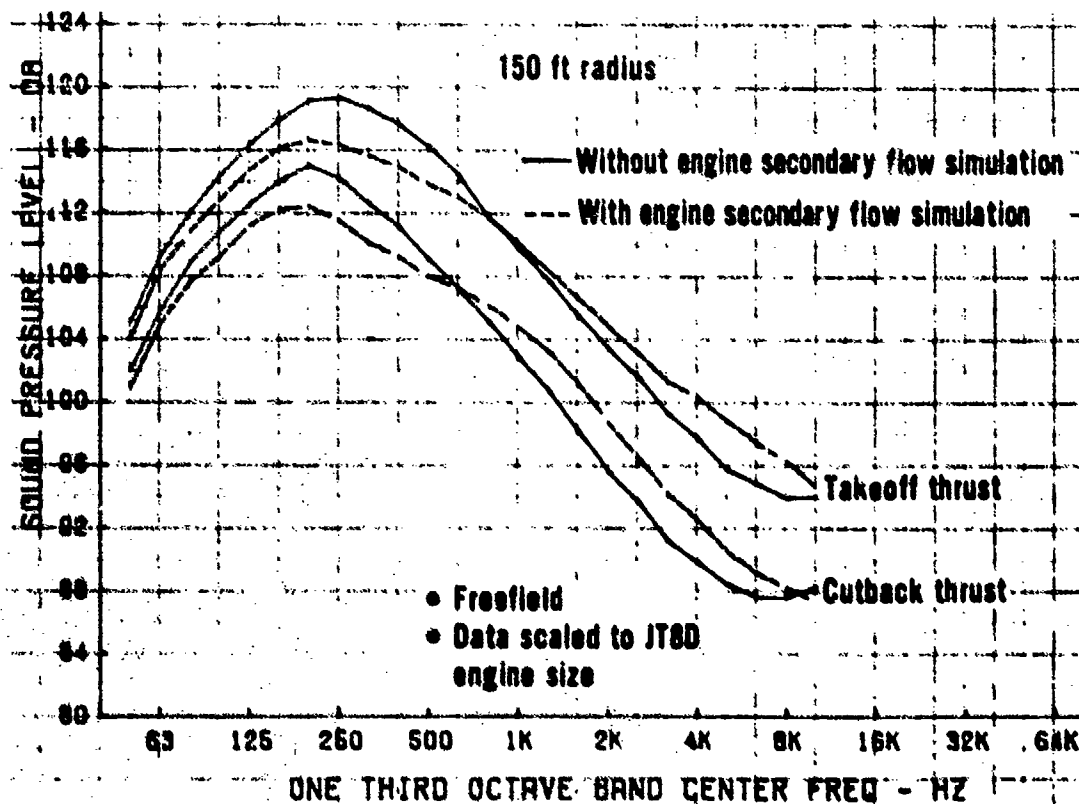

Figure 5-37(b)   SPL Spectra at 140 Degrees

Figure 5-38 shows a comparison of the model and JT8D engine spectra at 140 degrees
Since the model data obtained with the engine secondary flow simulation agree well with the
full scale data at frequencies important for jet noise, it appears that the engine secondary
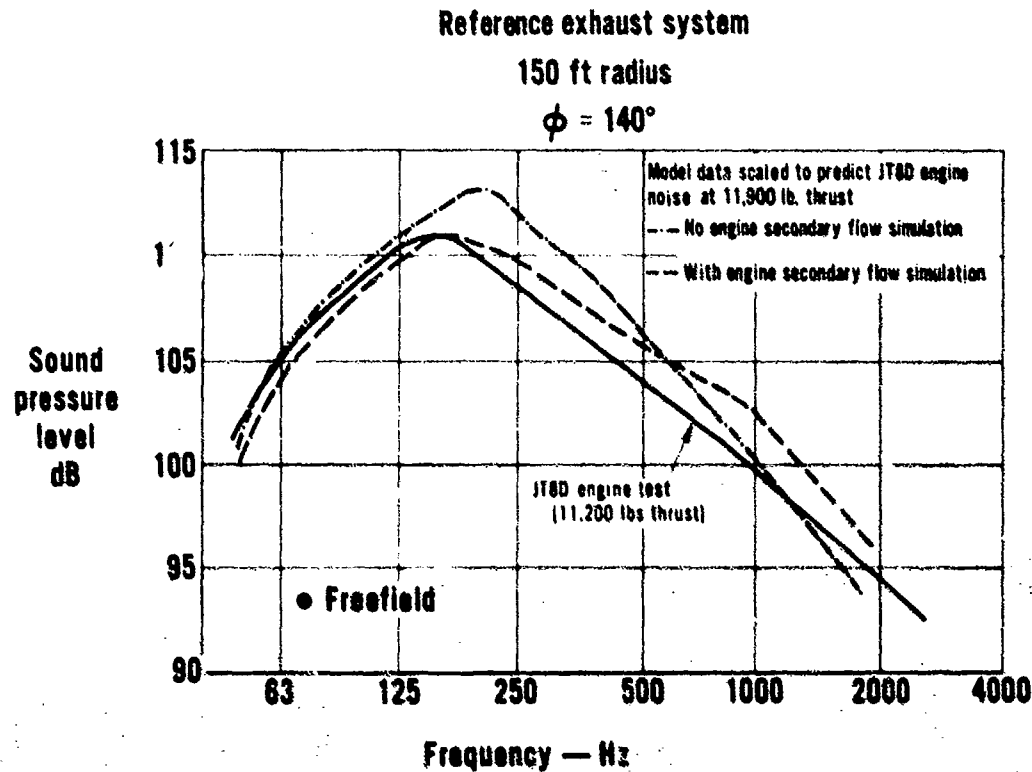flow simulation data provide the most realistic JT8D engine jet noise simulation.

Reference exhaust system

150 ft radius

$\phi = 140°$

Figure 5-38   Comparison of JT8D Engine Noise with Model Data Scaled to Predict
Noise of JT8D Engine

5.3.2.2 Mixer Exhaust System

The effects of engine flow simulation on noise and performance of the deep scalloped long
mixer with and without the lobe cutback are presented in this section.

Figure 5-39 shows the effect of engine flow simulation on the peak PNL of the cutback
deep scalloped long mixer. There is negligible effect below 14,000 lb. thrust, and a noise in-
crease of 1 PNdB at maximum takeoff thrust of 15,500 lbs. At high thrust, the PNL directi-
vity curves (Figure 5-40) show slightly increased levels at all angles, with the differences
increasing with angle. At cutback thrust, data at identical nozzle conditions were not avail-
able. The comparisons shown indicate a difference in peak PNL that is attributable to the
test condition thrust differences. At more aft angles, however, the PNL levels were increased
with engine secondary flow simulation. The SPL spectra comparisons in Figure 5-41(a and b)
show that at 90 and 140 degrees and at both thrust levels, the main effect of the engine flow
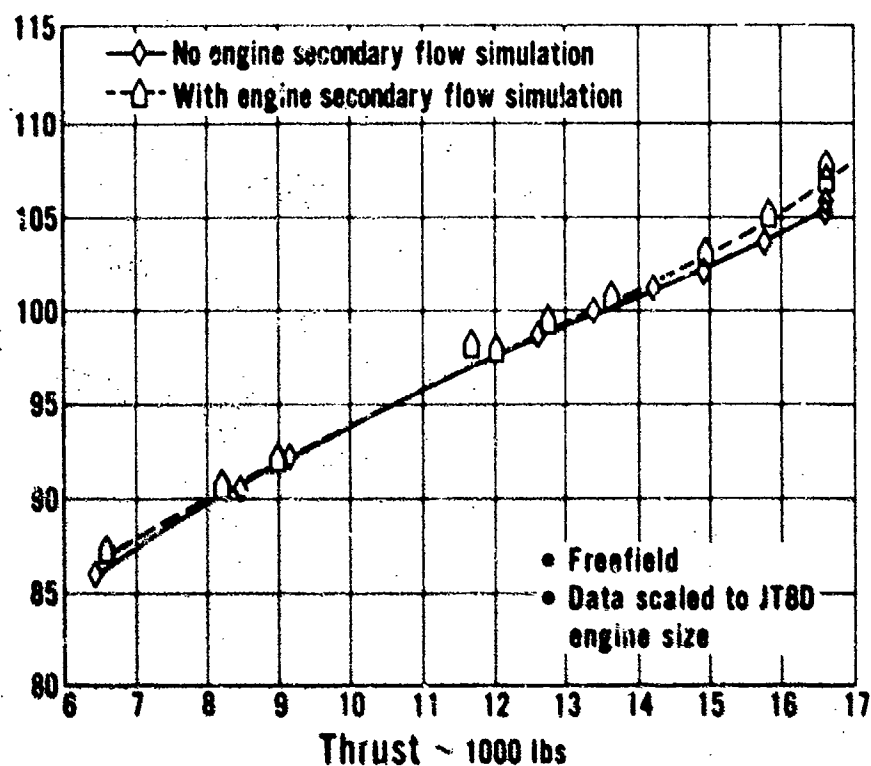simulation was to increase noise at the higher frequencies.

Figure 5-39   Effect of Engine Flow Simulation on Peak Perceived Noise Level of Cutback
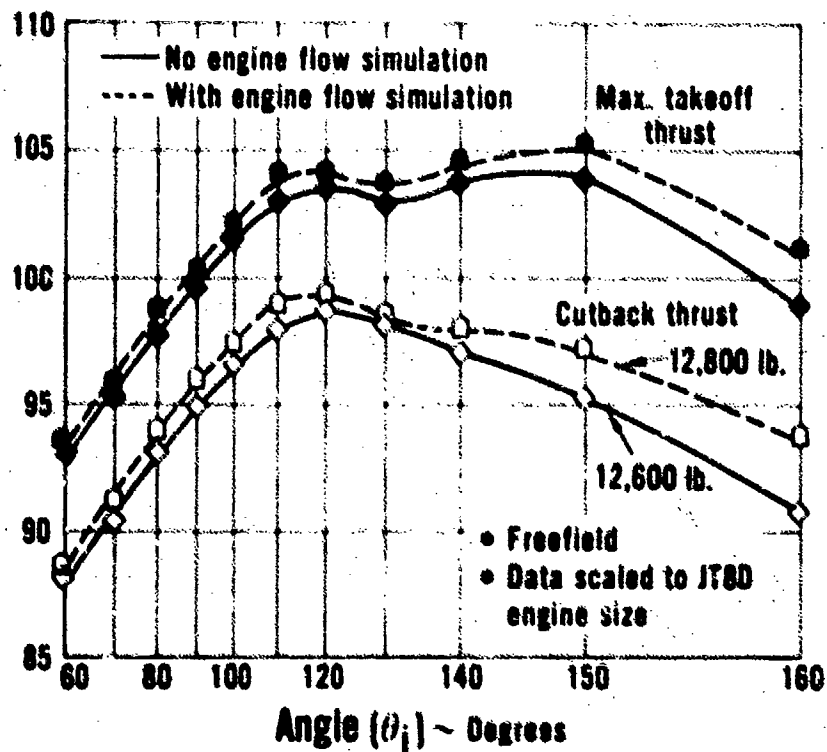Scalloped Long Flowpath Mixer

Figure 5-40   Effect of Engine Secondary Flow Simulation on Perceived Noise Level
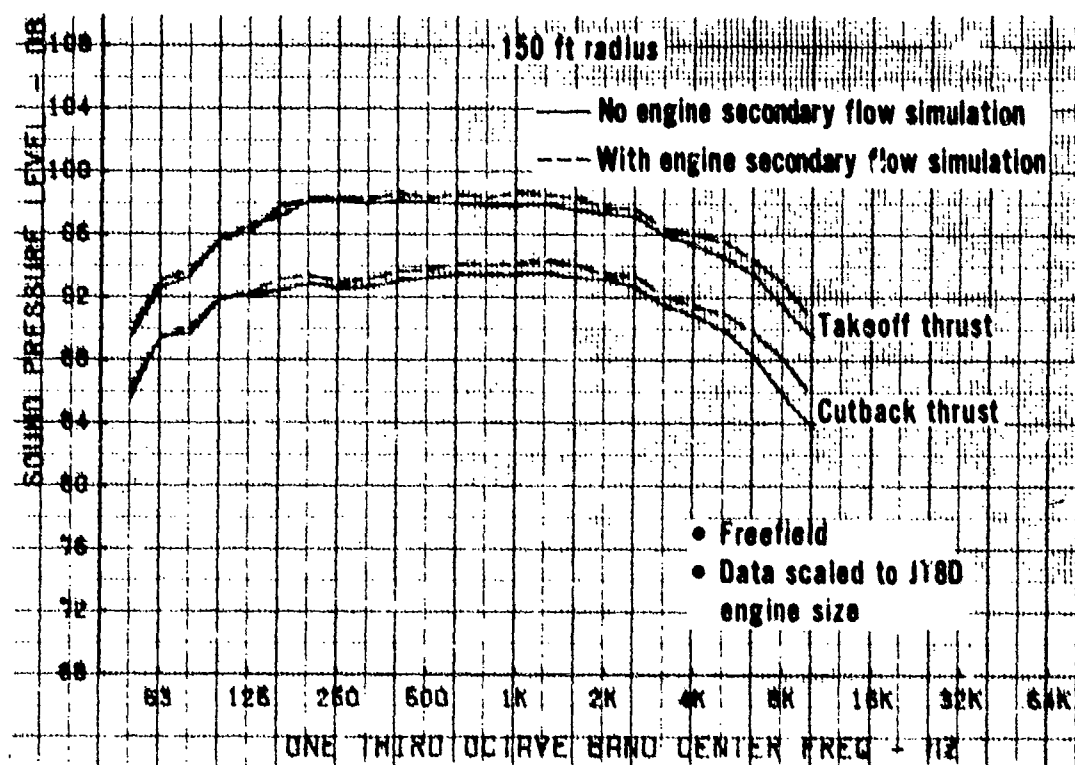Directivity of the Cutback Scalloped Long Flowpath Mixer

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Figure S-41(a)   Effect of Engine Secondary Flow Simulation on SPL Spectra at 90 Degrees of Cutback Scalloped Long Flowpath Mixer
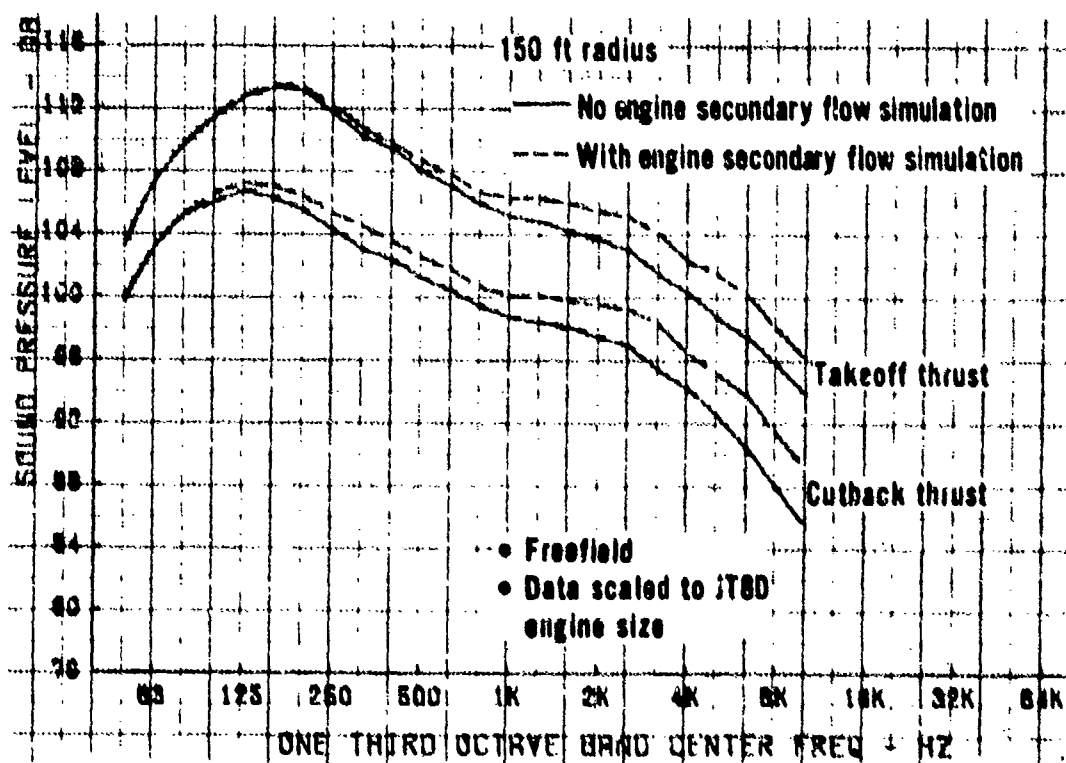

Figure S-41(b)   SPL Spectra at 140 Degrees

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The effect of engine flow simulation on noise of the deep scalloped mixer without cutback was slightly different than for the cutback version. The peak PNL was decreased by up to ½ PNdB at thrusts below 14,000 lbs., and slightly increased at the very highest thrust levels, as shown in Figure 5-42. SPL spectra at 90 degrees show decreased levels at low frequencies and no change in high frequencies at the cutback thrust condition, but at the takeoff thrust condition the low frequency levels were unchanged, while the high frequencies were increased, as shown in Figure 5-43(a). However, at 140 degrees the spectra shapes were unchanged, as shown in Figure 5-43(b).

Thus, the effect of engine secondary flow simulation on noise was relatively small and inconsistent for the two mixers evaluated, while the effect on the reference system was substantial. The net result of engine secondary flow simulation was to decrease the noise reductions due to a mixer relative to the tests conducted without the simulation of the secondary flow details.
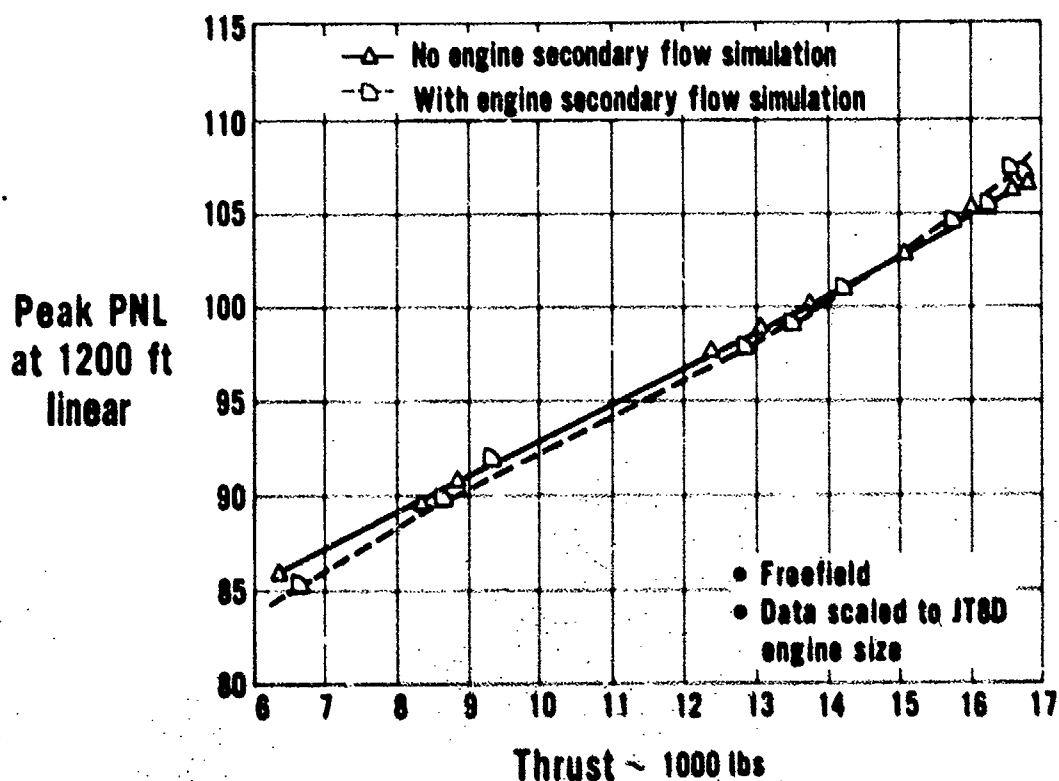

Figure 5-42   Effect of Engine Flow Simulation on Peak Perceived Noise Level of Scalloped Long Flowpath Mixer
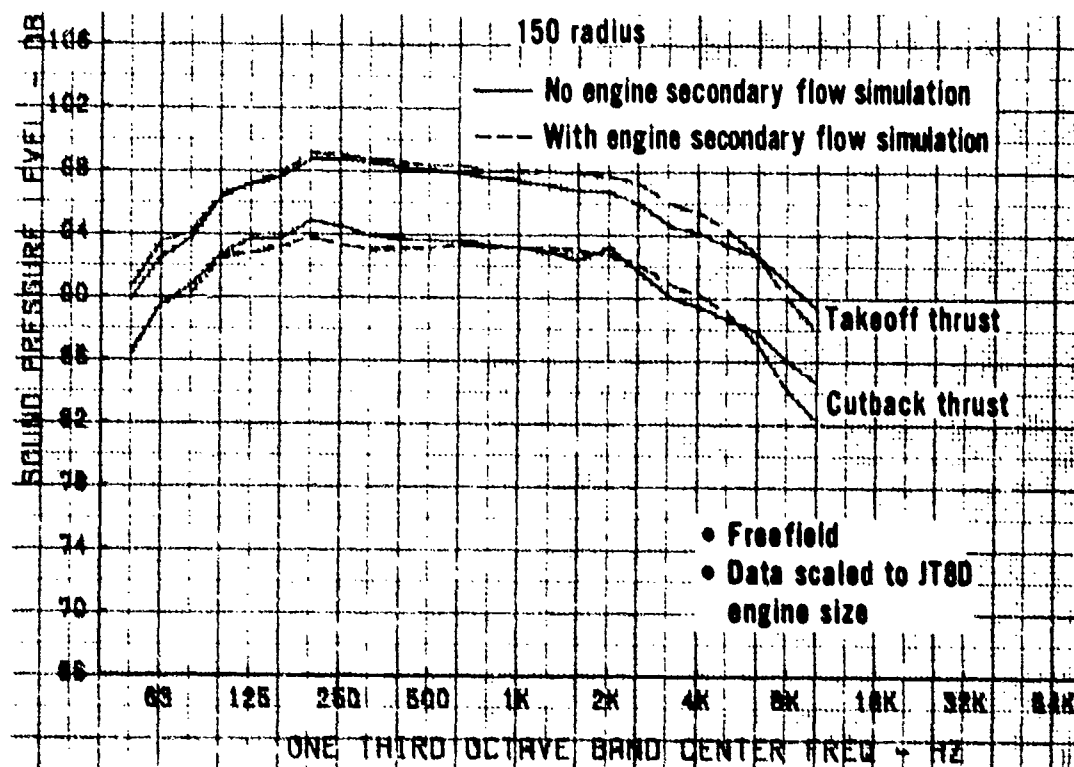
Figure 5.43(a)   Effect of Engine Secondary Flow Simulation on SPL Spectra at 90 Degrees
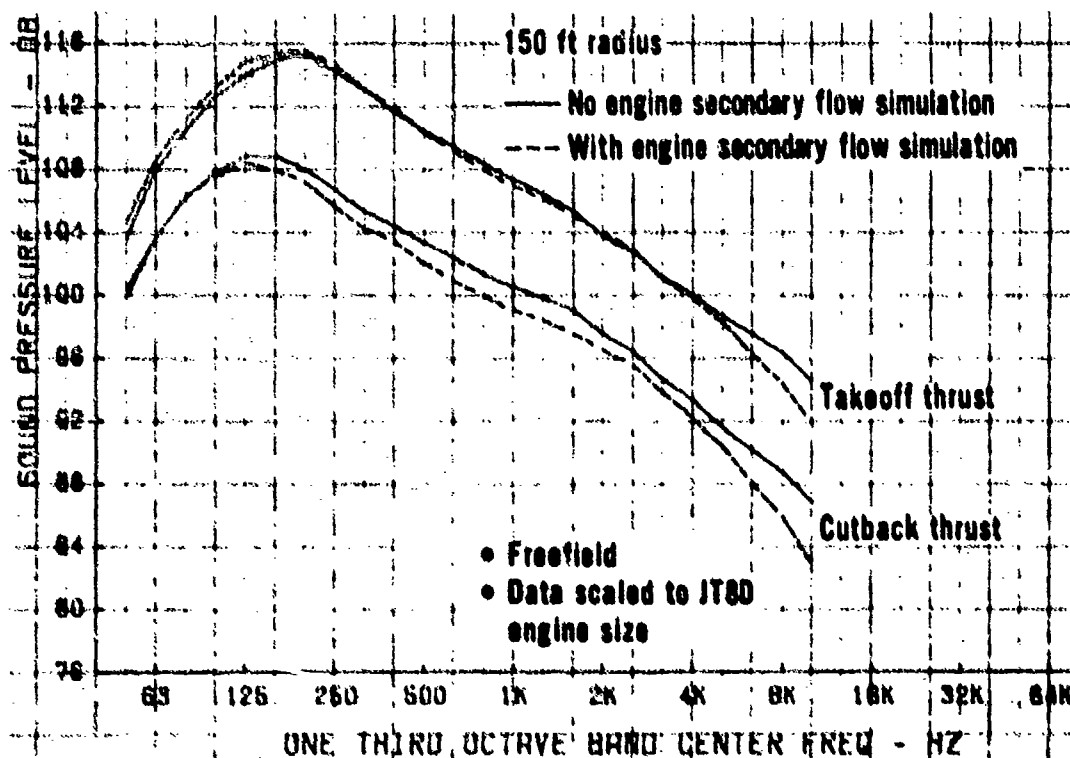   of Scalloped Long Flowpath Mixer

Figure 5.4?.?)   SPL Spectra at 140 Degrees

5.3.3 Performance Results

Performance data from the reference configuration indicated a small decrease in thrust coefficient that resulted from the increased pressure loss of the engine secondary flow simulation devices (swirl vanes and struts) between the charging station and the nozzle discharge. Analytical estimates were made of the contribution from each of these effects and are shown in Figure 5-44. Approximately 2/3 of the thrust loss coefficient resulted from increased pressure loss, and the remaining 1/3 was associated with residual swirl.

Several mixer configurations were tested both with and without the simulated secondary flow effects. Since the pressure loss of the flow simulation devices was small and equal for all the mixer configurations and the reference system, the change in performance levels caused by the mixers are on a consistent basis. The general trend in the results was that the presence of the engine secondary flow simulation increased the performance improvements of the mixers relative to the reference system. These performance improvement increases varied with mixer configurations, and were caused primarily with the conversion of tangential momentum (associated with the swirl) to axial momentum which provided increased thrust. The reference splitter has no means for this conversion of momentum. It is possible that redistribution of the distorted flow profiles and mixing changes may also be contributing to this improvement.
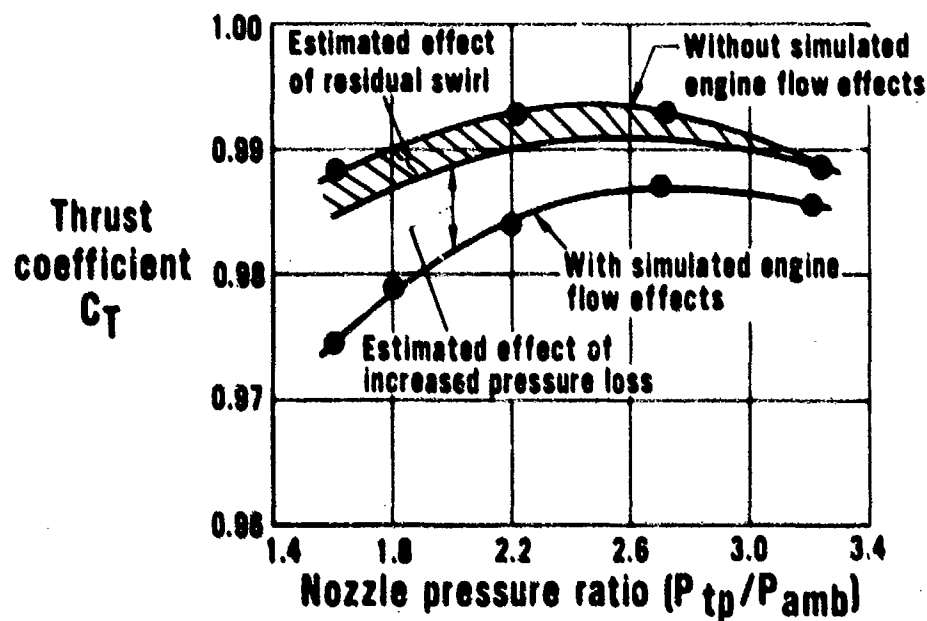

Figure 5-44   Effect of Engine Secondary Flow Simulation on Cold Flow Performance of Reference Exhaust System

A comparison of performance of the cutback scalloped mixer with and without simulated secondary flow effects is presented in Figures 5-45 and 5-46. As shown, a slight increase (0.5%) in pressure loss and a 10% gain in mixing can be attributed to the secondary flow effects. In combination with the effects of engine secondary flow simulation on the reference configuration, a net improvement of 0.3% in takeoff thrust and 0.1% cruise fuel consumption in the mixer minus reference system performance increment was realized with the secondary flow simulation.

◇ Without engine secondary flow simulation

△ With engine secondary flow simulation

Pressure loss; percent (mixer-reference)

Percent mixing

Nozzle pressure ratio (P_{tp}/P_{amb})

Figure 5-45   Effect of Engine Flow Simulation on Mixing and Pressure Loss of Cutback Scalloped Long Flowpath Mixer

Thrust coefficient change $\Delta C_T\%$ (mixer-reference)

1.2% Δ TSFC

1.3% Δ TSFC

With engine secondary flow simulation

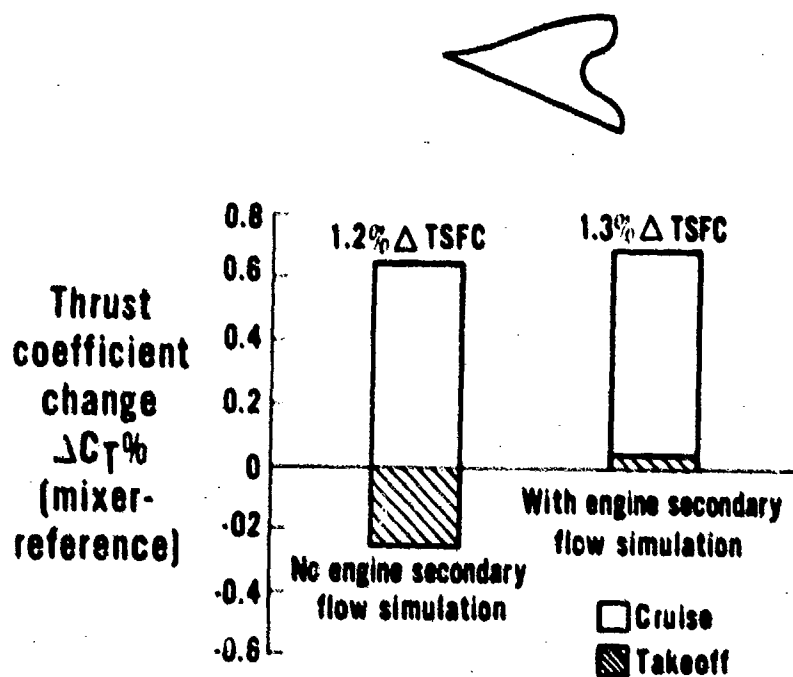No engine secondary flow simulation

☐ Cruise
▨ Takeoff

Figure 5-46   Effect of Engine Flow Simulation of Performance of Cutback Scalloped Long Flowpath Mixer

5.3.4 Implication of Engine Secondary Flow Simulation Results

Since the reference exhaust system results obtained with the engine flow simulation are consistent with full scale JT8D engine noise measurements, it appears that the engine flow simulation data from this program should be used to project the JT8D engine full scale effects. Accordingly, the major conclusions obtained from this program were based on results from tests conducted with the engine secondary flow simulation. These results are judged to be the more appropriate for projection to predict JT8D engine noise and performance. It is expected, therefore, that noise reductions of 3 to 4 PNdB and cruise TSFC improvements of approximately 1.2 to 1.3% would be obtained for a JT8D engine installed with full scale versions of the long flowpath mixer tested during this program.

5.4 SHORT FLOWPATH MIXERS

5.4.1 Basic Design

As discussed previously in Section 2.0, an alternate shorter mixer model was designed, fabricated and tested under a companion Pratt & Whitney Aircraft in-house program. The intent of this program was to evaluate a mixer scheme that would reduce the impact of the mixer on the aircraft installation even if some sacrifice in performance and acoustic properties was necessary. Figure 5-47 compares the mixer flowpaths for the long and short mixers. Note that the slope at the outer case for the long mixer is much more gradual than that for the short mixer which employs the existing exhaust case. Total length of the exhaust system was increased for both configurations, but the alternate mixer system is 8.4 inches shorter than the long mixer design when projected to a full scale JT8D engine.
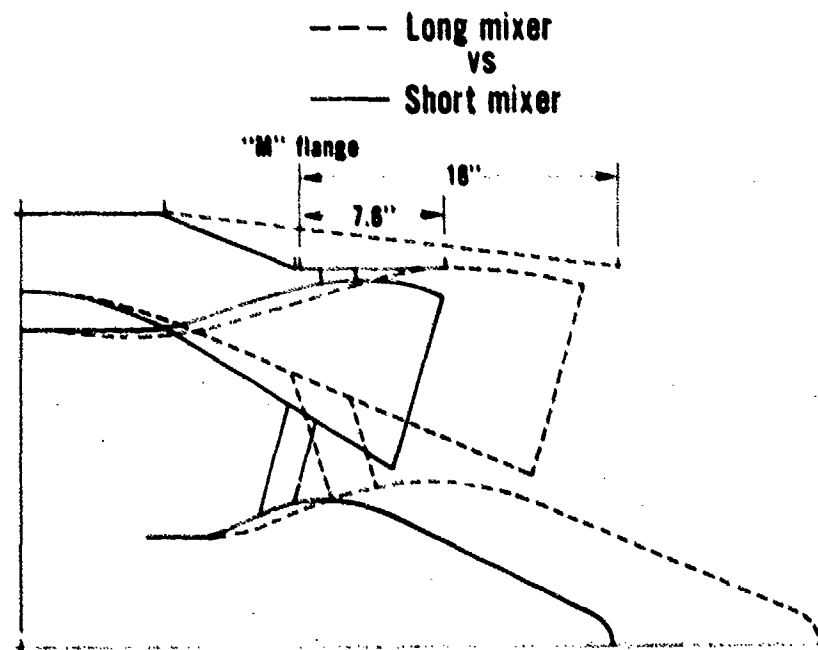

Figure 5-47   Schematic of Basic Long and Short Flowpath Mixers

Based on the experience gathered from the long mixer program, similar studies of lobe discharge turning angle and scalloping as well as the effects of engine flow simulation were investigated for the short mixer. The moderately cutback short mixer with essentially no lobe overturning yielded overall velocity distributions similar to the cutback, scalloped, long mixer as shown in Figure 5-48. Peak velocities were slightly higher at 8.5% above the ideally mixed value. The radial velocity profile differed from the slightly inverted profile of the long mixer to a profile that peaked at the center of the stream as well as at the nozzle wall.
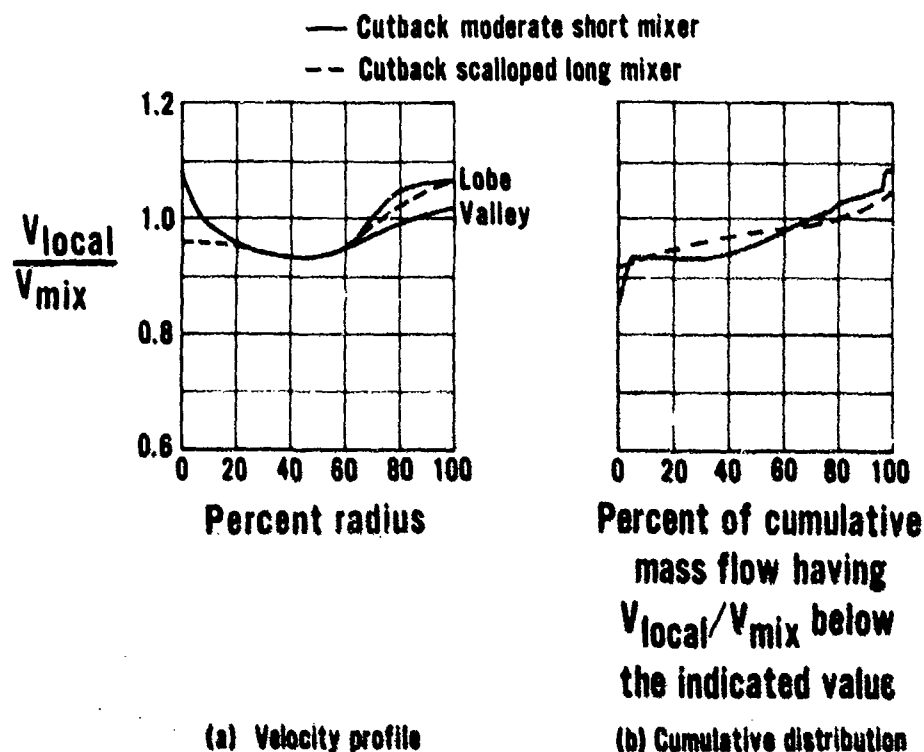

— Cutback moderate short mixer
-- Cutback scalloped long mixer

(a) Velocity profile   (b) Cumulative distribution

Figure 5-48   Comparison of Tailpipe Exit Velocity Profile and Cumulative Mass Flow Distribution for Moderate Cutback Short Flowpath and Cutback Scalloped Long Flowpath Mixers (with Engine Secondary Flow Simulation)

The short flowpath mixer provided excellent noise reduction at all thrusts, as shown in the peak PNL curves in Figure 5-49. The short mixer produced about 1 PNdB more noise reduction than did the long mixer at maximum takeoff and cutback thrusts.

Performance of this configuration showed, as expected, less improvement than did the long mixer (Figure 5-50). There was a 0.3% increase in pressure loss accompanied by a modest reduction in mixing. A net loss of 0.25% takeoff thrust and an improvement of 0.9% fuel consumption were obtained relative to the reference configuration.
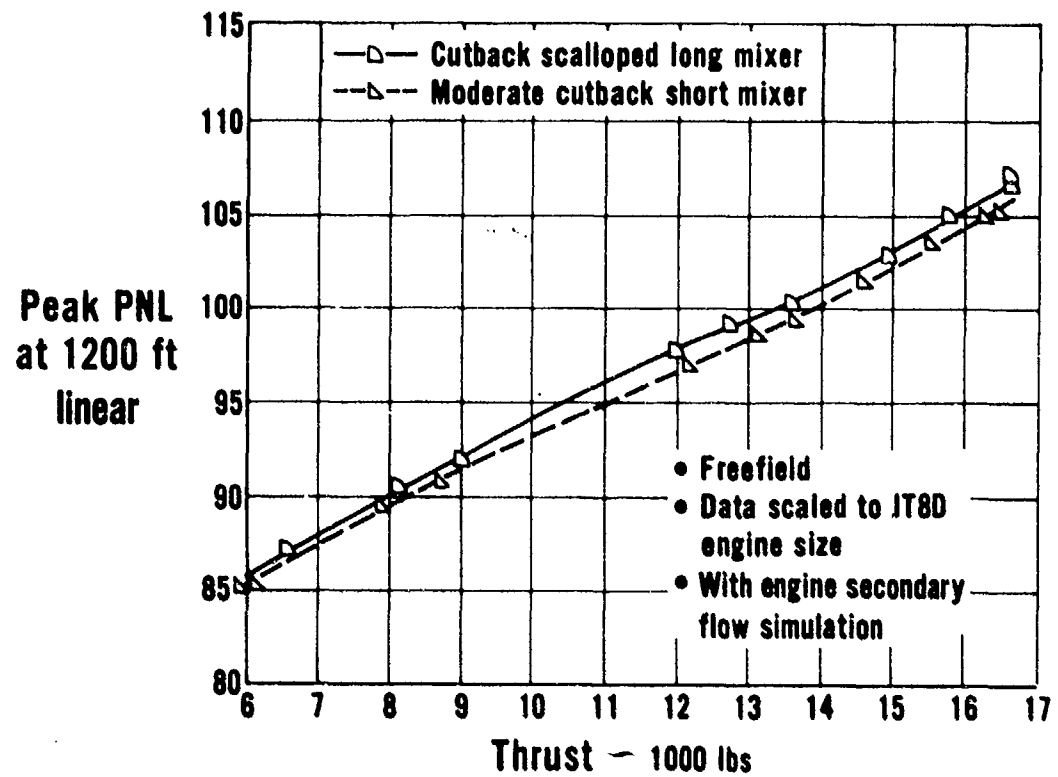
Figure 5-49   Comparison of Peak Perceived Noise Level of Moderate Cutback Short
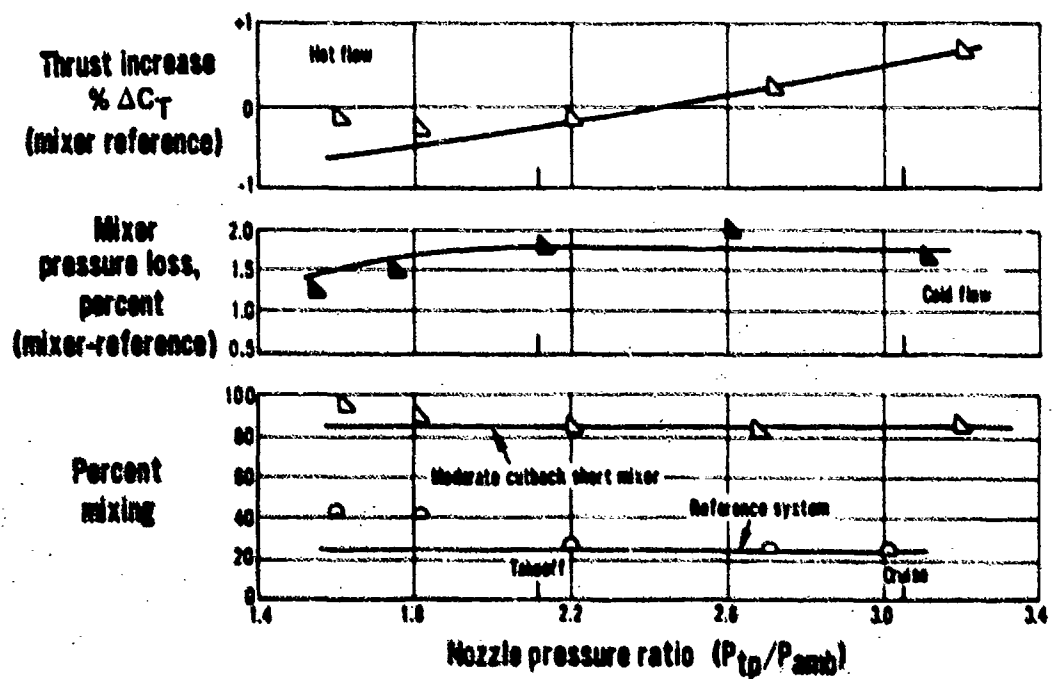Flowpath and Cutback Scalloped Long Flowpath Mixers

Figure 5-50   Performance of Moderate Cutback Short Flowpath Mixer Relative
Reference Exhaust System

5.4.2 Severe Cutback Mixer

Although the basic short flowpath mixer configuration would have a less severe impact on the airframe installation than the long mixer, some nacelle extension to install this mixer would be necessary to provide adequate mixing length and yet avoid interference with the thrust reverser doors of the Boeing 727 installation. In an attempt to explore the possibility of still shorter mixer schemes having less installation impact, the mixer used in the Pratt & Whitney Aircraft funded program was cut back so the lobe outer diameter ended at the interface of airframe and engine hardware ('M' flange) (Figure 5-51). This configuration was then tested for noise and performance. It may be possible to install this mixer on a JT8D engine without the necessity of an outer case extension, thus simplifying the task of incorporating a mixer on existing JT8D engines.
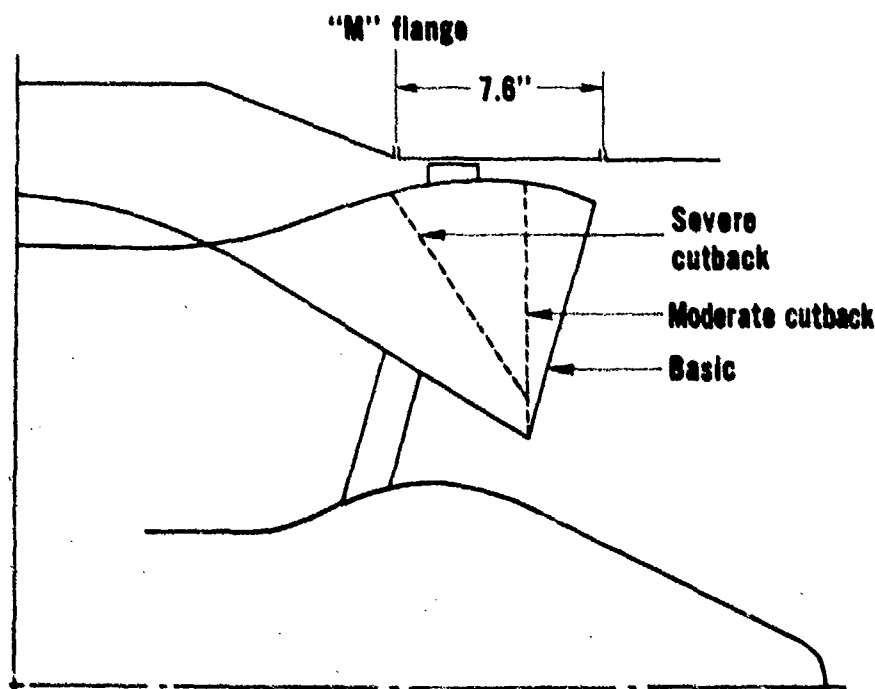

Figure 5-51   Schematic of Short Flowpath Mixer Showing Moderate and Severe Cutback Lobes

Traverse results for this configuration showed the velocity profiles to be essentially the same as those of the moderate cutback configuration, but with slightly higher velocities occurring at the center of the stream.

The noise results from this configuration were very encouraging. Figure 5-52 shows a comparison of peak PNL for this configuration compared to the other designs tested as well as the reference exhaust system. The noise levels of the severe cutback short mixer compared favorably with the other mixers tested. Although it did not provide the largest noise reduction, the noise reduction of 3-4 PNdB meets the goals of the program and the potential ease of incorporating it in the JT8D engine deems it an attractive configuration.
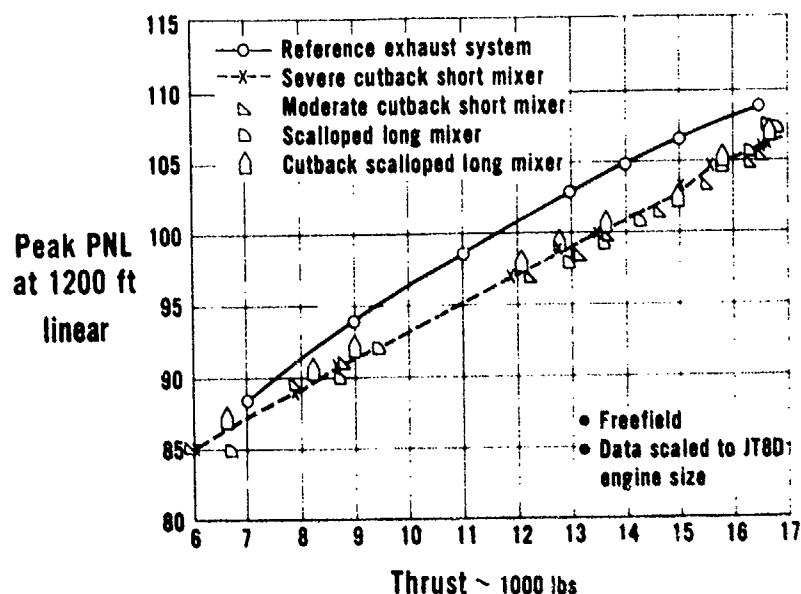
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Figure 5-52   Peak Perceived Noise Levels of Severe Cutback Short Flowpath Mixer·
Comparison with Results of Other Mixers Tested (with Engine Secondary
Flow Simulation)

Performance data indicated a substantial reduction in thrust at takeoff conditions amounting
to a 0.6% penalty relative to the reference configuration. Cruise performance was not com-
promised, with a 0.9% improvement in cruise TSFC still apparent, equal to the result for the
moderately cutback short mixer. A comparison of performance of the severe cutback and
typical short and long mixers is shown in Figure 5-53. Cold flow data were not acquired
and, therefore, the split between mixing and pressure loss could not be determined for the
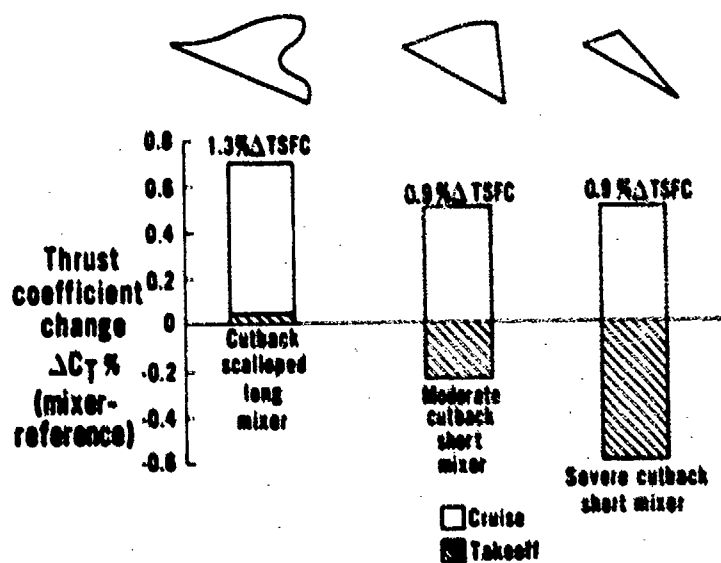severe cutback configuration.

Figure 5-53   Performance Comparison of Severe and Moderate Cutback Short Flowpath
and Cutback Scalloped Long Flowpath Mixers (with Engine Secondary
Flow Simulation)

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5.4.3 Performance Diagnostic and Improvement Program

The results presented in the previous sections indicated that a short mixer contained within the current JT8D engine case hardware could meet the 3-4 PNdB noise reduction goal for the JT8D engine. However, the .6% loss* of thrust at the takeoff condition was considered unacceptable since it would have an adverse impact on the operational characteristics of JT8D powered airplanes. In addition, the need for a 7.6 inch spool piece extension to the engine case was deemed a detriment to a commercially practical installation of a mixer on the JT8D engine since such an extension would require a nacelle re-design.

Thus, there was strong motivation to reduce the take-off thrust loss of the short mixer and to remove the spool piece from any JT8D mixer design. Removal of the spool piece would result in a mixer which has a high probability of fitting within present nacelle lines; but the impact of removing the spool piece on the mixer performance had to be determined. In addition, removal of the spool piece would move the thrust reverser of the Boeing 727 installation closer to the mixer. The flow field induced by the thrust reverser during reverse thrust operation could interact with the mixer primary and fan flows and adversely affect the engine match.

Data required to assess the impact of spool piece removal on mixer performance and engine match changes caused by mixer/thrust reverser flow field interaction was not obtained in the program described in the previous sections. In addition, data was not available to indicate ways of changing the mixer design to reduce the takeoff thrust loss. Thus an add-on program was defined with the intent of providing the required additional test data. This add-on program and its results are discussed in this section.

The detailed objectives of the add-on program were the following:

1. Assess the impact of the mixer on the engine match of a Boeing 727 reverser configuration without the spool-piece extension during reverse thrust operation. The effect on engine match would be based on changes to the effective throat area, as quantified in terms of the discharge coefficient.

2. Define the effect on short mixer performance of removing the spool-piece extension.

3. Provide diagnostic information to identify possible sources of losses in the short mixer using pressure surveys and flow visualization methods.

4. Based on the diagnostic information, identify and test configuration modifications designed to reduce or eliminate losses.

5. Use the results of the add-on program to select a mixer design for full scale JT8D engine (see Section 6).

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*It is noted that this result was obtained for the same mixer used in the noise tests, but the 7.6" (full scale) spool-piece was present in the performance testing.

5.4.3.1 Mixer-Reverser Compatibility

For DC-9 and 737 aircraft, the thrust reverser is mounted aft of the tailpipe exit. The resulting large axial distance between the mixing plane and the reverser would preclude any aerodynamic interaction between the mixer and reverser, and thus any effect on the engine match during reverse thrust operation. However, in the 727 installation, the reverser "blocker doors", which reverse the exhaust flow direction, are located within the tailpipe relatively close to "M" flange. Thus, during reverse thrust, the presence of a mixer might alter the normal flow-field, and possibly change the effective discharge area, indicating mixer/reverser incompatibility. Any reduction in effective discharge area would result in a higher fan operating line and could compromise engine stability during reverse operation.

In order to determine mixer/reverser compatibility, a 1/7 scale model which simulated the flow field of the internal clam-shell thrust reverser used on many Boeing 727 airplanes was mounted behind the severe cutback short mixer, as shown in Figure 5-54. Two additional configurations were tested with the reverser: the reference exhaust system was tested in order to establish the effect of the reverser on the discharge coefficient of the exhaust system without mixer present, and, a slightly longer version of the short mixer was tested to determine how a mixer having lobes extending into the reverser discharge would affect the discharge coefficient. (The motivation for testing the longer mixer was based on data that had indicated that as mixer lobe length was increased, mixer nozzle takeoff thrust tended to approach that of the reference exhaust system, as shown in Figure 5-55). Schematics of the three configurations tested with the reverser are shown in Figure 5-56.
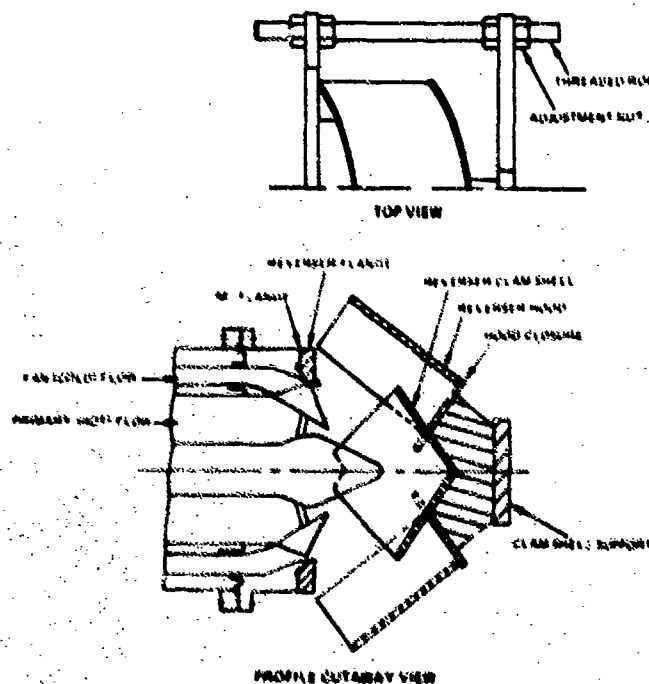

Figure 5-54   Hooded Clamshell Reverser Model Configuration Showing Fluidyne Installation With Severe Cutback Short Mixer
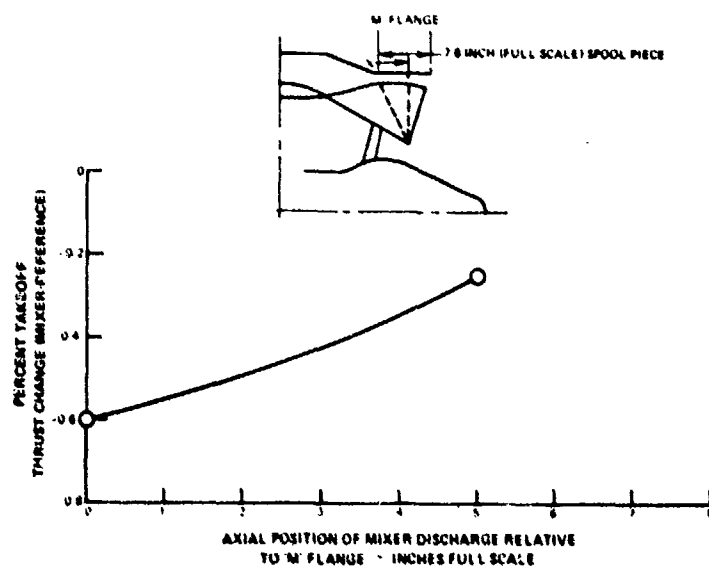
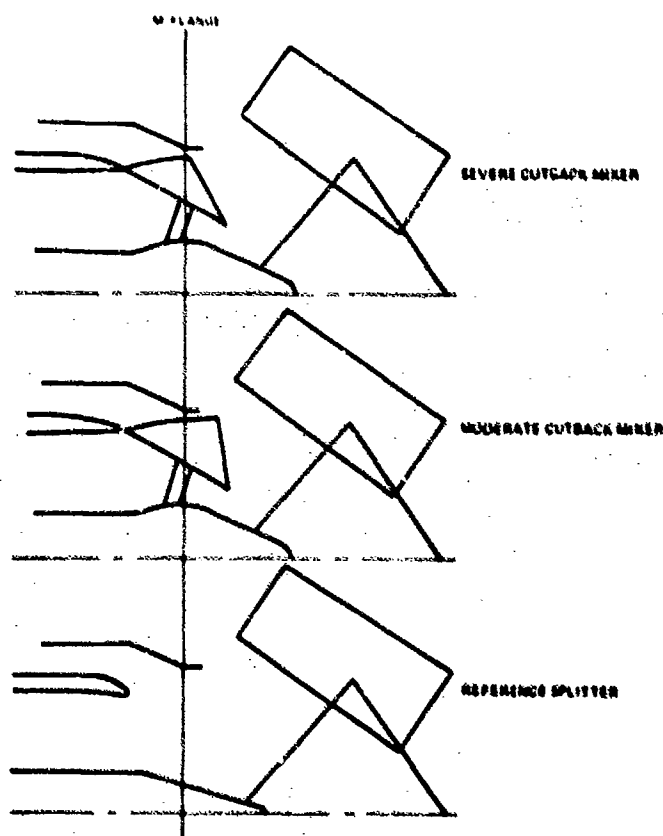Figure 5-55   *Effect of Lobe Length on Takeoff Thrust of Short Mixer With 7.6 Inch Spool Piece*

Figure 5-56   *Schematics of Reference Exhaust System and Mixer Model Configurations Tested With Hooded Clamshell Reverser*

All configurations were tested at simulated takeoff conditions. Discharge coefficients, C_D, were determined as follows. For the reference exhaust configuration, the addition of the reverser caused a small change in the flow ($< 1.0\%$). This change was assumed to be due to a slight error in positioning of the reverser, resulting in an improper discharge area. A new discharge area was calculated to account for this small effect and was defined as the discharge area for all of the reverser configurations.

Discharge coefficients for each configuration were then calculated by using the standard formula given in Section 4.2.2.

The results of the testing are shown in Figure 5-57. In this figure, the percent change in discharge coefficient, $\% \Delta C_D$, due to the presence of the reverser is plotted against the distance of the splitter or mixer relative to M flange. The decrease in discharge coefficient (or decrease in effective discharge area) due to the reverser was .3% for the severe cutback mixer, while the longer moderate cutback mixer caused an 8.8% decrease.
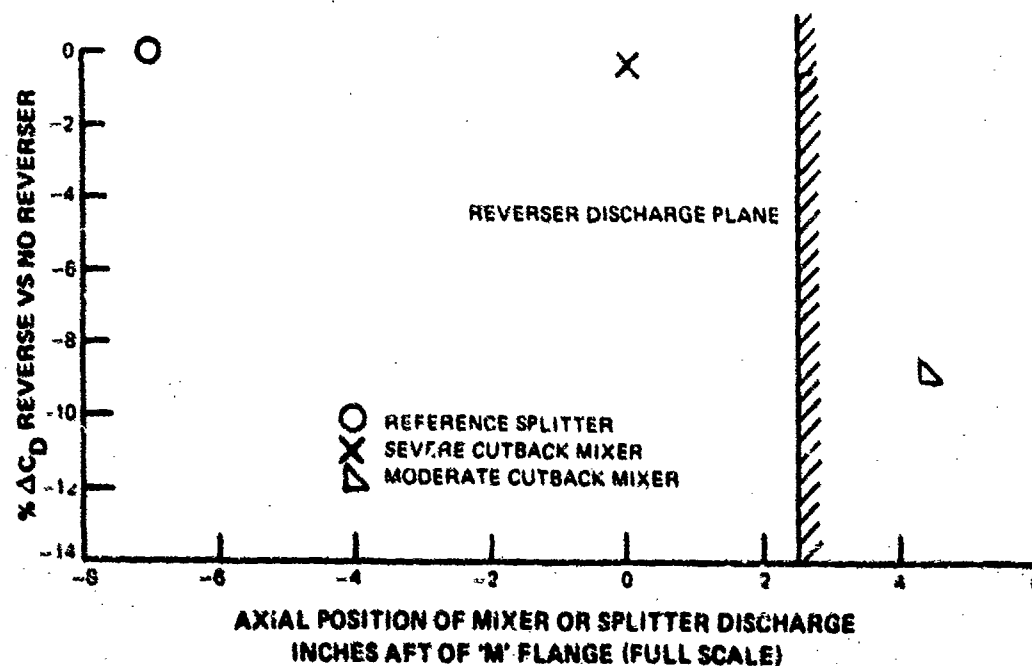

Figure 5-57   *Effect of Mixer Discharge Position on Hooded Clamshell Discharge Coefficient*

Using these results, it was judged that the mixer lobes could be extended to the upstream location of the reverser discharge opening without adversely affecting the effective area. A mixer with lobes extending beyond the reverser discharge was considered to be unacceptable in this regard. Since the earlier performance results had indicated that longer mixer lobes provided improved performance, the mixer was modified by extending the mixer lobes to the 727 reverser discharge plane. This modified mixer, called the intermediate length mixer, is illustrated on Figure 5-58. (The mixers having longer lobes than those of the intermediate

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length mixer are considered to have an adverse effect on discharge area during reverse thrust, while shorter mixers are judged to have poorer performance). Thus, it was established that the mixer/reverser compatibility was satisfactory (without the presence of the spool-piece extension) for a mixer having lobes not extending beyond the reverser discharge plane.
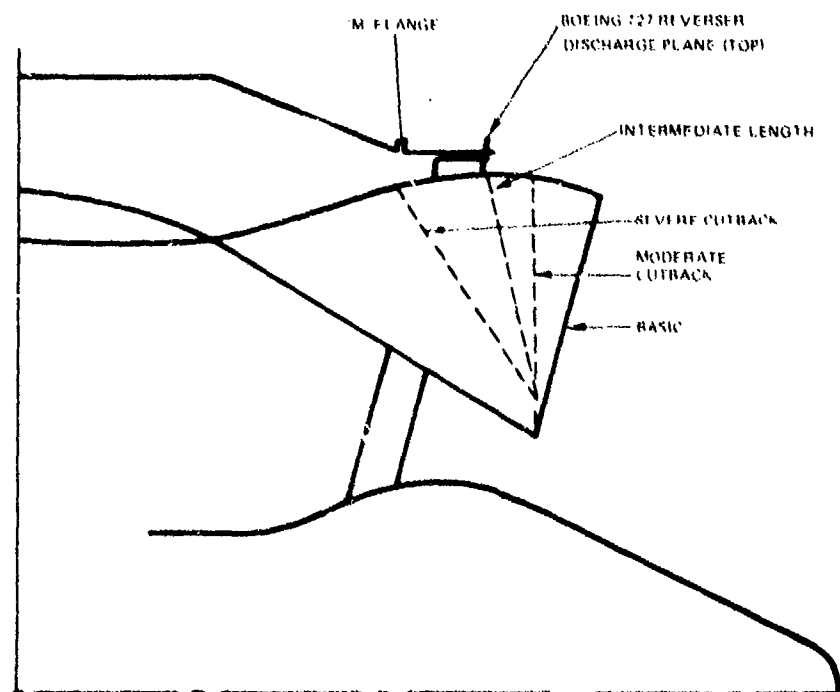

Figure 5-58   Schematics of Short Flowpath Mixers

5.4.3.2   Effect of Spool-Piece Extension On Performance

The previous performance tests of the short mixers (without reverser) had been conducted with the spool-piece extension inserted between "M" flange and tailpipe. The reverser tests described in the previous section indicated that the mixer/reverser compatibility was satisfactory without the spool-piece extension if the mixer lobes did not extend beyond the reverser discharge plane. Since it was extremely desirable to evolve a final mixer design not requiring the spool piece extension to the engine, it was necessary to determine the effect on mixer performance due to the removal of the spool-piece.

Since performance results for the moderate cutback mixer with spool piece were available, it was retested without the spool-piece to determine the impact of the spool-piece removal on the performance of a given mixer. Figure 5-59 presents a comparison of performance test results for the moderate cutback mixer with and without the spool-piece. These results indicate that the removal of the spool-piece caused a performance penalty relative to the mixer with the spool-piece. The takeoff thrust coefficient decreased by .3%, and cruise TSFC increased by .4%. The removal of the spool-piece also resulted in a 5% increase in bypasss ratio and essentially no change in nozzle discharge coefficient.
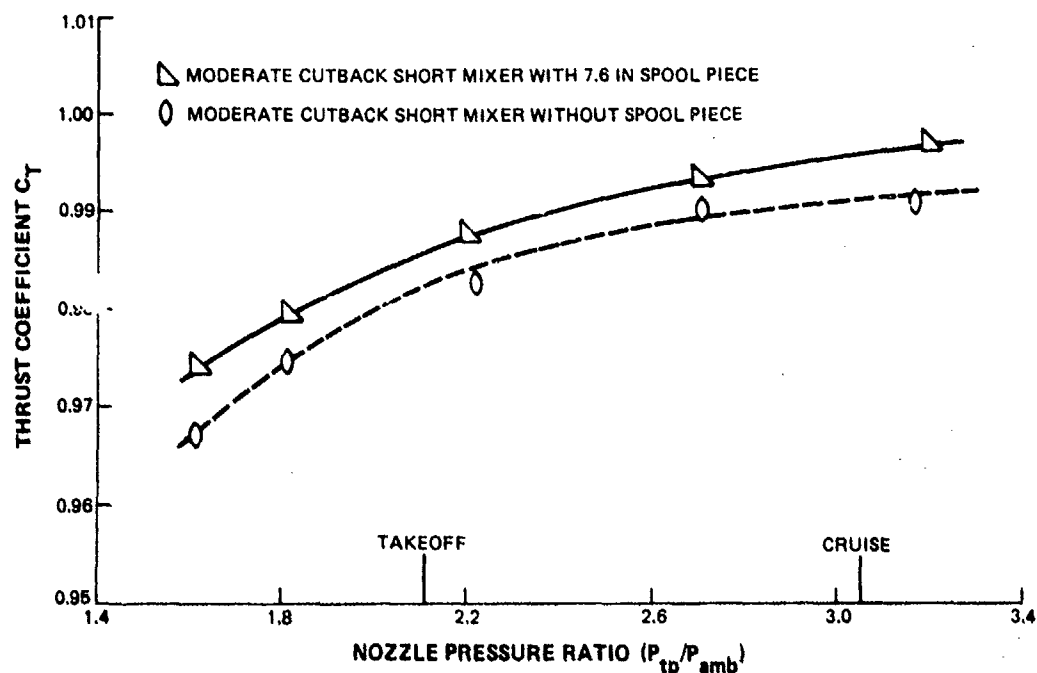
Figure 5-59   *Effect of 7.6-Inch Spool Piece on Moderate Cutback Short Mixer Perform-
ance (With Engine Secondary Flow Simulation)*

Testing of the intermediate length mixer (also without the spool-piece) resulted in perform-
ance essentially equivalent to that of the moderate cutback (without spool-piece) mixer, as
shown in Figure 5-60. The intermediate mixer without spool-piece was tested with both
hot and cold flow so that the data could be used to define mixing and pressure loss in order
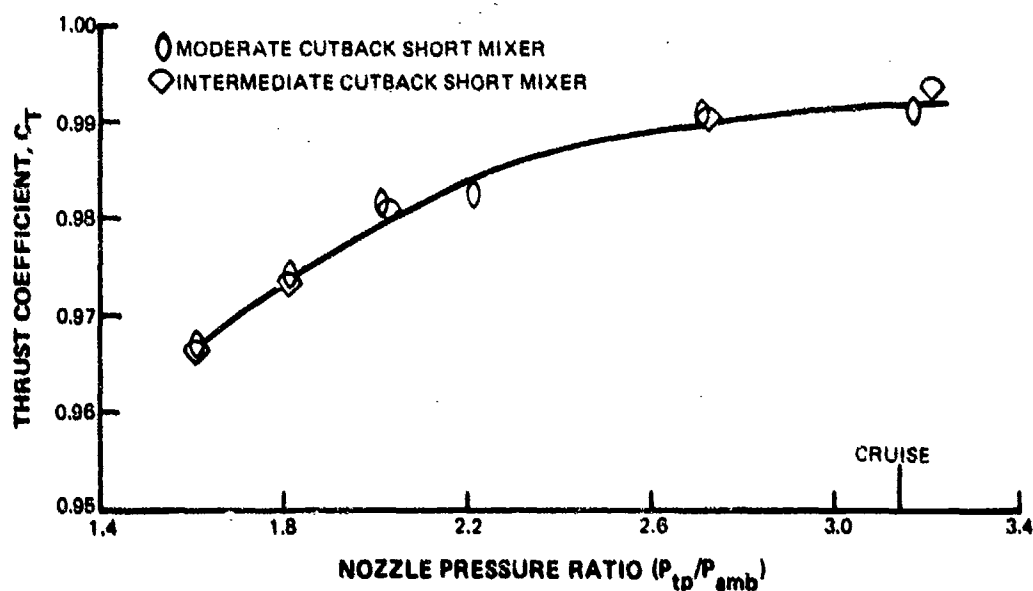to help determine the cause of the performance loss due to eliminating the spool-piece.

Figure 5-60   *Performance Comparison of Moderate Cutback and Intermediate Length
Short Mixers, Without Spool Piece*

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Since the intermediate length mixer had not been tested with the spool-piece, mixing and pressure loss with and without the spool-piece could not be compared directly for this specific configuration. However, as the performance levels of the intermediate length and moderate cutback mixers without spool-piece were essentially identical, it was assumed that the mixing and pressure loss of the moderate cutback mixer were equal to those of the intermediate length mixer. Using this assumption, the mixing and pressure loss of the intermediate length mixer with and without spool-piece could be estimated. These estimates are compared in Figure 5-61 and indicate that the thrust coefficient reduction caused by the removal of the spool-piece could be attributed to an increase of 0.25% in pressure loss and a 10% decrease in mixing.
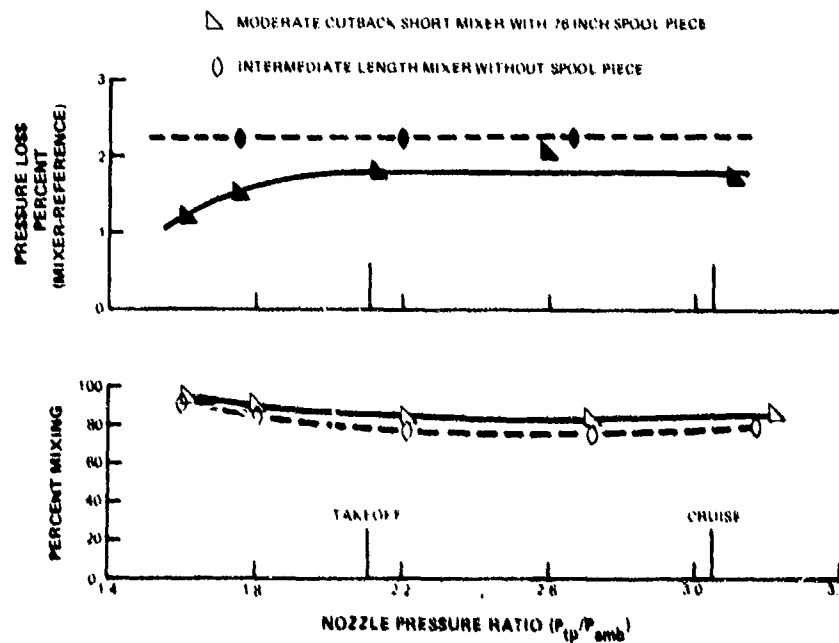

Figure 5-61   *Comparison of Mixing and Pressure Loss of Moderate Cutback and Compromise Length Mixers*

Since the removal of the spool-piece decreased the total distance from the mixer lobe discharge to the nozzle exit (i.e., it reduced the length over which mixing could take place), a test was conducted with the long 737 tailpipe in order to obtain additional data on the effect of nozzle to lobe discharge distance (i.e., mixing length). Using this additional data in conjunction with existing data, a plot of nozzle thrust coefficient versus distance was obtained, as is shown in Figure 5-62. The thrust coefficients are approximately equal for the long tailpipe and the reference tailpipe without spool-piece. Although the long tailpipe most likely increased the mixing due to its increased length, it also probably increased the pressure loss due to the flow scrubbing the increased surface of the long tailpipe (aggravated by high wall velocities due to the somewhat inverted nature of the flow). These two effects could cancel each other, producing no net change in performance. It is possible that the optimum performance could occur for a lobe-to-nozzle distance between the values present in the long and reference tailpipes. To qualitatively investigate this possibility, data from the moderate cutback mixer, tested with the reference tailpipe with and without the spool-piece, are also shown on Figure 5-62. As can be seen, an optimum value of thrust coefficient seems to exist at a mixing length of between 60 and 70 inches. This conjecture not withstanding, the advantage of not having the spool-piece is considered important enough to accept the performance loss shown on Figure 5-62 for the no-spool-piece case.

Therefore, a configuration was identified (intermediate length mixer) which eliminated the spool-piece, increased the mixer lobe length and produced a takeoff thrust loss of .7% and an improvement of .5% in cruise TSFC relative to the reference exhaust system. Therefore, the diagnostic and performance improvement testing conducted in the next phase of the program concentrated on the configurations without the spool-piece.
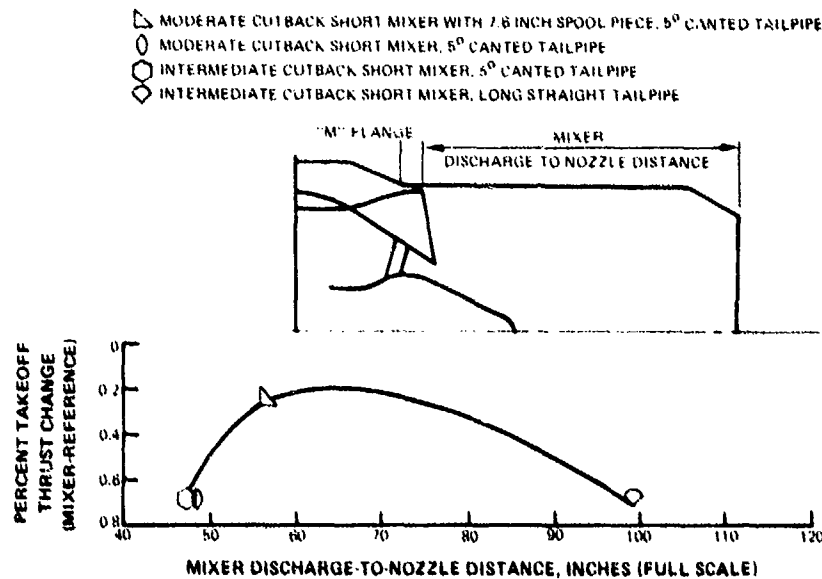

Figure 5-62   Effect of Mixer Discharge-To-Nozzle Distance On Mixer Performance
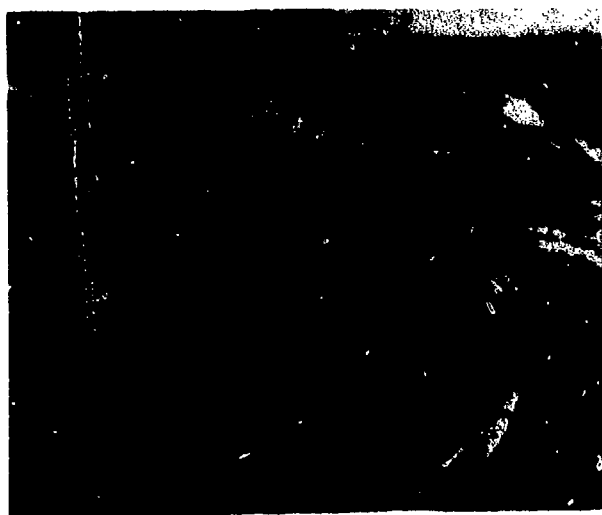
Diagnostic Testing

Diagnostic testing of the severe cutback mixer and the intermediate length mixer using flow visualization and pressure surveys was conducted in an attempt to isolate the cause or causes of the takeoff thrust loss and provide guidance for design changes which would improve performance. Flow visualization testing using cold flow were conducted with the intermediate length mixer at a pressure ratio simulating takeoff thrust conditions. The model was painted white for background contrast and spots of a lampblack and oil mixture were liberally dabbed on the mixer plug and tailpipe. The photographs in Figures 5-63(a, b, and c) show the results of this testing. Figure 5-63(a) shows that the fan flow over the mixer was generally well behaved with no indication of separation in the mixer valleys. All of the boundary layer flow on the inner wall of the fan stream did, however, appear to be accumulating in these valleys based on the high density of "streamlines" in the valley regions. This behavior could lead to high loss in this location of the mixer.

Flow in the primary stream (Figure 5-63(b) also appeared to be well behaved. The dispersion of the lamplack and oil on the plug is probably due to wakes produced by the plug struts. The shadowed regions on the outer case behind the lobes indicate that the high velocity primary flow was impinging on the outer case, a potential area of high loss.
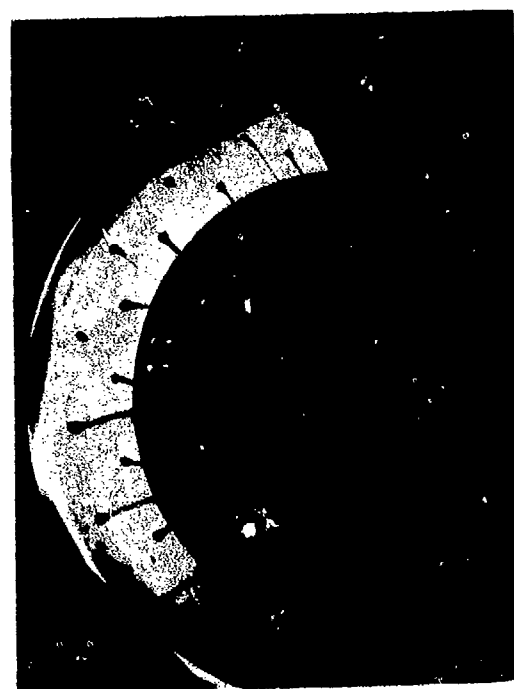
The flow along the outer case (Figure 5-63(c) appeared to stagnate or separate as evidenced by the oil spots in the area of "M" flange which were not dispersed by the flow.

(a)

(b)

(c)

Figure 5-63   *Flow Visualization Results: a) Tailpipe Removed; b) Viewing Upstream From End of Tailpipe; c) Viewing Downstream Into Tailpipe*

The flow visualization results are partially substantiated by the results of wall static pressures measured on the severe cutback mixer configuration. These data are presented as a ratio of local static pressure to average upstream total pressure on Figure 5-64. The sudden increase in outer case local static pressure at "M" flange could be an indication of separation at this point. Similar results are evident for the flow near the discharge of the fan valleys.
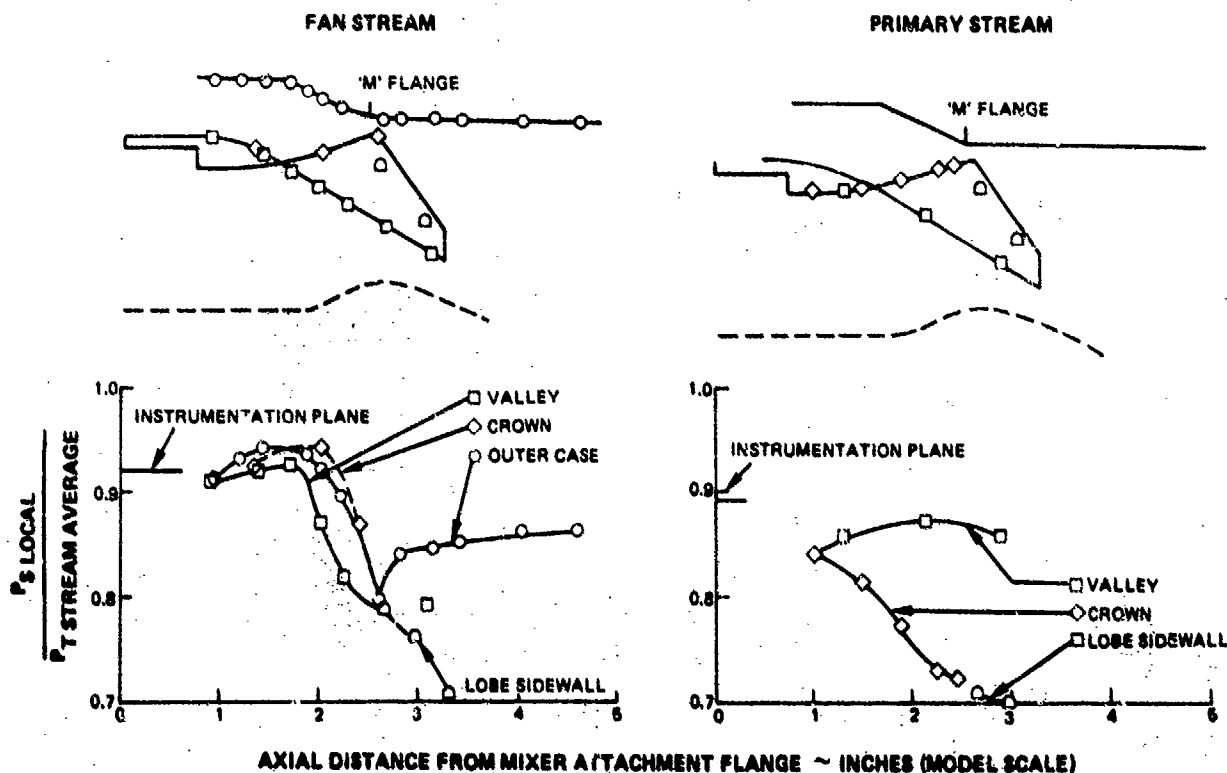

Figure 5-64   Results of Wall Static Pressure Survey For Severe Cutback Short Mixer at Takeoff Thrust

Based on the results of the diagnostic testing, it became evident that mixer flowpath improvements should be incorporated to avoid stagnation of the fan flow impinging on the mixer lobes, to attempt to improve the flowpath area distribution through the fan stream, to prevent flow separation along the outer wall, and to eliminate the primary flow impingement on the outer case.

Mixer Modifications For Performance Improvement

Three modifications to the mixer designed to improve the flowpath were investigated. These included: a) a fairing to cover the mixer crown on the fan stream side in order to eliminate the fan flow from impinging on the mixer lobes, and b) a filler to smooth out the sudden convergence in the outer case upstream of "M" flange thereby improving the area distribution in the fan stream, and c) the penetration of the compromise length mixer was reduced at the mixer discharge to redirect the high velocity primary flow away from the outer case. These modifications are illustrated in Figure 5-65.
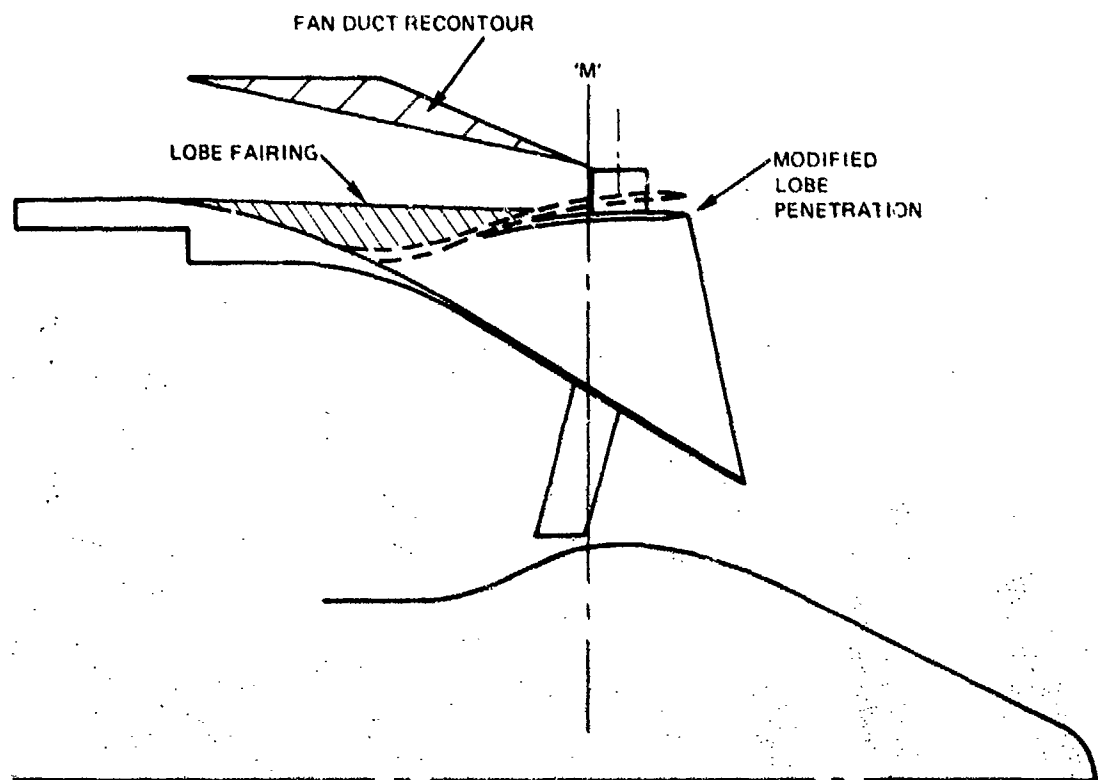
Figure 5-65 *Flow Revisions Designed To Improve Performance Of Intermediate Length Mixer.*

The results of the tests of the mixer with the lobe fairings and reduced penetration indicated a substantial improvement in takeoff performance with no change at cruise. The addition of the outer case filler provided no further performance improvements.

To summarize the results of this "add-on" performance program, a comparison of the performance obtained on the short mixer configurations is shown on Figure 5-66. The improvement in cruise TSFC and the loss in takeoff thrust is shown for three basic configurations. The severe cutback mixer with spool-piece, which was the "starting" configuration for the add-on tests, had a cruise TSFC improvement of .9% and a takeoff thrust loss of .65% relative to the reference exhaust system. Eliminating the spool-piece and extending the lobe length (intermediate length mixer) reduced the cruise TSFC benefit from .9% to .5% and had little effect on takeoff thrust. The mixer modified to reduce losses reduced the takeoff thrust loss to .3% while having negligible effect on cruise TSFC.

In addition, satisfactory mixer/reverser compatibility was demonstrated without the spool-piece extension, implying that this mixer could be incorporated in engines installed in DC-9, 737 and 727 airplanes without major engine/nacelle modifications. The results of model performance tests described in this section were significant in the mixer configuration recommended for incorporation in the full scale JT8D engine, as discussed in Section 6.
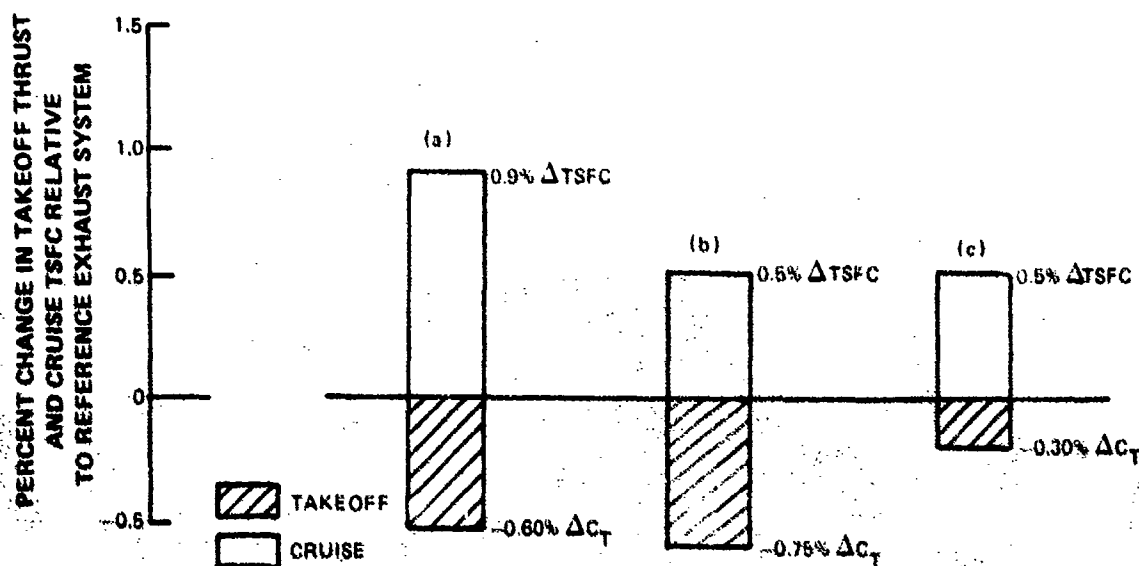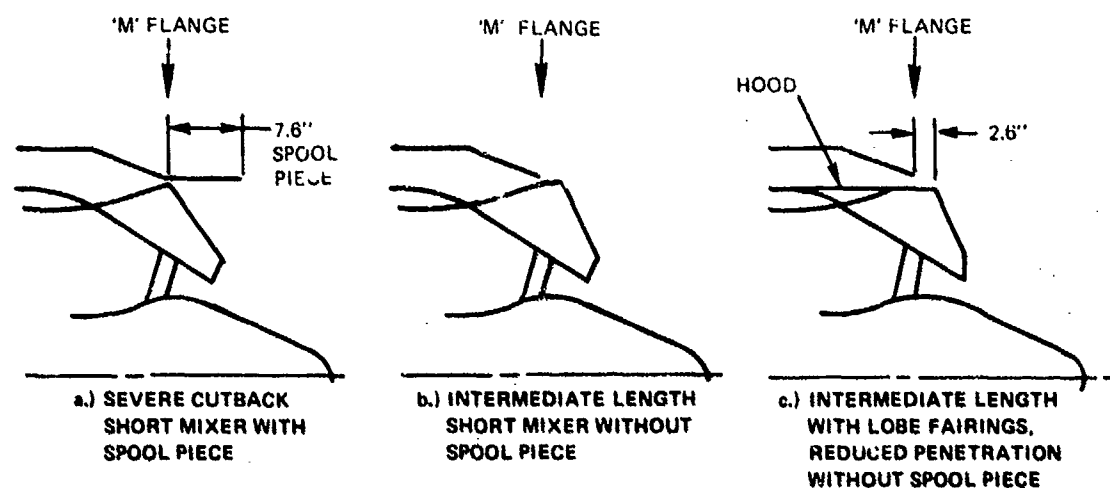
Figure 5-66   Performance of Short Mixers Relative To Exhaust System

5.5 EFFECT OF CANTED TAILPIPE

Current JT8D exhaust systems are canted from 3.5 to 5 degrees from the engine centerline to align the thrust vector below the airplane centers of gravity of the Douglas DC-9 and Boeing 727 aircraft and to increase the engine ground clearance during takeoff rotation of the 727. To accomplish this cant, a wedge shaped flange is inserted at the interface of the engine exhaust case and airframe supplied tailpipe. Since the reference exhaust system and mixer designs investigated in the FAA program were tested with tailpipes aligned parallel to the engine centerline, tests were conducted to investigate the effect of cant as part of the Pratt & Whitney Aircraft in-house program. The engine secondary flow details discussed previously were not simulated in these tests. A comparison of the canted tailpipe and the tailpipe used for the FAA program is illustrated in Figure 5-67.
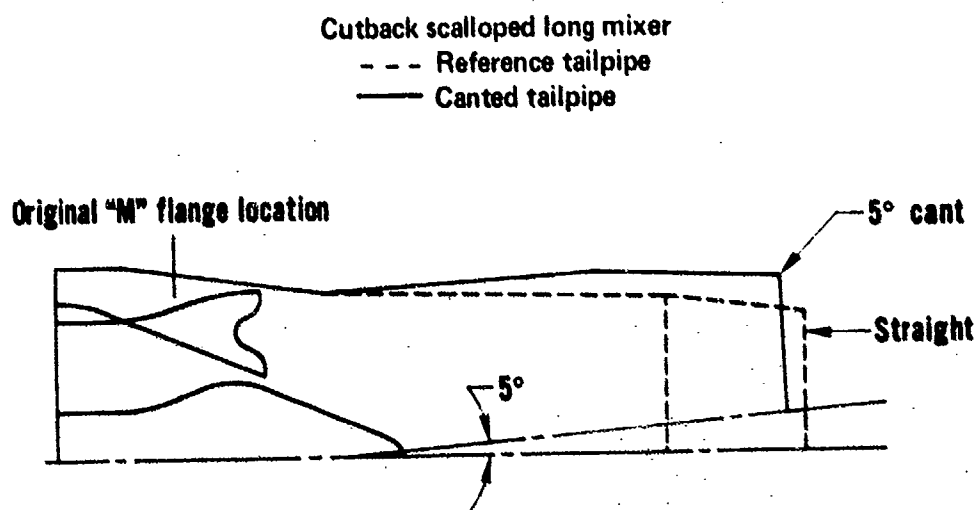
Cutback scalloped long mixer
- - - Reference tailpipe
——— Canted tailpipe

Original "M" flange location

5° cant

Straight

5°

Figure 5-67   Schematic of 5° Canted and Reference Tailpipes

Traverse results from the reference exhaust system (Figure 5-68), indicated that the primary stream was essentially unaffected by the canted tailpipe, while the annular fan stream was distorted to conform to the nonconcentric passage caused by the tailpipe cant. Traverse results from one mixer configuration tested with a canted tailpipe showed a general distortion of the velocity profile, but the bulk effect was to cause a redirection of the flow along the canted centerline direction.

For the acoustic measurements, the tailpipe was canted 5 degrees away from the microphones in order to simulate the overhead position of an airplane at the takeoff noise certification point (assuming the engine centerline is horizontal). The test setup is illustrated in Figure 5-69. Only the reference exhaust system and the cutback deep scalloped mixer were acoustically tested with the canted tailpipe.

For the reference exhaust system, only a slight effect on peak PNL was caused by the tailpipe cant, as shown in Figure 5-70. A slight increase (< 0.5 PNdB) was seen at low thrust, and a slight decrease (< 0.5 PNdB) occurred at higher thrusts. At a thrust of 13,400 lb. a comparison of perceived noise directivities, Figure 5-71, show that the canted tailpipe caused a slight distortion to the directivity pattern. The spectral comparisons of Figure 5-72 (a and b) show a slight change to the spectrum, where the noise is reduced slightly at low frequencies and increased slightly at high frequencies.
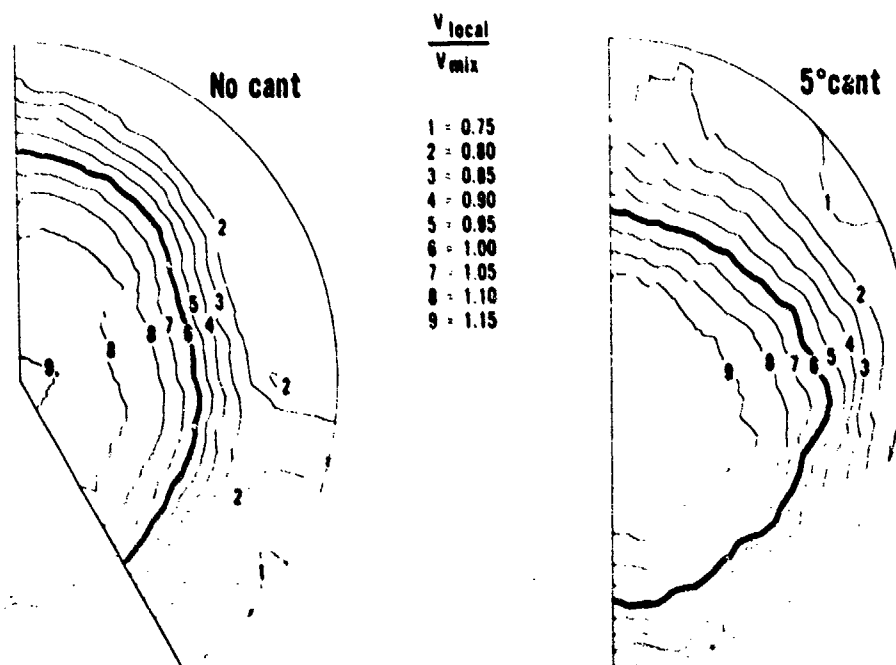
No cant

5°cant

$$\frac{V_{local}}{V_{mix}}$$

1 = 0.75
2 = 0.80
3 = 0.85
4 = 0.90
5 = 0.95
6 = 1.00
7 = 1.05
8 = 1.10
9 = 1.15

Figure 5-68   Effect of Canted Tailpipe on Tailpipe Exit Velocity Contour Map of Reference Exhaust System (No Engine Flow Simulation)
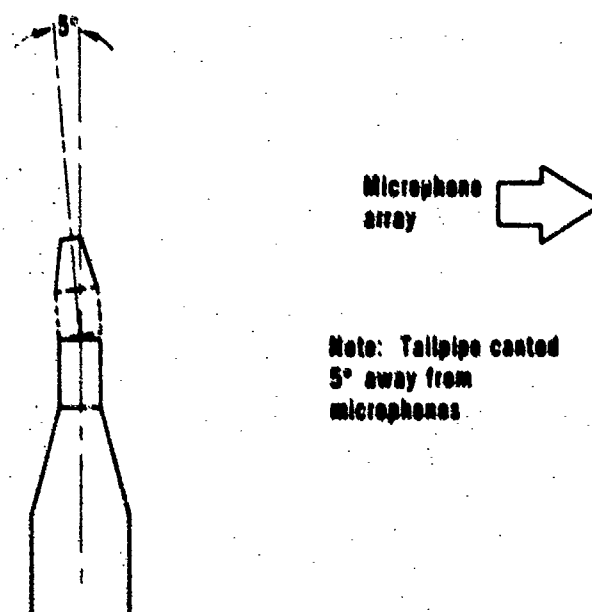
5°

Microphone array

Note: Tailpipe canted 5° away from microphones

Figure 5-69   Tailpipe Cant Acoustic Test Setup

88
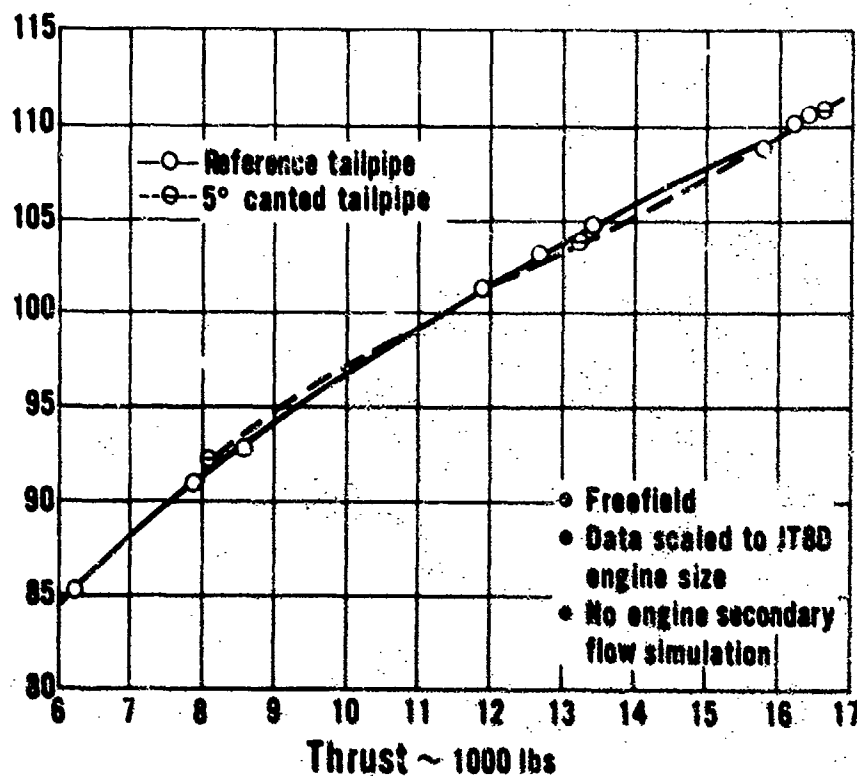
Figure 5-70   *Effect of 5° Canted Tailpipe on Peak Perceived Noise Level of Reference Exhaust System*
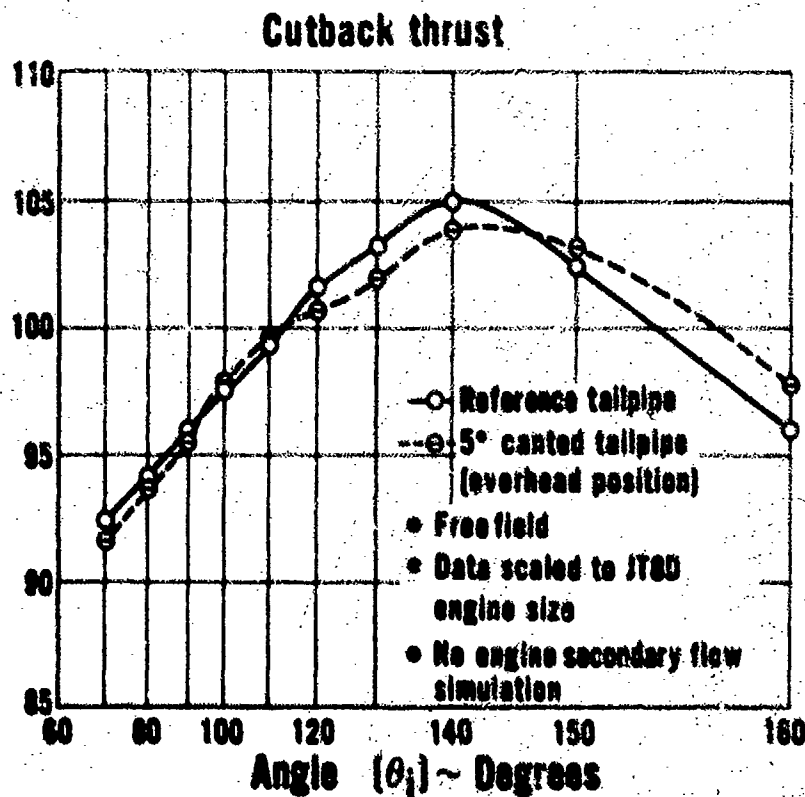

Figure 5-71   *Effect of 5° Canted Tailpipe on Perceived Noise Level Directivity of Reference Exhaust System*
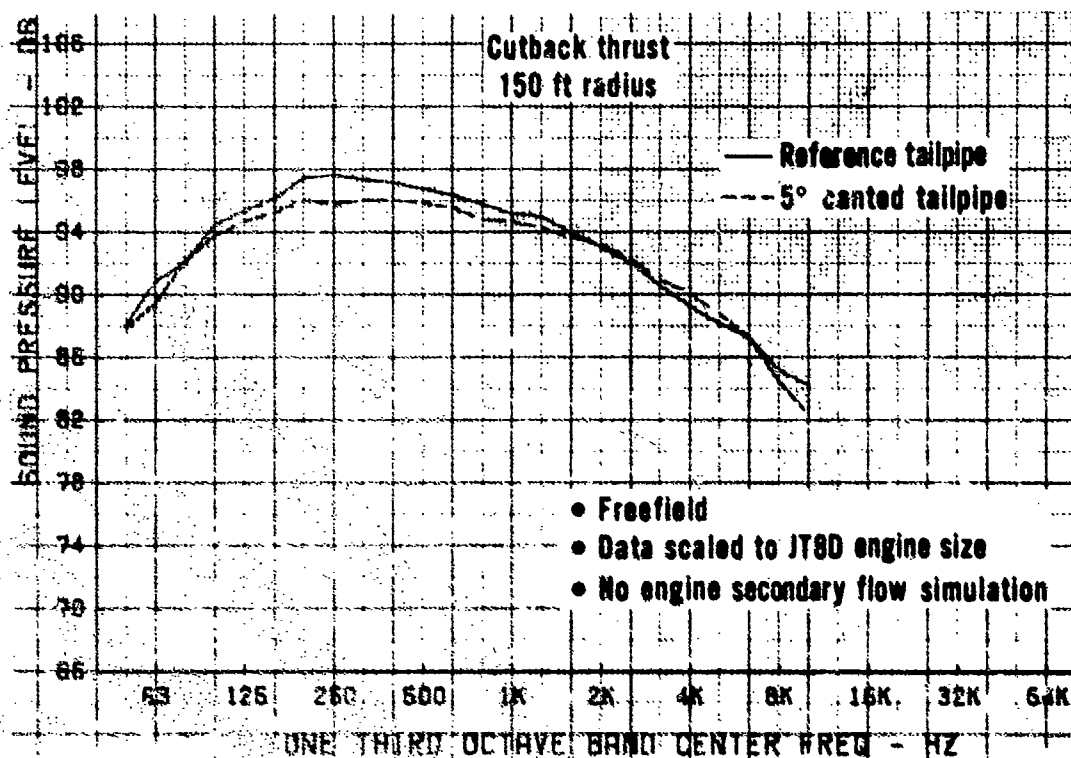
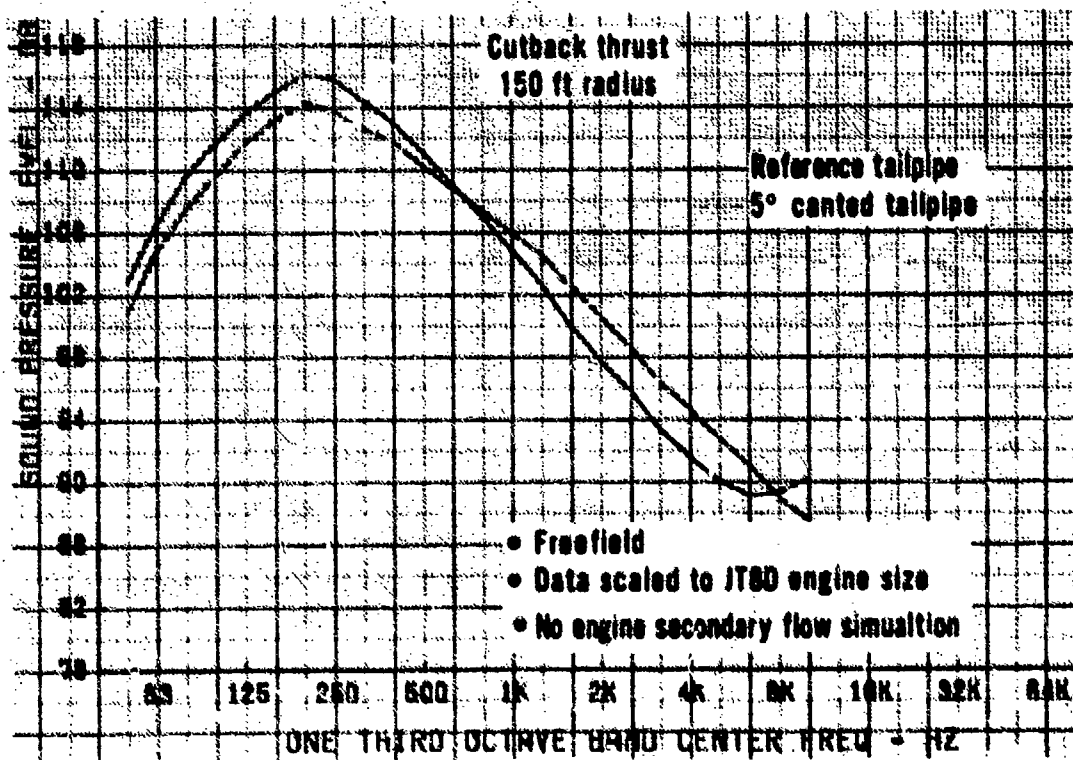Figure 5.72 a. Effect of 5° Canted Tailpipe on SPL Spectra at 90 Degrees of Reference Exhaust System

Figure 5.72 b. SPL Spectra at 140 Degrees

The canted tailpipe had a significant effect on the cutback scalloped long mixer peak PNL, as shown in Figure 5-73. PNL reductions of up to 1-½ PNdB occurred. The noise reduction was relatively consistent at all angles, as shown in the PNL directivity curve at 12,500 lb. thrust in Figure 5-74. Since the noise reduction was uniform for all angles, the effect of the tailpipe cant was not simply the result of redirecting the noise angularly by the amount of cant. It appears that the canted tailpipe improved the noise suppression mechanisms provided by the mixer. The SPL spectrum were changed as shown in Figure 5-75(a and b). At 90 degrees, the noise was reduced equally at all frequencies, while at 140 degrees there was significant reduction in the level at low frequencies with negligible change at high frequencies.

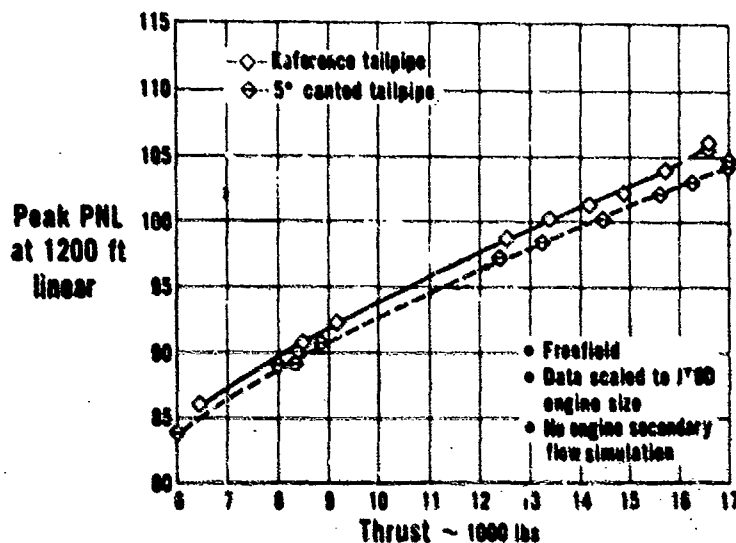Figure 5-73   Effect of 5° Canted Tailpipe on Peak Perceived Noise Level of Cutback Scalloped Long Flowpath Mixer
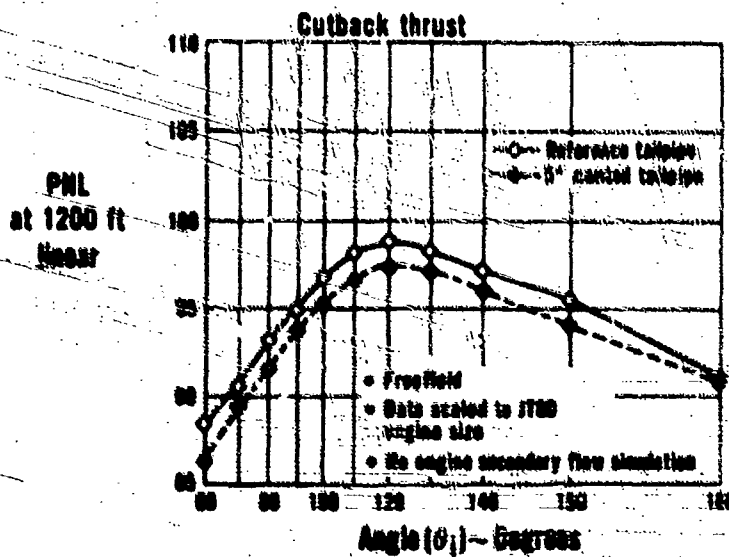

Figure 5-74   Effect of 5° Canted Tailpipe on Perceived Noise Level Directivity of Cutback Scalloped Long Flowpath Mixer
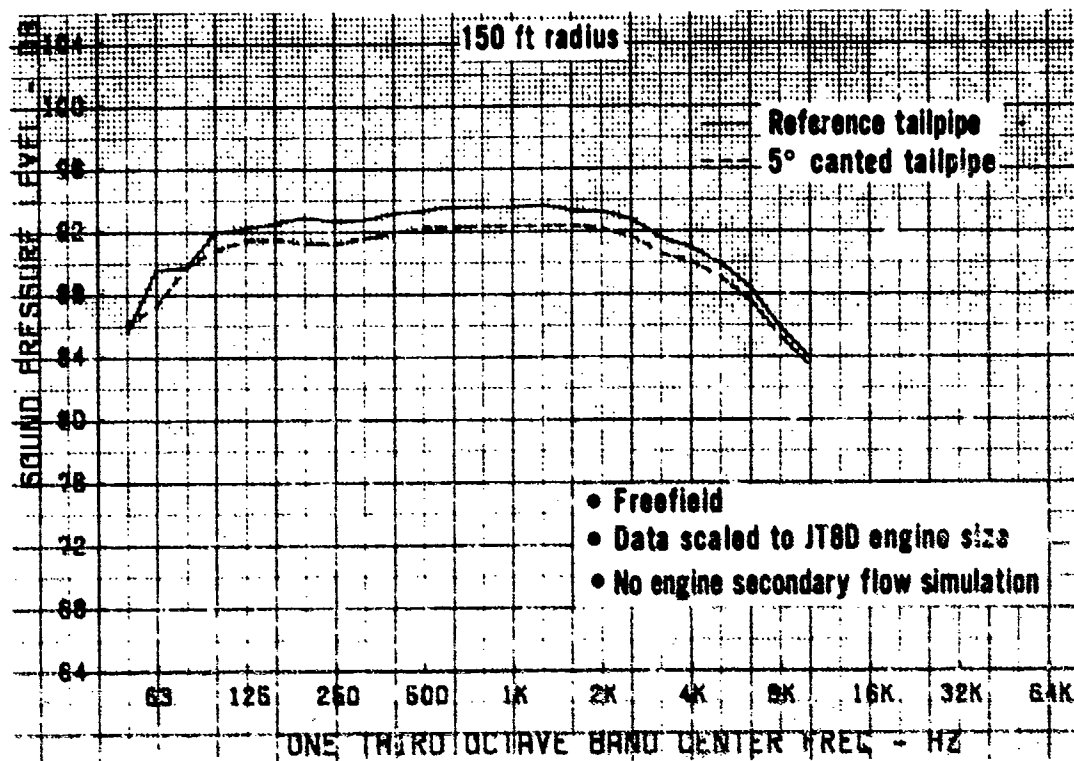
91

Figure 5-75(a) Effect of 5° Canted Tailpipe on SPL Spectra at 90 Degrees of Cutback Scalloped Long Flowpath Mixer
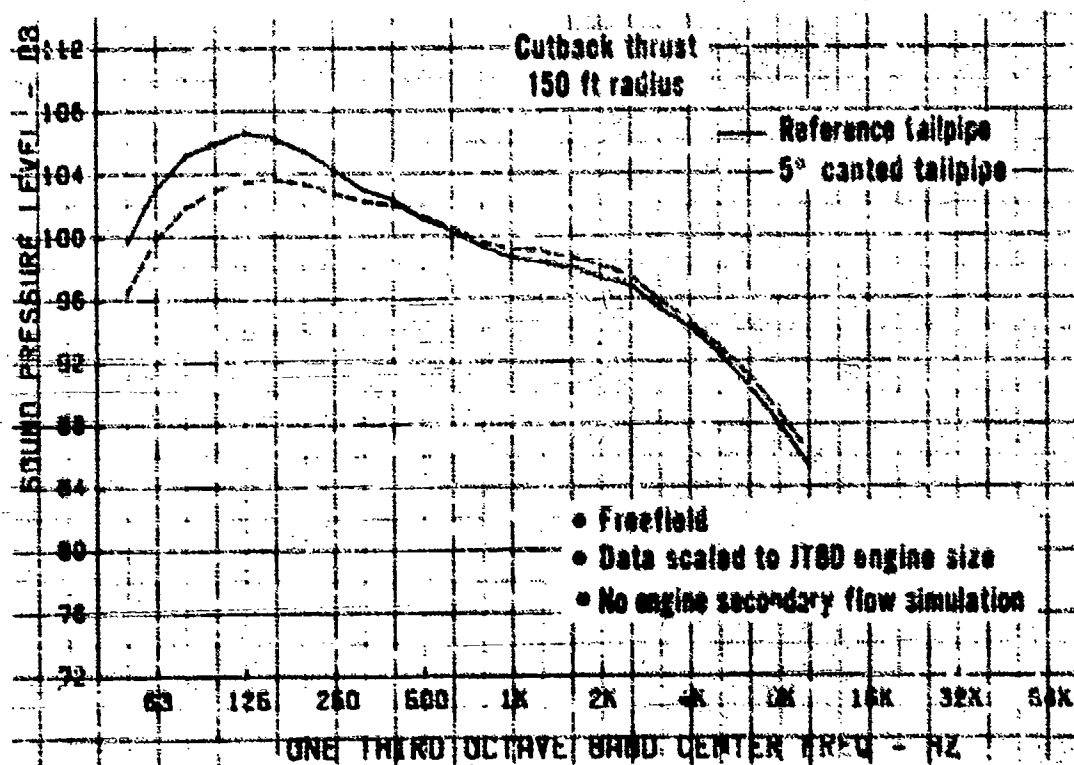

Figure 5-75(b) SPL Spectra at 140 Degrees

Thus, for both the reference and mixer nozzles, the canted tailpipe caused changes to the jet noise as compared with that measured with the standard tailpipe installed. These effects were more dramatic on the mixer configuration, with resultant noise reductions of 1½ PNdB compared to ½ PNdB for the reference nozzle. It must be noted, however, that since these particular data were obtained without engine secondary flow simulation, the results may not be directly applicable to a real JT8D engine.

Performance results indicated no significant difference in thrust output due to tailpipe cant when vector resultant forces were used to evaluate thrust coefficient.

5.6 EFFECT OF TAILPIPE LENGTH

A significant variable in determining the degree of mixing obtainable from a mixer is the length and volume of the tailpipe beyond the mixer discharge plane. These dimensions determine the residence time of gases within the mixer, and thus the amount of viscous shearing and mixing that can take place. In general, the longer the tailpipe, the more nearly 100% mixing theoretically can be obtained.

On at least one airplane type (Boeing 737) powered by JT8D engines, the engines are fitted with tailpipes significantly longer than the reference tailpipe used for this program which approximated those used on Boeing 727 and Douglas DC-9 aircraft. Therefore, as a part of the in-house program, the effect of tailpipe length was investigated on both the reference exhaust system and the cutback scalloped long mixer. As in the canted tailpipe tests, engine secondary flow simulation was not included in these tests. Schematics of the long and reference tailpipes are shown in Figure 5-76.

    - - - **Reference tailpipe**
    ───── **Long tailpipe**

Original "M" flange location

Figure 5-76   Schematics of Reference and Long Tailpipes

Traverse results for the reference exhaust and the cutback scalloped long mixer indicated improvements in mixing with the long tailpipe as indicated by the velocity contours in Figures 5-77 and 5-78. The profile for the mixer with the long tailpipe was the flattest profile obtained in the test program with peak velocities at approximately 3% above the ideally mixed value.

Reference tailpipe

$\dfrac{V_{local}}{V_{mix}}$

1 - 0.75
2 - 0.80
3 - 0.85
4 - 0.90
5 - 0.95
6 - 1.00
7 - 1.05
8 - 1.10
9 - 1.15

Long tailpipe

Figure 5-77   Effect of Long Tailpipe on Tailpipe Exit Velocity Contour Map of
Reference Exhaust System (without Engine Secondary Flow Simulation)

Reference tailpipe

$\dfrac{V_{local}}{V_{mix}}$

1 - 0.95
2 - 1.00
3 - 1.05

Long tailpipe

$\dfrac{V_{local}}{V_{mix}}$

1 - 0.95
2 - 1.00

Figure 5-78   Effect of Long Tailpipe on Tailpipe Exit Velocity Contour Map of Cutback
Sealloped Long Flowpath Mixer (without Engine Secondary Flow Simulation)

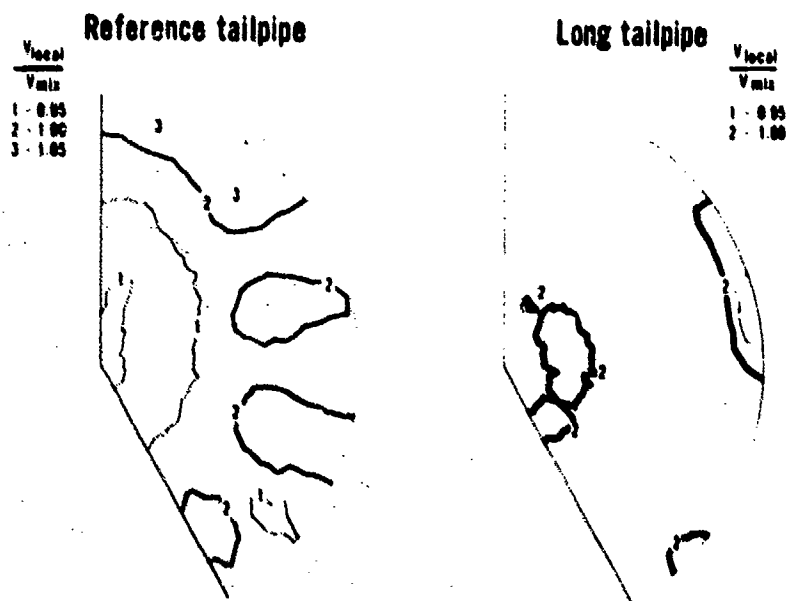The long tailpipe decreased the peak PNL of the reference exhaust system by ½ PNdB across the thrust range, as shown in Figure 5-79. The spectra at 90 and 140 degrees in Figure 5-80 (a and b) show only negligible changes due to the long tailpipe. (Since the data points of the two tests did not exactly coincide, the spectral levels of the long tailpipe data must be adjusted down by about ½ dB to make a direct comparison of noise levels). The slight decrease in noise level, with no change in spectra shape, is consistent with the increased mixing seen in velocity profile data.

Peak PNL at 1200 ft linear

Legend:
—O—Reference tailpipe
--●--Long tailpipe

- Freefield
- Data scaled to JT8D engine size
- No engine secondary flow simulation

Thrust ~ 1000 lbs

Figure 5-79   Effect of Long Tailpipe on Peak Perceived Noise Level of Reference Exhaust System

Figure 5.80(a) Effect of Long Tailpipe on SPL Spectra at 90 Degrees of Reference Exhaust System

Figure 5.80(b) SPL Spectra at 140 Degrees

The long tailpipe reduced the peak PNL of the cutback deep scalloped mixer by as much as 1 PNdB, at thrust below 16,000 lbs., had negligible effect at higher thrust as shown in Figure 5-81. The effect on the 90 and 140 degree spectra is shown in Figure 5-82 (a and b). The main effect was to reduce the high frequency noise, with negligible effect on the noise at low frequencies. This result is expected since the velocity profile data indicated a reduction of the high velocity "pockets" present at the tailpipe exit plane.

Figure 5-81   Effect of Long Tailpipe on Peak Perceived Noise Level of Cutback Scalloped Long Flowpath Mixer

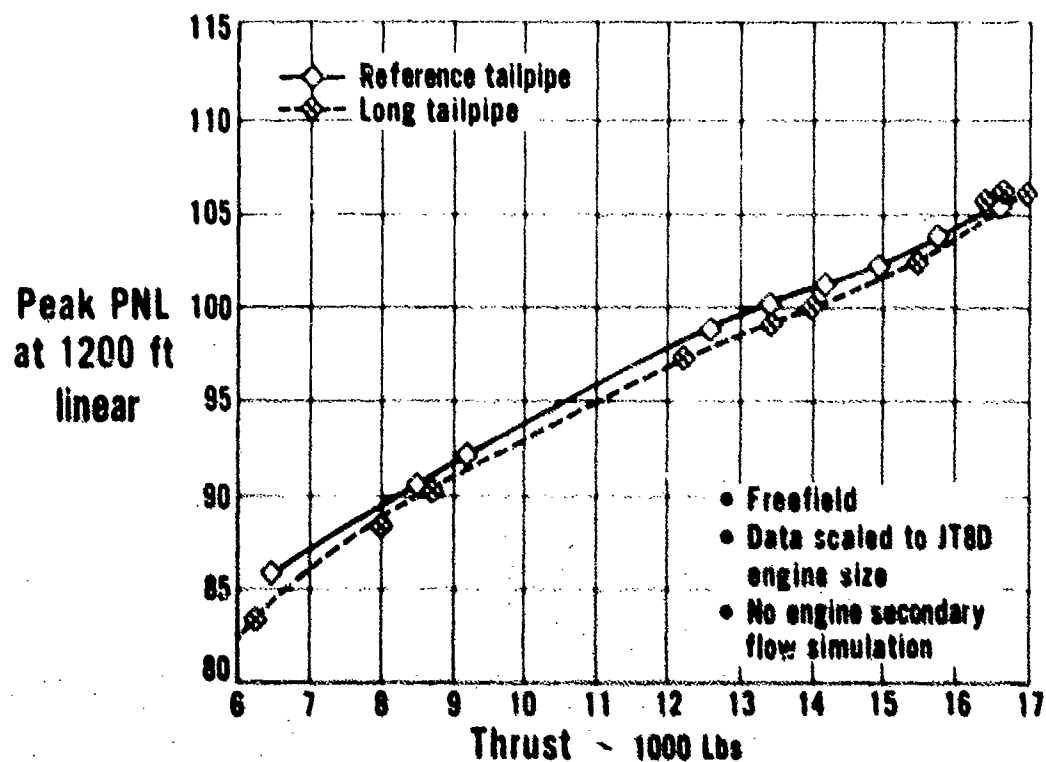Figure 8.2.a — Effect of Long Tailpipe on SPL Spectra at 90 Degrees of Cutback Scalloped Long Mixer

Figure 8.2 b — SPL Spectra at 140 Degrees

Test results for the reference exhaust system and the cutback scalloped mixer indicated increased mixing for both configurations. Figure 5-83 details the increased mixing for the reference configuration and indicates a 15% increase in mixing with thrust coefficient increases of 0.18 and 0.23% at takeoff and cruise respectively. Mixing increases encountered with the mixer exhaust system were essentially of the same magnitude as those of the reference system. Therefore the performance improvement increment remained the same as that for the shorter tailpipe.

Thus, the effect of the long tailpipe was to provide small noise reductions and thrust improvements on both the baseline and mixer nozzles consistent with the increased mixing achieved in the extra length of the long tailpipe. However, as was the case with the canted tailpipe tests, the acoustic data with the long tailpipe were obtained without the engine secondary flow simulation and thus may not be applicable directly to the JT8D engine.

Figure 5-83   Effect of Long Tailpipe on Reference Exhaust System Performance (without Engine Secondary Flow Simulation)

5.7 MIXER/ENGINE MATCH IMPLICATIONS

Incorporating a mixer in the JT8D engine will increase mixing and pressure loss of the exhaust system, causing the effective area of the jet nozzle to be reduced. This reduction in nozzle area is predicted to suppress the engine match and raise the fan operating line for the JT8D. Since this increase in operating line could detract from engine stability, an increase in physical area will probably be required for the jet nozzle and for the reverser discharge for a JT8D engine incorporating an internal mixer. For the intermediate length mixer recommended for full scale demonstration tests (See Section 6), the predicted decrease in effective area at takeoff thrust is 3.1% based on the model tests. As shown in Figure 5-84, 2% of the decrease is due to increased pressure loss of the mixer, and 1.1% is due to the increased mixing. This discharge coefficient decrease translates directly into a requirement for a 3.1% jet nozzle or reverser area increase in order to maintain engine match.

Figure 5-84   Effect of Compromise Length Mixer on Effective Jet Nozzle or Reverser
Discharge Coefficient

100

6.0 MIXER SELECTION FOR JT8D ENGINE

A major objective of the JT8D mixer investigation was to define an internal mixer that could be incorporated on the JT8D engine and have the following characteristics: produce a significant reduction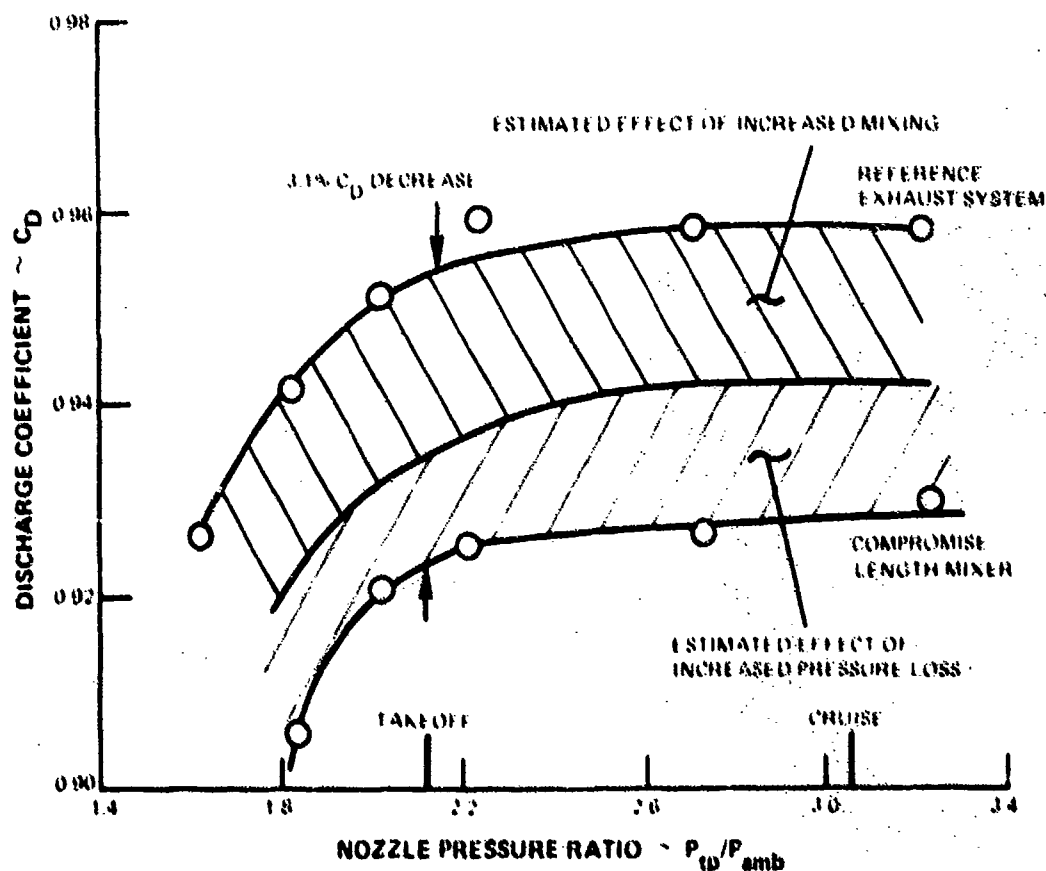 in jet noise (3 to 4 PNdB); be compatible with the JT8D engine structural limitations; be installed with minimum changes to Boeing 727 and 737 and Douglas DC-9 tailpipe hardware; provide acceptable performance and have acceptably light weight. In the course of this FAA program and the independently funded PWA program, three basic mixer designs have been investigated.

6.1 CANDIDATE MIXER DESIGNS

The first design, shown in Figure 6-1(a), achieved acceptable acoustic reductions (3 to 4 PNdB) and demonstrated acceptable performance with a 1.3% improvement in cruise TSFC and no impact on takeoff thrust. This design would require a new engine outer case resulting in a 16-inch downstream movement of the engine/aircraft interface flange ('M' flange). A mixer system requiring these changes would substantially increase engine cost and would increase engine weight by approximately 157 lbs. In addition, the increased length of the exhaust system envelope would have a substantial impact on the nacelle/reverser design with an accompanying weight increase and could limit aircraft takeoff rotation angles for some JT8D powered aircraft.

The second candidate design, shown in Figure 6-1(b), was designed to be compatible with the current JT8D outer case and utilizes a 7.6-inch cylindrical spool piece downstream of M flange for mixer support. Model testing of this design achieved a 3-4 PNdB noise reduction but sacrificed some performance relative to the longer mixer design. A net loss of 0.25% in takeoff thrust and an improvement of 0.9% in cruise TSFC (relative to the reference exhaust system) were evident from the testing. The weight increase over the current engine exhaust system was estimated to be 125 lbs. Although the impact of this configuration on aircraft hardware is less than for the long mixer configuration, substantial modification to aircraft hardware still appears necessary.

The third configuration (Figure 6-1(c)) was designed to have the minimum possible impact on existing engine and aircraft hardware. This design incorporates a thin support ring inserted at 'M' flange to support the mixer. The exhaust system envelope would not change forward of 'M' flange and would shift rearward only slightly (0.15 to 0.25 inch) aft of 'M' flange. In addition the mixer lobe length was chosen to limit the adverse effect of the mixer on thrust reverser effective flow area for internal clamshell reverser systems similar to the 727 design. This specific design was not tested for noise, but since its design fell within the geometric envelopes of other mixers that produced 3-4 PNdB reduction, it also was projected to produce similar noise reductions. Relative to the reference exhaust system, takeoff thrust was predicted to be decreased by .3%, and cruise TSFC was estimated to be 0.5% based on the scale model testing. The weight of this mixer exhaust system is estimated to be 105 lbs. more than the weight of the current exhaust system.

'M' FLANGE AND CUSTOMER
CONNECT MOVED DOWNSTREAM
16 INCHES

(a) JT8D CANDIDATE LONG MIXER

CURRENT 'M' FLANGE WITH
7.6 INCH SPOOL ADDED TO
CUSTOMER CONNECT FLANGE

(b) JT8D CANDIDATE SHORT MIXER

MAINTAINS CURRENT CUSTOMER
CONNECT 'M' FLANGE LOCATION

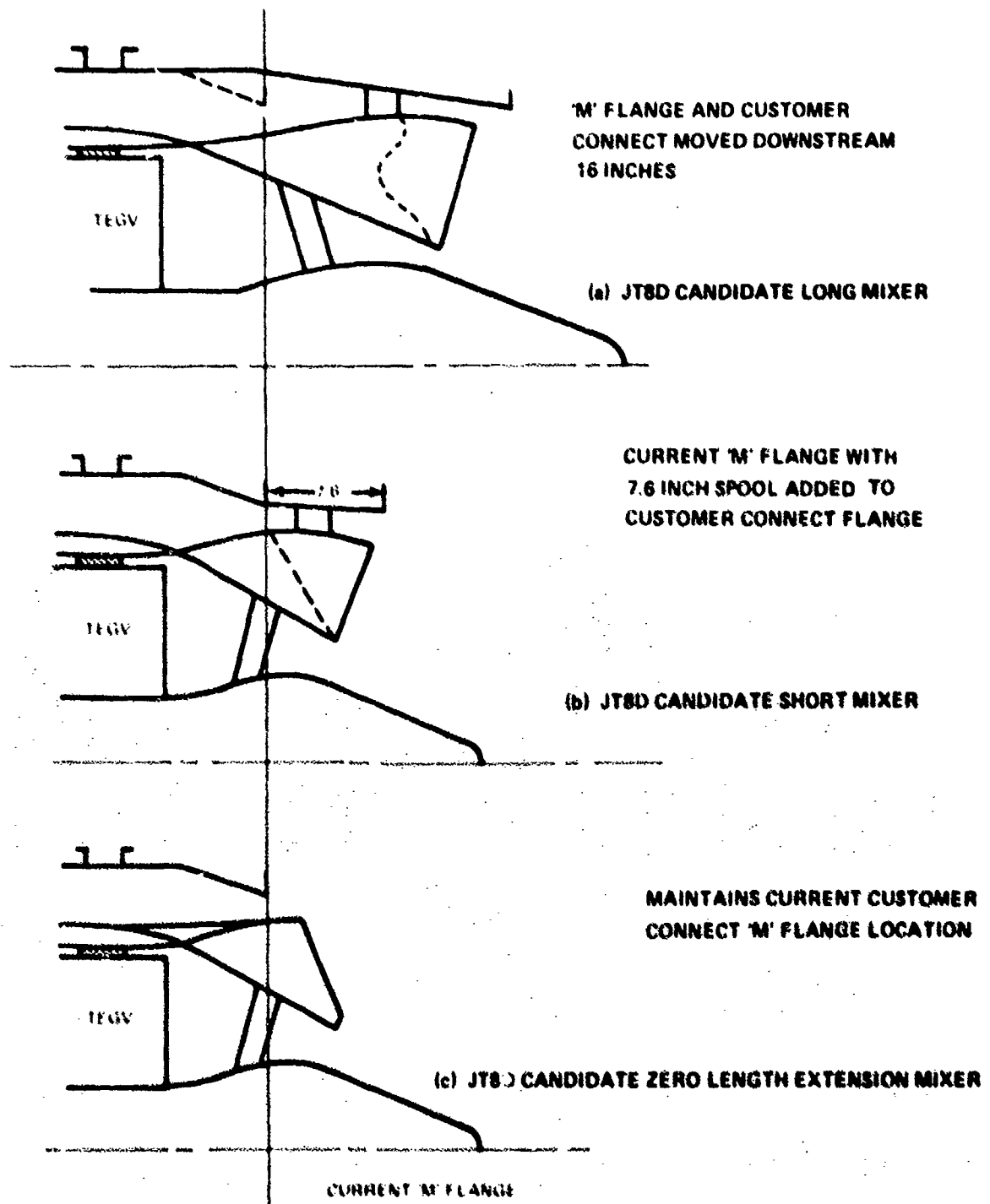(c) JT8D CANDIDATE ZERO LENGTH EXTENSION MIXER

CURRENT 'M' FLANGE

Figure 6-1   JT8D Mixer Flowpath Comparison

6.2 MIXER SELECTION

Based on the results described above, the third alternative is recommended as the candidate design for full scale mixer development. Since all three designs are predicted to produce 3-4 PNdB noise reductions for the JT8D engine, the lower weight and less severe projected hardware changes required for the 'zero-length extension' mixer were considered to outweigh the potential performance advantages of the longer mixer.

Although the 0.3% deficit in takeoff thrust indicated by the model test is a concern, there is a possibility that this deficit will not exist in the engine. The lower Reynolds numbers of the 1/7th scale models result in less boundary layer turbulence intensity which make the models more prone to separation and pressure loss than would be the full scale mixer

6.3 GENERAL ARRANGEMENT OF RECOMMENDED MIXER DESIGN

The general arrangement of the recommended mixer design is shown in Figure 6-2. This preliminary design incorporates a hardwall tailplug with a slip-joint at the forward end, a lobed, curved-wall, convoluted mixer with a slip-joint front flange, and an outer support ring (with cantilevered fingers) which supports the complete mixer system through struts. The struts would be welded to the mixer lobe crown and bolted to the support ring fingers. This design would permit installation of th mixer exhaust system without the need to replace existing engine cases with new cases The capability to remove the system as a single unit would enhance maintainability Allowance for differential thermal growth will be considered in the design of the slip joints Side-wall curvature in the lobes may be incorporated to minimize panel vibration and sensitivity to thermal and pressure gradients.
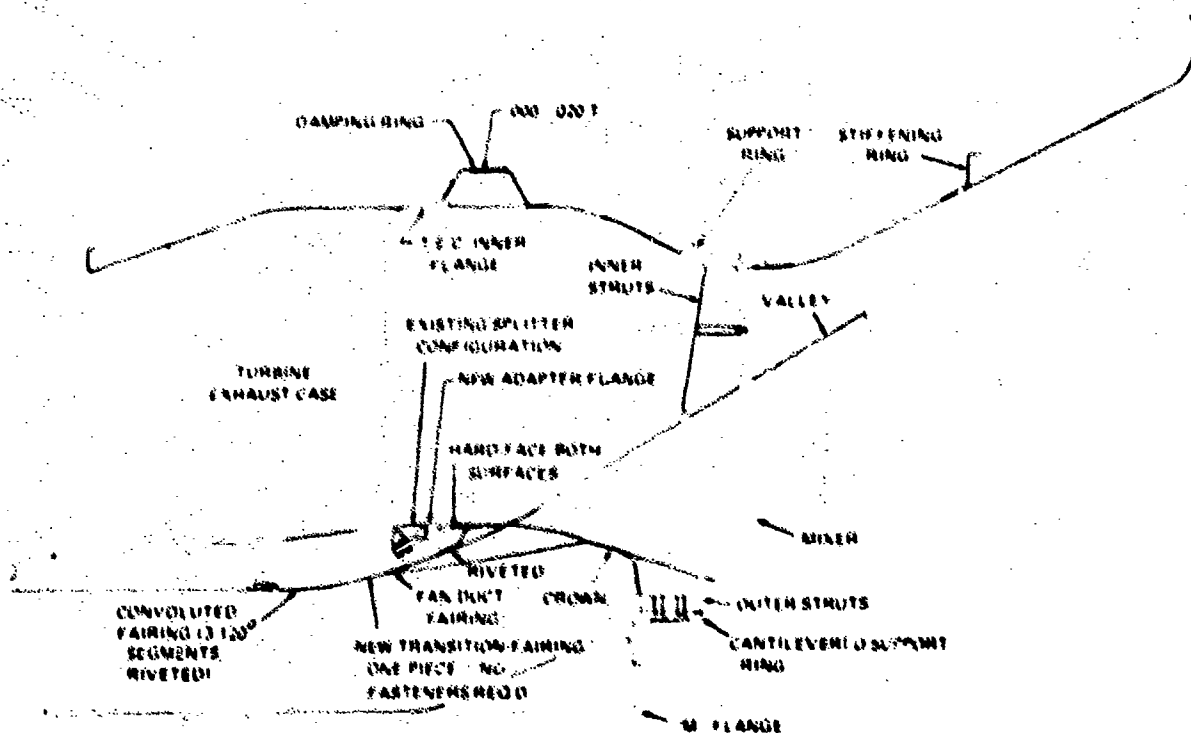

Figure 6-2   Intermediate Length Mixer Design For JT8D Engine

Struts at the ID would be designed to provide support for the tailplug, and OD struts would provide system support. In addition, the struts would provide eccentricity and circumferential pitch control to produce the most acceptable mixing profile. The convoluted aluminum fan duct fairings would be attached to the mixer by a segmented ring.

An outer support ring, sandwiched between the fan exhaust duct (flange 'M' in Figure 6-2) and the customer reverse flange, must be sized to absorb the engine maneuver, blow-off and thermal loads. The material of this outer support would be titanium to be compatible with current exhaust ducts and to minimize the weight impact.

The tailplug would be supported by the mixer through aerodynamic struts welded to the mixer ID lobes. This method of support will facilitate modular assembly and prevent the loads of the tailplug from being applied to the turbine exhaust case inner flange. The tailplug would be structurally supported by a ring with aerodynamic standup feet which are welded to the struts. The sheet metal ring on the turbine exhaust case inner flange will provide a flexible interface with the plug and additional stability to the system. An oil drain at the bottom centerline of the plug would provide fire safety.

Inco 625 is a good candidate material for the mixer, tailplug, and inner and outer struts because of its high strength at 1200°F, good formability, weldability, availability, and acceptable cost range. Inco 625 also has excellent repairability properties in the field.

7.0 CONCLUDING REMARKS

A scale model experimental program was conducted to determine the noise reduction and the impact on propulsive performance that would result from installing a multilobed internal mixer on the JT8D engine. Various mixer designs ranging from short to long were fabricated on 1/7 scale and tested along with a model of the JT8D reference exhaust system.

The results obtained during the program support the following conclusions:

MODEL MIXER RESULTS

1) Long mixer designs reduced peak PNL by 3-4 PNdB, reduced cruise specific thrust consumption by up to 1 3% and had no impact on takeoff thrust. However incorporation of this type mixer into the JT8D engine would require a new engine outer case 16 inches longer than the current design and would require extensive modifications to the current engine/nacelle installations.

2) A short length mixer reduced peak PNL by 3-4 PNdB, reduced cruise specific fuel consumption by 0.5%, but decreased takeoff thrust by 0.3%. This type mixer could be incorporated into the JT8D engine without a new outer case and would require relatively minor modifications to the current engine/nacelle installations.

RECOMMENDATION FOR FULL SCALE MIXER DESIGN

Based on the noise and performance results of the mixers tested during the program, in conjunction with installation requirements, a short length mixer was selected as the best candidate design for application to the JT8D engine since it produced acceptable noise reductions and cruise performance benefits and would require relatively minor modifications to the current engine nacelle. However, the possible adverse impact of the small takeoff thrust loss measured during the model tests, if present in the full scale engine, must be assessed in terms of engine and airplane operation procedures.

ADDITIONAL SIGNIFICANT RESULTS

1) The jet noise and performance were affected by incorporating turbine exit swirl, turbine case struts, fan stream distortion and fan case struts. These real engine "secondary" flow effects tended to decrease the noise reduction and enhance the performance changes due to the mixer.

2) For tests conducted without the real engine "secondary" flow effects, a tailpipe canted 5 degrees to simulate that used for some airplane installations caused an additional noise reduction for a mixer of up to 1½ PNdB for the overhead condition assuming that the engine centerline is horizontal. A long tailpipe, simulating the Boeing 737 installation, caused an additional noise reduction for a mixer of up to ½ PNdB.

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2. Society of Automotive Engineers, Inc., "Proposed ARP 876, Gas Turbine Jet Exhaust Noise Prediction", September 1976.

3. Society of Automotive Engineers, "ARP 866A, March 15, 1975.

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NOMENCLATURE

A	area
C_L	centerline
C_F	skin friction coefficient
C_T	thrust coefficient
C_D	nozzle discharge coefficient
dB, DB	decibel, re. 0.0002 $\frac{dyne}{cm^2}$
F	thrust or force (lbf)
°F	degrees Farenheit
g	acceleration due to gravity (32.174 ft/sec^2)
H	measured model force (lbf)
Hz	Hertz (cycles/sec.)
M	engine/aircraft interface flange
Mn	Mach number
OSPL	Model data Overall Sound Pressure Level, from 100 to 80 kHz, in dB
OASPL	Overall Sound Pressure Level, from 50 to 10 kHz, in dB
P	pressure (psia)
PNL	Perceived Noise Level, in units of PNdB
PNdB	Units of noise for Perceived Noise Level
R	radius
°R	degrees rankine
SPL	sound pressure level, in dB
T	temperature
T/C	thermocouple
T/O	takeoff
TSFC	thrust specific fuel consumption (lbm/lbf/hr)
V	velocity (ft/sec)
W	mass flow rate (lbm/sec)
Δ	incremental change (delta)
ρ	density (lbm/ft^3)
θ_i	angle relative to upstream jet axis (degrees)
Subscripts	
a, amb	ambient
f, fan	fan or bypass stream
i	ideal

NOMENCLATURE (Cont'd)

j	jet
p, pri	primary or core stream
s	static
t	total
7	engine axial station at inlet to mixer or splitter
8	engine axial station at discharge of mixer or splitter