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NOISE GENERATED BY STOL CORE-JET THRUST REVERSERS

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E-6975

Abstract

This paper summarizes the results of an experimental investigation on the noise generated by target-type thrust reversers. The experimental data are normalized and scaled up to sizes suitable for reversing the core jets of a 45 400-kg (100 000-lb) augmentor-wing-type STOL airplane. The scaling calculatings yield perceived noise levels well above the 95-PNdB design goal for both sideline and flyover at 152.5 m (500 ft). "V"-gutter and semicylindrical reversers were tested with a 5.24-cm-diameter circular nozzle, and a semicylindrical reverser was also tested with a 7.78-cm-diameter circular nozzle. The ratio of reverser frontal area to nozzle exit area ranged from 2.4 to 7.0. Other test variables were the spacing between nozzle and reverser, reverser orientation, and nozzle pressure ratio. The thrust reversers, in addition to being noisier than the nozzle alone, also had a more uniform directivity. The maximum overall sound pressure level and the effective sound power level both varied with sixth power of the nozzle jet velocity.

Introduction

In order to achieve the goal of landing in short distances, jet STOL aircraft may well employ thrust reversers, both for reducing the ground roll after landing and steepening the approach flight path. In particular, for the augmentor-wing-type airplane, high thrust is required through the wing to maintain high lift during approach. Complete or partial in-flight reversal of the core jets is thus being considered as a means of reducing forward speed during descent. At the same time, because of the desired capability to operate from airports in heavily-populated areas, STOL aircraft will have to meet much more severe noise limitations than conventional aircraft. Thus, an evaluation of the noise associated with thrust reversal is necessary.

There have been many studies on the aerodynamic performance of small-size thrust reversers of diverse types.[1-5] Reports are also numerous on the behavior of full scale reversers.[6-9] Many design reports are also available in the literature.[10-12] In addition, reports on applications of thrust reversers to commercial aircraft are also abundant.[13-15]

Although it is apparent from the preceeding references that the aerodynamic behavior of thrust reversers has been extensively studied and documented, this has not been the case with regard to noise. For future STOL aircraft, noise will need to be considered, and the Lewis Research Center has initiated a study of this problem. This paper summarizes data recently obtained at Lewis and presents the normalization of these data and scale-up to the core jets of a 45 400-kg augmentor-wing-type airplane. The detailed experimental data are given in Ref. 16.

Target-type reversers were chosen for this study, primarily because of their simplicity. They can be built in many variations, as shown in Fig. 1. The noise data reported here were obtained using the "V"-gutter with cover plates (fig. 1(f)) and the semicylinder configurations (fig. 1(g)). The noise data reported cover a range of velocities, reverser-frontal-area-to-nozzle-area ratios and spacing-to-nozzle-diameter ratios.

Experimental Apparatus and Procedure

Two test rigs were used to obtain the experimental data. The acoustic data were taken on a rig designed to minimize internal noises and equipped with sound measuring and analyzing instruments. The flow rig described in Ref. 17 was used to obtain aerodynamic data prior to the experiments on the acoustic rig.

Acoustic Rig

The acoustic rig is shown in Fig. 2 and described in more detail in Ref. 18. Air from a 1000 kN/m^2 abs source was supplied to the test nozzle at ~300 K through a nominal 10-cm pipe. The pipe was equipped with an orifice for flow measurement, a hand-operated flow-control valve, noise mufflers, and a straight run ending at the nozzle. The thrust reversers were mounted on an independent stand near the nozzle exit.

The sound was measured by eight condenser microphones on a 3.05-m radius semicircle centered on the nozzle exit and at the same elevation, 1.22 m, from the smooth asphalt surface as the nozzle centerline. The microphones had individual wind screens.

Thrust Reversers

The small-scale thrust reversers used in the experiments are sketched in Fig. 3. Two types of target reversers were tested, semicylindrical (fig. 3(a)) and V-gutter (fig. 3(b)). The reversers had frontal width Z and height Y; the leading edges of the side plates were located at an axial distance X from the nozzle. These reverser dimensions are given in table 1. Two semicylindrical reversers were used, the only difference between them being the width. Conversion from one to the other was made with removable inserts. A photograph of the smaller semicylindrical reverser (with inserts) is shown in Fig. 4. Figure 5 is a photograph of the V-gutter reverser; the sideplates are mounted at 90° to each other and to the cover plates, and the cover plates overlap the side plates by 1.9 cm.

Procedure

The shape of the reversers was chosen for simplicity. Their sizes, as indicated by their frontal-area-to-nozzle-area ratio, A_f/A_n, were selected to fall within the zone of maximum reverse thrust ratio as determined in Refs. 1 and 5.

The effect of reverser-nozzle spacing on thrust reversal for target reversers was also determined in Ref. 1. The maximum thrust-reversal efficiency was obtained at the closest spacing that did not decrease the mass flow through the nozzle.

The spacings used in the present noise tests were determined by tests run on the auxiliary flow rig. The effect of spacing on flow rate at constant inlet pressure was obtained, and based on these results, the acoustic test program was established.

Experiments. - The reverser-nozzle combination was set at the spacing and orientation desired. Flow of unheated air was set and regulated by the hand-operated throttle valve controlling the nozzle inlet pressure. After flow conditions stabilized, flow parameters and atmospheric conditions were recorded. Three noise data samples were taken for each microphone.

Data analysis. - A 1/3-octave-band analyzer was used to determine, for each sample, the sound pressure level in each band from 50 to 20 000 Hz. The three samples for each microphone were corrected for atmospheric absorption and averaged to eliminate gross errors. The sound pressure levels were 3 dB above free-field values due to ground reflections except for those frequency bands exhibiting cancellations or reinforcements. No correction is made to free field values in this report. From these data, the overall sound pressure, level, OASPL, was calculated for each microphone. The effective spectral sound power level, PWL, was obtained by integration over a hemisphere with radius equal to the microphone circle radius; the integration is performed only over one hemisphere since the sound pressure levels are 3 dB above free-field values. The effective overall sound power level, OAPWL, was then computed. In principle, the noise measured may be a function of the angle of the microphone-circle plane to the reverser, and the data are for one plane only; hence, these power levels are termed "effective." However, it should be noted that rotating the reverser 90 degrees had very little effect on the effective power levels, as discussed later herein.

Results

The experimental test conditions and major results are given in table 1; the detailed results are given in Ref. 16. A brief discussion of the more important effects follows.

Effect of Thrust Reversal on Noise

The effects of thrust reversal on noise directivity pattern and spectral distribution are shown in Fig. 6. Data for the 5.24-cm nozzle with and without the smaller semicylindrical reverser are compared at a 1.72 pressure ratio (isentropic nozzle jet velocity, U_j, 294 m/sec). The spacing between reverser and nozzle, X (see fig. 3), is zero, and the reverser orientation is horizontal.

Directivity. - Figure 6(a) is a polar plot of overall sound pressure level, OASPL, versus angular position, θ. The nozzle alone has a maximum OASPL of 107 dB (re 20 $\mu N/m^2$) at 160°; its directivity is very pronounced, with a difference of 12 dB between maximum and minimum OASPL. In comparison, the noise pattern for the reverser appears nearly uniform. The maximum OASPL is 113 dB, 6 dB more than the nozzle, alone and the minimum OASPL of 108 dB is about 1 dB above the maximum for the nozzle alone. The angle of maximum OASPL is 10° with the reverser. For the V-gutter the maximum OASPL is 14 dB greater than that of the nozzle alone.

SPL spectrum. - Figure 6(b) shows the effect of thrust reversal on the noise spectra at 10° and 160°, the angles of maximum OASPL for the reverser and nozzle, respectively. The sound pressure level, SPL, is plotted against the 1/3-octave-band center frequency, f_c. For the nozzle alone the peak SPL occurs at 1250 Hz in the direction of the maximum OASPL, θ = 160°, while at θ = 10°, the SPL has a flat peak in the 2000-to-6300-Hz range. The difference in SPL for the two angles is greatest at low frequencies. The effect of angular position on the noise spectrum is much less with the reverser than for the nozzle alone. The increased noise observed with the reverser is seen to occur at high frequencies, with the low-frequency noise being in the range of that of the nozzle alone. It should be noted that for the nozzle alone, the peak-SPL frequency shifts to higher values as the angle shifts away from the maximum-OASPL direction, whereas with thrust reversal, there is little effect.

Effect of Velocity on Thrust Reverser Noise

Maximum OASPL. - The variation of the maximum overall sound pressure level, OASPL, with velocity is shown in Fig. 7. This figure includes data for all of the reverser-nozzle combinations tested, at their optimum spacing. In addition to the reverser data, an eighth-power line drawn through the nozzle alone datum is included for comparison. The reverser data follow a sixth power relation with nozzle jet velocity over the range of velocity tested. All the semicylindrical-reverser data fall on nearly the same line, and the V-gutter data are about 5 dB higher. Note that the maximum OASPL with the reverser mounted vertically is less than 1 dB more than for the reverser mounted horizontally. At 294 m/sec nozzle jet velocity, the quietest of the reversers is 6 dB louder than the nozzle alone, and at lower velocities this difference increases.

SPL spectrum. - The effect of nozzle jet velocity on the sound pressure level spectrum at the angle of maximum OASPL is shown in Fig. 8 for both the smaller semicylindrical reverser (fig. 8(a)) and the V-gutter reverser (fig. 8(b)), both with the 5.24-cm nozzle. The frequencies for cancellations and reinforcements due to ground reflections assuming a point source, are tagged on the abscissa as C_1, C_2, C_3 and R_1, R_2, and R_3, respectively. In neither configuration is there a definite increase in peak-SPL frequency with increasing velocity; in fact, for the V-gutter, the peak is quite pronounced and occurs at 1250 Hz for each velocity. At other angles, for the semicylindrical reversers, the expected relation between peak-SPL frequency and velocity is obtained. Note the 1250-Hz peak with the V-gutter is observed in all directions. It should also be noted that for the V-gutter, the SPL rises more steeply at low frequencies and falls off more slowly at high frequencies in comparison with the semicylindrical reversers.

Effects of Geometric Variables on Thrust Reverser Noise

Spacing. - For each configuration the maximum thrust reversal efficiency is obtained at the smallest spacing which does not decrease the mass flow through the nozzle, according to Ref. 1. Decreasing the spaceing from this value sharply reduces the reverser efficiency, while increasing the spacing reduces the efficiency slightly, if at all. Noise levels decrease when the flow rate decreases for spacings less than the optimum.(16) For spacings greater than optimum the noise level increases through some range of spacing, and for one case, there was "screech", a dominant single tone.(16)

Area ratio. - For the 5.24-cm nozzle, increasing the ratio of the area of the semicylindrical reverser to that of the nozzle from 5.6 to 7.0 had very little effect. Similarly, for a fixed reverser area, increasing the nozzle diameter from 5.24 cm to 7.78 cm yielded no significant increase in noise level for a given velocity, as can be seen in Fig. 7; this is an area ratio decrease of 5.6 to 2.5. This result is somewhat surprising since for a fixed velocity the nozzle area, and hence the airflow, are increased by a factor of 2.2. But, the thrust reversal may be less efficient, which would be consistent with lower exiting velocities and, hence, noise levels. Thus, it appears that for small area ratios, the noise level may decrease with decreasing area ratio, an effect which might offset the increase expected due to nozzle area increase. However, this result has not yet been confirmed by any further tests.

Orientation. - The effect of reverser orientation on the noise directivity is illustrated in Fig. 9. The smaller semicylindrical reverser (fig. 9(a)) and the V-gutter reverser (fig. 9(b)) are mounted vertically with the 5.24-cm nozzle. This position simulates flyover. As shown in Fig. 7, the maximum OASPL is about 1 dB greater than for the reversers mounted horizontally. The overall power level is also increased about 1 dB (table 1). For the vertical position, the reverser noise pattern is slightly more directional, and the maximum OASPL is at 50° for both reversers.

Normalization of Data

Overall sound power level. - As shown in Fig. 7, the maximum OASPL increases with the sixth power of the nozzle jet velocity, as expected for dipole noise. This is also true of the effective total power as shown in Fig. 10, where the effective acoustic efficiency, $\eta = W/\rho_a A_n U_j^3$, is plotted against the ratio of nozzle jet velocity to the ambient speed of sound. The effective acoustic power in watts related to the effective overall sound power level by the following:

$$W = 10^{(OAPWL - 130)/10} \qquad (1)$$

The data for each reverser-nozzle combination at the optimum spacing follow a relation of the type, $\eta = K_1 (U_j/c_a)^3$, over the range of velocities tested, or in effective overall sound power level,

$$OAPWL = 130 + K + 10 \log \frac{\rho_a A_n U_j^6}{c_a^3} \qquad (2)$$

The data agree within ±1 dB with the faired line for each configuration, where K is -31.3 dB for the V-gutter reverser, -37.0 dB for the semicylindrical reversers with the 5.24-cm nozzle, and -39.5 for the smaller semicylindrical reverser with the 7.78-cm nozzle. As is the case for the maximum OASPL, the effect of reverser orientation is negligible.

Sound-pressure-level spectra on sideline. - In order to facilitate sideline and flyover noise calculations, normalized SPL at 3.05 m are given. The normalized sound pressure level, SPL-OAPWL, for the 3.05-m sideline is plotted against nozzle Strouhal number, $S_n = f_c D_n/U_j$. Figure 11 presents such a normalization for the smaller semicylindrical reverser mounted at 90° to the horizontal, simulating flyover, with the 5.24-cm nozzle. Frequency bands influenced by ground reflections, assuming a point source, are not plotted. Such normalized SPL data are a function of angle from the nozzle axis, or distance from the source, as can be seen in the figure. Similar normalization plots are given for the other configurations in Appendix A.

Scale-Up Calculations

From the normalized data given in Fig. 11 and Appendix A, and the overall sound power level relation (eq. (2)), the thrust reversal noise may be computed for full-scale applications. The example illustrated here is for in-flight core-jet reversal on a 45 400-kg, four-engine, augmentor-wing-type airplane at the 152.5-m flyover point.

The performance of a single engine with reverser may be calculated from Fig. 11 and Eq. (2). First, the sound pressure level along the ground at the 152.5 m flyover point is calculated. These data are corrected for standard-day atmospheric absorption and the perceived noise level then calculated; 6 PNdB are added to account for the four engines. No account is made of any reflection by the wing, but the 3-dB broadband ground reflection is included. This series of calculations is performed for three different velocities, 198, 244, and 274 m/sec, with the size of the nozzle adjusted to maintain the same thrust, 10 kN per engine.

The results of these calculations are shown in Fig. 12; for even the lowest velocity, 198 m/sec, the calculated noise levels are well in excess of the 95-PNdB design goal. At higher velocities, the peak noise level is increased, and a larger area is exposed to noise levels in excess of 95 PNdB. From these results, it is apparent that noise considerations may well limit the use of reversers, at least of the target type, for STOL applications.

Summary of Results

1. The small scale semicylindrical and V-gutter target-type reversers were significantly noisier than the nozzle alone by 6 to 14 dB. Test results, when scaled up to conditions suitable for a 45 400-kg STOL aircraft, showed that noise levels would be above the present design goal of 95 PNdB sideline noise. This indicates that target-type core flow reversers used during STOL flights will constitute an important noise source.

2. The noise directivity patterns for target-type reversers are very uniform. No more than 6 dB variation in overall sound pressure level, OASPL, was encountered among all of the angular directions tested, either in the plane of the exiting jets or at 90° to that plane. Maximum values of OASPL occurred between the angles of 10° to 50° from the nozzle upstream axis, depending on the particular configuration. The uniformity of the noise direc-

tivity extended to the spectral distribution. The SPL distribution throughout the spectrum was nearly the same in all directions.

3. The maximum overall sound pressure level and the effective overall sound power level at optimum spacing followed a sixth-power relationship to isentropic nozzle jet velocity over the range of velocity tested for each geometric configuration. The effective overall sound power level was correlated empirically as a function of the jet velocity and area and ambient density and speed of sound for each configuration.

4. Plots are given of sideline sound pressure levels, normalized to the overall sound power levels, versus Strouhal number based on nozzle diameter. The plots at each microphone angle for each configuration, along with the overall power level correlation, allow scale-up calculations to be performed.

Appendix A
Normalized Sideline Spectra

In order to facilitate sideline and flyover noise calculations, plots of the normalized sound pressure level, SPL-OAPWL, versus nozzle Strouhal number, $S_n = f_c D_n / U_j$, are given herein. Frequency bands influenced by ground reflections, assuming a point source, are generally not plotted.

Figure 11 is for the smaller semicylindrical reverser mounted vertically with the 5.24-cm nozzle; in Fig. 13, the same configuration is rotated to the horizontal position. Figure 14 is for the larger semicylindrical reverser mounted horizontally with the 5.24-cm nozzle. The spectra for the smaller semicylindrical reverser mounted horizontally with the 7.78-cm nozzle are shown in Fig. 15.

Data for the "V"-gutter reverser with the 5.24-cm nozzle are shown in Figs. 16 and 17. Because the peak sound pressure levels occur in ground-reflection-affected bands of 1000 and 1250 Hz, these values are plotted without correction. Since these are the third cancellation and reinforcement, respectively, any corrections would be small. Figure 16 is for the normal horizontal position, and Fig. 17 is for the vertical position.

Appendix B
Symbols

A_f	reverser frontal area, m^2
A_n	nozzle area, m^2
C_1, C_2, C_3	first, second, and third frequency bands exhibiting ground-reflection cancellations, assuming a point source
c_a	ambient speed of sound, m/sec
D_n	nozzle-exit diameter, m
f_c	1/3-octave-band center frequency, Hz
f_M	the 1/3-octave-band frequency exhibiting the highest sound pressure level, Hz
K	empirical coefficient in sound power correlation, dB
K_1	empirical coefficient in acoustic efficiency correlation, dimensionless
OAPWL	overall sound power level, dB re 10^{-13} W
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
PNL	perceived noise level, PNdB
PWL	1/3-octave-band sound power level, dB re 10^{-13} W
R_1, R_2, R_3	first, second, and third frequency bands exhibiting ground-reflection reinforcements, assuming a point source
S_n	nozzle Strouhal number, $f_c D_n / U_j$
SPL	sound pressure level, dB re 20 $\mu N/m^2$
U_j	isentropic nozzle velocity, m/sec
W	sound power, W
X	spacing between reverser and nozzle, m
Y	reverser height, m
Z	reverser width, m
α	angle of reverser to horizontal, deg
η	effective acoustic efficiency, $W/(\rho_a A_n U_j^3)$, dimensionless
θ	microphone angle from nozzle upstream axis, deg
θ_M	angle from nozzle axis at which maximum OASPL occurs, deg
ρ_a	ambient density, kg/m^3

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Table 1 Summary of experimental data

TEST CONDITIONS							MAJOR RESULTS			
Reverser			Nozzle diameter D_n, cm.	Spacing ratio, X/D_n	Angle to horizontal, α, deg.	Nozzle jet velocity, U_j, m/sec	Effective overall power, OAPWL, dB re 10^{-13} W	Frequency for maximum PWL, f_M, Hz	Maximum OASPL, dB re $20\mu N/m^2$ (at 3.05 m)	Angle for maximum OASPL, θ_M, deg.
Height, Y, cm.	Width, Z, cm.	Area ratio, A_f/A_n								
No Reverser										
---	---	---	5.24	---	---	294	129	1250	107	160
Cylindrical Reverser										
8.80	13.8	5.63	5.24	0	0	294	139	6300	113	10
↓	↓	↓	↓	↓	0	238	133	4000	107	10
↓	↓	↓	↓	↓	0	192	127	2000	101	10
↓	↓	↓	↓	↓	90	293	140	6300	114	50
↓	↓	↓	↓	↓	90	192	128	6300	102	30-50
↓	17.2	7.02	↓	↓	0	296	140	10000	114	10
↓	17.2	7.02	↓	↓	↓	193	128	5000	102	10
↓	13.8	2.55	7.78	0.84	↓	225	134	2500	108	30
↓	13.8	2.55	7.78	0.84	↓	164	124	1250	98	30
"V"-Gutter Reverser										
6.60	7.95	2.43	5.24	0.85	0	296	144	1250	121	10
↓	↓	↓	↓	↓	0	240	139	↓	116	10
↓	↓	↓	↓	↓	0	194	133	↓	110	10
↓	↓	↓	↓	↓	90	296	145	↓	120	50

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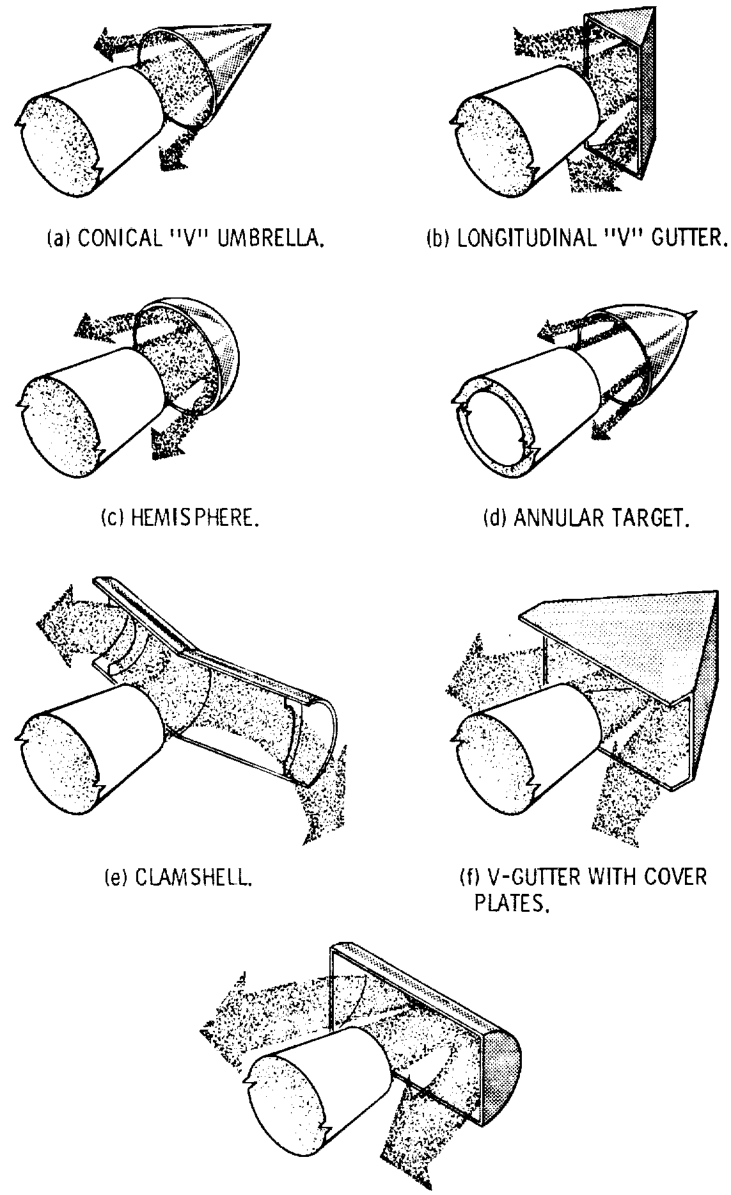

(a) CONICAL "V" UMBRELLA.

(b) LONGITUDINAL "V" GUTTER.

(c) HEMISPHERE.

(d) ANNULAR TARGET.

(e) CLAMSHELL.

(f) V-GUTTER WITH COVER PLATES.

(g) SEMICYLINDER.

Figure 1. - Target-type thrust reverser configurations.

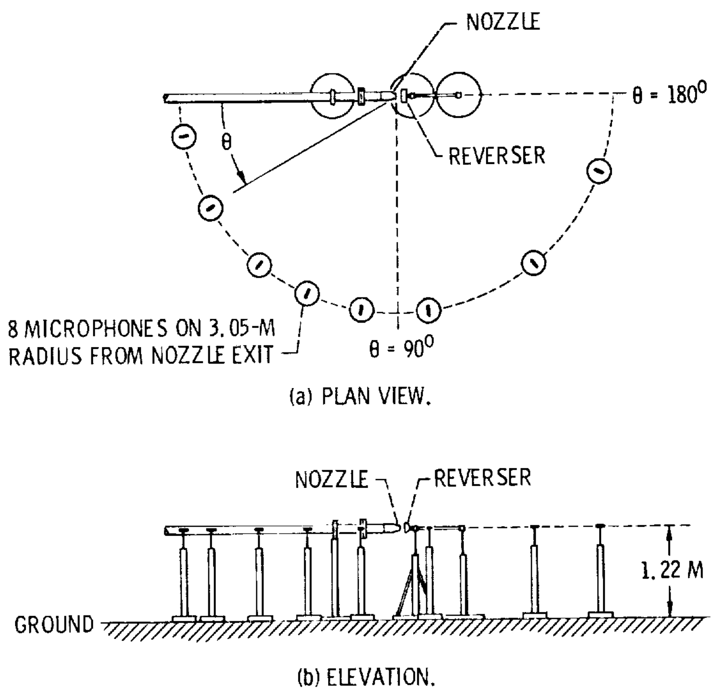

Figure 2. - Acoustic rig schematic diagram.

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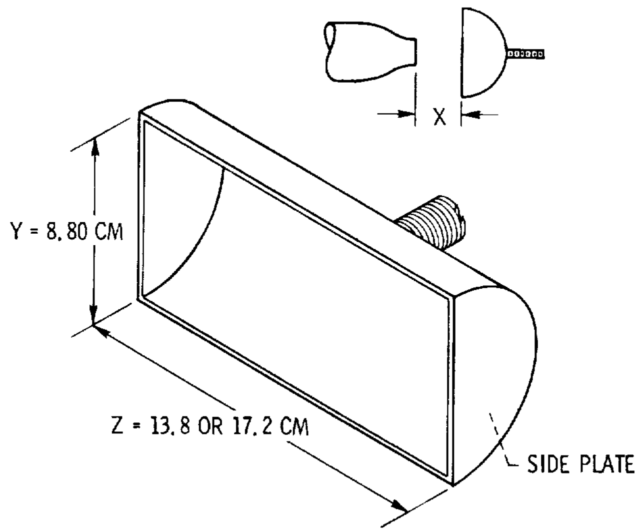
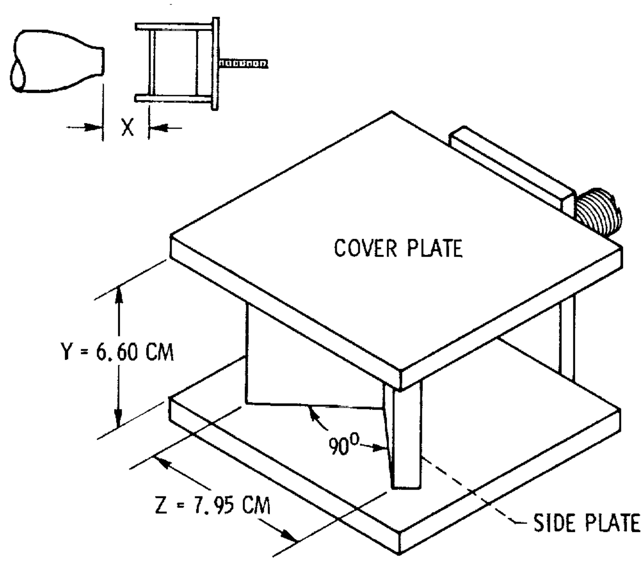


(a) SEMI-CYLINDRICAL.



(b) V-GUTTER.

Figure 3. - Small-scale model thrust reversers tested.

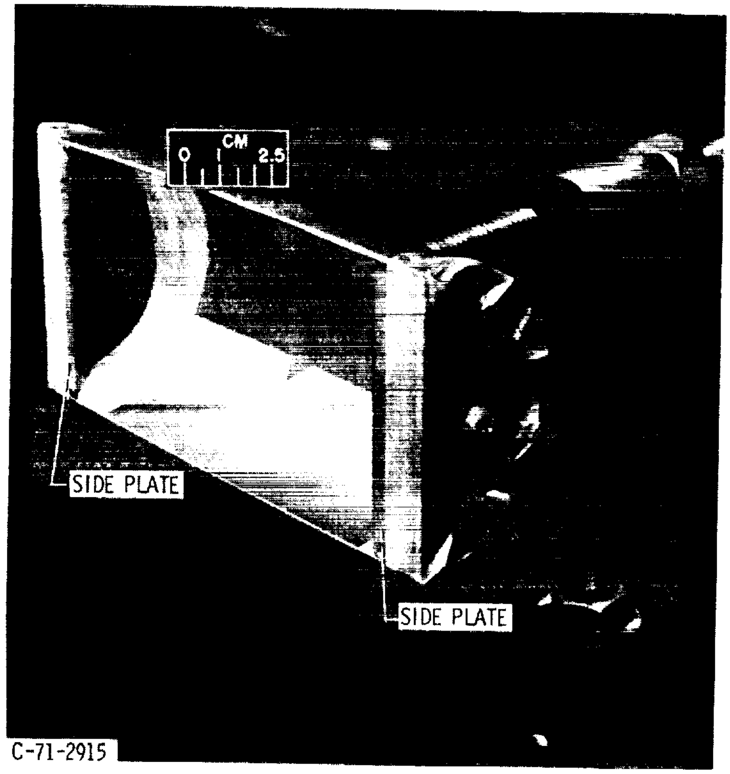


Figure 4. - Photograph of smaller semicylindrical thrust reverser.

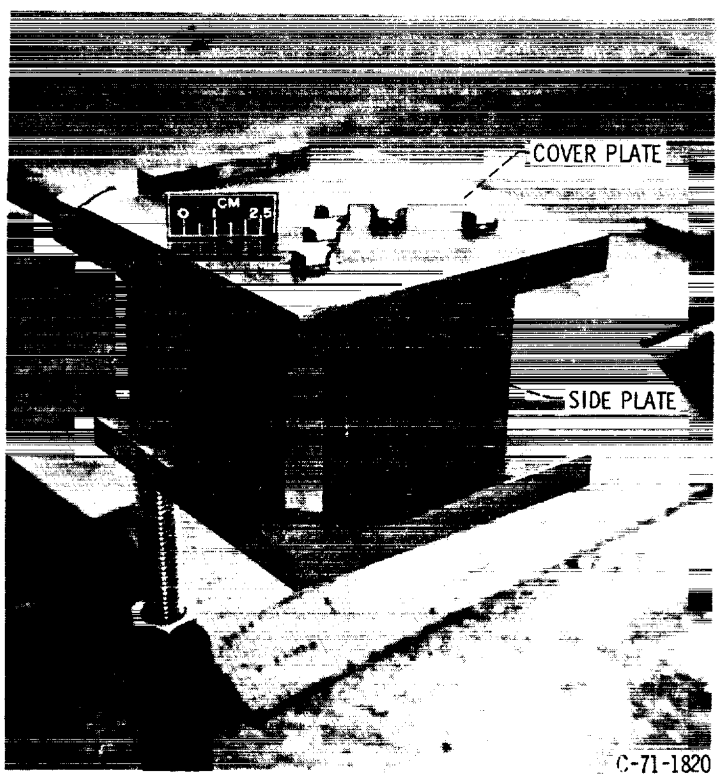


Figure 5. - Photograph of "V"-gutter thrust reverser.

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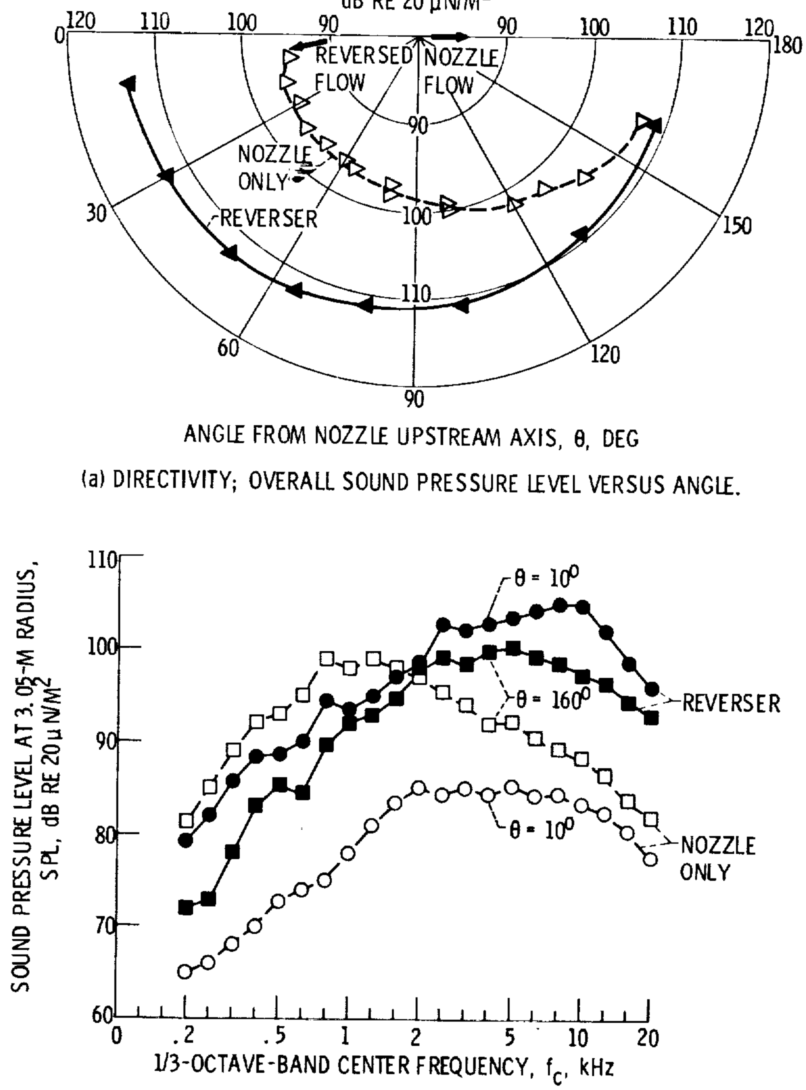

(a) DIRECTIVITY; OVERALL SOUND PRESSURE LEVEL VERSUS ANGLE.

(b) SPECTRUM; SOUND PRESSURE LEVEL VERSUS FREQUENCY.

Figure 6. - Effect of thrust reversal on noise. 5.24-cm nozzle with and without smaller semi-cylindrical reverser at nozzle jet velocity, $U_j \sim 294$ m/sec; horizontal orientation and zero spacing.

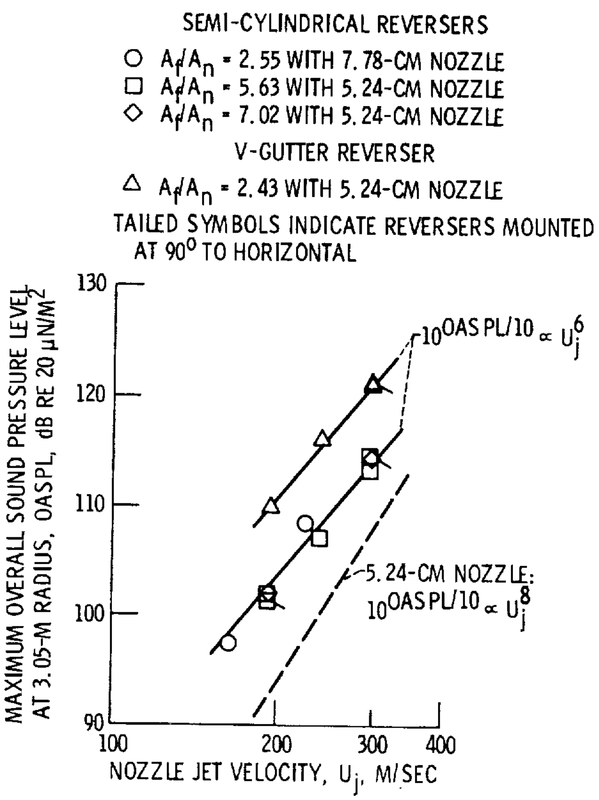

Figure 7. - Effect of nozzle jet velocity on maximum overall sound pressure level at optimum reverser spacing.

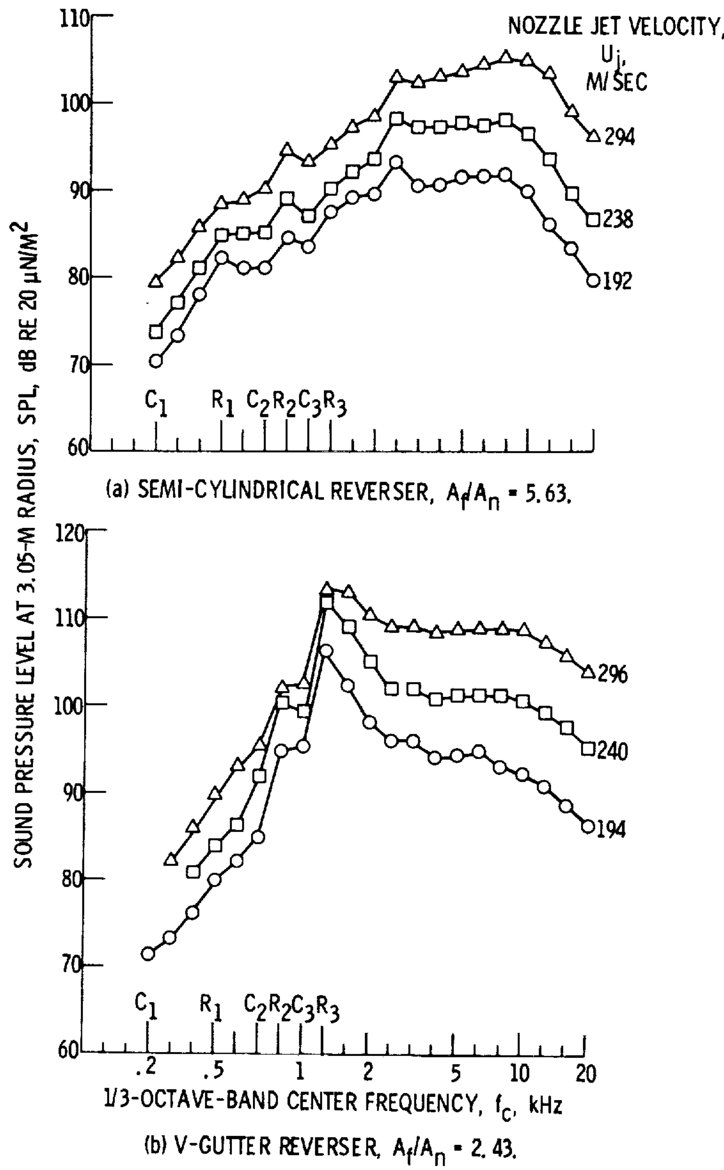

Figure 8. - Effect of nozzle jet velocity on sound pressure level spectrum at angle of maximum overall sound pressure level, 10°. Horizontal; optimum spacing; nozzle diameter, 5.24 cm.

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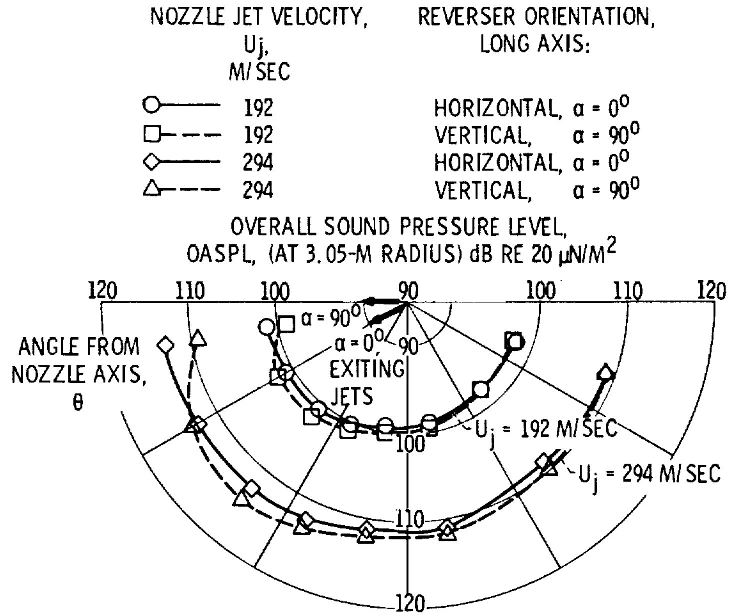
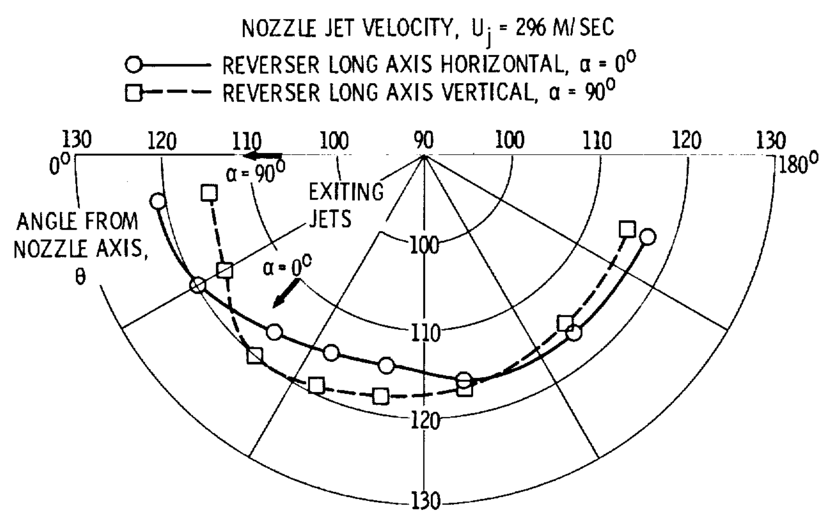


(a) SMALLER SEMI-CYLINDRICAL REVERSER WITH 5.24-CM NOZZLE.



(b) "V"-GUTTER REVERSER WITH 5.24-CM NOZZLE.

Figure 9. - Effect of reverser orientation on directivity of overall sound pressure level.

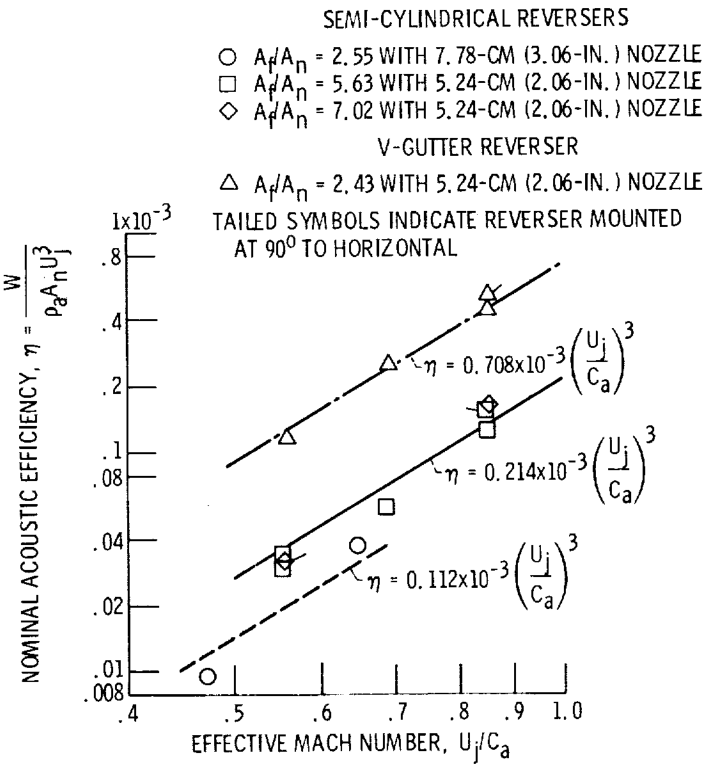


Figure 10. - Nominal acoustic efficiency as a function of effective Mach number at optimum reverser spacing.

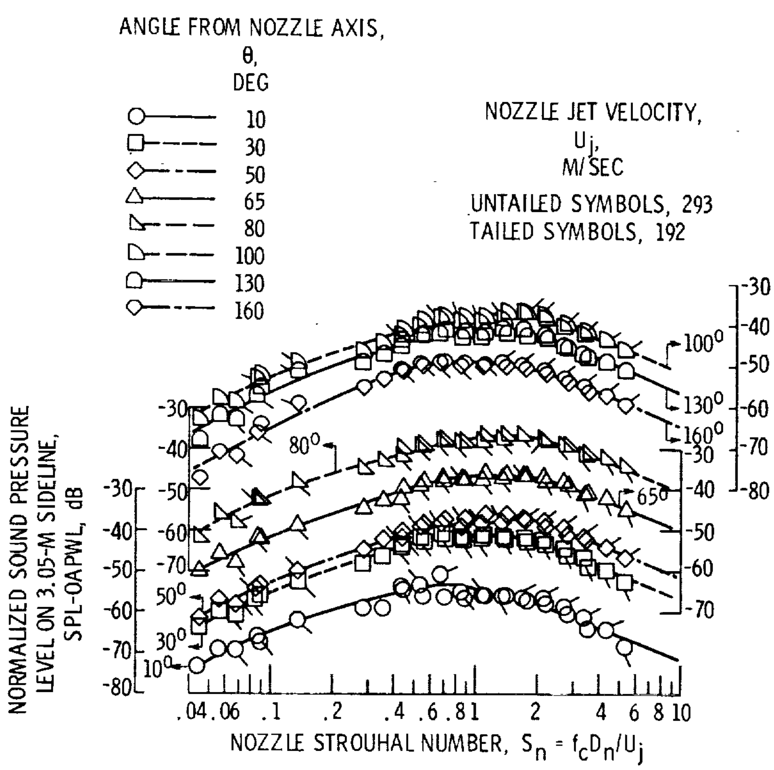


Figure 11. - Normalized sound pressure level on 3.05-m sideline for smaller semi-cylindrical reverser mounted vertically with 5.24-cm nozzle.

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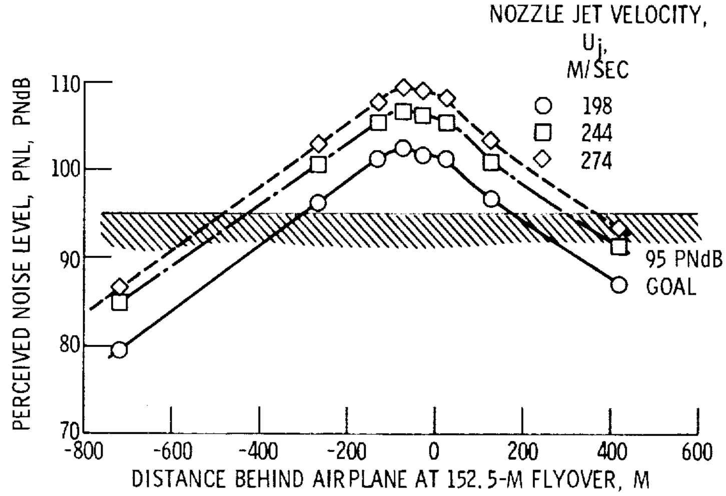

Figure 12. - Perceived noise level at 152.5-m flyover for in-flight core-jet reversal on 45 400-kg augmentor-wing-type airplane at various nozzle jet velocities.

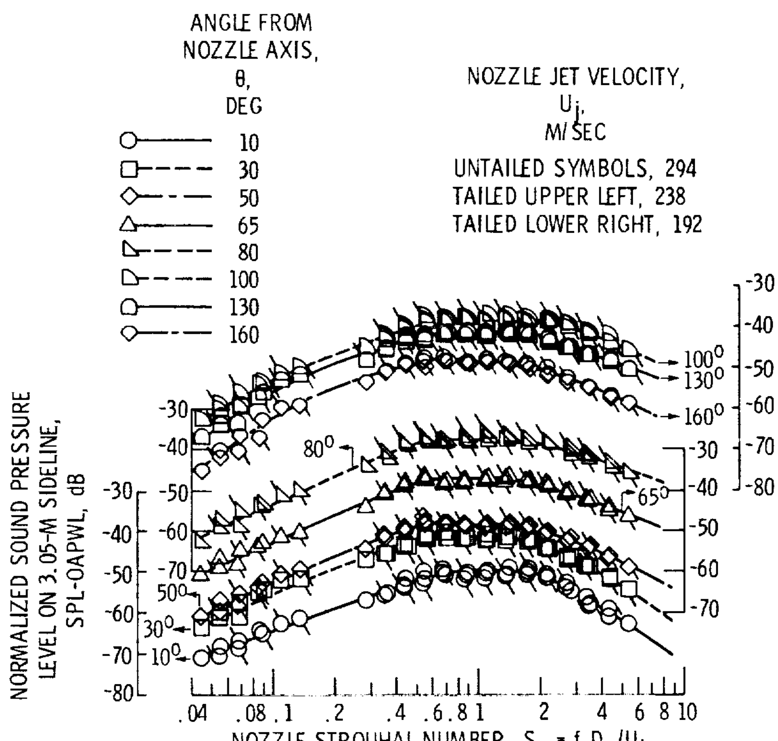

Figure 13. - Normalized sound pressure level on 3.05-m sideline for smaller semi-cylindrical reverser mounted horizontally with 5.24-cm nozzle.

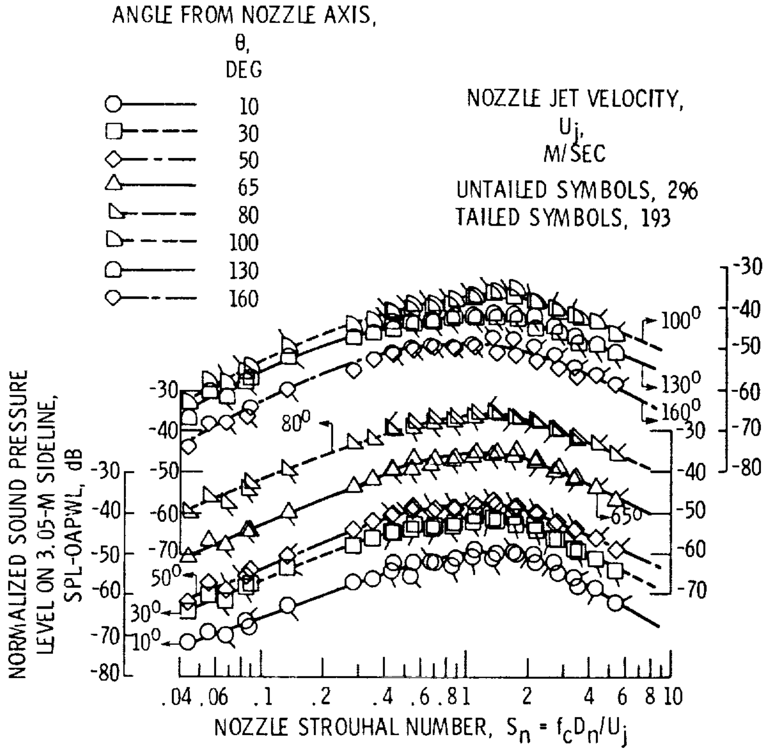

Figure 14. - Normalized sound pressure level on 3.05-m sideline for larger semi-cylindrical reverser mounted horizontally with 5.24-cm nozzle.

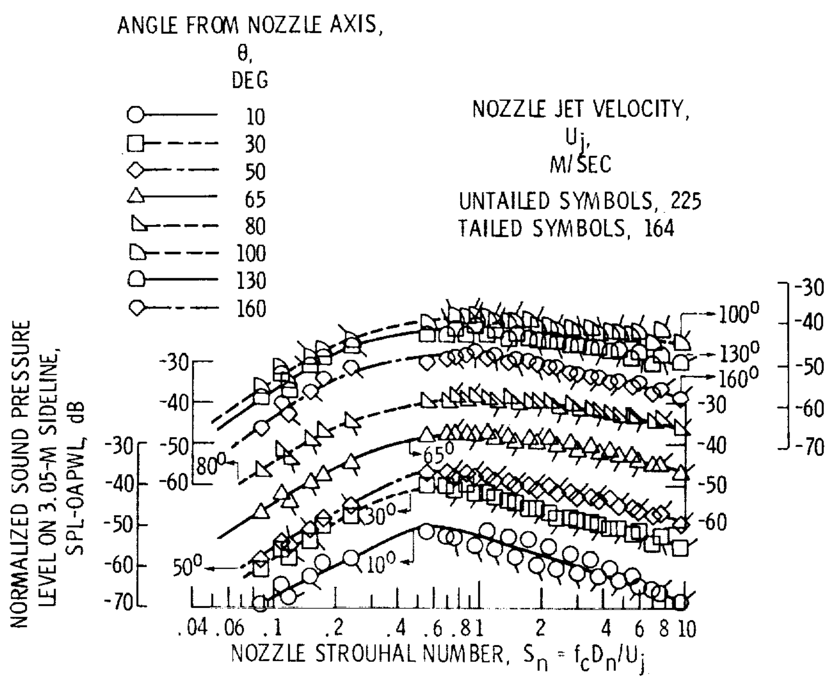

Figure 15. - Normalized sound pressure level on 3.05-m sideline for smaller semi-cylindrical reverser mounted horizontally with 7.78-cm nozzle.

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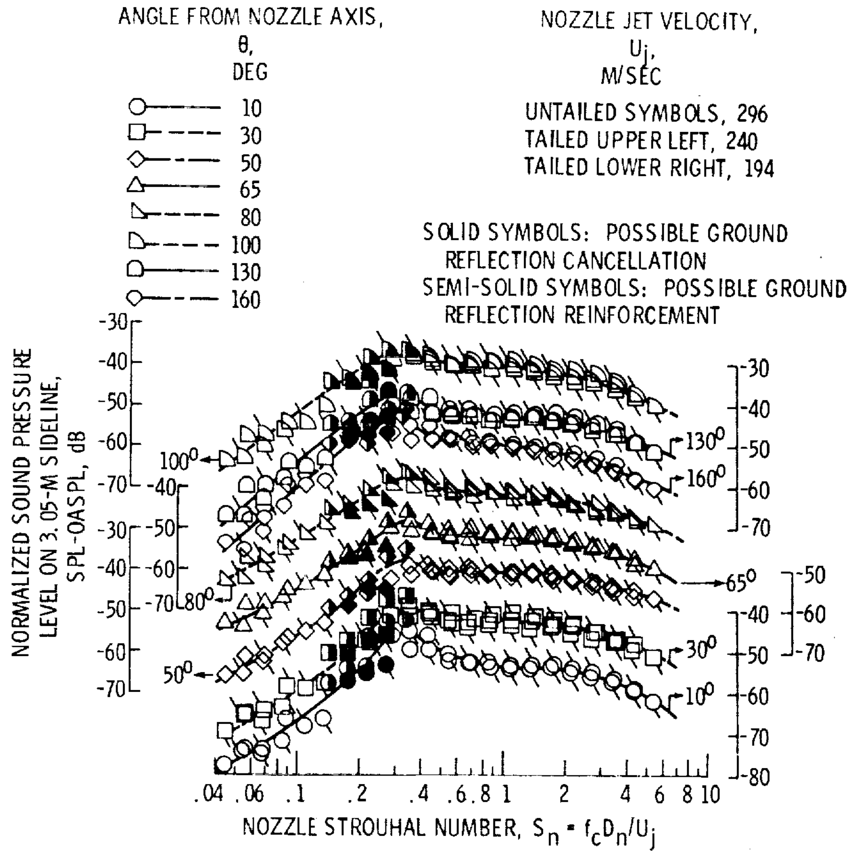

Figure 16. - Normalized sound pressure level on 3.05-m sideline for V-gutter reverser mounted horizontally with 5.24-cm nozzle.

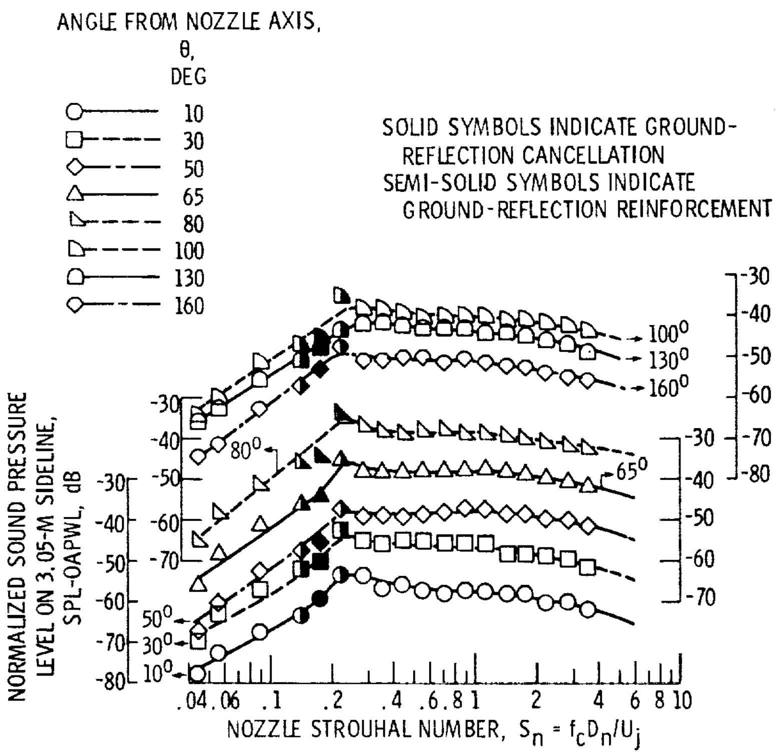

Figure 17. - Normalized sound pressure level on 3.05-m sideline for V-gutter reverser mounted vertically with 5.24-cm nozzle. Nozzle jet velocity, U_j = 296 m/sec.