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**ACOUSTIC TESTS OF  
A 15.2-CENTIMETER-DIAMETER  
POTENTIAL FLOW CONVERGENT NOZZLE**

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16. Abstract <p>An experimental investigation of the jet noise radiated to the far field from a 15.2-cm-diam potential flow convergent nozzle has been conducted. Tests were made with unheated airflow over a range of subsonic nozzle exhaust velocities from 62 to 310 m/sec. Mean and turbulent velocity measurements in the flow field of the nozzle exhaust indicated no apparent flow anomalies. Acoustic measurements yielded data uncontaminated by internal and/or background noise to velocities as low as 152 m/sec. Finally, no significantly different acoustic characteristics between the potential flow nozzle and simple convergent nozzles were found.</p>			
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# ACOUSTIC TESTS OF A 15.2-CENTIMETER-DIAMETER

## POTENTIAL FLOW CONVERGENT NOZZLE

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Lewis Research Center

### SUMMARY

An experimental investigation of the jet noise radiated to the far field by a 15.2-centimeter-diameter potential-flow convergent nozzle has been conducted. Tests were made with unheated airflow over a range of subsonic velocities from 62 to 310 meters per second. The outdoor flow facility was equipped with both internal noise suppression devices and flow quieting screens.

Mean and turbulent velocity flow field measurements at the exit plane of the nozzle and downstream thereof indicated no apparent flow anomalies with respect to exit plane and downstream mean velocity profiles, or with respect to the shear layer turbulent velocity spectra. In addition, the core turbulence intensity was determined to be 1 percent, or less.

The acoustic measurements including SPL spectra, power spectra, OASPL directivity, and total power indicated that reliable jet noise data (i. e., uncontaminated by internal and/or background noise) could be obtained on the test facility at subsonic nozzle exhaust velocities as low as 152 meters per second (500 ft/sec). At a velocity of 123 meters per second (402 ft/sec) the facility became marginal, and at 92 meters per second, and below, the data were clearly contaminated by internal and/or background noise.

Finally, a comparison of the acoustic data for the potential flow nozzle with acoustic data for simple convergent nozzles, indicated no significant differences; that is, nozzle shape was determined to be an insignificant acoustic parameter for the nozzles compared.

### INTRODUCTION

Since the introduction of commercial jet aircraft, aircraft noise during ground roll, takeoff, and landing has become a major annoyance to communities. It has long been

known that one of the major sources of this noise is the turbulent jet exhaust. Over the years, then, extensive research has gone into studying, both analytically and experimentally, the nature of turbulence generated jet noise. One of the earliest findings (by Lighthill, ref. 1) was that the total sound power radiated from a subsonic turbulent jet, over a wide range of operating conditions, is proportional to the jet velocity raised to the eighth power.

Relatively small reductions in jet velocity, therefore, are accompanied by substantial noise reductions. Although this presents favorable opportunities in some applications for jet noise reduction, it makes experimental investigations of the jet and its sound field at low subsonic velocities difficult. The jet noise is often at or below the level of internal noise. Examples of internal noise sources in cold flow noise rigs are upstream valve noise and scrubbing noise.

A program to investigate the turbulent structure of free jet shear layers as related to acoustic generation is underway at NASA-Lewis in cooperation with the University of Illinois (NASA grants NGR 14-005-177 and NGR 14-005-149). As part of this program both turbulence and acoustic data were taken on a 15.2-centimeter (6-in.) diameter free jet located at Lewis. To insure that the turbulent field measurements were minimally influenced by internal upstream acoustic and flow disturbances, caution was exercised in designing the cold flow system, especially the nozzle. The nozzle used was a potential flow nozzle; that is, its inner surface contour followed potential flow streamlines.

This report presents the far-field acoustic data from this facility, including sound pressure level (SPL) spectra, overall sound pressure level (OASPL) directivity patterns, and sound power level (PWL) spectra. The data were taken at nominal jet velocities from 62 to 310 meters per second (204 to 1015 ft/sec). Finally, a comparison of the acoustic data from the potential flow nozzle with that from simple convergent nozzles is also made.

## APPARATUS AND PROCEDURE

### Flow System and Valve Noise Quieting

The flow system is shown schematically in figure 1. The system was attached to the Lewis laboratory air supply and consisted of the following elements (proceeding downstream from the air supply): a 15.2-centimeter (6-in.) flow control valve, a valve noise quieting section, a 4.6-meter-straight section of 40.6-centimeter-diameter pipe, a series of screens to break up the larger turbulent eddies and remove large particles of dirt, rust, etc., and finally the test nozzle. The nozzle was designed and fabricated

so that its inner surface contour was smooth and coincided with potential flow streamlines (fig. 2) to minimize flow disturbances from within the nozzle. The first valve noise quieting element was a perforated plate to eliminate low-frequency internal noise. Downstream of the perforated plate was a large volume, acoustically lined muffler (with no line of sight through the flow axis) designed to eliminate the higher frequencies. The outside of the muffler and piping was wrapped with fiberglass and lead vinyl insulation to minimize direct radiation of internal noise.

The nozzle stagnation temperature, measured at the nozzle inlet, ranged from  $17^{\circ}$  to  $24^{\circ}$  C ( $62^{\circ}$  to  $75^{\circ}$  F). Ambient temperatures ranged from  $18^{\circ}$  to  $20^{\circ}$  C ( $65^{\circ}$  to  $68^{\circ}$  F).

### Acoustic Instrumentation and Data Analysis

The data were obtained outdoors with a vertical, semicircular, 10-microphone array, on a radius of 4.6 meters (fig. 1). The microphones were placed at angles  $\theta_1$  of  $20^{\circ}$ ,  $40^{\circ}$ ,  $60^{\circ}$ ,  $75^{\circ}$ ,  $90^{\circ}$ ,  $105^{\circ}$ ,  $120^{\circ}$ ,  $135^{\circ}$ ,  $145^{\circ}$ , and  $155^{\circ}$  measured from nozzle inlet. Open-cell polyurethane acoustic foam was placed on the ground to minimize ground reflection effects and 1.27-centimeter (1/2-in.) condenser microphones with wind-screens were used. The microphone plane passed through the flow axis (fig. 1). This vertical array arrangement (with the foam) provides free field noise data for frequencies above 400 hertz.

Noise data were obtained at each microphone position for each run condition. The noise data were analyzed directly by an automated one-third-octave band spectrum analyzer. The analyzer determined sound pressure level spectra SPL referenced to  $2 \times 10^{-5}$  newton per square meter ( $0.0002 \mu\text{bar}$ ). The resulting SPL spectra were then corrected for the small atmospheric attenuation (less than 1 dB) so that the reported data are lossless. They were then corrected for background noise and used to compute the overall sound pressure level (OASPL) for each microphone position. The sound power spectrum PWL and total sound power level  $\text{PWL}_T$  were computed by a spacial integration of these SPL spectra. The spatial integration used the "bread slice" elements for axisymmetric noise as described in reference 2.

The condenser microphones were calibrated before and after each day of testing with a standard piston calibrator (a 124-dB tone at 250 Hz). The one-third-octave band analyzer was periodically calibrated and checked with a pink noise generator. Considering the microphone calibrations, periodic checks of the data acquisition system, and redundant data, it is estimated that the data are repeatable to within  $1\frac{1}{2}$  dB from day to day and within 1/2 dB on a given day.

## Test Procedure

Far field noise and flow data were taken for the 15.2-centimeter-diameter potential flow nozzle at nozzle exhaust velocities  $V_j$  ranging from 62 to 310 meters per second (204 to 1015 ft/sec). These velocities were obtained by adjustment of the upstream valve to the desired nozzle pressure ratios, which ranged from 1.02 to 1.84. The flow, in all cases, exhausted smoothly to the atmosphere. The velocities were computed using the measured nozzle and ambient pressures and temperatures, assuming isentropic expansion.

### Nozzle Flow Characteristics

In conjunction with the previously mentioned grants, H. P. Planchon of the University of Illinois took mean and turbulent velocity field data on this facility (see, e.g., ref. 3). Figures 3 to 5 present a summary of a portion of this data.

Figure 3 is a plot of the dimensionless velocity (local mean velocity  $\bar{V}$  divided by centerline mean velocity  $V_j$ ) as a function of radial position at a jet velocity of 122 meters per second (400 ft/sec). The profile is at an axial position of 0.076 centimeter (0.03 in.) and therefore is essentially the exit plane profile. The flatness of the profile can readily be seen. The profile was obtained with a hot wire anemometer.

Figure 4 shows that the dimensionless mean velocity profile has similarity for axial distances  $x$  from 2 to at least 6 diameters. The spread parameter (which is a measure of the shear layer growth rate) was found to be 11.0 by Planchon (ref. 3) who also noted that his value agreed with that found by Liepman and Laufer (ref. 4).

The turbulent velocity spectra at the nozzle lip axis ( $r = 7.6$  cm) for the same range of axial locations are shown in figure 5. The data were obtained by passing the turbulent velocity hot wire signal through a one-third-octave band spectral analyzer and dividing the signal in each band by the bandwidth and normalizing with respect to the mean square. The resulting spectral density  $F(f)$  is then nondimensionalized by multiplying by  $V_j/x$ . The plot, therefore, is the normalized spectral density against a Strouhal number based on axial distance downstream. The similarity of the spectra are evident, as is the lack of any noticeable periodic turbulence "tones." The  $-5/3$  slope is a well established turbulent phenomena (see, e.g., ref. 5) and further verifies the lack of flow anomalies in this nozzle. The core turbulence intensity, as measured by Planchon, was approximately 1 percent.

## RESULTS AND DISCUSSION

### Potential Flow Nozzle Data

Figure 6 is a plot of the normalized sound pressure level (SPL) as a function of one-third-octave center band frequency, at a microphone angle of  $90^\circ$ , for various nozzle exit velocities tested. A comparison at  $90^\circ$  is made because spectral shifts at this angle are insensitive to convective effects. The SPL data at each velocity have been normalized with respect to the overall sound pressure level (OASPL) at that velocity. The one-third-octave center band frequencies have been normalized with respect to the nozzle diameter and nozzle exit velocity to form a Strouhal number. The resultant spectra plots collapse into a single dimensionless SPL spectrum over a velocity range of 123 to 310 meters per second (402 to 1015 ft/sec), with the peak occurring at a Strouhal number near 1.5. The data for nozzle exit velocities less than 123 meters per second are not plotted in this figure because they did not properly collapse (i. e., their spectral shapes were distorted), indicating internal and/or background noise contamination. The consistency of SPL spectral shape at  $90^\circ$  on this facility to velocities as low as 123 meters per second is clearly demonstrated. Therefore, at this microphone angle any internal or background noise contamination that may be present has no apparent effect on the SPL spectral shape even on the 123-meter-per-second data.

The data in figure 6 are for a single microphone angle. A special integration of the axisymmetric SPL spectra over all angles yields sound power level (PWL) spectra. The individual nonnormalized power spectra for this nozzle are shown in figure 7 for the same nozzle exit velocities shown in figure 6. It can be seen that the center frequency  $f_c$  does not appear to vary significantly with the jet velocity. The curves through the data were generated by translating the same curve along the dashed line through the peak. This peak occurs at a one-third octave center band frequency of approximately 800 hertz.

The SPL spectra at each microphone position were integrated over all frequencies to obtain an overall sound pressure level (OASPL). The variation of OASPL with microphone angular position then determines the noise radiation pattern, or directivity. Several investigators (e. g., ref. 6) have given the shape of the directivity curve as

$$\text{OASPL} \propto \left(1 - \frac{\beta V_j}{a_0} \cos \theta_j\right)^n \quad (1)$$

where  $V_j$  is the mean jet exit velocity,  $a_0$  is the ambient speed of sound,  $\theta_j$  is the angular position measured from the nozzle exhaust (fig. 2), and  $\beta$  is a constant related

to the axial convection velocity of the turbulence. Experimental evidence (e.g., ref. 7) indicates a value of approximately 0.62 for  $\beta$ .

For the value of the exponent Lighthill originally derived  $n = -5$  (ref. 8). Goldstein and Howes (ref. 9), however, arrive at a value of  $n = -3$ . Olsen, Gutierrez, and Dorsch (ref. 6) present experimental data for five different jet velocities and three different nozzle diameters that indicate that  $n = -3$  agrees with jet noise data better than  $n = -5$ . A plot of the OASPL directivity pattern at various velocities is shown in figure 8 for the present nozzle. The symbols are the experimental data, and the solid lines are expression (1) with  $\beta = 0.62$  and  $n = -3$ . Since expression (1) describes the shape of the directivity pattern and not the level, the curves defined by it were put through the data at the  $90^\circ$  position. This was done because the  $90^\circ$  data are not affected by convection. The data fit the curves reasonably well with only several points at the higher velocities deviating by more than about  $1\frac{1}{2}$  dB.

Integration of the SPL spectra spatially and with frequency yields the total sound power level  $PWL_T$ . As mentioned in the INTRODUCTION, Lighthill determined, through dimensional reasoning, that the total sound power radiated from a jet is proportional to jet exit velocity raised to the eighth power, at least for cold-flow subsonic velocities. This provides a relatively simple check on the lower velocity limit at which a jet noise facility can be operated before internal and background noise effects contaminate the data.

Figure 9 is a plot of the total sound power radiated from the jet as a function of jet exit velocity for the full range of velocities tested. The symbols are the measured data, and the solid line defines a velocity to the eighth power law. The line has been arbitrarily put through the 212-meter-per-second (700-ft/sec) data point. It can be seen that the data fit the eighth power line very well down to 152 meters per second (500 ft/sec). At 123 meters per second (402 ft/sec) the data are beginning to deviate from eighth power, and at 92 meters per second (302 ft/sec), and below, internal and/or background noise effects clearly become significant.

### Comparison with Other Nozzles

As a check on the shape of the power spectra, the data for the nozzle velocity of 184 meters per second (604 ft/sec) have been plotted together with power spectra for convergent circular nozzles of various diameters at a jet velocity of 183 meters per second (600 ft/sec) in figure 10. These other power spectra were obtained from reference 6. The peak frequency for the 15.2-centimeter-diameter potential flow nozzle falls on the dashed line defining the peak frequencies for the data reported in reference 6 for other nozzle diameters at the same jet exit velocity. This dashed line is approximately



defined by the peak frequency being inversely proportional to the nozzle diameter. The sound power levels at the peaks are proportional to the nozzle area (i. e., diameter squared) for all the nozzles including the one tested here.

Figure 11 is a normalized SPL spectrum as a function of Strouhal number based on nozzle diameter. The data in the figure are for the 15.2-centimeter-diameter nozzle with a nozzle exit velocity of 184 meters per second and for various other nozzle sizes at the velocities indicated (ref. 6). Again, the collapse of the data indicates consistency of spectral shape between the nozzle tested herein and simple convergent circular nozzles tested by previous investigators.

As final verification of the lack of significant differences between the potential flow nozzles and simple convergent nozzles, a plot of the total power against nozzle exit velocity for various nozzle sizes is shown in figure 12. The data from figure 9 for the 15.2-centimeter potential flow nozzle is repeated for comparison. The other nozzle data were area scaled from reference 6 to the area of the 15.2-centimeter-diameter nozzle. There are no significant differences in the total power radiated as a function of nozzle exit velocity for any of the nozzles.

## CONCLUSIONS

The acoustic tests of the 15.2-centimeter diameter potential flow nozzle indicate that the facility provides reliable jet noise data for nozzle exit velocities as low as 152 meters per second. The data also show that at an exit velocity of 123 meters per second the facility becomes marginal for acoustic tests. At that exit velocity the noise spectral shape is still consistent with the higher velocity spectra, but the total power level is beginning to deviate from the eighth power velocity relation. At this velocity, however, the aerodynamic and turbulence data show that there are no apparent flow or turbulent spectra anomalies. Below 123 meters per second the data are clearly contaminated with excess internal and/or background noise.

Comparisons of the noise data for the potential flow nozzle with data from simple convergent circular nozzles from tests by other investigators indicate that the far field noise is not sensitive to small differences in nozzle contours. This indicates that potential flow nozzles are probably not necessary for noise tests unless turbulence data are also taken as part of the experimental program.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, February 5, 1974,  
501-04.

## APPENDIX - SYMBOLS

$a_0$	ambient speed of sound
$D$	nozzle diameter
$F(f)$	turbulent velocity spectral density
$f$	frequency, Hz
$n$	exponent in expression (1)
OASPL	overall sound pressure level
PWL	sound power level
$PWL_T$	total sound power
$R$	nozzle radius
$r$	radial position
SPL	sound pressure level
$\bar{V}$	local mean velocity
$V_j$	mean nozzle exit velocity
$x$	axial position downstream of nozzle exit plane
$\beta$	constant related to axial convection velocity
$\theta_i$	angular position, measured from nozzle inlet
$\theta_j$	angular position, measured from nozzle exhaust

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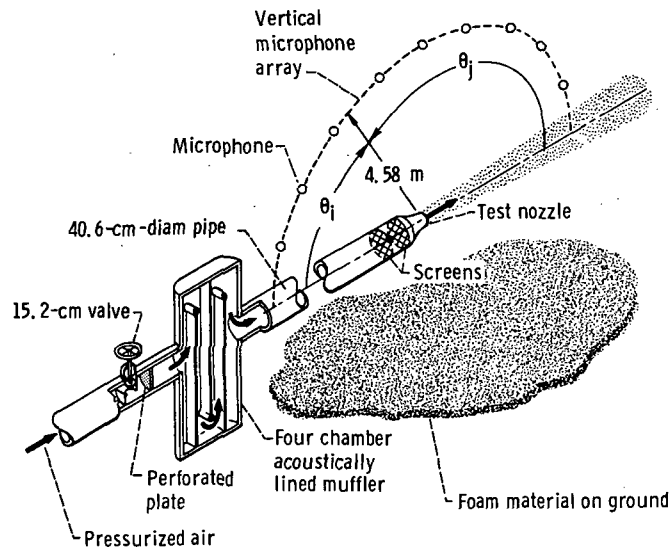
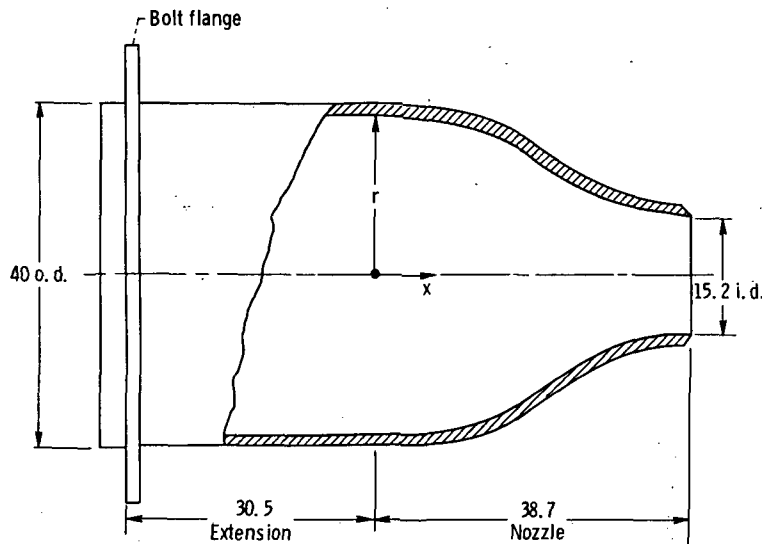


Figure 1. - Flow system for 15.2-centimeter-diameter nozzle tests with microphone array.



Coordinates, cm			
x	r	x	r
0	38.74	20.32	27.74
1.27	38.73	21.59	26.20
2.54	38.70	22.86	24.64
3.81	38.62	24.13	23.08
5.08	38.49	25.40	21.58
6.35	38.25	26.67	20.18
7.62	37.92	27.94	18.92
8.89	37.47	29.21	17.83
10.16	36.89	30.48	16.95
11.43	36.17	31.75	16.27
12.70	35.32	33.02	15.78
13.97	34.33	34.29	15.47
15.24	33.22	35.56	15.31
16.51	31.99	36.83	15.25
17.78	30.65	38.10	15.20
19.05	29.32		

Figure 2. - 15.2-Centimeter-diameter potential flow nozzle. (All dimensions are in cm.)

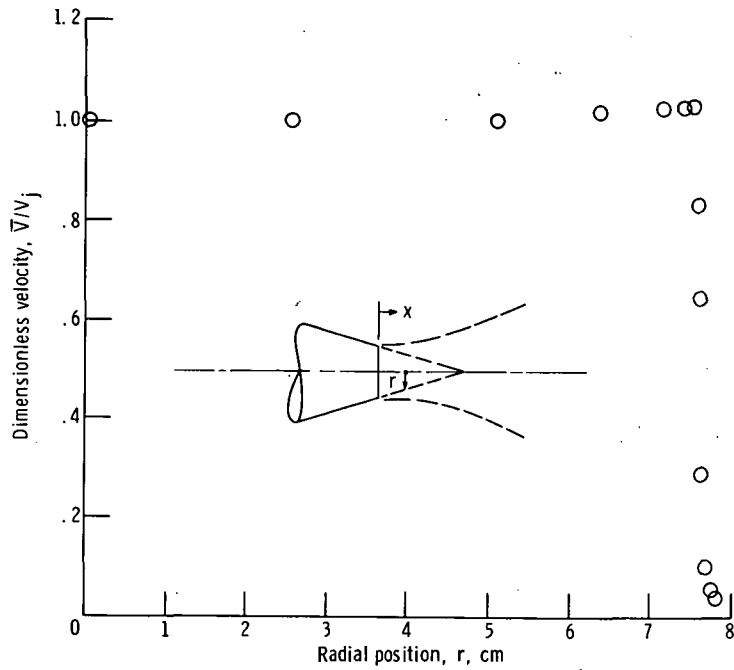


Figure 3. - Exit plane dimensionless velocity profile for 15.2-centimeter-diameter potential flow nozzle. Axial position,  $x$ , 0.075 centimeter; mean nozzle exit velocity, 122 meters per second.

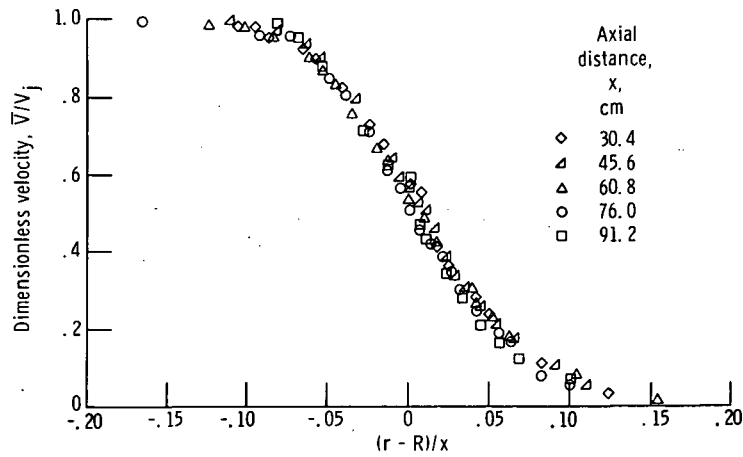


Figure 4. - Dimensionless mean velocity profiles for 15.2-centimeter-diameter potential flow nozzle. Mean nozzle exit velocity, 122 meters per second; nozzle radius,  $R$ , 7.6 centimeters.

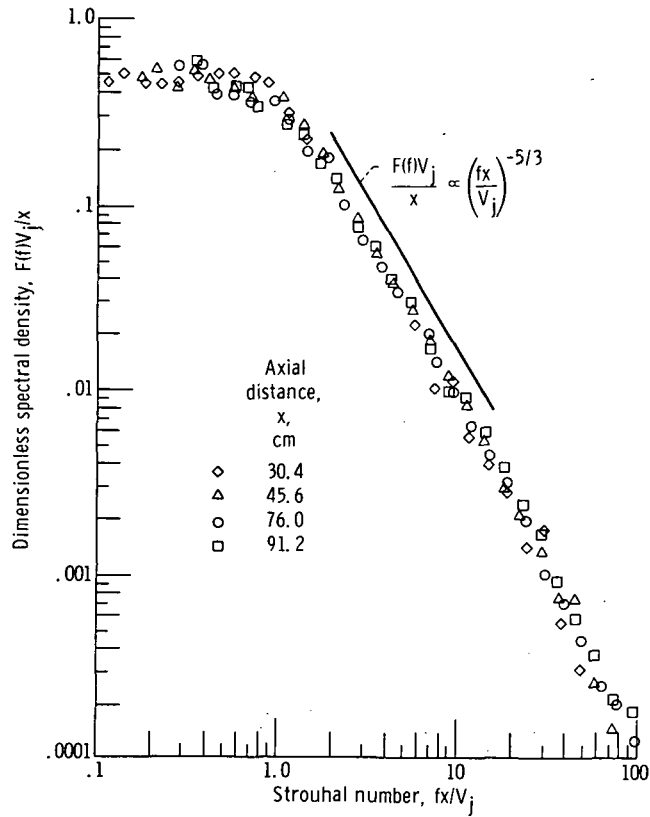


Figure 5. - Turbulent axial velocity spectral density at lip axis. Mean nozzle exit velocity, 122 meters per second; radial position, 7.6 centimeters.

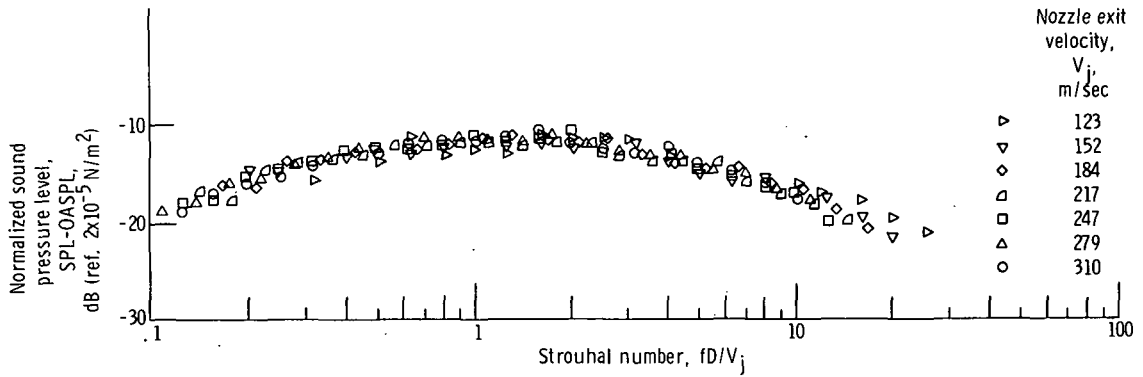


Figure 6. - Normalized sound pressure level spectra at microphone angle of 90° for 15.2-centimeter-diameter potential flow nozzle.

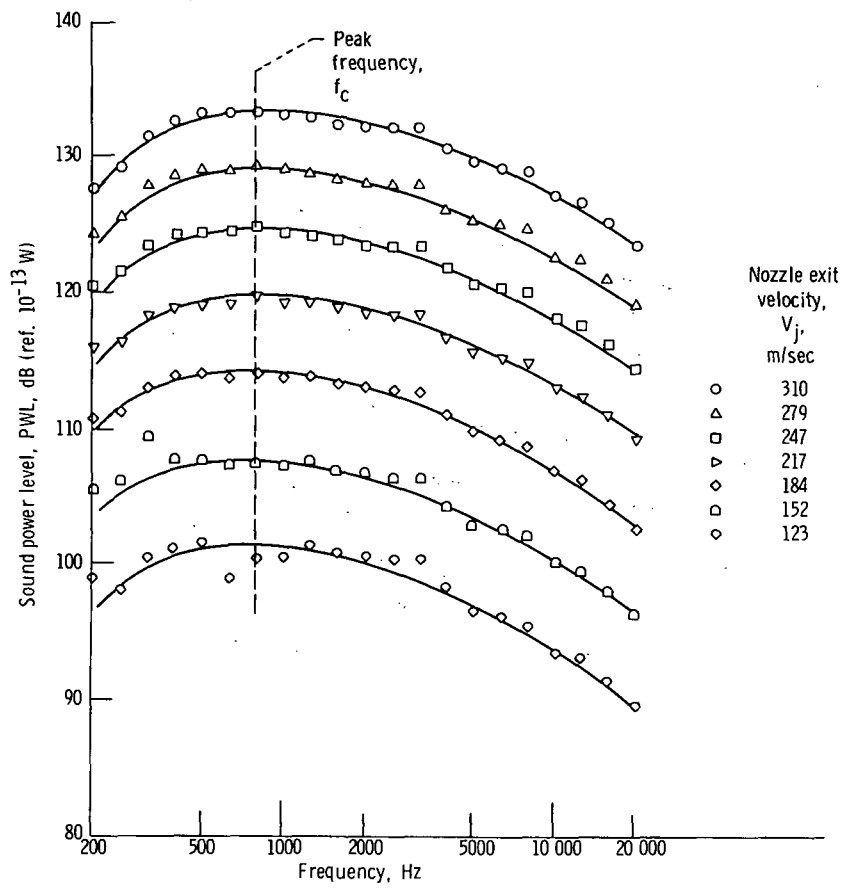


Figure 7. - Sound power level spectra for 15.2-centimeter-diameter potential flow nozzle for several exhaust velocities.

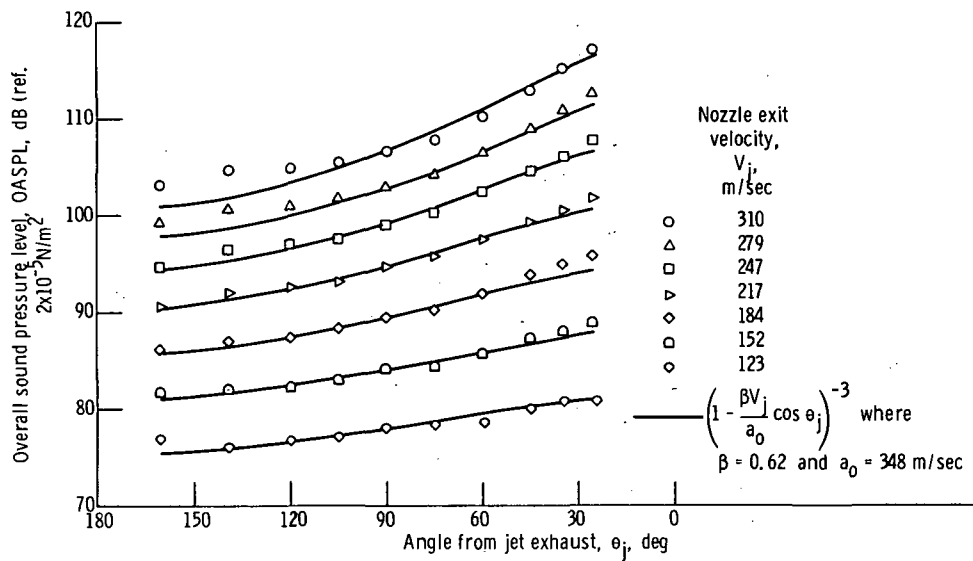


Figure 8. - Noise radiation pattern at 4.58 meter for 15.2-centimeter-diameter potential flow nozzle at several velocities.



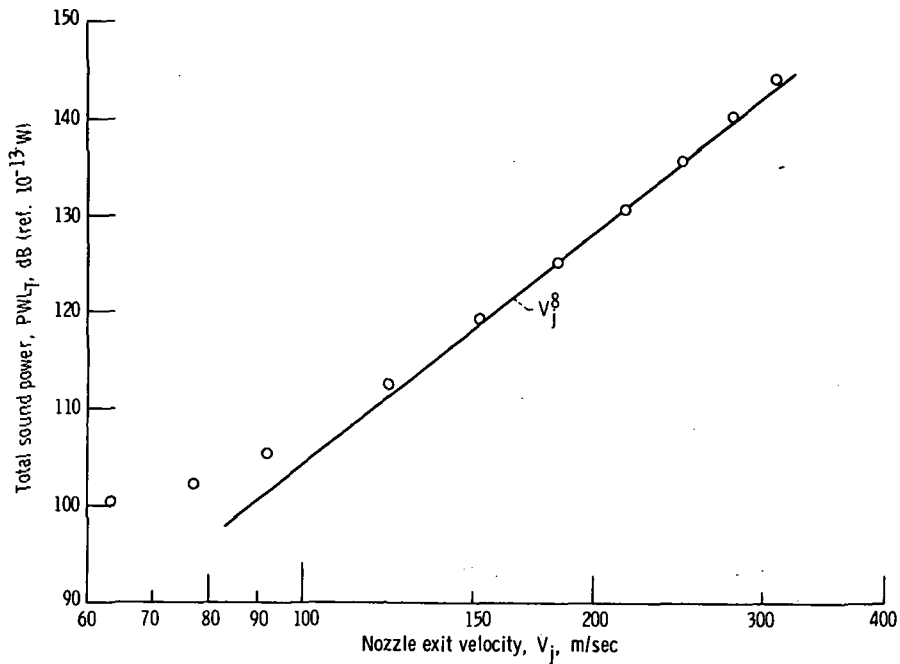


Figure 9. - Variation of total sound power level with nozzle exit velocity for 15.2-centimeter-diameter potential flow nozzle.

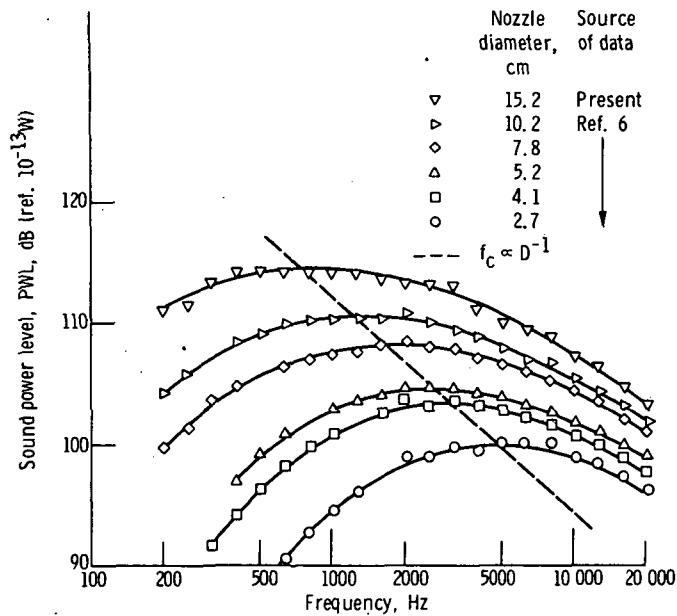


Figure 10. - Variation of power spectra with nozzle diameter at constant nozzle exit velocity of 183 meters per second.

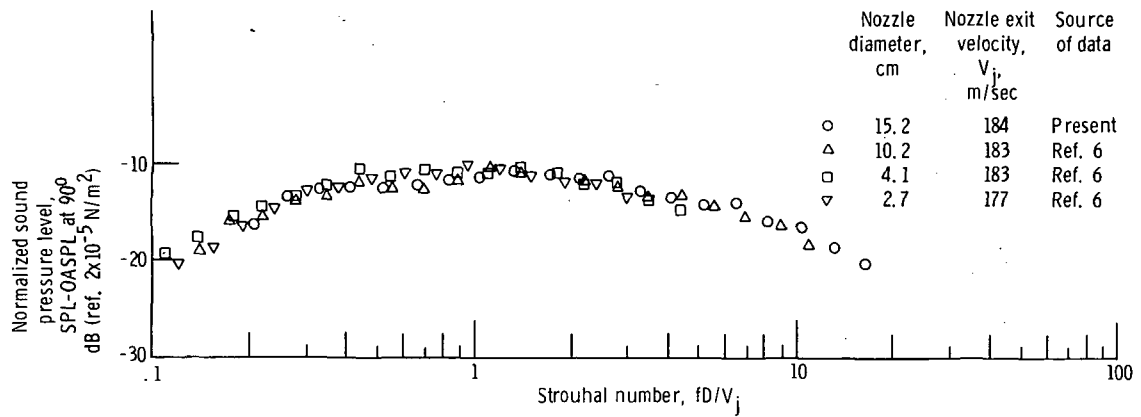


Figure 11. - Comparison of normalized sound pressure level as function of Strouhal number, for various nozzle diameters.

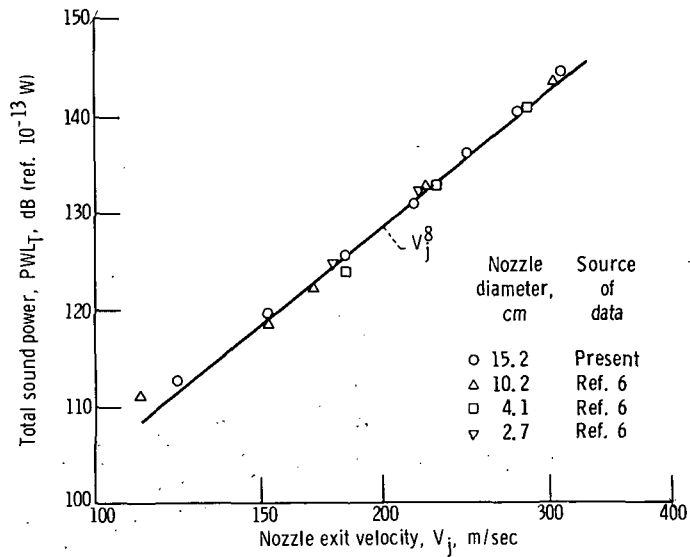


Figure 12. - Variation of total sound power level with nozzle exit velocity for various nozzle diameters.



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