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SYMBOLS

D	diameter of jet, m
f	frequency, Hz
OASPL	overall sound pressure level, dB
SPL	sound pressure level, dB
V_{jet}	velocity of jet, m/sec
V_T	velocity in wind tunnel, m/sec
$\frac{fD}{V_{jet}}$	Strouhal number
°K	degrees Kelvin
θ	reference angle to inlet

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COMPARISON OF ACOUSTIC DATA FROM A 102 mm CONIC NOZZLE AS MEASURED IN THE RAE 24-FOOT WIND TUNNEL AND THE NASA AMES 40- BY 80-FOOT WIND TUNNEL

A. Atencio, Jr. and J. McKie*

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SUMMARY

A cooperative program between the Royal Aircraft Establishment (RAE), England, and the NASA Ames Research Center was initiated to compare acoustic measurements made in the RAE 24-Foot Wind Tunnel and in the Ames 40- by 80-Foot Wind Tunnel. The acoustic measurements were made in both facilities using the same 102 mm conical nozzle supplied by the RAE. The nozzle was tested by each organization using its respective jet test rig. The mounting hardware and nozzle exit conditions were matched as closely as possible. The data from each wind tunnel were independently analyzed by the respective organization. The results from these tests show good agreement. However, in both facilities interference with acoustic measurement is evident at angles in the forward quadrant.

INTRODUCTION

In 1976, an agreement between the RAE and NASA Ames Research Center was initiated whereby a 102 mm conic nozzle that had been previously tested by the RAE in its 24-Foot Wind Tunnel at Farnborough, England, would be tested in the Ames 40- by 80-Foot Wind Tunnel. The purpose of the test was to determine if the two organizations would obtain the same results from the same nozzle after each organization independently tested the nozzle, and then used their respective methods to reduce and analyze the data. The RAE supplied Ames with the 102 mm nozzle and drawings showing their test apparatus and measurement approach. In addition, the RAE supplied Ames with reports from the previous tests. The test was performed in the Ames wind tunnel during the summer of 1977. The 102 mm nozzle was tested both hot and cold, and at wind tunnel velocities that matched previous test data from the RAE. The results and comparisons made with the previous set of data are presented in this report.

FACILITIES

The 102 mm conical nozzle was tested in the RAE 24-Foot Wind Tunnel and in the Ames 40- by 80-Foot Wind Tunnel. The difference in the facilities created a unique test environment. The following sections describe the wind tunnel test chambers and give some details on the installation of the 102 mm nozzle.

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*Royal Aircraft Establishment, England.

The Royal Aircraft Establishment Test Arrangement

The RAE 24-Foot Wind Tunnel at Farnborough, England, is an open jet test section of circular cross section. The open jet exhausts into an acoustically treated chamber that is 13.5 m × 13.5 m × 9 m. The downstream face of the chamber is a circular collector and, immediately following the collector, is the drive fan which exits to a short rectangular return circuit back to the 7.2 m free jet nozzle. Figure 1 shows the wind tunnel test chamber and collector. The wind tunnel is capable of speeds up to 50 m/sec, but background noise levels from the drive fan reduce the useful range for acoustic tests to velocities of 30 m/sec or less, with frequencies 500 Hz and lower still dominated by the tunnel background. The test nozzle was mounted as shown in figure 2 (ref. 1). The wing rig is placed vertically in the test section, and the test nozzles are mounted by means of a conical adaptor to a cascade corner. This turns the airflow to the tunnel downstream direction. The nozzle flow pipe was treated to minimize rig noise. Reference 1 describes the installation in more detail.

The NASA Ames 40- by 80-Foot Wind Tunnel Test Arrangement

The 40- by 80-Foot Wind Tunnel at NASA Ames Research Center, Moffett Field, California, is a closed-return wind tunnel with a constant area test section measuring 12.2 m high by 24.4 m wide by 24.4 m long. The cross section has 6.1 m semi-circular sides, and a middle section that is 12.2 m square. The wind tunnel is capable of test section speeds up to 200 knots (103.0 m/sec). The floor and part of the curved side walls were treated with a 76 mm (3 in.) acoustic foam mat during the test of the 102 mm nozzle as shown in figure 3. The mat was designed to increase the effective hall radius for acoustic measurements and, for this test, was effective down to 500 Hz. Even though the untreated portions remain a source of reflection and reverberant field noise in the closed test section, the treatment increases hall radius two to three times. The background noise levels measured for this test are shown in figure 4. This noist is created by the drive system, the aerodynamic noise of the test rig, and self noise of the microphone. The 102 mm nozzle was tested in two different configurations in the 40 × 80. The first configuration was the nozzle mounted to the standard rig S-duct. The S-duct is a transition tube from the burner, which sits on the wind tunnel floor and rises to a model exit height of 1.52 m. The S-duct attachment is sketched in figure 5. The second mounting configuration was the nozzle mounted to a wing rig, attached to the S-duct as shown in figure 6. This rig mounting was meant to match the RAE nozzle mounting.

The Ames model jet burner is a kerosene fueled burner that was designed for nozzles of 135.2 mm (6 in.) diameter and for continuous hot operation at 810 K (1000 F). The burner air was supplied by bleeding the air mass flow from a Rolls Royce Viper engine compressor. The compressor was driven by the hot exhaust from a G.E. J-85 Turbojet. The compressor was located outside the wind tunnel in an acoustically treated enclosure (Fig. 7). The air was ducted through more than 15 m of pipe to the model burner. There was a remotely operated dump valve at the entrance to the feed pipe to control the air mass flow from the compressor. There was also a short section of pipe at the burner entrance that was acoustically treated to absorb the compressor noise. Since the burner was operated at 820 K, there was no acoustic treatment in the burner and before the nozzle exit on either the S-duct configuration or the wing configuration. The wing configuration was made from steel in order to withstand the high temperature. Since the burner was operated at an off design point, there was a tendency for the burner can to "carbon up." When the burner was cold, the carbon would break loose from the burner can and, on subsequent hot operation, chunks of carbon would be forced out of the nozzle exit for a few seconds. Therefore, the screen (used by the RAE before the nozzle exit) was not used and no data were taken until the burner was free of the carbon chunks. The expelled carbon was about the size of a small pea and was not considered large enough to change sound characteristics.

MODEL

The test nozzle supplied by the RAE was a conic nozzle with an exit diameter of 102 mm. The nozzle barrel was 73 cm long and was designed with a half angle of 7°. (Fig. 8.) The Ames wing configuration was designed using the RAE mount system as a guide. However, the Ames wing was made from steel and was not acoustically treated because it was intended to be run with the hot flow. The RAE supplied cascade elbow was used only with the Ames wing configuration to turn the flow streamwise at the nozzle attachment. An Ames designed cascade corner was used for the attachment and turning off the burner S-duct. Th jet exit height above the wind tunnel floor was maintained at 1.52 m for both configurations.

INSTRUMENTATION

RAE Instrumentation

The RAE instrumentation for the 102 mm nozzle consisted of a single pitot pressure probe upstream of the cascades in the corner of the elbow where the 102 mm nozzle was attached. The pitot probe was calibrated using a reference pressure at the exit plane of the nozzle. The air total temperature was measured in the plenum chamber of the air supply. The RAE microphone instrumentation consisted of a single 6-mm (1/4-in.) Bruel and Kjaer (B&K) microphone fitted with a nose cone and aligned with the tunnel flow. The microphone was traversed on a 3-m sideline at nozzle exit centerline height, but acoustic measurements were made at fixed positions along the traverse. The data were not corrected for convection.

40 by 80 Instrumentation

The 40 by 80 test rig had pressure and temperature instrumentation at the coupling joint at the end of the S-duct. Two area weighted rakes were used and each had ten probe positions: one was total pressure and the other was total temperature. The readings from these rakes were input to the 40 by 80 computer system where calculations were made to determine jet exit velocity and pressure ratio. These quantities were continuously displayed on digital panel meters, and update was achieved by the real time section of the 40 by 80 computer system. Hard copies of the data were available following a data point. In addition to the model instrumentation, tunnel parameters were obtained using the tunnel instrumentation system. No thrust measurements were made since the jet rig is not designed for metric measurements.

Bruel and Kjaer 6-mm (1/4 in.) microphones with attached nose cones were used for all acoustic measurements. The data were measured by traversing a single microphone along a 2.96-m sideline parallel to the jet axis. The microphone covered angles from 27° to 166° relative to the jet exhaust plane with zero degrees upstream toward an imaginary inlet. The signal from the single microphone was passed through a B&K signal conditioner, and then through two separate amplifiers where gain settings were made. The two separate amplifiers were used to assure a good signal-to-noise ratio throughout the traverse. The position of the microphone was determined using a rotating potentiometer which gave a continuous reading of voltage level. The voltage level was transferred to linear position on the traversing rail, and then to angle by a second transformation. The microphone acoustic signals and traverse position voltage signal were recorded on magnetic tape using an Ampex 14 track recorder. The recorder was set up with direct record modules to allow recording of the higher frequencies at reasonable tape speed. However, the dynamic range or signal/noise ratio was reduced to about 25 dB and the upper limit on frequency was around 31.5 kHz at 30 ips, which was adequate for the 102-mm nozzle. As it was necessary for the microphone to always point upstream, the orientation of each microphone nose cone to the jet changed constantly with distance down the traverse. Corrections for the change in microphone directivity, as a function of the orientation, were applied using an "average correction." This was very accurate up to 20 kHz and was good to ±2 dB for higher frequencies with the largest errors occurring at shallow angles to the jet. Other corrections made to the data were for atmospheric attenuation and tape recorder response. The speed of the microphone traversing system was set by a motor controller. The speed was set without wind blowing through the test section. The traverse time used was approximately 5 min with slight variations depending on wind speed and microphone cable drag.

TEST PROCEDURES

The test procedure for the RAE tests is outlined in reference 1. Basically, conditions were set for the nozzle to maintain a certain total pressure at the regulated temperature of 300 K, and wind speed was set at either 0, 15, or 30 m/sec. The microphone was then traversed on the sideline to fixed locations where data were recorded. The positions were 145°, 135°, 120°, 105°, 90°, 75°, and 60° reference to an imaginary inlet.

The test procedure used during the test in the 40 by 80 was to set all flow conditions at the nozzle exit for desired temperature, pressure ratio, and exit velocity. When the conditions were set, the microphone was quickly traversed to upstream so that gain settings could be made. The microphone was then slowly traversed downstream from forward of the nozzle exit to the aft stop to take data. Traverse time was about 5 min. During the traverse, propulsion data were recorded at selected points which were later averaged to get jet nozzle test conditions. The data taken during the Ames tests included both "cold" and "hot" flow data. The "cold" data were obtained by operating without the burner being turned on. The air from the Viper compressor was simply passed through the burner can to the S-duct, to the nozzle. Since the compressor operated with ambient air, the nozzle exit temperature depended on pressure ratio through the compressor. There was no means of independently controlling temperature within the supply system so that an exact match with the RAE results was not possible. The "cold" flow temperatures ranged from 320 K to 360 K, whereas the RAE cold flow was maintained at 300 K. The "hot" flow temperature was maintained by regulating the fuel flow through the burner. Temperature was maintained within ±5 K for most test conditions. Hot operation, however, did require that the nozzle be run without the screen gauge that was supplied by the RAE. The Ames model burner was designed for larger exit area nozzles than the 102 mm, and off design operation tended to be fuel rich, causing some carbon buildup inside the burner combustion chamber. When the burner was cooled between runs, the carbon buildup would break up due to the difference in expansion. When the burner was restarted, the carbon chunks would be expelled through the nozzle exit for a few seconds until gone. No data were taken under these conditions.

Several runs were made for both the S-duct configuration and for the wing configuration. A summary of runs and conditions is given in table 1.

DATA REDUCTION

The data taken during the RAE test were reduced through a GR 1926 real time third-octave spectrum analyzer from 315 Hz to 80 kHz using an integrating time of 2 sec. Digitized paper tapes output from the analyzer were processed further using a digital computer. The computer calculations included corrections for microphone frequence response and directivity, atmospheric attenuation, and summations of the one-third-octave levels to give OASPL. The propulsion data were processed using the total pressure and temperature measurements to calculate jet exit velocity assuming isentropic flow.

The propulsion data taken during the Ames test were reduced using a program on the Ames 40- by 80-computer system. Most of the propulsion data were available immediately following each wind tunnel run. The calculations provided wind tunnel velocity and ambient temperature, jet nozzle velocity, jet pressure ratio, and jet exit temperature.

The acoustic data from the traversing microphone were reduced using an Ames wind tunnel system called the Dynamic Analysis System (DAS). The DAS is a synthesized system composed of several special function components that are coupled to a PDP 11 minicomputer. The acoustic data were reduced through a GR 1925 one-third-octave band analyzer that was triggered by commands from the DAS. The commands were part of a special program written to reduce traversing microphone data. The output from the DAS was put on punched paper tape and was later reduced on an IBM 360 computer through a general acoustic program. The acoustic program provided microphone response corrections, tape recorder response corrections, atmospheric attenuation corrections, and source convection correction for wind on data. The final listings included angular position and SPL for each one-third-octave band frequency. Convection corrections were applied to the nozzle exit rather than to actual source location. The correction relates initial sound emission angle (θ) and the geometric angle (Ψ) at a particular microphone position. The relationship is:

$$\mathrm{Tan}\ \psi = \frac{\sin\theta}{M_A - \cos\theta}$$

where

$$M_A = \frac{V_{TUNNEL}}{a_o}\text{, flow Mach number}$$

a_o = ambient sound speed

In addition to the angle change, there is also a small level correction to account for the difference in microphone position as measured and the corrected position. The correction is simply:

$$-20 \text{ Log}_{10} \left(\frac{\text{New Radial Distance}}{\text{Measured Radial Distance}} \right)$$

At 30 m/sec, the level corrections range from 0.1 dB at 90° to 0.75 dB at 160°. The change in angle ranges from -5° at 90° to -2° at 160°.

RESULTS

Comparison of data from the 40 by 80 and the RAE 24-Foot Wind Tunnels is limited. Only cold flow data with the wing rig were measured by the RAE for the 102-mm nozzle. The Ames data for hot flow had to be compared to a limited set of data from smaller nozzles run hot by the RAE in previous tests. The hot data had to be normalized to account for scale difference and temperature difference. Ames tests included both a wing rig mounting and a simple S-duct attachment without the wing. A comparison of these data is shown in figure 9 for zero wind speed and cold flow. There is essentially no difference in the data with or without the wing. However, since the RAE data are for the wing configuration, only data taken in the 40 by 80 with the wing configuration are compared in this report. Also, the RAE data are primarily restricted to angles in the aft quadrant of the jet. The initial comparison of noise from the two facilities for the 102-mm nozzle is shown in figure 10. These data are for the 90° position for nominal zero wind tunnel speed. In addition to the facilities data, a jet noise prediction curve is shown using a prediction method from reference 2. The data comparisons show differences up to 4 dB in the lower frequencies, almost match at mid frequencies near the peak, and 3-4 dB separation at the high frequencies.

The Ames data are consistently below the RAE data. Comparison with the predicted curves show the RAE data above the prediction for low frequencies, and almost exact for mid and high frequency. The Ames data, on the other hand, match the prediction at the low and mid frequencies, and are below the prediction for the higher frequencies. The differences are probably attributable to the respective facilities and jet test rigs. The low frequency behavior of the RAE data may be due to the close proximity of reflecting surfaces to the test nozzle, or possibly some residual noise from the model flow system (ref. 1). The high frequency behavior of the Ames data suggested a tape recorder response problem; in fact, the data above 31 kHz (not shown) appear to be spurious electrical noise.

Since it is recognized that severe problems exist with the RAE data at frequencies below 250 Hz and for the Ames data above 31.5 kHz, the comparisons to follow will be restricted to cover only 250 Hz to 31.5 kHz. When the data were compared for a more aft angle near peak jet noise as shown in figure 11 (135° position as measured from the inlet), the data from the two facilities come closer together, suggesting that facility differences are being masked by the jet noise. However, agreement is exact only for the middle frequencies. The data from the 40 by 80 are still lower for the low frequencies and high frequencies by a margin of 1-3 dB or about 1 dB or so less than shown for 90°. The spectrum shapes at the aft position are much more consistent. The results for wind on are shown for these two positions in figures 12 and 13.

The RAE data are line-of-site data and have not been corrected for convection; therefore, only RAE and Ames differences due to forward wind speed for their respective data will be discussed. Figure 12 shows the change in level due to forward speed for the data taken in the RAE wind tunnel. The high background noise level shows in the lower frequency data for wind on at both 90° and 135°; however, when the rest of the spectra is studied, the 90° data show a consistent reduction due to forward speed for the whole range of frequency. This difference is approximately 2 dB for each one-third-octave band frequency from 500 Hz to 50 kHz.

On the other hand, the 135° data show more reduction in the lower and mid frequencies and almost no change for the high frequencies. The data from the Ames tests, shown in figure 13, show that for 90° at 160 Hz up to approximately 600 Hz almost no changes in level take place. In the middle and higher frequencies, however, a fairly consistent 2-3 dB difference is maintained, which is similar to that observed for the RAE data. The data for 135° measured in the 40 by 80 shows the same trend for the low frequency data as was observed for the RAE data and, also, the lack of level chance for the higher frequencies. An overlap of spectra for the 135° case where errors in position should be small due to the low velocity is shown in figure 14. The data from about 500 Hz to 10 kHz are almost exact, but above 10 kHz the Ames data tend to be lower by 2-4 dB.

The zero wind speed data were also plotted as Strouhal number versus a ΔdB parameter formed by taking the difference between the one-third-octave band SPL minus the OASPL of the spectra as used in reference 2. The normalized data are shown in figures 15 and 16 for the cold flow case and in figure 17 for a comparison of hot flow data. Figure 15 shows the comparison for data at the 90° position. The solid line is a prediction for clean jet noise (ref. 2). The data trend is similar to the previous spectra comparisons with the exception that the Ames data and RAE data tend to agree at the higher Strouhal numbers, although neither the RAE nor Ames data match the predicted curve. The comparison with the clean jet prediction suggests that more than jet noise may be present at the lower frequencies for both the RAE and Ames data sets. Figure 16 shows the comparison at 140° (where the RAE and Ames data agree well with themselves as well as with the prediction) again suggesting that at the peak noise angle, the effect of the facilities was minimal. Figure 17 shows a comparison of hot flow data plotted in the same manner as figures 15 and 16. The hot flow data from the RAE and Ames tend to agree well one to the other, and deviate from the prediction at low and high Strouhal numbers. The data for figure 17 is for an angle of 90°.

The difference between the data sets and the prediction curve is due primarily to the original one-third-octave spectra from which the normalized curves were constructed. For example, the RAE data in the original one-third-octave comparison at 90° showed much higher levels in the lower frequencies than the prediction. This results in the RAE data having a higher OASPL than the prediction curve. When the differencing is made to construct the curves of figure 15, the RAE data have less difference between OASPL and SPL at the lower Strouhal number corresponding to low frequencies, and a larger difference at the high Strouhal numbers since the original comparisons were similar at the high frequencies. The Ames data set shows similar bias when differenced, but in the Ames case the OASPL is lower due to the high frequency dropoff in the original one-third-octave spectra. The resulting comparison of the normalized data at 90° was somewhat fortuitous since the original comparison at 90° of the one-third-octave spectra was not good.

In order to show directivity, the data from the 40 by 80 are compared to the data from the RAE. OASPL have been calculated from the 40 by 80 data by summing only frequencies from 500 Hz, discarding the lower frequencies because of the reverberant field influence. The cutoff at 500 Hz is to stay consistent with the RAE data where a similar cutoff was made to avoid background contamination.

The comparison for nominal zero wind speed is shown in figure 18. The data have been straight line connected for clarity. The zero wind speed data show the RAE data above the 40 by 80 data by 1 to 1.5 dB up to 120°, and then both data sets match at the peak noise angles. The difference in level can be partially explained by the different jet exhaust temperatures. Others reasons for this difference may be analyses techniques, data reduction equipment, and other processing differences between the two facilities, or the reflecting surfaces in the forward arc from both facilities.

The directivity for wind on is shown in figure 19. The RAE data have been corrected from line of sight to convected angle to make the comparison. The data in this case are almost matched below 90°, and gave differences up to 1.5 dB in the aft angles with the RAE data being lower than the 40 by 80. An estimate of the OASPL differences, due to temperature difference between the Ames and RAE data, was made using figures 11, 12, and 13 from reference 4. The figures give a correction of ~0.4 dB to be added to the Ames data at angles less than 90° and a zero dB correction above 90° which leaves a difference between the Ames and RAE data of about 1.5 dB. These aft quadrant differences suggest that a larger change in level occurs in the RAE data due to forward speed than happens in the 40 by 80. The correction for temperature improves the comparison below 90°.

CONCLUSIONS AND RECOMMENDATIONS

The test of the RAE 102-mm conical nozzle in the 40- by 80-Foot Wind Tunnel and comparison of data with previous RAE results for the same nozzle tested in the RAE 24-Foot Wind Tunnel have shown good agreement between the data sets, especially at the peak noise angles. There are, however, some discrepancies between the data sets in the forward quadrant noise measurements that may be due to facility contamination, or data acquisition and reduction techniques. The following items are noted:

1. The spectra comparisons for 90° without wind speed show that the RAE data are higher than expected at frequencies up to about 800 Hz. This higher level does not show the usual peaks and troughs associated with reflected noise, although reflection may be responsible. The RAE spectrum is also rather flat through the mid-frequency region before falling off. The RAE spectrum, however, does come close to prediction in the mid- and high-frequency area. The 40 by 80 data for the same condition show fairly good agreement with the prediction in the lower and mid-frequencies, although some reflection is evident up to about 500 Hz. At the higher frequencies, the 40 by 80 data tend to fall more rapidly than the prediction.

2. For the peak noise region, the spectra from the two facilities are nearly the same with little of the effects shown at 90° being present.

3. The forward speed effect on the jet noise appears similar for both facilities. There appears to be a slightly larger change due to forward speed for the RAE data, however, when comparisons are made using OASPL directivity. This may be due

to slight differences in how the OASPL were constructed from the raw data sets. The quality of the data sets restricted the construction of OASPL to frequencies above 500 Hz. Some residual reflection data above 500 Hz may tend to increase the value of OASPL calculated on this basis.

The tests were not as conclusive as expected, but did show that the facilities, although different in many respects, produced about the same results. The joint program may have been better addressed if the only variable was the facility in which the tests took place and not the differences in the jet rigs, the measurement technique, and data reduction.

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TABLE 1.- NOZZLE TEST SCHEDULE

PR	V_{jet} (nom), m/s	V_T (nom), m/s	Temperature
102-mm conical nozzle without wing			
1.6	300	0	Cold
1.6	300	15	Cold
1.6	300	30	Cold
1.73	480	0	Hot
1.73	480	30	↓
1.73	480	60	
1.73	480	90	
2.02	550	0	
2.02	550	30	
2.02	550	60	
2.02	550	90	
2.45	600	0	
2.45	600	30	
2.45	600	60	
2.45	600	90	
102-mm conical nozzle with wing			
1.6	300	0	Cold
1.6	300	15	Cold
1.6	300	30	Cold

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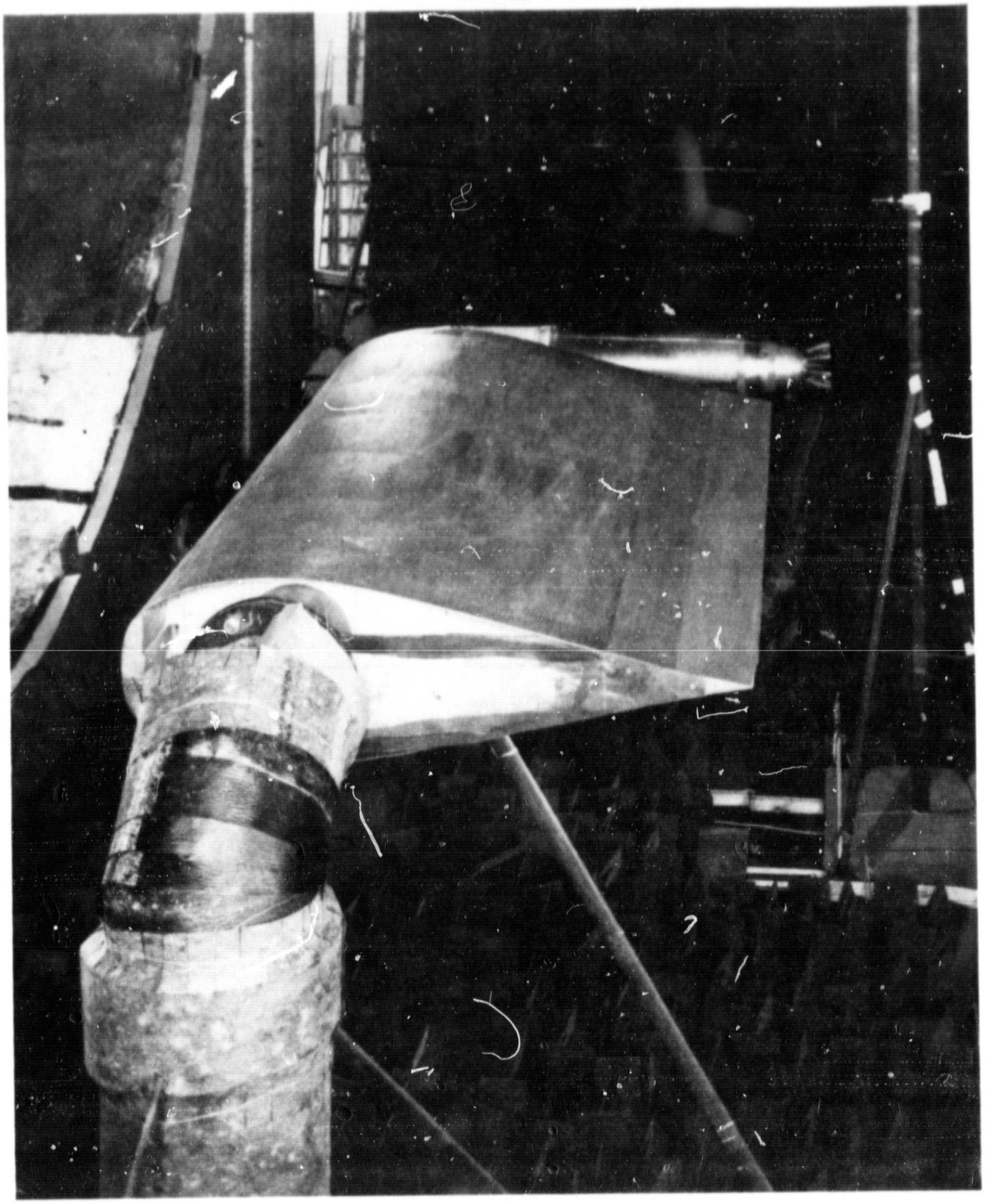

Figure 1.- RAE 24-Foot Wind Tunnel.

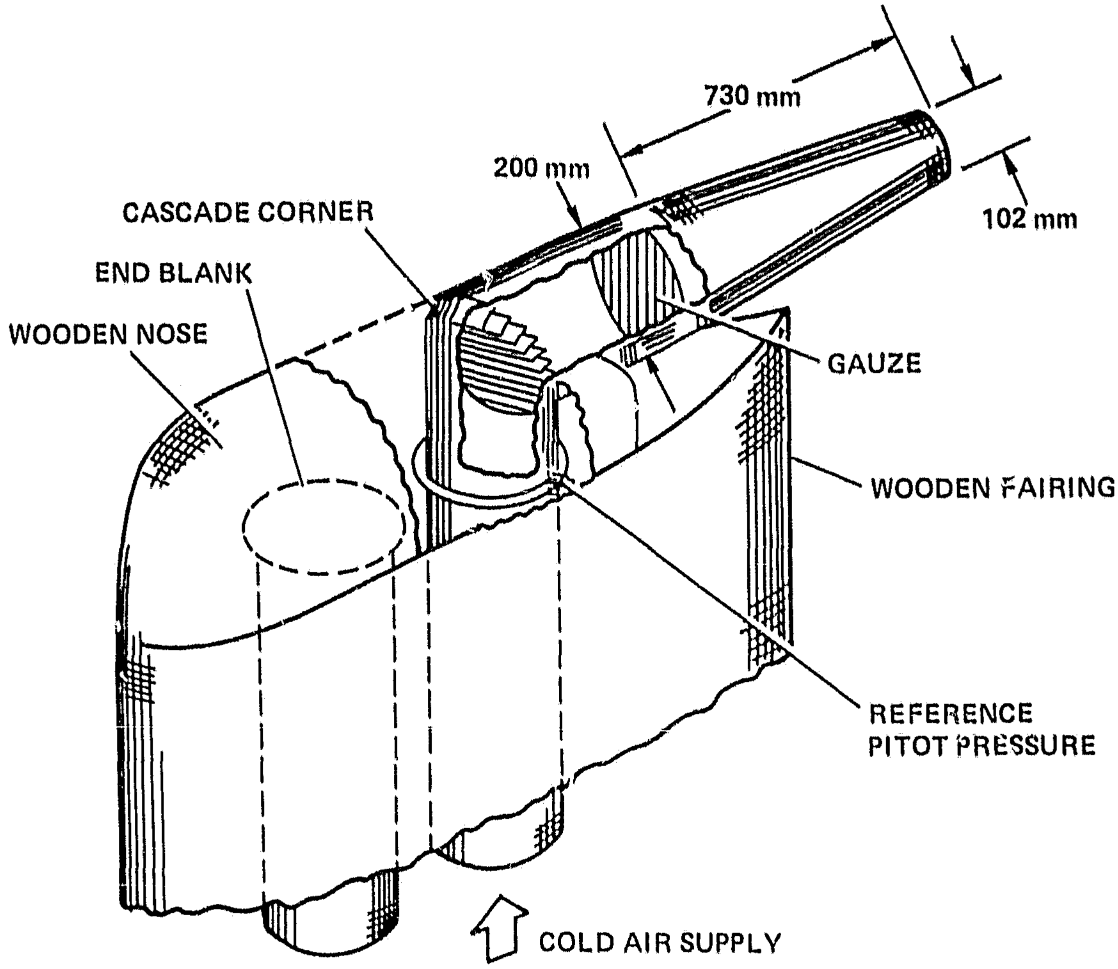

Figure 2.- RAE jet test rig.

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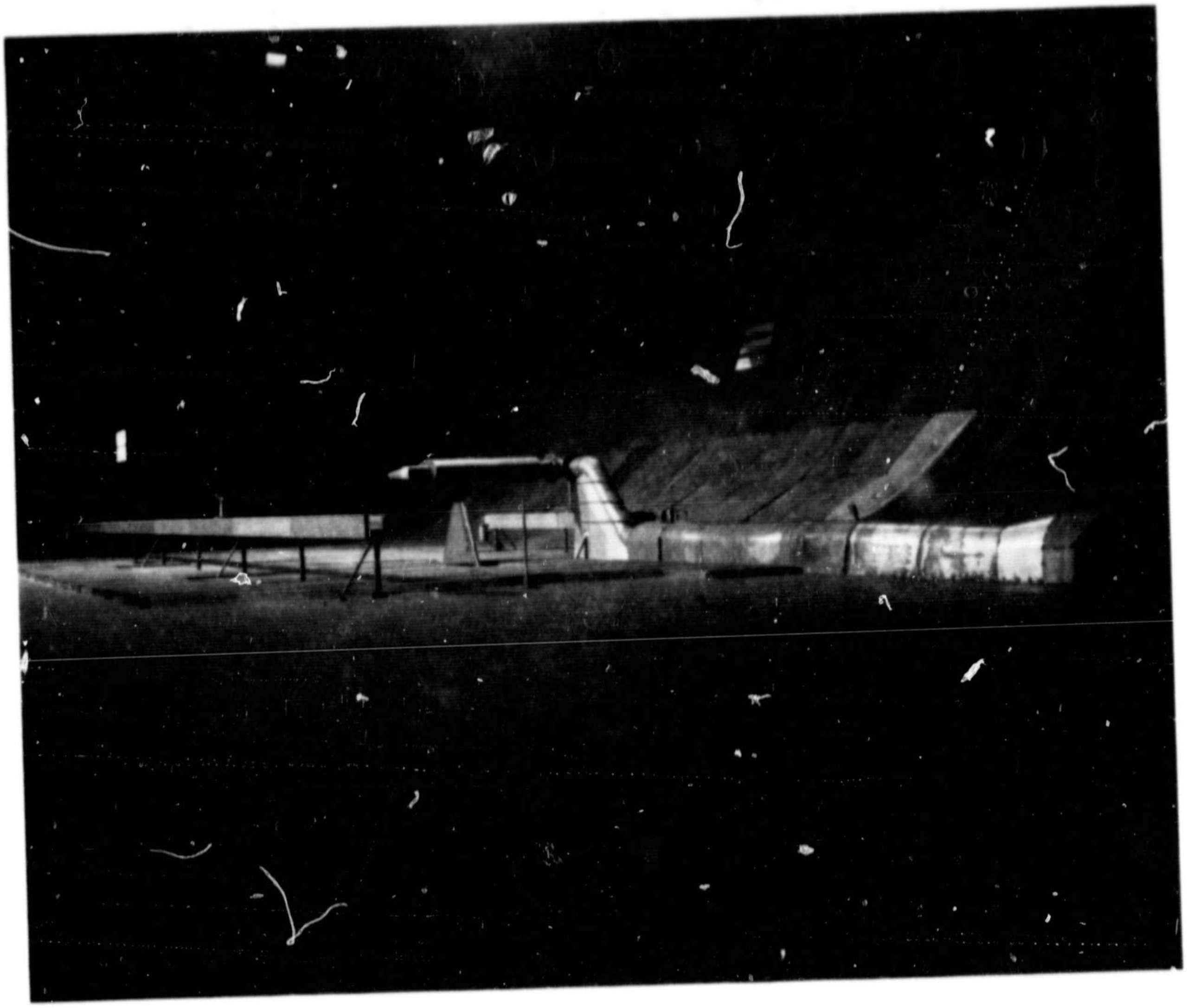

Figure 3.- 40- by 80-Foot Wind Tunnel test section.

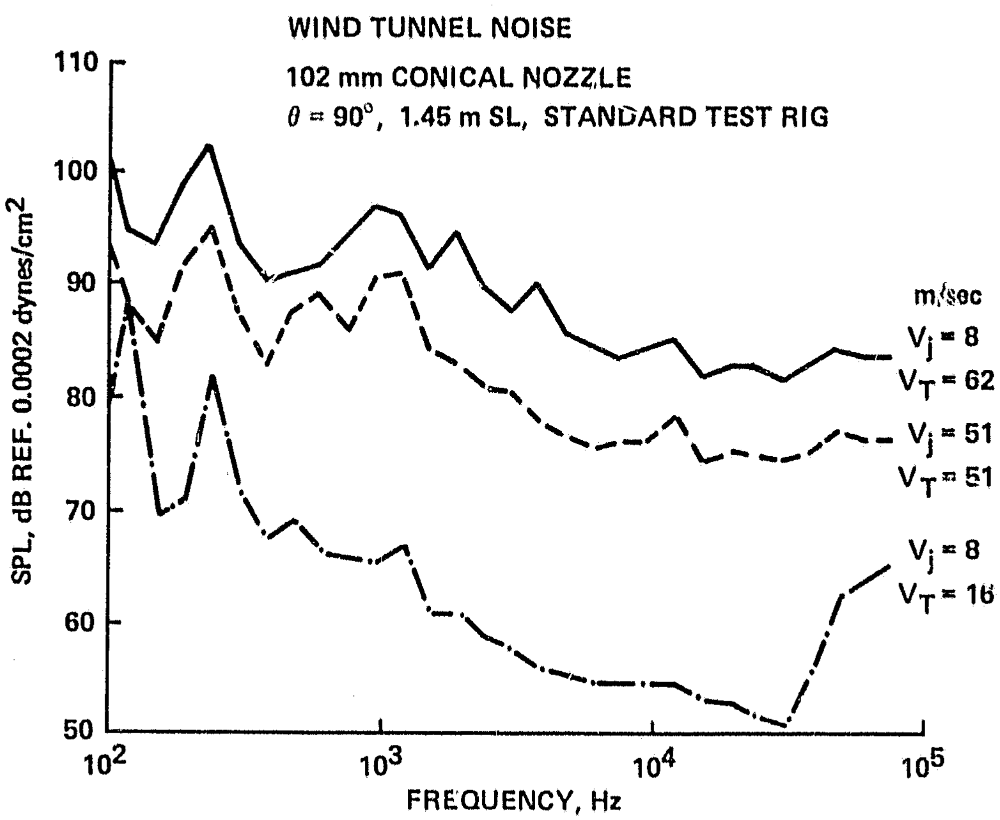

Figure 4.- Background noise in the 40- by 80-Foot Wind Tunnel.

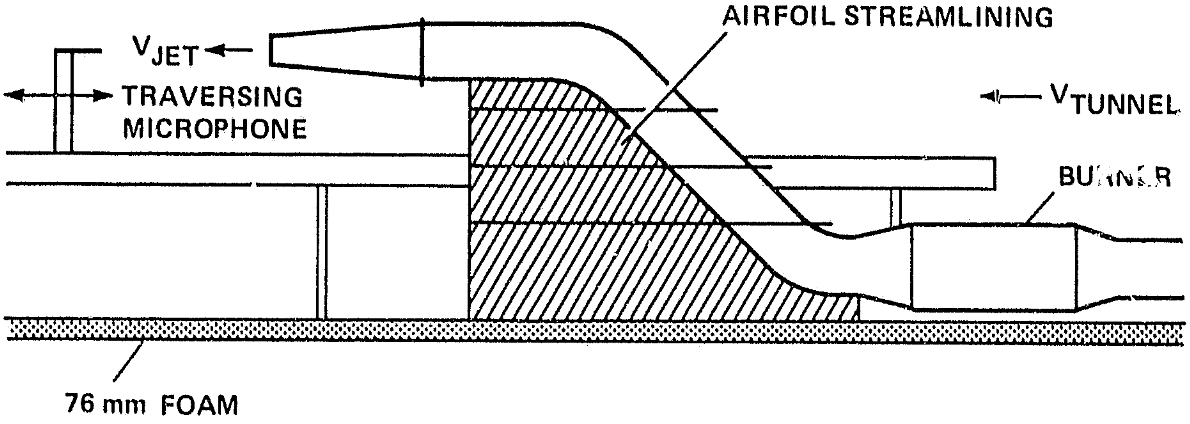

Figure 5.- S-duct jet test rig mount in the 40- by 80-Foot Wind Tunnel.

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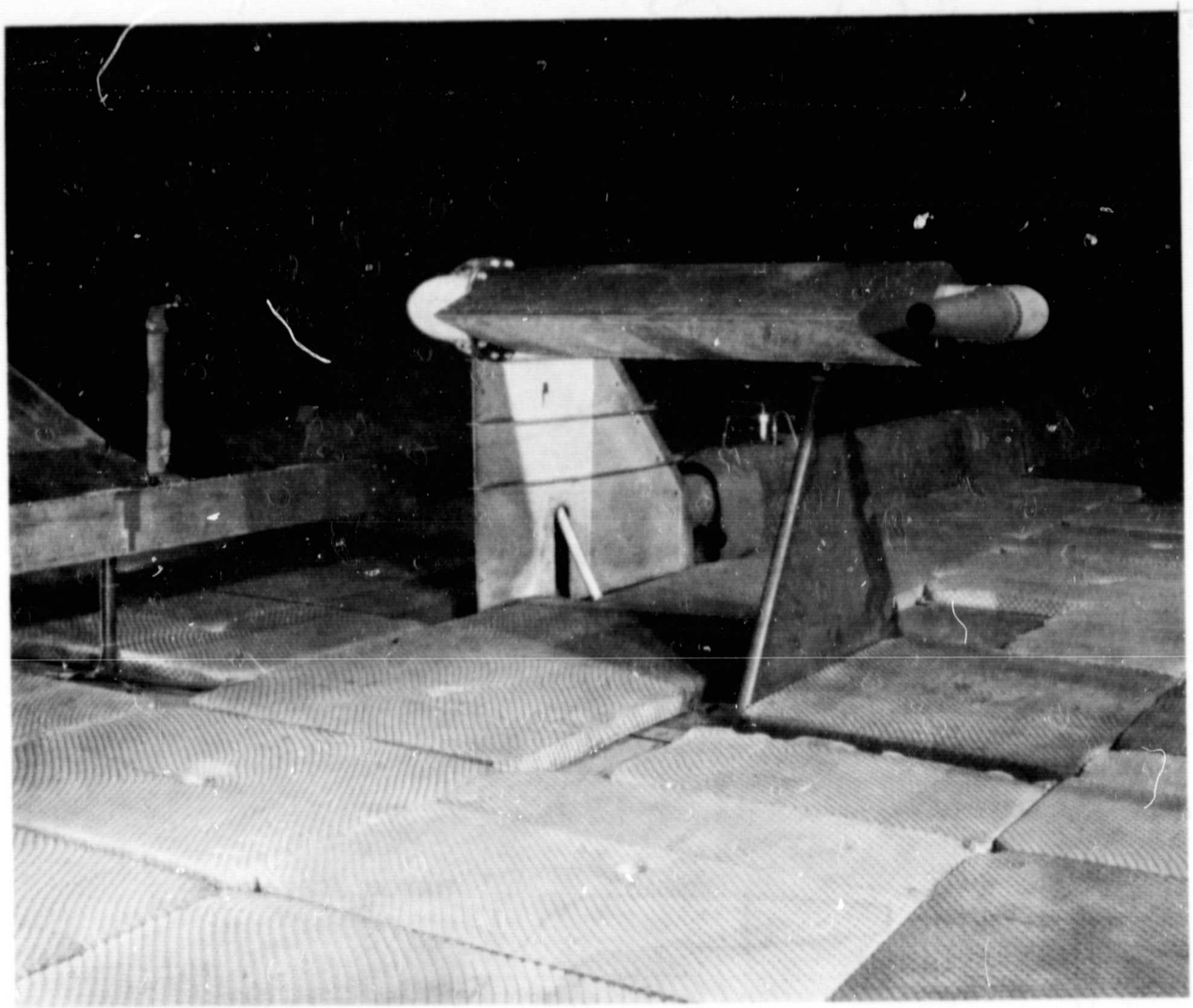

Figure 6.- Wing rig mount in the 40- by 80-Foot Wind Tunnel.

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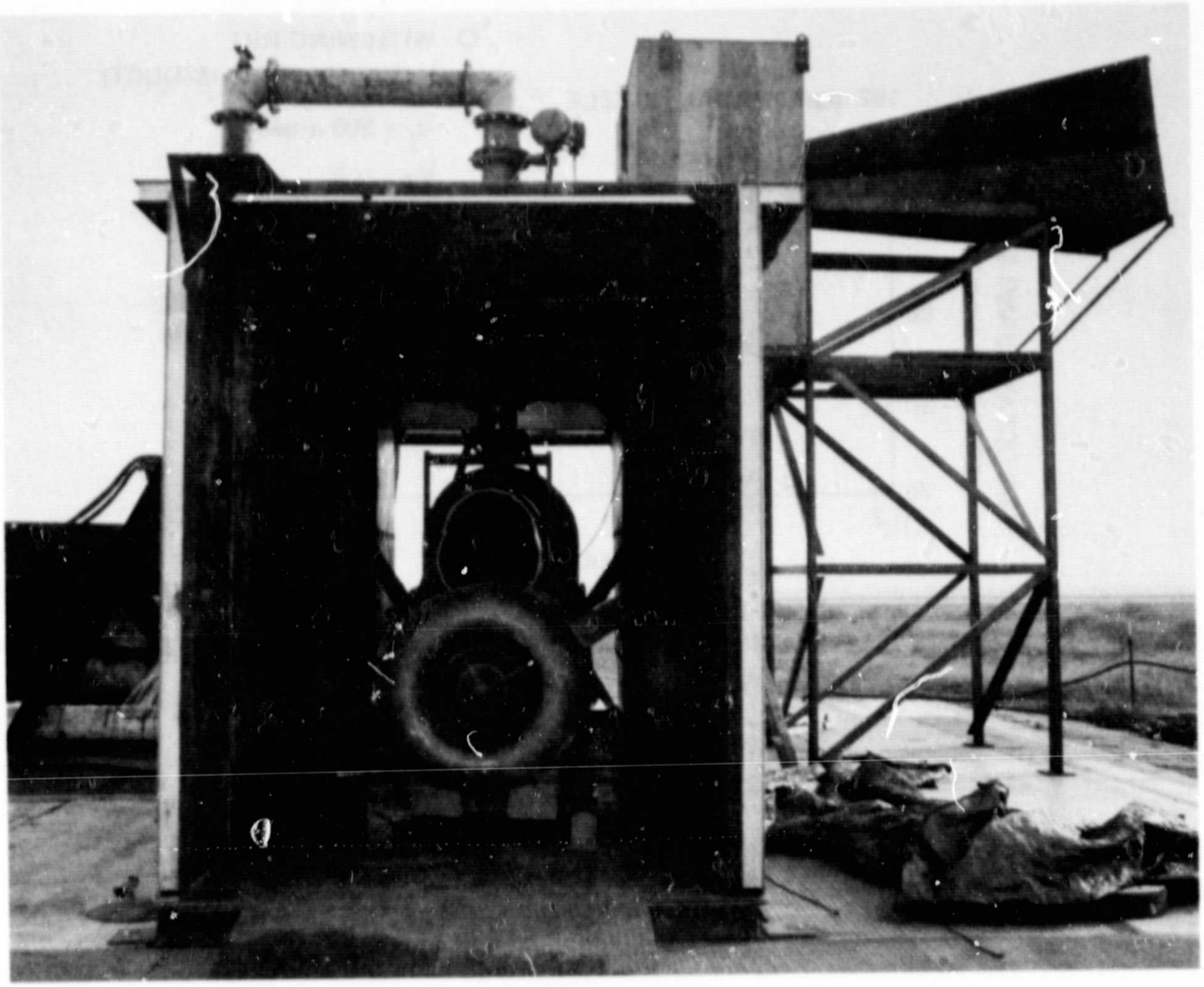

Figure 7.- Viper compressor in the treated enclosure.

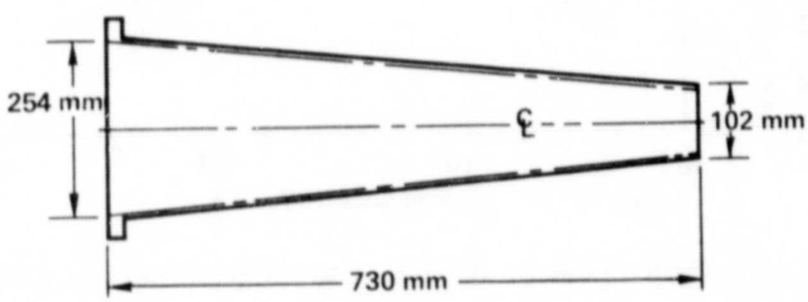

Figure 8.- RAE 102-mm conic nozzle.

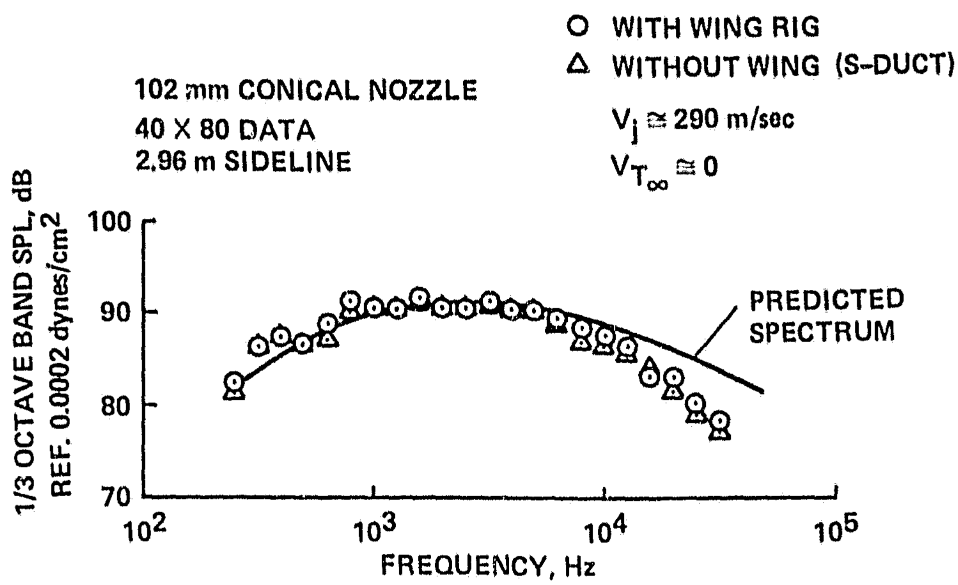

Figure 9.- Rig comparison — effect of wing rig on 40- by 80-Foot Wind Tunnel data.

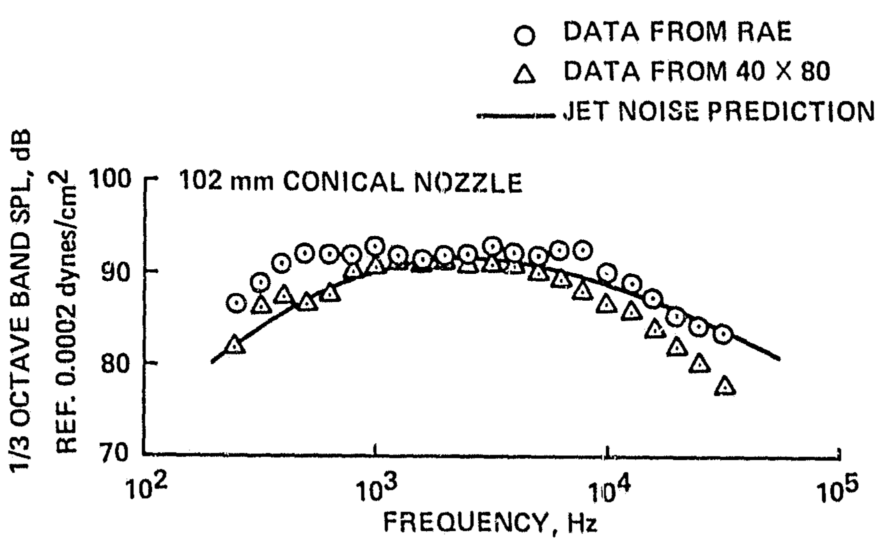

Figure 10.- Comparison of data for 90° approximately zero wind speed.

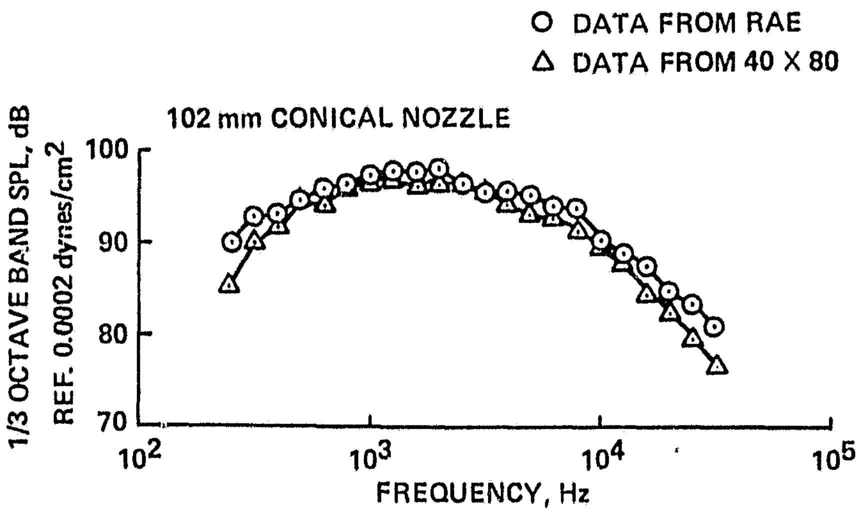

Figure 11.- Comparison of data for 135° approximately zero wind speed.

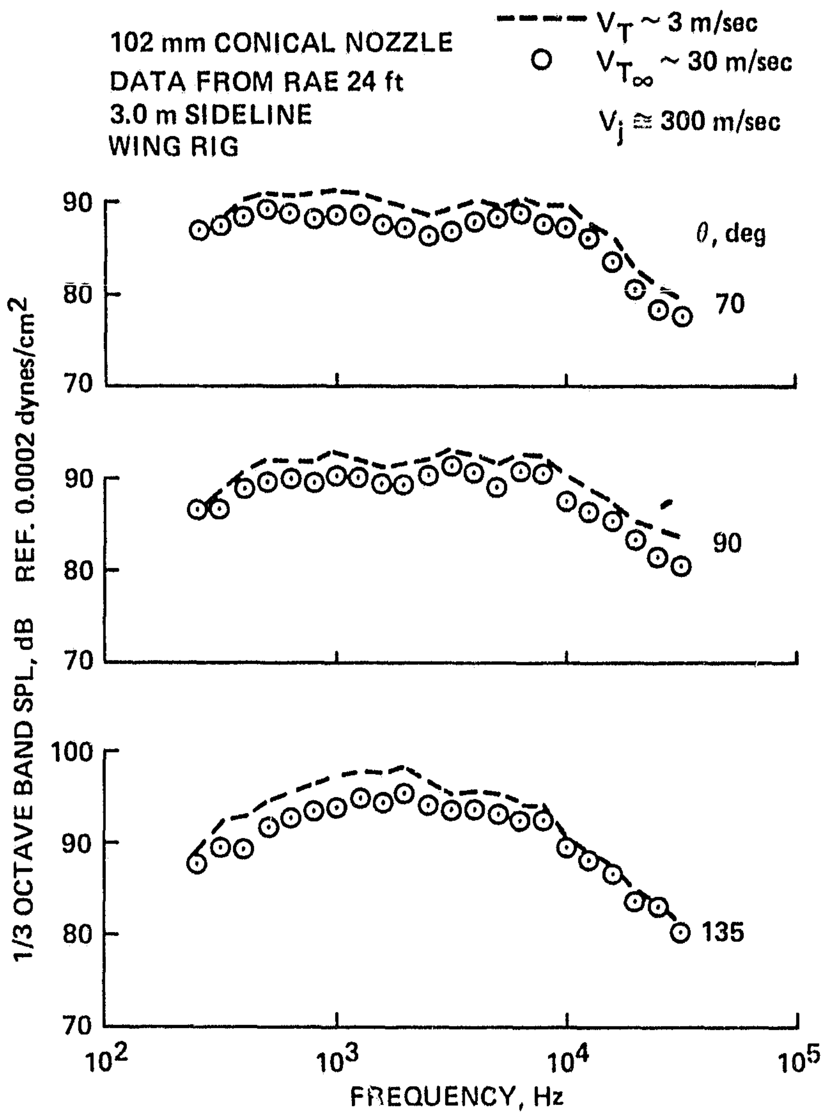

Figure 12.- Comparison of data with tunnel on and tunnel off — RAE 24-Foot Wind Tunnel data.

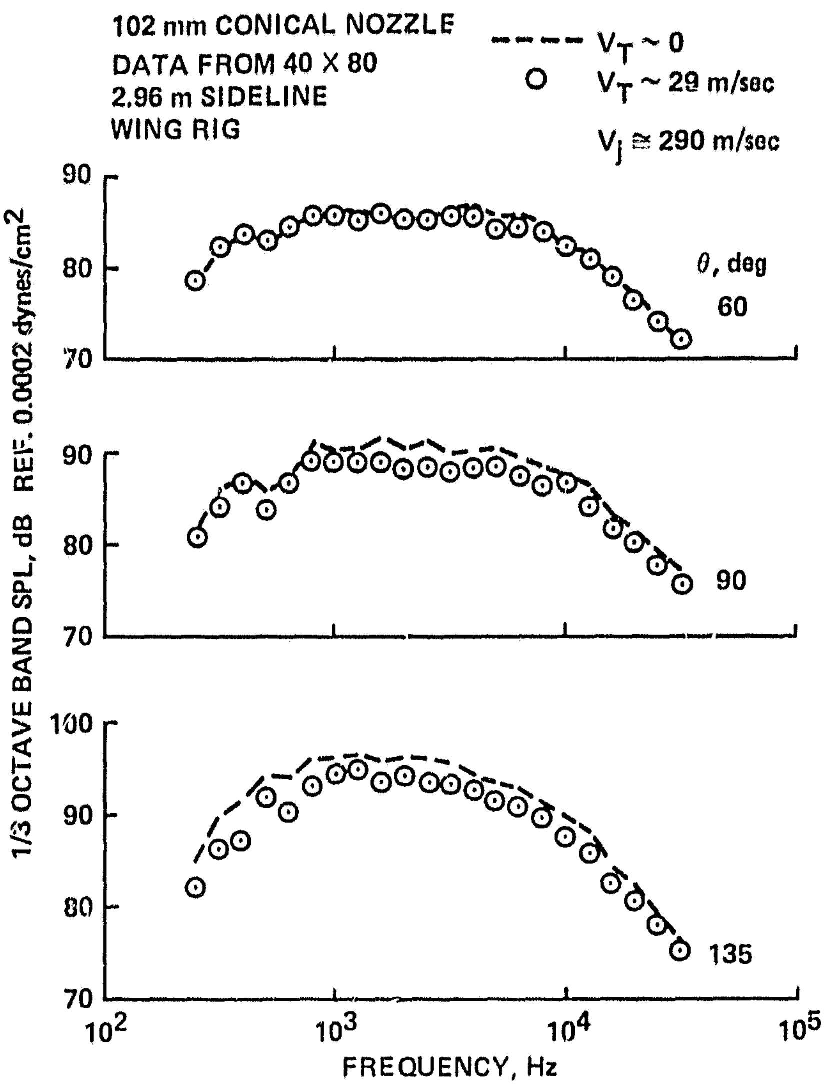

Figure 13.- Comparison of data with tunnel on and tunnel off — 40- by 80-Foot Wind Tunnel data.

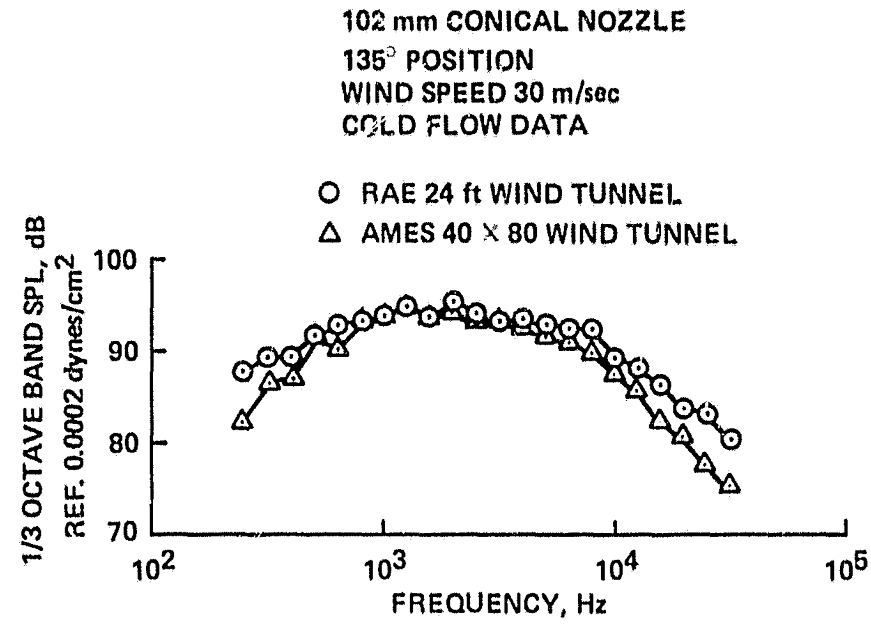

Figure 14.- Comparison of data at 135° - wind speed ~30 m/sec.

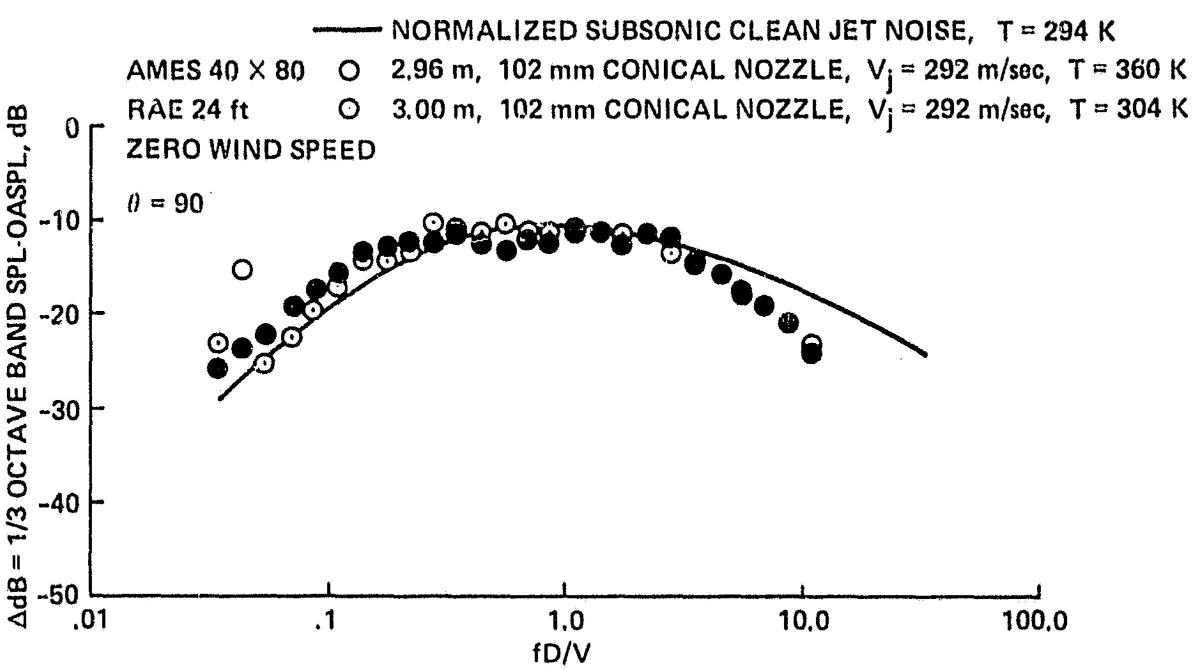

Figure 15.- Normalized jet noise spectra at $\theta = 90°$ cold jet.

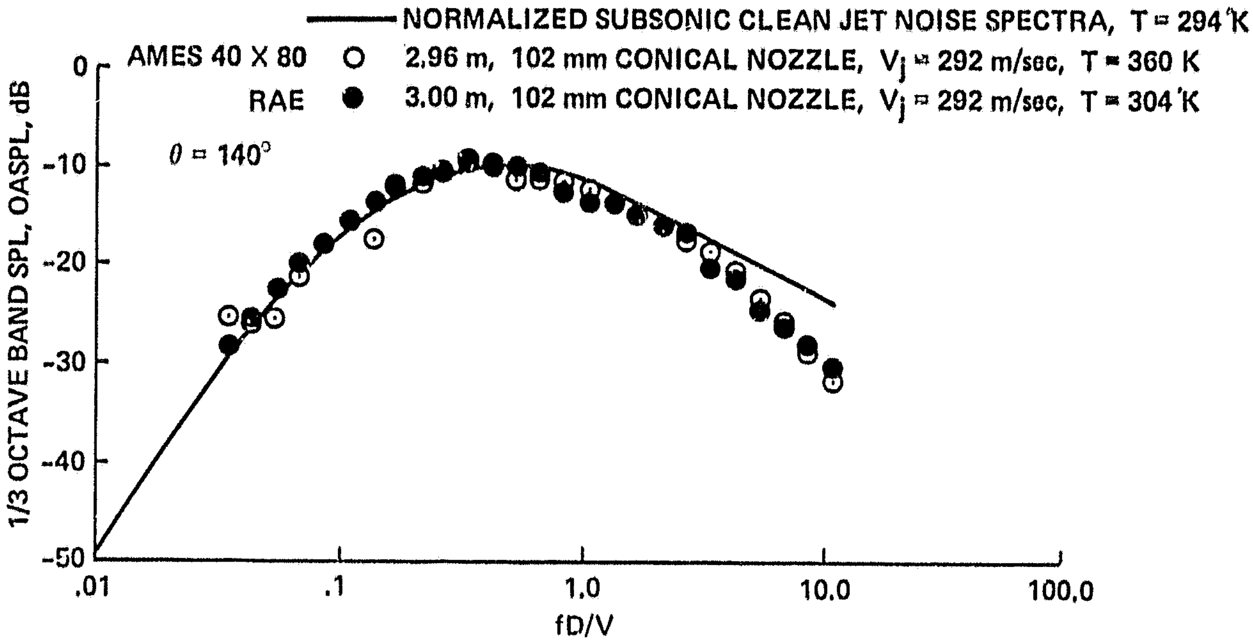

Figure 16.- Normalized jet noise spectra at θ = 140° cold jet.

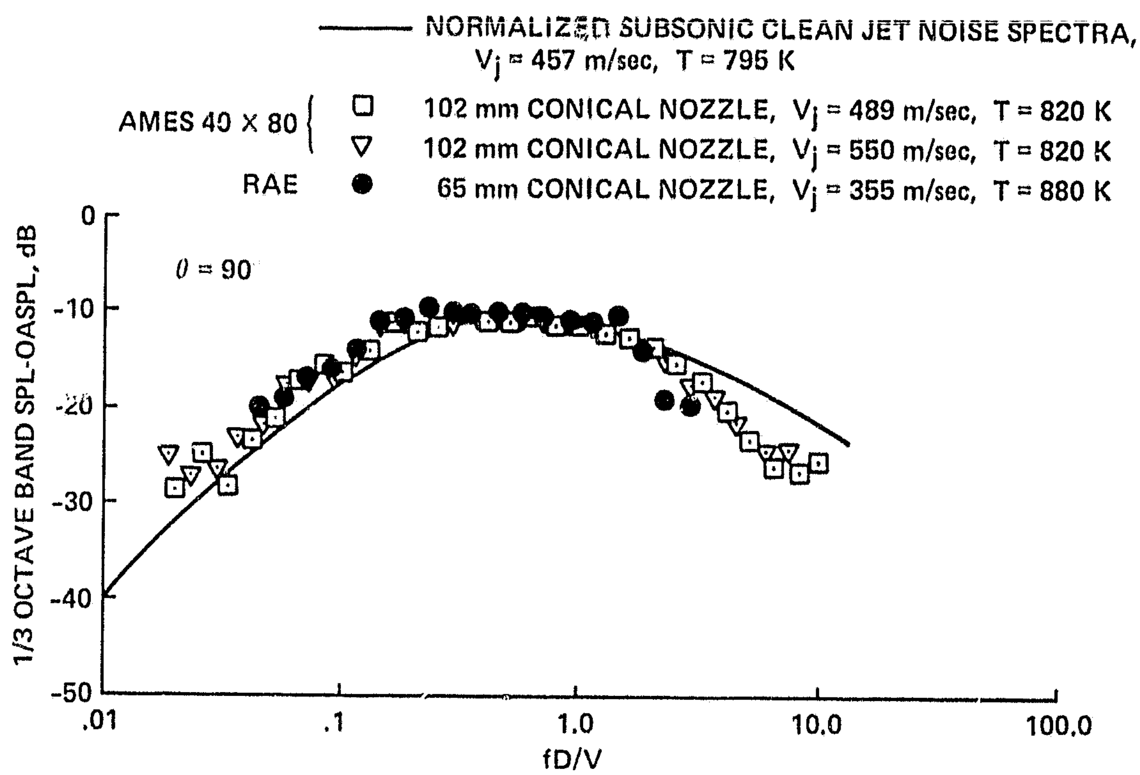

Figure 17.- Normalized jet noise spectra at θ = 90° hot jet.

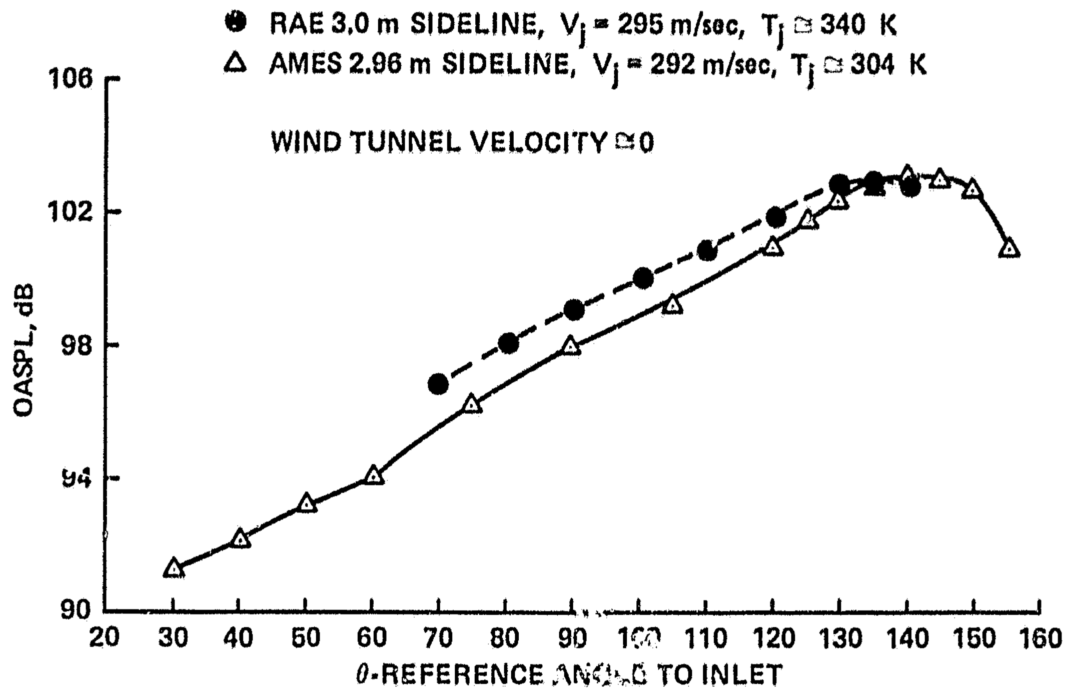

Figure 18.- OASPL directivity comparison — wind speed approximately zero.

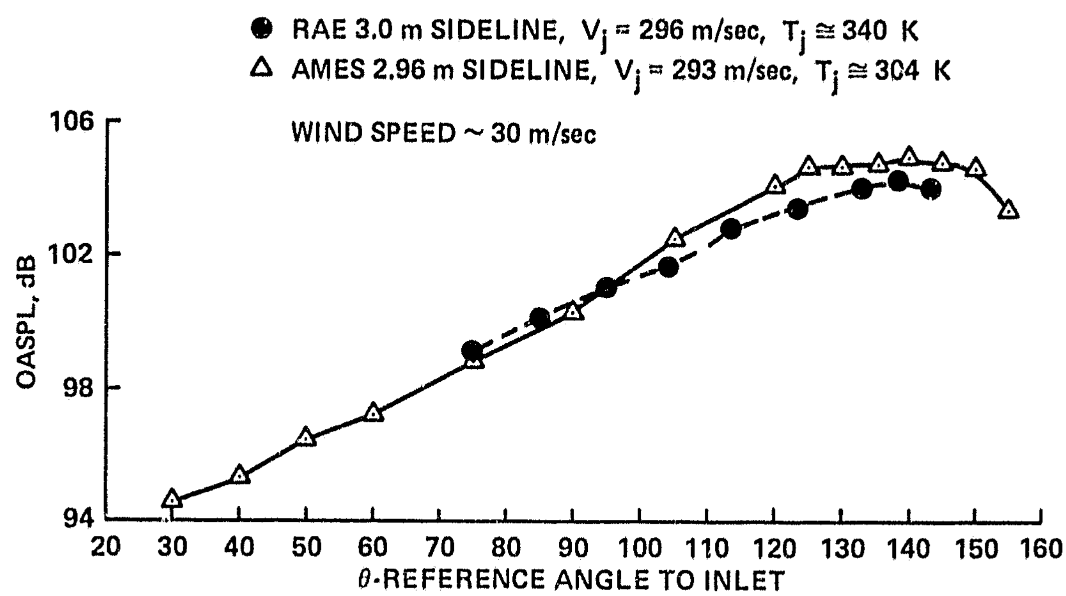

Figure 19.- OASPL directivity comparison — wind speed ~30 m/sec.