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Acoustics Measurements in Normal Jet Impingement

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Introduction

This report represents the final technical report for NASA Grant NSG 1277 - Acoustics Measurements in Normal Jet Impingement. The present investigation is an extension of the initial acoustics measurements for NASA Grant NGR 23-004-091 reported in [1]. The period of the present grant is February 15, 1976 to February 14, 1977.

The major objectives of the present investigation are: 1) to provide a data base of far field acoustics measurements for a uniform exit condition jet, determining the dependence of this data on nozzle to plate spacing for small dimensionless spacings (h/d - 0.75 to 3.0), 2) to generate similar data for a fully developed pipe flow exit condition jet to compare with other investigations (see [2]), 3) to extend the data base for normal jet impingement to smaller valves of nozzle to plate spacing (see also [3]), and 4) to show the effects of slight heating (30°C rise) of the jet on the far field noise produced by the impinging jet.

The initial motivation for the small nozzle to plate spacing was to provide a relatively simple flow field (narrow shear layer with a potential core extending into the jet impingement region on the plate) in which vorticity measurements could be made for comparison with the far field noise data. These vorticity measurements were to be made at Michigan State Univ. under NASA Grant NSG 23-004-091.

Finally, in analyzing the data to meet these objectives, some interesting trends were observed in the directivity patterns of the far field noise. In an attempt to identify possible causes of these patterns, experiments were conducted which demonstrate that the far field noise is correlated with a "large scale" (spacially coherent) structure in the impingement region of the jet.

Flow Facility

The two jet flow velocity exit conditions for the present study were produced with the same basic flow system. Care was taken to maintain the same geometric boundary conditions. The same surface was used on which to impinge the jets and the pipe used to generate the fully developed pipe flow velocity exit condition was fitted with a pseudonozzle, externally similar to the contraction used to produce the uniform exit velocity jet. The fully developed pipe was then placed inside the plenum used for the uniform jet (see Figures 1 and 2).

Air was supplied to the jets through a heat exchanger and two large settling chambers (each 1 m^3 volume) with flexible couplings to reduce the turbulence level and isolate the jets from mechanical vibrations as well as noise produced by valves and the heat exchanger. Measurements of Sound Pressure Levels (SPL) for different settling chamber combinations for the uniform impinging and free jets are given in [1]. Those results demonstrate that the far field noise produced by the final configuration is dominated by the impinging jet with little or no effect of upstream noise.

The uniform velocity exit condition jet was produced by a plenum 6.35 cm inside diameter, 240 cm long, with a smooth contraction having an area contraction ratio of 8.45:1. The resulting jet is 2.18 cm at the exit with a nearly uniform velocity profile.

The fully developed velocity exit condition jet was produced by a 300 cm long extruded stainless steel pipe; 2.29 cm inside diameter. The length to diameter ratio is thus greater than 130 and a fully developed pipe flow results.

Both jets impinge on a large (122 cm x 122 cm) wooden plate. The plate is 1.9 cm thick furniture grade plywood providing a rigid smooth surface. Measurements of far field noise were also made using a .64 cm thick aluminium plate with identical results. The wooden plate was used for the measurements of the present investigation.

Data Acquisition System

A Bruel and Kjaer type 3347 Real Time Analyzer (RTA) was used for Sound Pressure Level (SPL) frequency spectra measurements. The RTA is a 1/3 Octave spectrum analyzer with filter center frequencies ranging from 22.5 Hz to 40 KHz. A Bruel and Kjaer condenser microphone, 1.2 cm in diameter, was used for all measurements. The microphone calibration was checked and found to have constant frequency response at normal incidence to 40 KHz (within ± 1 db). The spectra from the RTA were read and processed by an HP 2116 mini-computer in an on-line mode.

The computer also recorded the exit temperature and velocity of the jet. The velocity was computed from the plenum static pressure for the uniform jet. For the fully developed pipe flow, the pressure drop over the length of the pipe was calibrated against the exit total pressure and used to compute exit velocity. The microphone was positioned in the far field region of the jet acoustic field at a constant radial distance from the center of the jet exit. The microphone angular position was determined by a DC stepping motor giving increments of angular position of 1.8° with an accuracy of 3% of the increment. All data were taken at a dimensionless radius (radial position/jet exit radius) of 50 and angular increments of 3.6°. The angular positioning was done by computer control.

Results

One-third octave sound pressure level (SPL) spectra measurements were made at a constant radius of 50 jet exit radii as a function of angular position for each geometry. The angular position ranged from 86.4° to 7.6° from the jet axis in increments of 3.6°. Each spectra was computed from the average of ten readings from the RTA. Pressure and temperature measurements were made for each spectra to allow minor corrections for variations in jet exit velocity. All measurements were made for a nominal jet exit mach number of 0.28. Each spectra was corrected to the nominal value assuming an eighth power dependence on the velocity as shown by [2].

The SPL spectra were used to compute the sound power level spectra (PWL), the overall sound pressure level (OASPL), and the overall sound power level (OAPWL) for each flow and geometry.

Overall Sound Power Level

The effects of variations in nozzle to plate spacing and exit velocity structure are readily established by considering the OAPWL for each condition. Figure 4 is a plot of OAPWL as a function of nozzle to plate spacing for the uniform and fully developed pipe flow velocity exit conditions.

The OAPWL for both jet exit conditions show an increase as the nozzle to plate spacing is decreased. The uniform jet shows a maximum OAPWL for a dimensionless spacing of about one jet diameter while the fully developed exit condition exhibits no clearly defined maximum for the limited data. It should be noted that the exit velocity was not influenced by the presence of the plate until the nozzle to plate spacing was reduced to a value somewhat less than one jet diameter.

The small change in OAPWL for nozzle to plate spacings of 5 and 7 indicate a rapid approach to an asymptotic value. This is consistent with the noise producing region of a free jet being up to seven to ten diameters from the jet exit. That is, one would not expect a significant dependence of OAPWL on nozzle to plate spacing when the plate is placed beyond the noise producing region of the free jet.

It is also reasonable to expect the stronger dependence of the uniform jet as compared with the fully developed pipe flow exit condition on nozzle to plate spacing. The velocity gradients in the radial direction are larger for the uniform exit condition near the jet exit. The impinging of the jet, for small nozzle to plate spacing, causes intensification of the velocity gradient (stretching of the azimuthal vorticity). The noise produced in the free shear layer (rather than the boundary layer of the jet on the surface of the plate), being related to the spatial variation of the velocity, should be greater for the uniform jet impinging with small nozzle to plate spacing.

Data from the uniform velocity exit condition with the plate removed (free jet) gives an asymptotic value of approximately 80 db for the OAPWL. Thus, the maximum OAPWL, which occurs for a nozzle-to plate spacing of unity, represents an increase in OAPWL of ~12 db. The increase in OAPWL for the fully developed pipe flow velocity exit condition is approximately 9 db. That is, the noise produced by free jets with the different exit conditions is nearly the same, but the increase in OAPWL, as the nozzle to plate spacing is decreased, occurs more rapidly for the uniform jet.

Effects of Slight Heating of the Jet

Two nozzle to plate spacings with the uniform exit velocity condition were run with a slightly heated jet (30°C above ambient temperature). The OAPWL points are shown on Figure 4. There is, as expected, no significant change in OAPWL for this small temperature difference.

The dependence of the OAPWL on nozzle to plate spacing for the cold and slightly heated jets provides a simple and important characterization of the acoustics of the impinging jets. However, when the primary interest is in noise pollution by such a jet or in controlling the noise produced, measures of the directivity pattern and spectral content become important.

<u>Overall Sound Pressure Level</u>

The angular dependence of OASPL for the uniform and fully developed pipe flow exit conditions are shown in Figures 5 through 16 for each nozzle to plate spacing. There are two striking features of the OASPL angular dependence. First, the difference between the maximum and minimum values of OASPL is 7 to 10 db, a significant variation. Second, the dependence upon nozzle to plate spacing is very strong and complicated. That is, very small changes (0.25 exit diameters) in nozzle to plate spacing completely changes the angular location of maxima and minima in OASPL.

Because a variation of 7 to 10 db is large when noise pollution and control are of interest, a major effort was undertaken to determine the nature and possible causes of the effect. Two fundamentally different concepts were considered. Such a variation in OASPL could be caused by reinforcement and cancellations of noise produced in a distributed source. Such an effect would require a dominant frequency or at least a fairly narrow band of frequencies. This is not unrealistic considering the possibility of acoustic feedback from the impingement region to the jet exit. However, the PWL spectra and the SPL spectra at each angular position show no dominant band of frequencies. Also, no pure tones were heard at any of the geometries tested.

Another possible cause of the observed variations in OASPL is refraction of the noise by the fluid in the flow impingement region. The effect may be similar to that reported by [4] for a free jet. The magnitude of the decrease in sound pressure level on the axis of a free jet for frequencies above 2000 Hz reported in [4] are 5 db and larger for a mach number of 0.3. Also, the impinging jet has the additional mechanism for refraction by relatively large pressure gradients in the noise producing region.

<u>Sound Power Level Spectra</u>

The 1/3 octave sound power level (PWL) spectra are shown in Figures 17 through 28 for the cold jets and Figures 33 through 36 for the heated jets. These data indicate an increase in PWL with frequency up to some maximum value at a Strouhal number ($\frac{fD}{U}$) of 0.2 to 0.5. This increase in PWL is nearly independent of nozzle to plate spacing (although the maximum value is dependent on nozzle to plate spacing). The decrease in PWL at higher frequencies is more rapid for the larger nozzle to plate spacing. That is, the jet exit being closer to the plate produces a larger proportion of high frequency noise. This is consistant with the spectral content of the turbulence of a jet with a small nozzle to plate spacing compared to a larger nozzle to plate spacing.

Examination of the PWL spectra for evidence of a narrow band of prefered frequencies is inconclusive. One could imagine some peaks in the PWL spectra plots indicating possible narrow band noise. However, none of the PWL spectra show large enough peaks to cause the 7 to 10 db variations observed in the OASPL.

Accelerometer Correlations

To resolve the question of interference versus refraction, directivity patterns were taken for a nozzle to plate spacing of unity and a uniform exit velocity condition at different radii. The patterns were found to be independent of radius. This is strong evidence that the patterns are not due to interference, which would be radius dependent.

The complexity of the directivity patterns and the rapid variation with small changes in nozzle to plate spacing suggest a relocation of the noise producing region as the nozzle to plate spacing is varied. Since the time mean flow field would change very little for such small variations in nozzle to plate spacing, the far field noise could be related to the large scale (spacially coherent) structure of the jet shear layer which are known to change rapidly in the first several jet diameters. In particular, recent evidence [5] indicates the formation and subsequent pairing of azimuthal rings of vorticity in this region of the flow. Although the investigation of the detials of this hypothesis are beyond the objectives of the present investigation, some simple experiments were conducted which show that the far field noise is correlated with a spacially coherent jet structure striking the plate.

An accelerometer was placed on the back side of the plate on the jet centerline. The output of the accelerometer was cross-correlated (using a PAR correlation function computer) with the far field noise. For the uniform exit condition jet a correlation coefficient of 0.2 was measured. With much higher turbulence levels at the jet exit, correlation coefficients as high as 0.7 were found. One might suspect that this large of a correlation would be caused by the board being driven at some resonant mode. This, however is not the case as evidenced by two facts. First, there is very little noise produced on the back side of the plate (and uncorrelated with the accelerometer) which would not be the case if the plate itself was radiating noise. Second, the accelerometer was moved radially outward from the jet centerline and the correlation indicated a rapidly decaying progressive wave generated near the jet axis moving toward the edge of the plate, rather than a flexural wave which would exhibit maxima and minima and different phase behavior.

The significance of the accelerometer measurement is that it will respond only to a spacially coherent structure striking the plate. That is, the plate will effectively integrate spacially and respond (move) only when a large structure impinges on the plate. These experiments were only exploratory in nature and much more detailed and exhaustive measurements would be necessary to document the details of the large scale structure - far field noise interaction. However, the relatively large cross-correlations demonstrate that a significant portion of the far field noise is related to the large scale structures of the jet in the impingement region.

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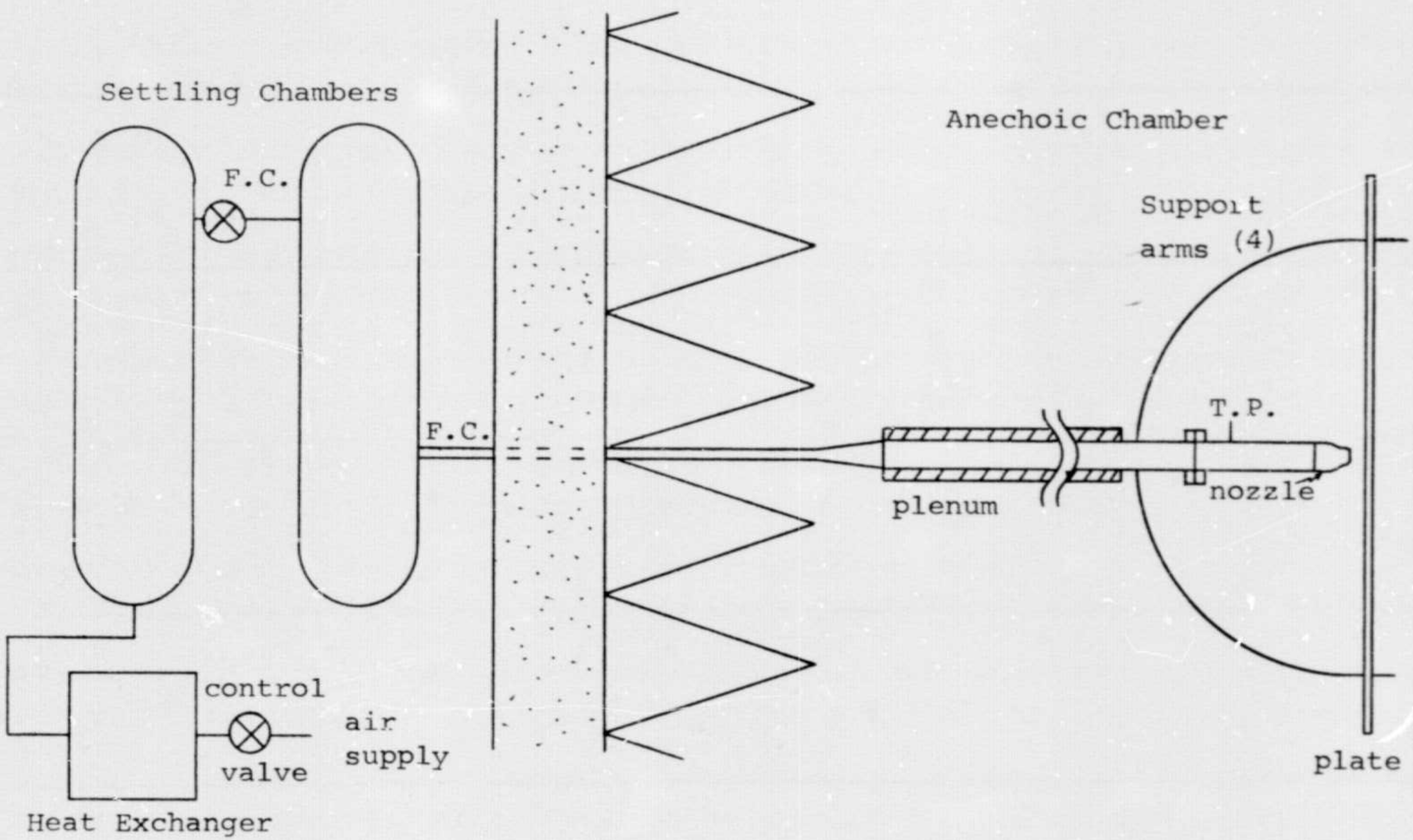

Figure 1. Uniform Jet Flow Facility

Note: F.C. - Flexible Connection

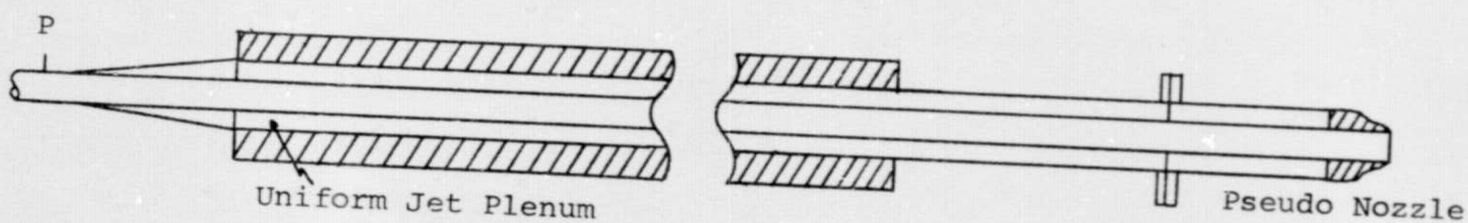

Figure 2. Pipe Flow Jet

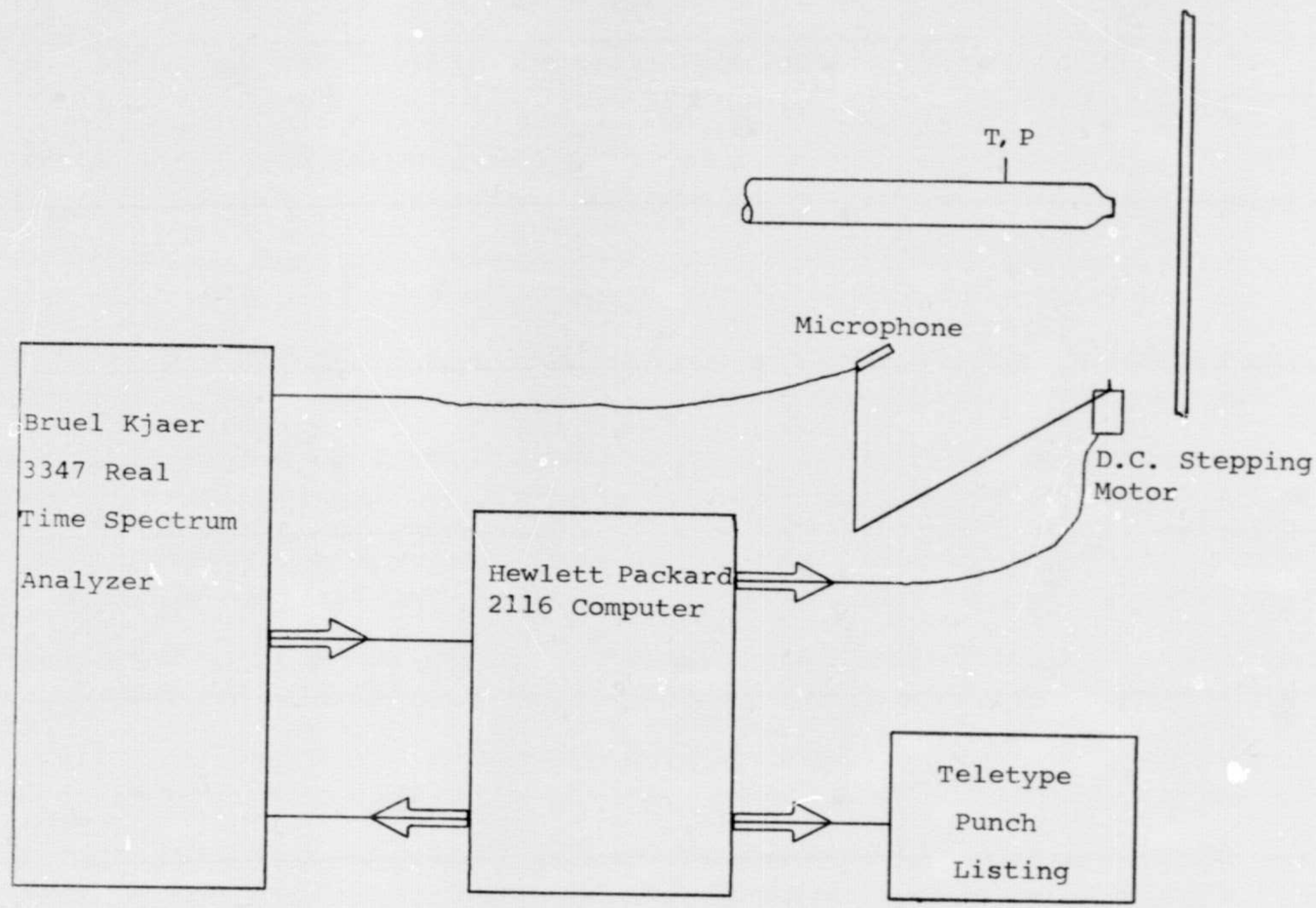

Figure 3. Data Acquisition System

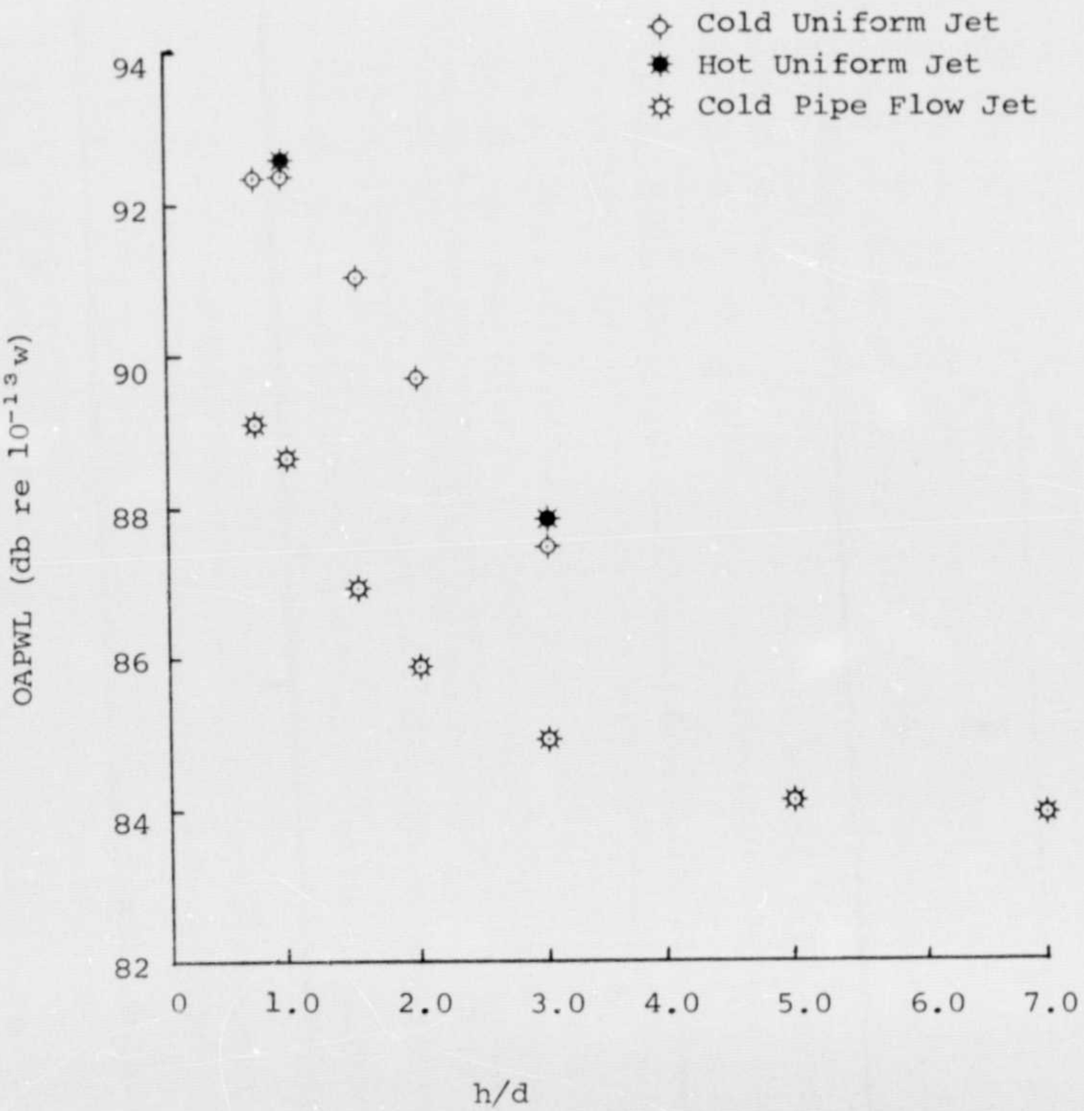

Figure 4. Overall Sound Power Level Versus Nozzle to Plate Spacing, Mach Number 0.28

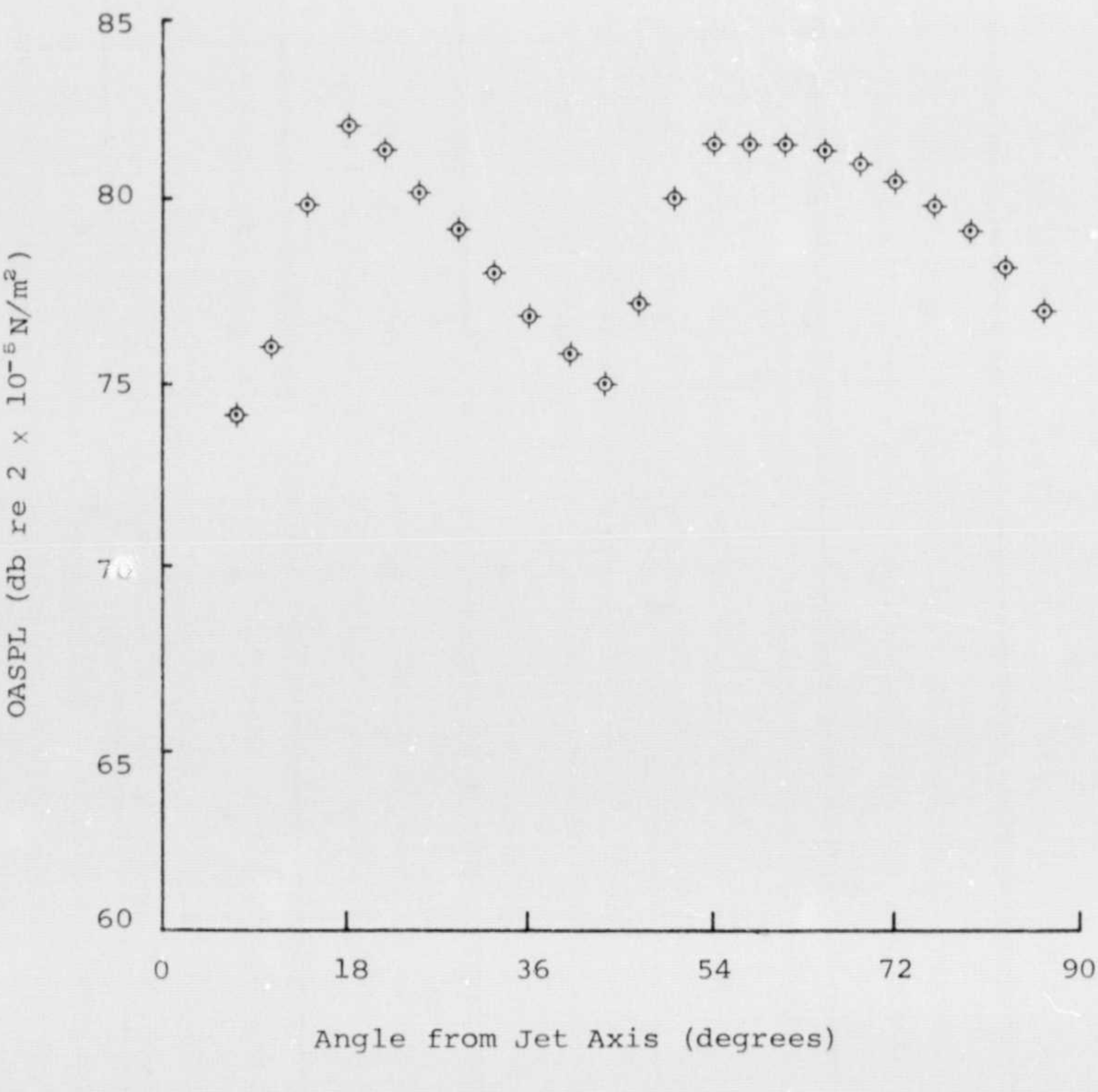

Figure 5. Overall Sound Pressure Level Versus Angle from Jet Axis; Uniform Jet, Mach Number = 0.28, h/d = 0.75

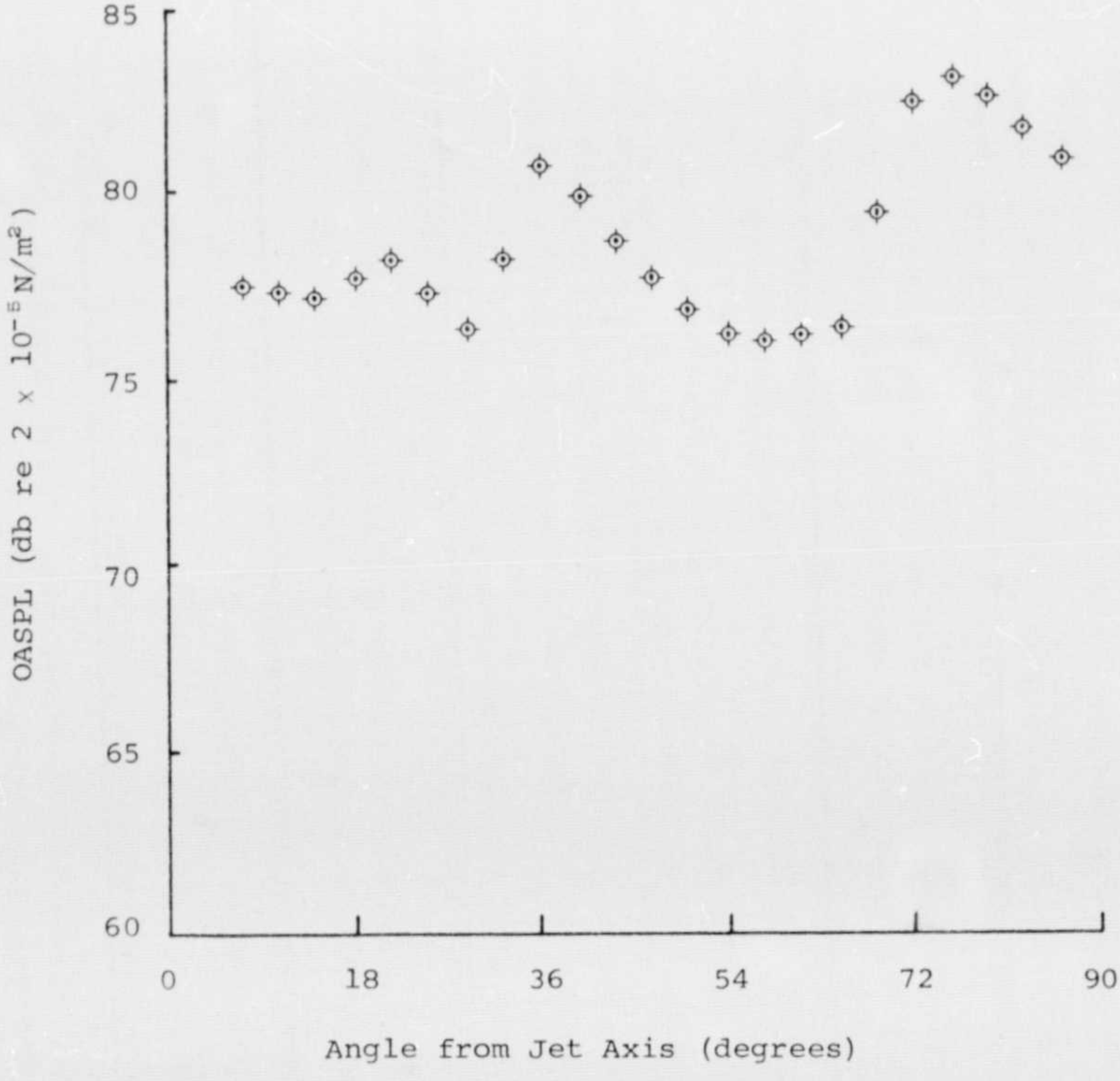

Figure 6. Overall Sound Pressure Level Versus Angle from Jet Axis; Uniform Jet, Mach Number = 0.28, h/d = 1.0

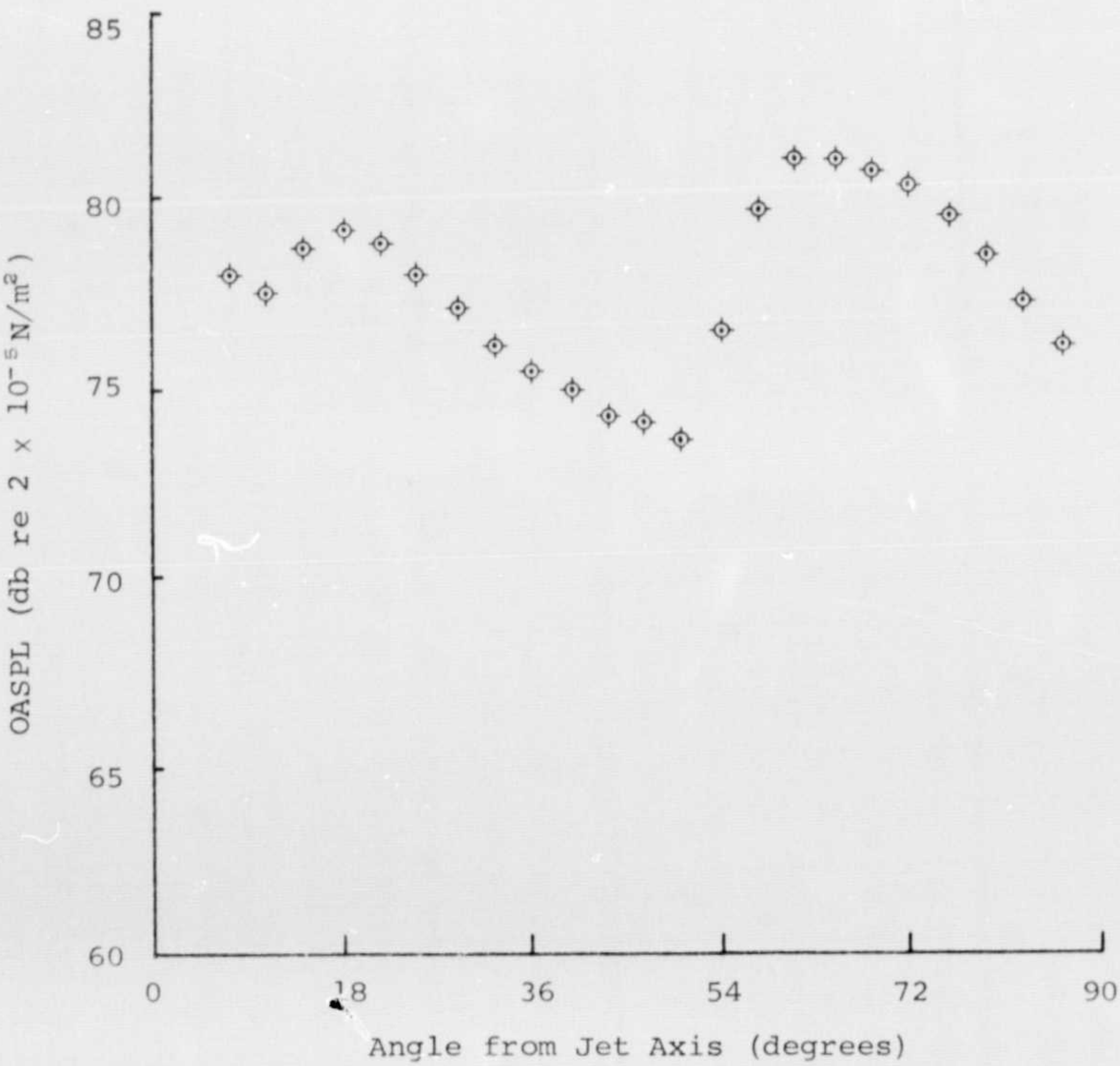

Figure 7. Overall Sound Pressure Level Versus Angle from Jet Axis; Uniform Jet, Mach Number = 0.28, h/d = 1.5

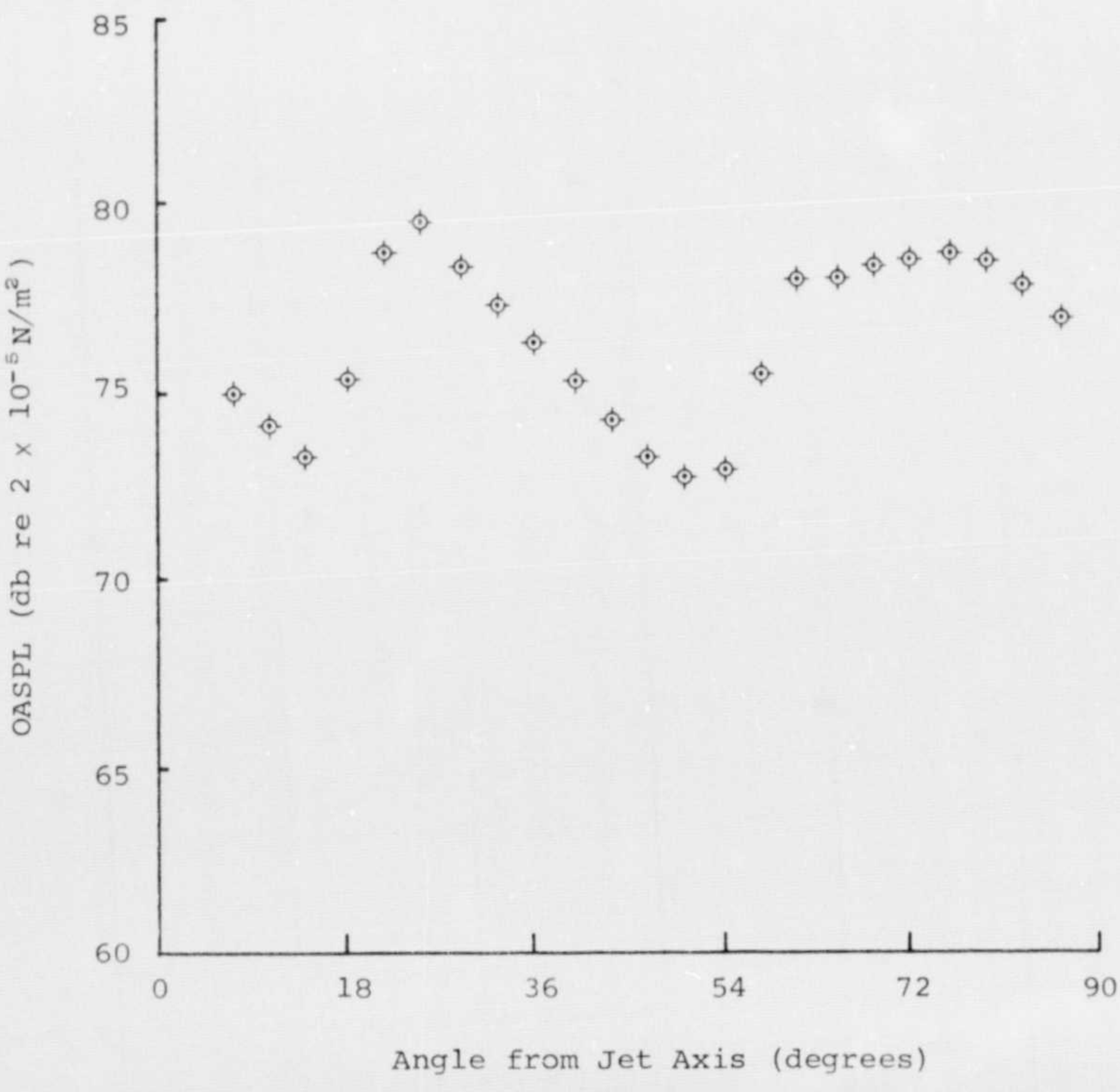

Figure 8. Overall Sound Pressure Level Versus Angle from Jet Axis; Uniform Jet, Mach Number = 0.28, h/d = 2.0

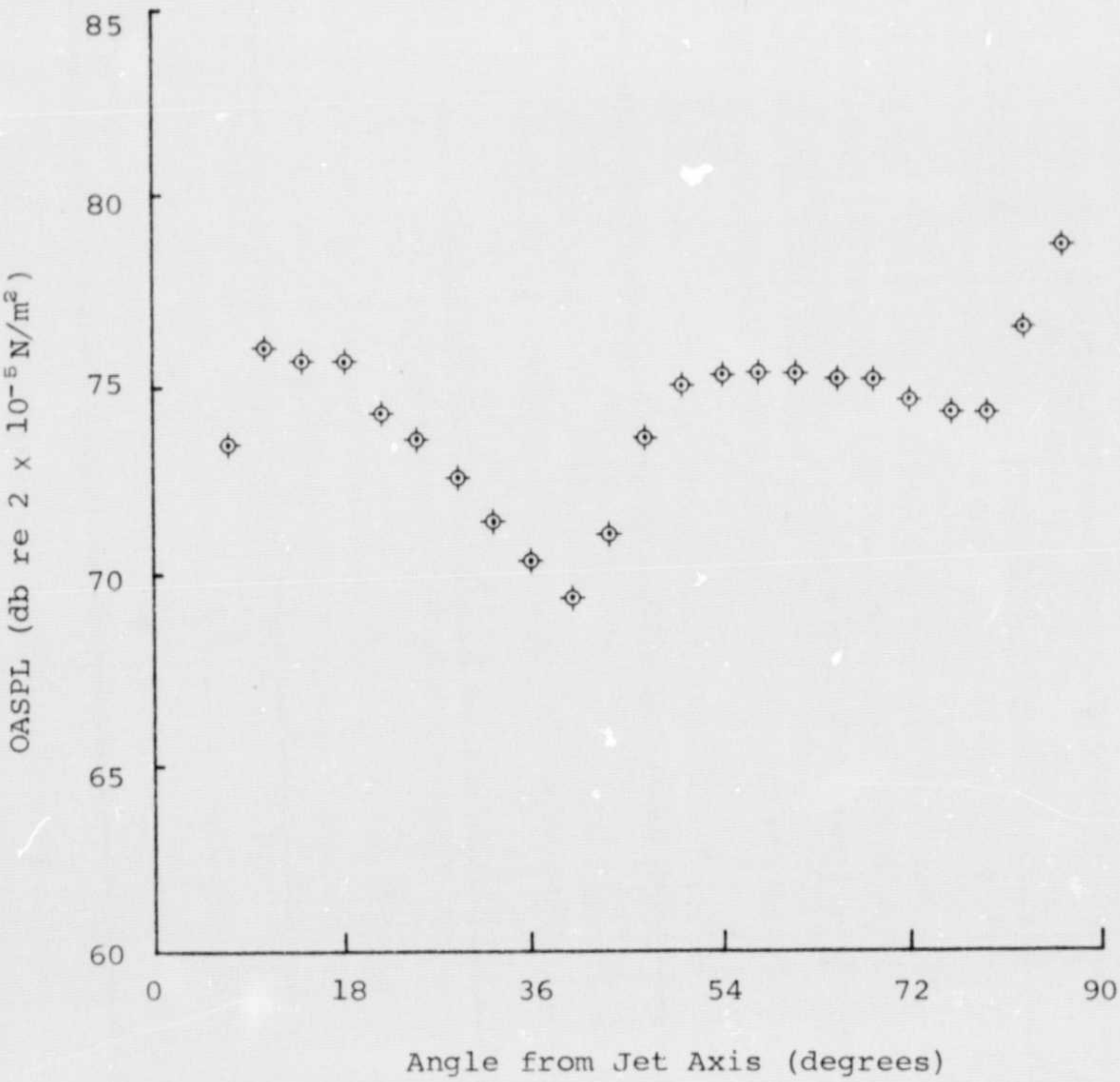

Figure 9. Overall Sound Pressure Level Versus Angle from Jet Axis; Uniform Jet, Mach Number = 0.28, h/d = 3.0

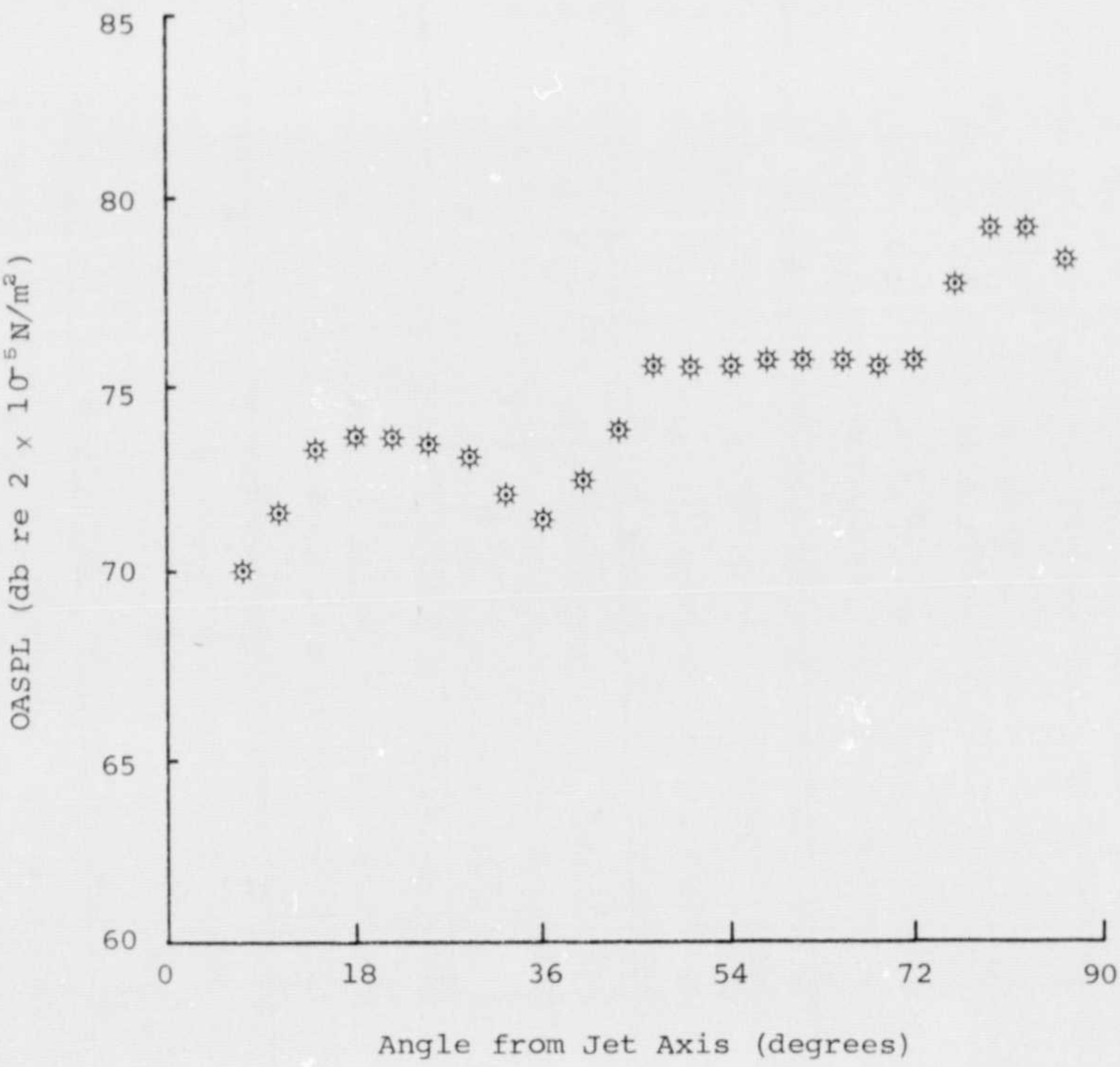

Figure 10. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 0.75

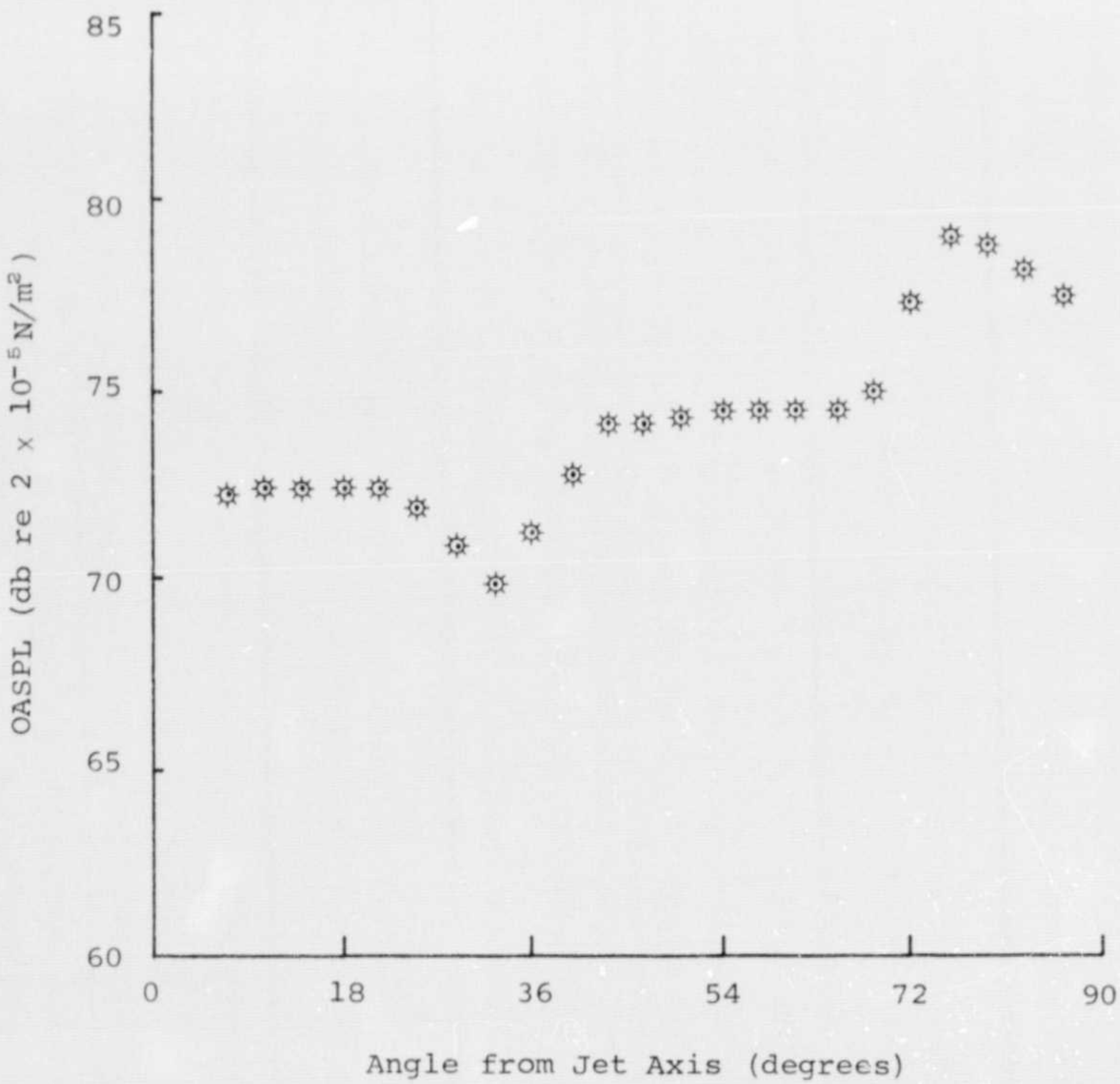

Figure 11. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 1.0

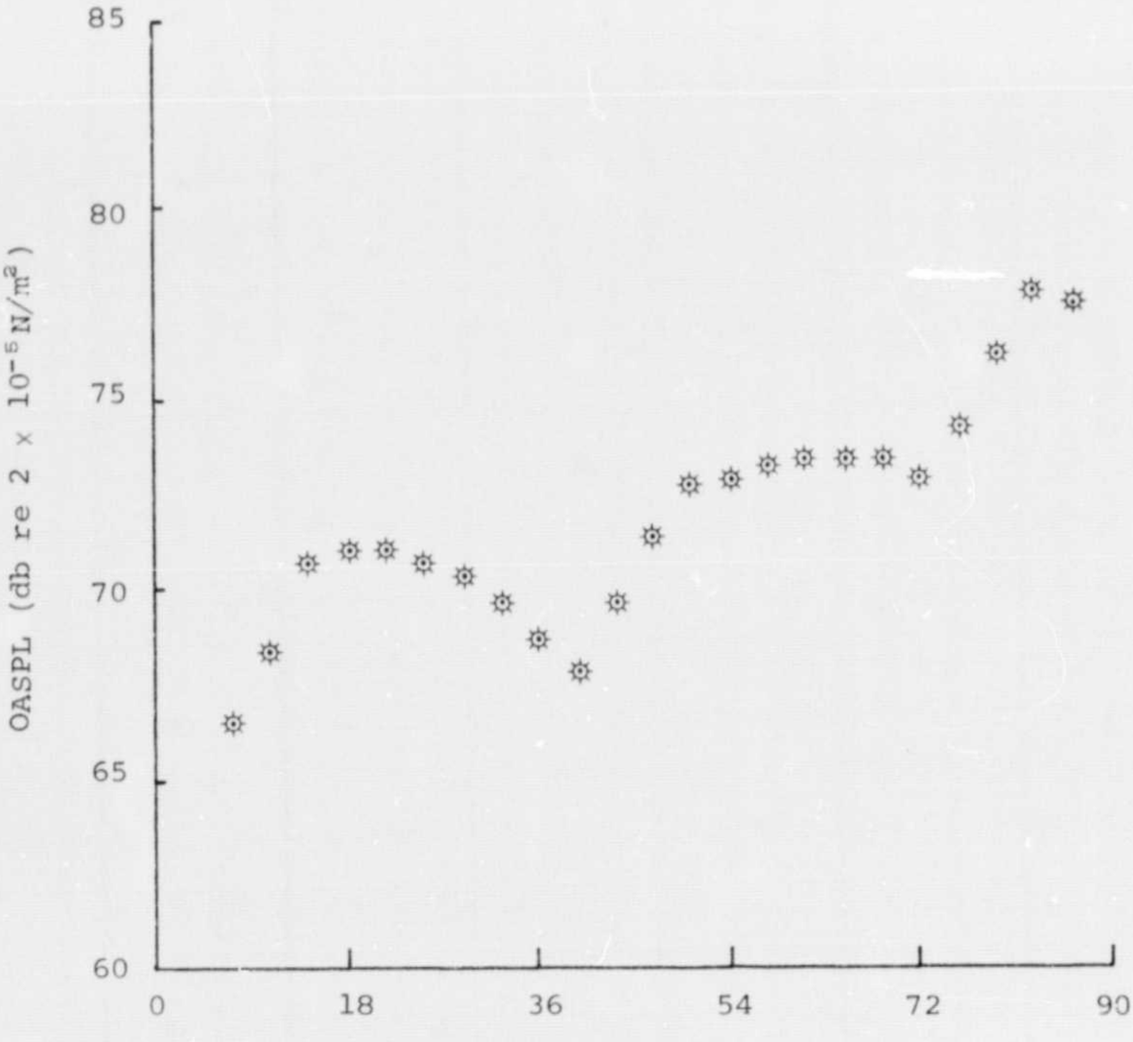

Figure 12. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 1.5

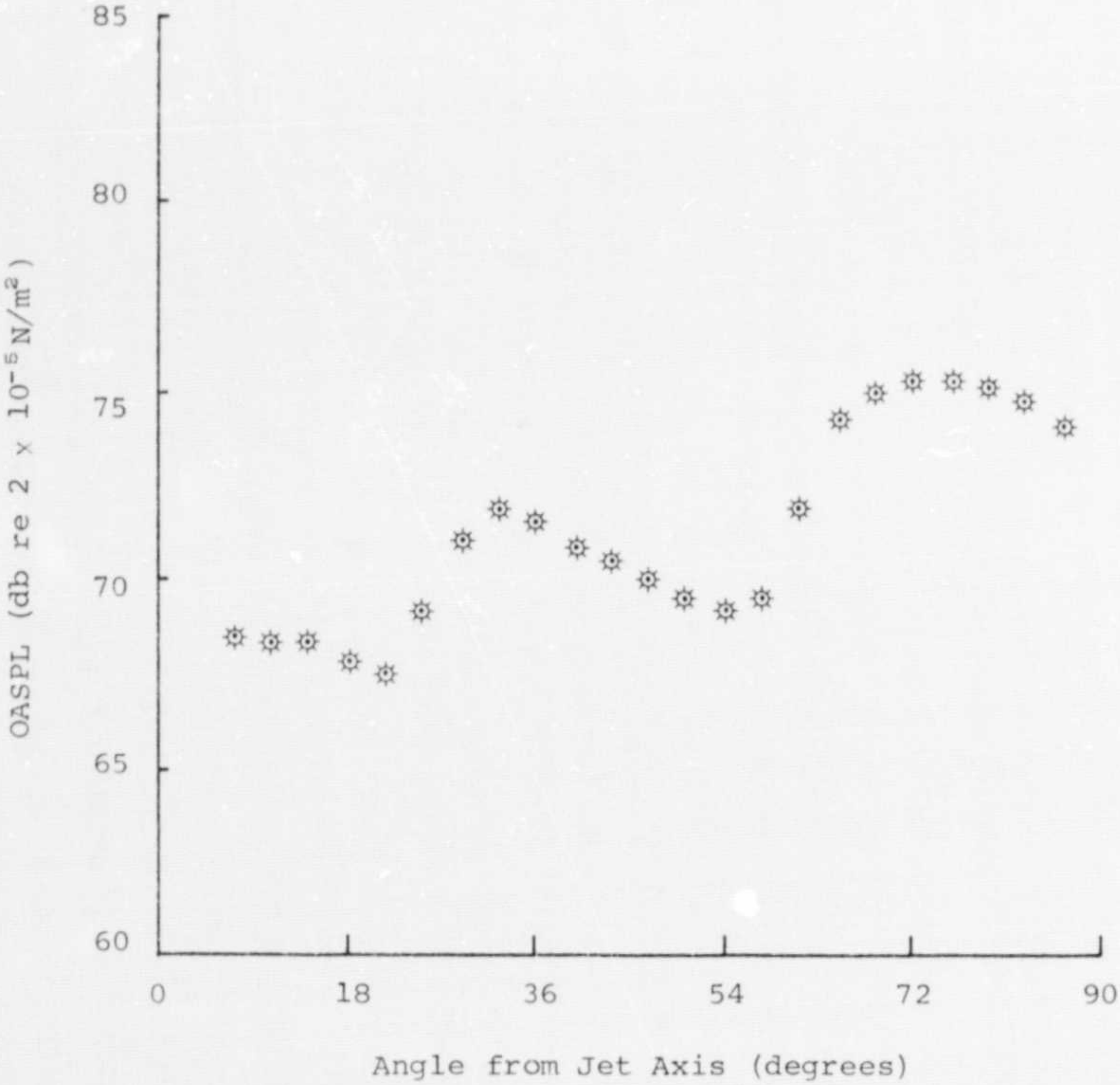

Figure 13. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 2.0

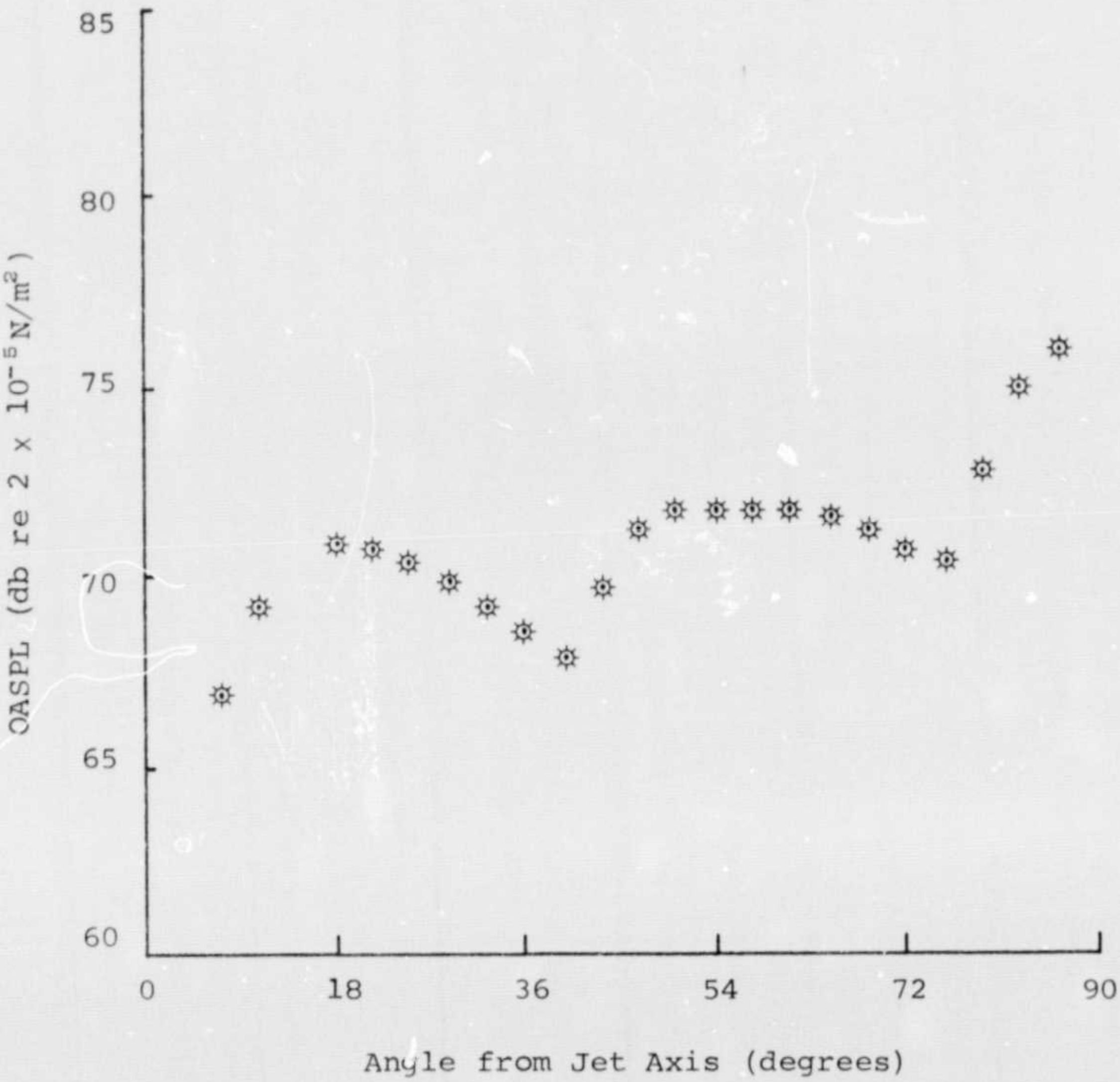

Figure 14. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 3.0

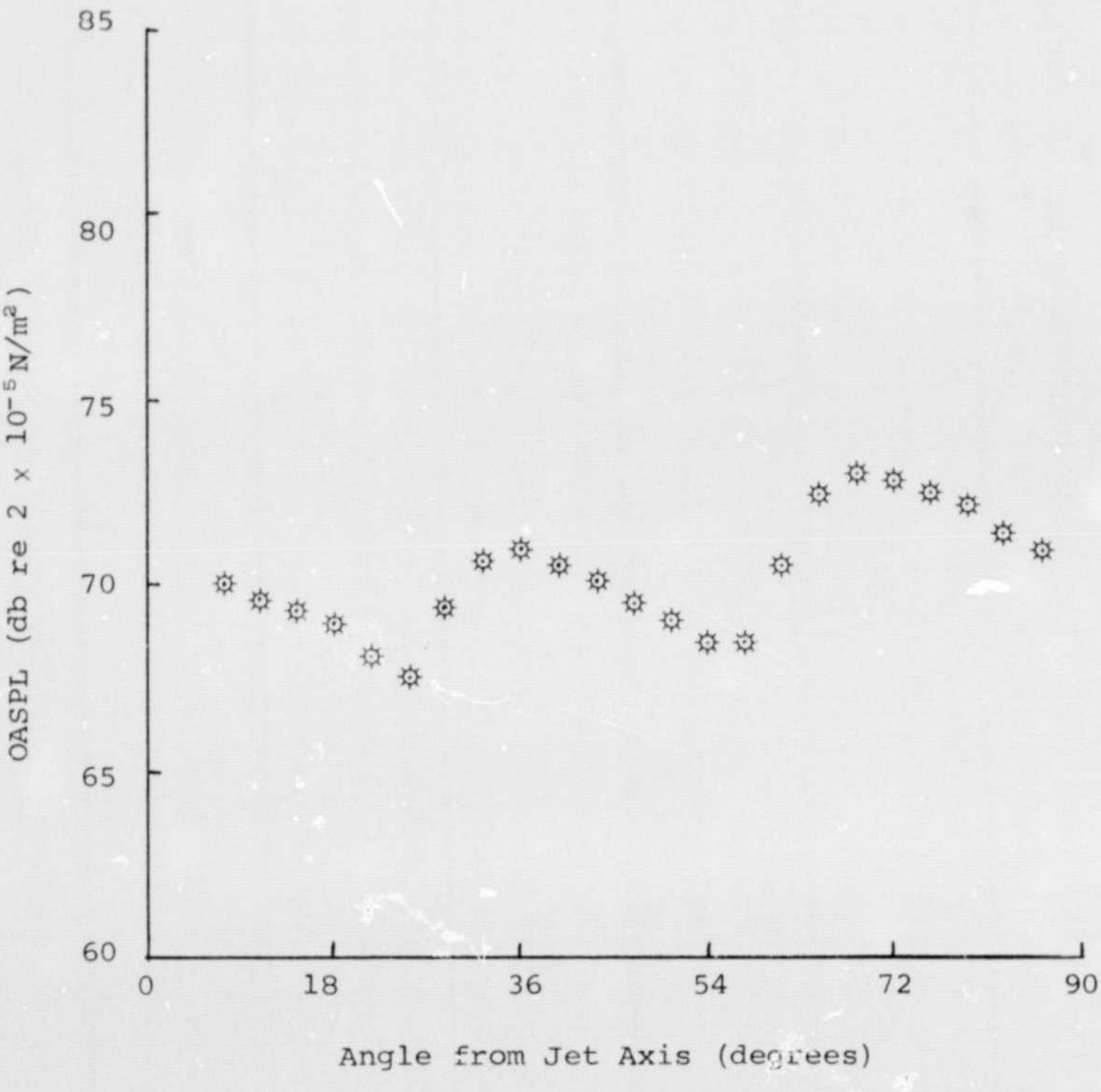

Figure 15. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 5.0

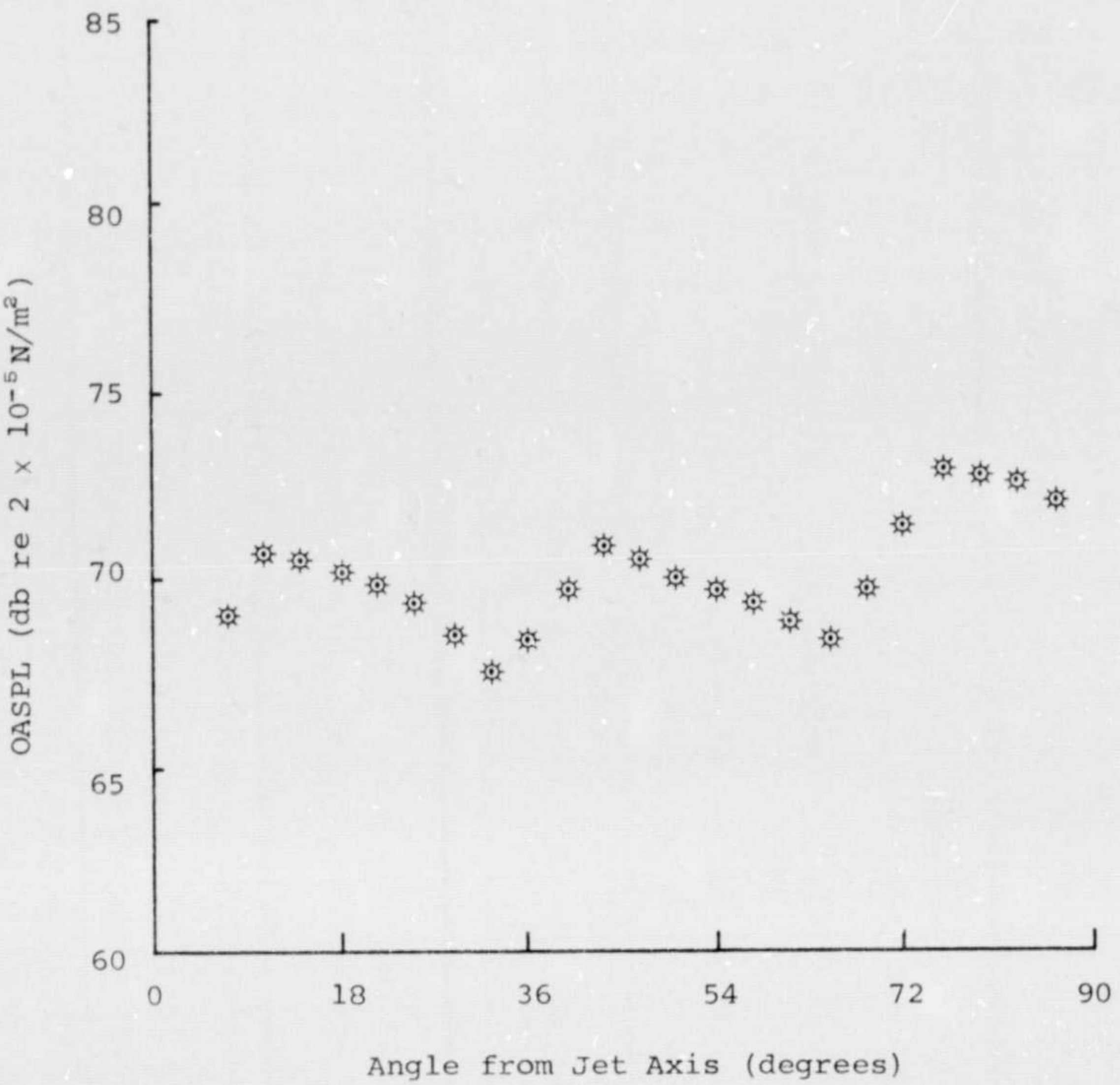

Figure 16. Overall Sound Pressure Level Versus Angle from Jet Axis; Pipe Flow Jet, Mach Number = 0.28, h/d = 7.0

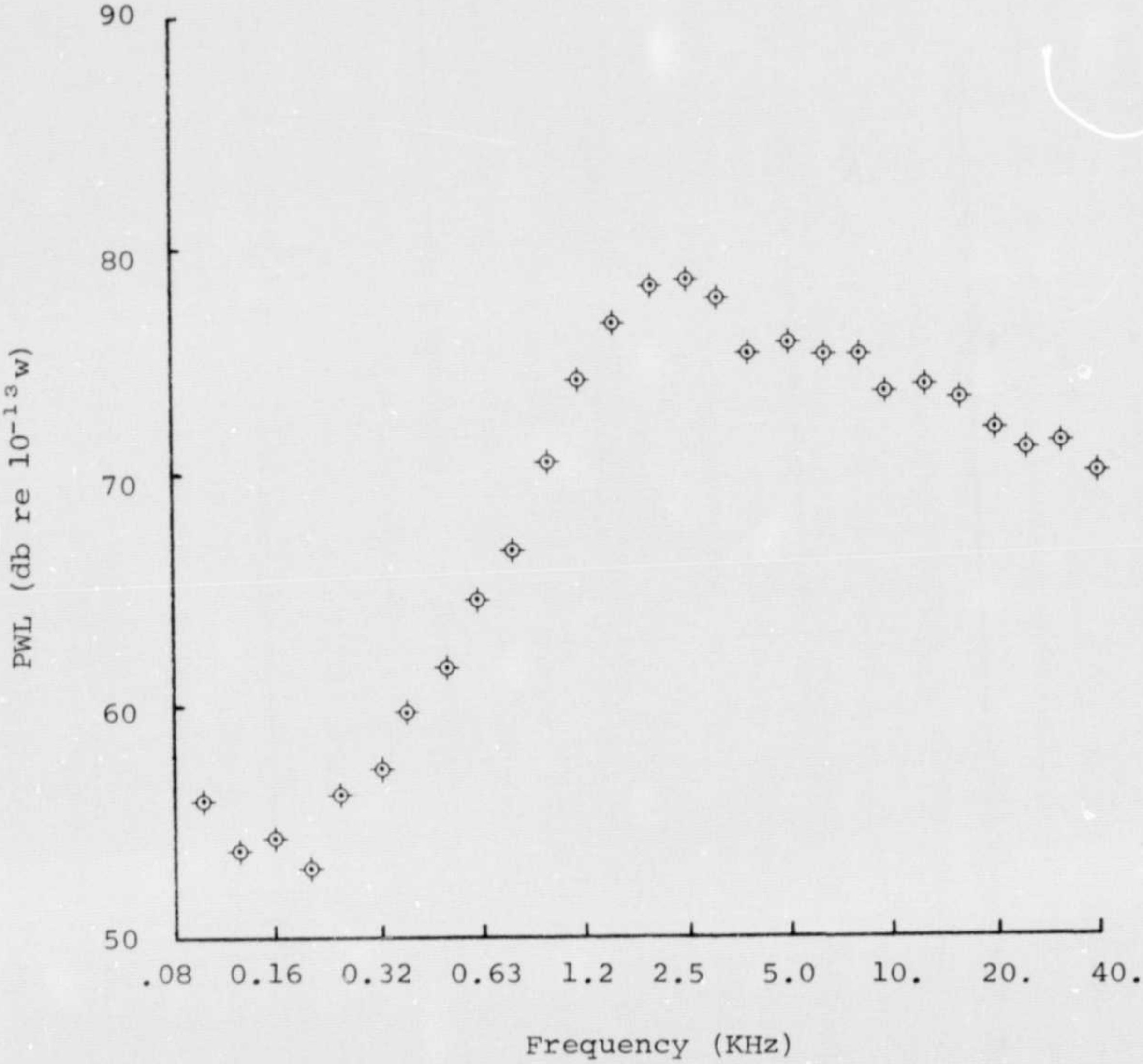

Figure 21. 1/3-Octave Sound Power Level Spectra; Uniform Jet, Mach Number = 0.28, h/d = 3.0

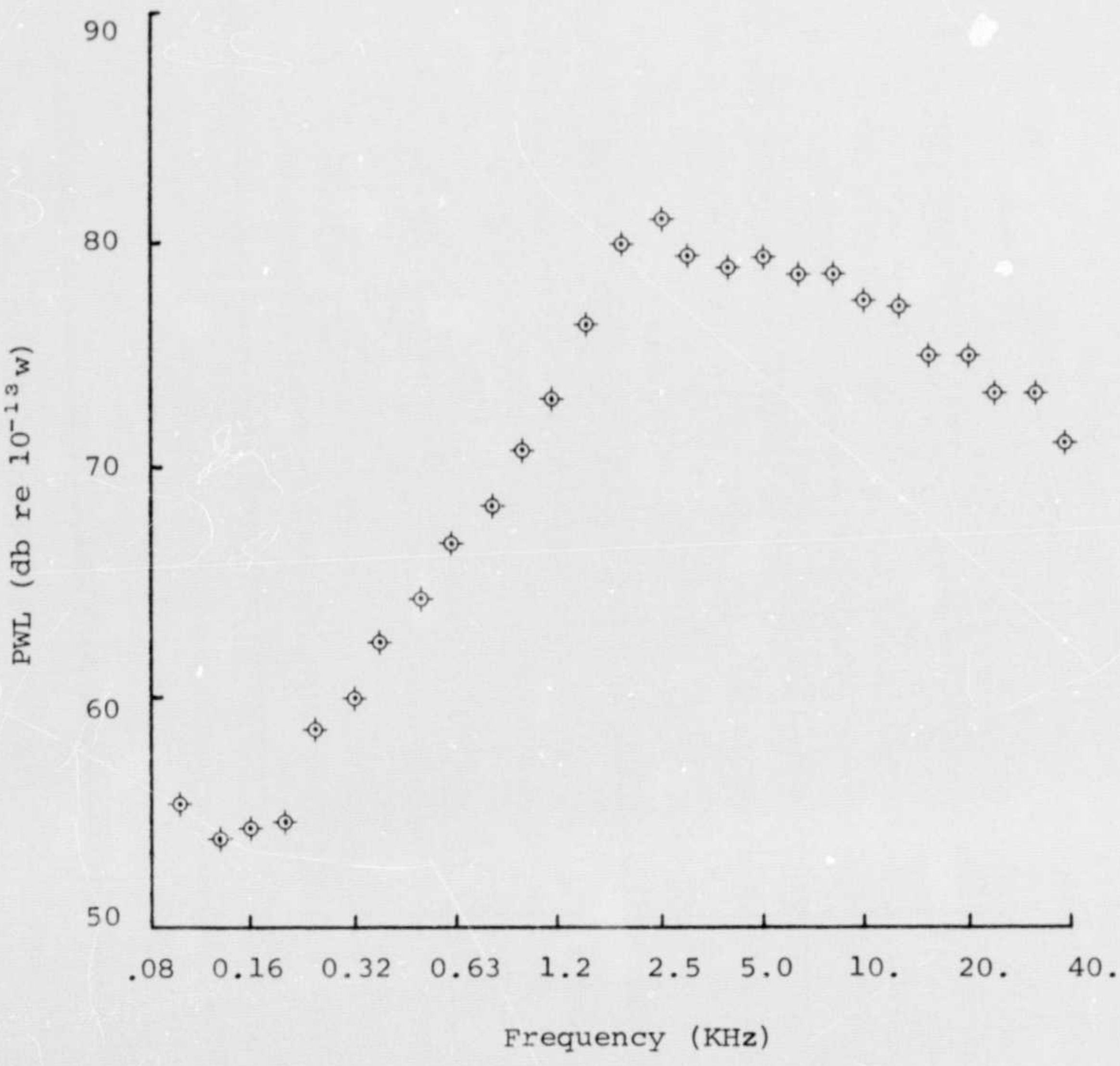

Figure 20. 1/3-Octave Sound Power Level Spectra; Uniform Jet, Mach Number = 0.28, h/d = 2.0

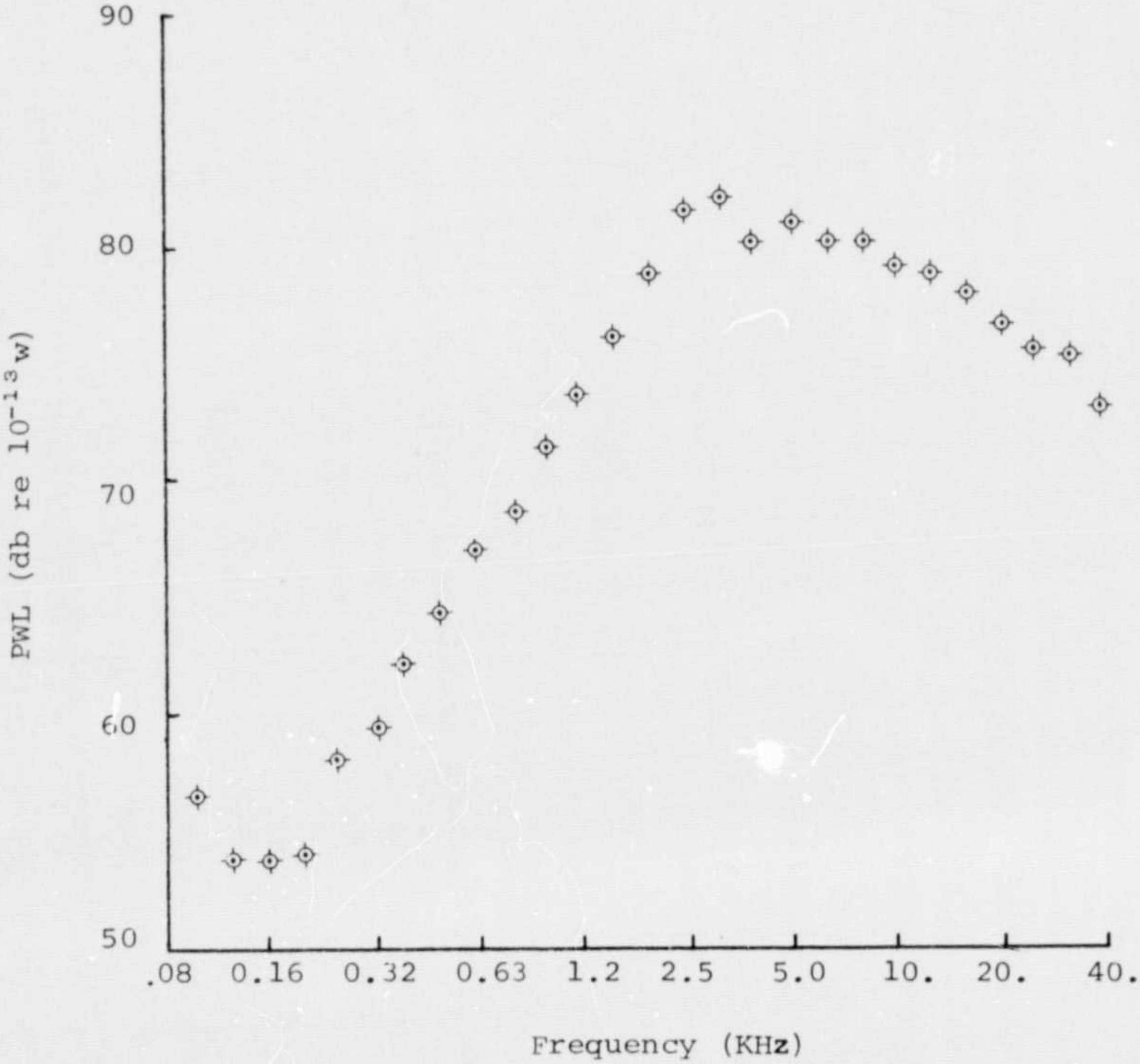

Figure 19. 1/3-Octave Sound Power Level Spectra; Uniform Jet, Mach Number = 0.28, h/d = 1.5

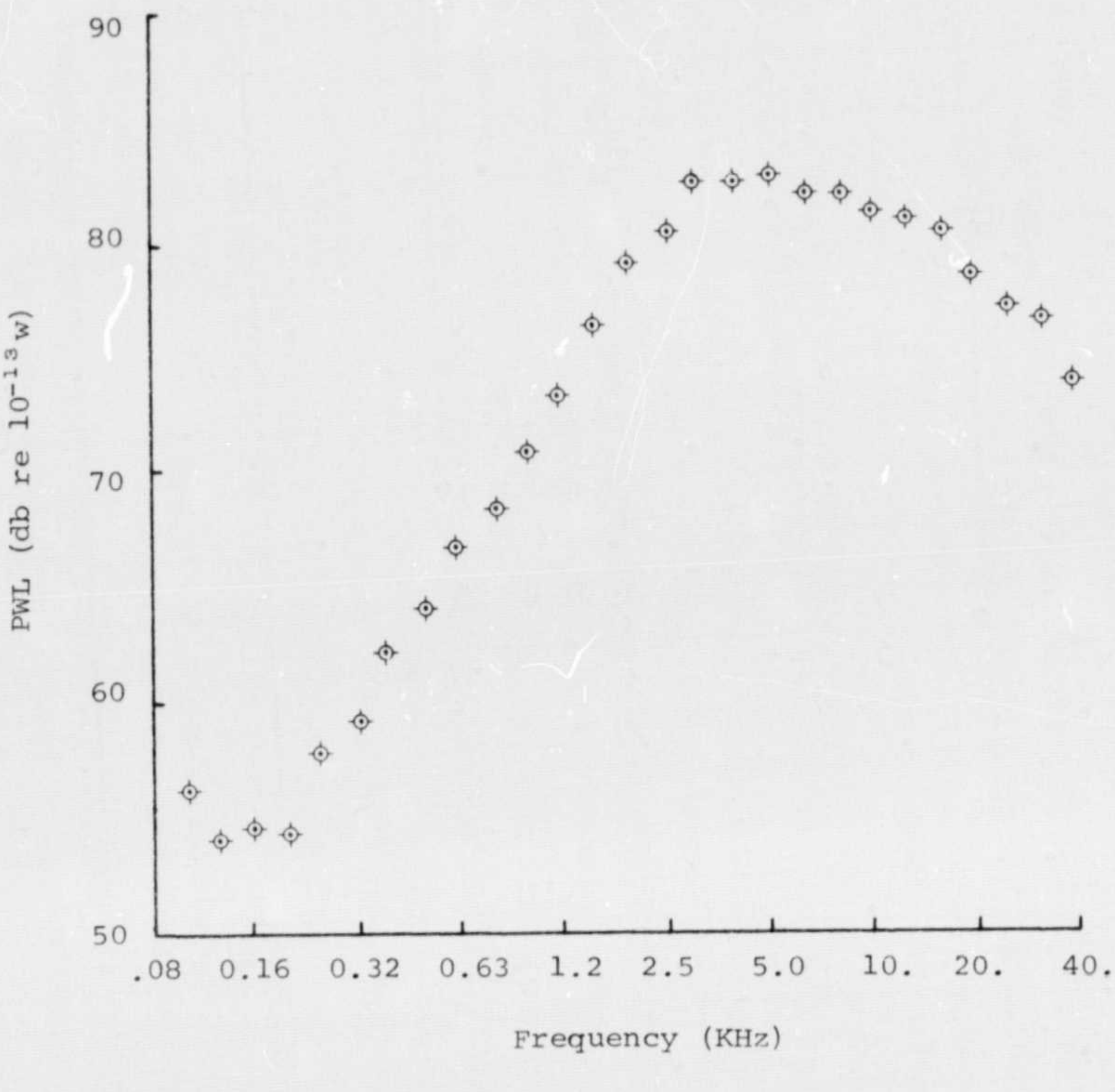

Figure 18. 1/3-Octave Sound Power Level Spectra; Uniform Jet, Mach Number = 0.28, h/d = 1.0

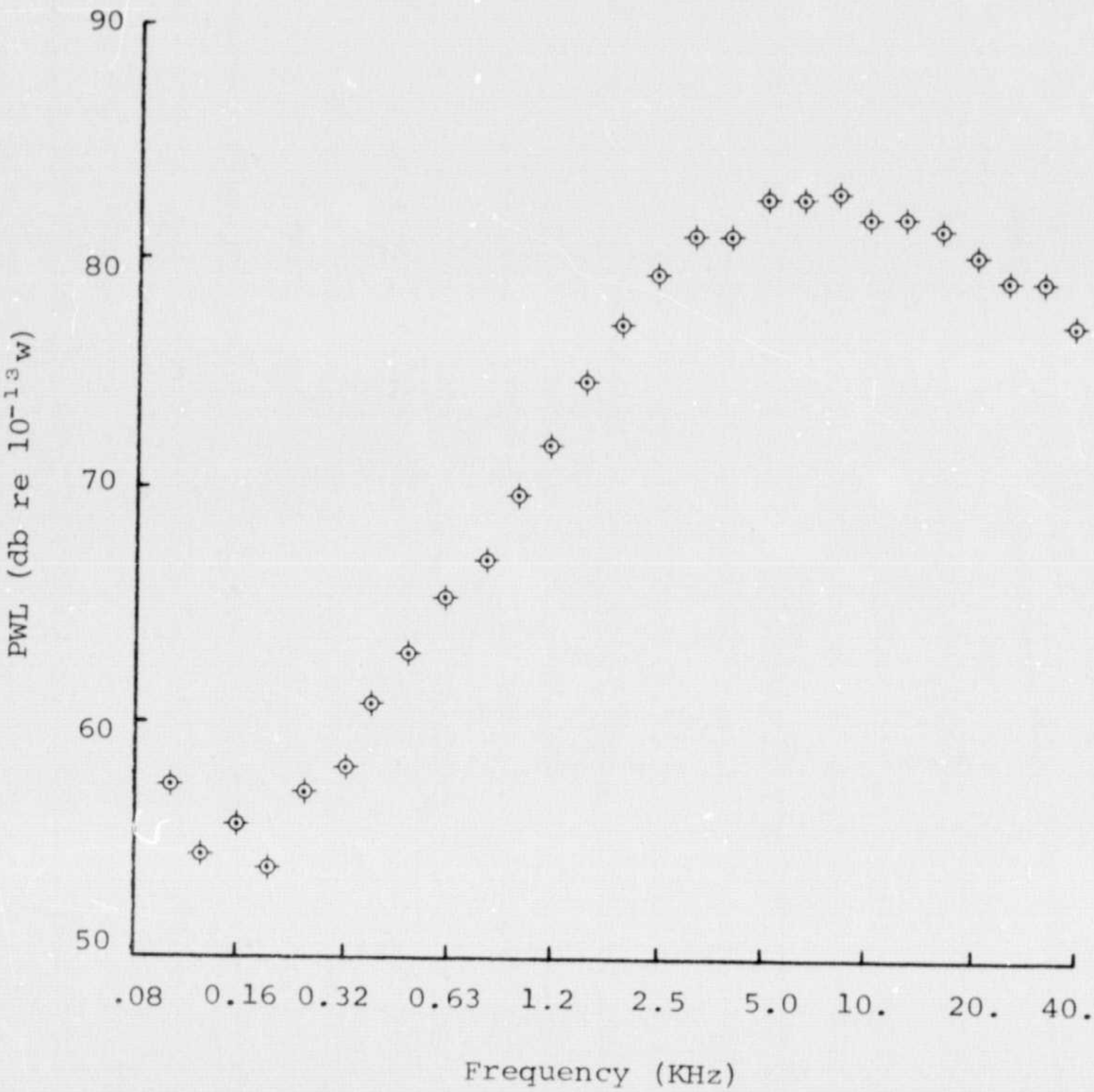

Figure 17. 1/3-Octave Sound Power Level Spectra: Uniform Jet, Mach Number = 0.28, h/d = 0.75

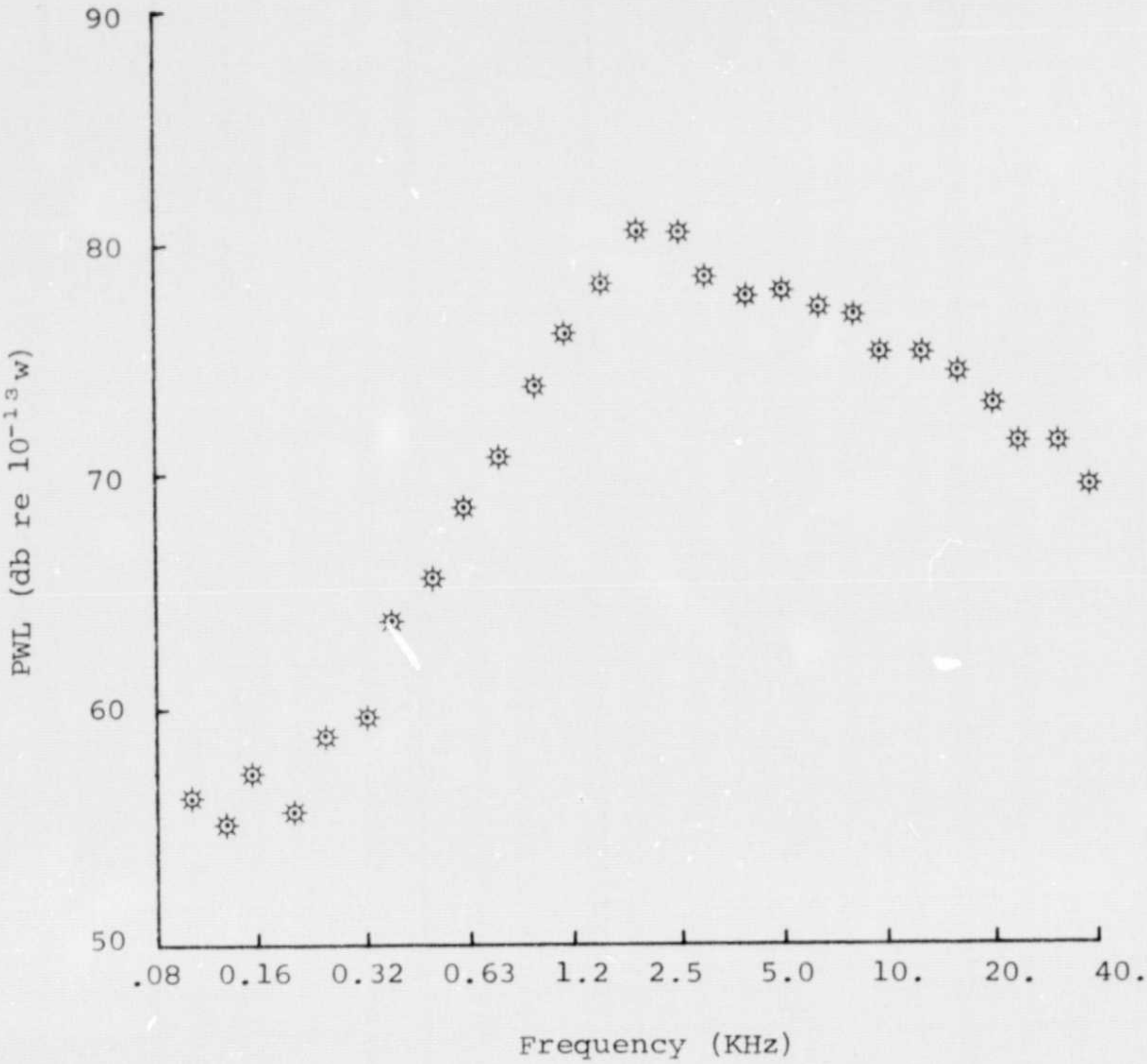

Figure 22. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 0.75

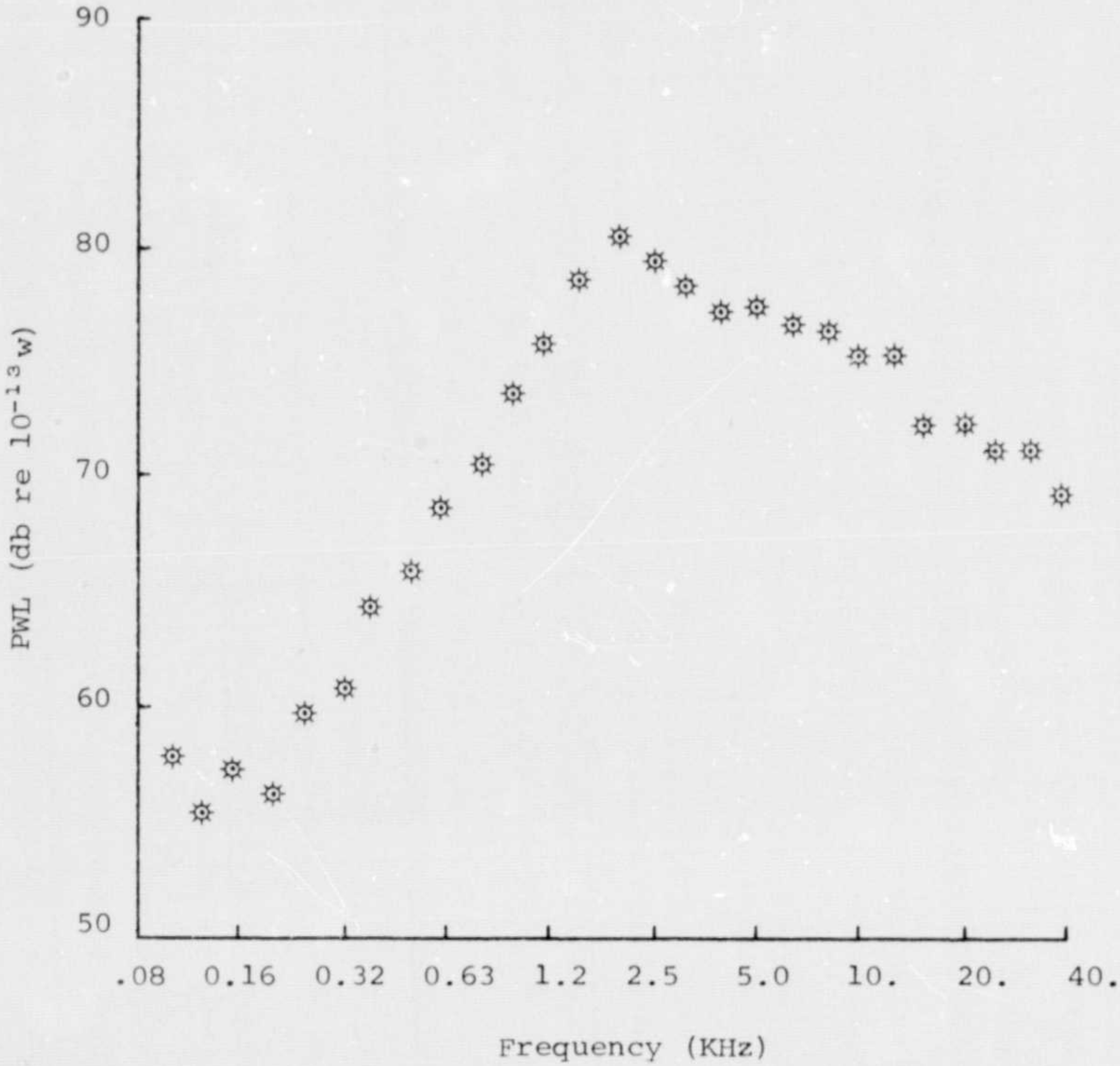

Figure 23. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 1.0

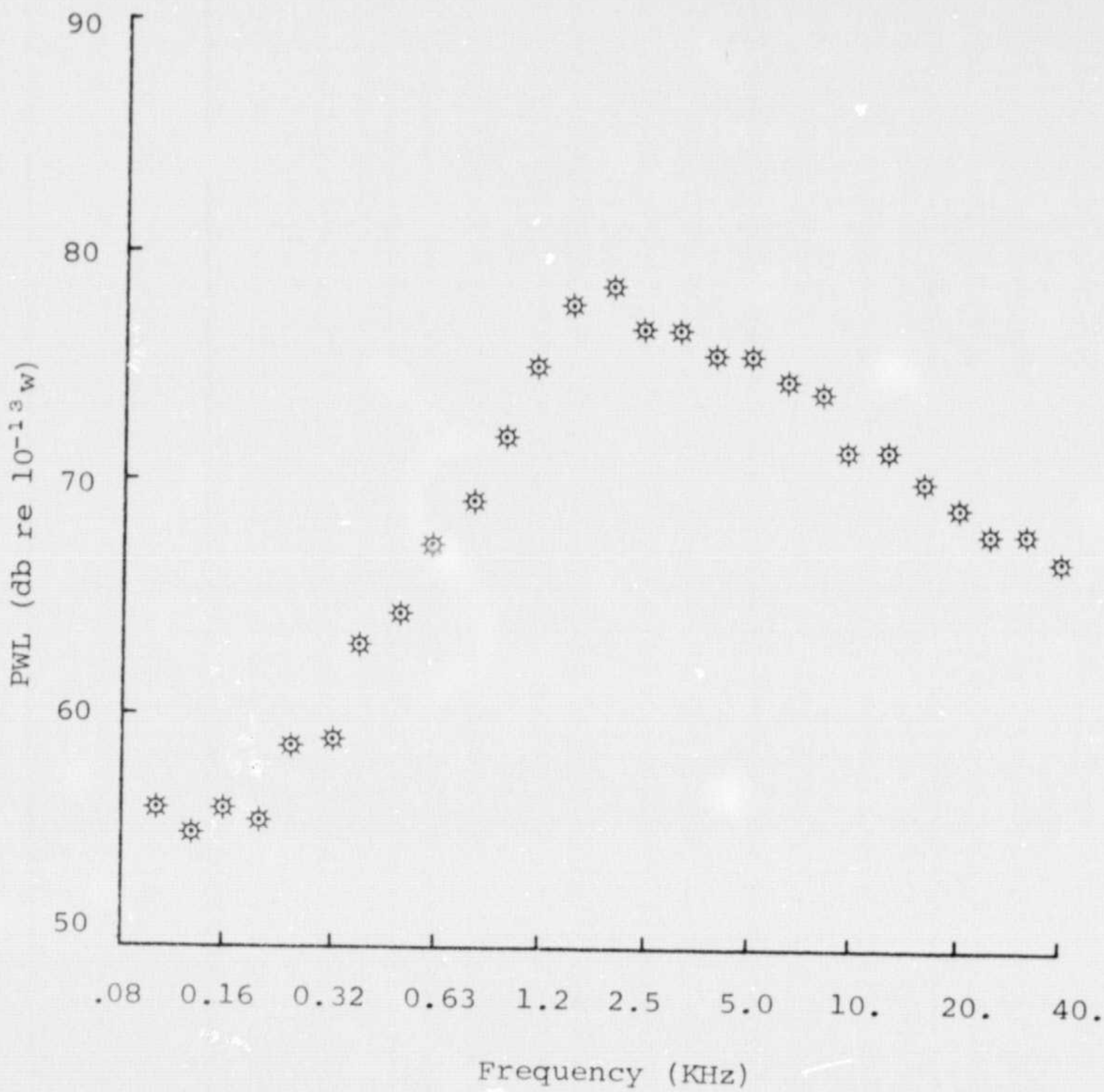

Figure 24. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 1.5

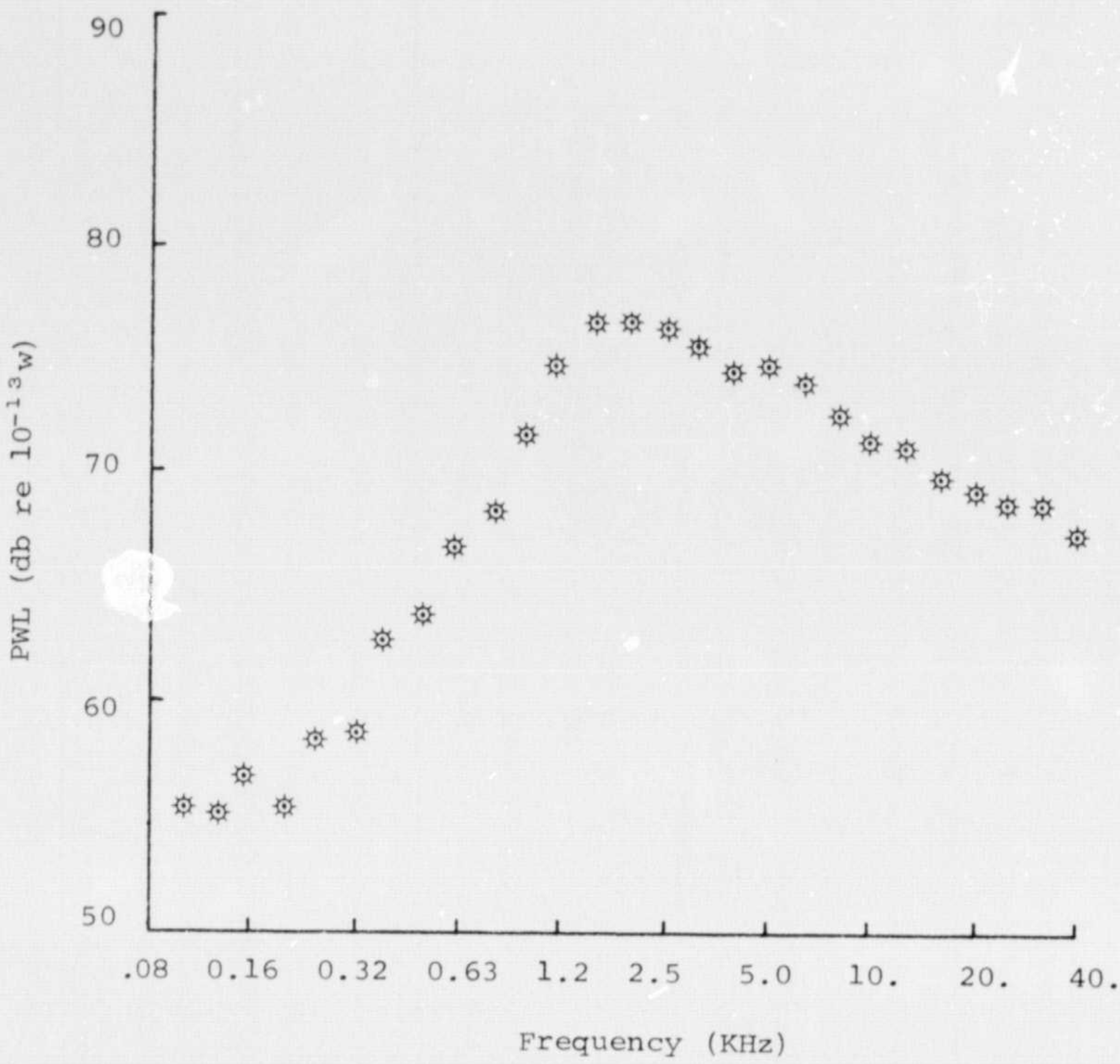

Figure 25. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 2.0

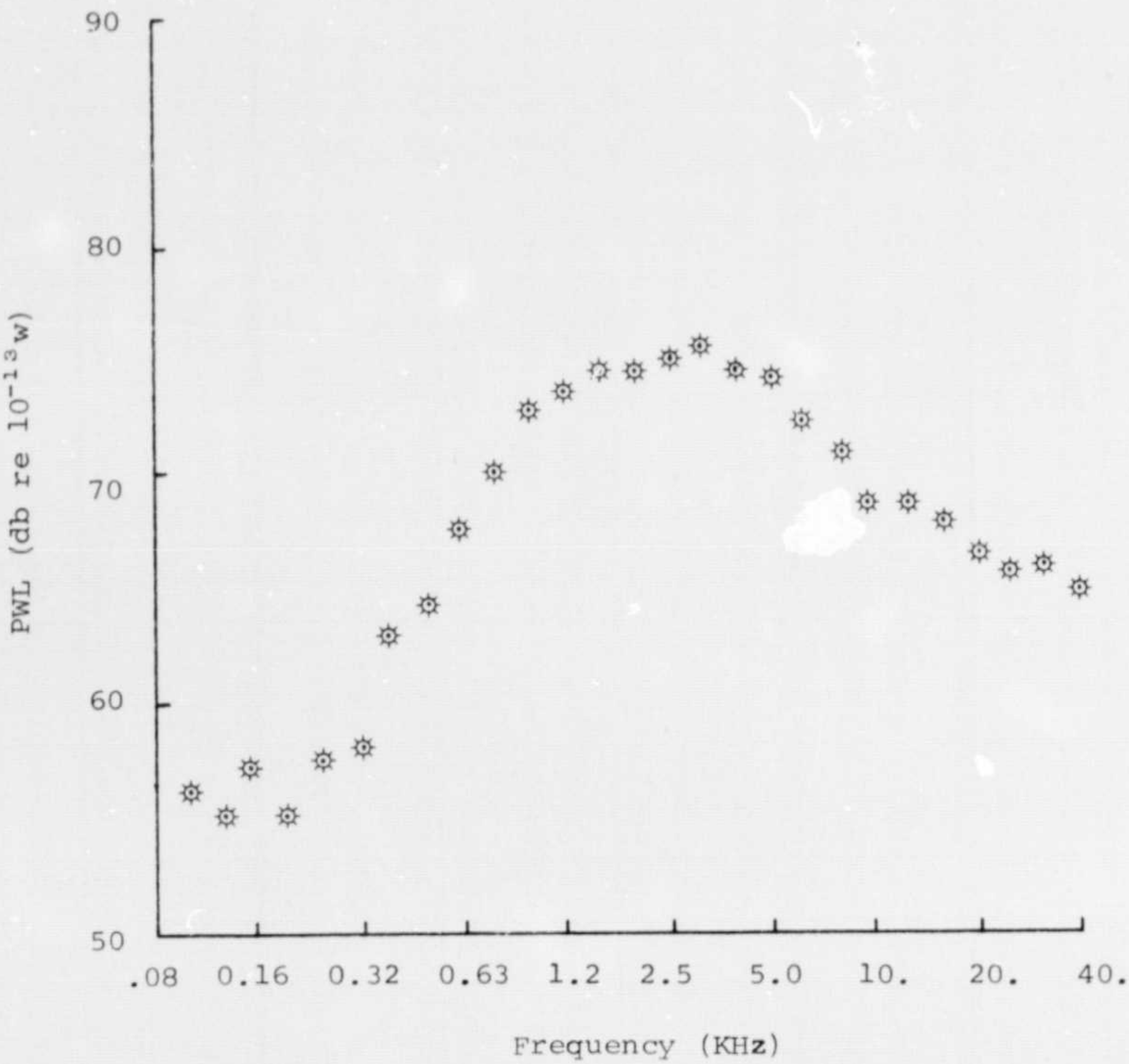

Figure 26. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 3.0

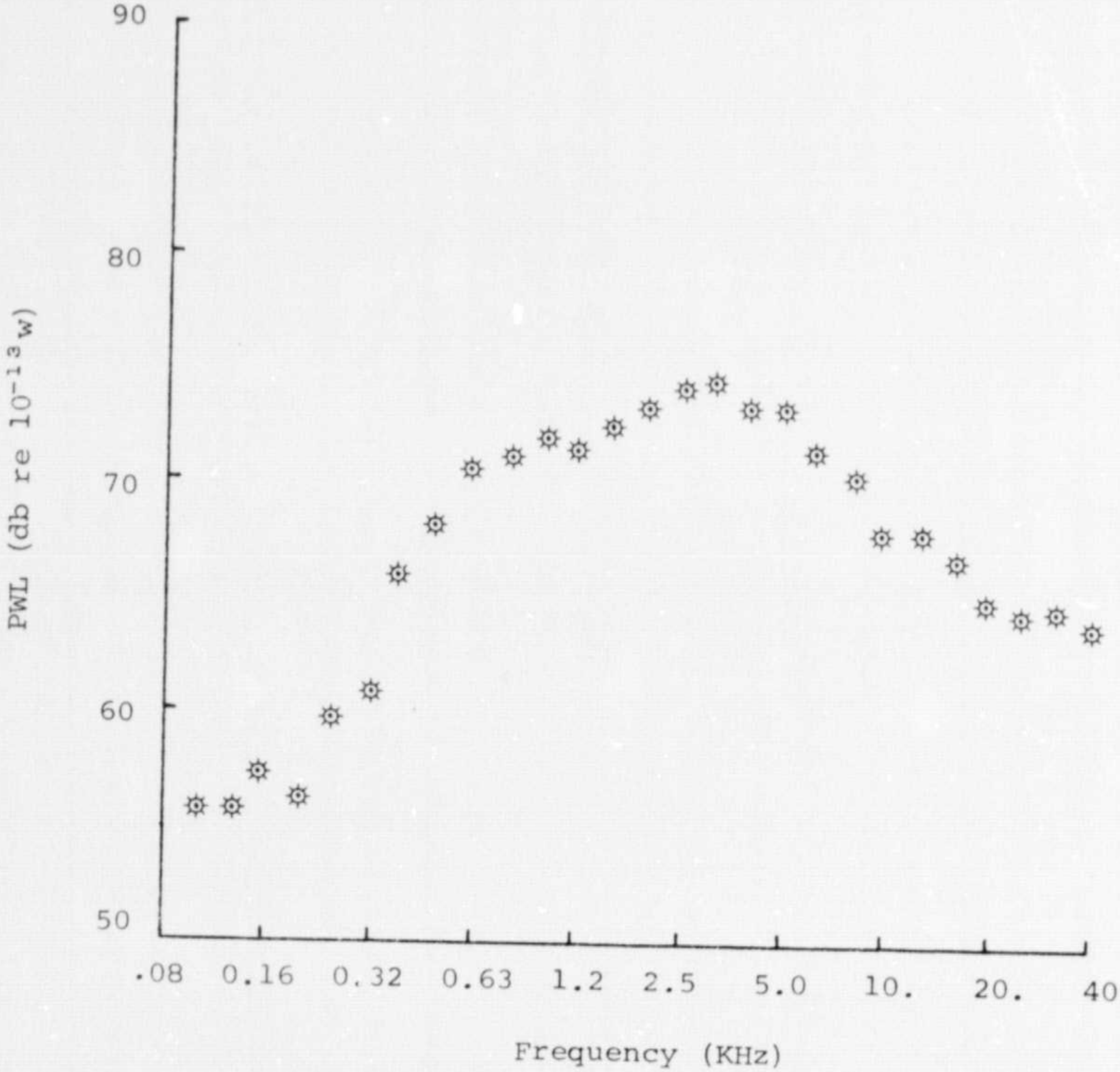

Figure 27. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 5.0

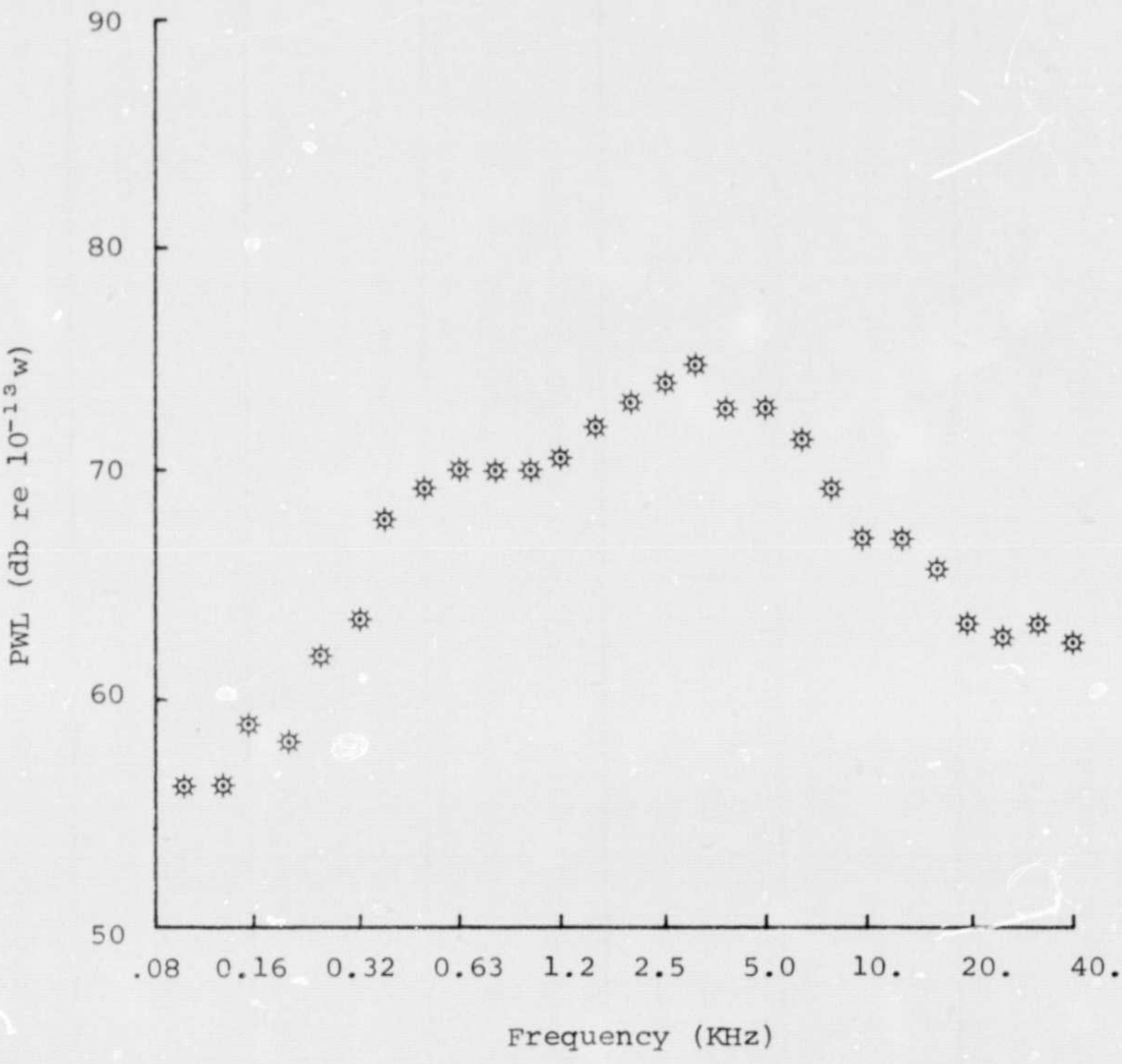

Figure 28. 1/3-Octave Sound Power Level Spectra; Pipe Flow Jet, Mach Number = 0.28, h/d = 7.0

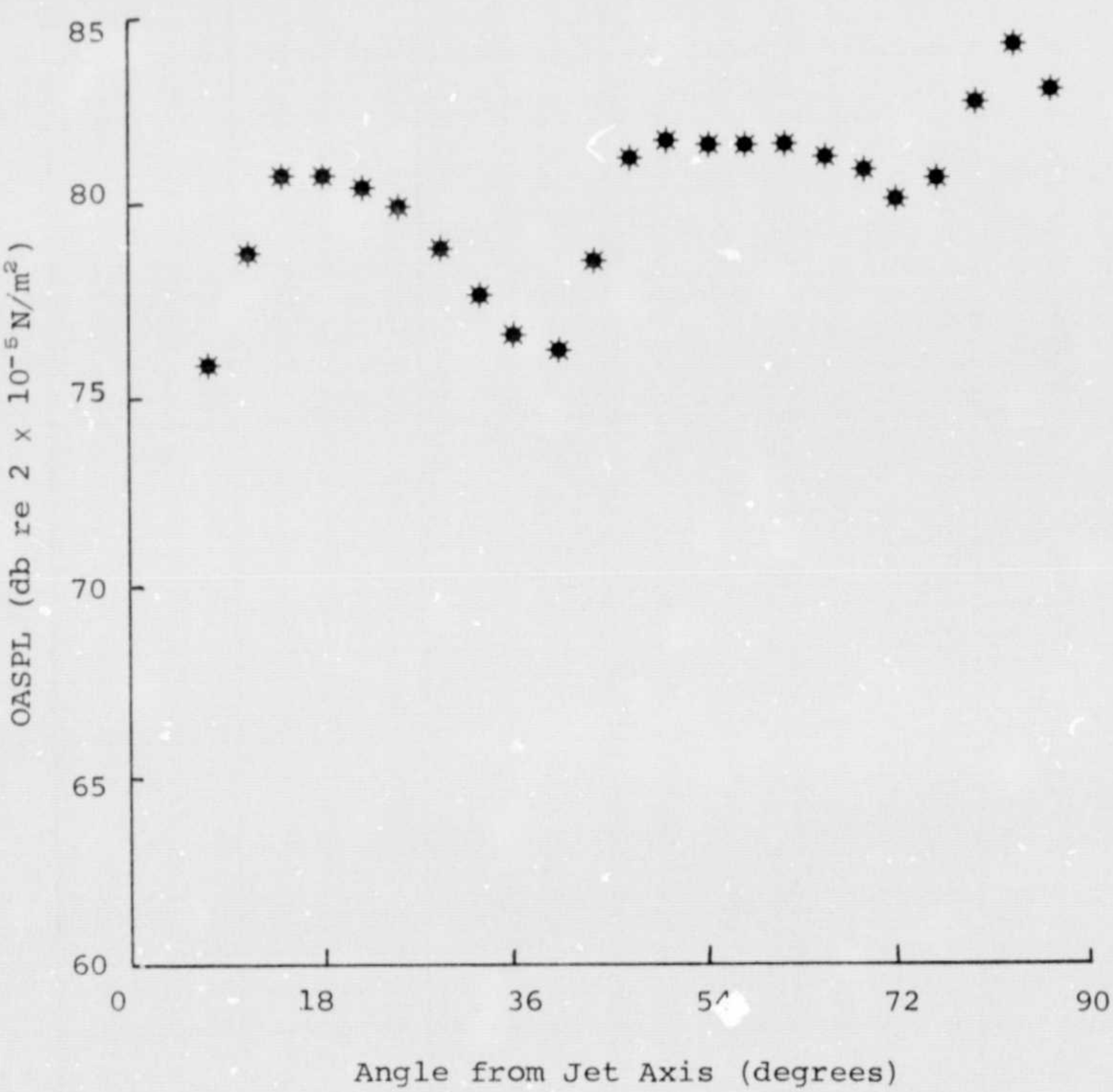

Figure 29. Overall Sound Pressure Level Versus Angle from Jet Axis; Heated Uniform Jet, Mach Number = 0.28, h/d = 1.0

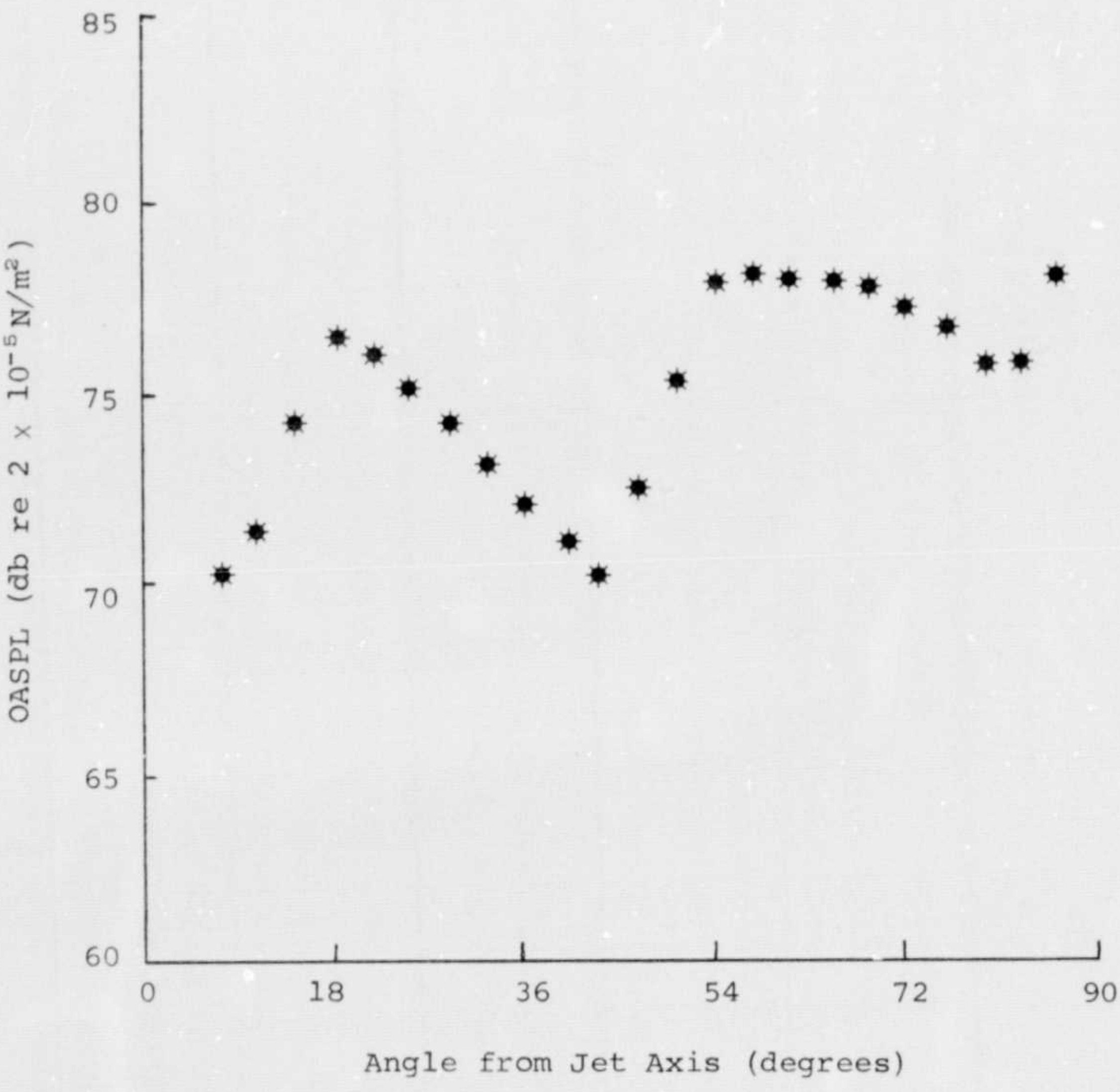

Figure 30. Overall Sound Pressure Level Versus Angle from Jet Axis; Heated Uniform Jet, Mach Number = 0.28, h/d = 3.0

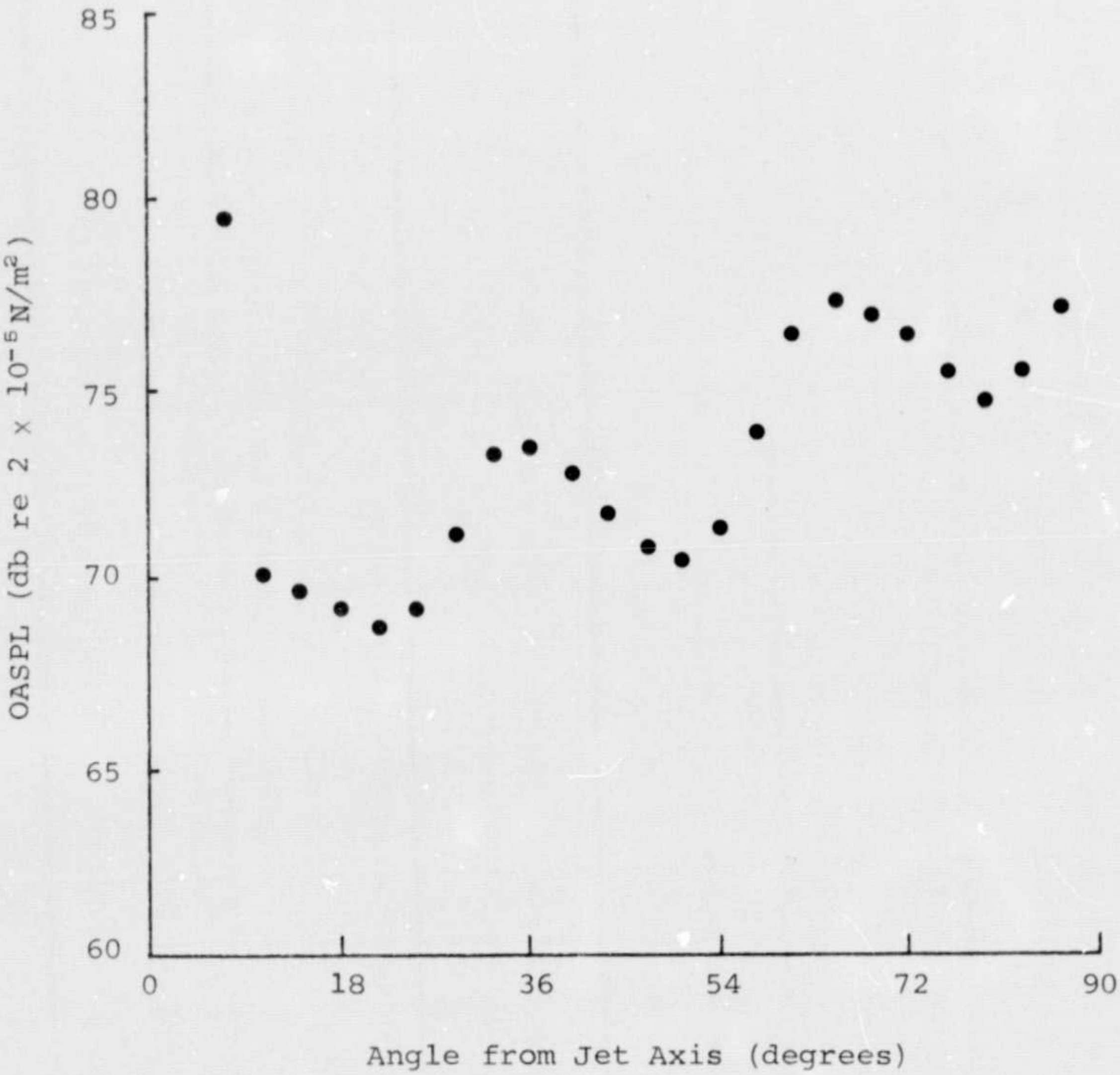

Figure 31. Overall Sound Pressure Level Versus Angle from Jet Axis; Heated Pipe Flow Jet, Mach Number = 0.28, h/d = 1.0

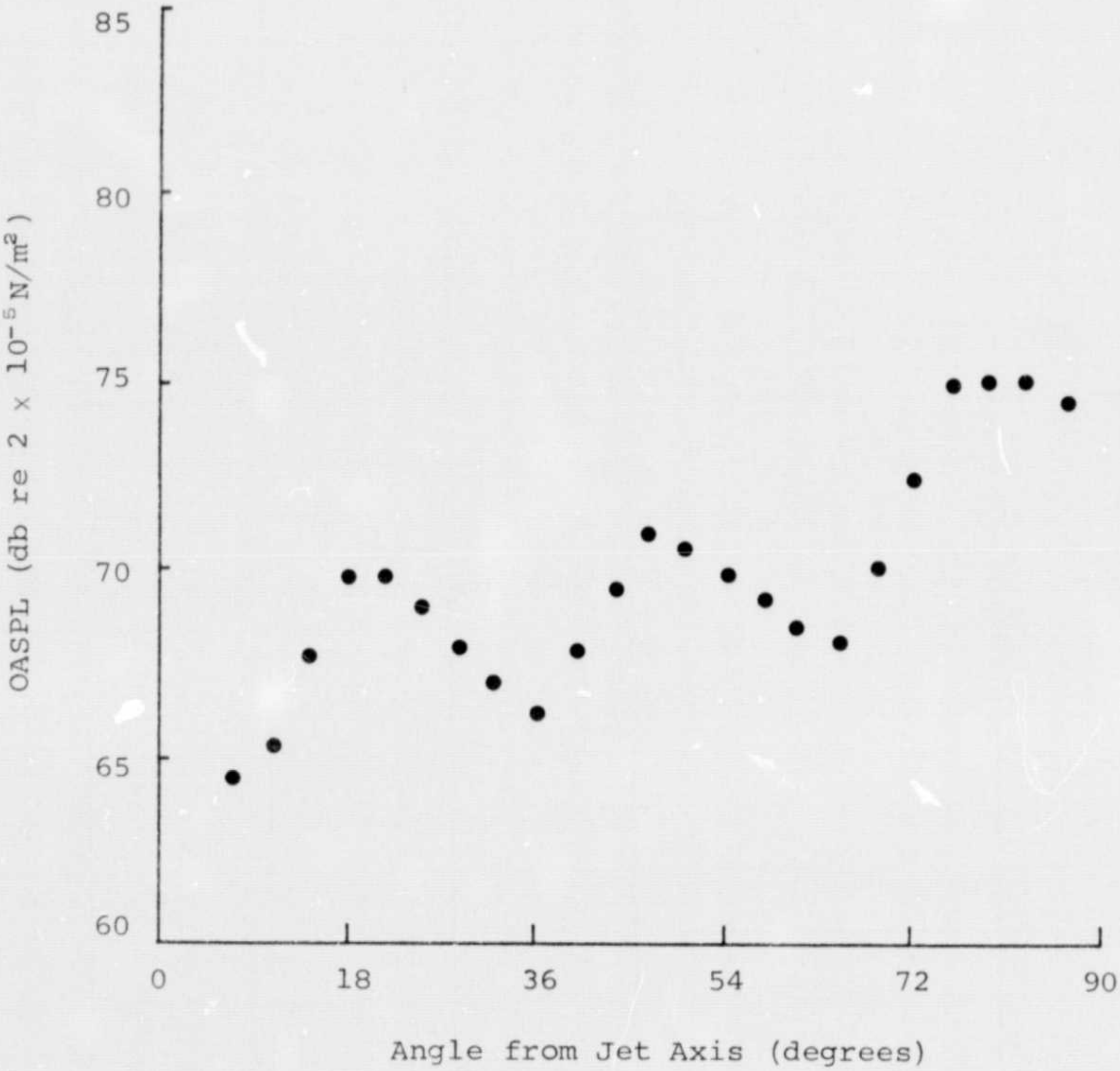

Figure 32. Overall Sound Pressure Level Versus Angle from Jet Axis; Heated Pipe Flow Jet, Mach Number = 0.28, h/d = 3.0

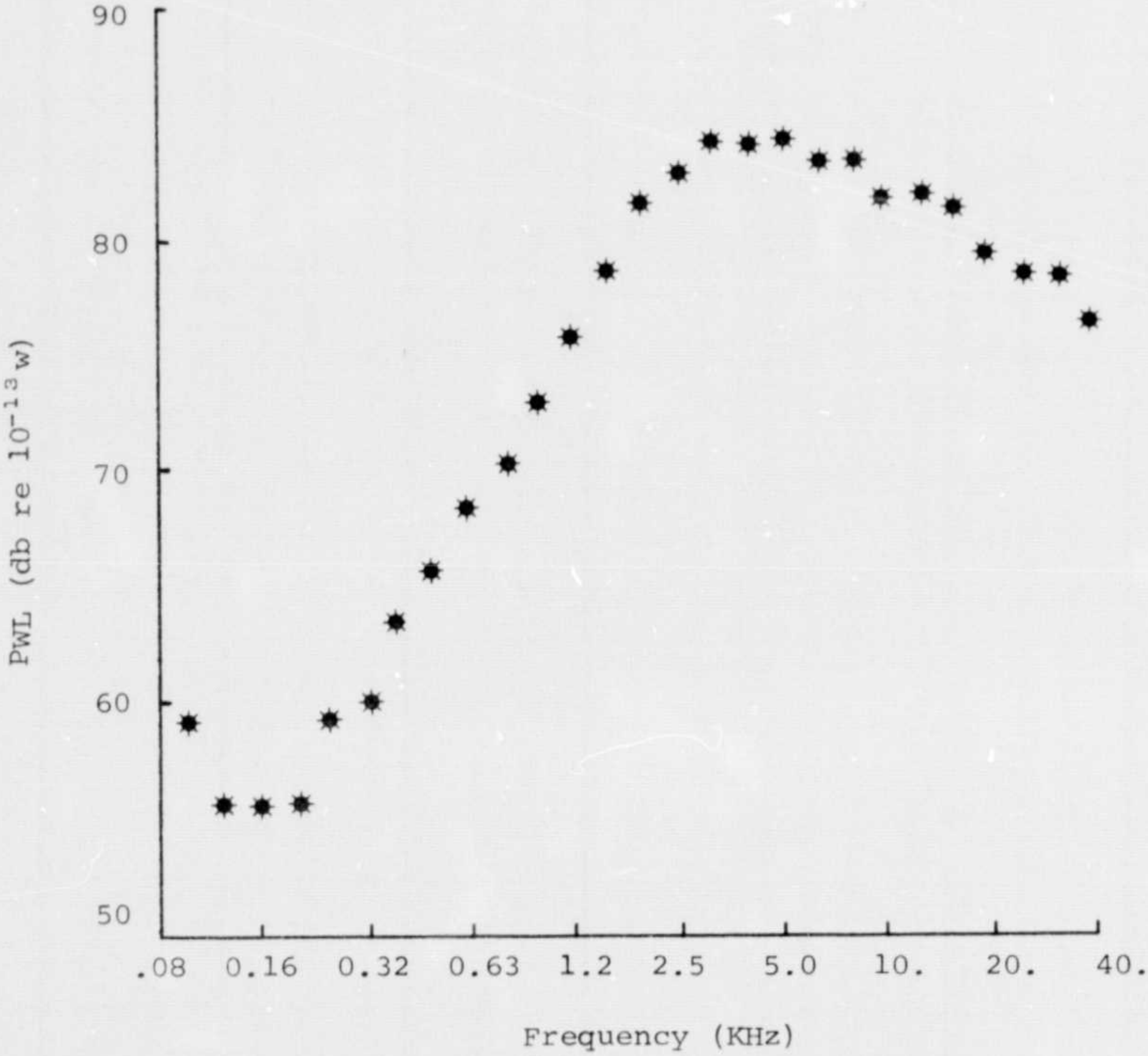

Figure 33. 1/3-Octave Sound Power Level Spectra; Heated Uniform Jet, Mach Number = 0.28, h/d = 1.0

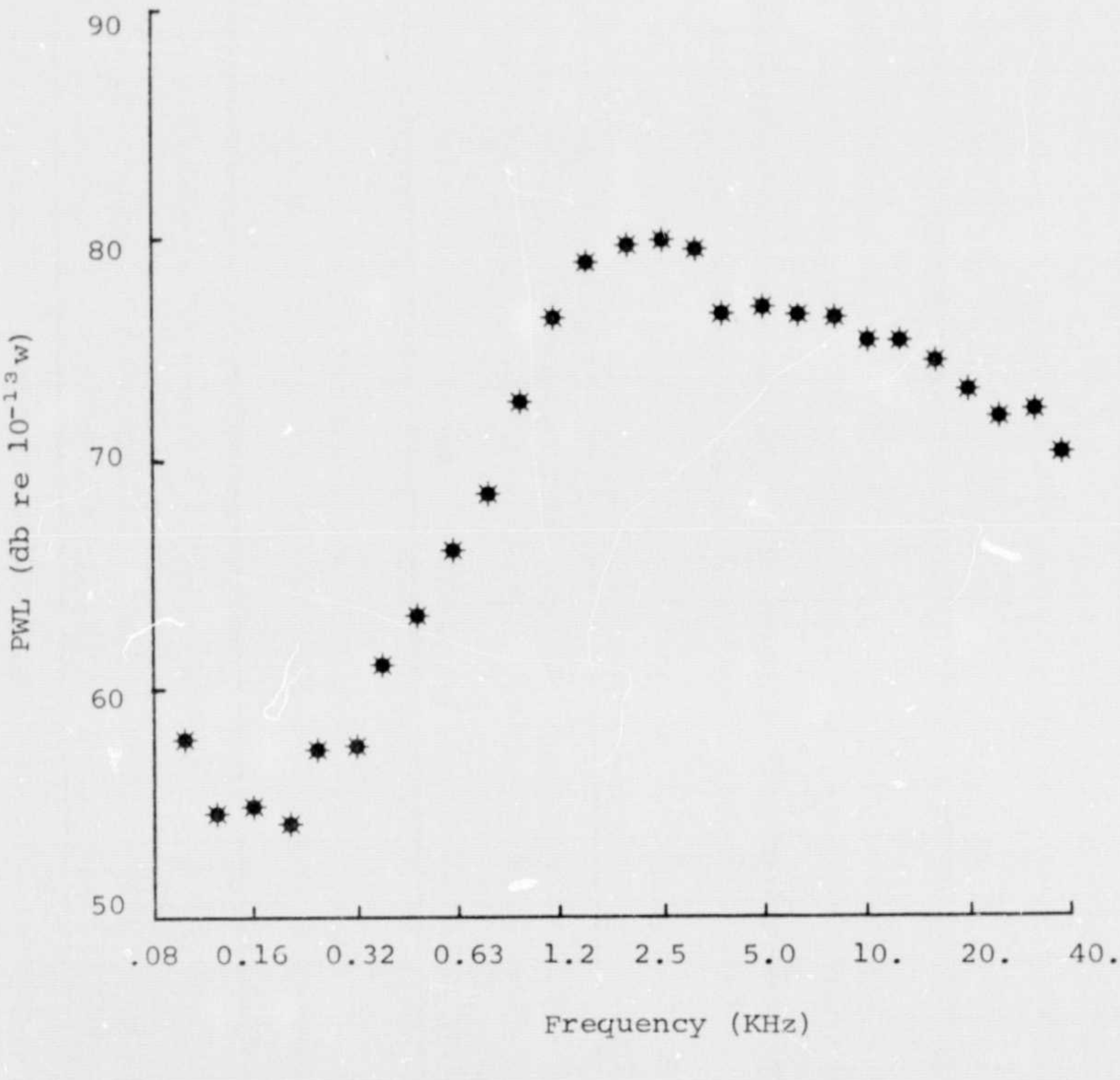

Figure 34. 1/3-Octave Sound Power Level Spectra; Heated Uniform Jet, Mach Number = 0.28, h/d = 3.0

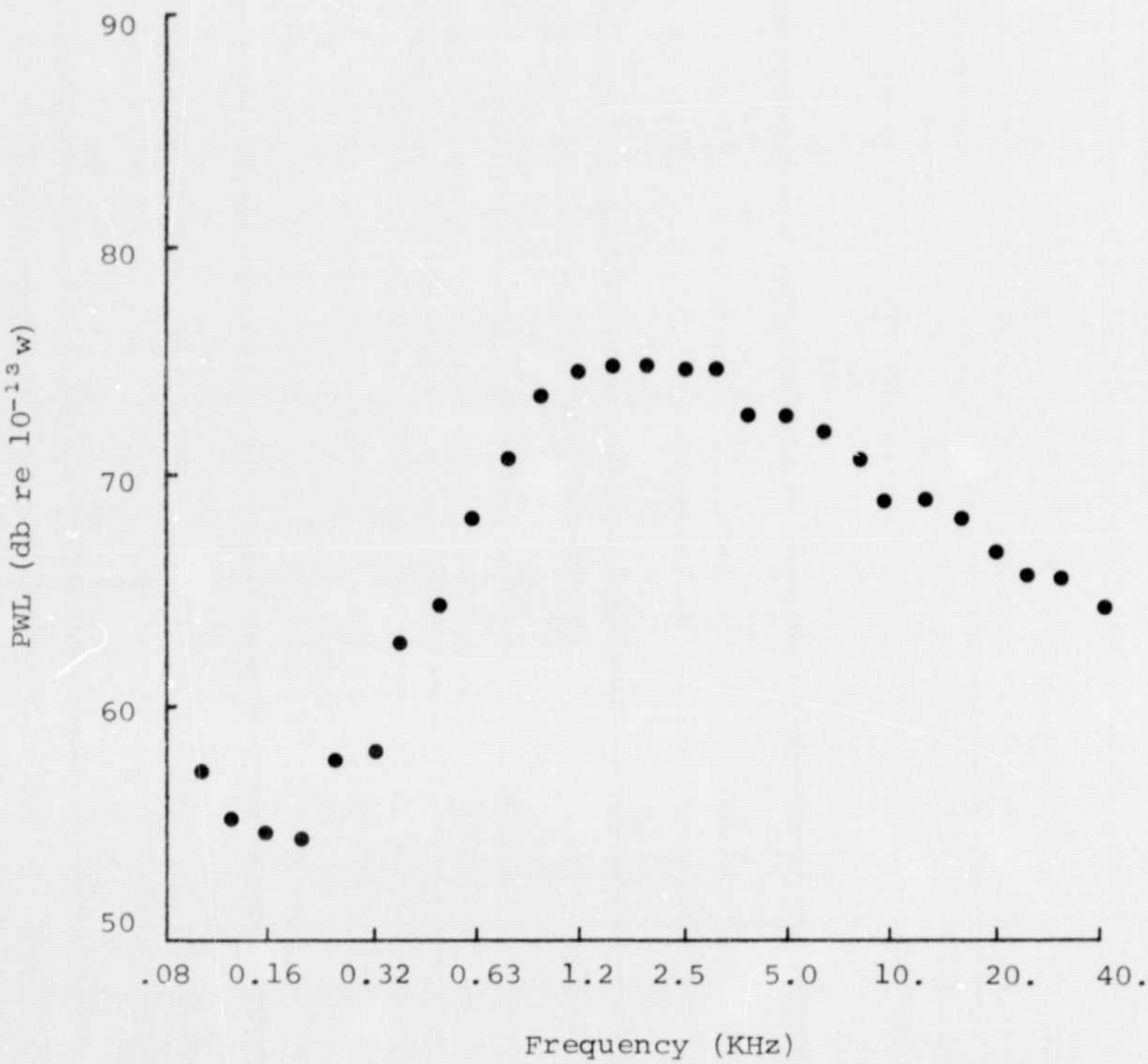

Figure 36. 1/3-Octave Sound Power Level Spectra; Heated Pipe Flow Jet, Mach Number = 0.28, h/d = 3.0

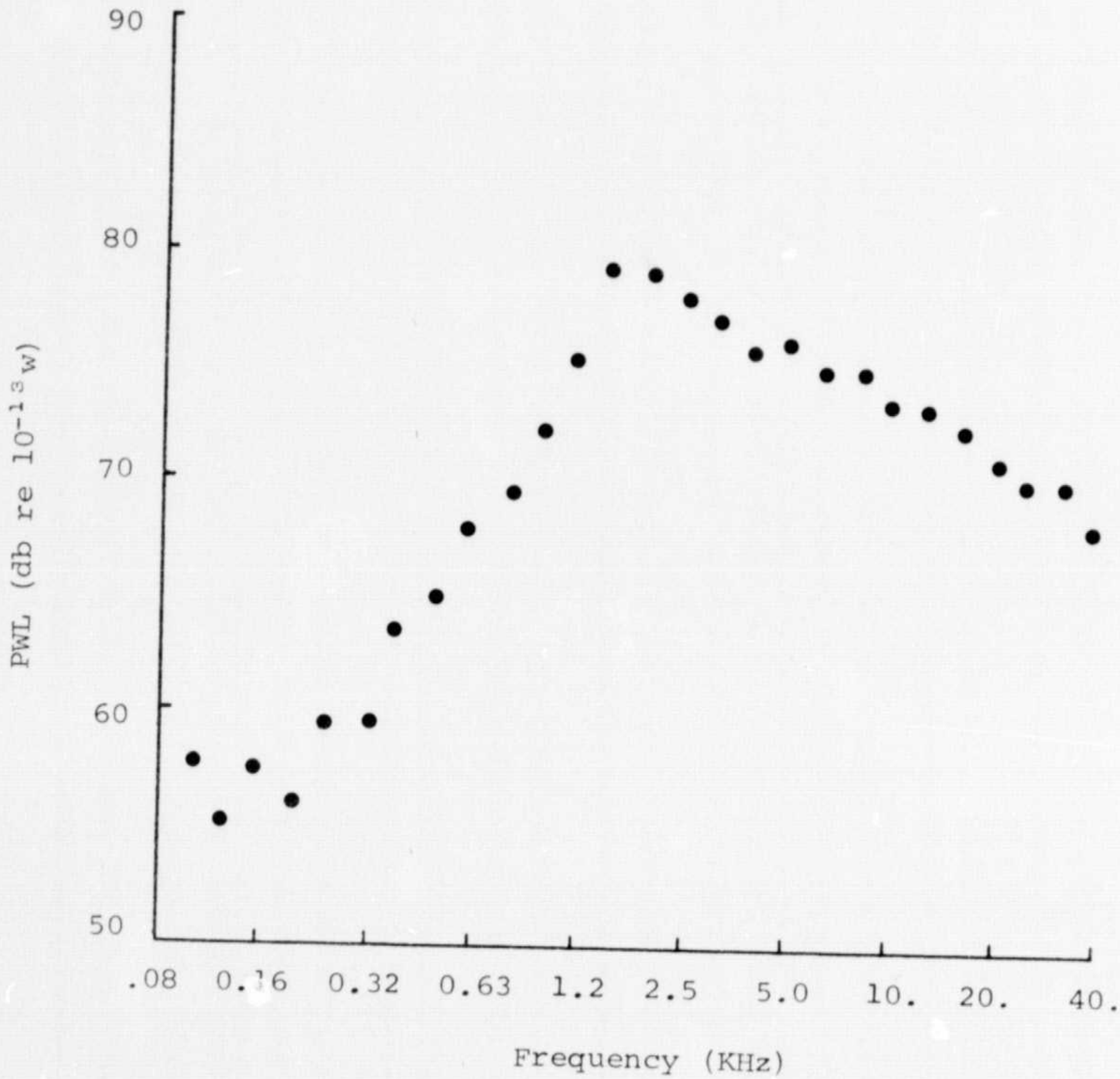

Figure 35. 1/3-Octave Sound Power Level Spectra; Heated Pipe Flow Jet, Mach Number = 0.28, h/d = 1.0