

BOLT BERANEK AND NEWMAN INC

CONSULTING • DEVELOPMENT • RESEARCH

Report No. 1272
BBN Job No. 11189STUDIES OF THE NEAR-FIELD NOISE
PROPERTIES OF A SMALL AIR JET

FINAL REPORT

Contract No. NAS1-4656

GPO PRICE \$ _____

CFSTI PRICE(S) \$ _____

Hard copy (HC) 4.00Microfiche (MF) .75

FF 653 July 65

Distribution of this report is provided in the interest of
information exchange. Responsibility for the contents
resides in the author or organization that prepared it.

February 1966

FACILITY FORM 602	N66-24941 (ACCESSION NUMBER)	_____ (THRU)
	103 (PAGES)	_____ (CODE)
	CR-74699 (NASA CR OR TMX OR AD NUMBER)	23 (CATEGORY)

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365
Attention: Mail Stop 126

Report No. 1272
BBN Job No. 11189

STUDIES OF THE NEAR-FIELD NOISE
PROPERTIES OF A SMALL AIR JET

FINAL REPORT

Contract No. NAS1-4656

David N. Keast and Gideon Maidanik
Bolt Beranek and Newman Inc.
50 Moulton Street
Cambridge, Massachusetts

February 1966

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Langley Station
Hampton, Virginia 23365
Attention: Mail Stop 126

TABLE OF CONTENTS

	<u>Page No.</u>
LIST OF FIGURES	
LIST OF TABLES	
I. INTRODUCTION	1
II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS	3
A. Conclusions.	3
B. Recommendations.	3
III. NOISE RADIATED BY SUPERSONIC EDDIES. . . .	5
A. Boundary Effects	5
B. Effect of the Source on the Surrounding Medium	6
C. Radiation from a Vibrating Plate . . .	10
D. Radiation from a Supersonic Jet. . . .	11
IV. THE EXPERIMENTAL PROGRAM	16
A. Experimental Facility and Instrumenta- tion	16
B. Measurement Configurations	18
C. Experimental Data.	21
D. Comments on the Experimental Data. . .	23
V. THEORETICAL INTERPRETATION OF THE EXPERIMENTAL RESULTS	28
REFERENCES	
APPENDIX A	A-1

LIST OF FIGURES

Figure No.

- 1 Spatial Cross-Correlation of a Bounded Disturbance.
- 2 A, B, C and D Regions of Concentrated Spectral Components Associated with a Single Point in a Disturbance Mapped on a Cross Section of the (k, ω) -Space. The Cross Section is Defined by the Angular Co-ordinates θ and ϕ .
- 3 Single Traveling Wave on an Infinite Plate. Figures (a), (b) and (c) Present a Spectral Analysis Associated with a Single Point in the Disturbance Plotted in the (k, ω) -Space.
- 4 Spectral Analysis of a Disturbance Associated with a Single Point in the Flow Plotted in the (k, ω) -Space.
- 5 Spectral Analysis of a Disturbance Associated with a Single Point in the Flow Plotted in the (k, ω) -Space.
- 6 The Effects on the Mach Waves Due to a Spectral Width in the Convective Velocities in the Flow.

LIST OF FIGURES (cont)

Figure No.

- | | |
|----|--|
| 7 | Model Jet Noise Studies - Frequency Responses
of Correlation System |
| 8 | Model Jet Noise Studies - Measurement
Locations: 16-19 Feb 1965 |
| 9 | Model Jet Noise Studies - Measurement
Locations: 20-26 May 1965 |
| 10 | Model Jet Noise Studies - Correlation vs
Separation |
| 11 | Model Jet Noise Studies - Correlation Parallel
to Jet Axis vs Microphone Separation |
| 12 | Illustrating the discussion of eddy size
vs distance |

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I	Key to Jet Noise Data in Appendix A	22
II	Convective Mach Numbers and Mach Angles Computed from the Data in Table T-2, Appendix A	29

STUDIES OF THE NEAR-FIELD NOISE
PROPERTIES OF A SMALL AIR JET

I. INTRODUCTION

In 1963, Dr. John E. Ffowcs Williams suggested that certain properties of the sound field in the immediate vicinity of a supersonic jet would be related directly to the properties of turbulent eddies within the jet.^{1/} To the extent that this is the case, it provides a unique means for studying turbulence within supersonic jets by analyzing their near-field noise properties. From an analytical point of view, a new tool is available for the study of supersonic jets and their noise fields produced by devices of considerable practical importance, such as rocket engines. From an experimental point of view, the difficulties of penetrating a jet with instrumentation during turbulence studies are avoided.

The Langley Research Center of the National Aeronautics and Space Administration (NASA/LaRC) has contracted with Bolt Beranek and Newman Inc. (BBN) to participate in a joint experimental study of the relationships postulated by Ffowcs Williams. This study has been completed, and the results are reported herein.

The experimental program was initially outlined by Dr. Ffowcs Williams, and he has provided periodic comments on the experimental results. Measurements were performed with a small supersonic air jet in a facility at NASA/LaRC. The data were processed, analyzed and reported by BBN.

The conclusions and recommendations of this experimental program are summarized in Section II of this report. Section III provides a qualitative description of the physical relationships which have been investigated between supersonically-convected eddies in jets and the near-field noise produced by such eddies. The experimental program and the data acquired are summarized in Section IV. (Most of the actual data are in Appendix A.) A discussion of the experimental results is given in Section V.

II. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions:

1. The spectral and spatial-correlation properties of the noise field in the immediate vicinity of a small air jet have been recorded and analyzed over the frequency range from 1000 cps to 60,000 cps.

2. The observed near-field noise properties of the air jet appear qualitatively to be related to the properties of turbulent eddies convected supersonically within the jet. This relationship appears to hold for the mean convection velocity of the eddies, and for the mean eddy size.

3. Anomalous spatial correlations which were observed early in the experimental program now appear to be explainable by the supposition that the reference microphone location for these spatial correlations was ill-chosen.

B. Recommendations:

1. A considerable amount of additional information can be obtained from further study of the experimental data now available. It is recommended that such further study include:

- a. Processing of additional spatial correlations from the data now recorded, but using a base or reference microphone position other than the one used to date.
- b. More detailed analytical development of the sound-turbulence relationships outlined in subsequent sections of this report, leading to a quantitative definition of these relationships which could have considerable practical application.

- c. Fourier transformation of the cross-correlation results now available to yield cross power spectra related directly to the propagating eddies.

2. It is also recommended that further experimental studies with small supersonic jets be performed to contribute to the clarification and refinement of the results reported herein. Such additional studies could include:

- a. Establishment of spatial correlations at elevated jet temperatures without microphone baffles.
- b. Measurement of spatial correlations at various calculated Mach angles. This may lead to a correspondence between shadowgraphs and acoustic data. It may also lead to the establishment of effects associated with diffraction due to the discontinuity in the speed of sound at the jet boundary.
- c. Investigation of the optimum location for a spatial-correlation-reference-microphone position along lines parallel to the jet axis.
- d. Studies of the effects of varying such parameters as jet diameter, jet velocity (at a fixed jet temperature) and jet fluid.
- e. Further investigation of the influence of instrumentation, including studies of the effects of microphone orientation and microphone size.

III. NOISE RADIATED BY SUPERSONIC EDDIES

This section provides a heuristic approach to the subject of the acoustic radiation in the near and far fields of a supersonic jet. A comprehensive theoretical dissertation on the subject has been avoided. Rather, the attempt here is to draw a coherent picture of the mechanism that is responsible for generating the radiation, and of those features of the radiation which indicate that near-field acoustic measurements can lead to information on the flow.

A. Boundary Effects

Consider a disturbance or source in a stationary fluid medium. This source may be described by $b(\underline{y}-\underline{y}_0) p(\underline{y},t)$. The function $b(\underline{y}-\underline{y}_0)$ has to do with the boundaries of the source, which are assumed to be independent of time; $\underline{y}_0$ is the position vector of these boundaries; $\underline{y}$ is the position vector variable; and t is the time variable. The cross-correlation of the disturbance at position $(\underline{y},t)$ is given by:

$$\begin{aligned} \langle b(\underline{y}-\underline{y}_0) p(\underline{y},t) b(\underline{y}+\underline{\xi}-\underline{y}_0) p(\underline{y}+\underline{\xi},t+\tau) \rangle \\ = B(\underline{y}-\underline{y}_0,\underline{\xi}) P(\underline{y},t,\underline{\xi},\tau) \end{aligned} \quad (3.1)$$

where $\underline{\xi}$ and τ are the spatial and temporal variables of the correlation. The brackets $\langle \rangle$ indicate the proper averaging and normalization of the correlation.

The function B modifies the function P only if the correlation is taken at a position $\underline{y}$ which is closer to a boundary than the correlation distance in the same direction. When the

position $\underline{y}$ is far from any boundary, B reduces to unity. This is illustrated in Fig. 1, where the source is assumed to be vibration in a plate. (This analogy between radiation from a vibrating plate and from eddies in a jet is developed further below.)

B. Effect of the Source on the Surrounding Medium

In considering the effect of the source on the surrounding medium, it is convenient to transform the function BP into its spatial and temporal Fourier components with respect to $\underline{\xi}$ and τ :

$$\tilde{BP} = \tilde{B}(\underline{y}-\underline{y}_0, \underline{k}) * \tilde{P}(\underline{y}, t, \underline{k}, \omega) \quad (3.2)$$

where

$\underline{k}$ = wavevector component associated with $\underline{\xi}$,

ω = angular frequency associated with τ

The symbol $\sim$ over a function denotes the Fourier transform of this function, and the symbol $*$ between two functions denotes the convolution of these functions.

It should be noted that the remarks made above with respect to the role that B plays in modifying P hold now for the function $\tilde{B}^*$. Thus, only when $\underline{y}$ is within the correlation distance of $\underline{y}_0$ may $\tilde{B}^*$ be different from unity.

A spectral component of BP that will produce a signal at an observation position $\underline{x}$ in the surrounding fluid must obey certain specific conditions. These conditions are:

1. The wavevector $\underline{k}$ must be pointing in the direction defined by $(\underline{x}-\underline{y})/|\underline{x}-\underline{y}|$.
2. The spectral component of the source $(\underline{k}, \omega)$ must match a corresponding acoustic spectral component $(\underline{k}_0, \omega_0 = |\underline{k}_0| a_0)$ in the fluid if it is to arrive unattenuated at the observation position. (The subscript 0 identifies parameters associated with the fluid: a_0 is the speed of sound in the fluid.) The degree of attenuation of all other spectral components that satisfy condition 1 but do not match a corresponding acoustic component increases with the degree of non-matching.

A one-to-one correspondence between a spectral component in the source and the signal at $\underline{x}$ can exist only when $(\underline{k}, \omega) = (\underline{k}_0, \omega_0)$, provided a time delay is taken into account, i.e. provided $t' = t - |\underline{x}-\underline{y}|/a_0$, where t' = time of observation. The correspondence fades more and more as the inequality between the spectral component in the source and the fluid medium increases.

This matching requirement is illustrated with the aid of Fig. 2. The spectral component $(k_{\theta\phi}, \omega)$ in the source is plotted in a specific cross section of the (k, ω) -space. The orientation of this cross section is defined by the angular coordinates θ and ϕ . It is assumed for example that the source gives rise to four distinct spectral regions in this specific space. These four regions are denoted by A, B, C and D. The circles about these regions in Fig. 2 indicate

constant-power contours where the power decreases with distance from the center. (The contours should be thought of as extending with decreasing significance throughout the $(k_{\theta\phi}, \omega)$ plane.)

The locus of the acoustic spectrum corresponding to this cross section of the spectrum constitutes a straight line through the origin. From the above argument it is clear that the spectral components associated with A, B and C propagate signals in the fluid that decay as the distance from the source in the direction (θ, ϕ) is increased. The disturbance due to A in this case decays more than that due to B. On the other hand, a fraction of the spectral components in D generates signals that propagate without attenuation to the far field. Other spectral components in D attenuate relatively slightly as they traverse the fluid medium.

The spectral components in D are called "propagating waves," and those in A, B and C are called "non-propagating waves." The latter waves register signals in the near and intermediate fields which are dependent on the degree of mismatch that they possess with respect to an acoustic wave. Thus, for example, some of the spectral components in D induce far-field radiation; other components propagate not quite so efficiently, and are somewhat attenuated with distance. Assume that spectral components associated with B and C propagate as far as the intermediate field, and of course spectral components associated with D transverse the intermediate field on their way to the far-field. Thus, the intermediate field is made up of spectral components associated with the source spectral components belonging to B, C and D. Finally, the near field consists of spectral components associated with the source spectral components in A, B, C and D. Because of differing

attenuations and speeds of propagation, there is no close resemblance between the spectrum of the source and the acoustic near and intermediate fields that it generates. Moreover, the spectral contents in the acoustic near and intermediate fields are a strong function of distance from the source. There is, however, some resemblance between the spectral components in the far field and the spectral components of that part of the source denoted by D.

Fig. 2 pertains to the radiation field associated with a "single field point" in the source, the point (y,t) . In order to determine the signal to be expected from an extensive source at a given point in the field of observation, the signals arriving at this point from the various points in the source field must be added, taking proper account of their magnitudes and phases. (The magnitudes allow for attenuation, and the phases allow for the various different times involved in the propagation of the signals to the point of observation.) It is not difficult to visualize that, in general, the signal so obtained at a given point of observation will be highly complex. Moreover, the correlations between different points in the observation field do not generally reproduce the source correlation. Furthermore, if the point of observation is chosen in the far-field, the signals received there are generated only by a very small fraction of the total spectral components in the source. This fraction is not likely to reflect the spectral content of the source (e.g. in Fig. 2 the spectral components in D alone hardly represent the spectral content of the source consisting of regions A B C and C.)

There exist, however, important cases where the above conclusions do not apply. In these cases there is a close correlation between the spectral components in the source

and the spectral components of the signal at a point of observation. Furthermore, the correlations in the radiating spectral components of the source are somewhat reproduced in the field of observation. This report is primarily concerned with these special cases. In order to clarify the conditions that must be satisfied to produce such exceptional cases, a specific example, that of the vibrating infinite plate, is considered.

C. Radiation from a Vibrating Plate

Assume a single-frequency traveling wave in a plate propagating in the positive y -direction, as indicated in Fig. 3. In this two-dimensional problem the correlation at any point x is essentially the same as the vibratory field itself, requiring only a single spectral component to specify it. If the phase speed a_p of the traveling wave is less than the speed of sound in the fluid medium, matching cannot be effected between the traveling wave on the plate and a propagating wave in the fluid. In this case, the spectral components on the plate, viewed at all angles, lie below the locus of the acoustic spectral components, thus giving rise to near-field signals only. When the phase speed a_p exceeds the speed of sound in the fluid, matching can be effected. This matching occurs at a particular angle θ as illustrated in Fig. 3b. At smaller angles the spectral component lies above the acoustic locus line as shown in Fig. 3c. At larger angles the spectral component lies below the acoustic locus line, as shown in Fig. 3a.

It is clear then that if one observes the acoustic field at a somewhat distant point, so that hk [see Fig 3.] exceeds unity, the acoustic signal is highly directional and arrives at this field point from essentially a single point on the

plate; no interference of waves occurs at this field point due to signals arriving from many points on the plate. Moreover, the correlation in the acoustic field along a plane parallel to the plate and at a height h above the plate is essentially a replica of the correlation of the vibrational motion on the plate. Thus there exists essentially one-to-one correspondence between the field on the plate and on this plane in the acoustic field.

The directionality of the acoustic waves can also be deciphered by correlation measurements. In the proper direction defined by θ in Fig. 3, the spatial and temporal variables are related by $x_1 - x_2 = a_0(t_1 - t_2)$ where x_1 and x_2 are two acoustic field positions and $t_1 - t_2$ is the time delay between the times of measurement at x_1 and x_2 , respectively, for maximum correlation. Measurements along a line not defined by θ will yield poor correlations.

D. Radiation from a Supersonic Jet

Although the example of the vibrating plate is rather an idealized case, there are many similarities between the features of the radiative field in that case and in the case of supersonic jet flow. In examining the case of the jet, it is convenient to ignore the effects of the finiteness of the flow boundaries on the spectral contents of the source. This assumption may be partially justified if the observation points are chosen so that the contribution from regions close to a boundary form a minor portion of the signal. The additional assumption is made that the flow is confined to a cylindrical shape, as indicated in Fig. 4. Finally, it is assumed that the flow has essentially a single convective velocity U_c in the positive y -direction. Because of the symmetry of the flow, it is sufficient to denote the acoustic field by a single angle θ , as is indicated in Fig. 4.

A typical spectral cross sectional plot of a given point in the source field on the (k, ω) -space is the lower half of Fig. 4.^{1/} The majority of the power is at A. Under the condition illustrated in Fig. 4, it is seen that only the very low wavenumbers of the source spectral components will radiate to the far-field in the θ direction. Most of the spectral components in the source generate a near field only. If U_c is smaller than a_0 (a_0 is the speed of sound in the acoustic medium in which the jet is immersed), then no direction can be found for which the concentrated power of the spectral components (e.g. in region A) can radiate to the far-field. This is analogous to the situation of radiation from Region A in Fig. 2. The acoustic field at any location distant from the source will bear little resemblance to the source. Moreover, the efficiency with which the source radiates to the far-field is rather low. Most of the acoustic disturbance is confined close to the source, in the near field. This near field also bears little resemblance to the source, even at short distances away from the source point.

The picture changes radically when U_c is allowed to exceed the speed of sound ($U_c/a_0 > 1$), for now there exists a direction θ such that the concentrated power of the spectral components can be made to match an acoustic radiation condition, as illustrated in Fig. 5. The issuing radiation in this case is termed "Mach Waves", and the direction θ is the "Mach Angle". The analogy between this situation and the situation in the infinite plate (Fig. 3) is apparent.

Of course, in this practical case some contamination of the acoustic field is caused by signals generated by small-wavenumber components which are usually present in the source. Also, unlike the case in the infinite plate, not all the

spectral components in the source bear a simple relationship to the spectral components in a single cross sectional plane of the (k, ω) -space, although it appears reasonable that some close relationship may exist.

Thus, on a cylinder in the acoustic field concentric with the flow cylinder but having a larger radius, the acoustic field should bear close resemblance to some of the spectral components of the source in the sense that correlation measurements on the cylinder in the acoustic field should duplicate to some degree the corresponding correlations in the source. The signals due to the spectral components in the source belonging to different locations in the source should not interfere in the acoustic field to a significant degree. (As in the example of the vibrating plate, the signals from different locations in the source are highly directional and their directions are essentially the same, thus avoiding the possibility of substantial interference effects.)

The directionality of the field can be determined in a manner analogous to the situation of the plate. This measurement furnishes the value of θ , and hence of U_c .

The source system has been idealized by assuming that the flow of jets possesses a single convective velocity U_c . In practice, the flow possesses a narrow but finite spectrum of velocities. The effect of this finite spectrum of convective velocities will tend to smear the directionality of the acoustic signal emanating from a given position in the source. This can be deduced as follows: Consider the spectral components at a given position in the source and belonging to a given convective velocity U_{ci} . These spectral components, if $U_{ci} > a_0$, will generate acoustic signals predominantly in a

direction given by $\cos \theta_1 = a_o/U_{ci}$. Thus if several convective velocities exist simultaneously a spread, $\delta\theta_1$ in angle, and hence in directionality, will result. The effect of a loss in directionality is to cause interference in the acoustic field and thus destroy the correlation between the supersonic source and the acoustic field that it generates. However, provided the spectrum in the convective velocities is narrow enough, and provided that one takes measurements close enough to the source, the interference does not develop enough to cause considerable mixing of signals arriving at a given location in the acoustic field from different locations in the source. This is illustrated in Fig. 6. In this way a fair resemblance will still exist between this acoustic field and the appropriate spectral components in the source. Effects associated with the gradual decrease in the mean convective velocities downstream are discussed in Section V.

One further point of practical importance is that related to radiation from the downstream portion of the exhaust flow (i.e., beyond about 10 diameters downstream of the jet exit). This flow is subsonic even if the exit velocity is supersonic. The volume occupied by the subsonic portion of the flow may be considerably larger than that occupied by the supersonic portion. Since the radiation from the subsonic portion is not highly directional, signals from it will interfere with the supersonic signals at a given location in the acoustic field. Although the radiation efficiency of subsonic flow is low compared with that of the supersonic flow, its larger volume may compensate for this low efficiency. This argument, if carried out to its conclusion, would support the fact that measurements in the acoustic field, to infer correlations in the supersonic flow, should be carried out close to the supersonic portion of the flow.

In conclusion then it appears that, if measurements of the acoustic field are carried out in the "near field" of a supersonic jet exhaust flow, the sound so measured will contain information regarding the properties of the flow. The conditions that must be met in order to make such measurements feasible are as follows: The flow must be supersonic in the sense that the convective velocities of the radiation-producing elements in the flow (the eddies) are greater than the speed of sound in the fluid medium in which the flow is immersed. The spectrum of these convective velocities must be narrow.

It should be stressed again that this discussion does not constitute a theory. At present it is in the nature of a feasibility argument. Considerably more thought and work on this line of approach is needed to construct a working theory. The functions describing the behavior of the source require more precise definitions, and the effects of boundaries on the spectral contents of a source point must be determined with some detail. The attenuation of the non-propagating signals should be ascertained more precisely so that the optimum locations for measurements can be established. The relationships that exist between the spectral components in the source and that fraction of them that lie in a given cross sectional plane of the $(\underline{k}, \omega)$ -space should be determined with some care. Finally, a reasonable theory to take account of the gradual decrease in the mean convective velocities as the distance downstream is increased must be developed.

IV. THE EXPERIMENTAL PROGRAM

A. Experimental Facility and Instrumentation

In order to investigate the suppositions outlined in Section III an experimental program was performed at the model jet noise research facility at NASA/LaRC. This facility includes a small air jet which is capable of continuous operation within a large anechoic space. The properties of this jet for the experiments reported here were:

Jet exit diameter:	2.54 cm (1 in.)
Jet fluid:	air
Jet Temperature:	varied from ambient to 640°C
Stilling-chamber pressure (gauge):	$3.17 \times 10^5 \text{ kg/m}^2$ (450 psig)
Jet exit Mach No.:	1.7 approx.

The nozzle design was optimized for the particular pressure ratio investigated, so that no shock patterns were created in the region immediately downstream of the jet exit. Shadowgraphs were taken to verify the nozzle design, and to investigate visually the radiation of Mach waves from the supersonic portion of the jet.

Acoustic data were acquired in the vicinity of the jet exit with pairs of phase-matched 1/4 inch diameter condenser microphones (Bruel and Kjaer Type 4135).^{*} These data were amplified by phase-matched signal-conditioning equipment and direct-recorded with an Ampex FR-600 magnetic tape recorder.

^{*}Because of the necessity for correlation analyses, phase matching was essential. Achieving and maintaining this phase matching throughout the system was a significant portion of the experimental effort.

Numerous tests were performed at the outset of the experimental program to verify the phase-matching of the data acquisition system, to maximize the system signal-to-noise ratio (and to minimize inter-channel cross talk), and to record on the data tapes artificial signals which would enable adjustment of the processing system for optimum "end-to-end" response. These tests were repeated from time to time during subsequent experimentation in order to verify consistency of system performance.

All data recordings were processed by BBN with analog spectrum analysis equipment and an analog cross-correlator.^{2/} The data tapes were reproduced at 1/4 speed in order to stay within the bandwidth capabilities of the processing system.

Adjustments were made in the phase and amplitude response characteristics of the processing system to partially compensate for the characteristics of other portions of the entire system. This included equalization of those system phase shifts which were a non-linear function of frequency. (Phase shifts which were a linear function of frequency were corrected by a shift in the time delay scale of the cross correlations. This correction was approximately 1.5 microseconds.) The end-to-end system response obtained is illustrated on Fig. 7. The recording system response (the lower solid curve) was down about 10 db at 35,000 cps, due to microphone sensitivity and cable losses. This was compensated during processing to yield an effective flat response (± 3 db) to 40,000 cps. The phase response, to the extent that it would influence cross-correlation analyses, was compensated to at least 50,000 cps. This is indicated on Fig. 7 by the agreement of the "system response" curve (marked with small rectangles) with the responses of "Channel A" and "Channel B".

In some cases, cross correlation results were computed not only with broad-band data, but also with the same data filtered into two spectral regions above and below 20 kc. Phase-matched pairs of high-pass and low-pass filters were used for this purpose.

B. Measurement Configurations

Three separate measurement programs were conducted at NASA/LaRC. One of these was over the period 16-19 February 1965 and involved observations of a jet operating at ambient temperature. The other two occurred in the period 17-26 May 1965. These latter involved first an extensive series of measurements during 17-20 May with a loudspeaker sound source in order to investigate scattering by microphones and the effects of microphone grids as possible sources of experimental artifacts. Secondly, the program concluded during 20-26 May with a set of jet noise measurements at various jet temperatures.

The measurement points at which observations were taken on 16-19 February are illustrated on Fig. 8. Each observation point is identified with a number from one to 29. These measurement points were selected to satisfy four objectives:

1. Positions 1 through 7 were on a line parallel to and two inches away from the jet exhaust axis. Measurements taken at these positions were time-correlated in order to examine the propagation and decay characteristics of the eddy-produced Mach waves.
2. Measurement positions 23 through 28 were taken along a line inclined at 8° from the vertical jet axis. Along with data from positions 1 through 7, these data contributed to a description of the "very near field" jet noise spectra.

3. Measurements at positions 15 through 22 were taken at $22\frac{1}{2}^{\circ}$ angular increments from the jet axis in one quadrant of the jet noise field. Observations were made at radii of 10 and 20 inches from the center of the jet exit plane. Along with data from positions 7 and 21, these measurements are useful for describing the near field directivity characteristics of the jet.
4. Measurements were taken at position 29, 55° from the jet axis and 8 inches from the center of the jet exit plane, in order to examine the effect of microphone orientation (directivity) on the apparent noise spectrum. (See Fig. A-5)

The tests conducted on 17-20 May with a loudspeaker sound source had the following objectives:

- a. To determine whether or not a presumed "microphone scattering" effect was responsible for unexpected correlation values observed during the previous jet noise study.
- b. To determine whether or not this difficulty could be corrected through the use of a microphone baffle.
- c. To investigate the effects of microphone protective grids on the data.

The experimental configuration simulated that for pos. 1 - 7 on Fig. 8. All experiments were performed at twice the normal scale. That is, $\frac{1}{2}$ inch diameter microphones were used rather than $\frac{1}{4}$ inch diameter microphones, and acoustic frequencies were scaled down by a factor of two. This had the advantages of relaxing dimensional tolerances and of easing the requirement for loudspeaker high-frequency response.

A conventional loudspeaker driver (without a horn) was used as a sound source. This driver was located approximately 24 inches away from a point $1/2$ inch below the centerline of the uppermost microphone (Pos. 7). Octave bands of noise centered at 12.5 kc and 25 kc, and $1/3$ octave bands of noise centered at 16 kc were radiated from the loudspeaker. Sound incidence upon the array of two microphones was normal, 40° from normal, and essentially grazing.

A plywood microphone baffle was constructed with holes drilled so that microphones could be mounted with their diaphragms essentially flush with the baffle surface. The tests mentioned above were repeated with the baffle.

All data were recorded so that subsequent processing could uncover any possible microphone interaction effects, as well as establish the effect of the baffle.

The jet noise observations of 20-26 May were similar to those of 16-19 February, except that:

1. The jet was operated at ambient temperature, at 370°C (700°F), and at 640°C (1200°F).
2. The microphones at positions where spatial correlations were desired were mounted in a baffle. These "baffled-microphone" positions are indicated as pos. 1-14 on Fig. 9.

The measurement locations on Fig. 9 which correspond directly with those of Fig. 8 have the same position number.

C. Experimental Data

In general, the spectra of all jet noise data were established in one-third octave bands, reduced to spectrum level, and corrected for system response. In addition, the data acquired at pos. 1 through 14 were autocorrelated. The data from pos. 2 through 7 were then cross-correlated with respect to pos. 1, and the data from pos. 9 through 14 were cross-correlated with respect to pos. 7.

The experimental jet noise data are contained in Appendix A. All of the spectral data are included as figures (designated by the letter A), and all of the correlation data are tabulated in Table T-1. Approximately half of the correlation data are also included as figures. The remainder of the correlation data are quite similar to those illustrated, and the actual curves have been omitted for brevity. Autocorrelation functions (which were determined for convenience in normalizing the cross-correlation functions) are not reported, for they duplicate the information contained in the power spectra.

The figures and/or tables in Appendix A containing a particular jet noise data item can be located by reference to Table I. For instance, curves and tabulations containing data acquired at measurement position 7 are listed in the row starting on the left with the number 7. Similarly, all broad-band cross-correlation data acquired at 640°C with baffled microphones are contained in figures and tables listed in the column headed with this designation. In some cases, two illustrations are required to present a single cross-correlation function extending out to both positive and negative time delays. The two parts of such illustrations are identified as a and b.

Table I

Key to Jet Noise Data in Appendix A.

Measurement Positions	Spectra				Broad-Band Cross-Correlations						Cross Correlations of Data			
	27°C		370°C		With Respect to Pos.	27°C		370°C	640°C	below 20 kc		above 20 kc		
	Baffled	Unbaffled	Baffled	Unbaffled		Baffled	Unbaffled							
1	A-6	A-1	A-7	A-8	1	A-12, T-1	A-18, T-1	A-24, T-1	A-30, T-1	T-1	T-1	T-1	T-1	
2	A-6	A-1	A-7	A-8	1	A-13, T-1	A-19, T-1	A-25, T-1	A-31, T-1	T-1	T-1	T-1	T-1	
3	A-6	A-1	A-7	A-8	1	A-14, T-1	A-20a, b, T-1	A-26a, b, T-1	A-32a, b, T-1	T-1	T-1	T-1	T-1	
4	A-6	A-1	A-7	A-8	1	A-15, T-1	A-21a, b, T-1	A-27a, b, T-1	A-33, T-1	T-1	T-1	T-1	T-1	
6	A-6	A-1	A-7	A-8	1	A-16, T-1	A-22a, b, T-1	A-28, T-1	*	T-1	T-1	T-1	T-1	
7	A-6	A-1, A-2	A-7	A-8	1	A-17, T-1	A-23a, b, T-1	A-29, T-1	*	T-1	T-1	T-1	T-1	
8	A-9				8	-	-	-	-	-				
9	A-9				8		*	*	*					
10	A-9				8		*	*	*					
11	A-9				8		*	*	*					
12	A-9				8		*	*	*					
13	A-9				8		*	*	*					
14	A-9				8		*	*	*					
15	A-9				8		*	*	*					
16		A-2	A-10	A-10										
17		A-2	A-10	A-10										
18		A-2	A-10	A-10										
19		A-3	A-11	A-11										
20		A-3	A-11	A-11										
21		A-3	A-11	A-11										
22		A-3	A-11	A-11										
23		A-4	A-4	A-4										
24		A-4	A-4	A-4										
25		A-4	A-4	A-4										
26		A-4	A-3, A-4	A-4										
27		A-4	A-4	A-4										
28		A-4	A-4	A-4										
29		A-5	A-5	A-5										

NOTES: 1. A blank space indicates either that no data were acquired, or that the data were not processed in that mode.
2. Figures are identified by the letter "A", as in Fig. "A-3".
Tables are identified by the letter "T" as in Table "T-2".
3. An asterisk (*) indicates that the data were processed, but are not considered significant.

- NOTES: 1. A blank space indicates either that no data were acquired, or that the data were not processed in that mode.
2. Figures are identified by the letter "A", as in Fig. "A-3". Tables are identified by the letter "T" as in Table "T-2".
3. An asterisk (*) indicates that the data were processed, but are not considered significant.

The results of the tests performed with a loudspeaker noise source and microphone baffles are summarized in Tables T-2 and T-3 in Appendix A.

D. Comments on the Experimental Data

The spectra observed at ambient temperature and without a microphone baffle at positions 1 through 7 are plotted on Fig. A-1. There is a gradual rise in spectrum level (very roughly 5 dB to the inch) as the observation position is moved away from the jet exit and parallel to the jet axis. Close to the jet exit, the typical spectrum shape increases about 3 dB per octave to a strong peak in the vicinity of 30-40 kilocycles. Further away from the jet exit (e.g. position 7), a more typical jet noise spectrum is observed, although the high frequency peak is still in evidence.

In the region from 2 to 3 kilocycles close to the jet exit, an anomaly is evident in the spectra on Fig. A-1. It is assumed that this was due to reflections from the assembly used to mount the microphones.

Spectra observed at these same positions with baffled microphones are markedly different (Fig. A-6). Above 10,000 cps, the 40 kc peak previously observed is no longer in evidence. Below 10,000 cps, the presence of the baffle increases the levels 3 - 4 dB above those observed without a baffle.

In general, as the jet temperature is increased (Figs. A-7 and A-8), the acoustic levels at pos. 1 through 7 also increase. There is a marked increase in noise level (particularly at high frequencies) as the temperature is

increased from ambient to 370°C (Fig. A-7). A smaller increase is noted as the jet temperature is further elevated to 640°C. An exception occurs at pos. 7, where the noise level decreases as the temperature is increased from 370°C to 640°C.

Observations were made at pos. 23 through 28 only with an ambient temperature jet and unbaffled microphones. (Fig. A-4) When these data are compared to those in Fig. A-1, it is evident that the spectral transition to a lower-frequency peak observed on Fig. A-1 continues for measurement positions further removed from the jet exit. However, the spectrum level in the region from 1000 to 10,000 cps apparently maximizes in the vicinity of measurement position 7, for the levels on Fig. A-4 are all lower than those illustrated on Fig. A-1 for position 7.

The spectra observed over one quadrant of the jet noise field are illustrated for the 10 inch radius on Figs. A-2 and A-10, and for the 20 inch radius on Figs. A-3 and A-11. In general, the noise levels are highest close to the jet axis, and lowest at 90° from the jet axis. Furthermore, the noise levels are generally (but not always) lower on the 20 inch radius than on the 10 inch radius. The difference is never as much as 6 dB, however, indicating that the observations were all within the near field of the jet noise source.

The increase of jet temperature from ambient to 640°C has the expected effect of increasing the noise levels in the intermediate frequency range at pos. 15 through 22. The increase at position 20 is, however, somewhat greater than at the other positions.

There appears to be no significant difference among the spectra observed (with baffled microphones) at positions 8 through 14 (Fig. A-9).

In order to evaluate the effect of unbaffled-microphone orientation on the noise spectra, a microphone was mounted at position 29 and measurements were made with two different microphone orientations. One orientation was with the microphone diaphragm normal to a radius from the jet exit, and the other was at 90° to the first with the diaphragm parallel to a radius from the jet exit. The difference in these two orientations is illustrated on Fig. A-5. It is evident from the data that microphone orientation is important above 3 kilocycles. When the microphone is pointed at the jet exit, it is less sensitive to the lower frequency jet noise components, and more sensitive to the 40 kilocycle spectral peak. The difference is as much as 5 dB over the frequency range of interest.

The initial correlation results acquired at pos. 1 through 7 (Fig. A-12 through A-17) were quite disconcerting at the time. They indicated the spatial correlation characteristic identified by large solid circles in Fig. 10. (The expected characteristic would have been roughly an exponential decay with separation.) This result led to several hypotheses, one of which was that each microphone was responding to sound scattered by its partner when the two were close together. In order to test this hypothesis, the experiments mentioned previously with microphone baffles and a loudspeaker sound source were conducted. As can be seen from the curve marked with solid triangles in Fig. 10, the use of a microphone baffle to suppress scattering did not significantly improve the abnormal spatial correlation.

It now appears that this artifact was due to the reference microphone (pos. 1) being too close to the jet exit plane for the Mach angle under investigation (see Section III-A and Section V). Clearly (now!) the Mach angle would have to have been greater than 45° for any Mach waves to have arrived at position 1. This was not the case at ambient jet temperatures. This is most likely the cause of the abnormal spatial correlations observed at ambient jet temperatures parallel to the jet axis. It probably also explains why no correlations were observed along the array from pos. 8 through pos. 14.

When the jet temperature was elevated to 370°C (Figs. A-24 through A-29) the Mach angle increased sufficiently so that Mach waves could occur at pos. 1. This produced the expected correlation decay characteristic, as indicated on Fig. 10. Similar results were, of course, observed at a jet temperature of 640°C . Reprocessing of the existing data using pos. 2 or 3 as a reference point would help to verify this explanation.

An attempt was made to approximate the spectra of the propagating signals which produced the cross-correlation peaks. This could only be done in broad spectral regions above and below 20 kilocycles without encountering unwieldy phase matching problems. A typical set of results (from Figs. A-24 through A-29 and Table T-1) is illustrated on Fig. 11. These results indicate that the low-frequency signals have a slightly longer correlation length than the high frequency signals. More detailed information could be obtained by Fourier transformation of the broad-band cross-correlation functions.

The experiments conducted with a loudspeaker noise source to investigate microphone scattering (Table T-2) revealed no particular scattering difficulties. The use of baffled microphones lead to different but not significantly improved spatial correlation characteristics. Likewise, the presence or absence of microphone protective grids was found to have no effect (Table T-3).

V. THEORETICAL INTERPRETATION OF THE EXPERIMENTAL RESULTS

As the discussion in Section III indicated, the correlations in the acoustic field can lead to information concerning the correlations in the flow. These correlations are related to those spectral components of the flow that radiate Mach waves. Other spectral components are, in the ideal case, absent. Indeed, it is assumed herein that the correlations of the radiating components represent adequately the correlations of all spectral components of the flow. The reader should, nevertheless, keep in mind the distinction between the radiating waves and non-radiating waves as outlined in Section III.

The experimental data were obtained by auto- and cross-correlating the acoustic field in the direction of the flow. Invariably position 1 [see Figs. 4, 8 and 9] has been cross-correlated in turn with positions 2 through 7 downstream. Auto-correlations were taken at each field position, 1 through 7. Three sets of tests were performed with jet temperatures of ambient (27°C), 370°C , and 640°C respectively. [The term "set" is used to indicate a condition of flow at a given outlet temperature.] The exit Mach number with respect to the speed of sound in the jet at these three temperatures was in all cases about 1.7. With respect to the speed of sound in the surrounding air, the exit Mach numbers were about 1.7, 2.55 and 3.0, respectively.

The time delays that are required to establish cross-correlation maxima in the direction of the flow lead to values of the mean convective velocities in the flow. The convective velocities for baffled microphones were computed from the data in Table T-II using this method. The results are summarized

in Table II in terms of the convective Mach numbers M_c .
 [Hereafter, all Mach numbers are with respect to the speed of sound a_0 in the surrounding air.]

Table II
 Convective Mach Numbers and Mach Angles
 Computed from the Data in Table T-2,
 Appendix A

Positions	27°C		370°C		640°C	
	M_c	θ_c	M_c	θ_c	M_c	θ_c
1 - 2	1.42	45°	1.32	40°	1.47	47°
1 - 3	1.13	28°	1.56	50°	1.71	55°
1 - 4	1.19	32°	1.60	52°	1.87	58°
1 - 5	1.24	36°	1.69	54°	2.12	62°
1 - 6	1.24	36°	-		-	
1 - 7	-		-		-	

For completeness the corresponding Mach angles θ_c are included in this table as computed from $\cos \theta_c = M_c^{-1}$.

It is immediately apparent that the measured convective velocities increase as the separation between the reference position, position 1, and the other positions (2-7) increases. [This is particularly evident and consistent in the sets with

the jet temperatures 370°C and 640°C.] This effect may be explained by assuming that in a given set those eddies moving with the higher convective velocities have the longer life-times. This assumption is plotted for a hypothetical example in Fig. 12(a).

It is to be expected that the mean convective flow velocities will diminish with distance downstream. A physical process leading to such slowdown can be visualized as follows: The probability of creation of a fast-moving eddy diminishes with distance downstream. On the other hand, the probability of creation of a slower-moving eddy increases with distance downstream. This process is illustrated for a hypothetical example in Fig. 12(b).

Figs. 12(a) and (b) can now be made consistent with the results presented in Table II. Of those eddies that were present at position 1, only the faster-moving ones survive the journey as the observation point is moved downstream. Thus the cross-correlations will be more and more controlled by the faster-moving eddies as the separation between the reference position, position 1, and a downstream position is increased. In this way the increase in the measured convective Mach numbers is explained. This argument is reminiscent in some ways of the argument that explains the increase in sound speed in rarefied gases.^{3/} The explanation makes it clear that it would be erroneous to deduce from such measurements that an increase in the mean convective Mach number occurs in the flow with increased downstream distance.

An examination of the autocorrelation data (not included here) indicates that the widths of the autocorrelation functions increase but slightly with distance downstream over the first

6 to 8 in. from the jet exit. (At larger distances downstream the increase in the width becomes more pronounced.) However, as Fig. 12(b) indicates, eddies with smaller and smaller convective Mach numbers are created at greater rates as one proceeds downstream, while the rate of creation of faster-moving eddies diminishes. This suggests that the widths of the autocorrelation functions should increase with downstream distance. The observed increase in the autocorrelation are not substantial enough to correspond to changes in the convective Mach number at the shorter distances downstream.

This discrepancy can be partially resolved by assuming that a typical linear dimension of the eddies is a function of their convective Mach number, with a dependence such that their sizes decrease with a decrease in their convective Mach number. This conclusion is in apparent agreement with the findings of Willmarth and Wooldridge relating to turbulent boundary layers.^{4/} However, the measurements performed to date cannot lead to quantitative values. Further measurements with this goal in mind are required.

An additional, if indirect, indication of the increase in size of the eddies with an increase in their convective Mach number exists in the cross-correlation data. This indication is in the form of an inference. It appears that the width of the cross-correlation increases slightly as position 1 is correlated with a position further downstream. If the assumption is correct that the cross-correlation so obtained becomes more and more related to the faster-moving eddies, then the increase in cross-correlation width can be explained only by assuming that the eddy size is greater for larger convective Mach numbers. If the sizes of the eddies were independent of their convective Mach numbers, the cross-correlation width would have decreased with distance downstream of the reference position.

There is one further check on the validity of the above argument in the power spectra. It is generally accepted that the center frequency ω_m of a power spectrum associated with eddies of linear size δ and convective Mach number M_c is given by:

$$\omega_m \delta \sim a_o M_c \quad (5.1)$$

The conclusion of the preceeding paragraph is that the size of the eddy increases with its convective Mach number. Therefore it is reasonable to expect that ω_m will not change appreciably with the convective Mach number.

Furthermore, the width of the frequency spectrum $\Delta\omega$ is inversely proportional to the lifetime τ_e of an eddy:

$$\nabla \Delta \delta \quad \Delta\omega \sim \frac{1}{\tau_e} \quad (5.2)$$

Since it has been concluded that the faster eddies have somewhat longer lifetimes, their spectral width should be smaller. On this basis the spectrum can be expected to increase in width with distance downstream while its center frequency remains unchanged. This conclusion is supported by the experimental data at positions close to the exit (1 through 3 or 4); it is not supported by data acquired further downstream.

To explain the spectra downstream of pos. 3 or 4, it is necessary to assume that, although the size of an eddy may depend on its convective Mach number at supersonic speeds, the size levels off or even increases as its convective Mach number decreases below unity. An alternative measure is to

assume that eddies associated with subsonic convective Mach numbers are created of various sizes, within certain limits, that are not strongly dependent on convective Mach number.

These downstream effects could not be seen in the cross-correlations determined with position 1 as a reference, for subsonic eddies are created and exist only further downstream of this position (at least in the flows involving jet temperatures of 370°C and 640°C). Thus the effect of these subsonically convected eddies appears only well downstream, where their numbers are sufficiently large to dominate the situation.

The radiation field that these subsonically convected eddies generate is "diffused" and does not possess the clean-cut features of Mach waves. If the above picture is representative of the physical situation, the power spectra taken downstream at first broadens gradually about an approximately fixed center frequency and then, as the downstream distance of the position of observation is further increased (e.g. at positions 5, 6 and 7), the lower-frequency content of the spectrum increases substantially. This should be accompanied by an increase in the width of the autocorrelation function.

Because of the poor directionality of the radiation field produced by eddies convected subsonically, signals registered further downstream come from locations in the flow that may extend over a considerable extent of the flow. It should also be noted that the near field associated with non-propagating waves from subsonic eddies extends to larger distances in the direction normal to the axis of the flow than does the near field associated with non-propagating waves from supersonically convecting eddies. The width of the cross-correlation

function, according to this argument, should increase a little with downstream distance. This is indeed observed. The autocorrelation width should increase only slightly at short distances downstream but should increase more rapidly as the distance is increased. This is also in agreement with the observations.

Although the above arguments have shown some qualitative consistency with the experimental data, they run into trouble when quantitative examination is made. The most significant quantitative feature in variance with the above discussion is that the mean distance traveled by the eddies, before they dissipate, is found from the cross-correlation measurements to be somewhat smaller in the set of experiments taken with a jet temperature of 640°C than with a jet temperature of 370°C . As Table II shows, the convective Mach numbers in the former set were higher than in the latter set. It is difficult to visualize a situation where, with increase in the exit velocity, the lifetimes of the eddies traveling with differing convective Mach numbers decrease uniformly faster than the increase in exit velocity. One may speculate that temperature effects may account partially for these changes. Another effect that may bring about such changes is the change in the shear in the boundaries between the surrounding medium and the flow as the mean convective Mach number increases.

Some support for these contentions may be found in the power spectra. It is observed that the power spectra of the tests with jet temperatures of 370°C and 640°C are quantitatively similar. This suggests, using Eq. (5.1), that the sizes of the supersonically convected eddies for the jet temperature

of 640°C are uniformly smaller than those for the jet temperature of 370°C . If the rule that the smaller eddies possess shorter lifetimes is generalized, the data are partially accounted for. Such an argument suggests that, in a flow with a supersonic velocity of the type considered here, the transition from mean supersonic to mean subsonic flow conditions occurs at a distance downstream that is only slightly dependent on the exit velocity.

Finally, another effect that is unaccounted for and that may play an important role here is that associated with the Mach angle. If the flow field is anisotropic, its spectral components in one cross section of the (k, ω) -space may differ from those in another. Since the cross section that radiates depends on the Mach angle, which in turn depends on the convective Mach number, some differences in the correlations that depend on the Mach angle may be introduced.

This conclusion has important implications to the acoustic power radiation from supersonic rocket flow. It suggests that the volume occupied by the supersonic portion of the flow does not grow with increasing exit velocity. Thus the relative contribution from Mach waves to the total power radiated may even decrease with an increase in the exit flow velocity. However, further experimental and theoretical programs designed to study this problem in greater detail are necessary.

The remaining part of this section is devoted to a cursory examination of the reasons for the failure to obtain some of the expected experimental data, and to suggesting possible avenues for further experimental research work.

The initial experiments, those conducted with a jet temperature of 27°C , failed to show the expected characteristic for normalized cross-correlation as a function of microphone separation. In particular, the amplitudes of the cross-correlations were relatively small when the separation between position 1 and another point in the downstream direction was small. Examination of the experimental arrangement shows that the microphone at position 1 was set so that it intersected the axis of the jet at the exit at 45° . As Table II shows, Mach waves that impinged on that microphone possessed this very angle. It is doubtful that much of the strength of the Mach waves at the appropriate exit velocity had this directionality [see Table II]. Thus the microphone at position 1 in this test received only a small fraction of the generated Mach waves.

This contention appears to be supported by the measured power spectra. The power spectra for the test with a jet temperature of 27°C differ from those obtained for the tests with jet temperatures of 370°C and 640°C . This difference is substantial at small distances downstream of the reference position, position 1, specifically at positions 1 to 3. The high-frequency content in these power spectra is somewhat suppressed.

This may account, in part, for the failure to obtain reasonable correlation decay rates in the tests at 27°C jet temperature. As to the reasons for the partial recovery at larger microphone separations, it may be argued that at larger separations the surviving eddies are those that initially contributed, in some measure, to the signal at position 1 and, since they possess the higher convective Mach numbers, they are associated with the larger Mach angles.

It is interesting to note that shadowgraphs taken at an ambient jet temperature show "Mach waves" emanating almost exclusively from no farther than one or two diameters downstream of the jet exit. Essentially none of these waves can be traced to locations farther downstream. If the shadowgraphs reflect the actual Mach wave field, the cross-correlation observed at the larger separations appear to be artifacts. In this connection it is worth mentioning that shadowgraphs taken with the jet at a temperature of 370° clearly show a "Mach waves" field that is distributed as though it emanated from as far as 4 to 5 diameters downstream. This is in good qualitative agreement with the cross-correlation measurements at elevated jet temperatures.

In view of the discussions above, the following additional processing of the data now recorded seems worthwhile:

1. Cross-correlate the downstream pressure with successive downstream positions as a reference, starting with position 2. This should indicate whether the above assumptions with regard to the eddy lifetimes, sizes and creations are reasonable. Moreover, should the edge effects of the exhaust nozzle be important, they will be partially eliminated by this analysis.
2. Make a more careful analytical study of the processed data so that some quantitative test of the arguments set forth above can be made.
3. Ascertain, if possible, the center frequency and the spectral width of the frequency spectrum that is most closely related to the cross-correlation measurements.

Further experimental observations that appear worthwhile are listed below:

1. Further examine the directionality of the microphones. This is important in order to optimize the observation of Mach waves.
2. Search for the optimum distance from the jet axis at which data should be obtained. This may vary with exit velocity.
3. Take measurements along calculated Mach angles. This may help to establish a correspondence between shadowgraphs and microphone data. There is also a possibility of establishing effects that may be associated with diffraction due to the discontinuity in the speed of sound at the boundary of the flow.

REFERENCES

1. J. E. Ffowcs Williams, "The Noise from Turbulence Convected at High Speed," Phil. Trans. A, 255, 469, 1963.
2. D. N. Keast, "An Analog System for the Analysis of Random Data Signals Up to 10 KC." IRE Trans. on Instr., I-11, 52-27, 1962.
3. G. Maidanik, H. Fox and M. Heckl, "Propagation and Reflection of Sound in Rarefied Gases. I. Theoretical," Phys. Fluids 8, 259, 1965.
4. W. W. Willmarth and C. E. Wooldridge, "Measurements of the Fluctuating Pressure at the Wall Beneath a Thick Turbulent Boundary Layer," University of Michigan, Report No. 02920-1-T, ONR, Nonr. 1224(30), April 1962.

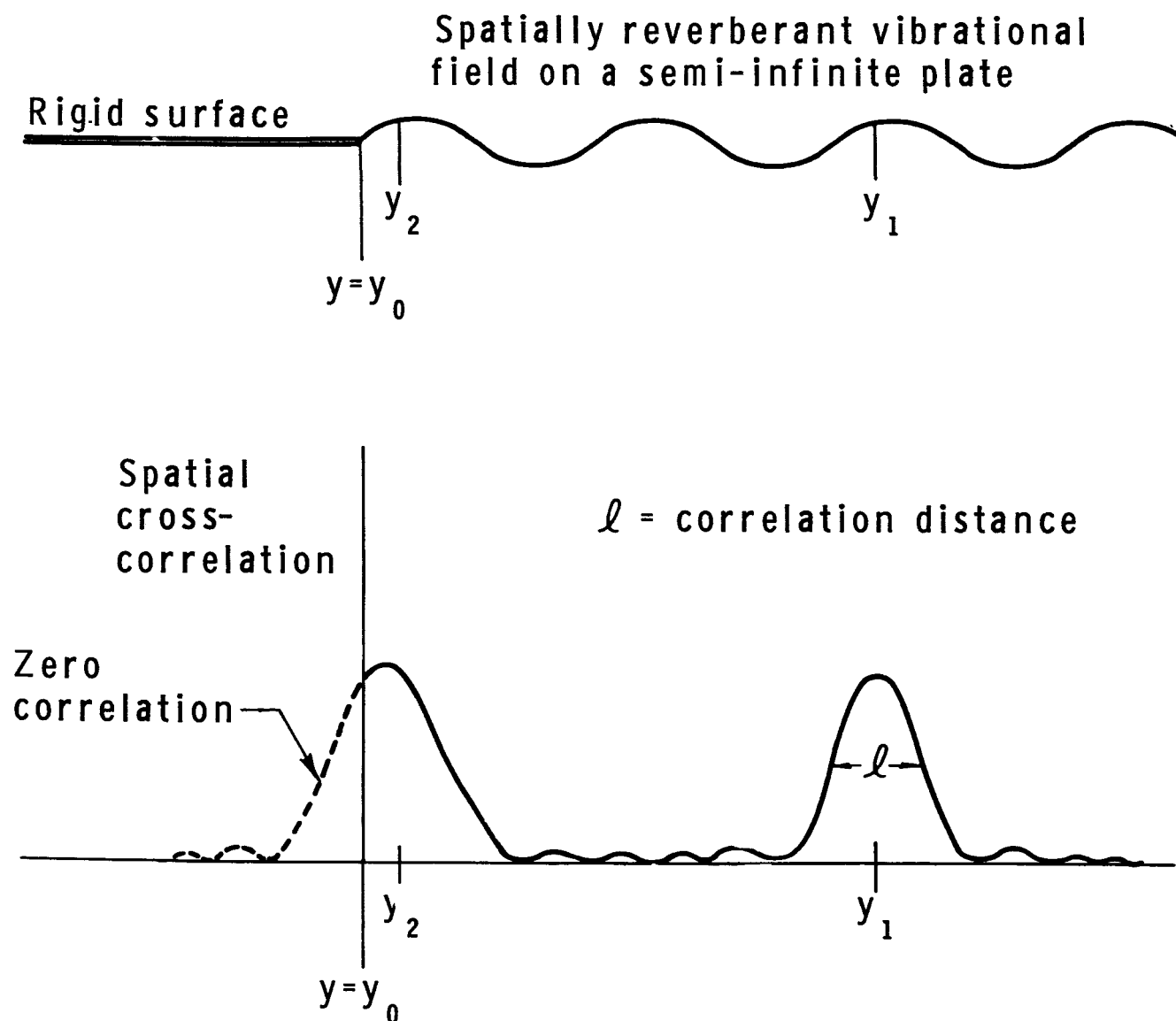


FIGURE 1.
SPATIAL CROSS-CORRELATION OF A BOUNDED DISTURBANCE

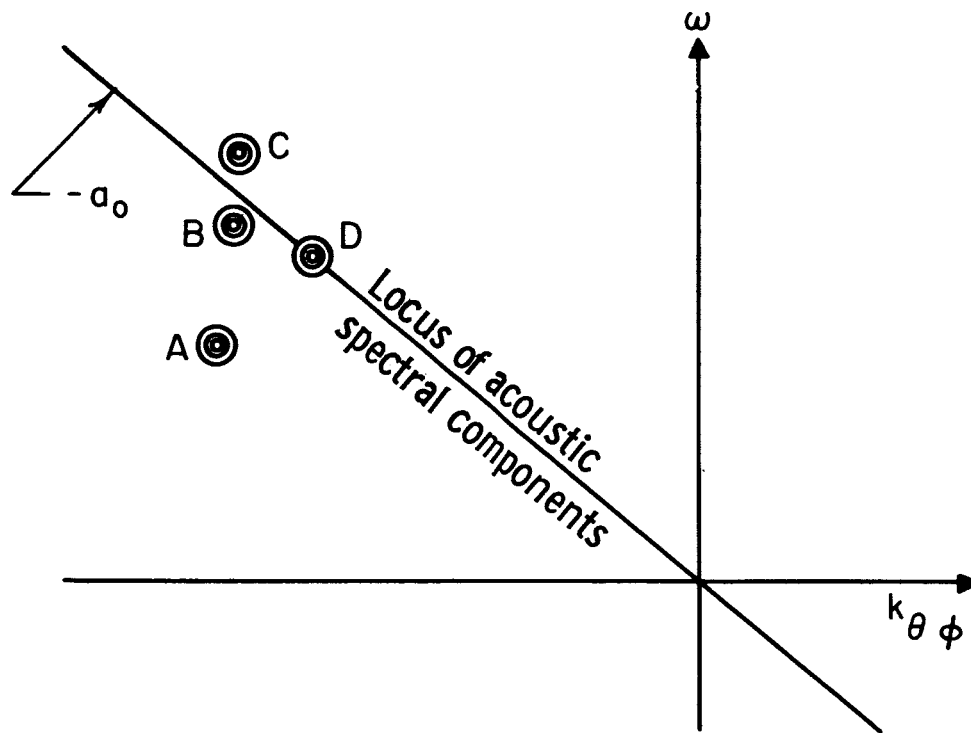


FIGURE 2.

A, B, C AND D REGIONS OF CONCENTRATED SPECTRAL COMPONENTS ASSOCIATED WITH A SINGLE POINT IN A DISTURBANCE MAPPED ON A CROSS SECTION OF THE $(\tilde{k}, \omega)$ -SPACE. THE CROSS SECTION IS DEFINED BY THE ANGULAR CO-ORDINATES θ AND ϕ .

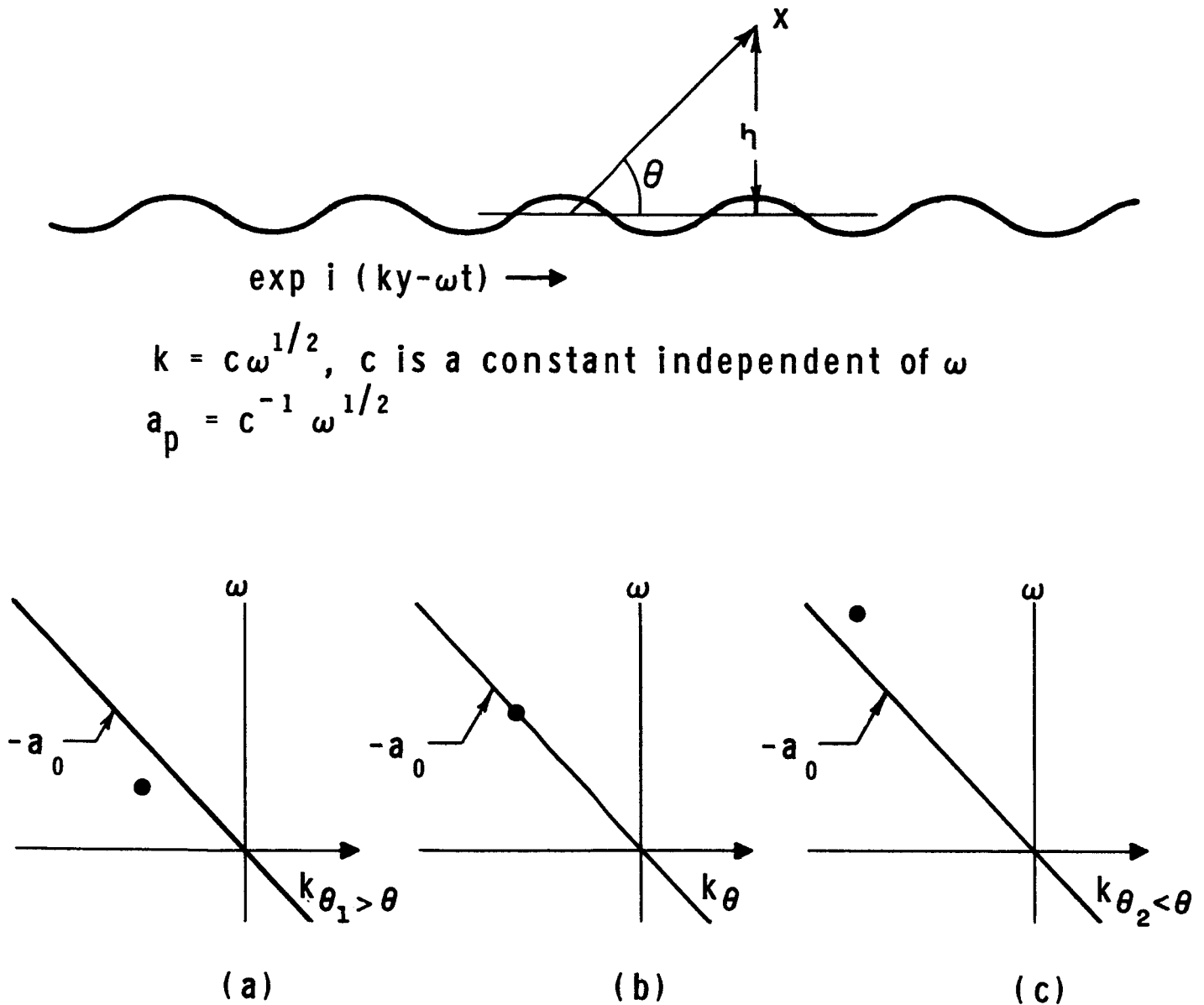


FIGURE 3.

SINGLE TRAVELING WAVE ON AN INFINITE PLATE.

FIGURES (a), (b) AND (c) PRESENT A SPECTRAL ANALYSIS ASSOCIATED WITH A SINGLE POINT IN THE DISTURBANCE PLOTTED IN THE $(\tilde{k}, \omega)$ - SPACE

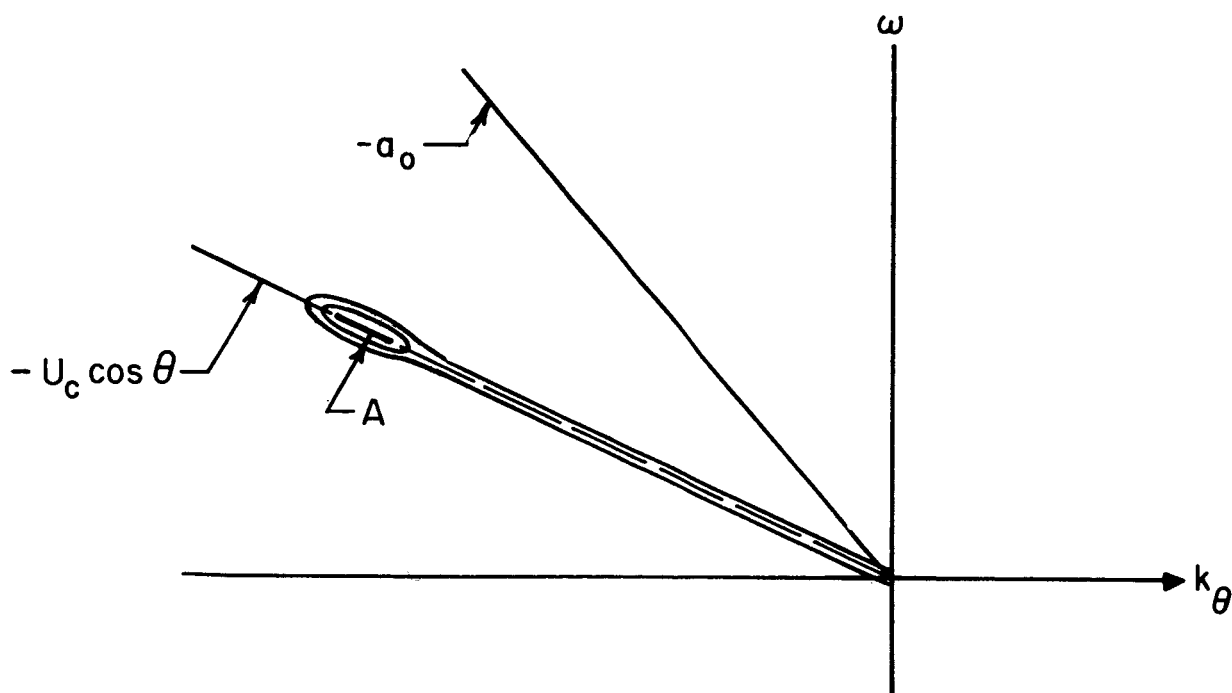
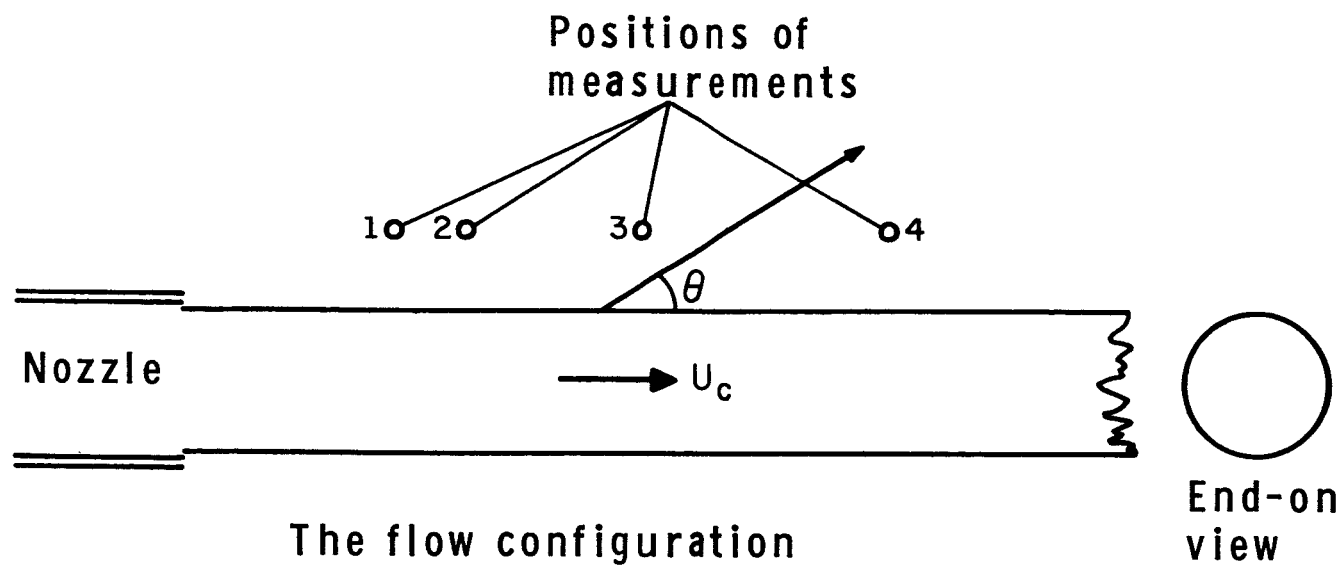


FIGURE 4.

SPECTRAL ANALYSIS OF A DISTURBANCE ASSOCIATED WITH A SINGLE POINT IN THE FLOW PLOTTED IN THE $(\underline{k}, \omega)$ - SPACE

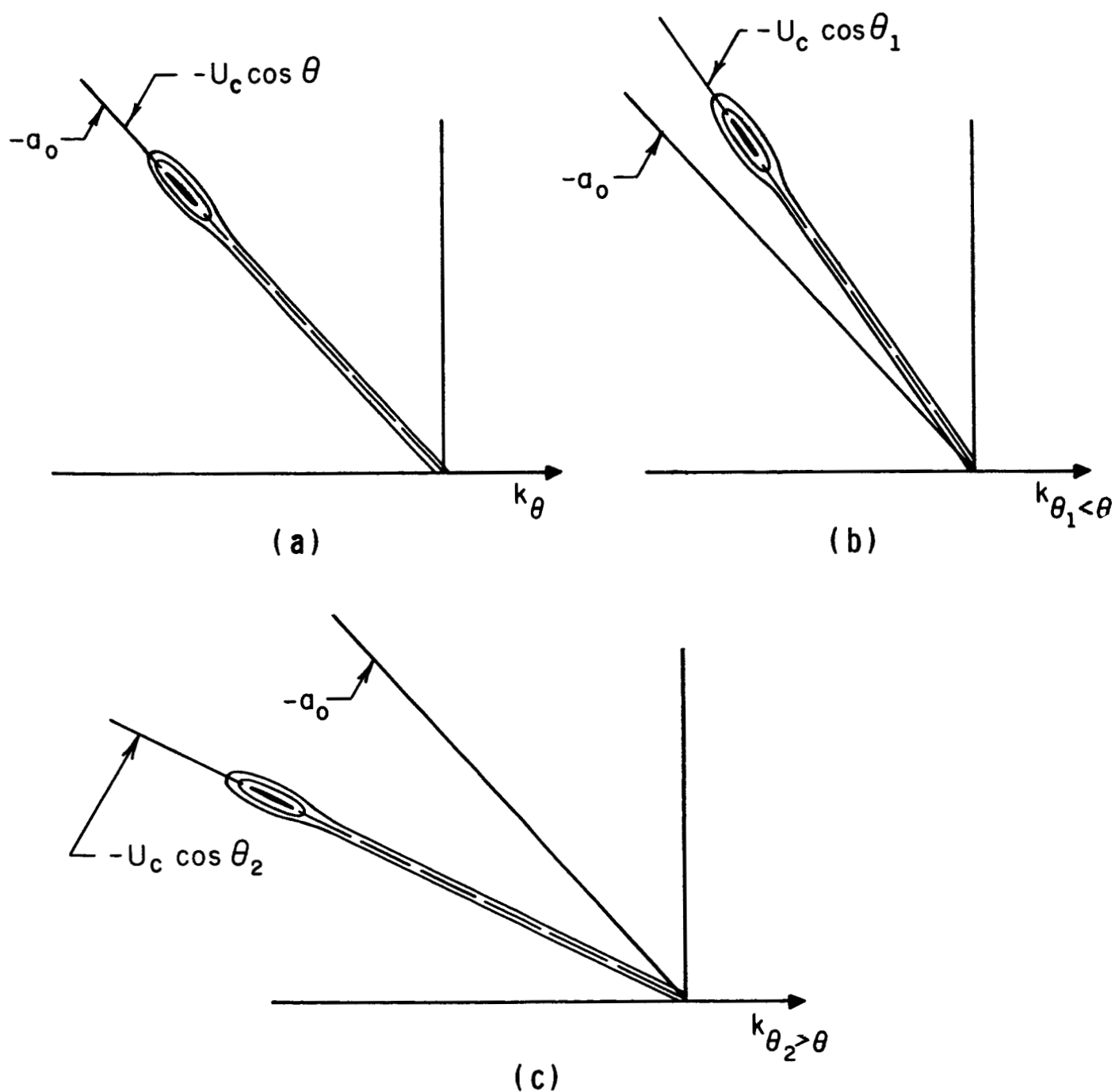


FIGURE 5.

SPECTRAL ANALYSIS OF A DISTURBANCE ASSOCIATED WITH A SINGLE POINT IN THE FLOW PLOTTED IN THE $(\underline{k}, \omega)$ -SPACE

(a) - Mach wave conditions

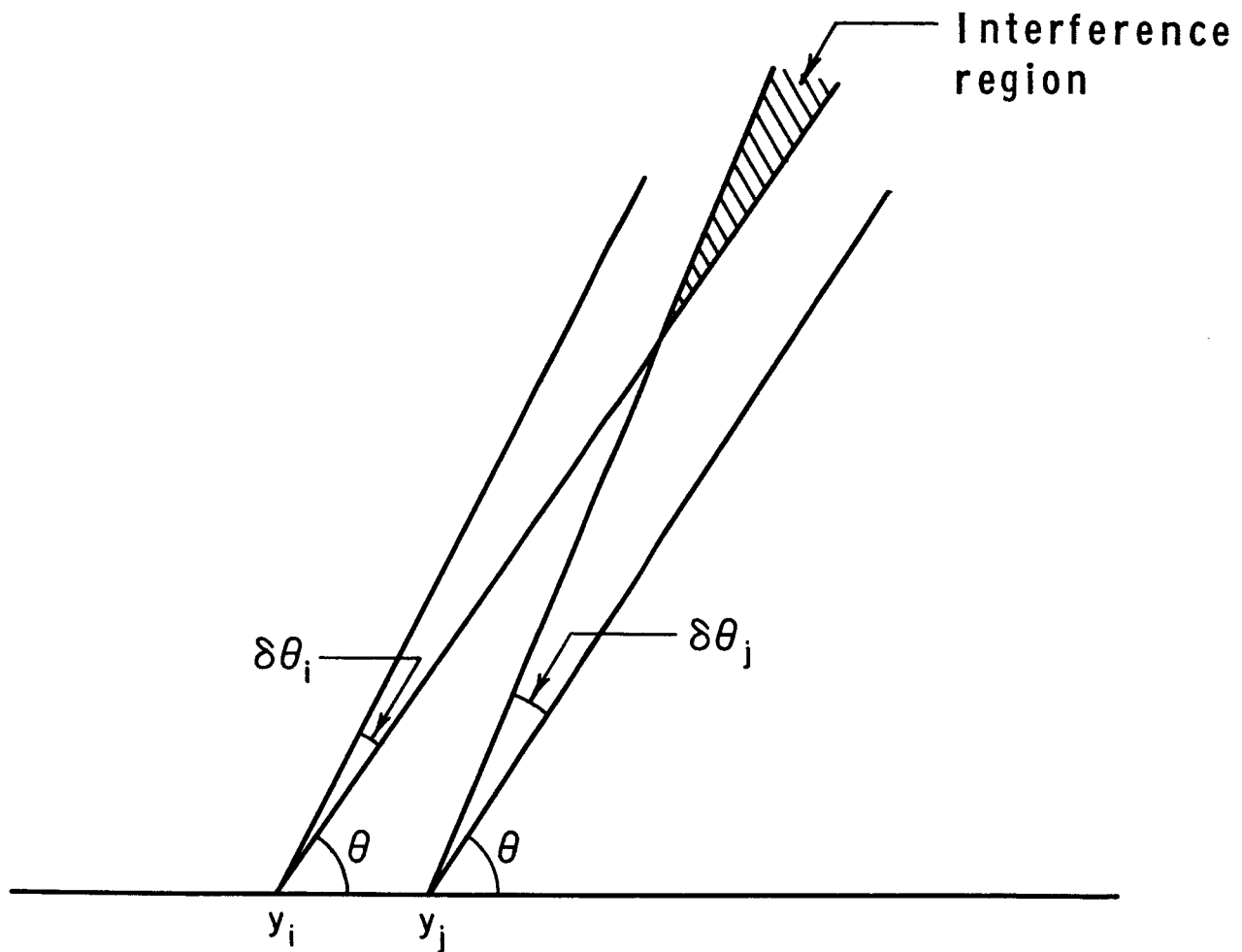
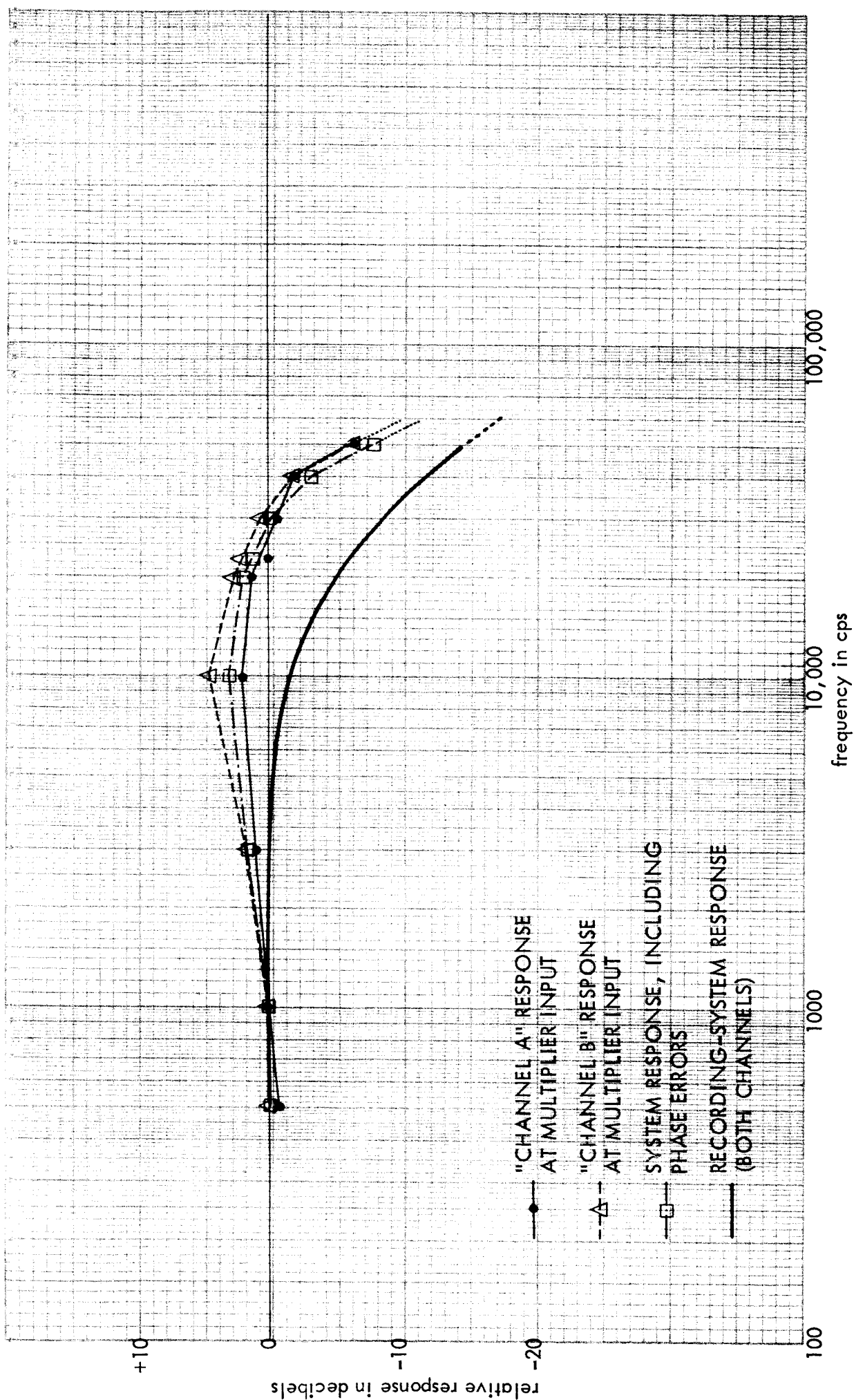


FIGURE 6.
THE EFFECTS ON THE MACH WAVES DUE TO A SPECTRAL
WIDTH IN THE CONVECTIVE VELOCITIES IN THE FLOW

FIGURE 7. MODEL JET NOISE STUDIES
Frequency Responses of Correlation System (See Text)



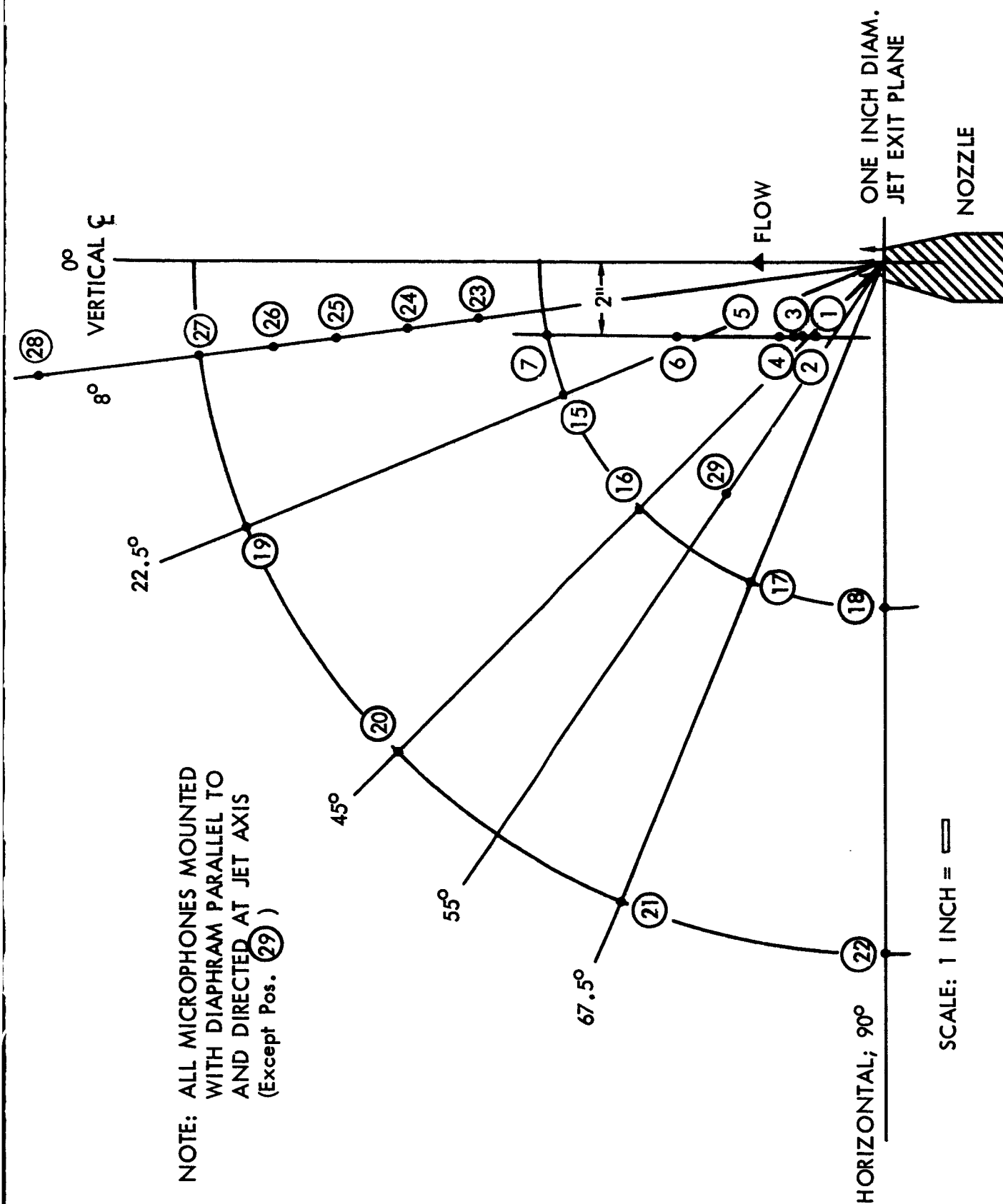


FIGURE 8. MODEL JET NOISE STUDIES
Measurement Locations: 16-19 Feb '65

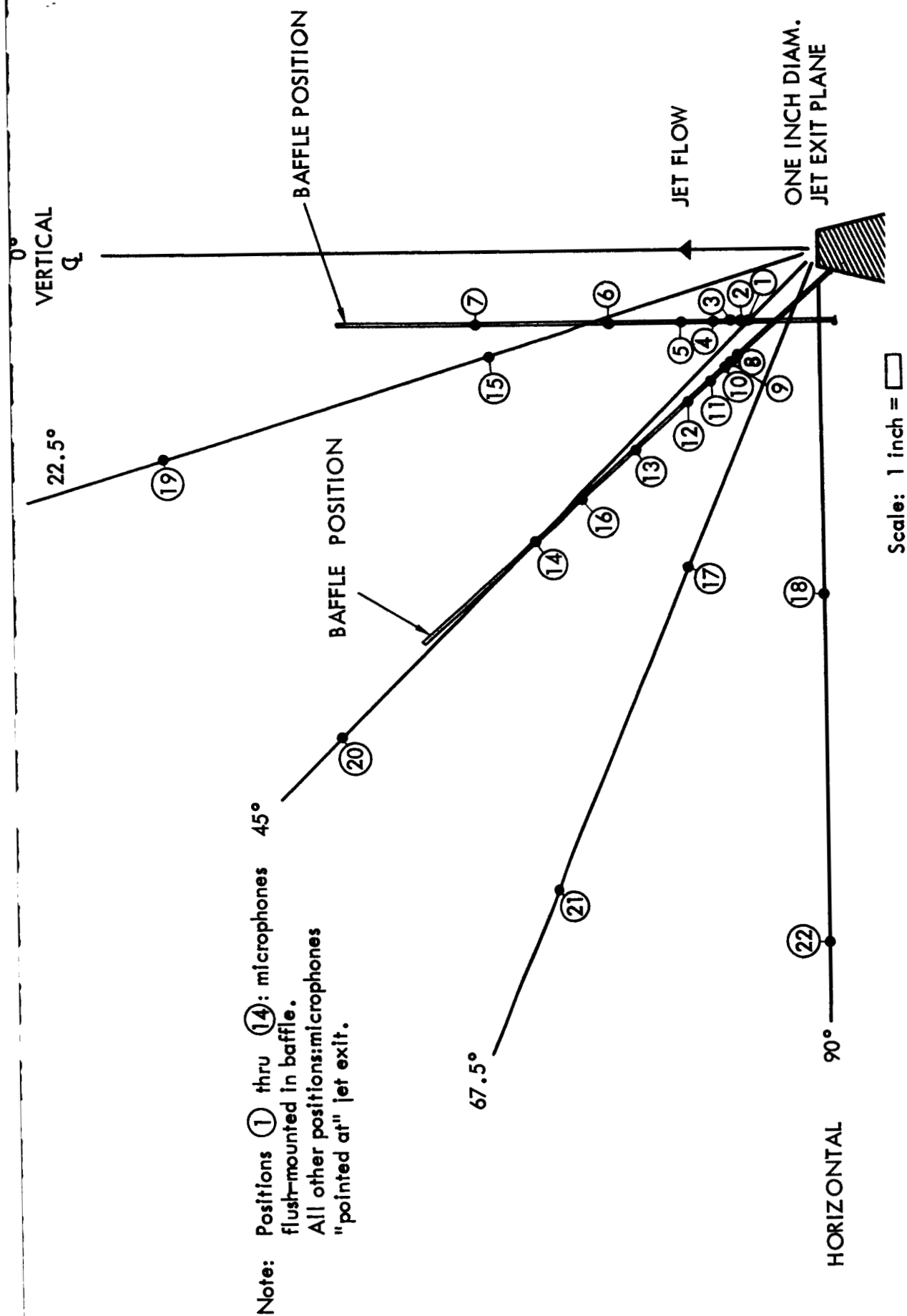
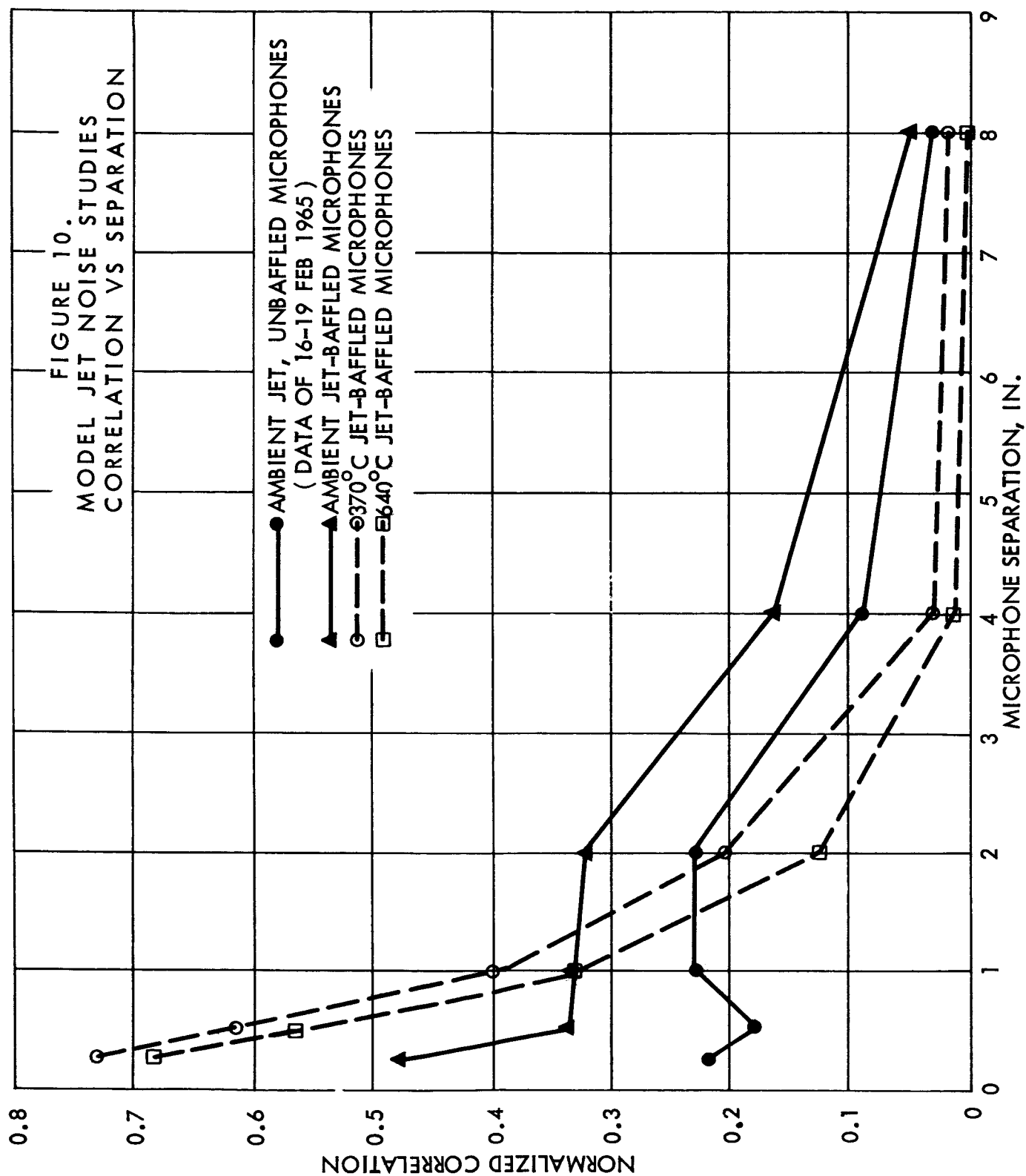
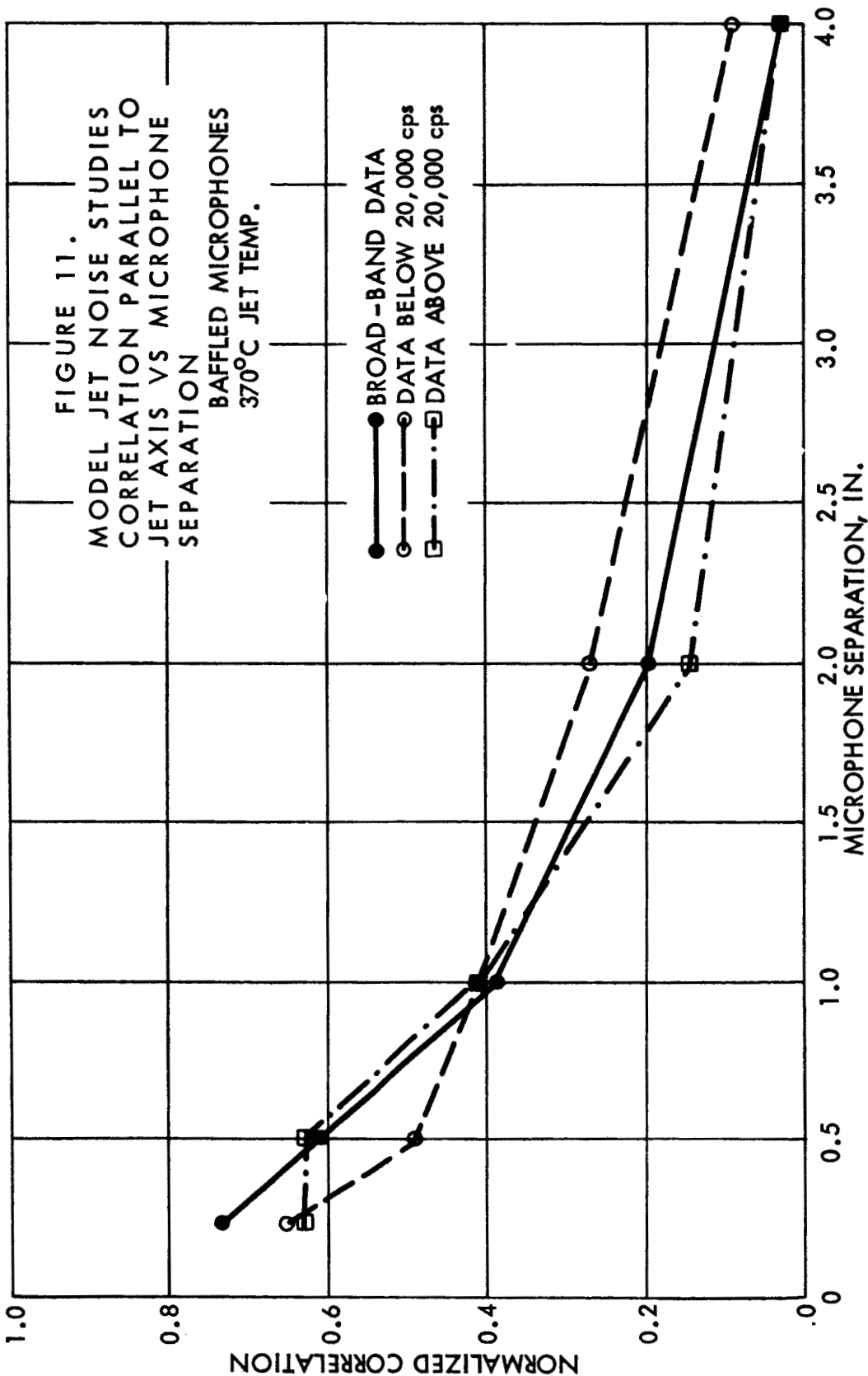
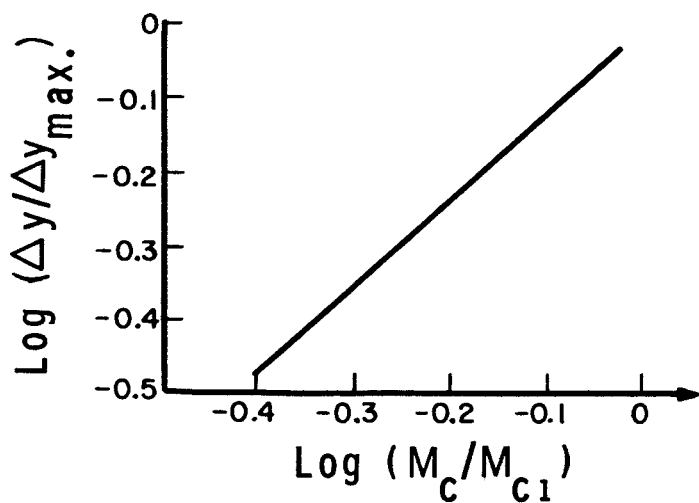


FIGURE 9. MODEL JET NOISE STUDIES
Measurement Locations: 20-26 May, 1965

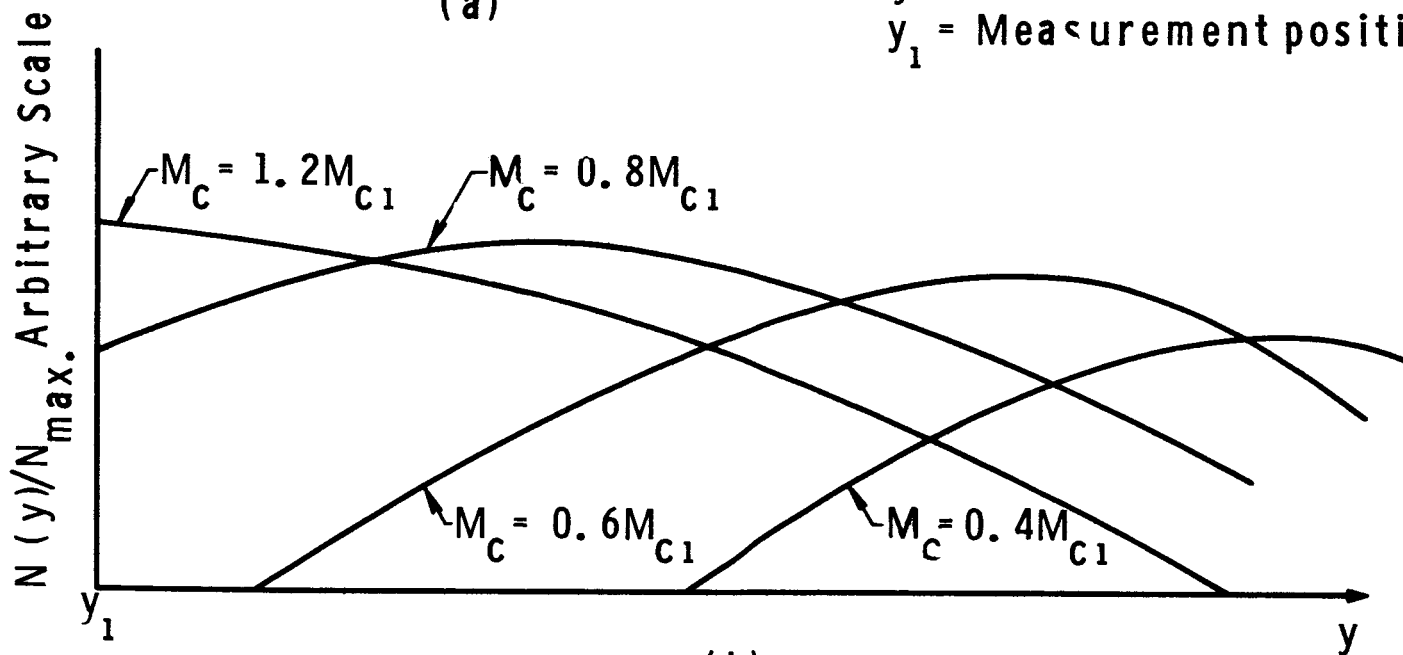




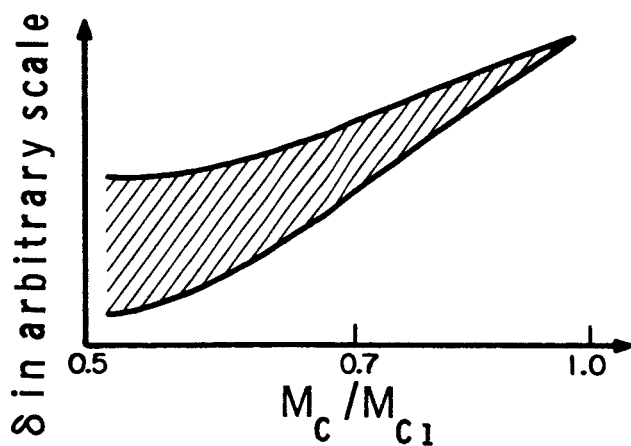


(a)

Δy = Differential distance downstream
 $\Delta y_{\text{max.}}$ = Maximum average distance traveled by an eddy
 M_{c1} = Average convective Mach number at position 1
 M_c = Convective Mach number of uniformly moving set of eddies
 δ = Linear size of eddies
 y = Downstream distance
 y_1 = Measurement position 1



(b)



(c)

FIGURE 12

APPENDIX A

All of the data acquired and processed under this contract are presented in this appendix. A key to the organization of the data is given in Table I and described in Section IV-C of the text. In brief:

- a. Jet noise spectral data are presented in Figs. A-1 through A-11.
- b. Jet-noise cross-correlation data are summarized in Table T-1.
- c. The more significant jet-noise cross-correlation data are also illustrated in Figs. A-12 through A-33.
- d. The results of loudspeaker-noise tests for microphone scattering artifacts are summarized in Table T-2.
- e. The results of loudspeaker-noise tests of the effects of microphone protective grids are summarized in Table T-3.

Appendix A

Table T-1

Summary of Cross-Correlation Data Acquired Parallel to

Jet Axis

- NOTES: 1) O.A. indicates correlations computed from broad-band data
 2) <20 kc indicates data correlations computed from data low-pass filtered at 20 kc. >20 kc indicates correlations computed from data high-pass filtered at 20 kc.
 3) ϕ_{12} is the normalized cross-correlation function; τ is the time delay to the peak of ϕ_{12} in microseconds.
 4) A blank space indicates the data were not processed in the indicated mode. An asterisk (*) indicates that the data were processed, but are not considered significant.

Microphone Positions	Spacing, inches	27°C						370°C						640°C	
		Unbaffled Microphones						Baffled Microphones						Baffled Microphones	
		O.A.			< 20 kc			O.A.			< 20 kc			O.A.	
		ϕ_{12}	τ	ϕ_{12}	τ	ϕ_{12}	τ	ϕ_{12}	τ	ϕ_{12}	τ	ϕ_{12}	τ	ϕ_{12}	τ
1 - 2	1/4	0.22	9	0.56	-2	0.11	8	0.48	13	0.73	14	0.65	12	0.63	12
1 - 3	1/2	0.18	31	0.19	26	0.18	30	0.34	32	0.62	24	0.49	23	0.63	23
1 - 4	1	0.23	57	0.28	57	0.22	56	0.33	62	0.39	46	0.41	49	0.41	44
1 - 5	2	0.23	115	0.23	114	0.19	112	0.32	119	0.20	88	0.27	100	0.15	85
1 - 6	4	0.09	230	0.14	218	0.05	213	0.16	240	0.03	175	0.09	175	0.03	160
1 - 7	8	0.03	470					0.05	510	0.02	380			*	*

Appendix A

Table T-2

Part 1

EFFECT OF MICROPHONE BAFFLE
FOR THREE ANGLES OF SOUND INCIDENCE

- A. Normal Incidence of Sound on Microphone Pair
 (All data scaled to Equivalent 1/4" Microphone Case)
 Microphone separation: 1/2"; Temperature 82°F

	Frequency Band of Noise		
	<u>25 KC</u> <u>Octave</u>	<u>32 KC</u> <u>1/3 Octave</u>	<u>50 KC</u> <u>Octave</u>
Cross Correlation without baffle:	1.0	1.03	1.00
τ max without baffle	2 μ sec.	2 μ sec.	2 μ sec.
Cross Correlation with baffle:	-	1.0	0.99
τ max with baffle:	-	5 μ sec.	5 μ sec.
"Ideal" Cross Correlation:	1.0	1.0	1.0
"Ideal" τ max	0	0	0

Table T-2 (cont)

Part 1

- B. Grazing Incidence of Sound on Microphone Pair
 (All data scaled to equivalent 1/4" microphone case)
 Microphone separation: 1/2"; Temperature 82°F

	Frequency Band of Noise		
	<u>25 KC</u> <u>Octave</u>	<u>32 KC</u> <u>1/3 Octave</u>	<u>50 KC</u> <u>Octave</u>
Cross Correlation without baffle:	0.95	0.99	-
τ max without baffle:	37 μ sec.	37 μ sec.	-
Cross Correlation with baffle:	1.0	0.965	0.95
τ max with baffle:	37 μ sec.	38 μ sec.	37 μ sec.
"Ideal" Cross Correlation:	1.0	1.0	1.0
"Ideal" τ max	36 μ sec.	36 μ sec.	36 μ sec.

- C. 40° from Normal Sound Incidence on Microphone Pair
 (All data scaled to equivalent 1/4" microphone case.)
 Microphone Separation: 1/2"; Temperature 82°F

	Frequency Band of Noise		
	<u>25 KC</u> <u>Octave</u>	<u>32 KC</u> <u>1/3 Octave</u>	<u>50 KC</u> <u>Octave</u>
Cross Correlation without baffle:	0.98	0.95	-
τ max without baffle:	25 μ sec.	25 μ sec.	-
Cross Correlation with baffle:	1.02	0.97	0.96
τ max with baffle:	25 μ sec.	26 μ sec.	26 μ sec.
"Ideal" Cross Correlation:	1.0	1.0	1.0
"Ideal" τ max	23 μ sec.	23 μ sec.	23 μ sec.

Table T-2

Part 2

EFFECT OF MICROPHONE BAFFLE
FOR DIFFERENT MICROPHONE SEPARATIONS
NORMAL SOUND INCIDENCE

(All Data Scaled to equivalent 1/4" microphone case)

	Microphone Separation		
	<u>1/4 in.</u>	<u>1/2 in.</u>	<u>1 in.</u>
<u>25 KC Octave</u>			
Cross correlation without baffle:	0.99	1.0	1.0
τ max without baffle:	1 μ sec.	2 μ sec.	3 μ sec.
Cross correlation with baffle:	0.96	-	0.95
τ max with baffle:	2 μ sec.	-	1 μ sec.
<u>32 KC 1/3 Octave</u>			
Cross correlation without baffle:	1.0	1.03	0.94
τ max without baffle:	1 μ sec.	2 μ sec.	4 μ sec.
Cross correlation with baffle:	0.98	1.0	0.99
τ max with baffle:	2 μ sec.	5 μ sec.	0 μ sec.

Appendix A

Table T-3

EFFECT OF MICROPHONE PROTECTIVE GRIDS

FOR NORMAL SOUND INCIDENCE: WITHOUT BAFFLE

(All data scaled to equivalent 1/4" microphone case.)

	<u>With Grids</u>	<u>Without Grids</u>
<u>1/4 inch spacing, 25 KC Octave</u>		
Cross correlation	0.99	0.985
τ max., μ sec.	1 μ sec.	1 μ sec.
<u>1/4 inch spacing, 32 KC 1/3 Octave</u>		
Cross correlation	1.0	0.99/0.995
τ max., μ sec.	1 μ sec.	1/1 μ sec.

FIGURE A-1 MODEL JET NOISE STUDIES
Acoustic Spectra Parallel to Jet Axis: 16-19 Feb '65

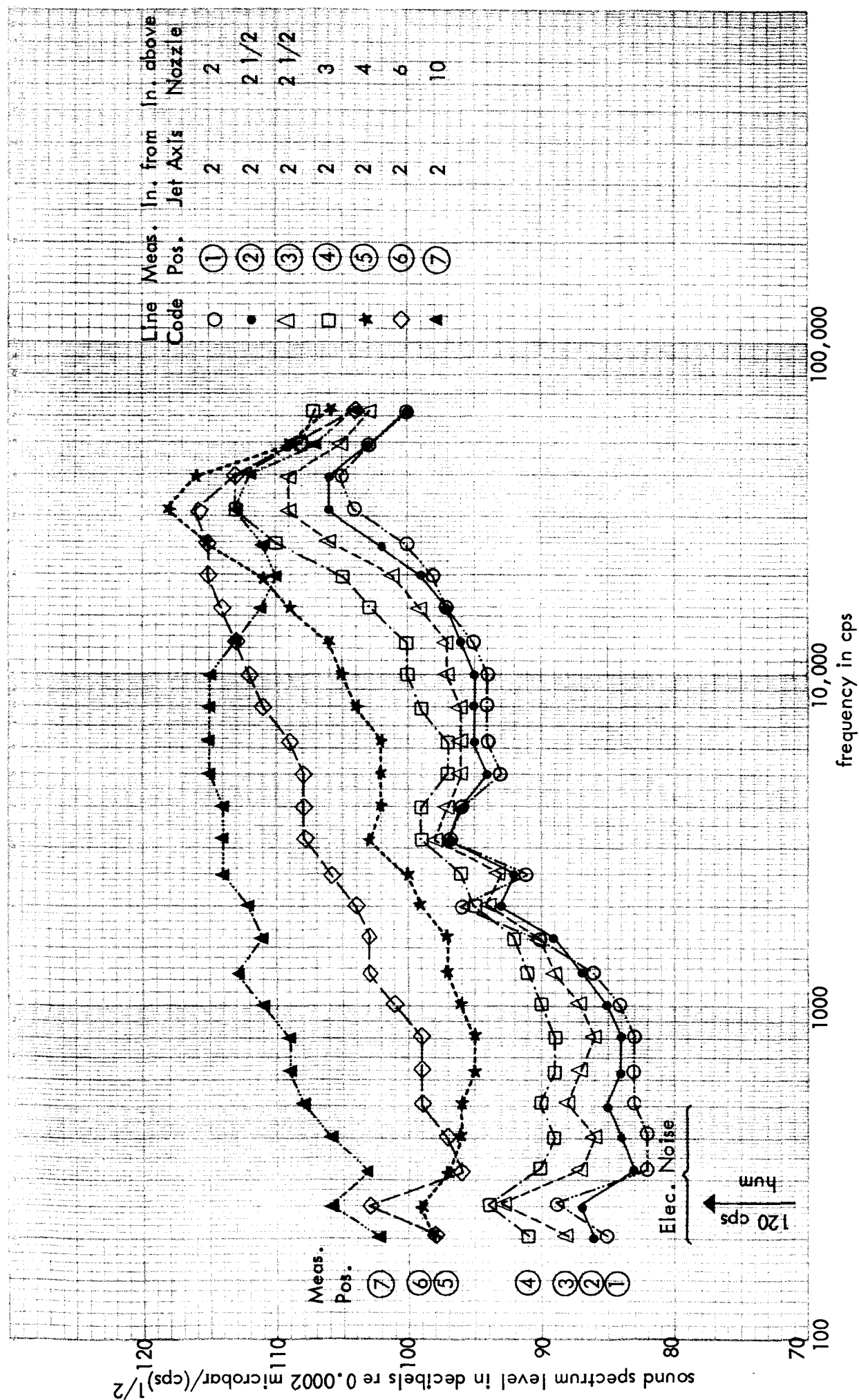


FIGURE A-2 MODEL JET NOISE STUDIES
Acoustic Spectra on 10 Inch Radius from Nozzle Exit 16-19 Feb '65

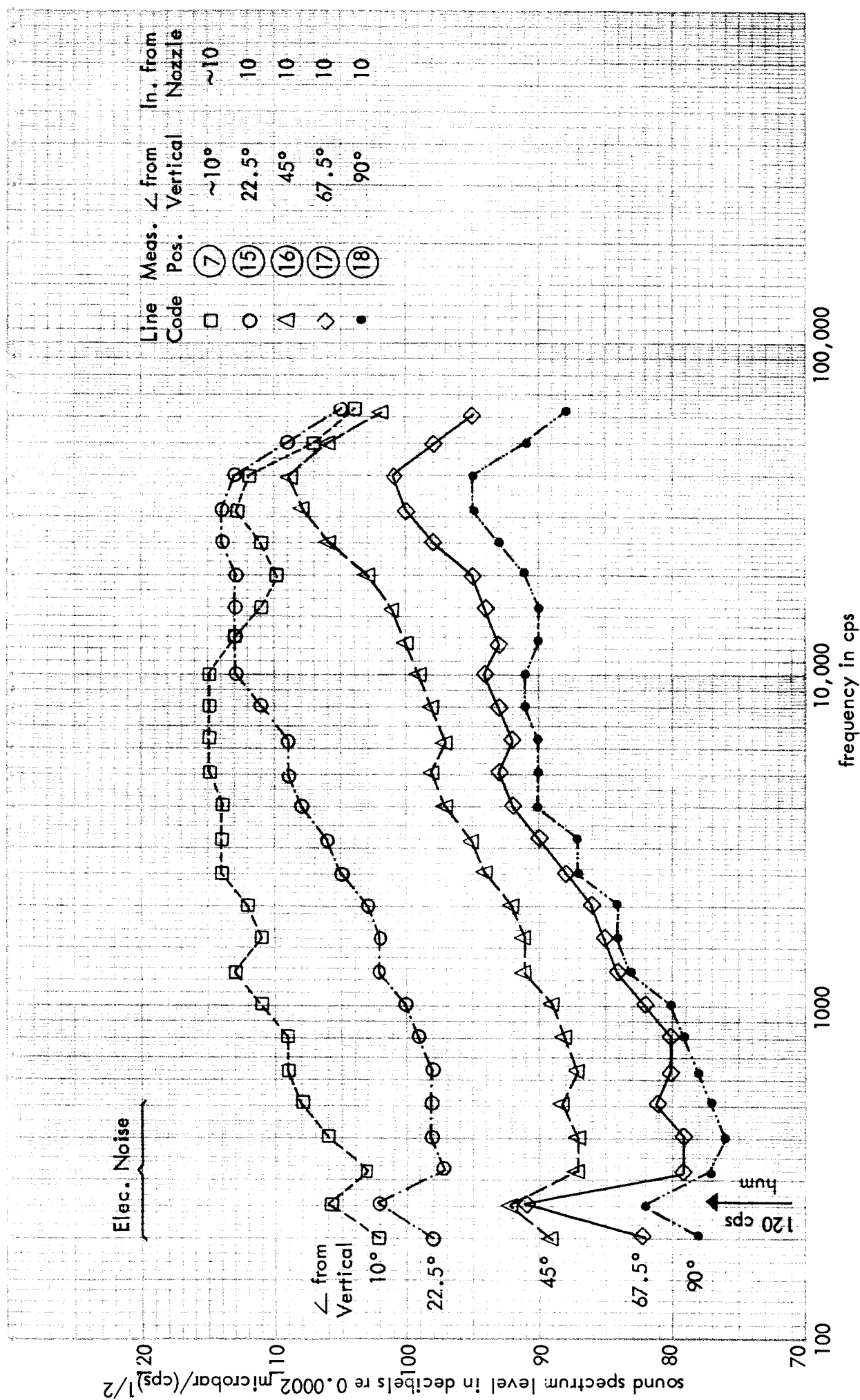


FIGURE A-3 MODEL JET NOISE STUDIES
Acoustic Spectra on 20 Inch Radius from Nozzle Exit 16-19 Feb '65

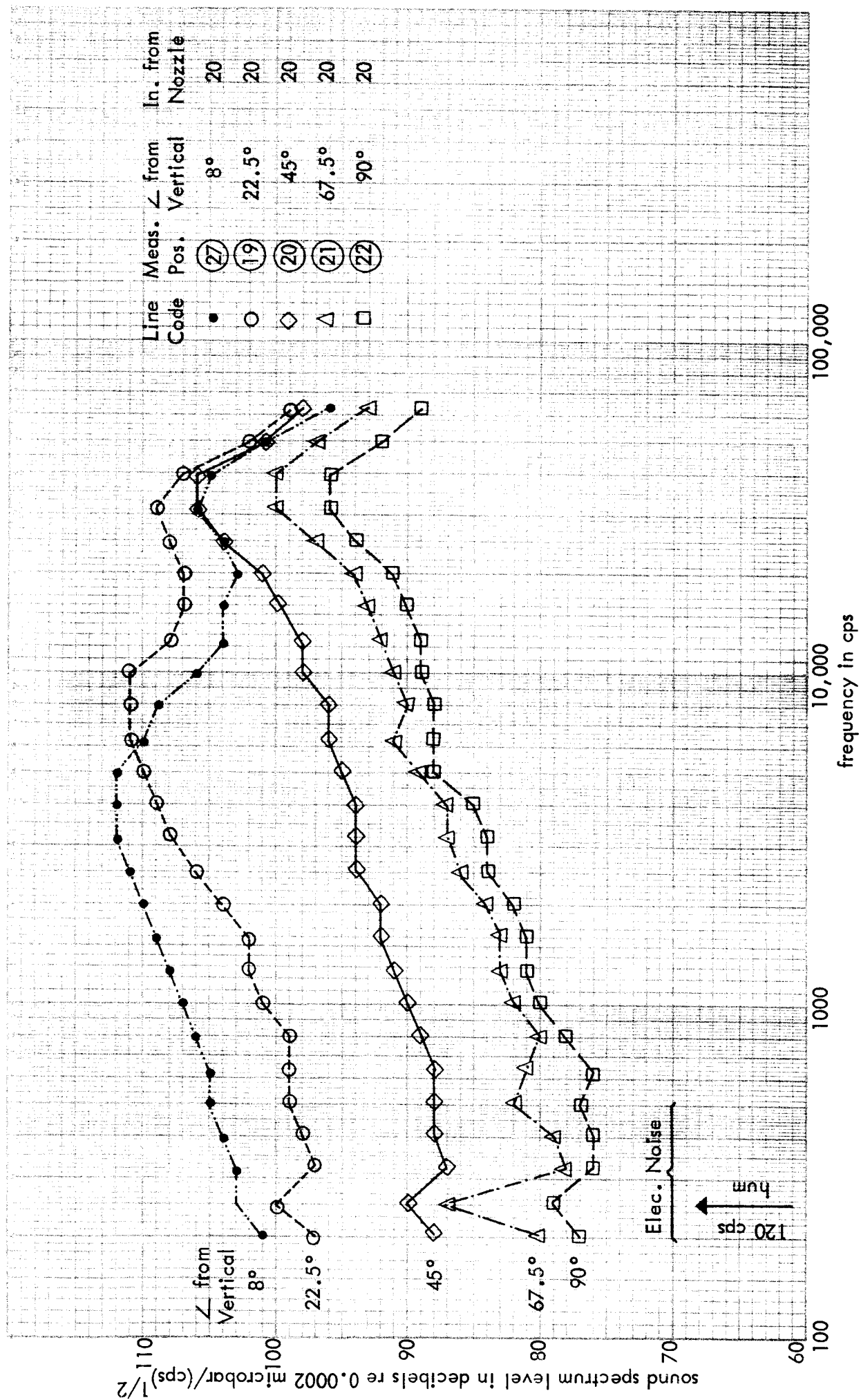


FIGURE A-4 MODEL JET NOISE STUDIES
Acoustic Spectra at 8° from Jet Axis: 16-19 Feb '65

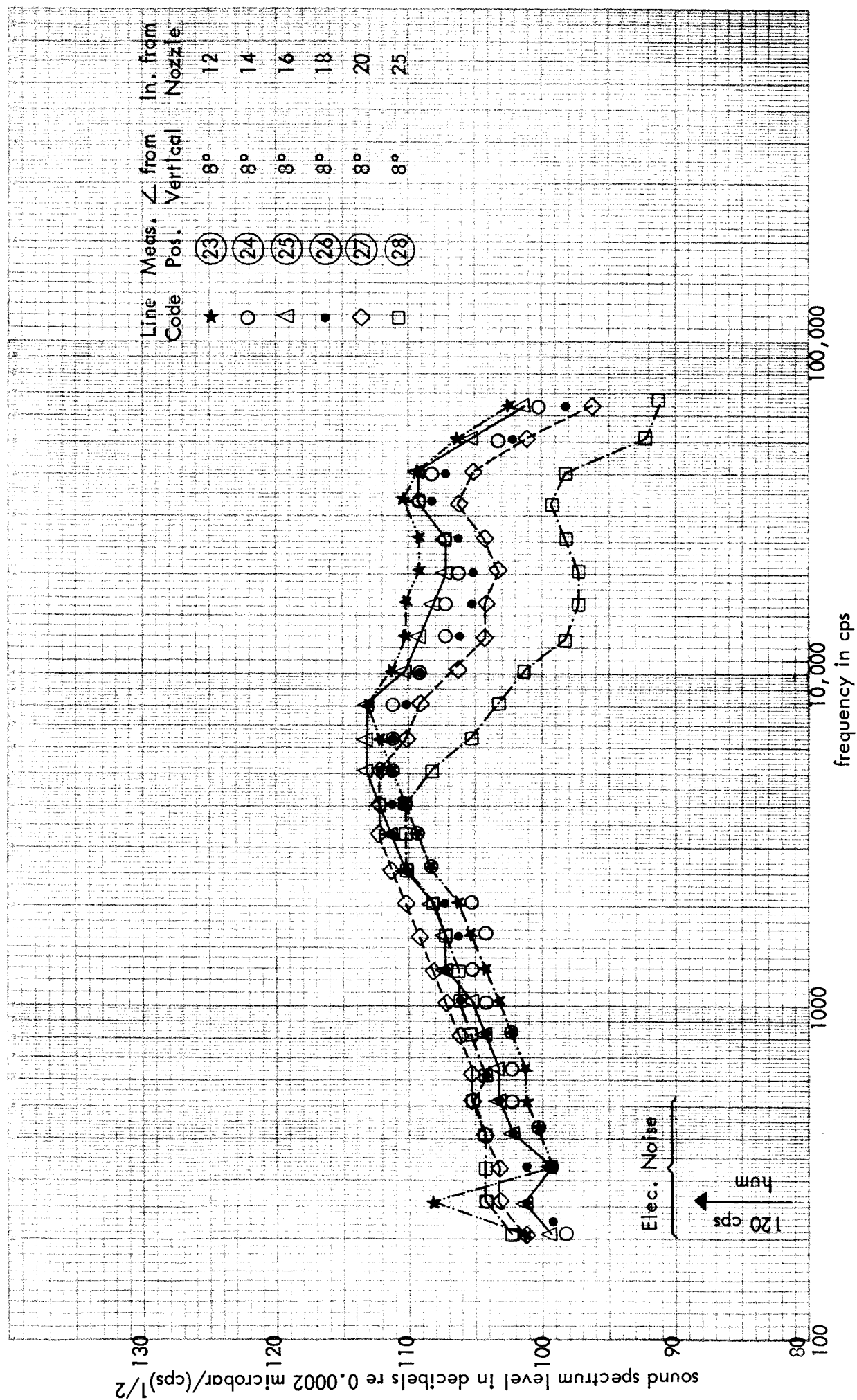
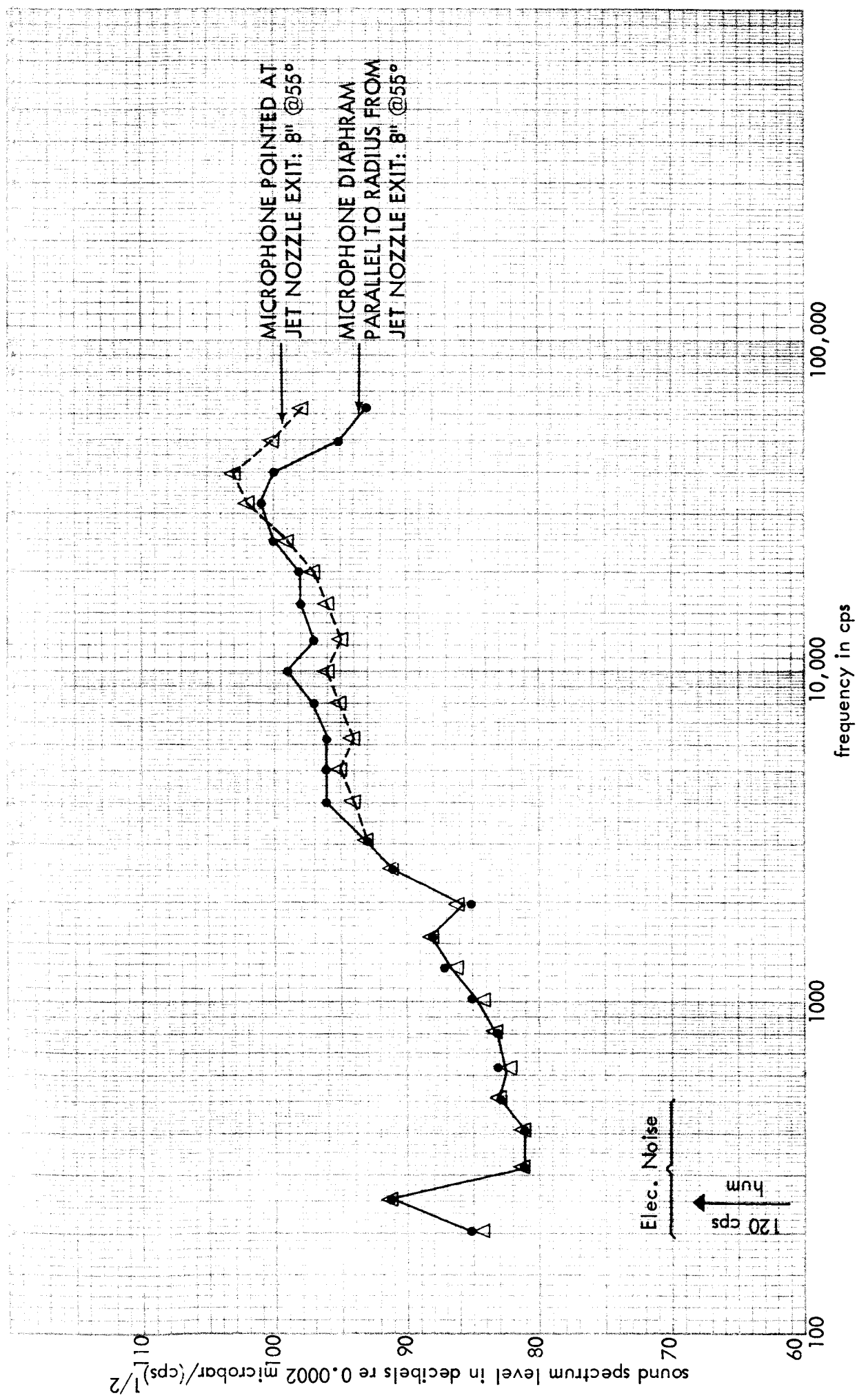


FIGURE A-5 MODEL JET NOISE STUDIES

Acoustic Spectra Illustrating Effect of Microphone Orientation at Meas. Pos. 29 16-19 Feb '65



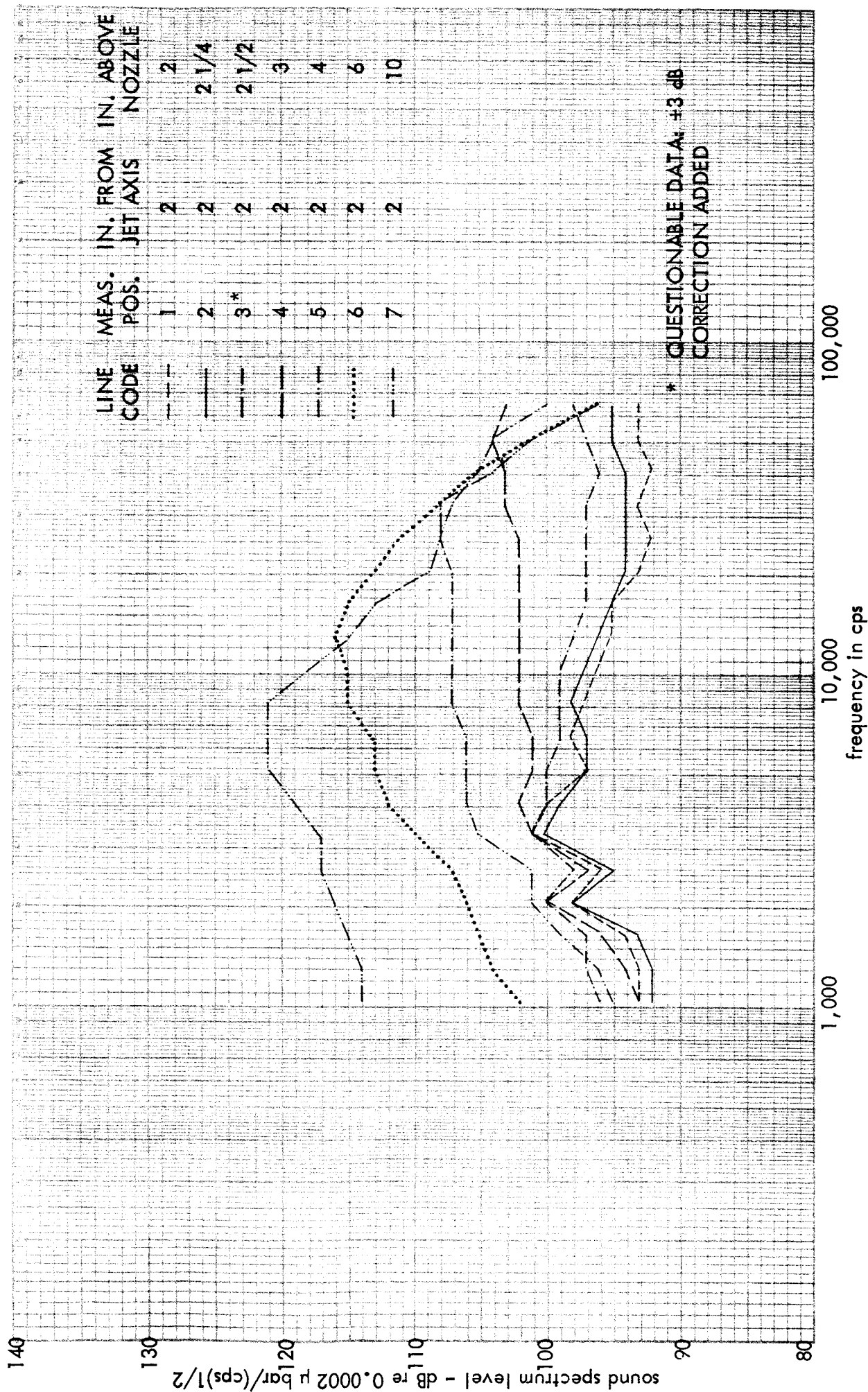


FIGURE A-6 MODEL JET NOISE STUDIES
 ACOUSTIC SPECTRA PARALLEL TO JET AXIS WITH BAFFLED MICROPHONES: 20-21 MAY, 1965
 Jet at Ambient Temperature

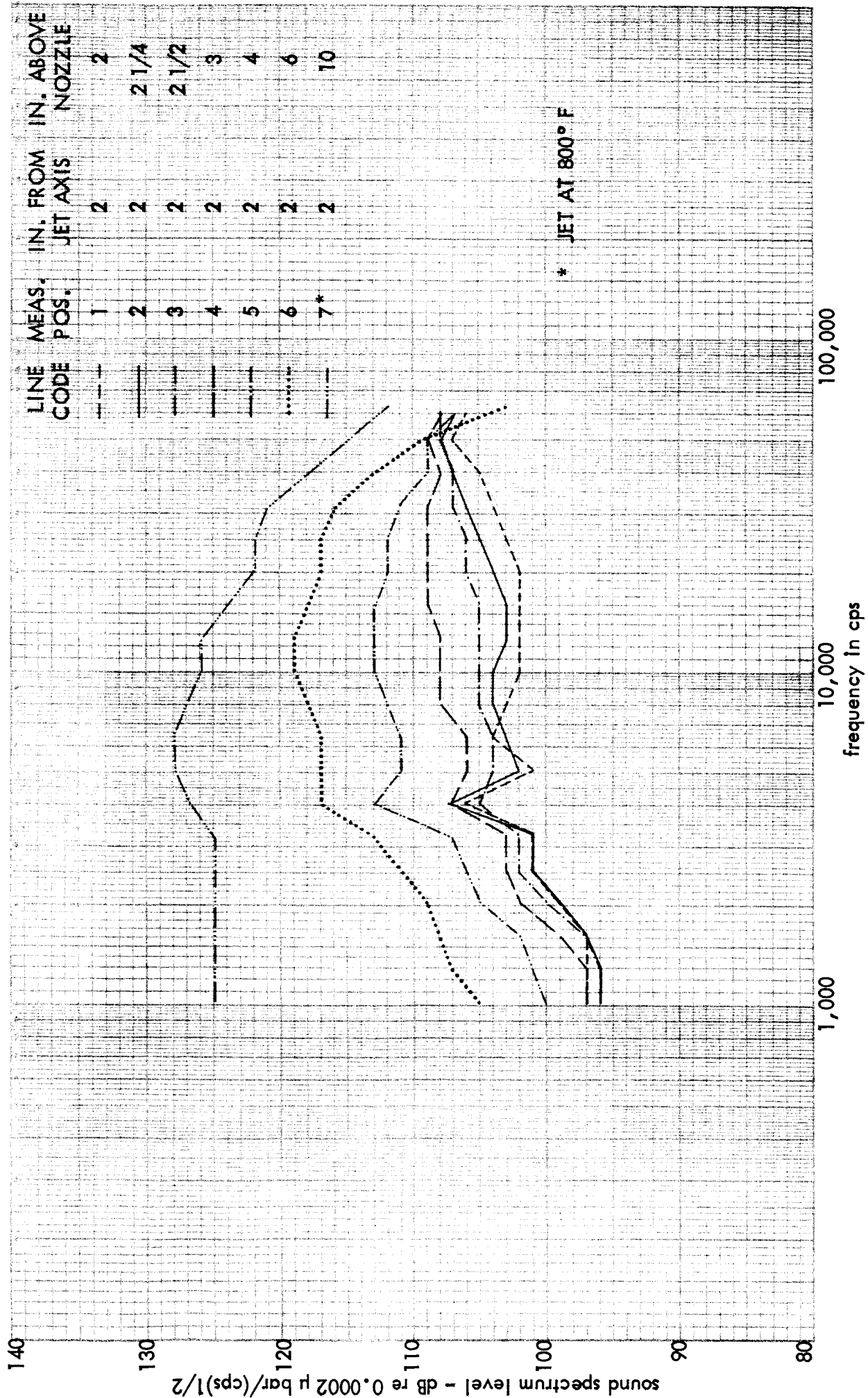


FIGURE A-7 MODEL JET NOISE STUDIES
ACOUSTIC SPECTRA PARALLEL TO JET AXIS WITH BAFFLED MICROPHONES: 20-21 MAY, 1965
Jet at 370°C Temperature

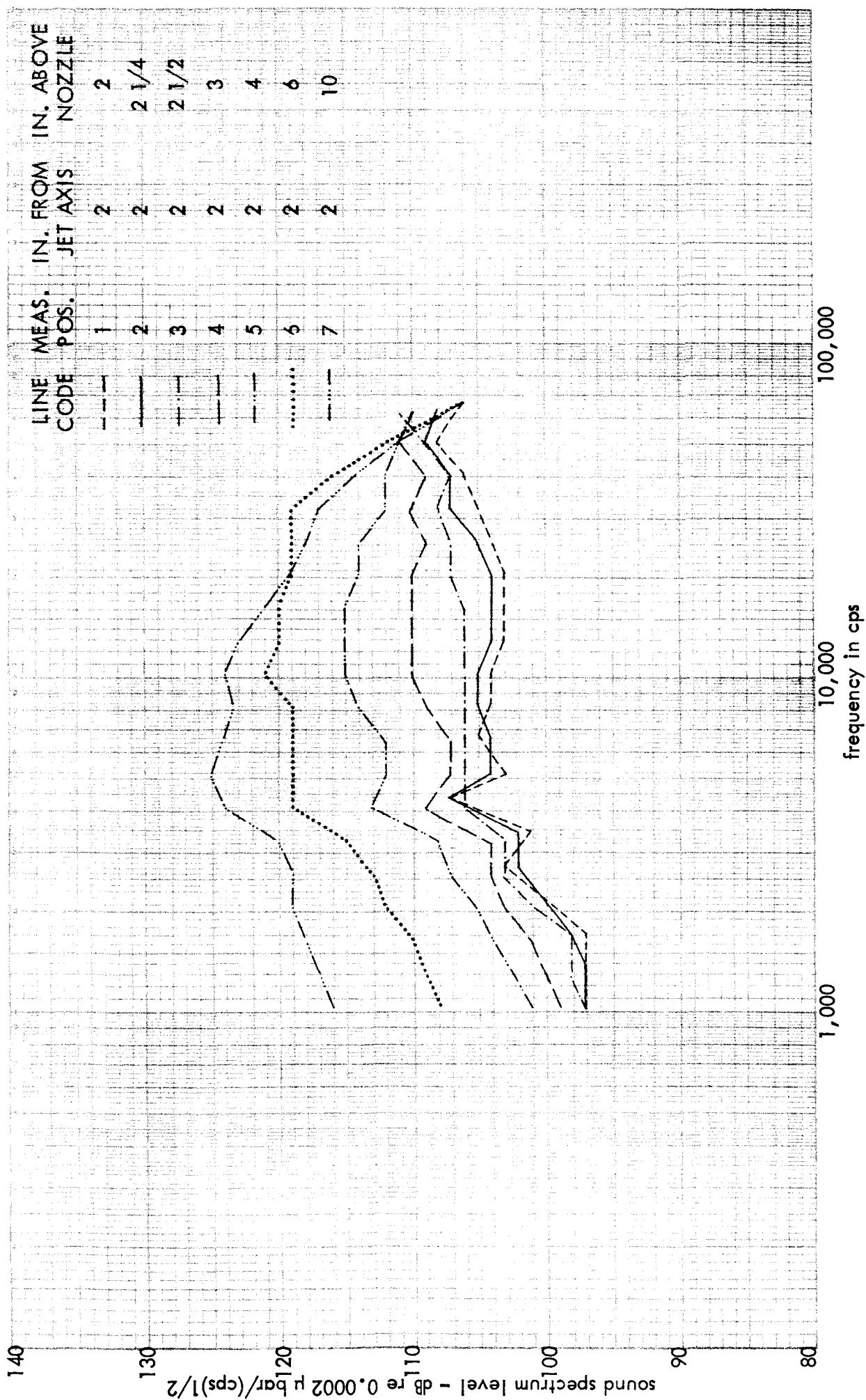


FIGURE A-8 MODEL JET NOISE STUDIES

ACOUSTIC SPECTRA PARALLEL TO JET AXIS WITH BAFFLED MICROPHONES: 20-21 MAY, 1965

Jet at 640°C Temperature

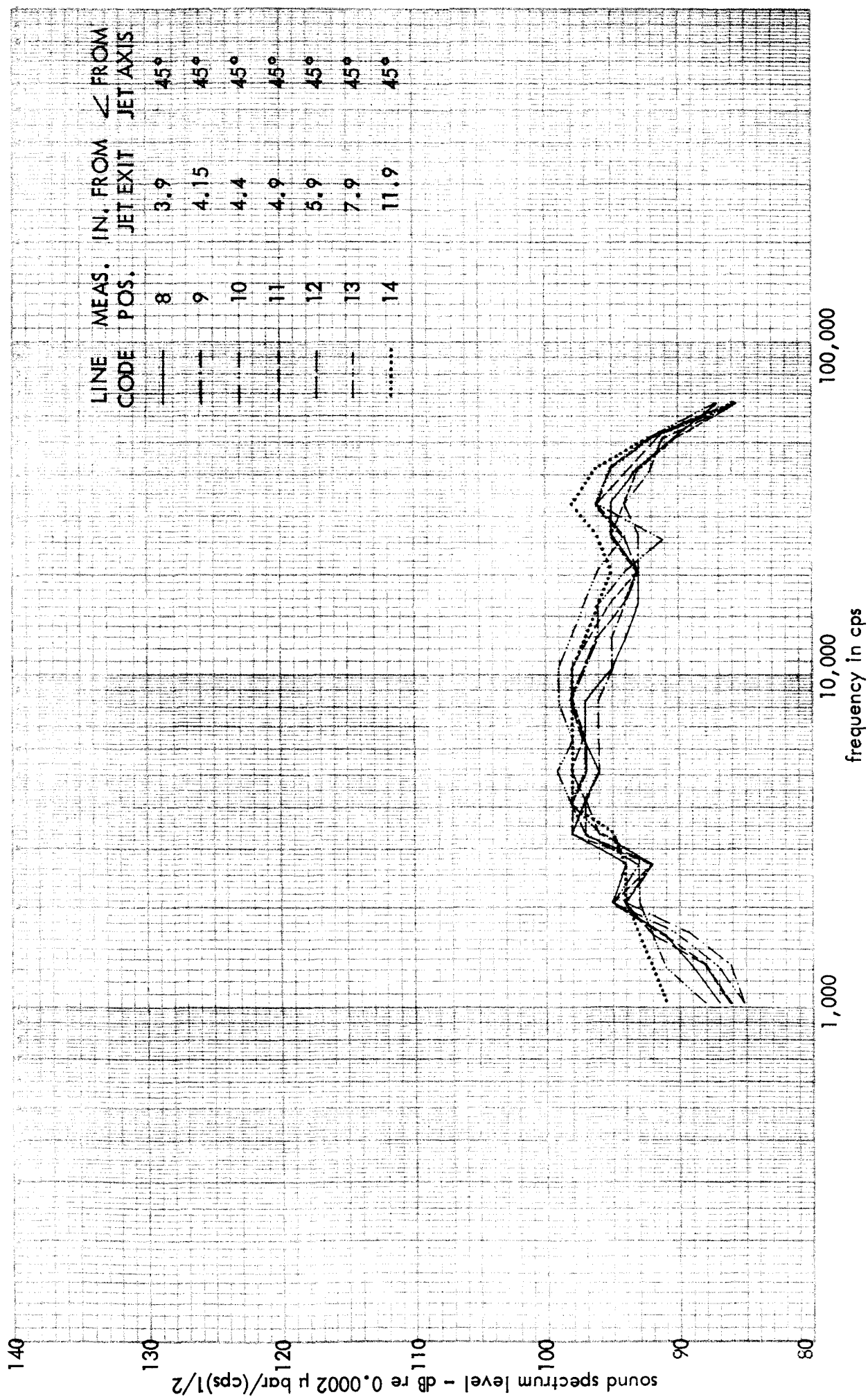


FIGURE A-9 MODEL JET NOISE STUDIES: 25 MAY, 1965
 SOUND SPECTRUM LEVEL WITH BAFFLED MICROPHONES ALONG A RADIUS
 FROM THE JET EXIT AT AN ANGLE OF 45°
 Jet at Ambient Temperature

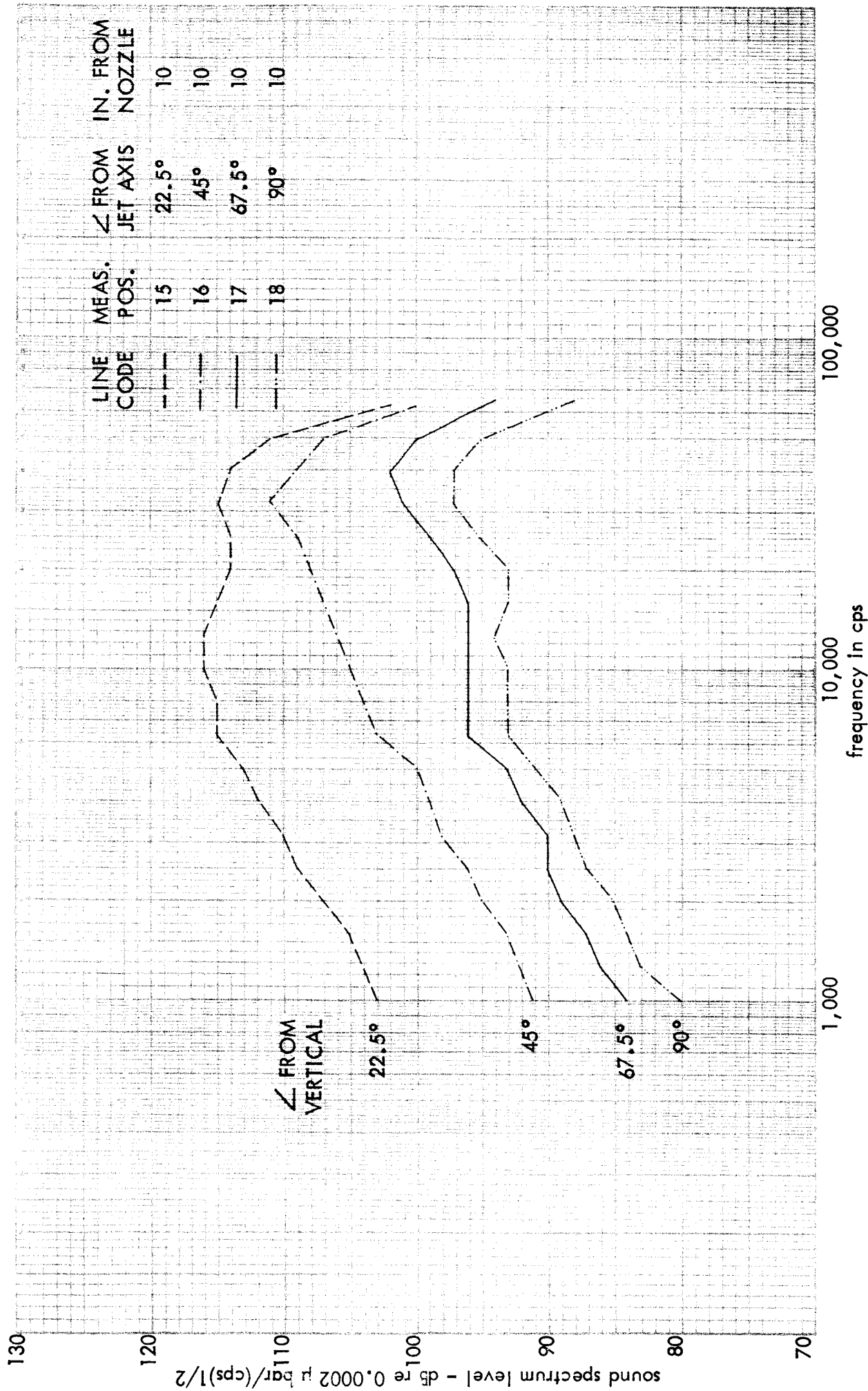


FIGURE A-10 MODEL JET NOISE STUDIES: 25 MAY, 1965
ACOUSTIC SPECTRA ON 10 IN. RADIUS FROM NOZZLE EXIT
Jet at 640°C Temperature Unbaffled Microphones

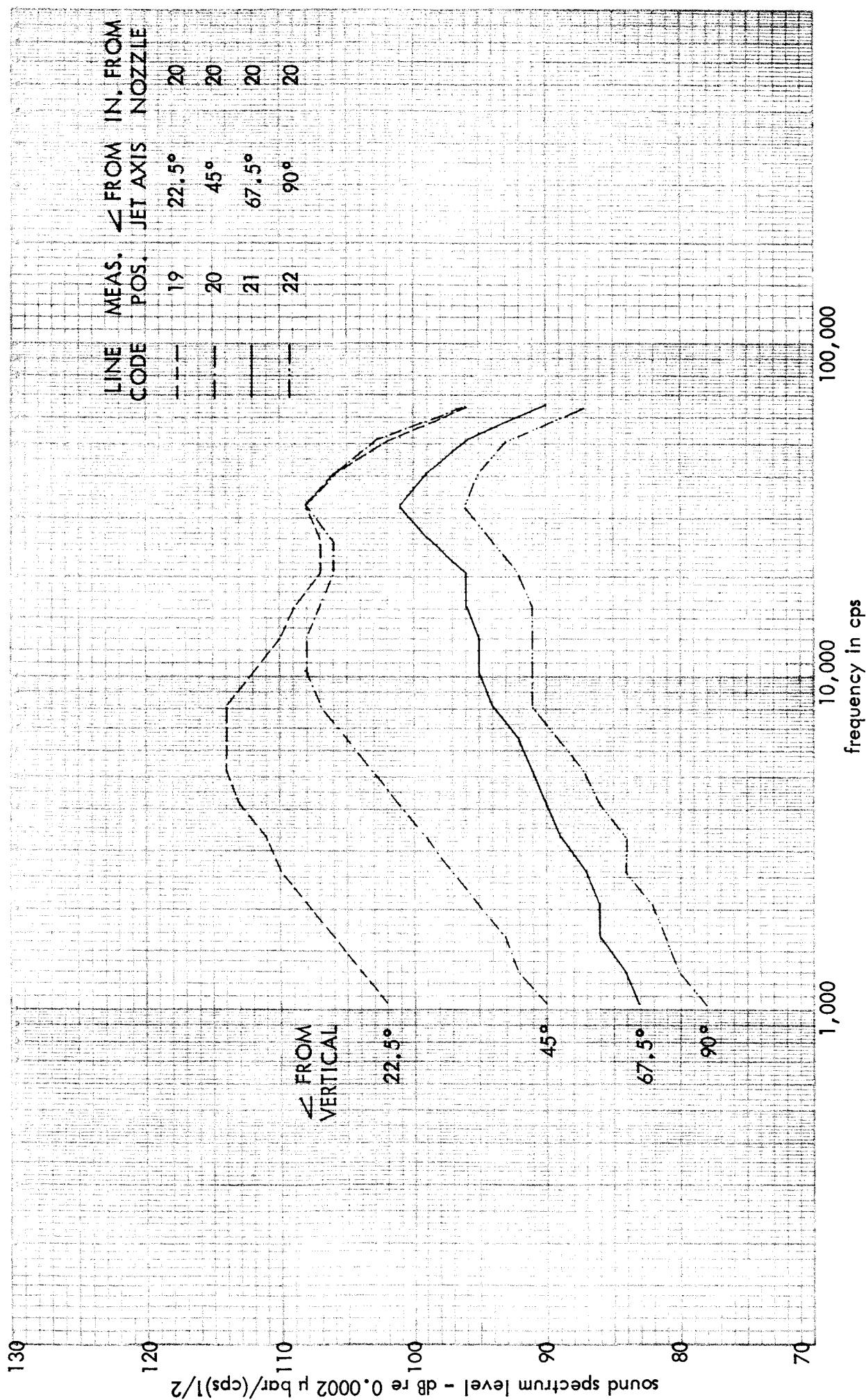


FIGURE A-11 MODEL JET NOISE STUDIES: 25 MAY, 1965
 ACOUSTIC SPECTRA ON 20 IN. RADIUS FROM NOZZLE EXIT
 Jet at 1200°F Temperature Unbaffled Microphone

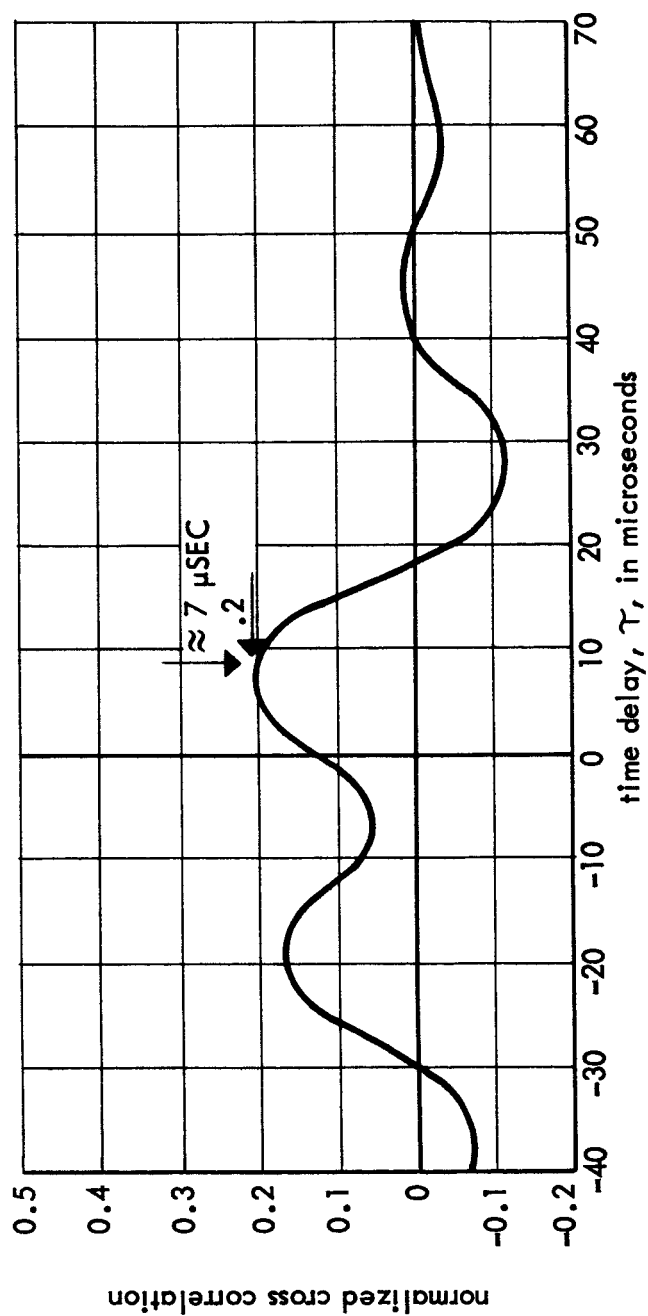


FIGURE A-12. MODEL JET NOISE STUDIES
Normalized Cross Correlation at 1/4 in. Spacing (Positions 1 and 2)
Ambient Temperature, Unbaffled Microphones

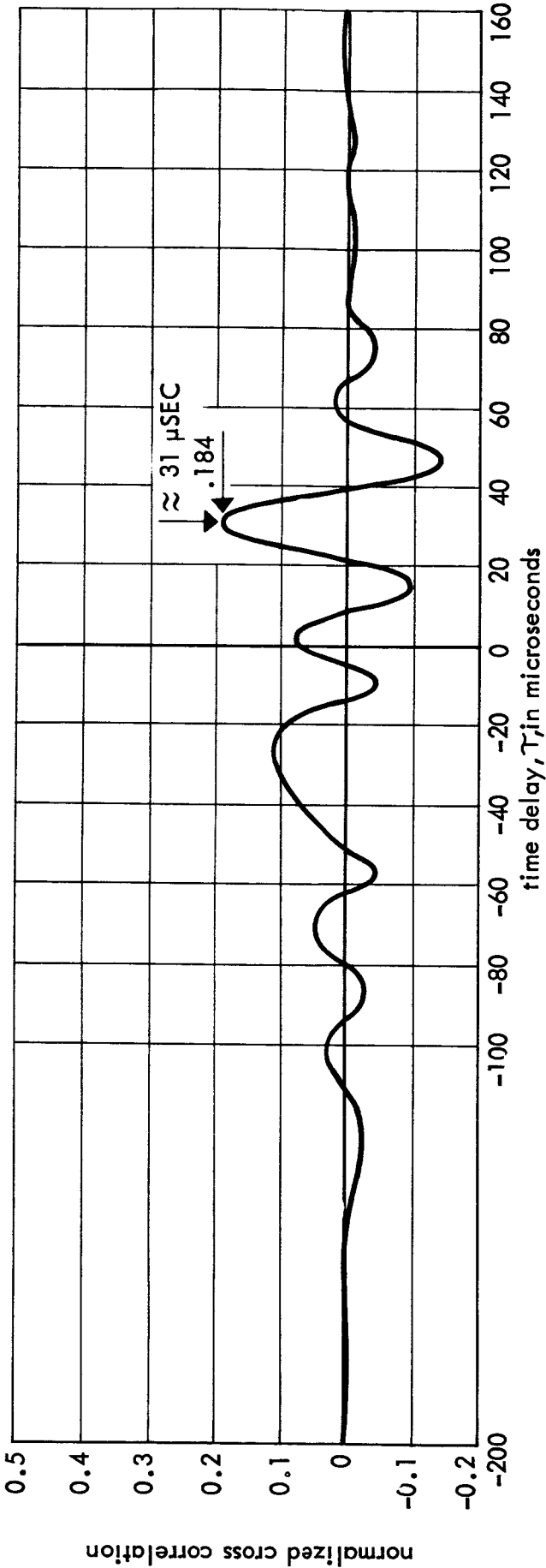


FIGURE A-13. MODEL JET NOISE STUDIES
Normalized Cross Correlation at 1/2 in. Spacing (Positions 1 and 3)
Ambient Temperature, Unbaffled Microphones

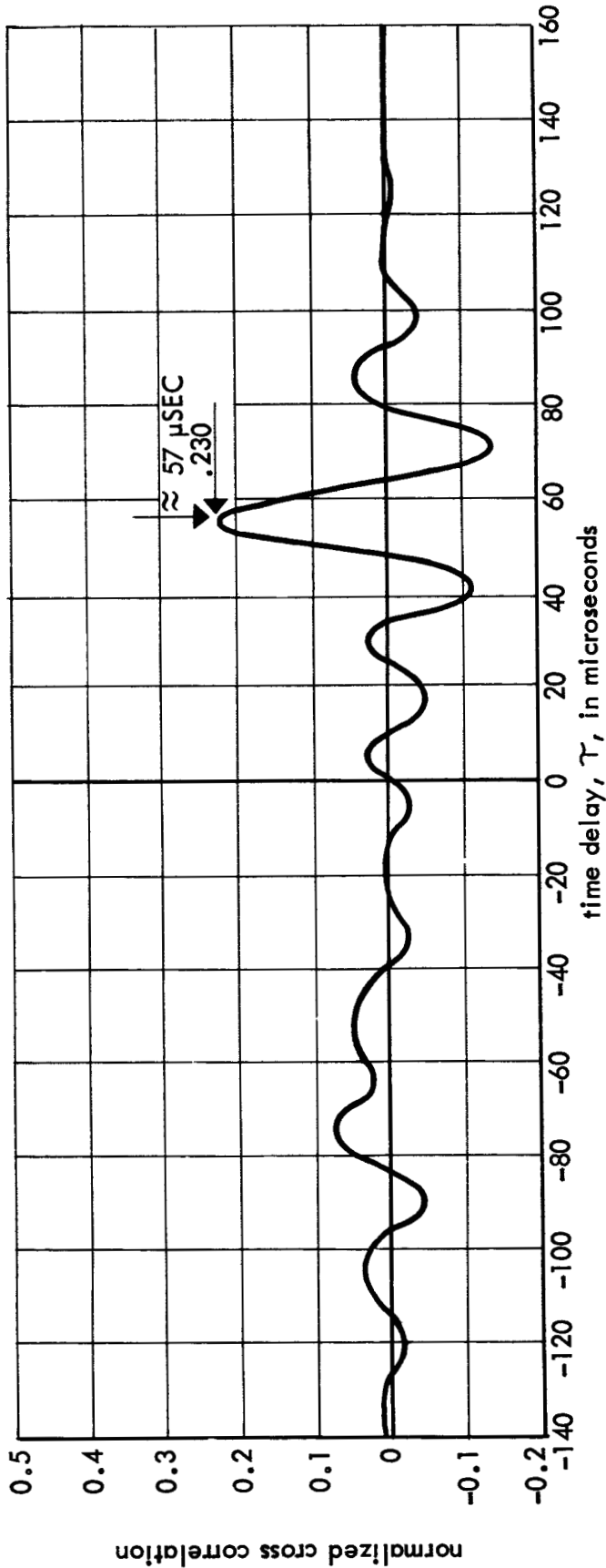


FIGURE A-14 MODEL JET NOISE STUDIES
Normalized Cross Correlation at 1 in. Spacing (Positions 1 and 4)
Ambient Temperature, Unbaffled Microphones

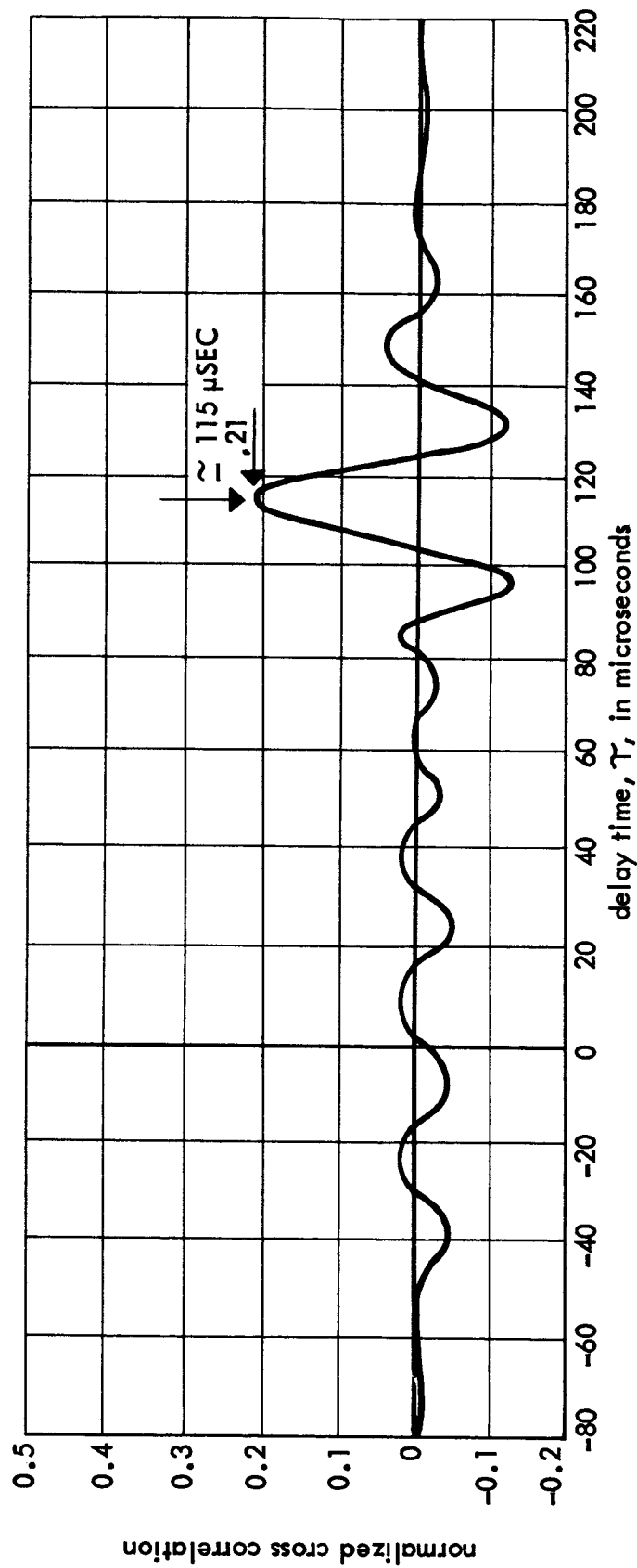


FIGURE A-15 MODEL JET NOISE STUDIES
Normalized Cross Correlation at 2 in. Spacing (Positions 1 and 5)
Ambient Temperature, Unbaffled Microphones

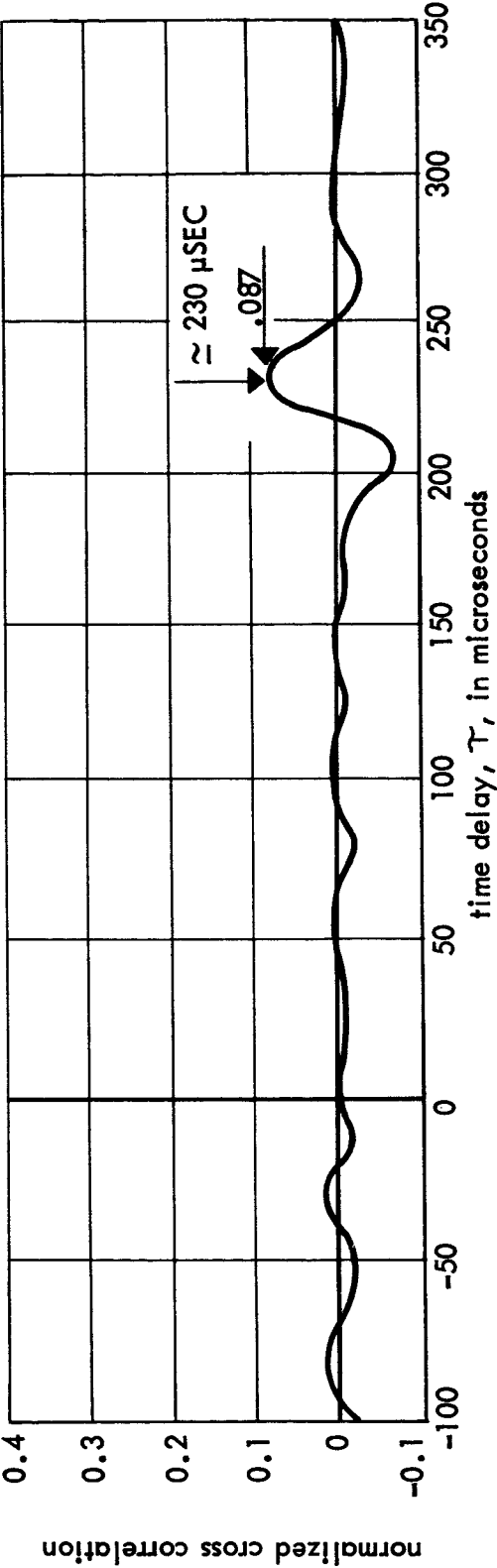


FIGURE A-16. MODEL JET NOISE STUDIES
Normalized Cross Correlation at 4 in. Spacing (Positions 1 and 6)
Ambient Temperature, Unbaffled Microphone

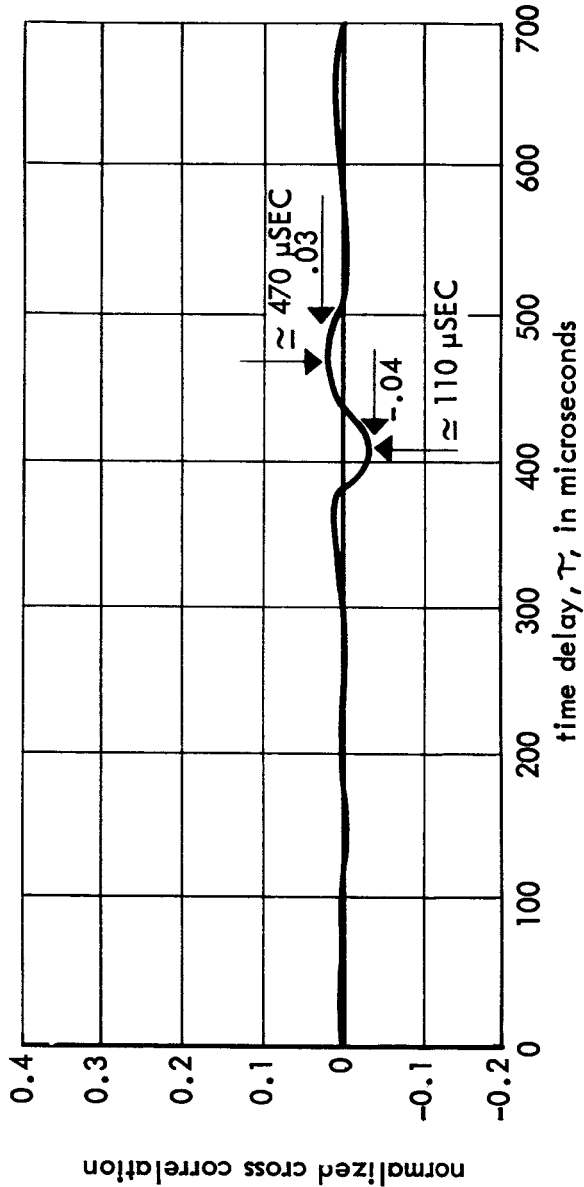


FIGURE A-17. MODEL JET NOISE STUDIES
Normalized Cross Correlation at 8 in. Spacing (Positions 1 and 7)
Ambient Temperature, Unbaffled Microphones

FIGURE A-18
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/4" SPACING (POS ① & ②)
AMBIENT JET TEMP.

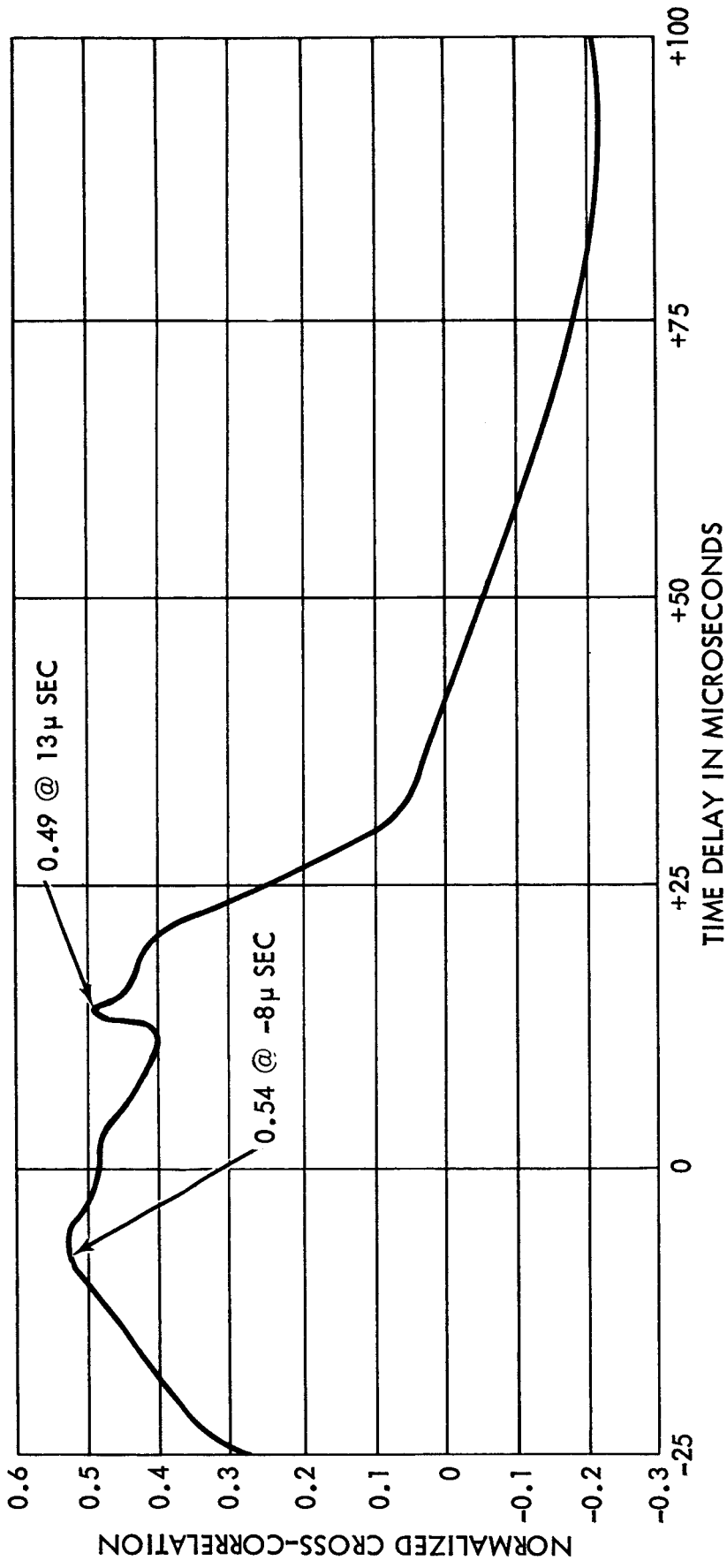


FIGURE A-19
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/2" SPACING (POS ① & ③)
AMBIENT JET TEMP.

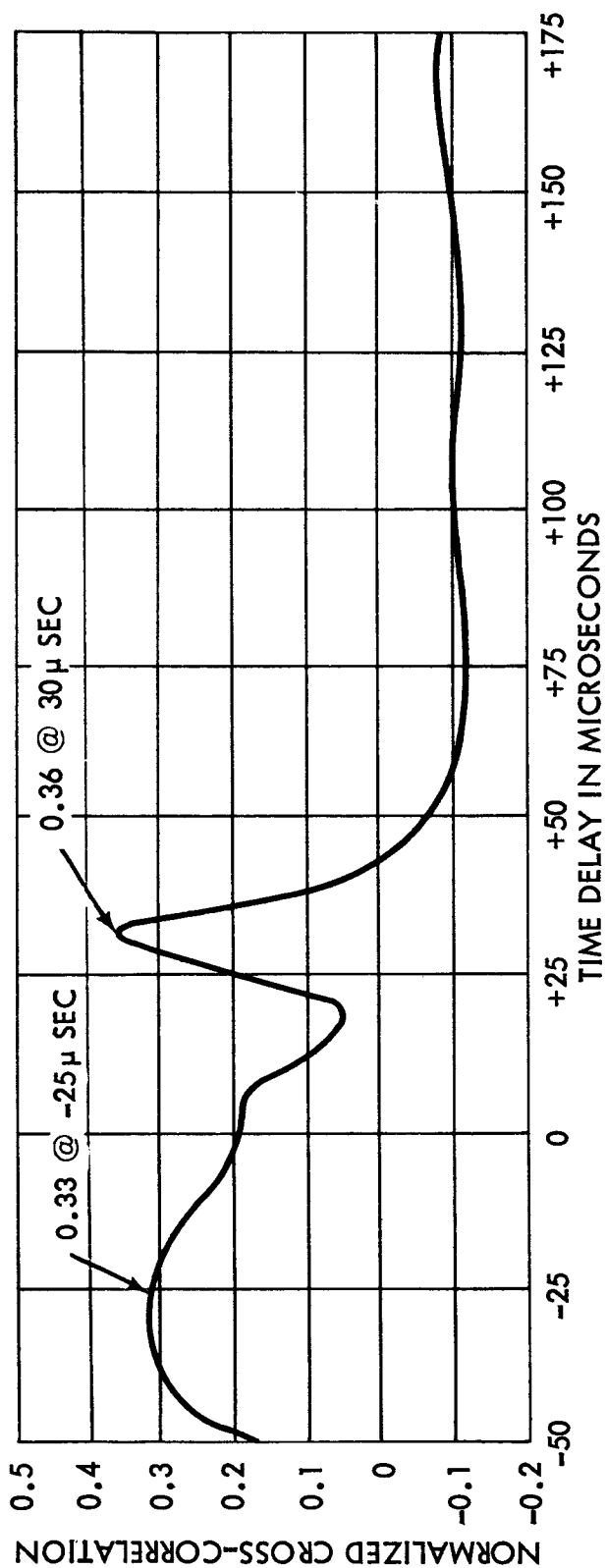


FIGURE A-20a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS ① & ④)
AMBIENT JET TEMP.

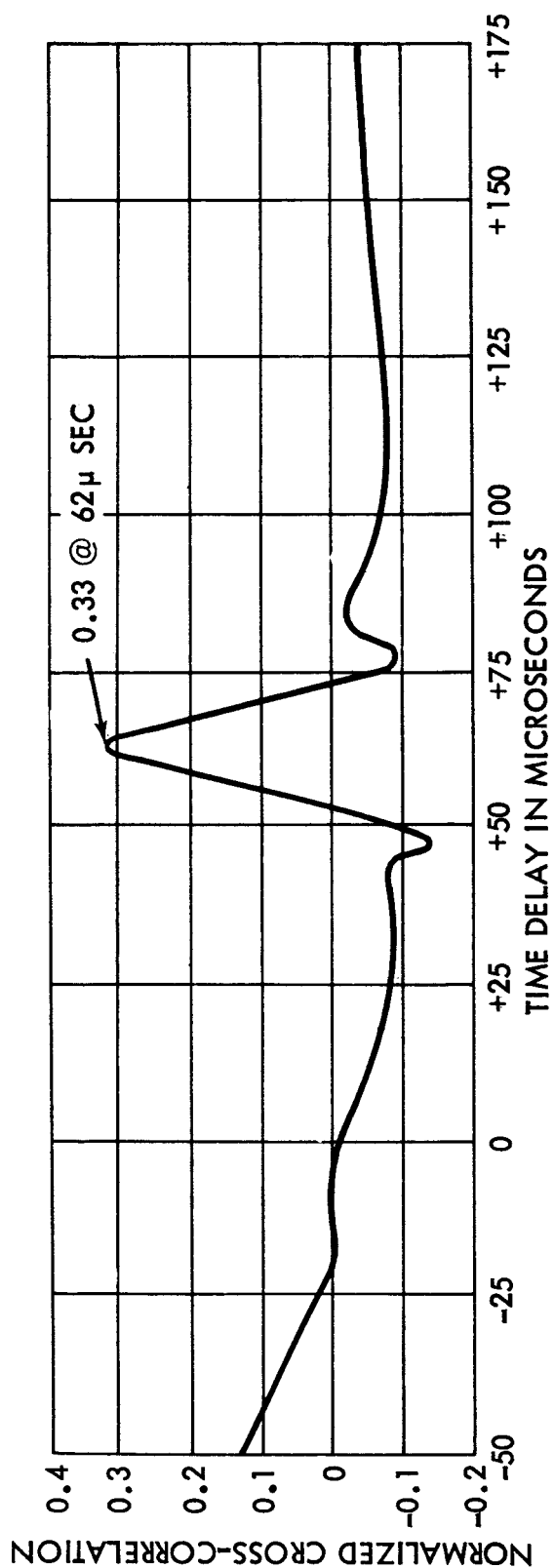


FIGURE A-20b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS ① & ④)
AMBIENT JET TEMP.

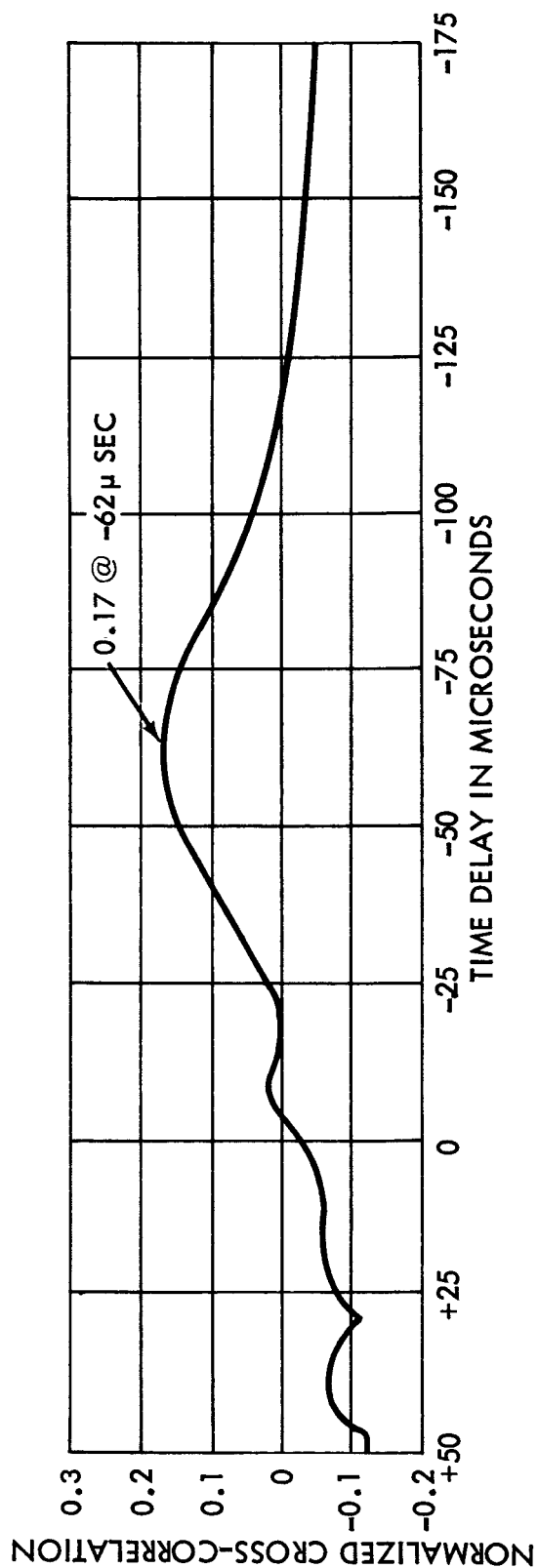


FIGURE A-21_a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
2" SPACING (POS ① & ⑤)
AMBIENT JET TEMP.

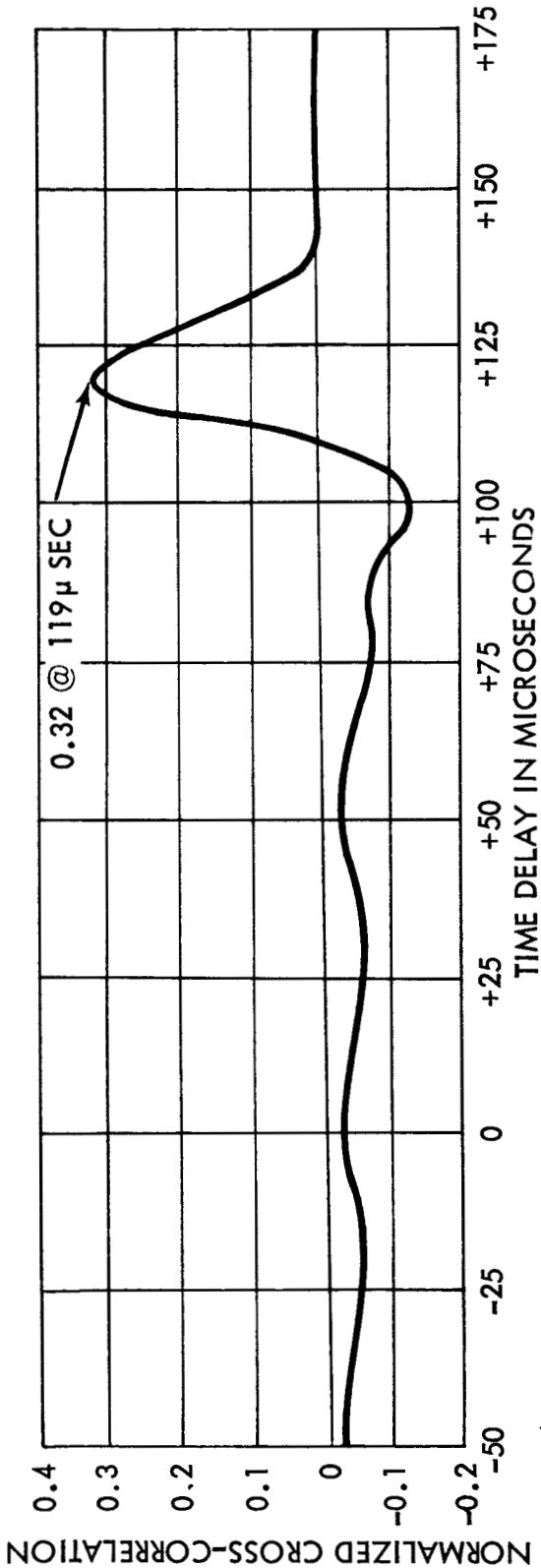


FIGURE A-21b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
2" SPACING (POS ① & ⑤)
AMBIENT JET TEMP.

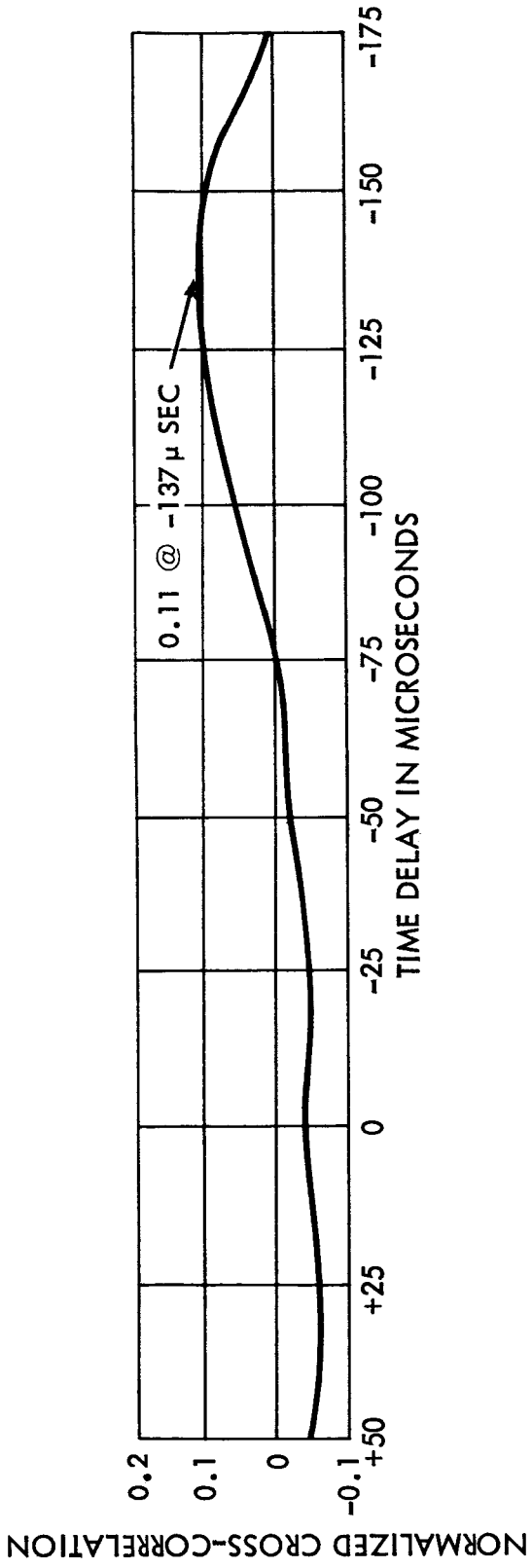


FIGURE A-22a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
4" SPACING (POS ① & ⑥)
AMBIENT JET TEMP.

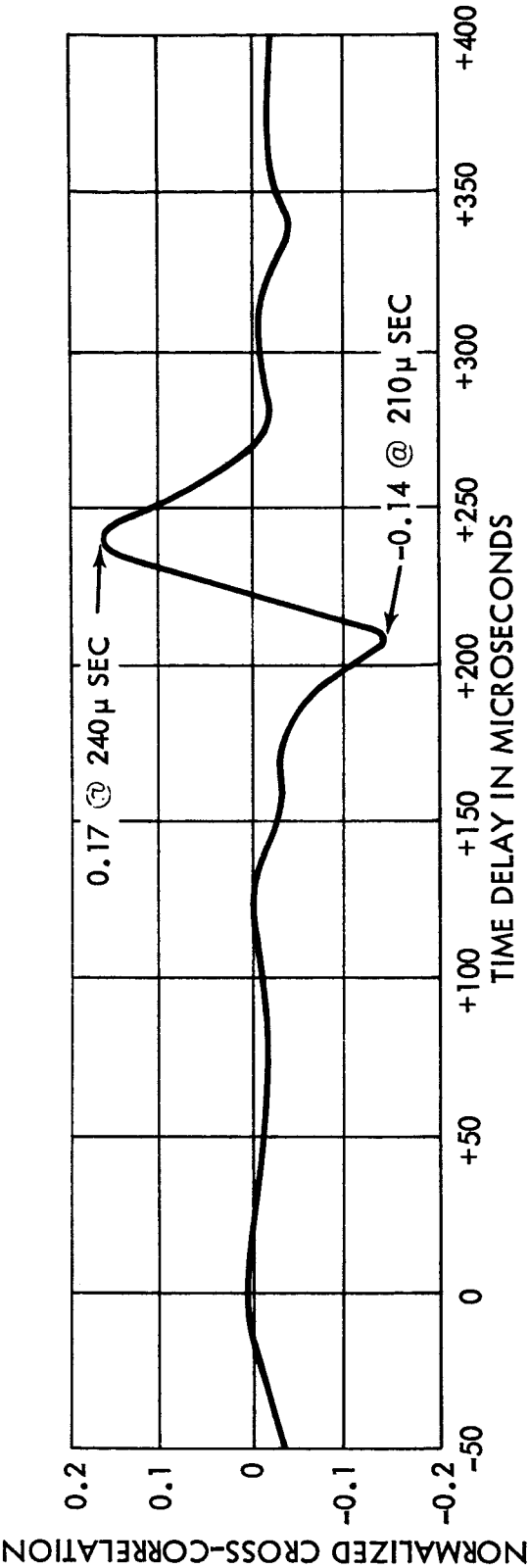


FIGURE A-22b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
4" SPACING (POS ① & ⑥)
AMBIENT JET TEMP.

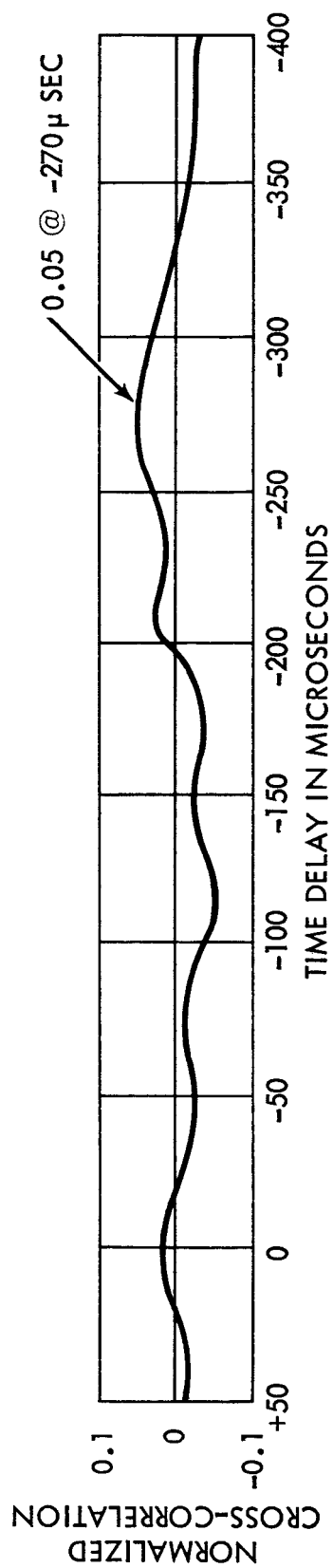


FIGURE A-23a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
8" SPACING (POS ① & ⑦)
AMBIENT JET TEMP.

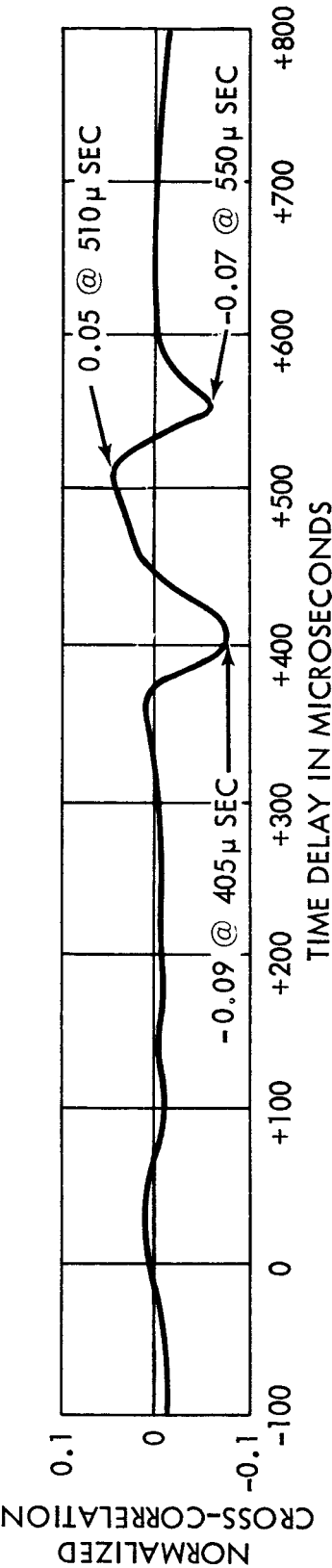


FIGURE A-23b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
8" SPACING (POS ① & ⑦)
AMBIENT JET TEMP.

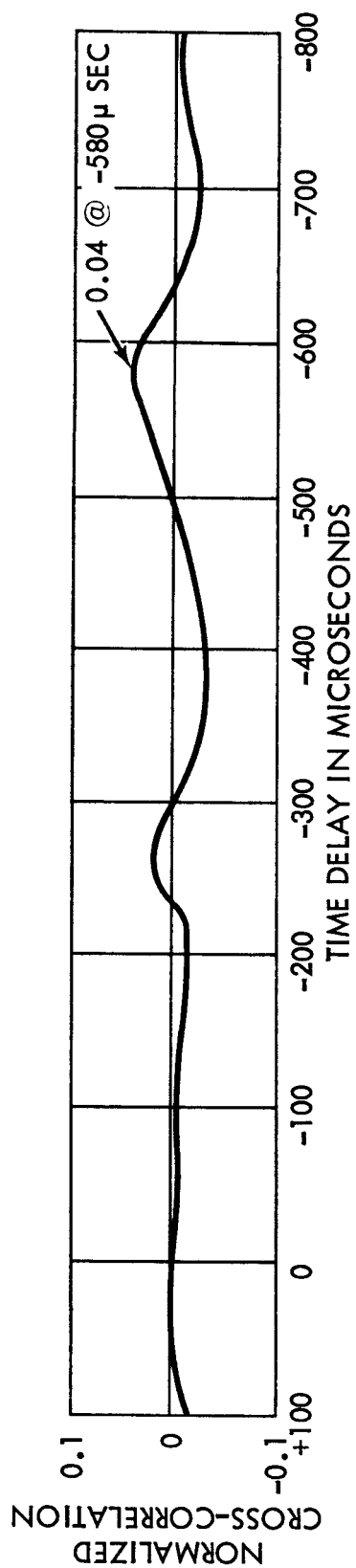


FIGURE A-24
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/4" SPACING (POS ① & ②)
370°C JET TEMP.

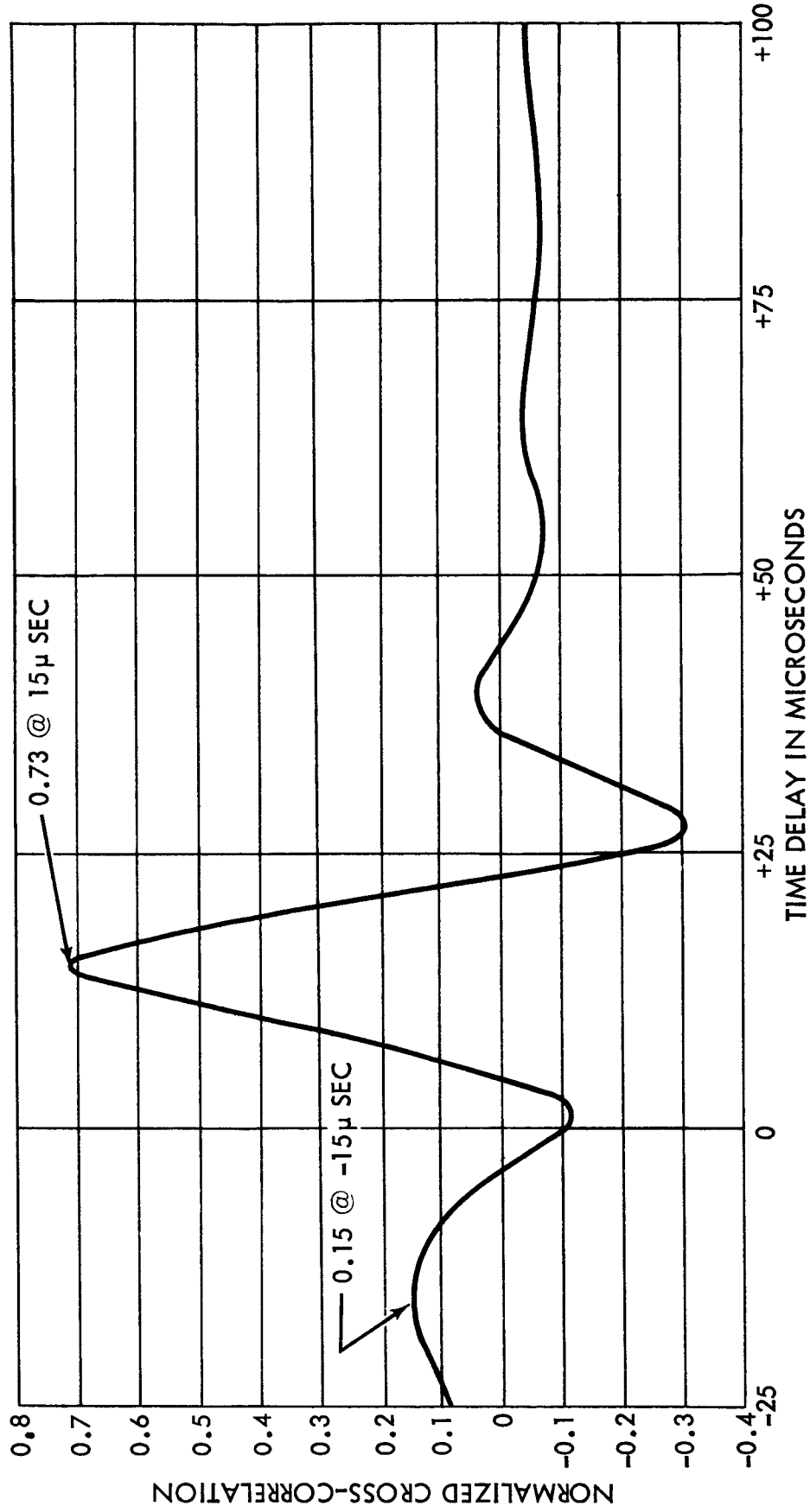


FIGURE A-25
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/2" SPACING (POS ① & ③)
370°C JET TEMP.

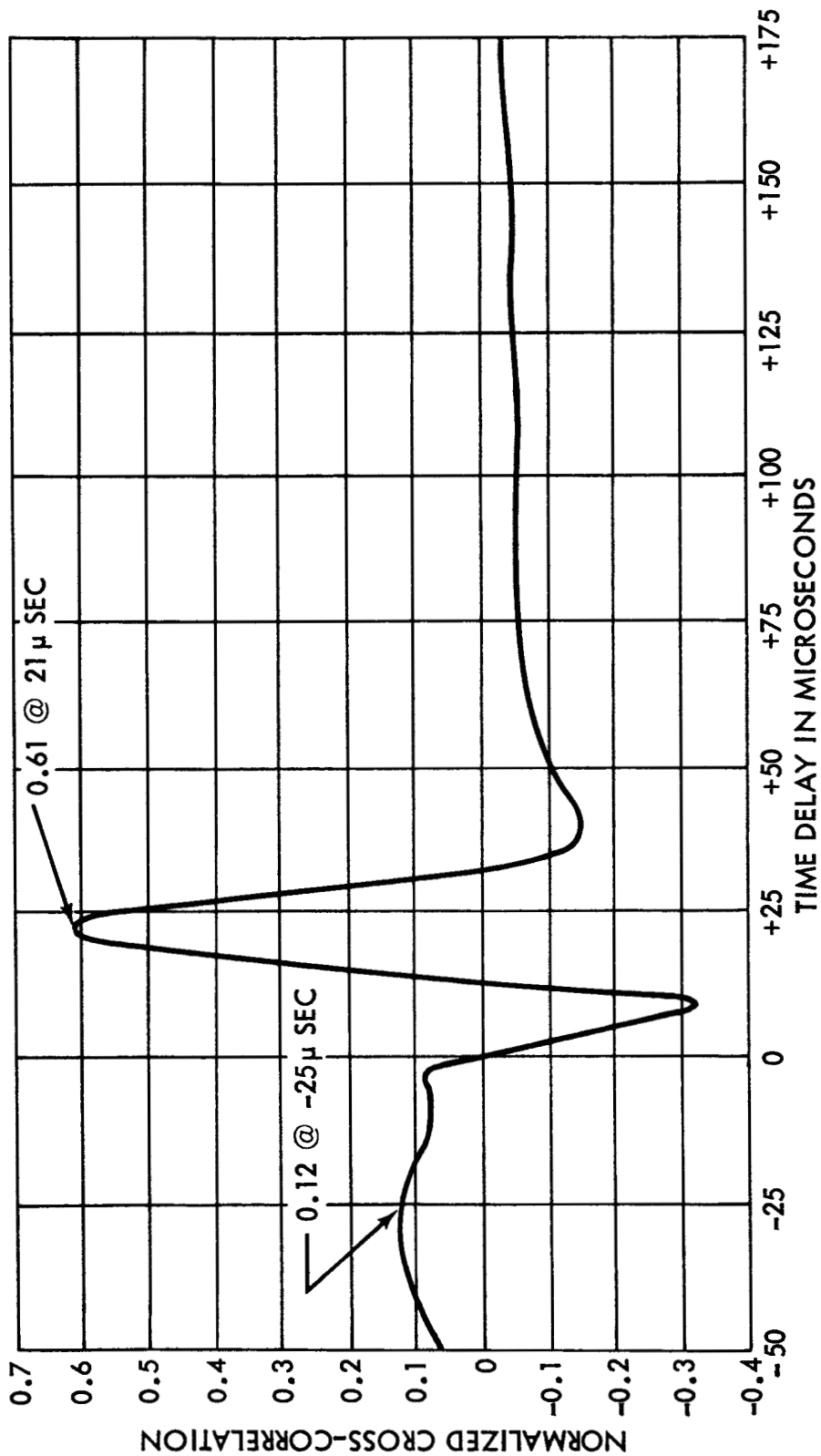


FIGURE A-26a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS ① & ④)
700°F JET TEMP.

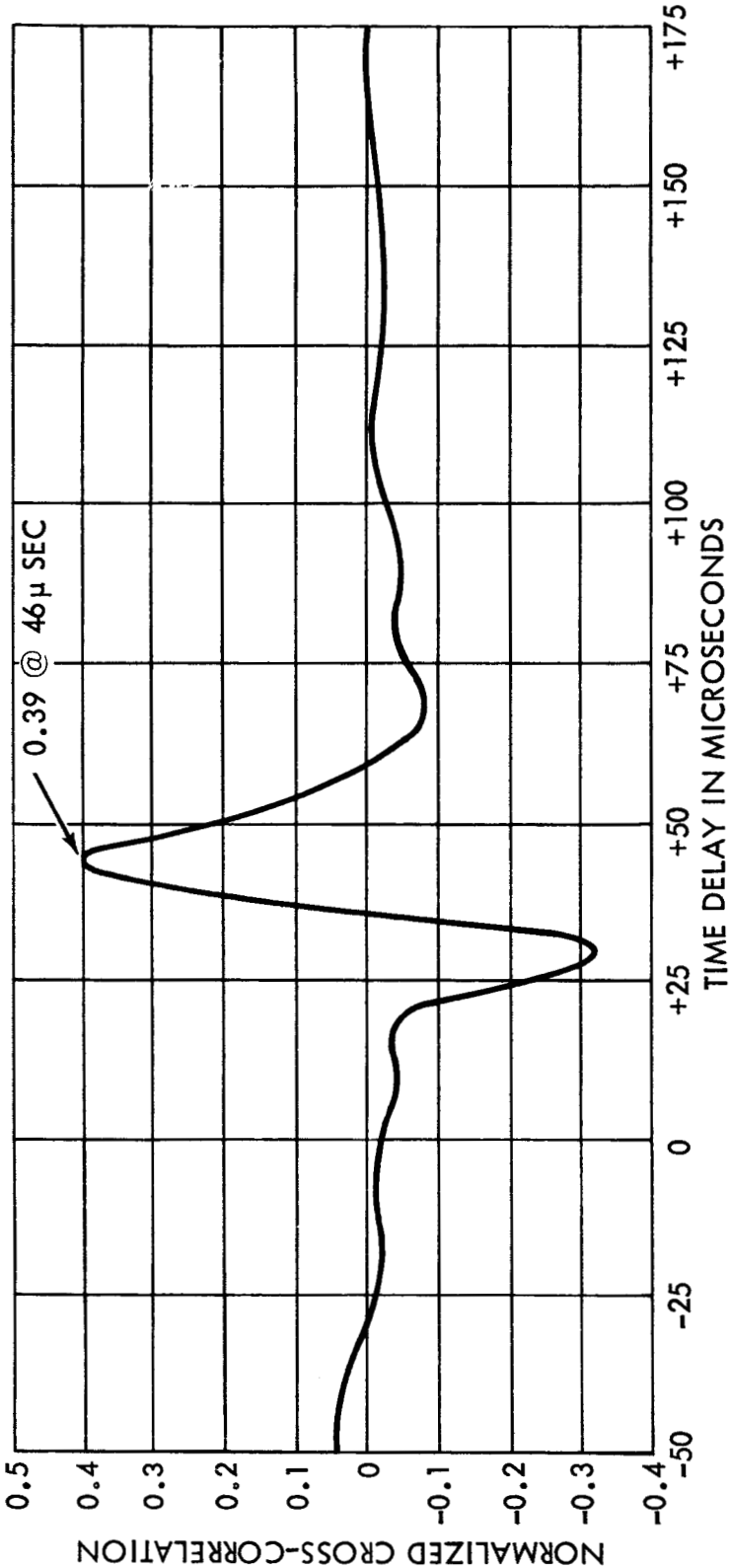


FIGURE A-26b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS ① & ④)
700°F JET TEMP.

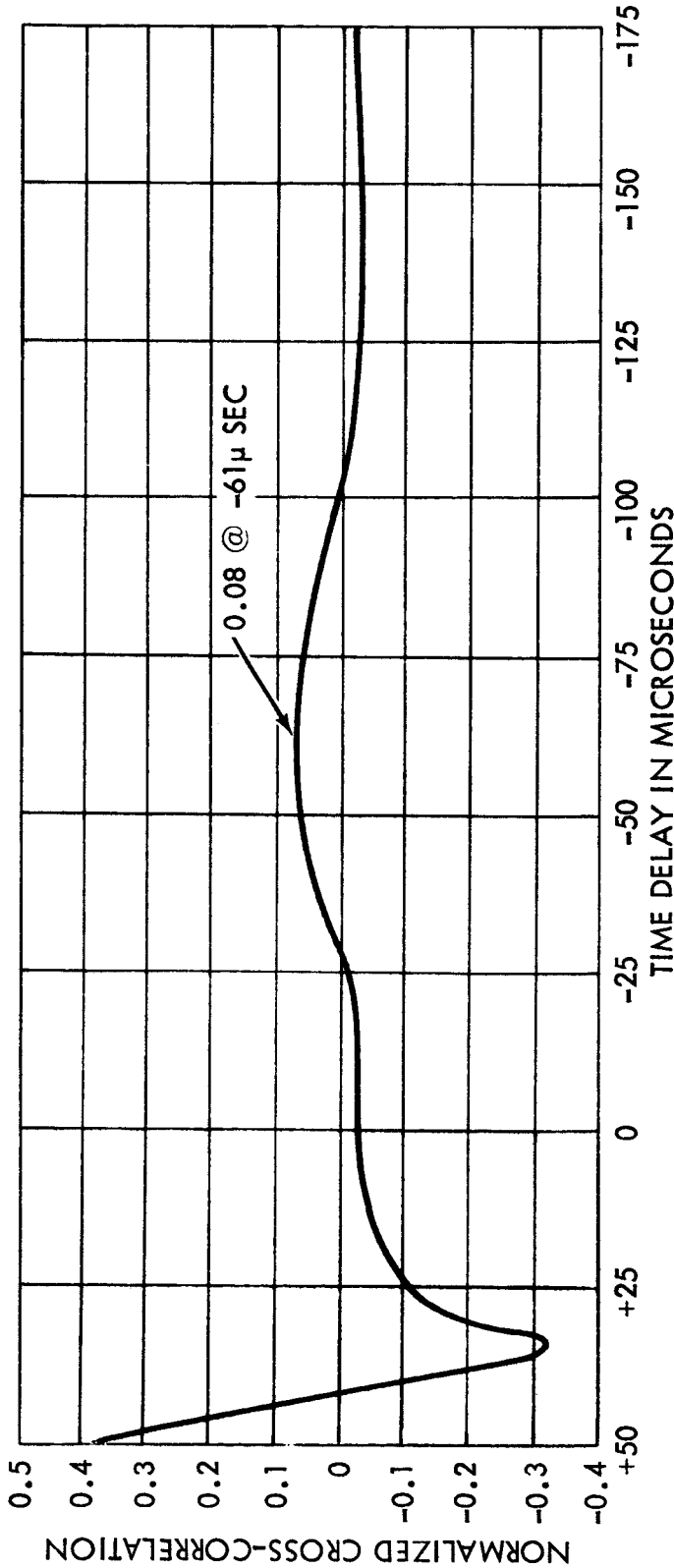


FIGURE A-27a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
2" SPACING (POS ① & ⑤)
700°F JET TEMP.

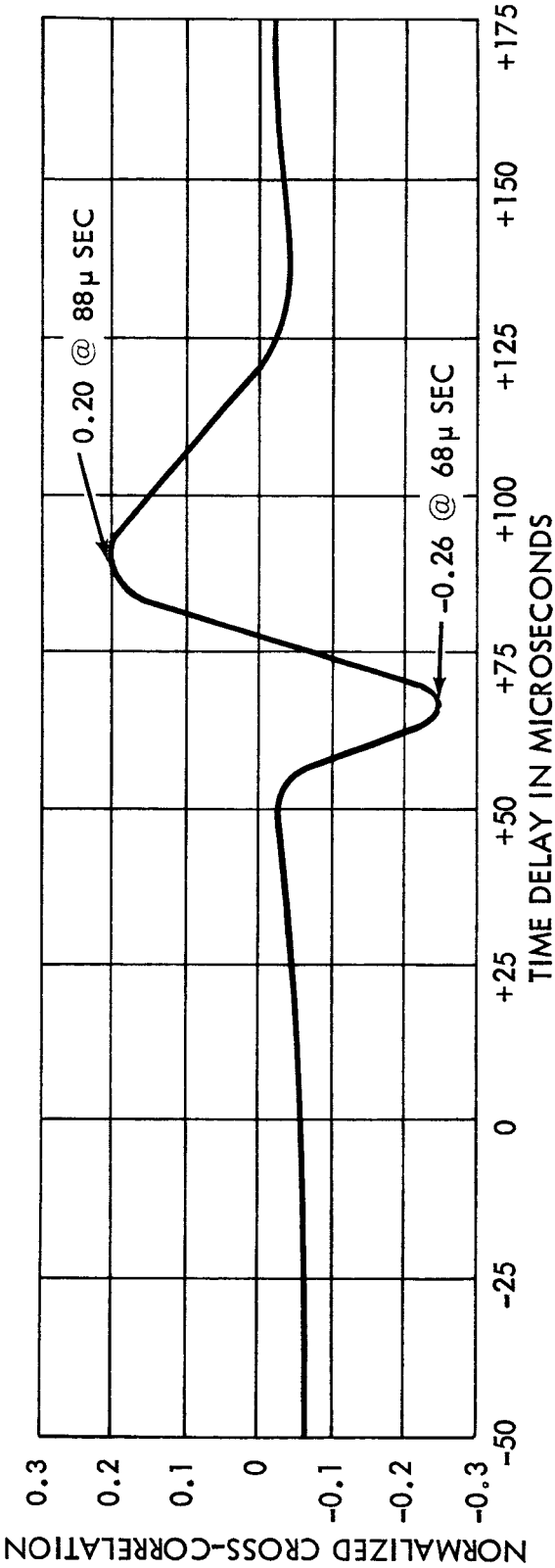


FIGURE A-27b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
2" SPACING (POS ① & ⑤)
700°F JET TEMP.

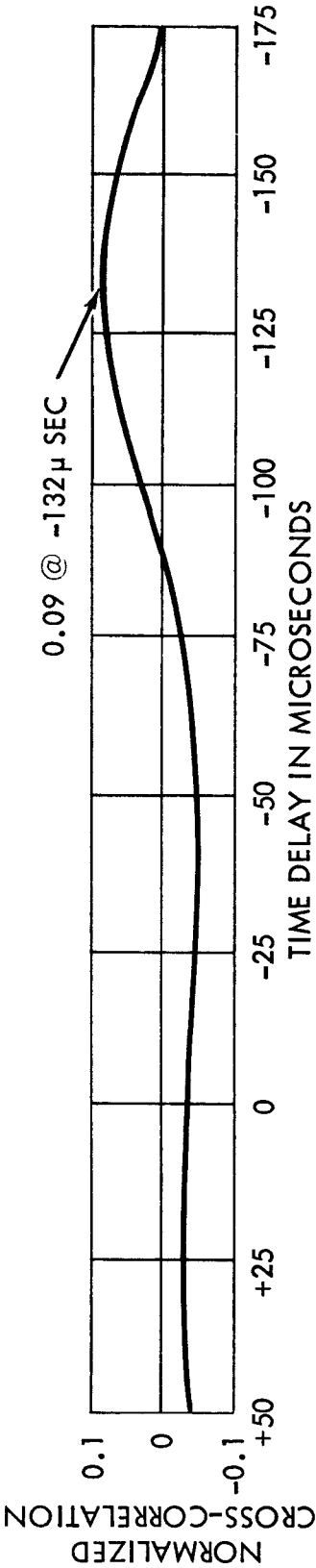


FIGURE A-28
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
4" SPACING (POS ① & ⑥)
700°F JET TEMP.

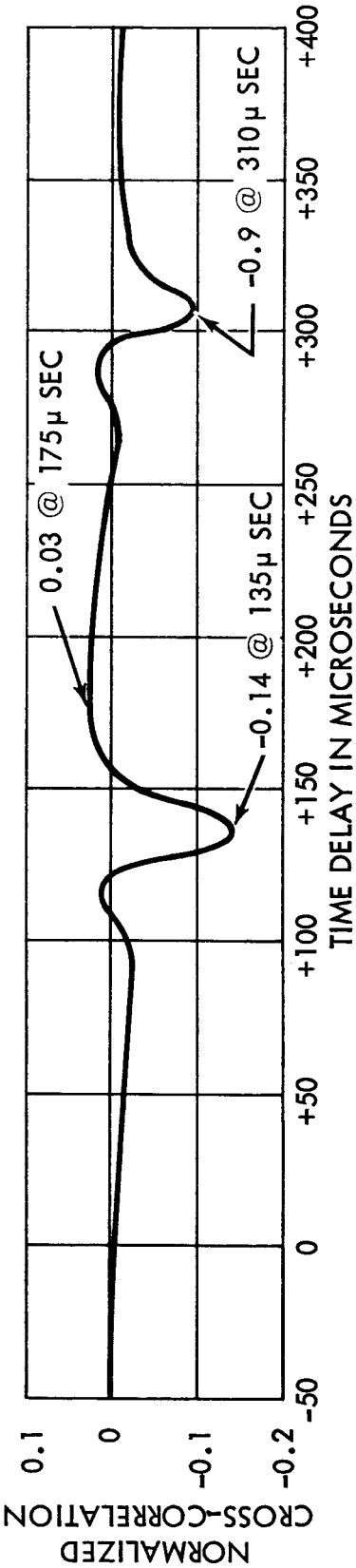


FIGURE A-29
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
8" SPACING (POS ① & ⑦)
410°C JET TEMP.

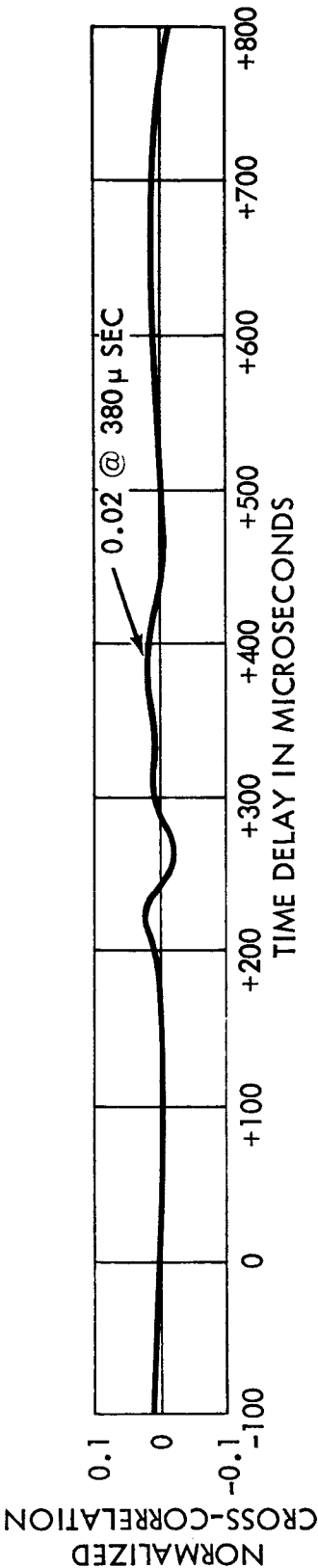


FIGURE A-30
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/4" SPACING (POS ① & ②)
640°C JET TEMP.

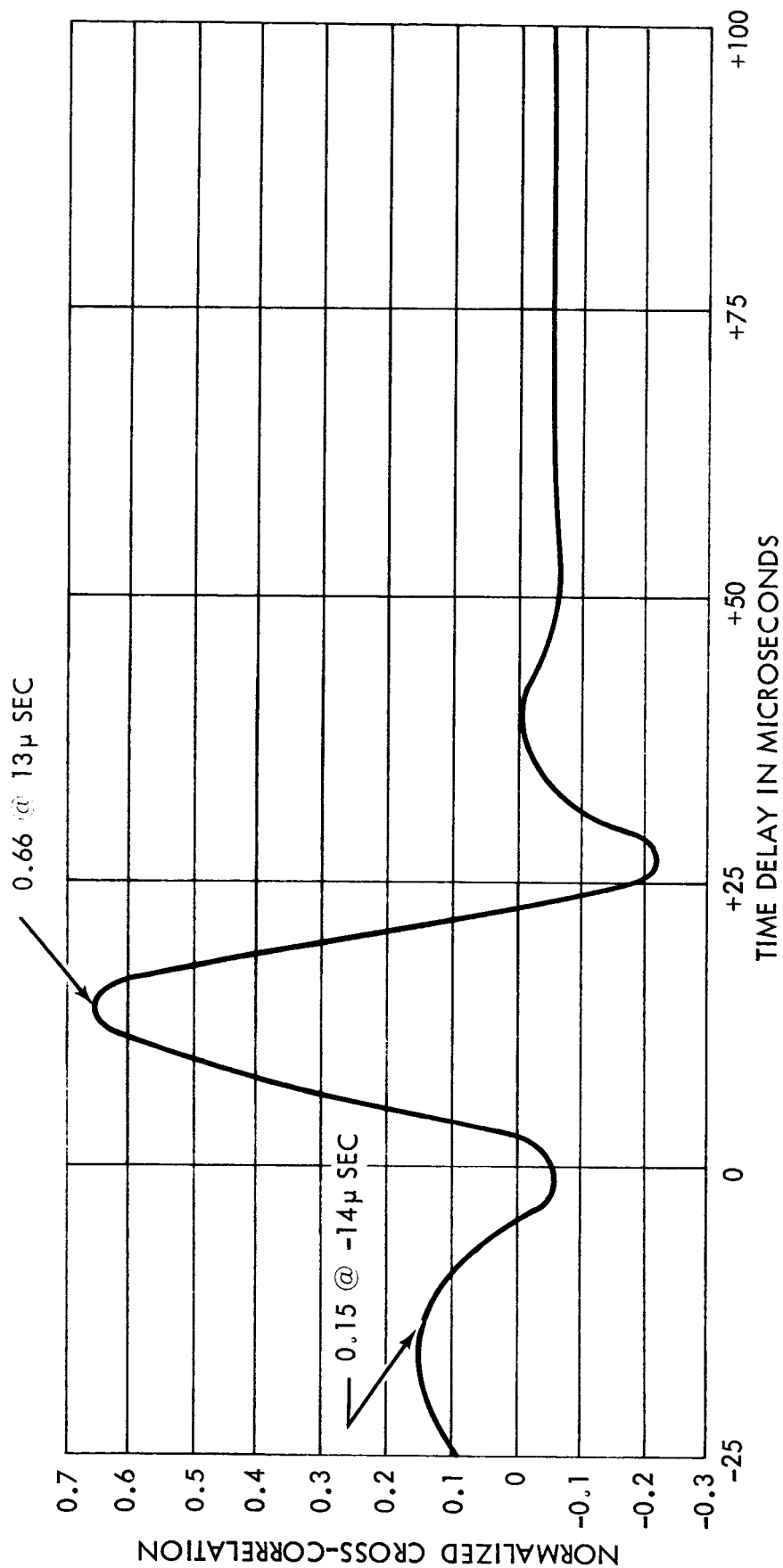


FIGURE A-31
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1/2" SPACING (POS ① & ③)
640°C JET TEMP.

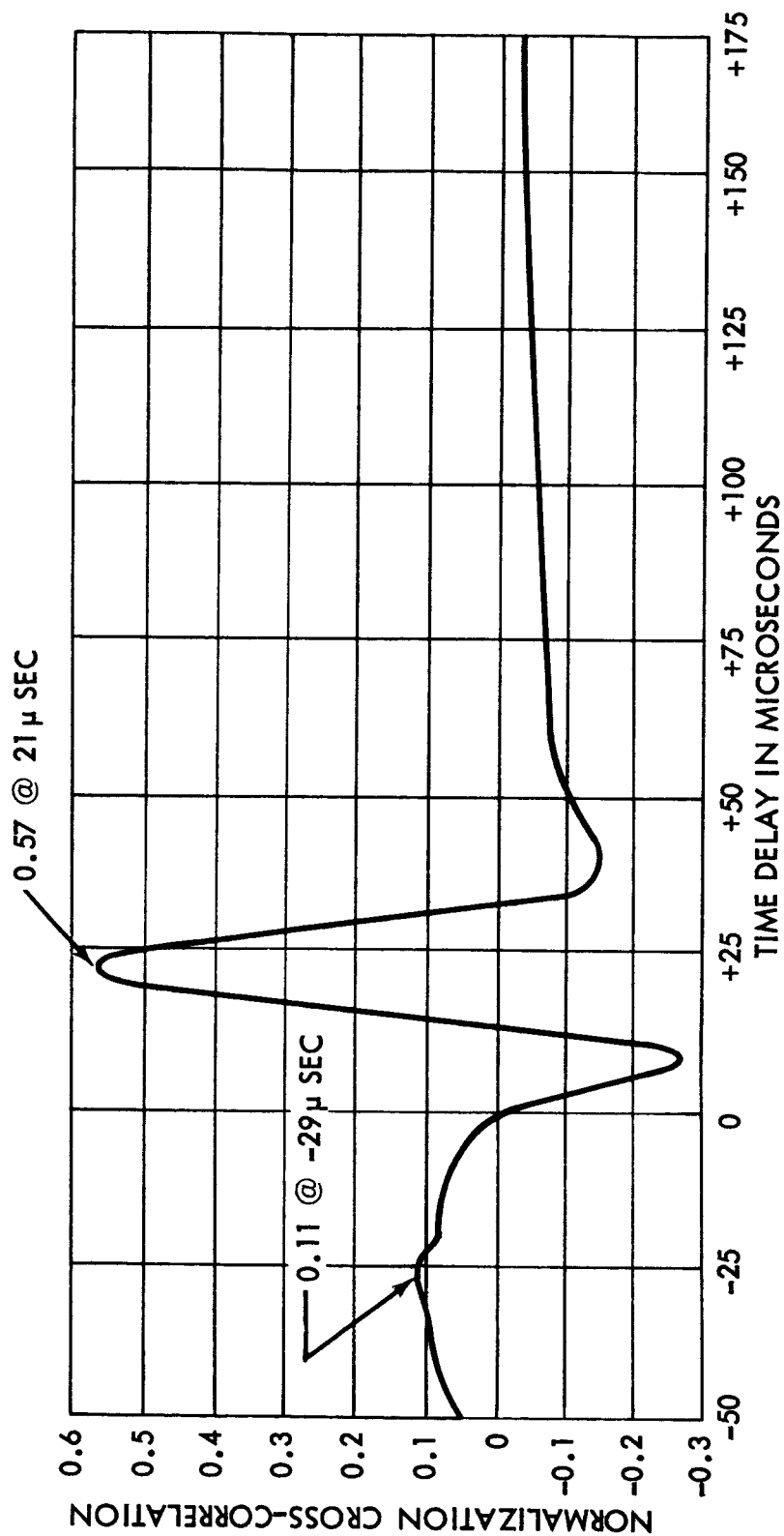


FIGURE A-32a
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS (1) & (4))
640°C JET TEMP.

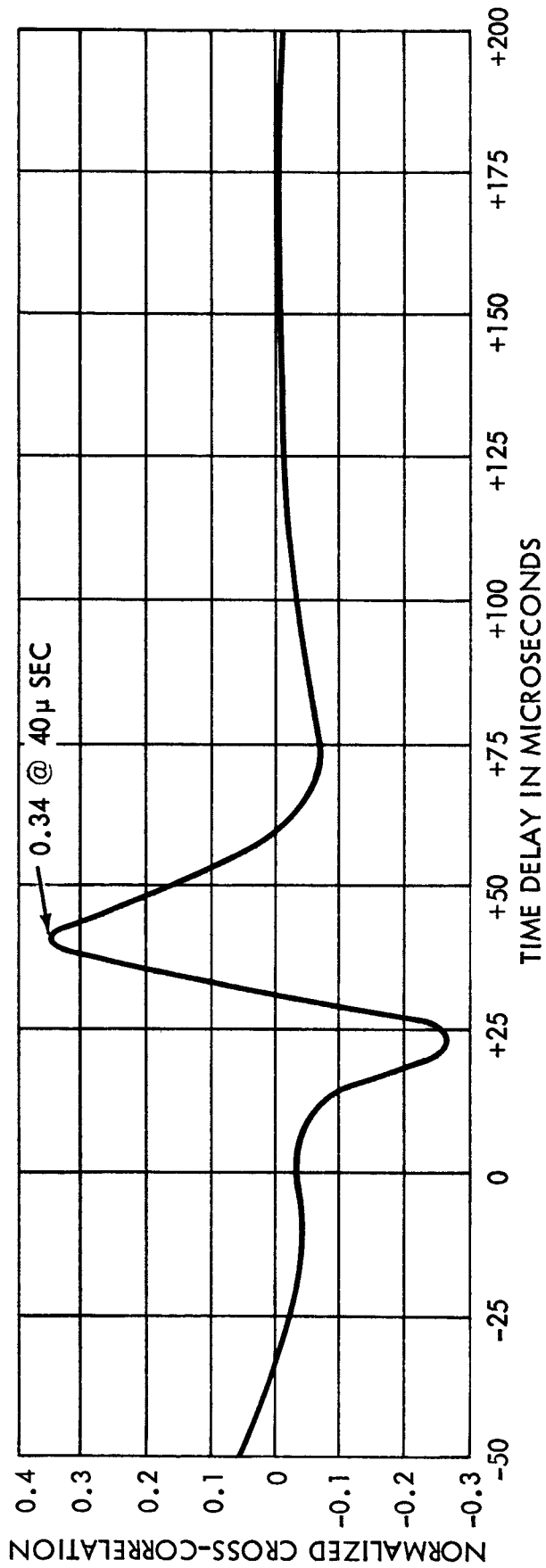


FIGURE A-32b
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
1" SPACING (POS ① & ④)
640°C JET TEMP.

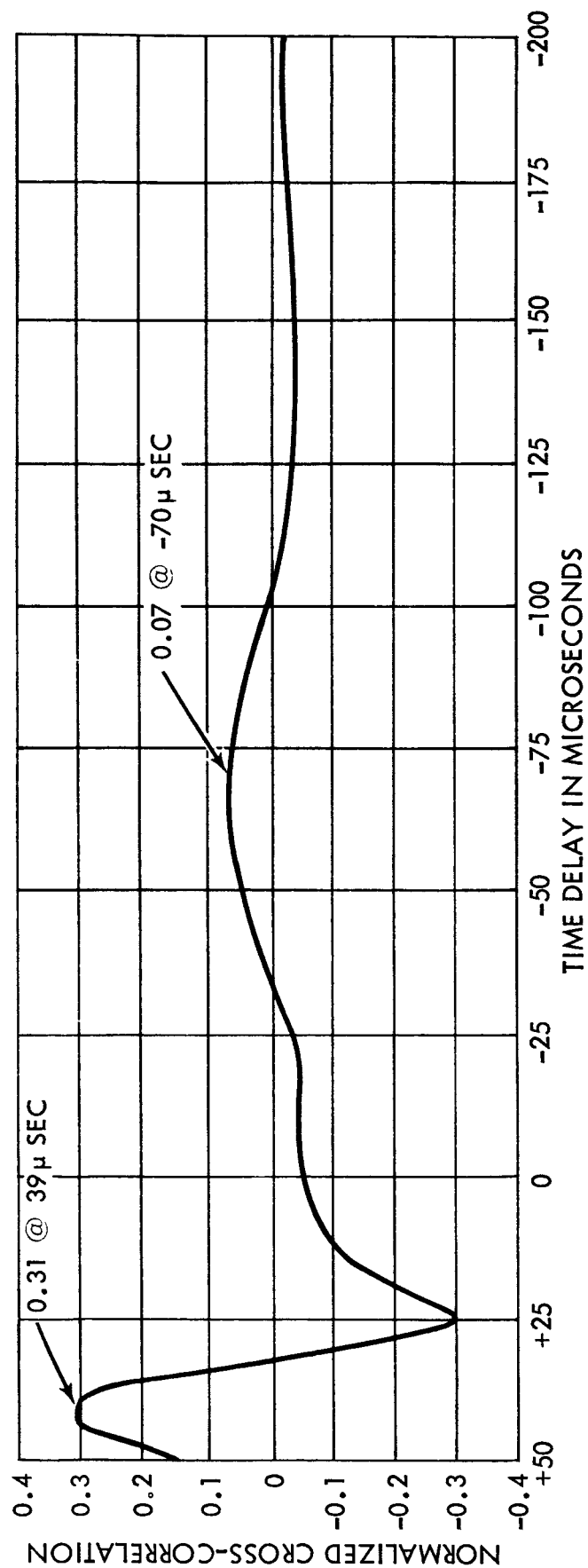


FIGURE A-33
MODEL JET NOISE STUDIES
BAFFLED-MICROPHONE CORRELATIONS
2" SPACING (POS ① & ⑤)
640°C JET TEMP.

