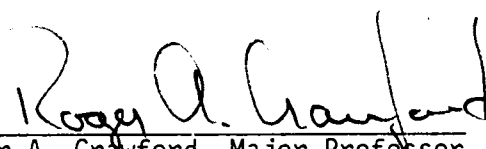


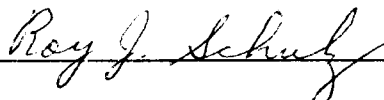
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LAMINAR BOUNDARY LAYER INSTABILITIES
ALONG SLENDER BLUNT CONES AT MACH 8

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Norman Harold Patnode

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ABSTRACT

To provide insight into the effects of nosetip bluntness on the stability characteristics of hypersonic flow over slender cones, the author analyzed the data from Stetson, Thompson, Donaldson and Siler's 1986 stability investigation. This was Stetson, et al.'s second investigation of a 0.70-inch nosetip radius sphere-cone.

Stability data, collected in the entropy layer by Stetson, et al. using hot-wire anemometers, were reduced into mass-flux and total temperature components using modal analysis and fluctuation-diagram techniques. Amplitude and amplification rates were calculated for each component, and the entropy layer is examined for instabilities. The stability characteristics of the entropy layer are summarized in an entropy layer stability diagram.

Disturbances are observed in the entropy layer along the cone frustum which grow in amplitude as they progress down the model. This growth is likely the result of instabilities seen in the entropy layer. Previous data indicate the entropy layer disturbances enter the boundary layer and grow rapidly. For large-bluntness sphere-cones the flow undergoes transition shortly after these large-amplitude disturbances enter the boundary layer. However, the boundary layer remains stable on small-bluntness sphere-cones after swallowing the entropy layer.

TABLE OF CONTENTS

SECTION	PAGE
1.0 INTRODUCTION	1
2.0 BACKGROUND	5
3.0 APPARATUS	10
3.1 Test Facility	10
3.2 Test Article	11
3.3 Flow-Field Survey Mechanism	11
3.4 Flow-Field Survey Probes	12
3.5 Hot-Wire Anemometer Instrumentation	13
4.0 TEST DESCRIPTION	15
4.1 Test Conditions	15
4.2 Test Procedures	16
4.3 Data Acquisition	16
4.4 Probe Calibration	19
5.0 REDUCTION OF QUANTITATIVE HOT-WIRE DATA	21
5.1 Anemometer Signal Analysis	21
5.2 Anemometer Signal Restoration	22
5.3 Modal Analysis of Restored Anemometer Signal	23
5.4 Determination of Disturbance Amplitudes	28
5.5 Determination of Disturbance Amplification Rates	30
6.0 RESULTS AND DISCUSSION	32
6.1 Boundary Layer Profiles	34
6.2 Qualitative Hot-Wire Data	35
6.3 Quantitative Hot-Wire Data	38
6.3.1 Fluctuation Spectra	39
6.3.2 Disturbance Amplitudes vs R	40
6.3.3 Disturbance Amplification Rates versus Frequency	41
6.3.4 Comparison of 1986 Data with 1981 Data	42
6.4 Entropy Layer Stability Diagram	43

SECTION	PAGE
7.0 SUMMARY AND CONCLUSIONS	45
BIBLIOGRAPHY	50
APPENDICES	54
A. FIGURES	55
B. SUPPLEMENTARY INFORMATION	98
VITA	105

LIST OF FIGURES

FIGURE	PAGE
1. Schematic Illustration of Flow Over a Slender, Blunt Cone	55
2. A Comparison of Nosetip Bluntness Effects on Cone Frustrum Transition	56
3. AEDC Tunnel B	57
4. Model Installed in Tunnel B	58
5. Model Installed (Survey Mechanism Visible)	59
6. Model Geometry and Instrumentation Locations	60
7. Survey Probe Configuration	61
8. Survey Probe Details	63
9. Hot-Wire Instrumentation	65
10. Square of the Hot-Wire Voltage Obtained in Continuous Sweeps of the Probe Across the Cone Flow Field, at Different Stations Along the Length of the Cone	66
11. Representative Spectra of Hot-Wire Data and Corresponding Noise	69
12. Entropy Layer Fluctuation Spectra	70
13. Mass-Flow Fluctuation Amplitudes at 12 kHz	71
14. Total Temperature Fluctuation Amplitudes at 12 kHz	72
15. Mass-Flow Fluctuation Amplification Rates at 12 kHz	73
16. Total Temperature Fluctuation Amplification Rates at 12 kHz	74
17. Amplification Rate Spectra of Mass-Flow Fluctuations	75
18. Amplification Rate Spectra of Total Temperature Fluctuations	79

19. Entropy Layer Stability Diagram Based on the Variation of Dimensionless Frequency, F , versus the Square Root of the Local Reynolds Number, R	84
20. Mean Total Temperature Boundary Layer Profiles	85
21. Mean Velocity Boundary Layer Profiles	87
22. Transverse Profiles of $\rho \partial u / \partial y$ and $\partial M / \partial y$ Across the Boundary Layer and External Flow on $R_n = 0.70$ in Cone	95
23. Boundary Layer Total Thickness as a Function of Distance Along Cone Surface	96
24. Comparison of Spatial Locations of the Points where Quantitative Data was Measured Compared to the Boundary Layer Thickness	97

LIST OF SYMBOLS

A	Amplitude of disturbance fluctuations, arbitrary units
A'_w	Overheating parameter, $(R_w - R_r)/R_r$
ALPHA	Angle of attack, degrees
D_j	Coefficients used in fluctuation diagram technique, $j = 1-5$
e	Voltage across hot-wire sensor, volts
E'	Finite-circuit parameter
f	Frequency, Hz
F	Dimensionless frequency, $2\pi f/u_e \text{ Re}_x/ft$
k	Thermal conductivity, BTU/hr ft °R
K	$(d \log R_w)/(d \log T_w)$
m	Mass-flux, lbs/ft ² -sec
m	$(d \log \mu)/(d \log T_w)$, (Equation (2))
M	Mach number
n	$(d \log k)/(d \log T_w)$
Nu	Nusselt number
PHI	Roll angle, degrees
r	Fluctuation diagram parameter, $\Delta e_m/\Delta e_T$
R	Resistance of wire, (Equation (2))
R	$\sqrt{\text{Re}_x}$
Re	Reynolds number
Re_x	Reynolds number based on conditions at the boundary layer edge and curvilinear surface distance from the nosetip
R_{mT}	Coefficient correlating mass-flow and total temperature fluctuations
R_n	Nosetip radius of sphere-cone model, inches

RMS	Root mean square of the value
s	Curvilinear distance along model surface measured from stagnation point, inches
T	Temperature (usually subscripted or superscripted), °R
TT	Tunnel stilling chamber pressure, psia
TTL	Local total temperature, psia
THETA	Peripheral angle on the model measured from ray on model top, positive clockwise when looking upstream, degrees
u	Velocity, ft/sec
x	Location on model measured axially from the virtual nosetip, inches
XSTA	Measurement station on model at location x
X _{sw}	Location where entropy layer is swallowed by the boundary layer, inches
X _T	Location where transition begins on the model, inches
z	Distance measured perpendicular to model surface, inches
Z	Fluctuation diagram parameter, $e/\bar{e}\Delta e_T$
α	Angle of attack, degrees
$-\alpha_i$	Amplification rate of disturbance fluctuations (positive $(-\alpha_i)$ indicates growth of fluctuation amplitudes), $1/2A \partial A/\partial R$
γ	Ratio of specific heats
δ	Boundary layer thickness determined from overshoot in total temperature profile, inches
Δe	Instantaneous fluctuation of the hot-wire response, volts
$\Delta()$	Fluctuating component of ()
$\Delta e()$	Sensitivity coefficient of wire for () component, volts
η	Recovery factor, T_r/T_t
θ_c	Cone half angle, degrees
μ	Viscosity

ρ	Density, lbs/ft ³
τ_{wr}	Temperature loading, $(T_w - T_r)/T_r$
ϕ	Roll angle, degrees

Subscripts

∞	Freestream conditions
o	Total or stagnation conditions
e	Conditions at edge of boundary layer
r	Radiating source
w	Pertaining to the wire
$()_B$	Blunt cone
$()_s$	Sharp cone

Superscripts

$\sim$	Square root of the mean square value
$-$	Average with respect to time

1.0 INTRODUCTION

Transition is the change of the boundary layer flow from laminar to turbulent. This is caused by amplification of the disturbances within the flow (1).¹ The transition of hypersonic flows has been studied for many years. Transition experiments were used to determine the location of transition for given flow conditions and configurations. Most of these experiments investigated the flow over flat plates and slender cones, (2,3) with slender cones being of particular interest because of their applicability to missiles and reentry bodies.

Data from transition experiments were used to determine how various parameters, such as Mach number, Reynolds number, and nosetip bluntness, affected the location of transition. The experiments involving slender cones revealed that blunting the nosetip changed the location of transition. Initially, the nosetip was blunted only slightly, which moved the location of transition downstream. This rearward displacement of transition continued with increasing nosetip bluntness. However, as the nosetip bluntness continued to increase, this trend of rearward displacement of the transition location ceased. In fact, the location of transition began to move back upstream as the nosetip bluntness was further increased. With sufficiently large nosetip bluntness, the location of transition actually moved forward of the sharp-tipped cone transition location (2,3).

¹Numbers in parentheses refer to similarly numbered references in the Bibliography.

The transition displacement reversal suggested that two phenomena were affecting transition on slender blunt cones (2,3). It was known that the pressure losses across the shock upstream of the nosetip caused a reduction in the local Reynolds number of the flow. In addition, experimentation had shown that for bluntness small enough to displace transition downstream, transition always occurred at the same local Reynolds number. Consequently, the rearward displacement of transition was attributed to the reduction in local Reynolds number (2,3). However, the cause of the forward displacement for large bluntness was not known, although changes in the stability mechanisms of the boundary layer flow were suspected. These two effects, local Reynolds number reduction and changes in boundary layer stability, were believed to be competing for dominance in the hypersonic flow over slender blunt cones (3).

To further evaluate the cause of the transition displacement reversal a better understanding of the causes of boundary layer transition was needed. This led Ken Stetson, Elton Thompson, Joe Donaldson, and Leo Siler to conduct a series of experiments to investigate the stability of hypersonic boundary layers (4,5,6,7). Using hot-wire anemometers, Stetson, et al. probed the boundary layer to obtain data on the characteristics of the flow. The intent was to understand the stability mechanisms which caused transition, and thus provide insight into the cause of the forward displacement of transition (4,5,6,8).

The stability investigations of Stetson, et al. were conducted in Arnold Engineering Development Center's Tunnel B at Mach 8 using seven degree half-angle cones. The investigations began with a sharp cone, which was compared to linear stability theory and used as a baseline for the bluntness investigations (4). After establishing a baseline, the small bluntness ($R_n = 0.15, 0.25$ inch) sphere-cones were investigated. Small blunting resulted in large increases in flow stability, and a rearward displacement of transition. Next, the large bluntness ($R_n = 0.50, 0.70$ inch) sphere-cones were investigated.

The highly curved detached shock at the nose of these large bluntness configurations generates a high entropy gradient fluid layer as shown in Figure 1.² This high entropy layer is subsequently entrained by the boundary layer as the boundary layer grows along the cone frustrum. This region of high entropy fluid between the boundary layer and that portion of the flow which has passed through a nearly conical shock is referred to as the entropy layer. During the large-bluntness investigations flow perturbations, or disturbances, were observed in the entropy layer outside of the boundary layer. These disturbances showed significant amplification in the entropy layer, and as the boundary layer swallowed the entropy layer, these disturbances entered the boundary layer and grew rapidly. This came as a complete surprise to Stetson, et al. The observation that disturbances existed in the entropy layer and were affecting the stability of the boundary layer was unexpected (8).

²Figure 1 and all subsequent figures are contained in Appendix A.

To further investigate their observations, Stetson, et al. conducted a second investigation of the $R_n = 0.70$ inch sphere-cone (9). However, funding constraints prevented the analysis and presentation of these data.

Thus, the reporting of this stability mechanism remained incomplete (5,6). This paper discusses the work leading up to the large bluntness ($R_n = 0.70$ inch) investigations. Data from Stetson, et al.'s second large-bluntness investigation was analyzed by the author, and an explanation of the data reduction procedures is presented. For consistency, the methods used were those developed by Stetson, et al. Comparisons are made by the author between this data and that of Stetson, et al.'s first investigation of the 0.70 inch radius sphere-cone. In addition, large-bluntness flow stability is compared by the author with both sharp cone and small-bluntness flow stability. The results of the second $R_n = 0.70$ inch investigation, taken in conjunction with Stetson, et al.'s previous work, provide insight into the reversal of transition displacement in hypersonic flow over slender blunt cones.

2.0 BACKGROUND

When Stetson, et al. began their investigation into the characteristics of boundary layer flow over slender cones, they had the benefit of the linear stability theory previously developed by Leslie Mack. Using a linearized, three-dimensional, locally parallel, compressible-flow stability code, Mack established the existence of unstable higher modes, and their dominance in hypersonic flows. Mack had predicted that the growth, or damping, of these higher mode fluctuations would be strongly frequency dependent (10-15). The basic aspects of this linear stability theory were experimentally verified for flat plates and sharp cones by both Kendall (16) and Demetriades (17).

Stetson, et al. began with a sharp ($R_n = 0.0015$ inch) seven degree half-angle cone to first verify their experimental techniques and analysis procedures, although their interests were more expansive. Stetson, et al. conducted five separate experiments in AEDC's Tunnel B, including the second experiment with the 0.70-inch nosetip configuration (9,18,19). The initial work with the sharp cone also served as a comparison baseline for the later, blunter configurations. (4,8) The configurations and conditions of each investigation, along with a summary of all the data collected by Stetson et al is presented as Supplementary Information in Appendix B.

In 1983, Stetson, et al. reported the results of the sharp cone data collected from the first three experiments at AEDC (4). As predicted by Mack, second mode fluctuations existed, and were the most amplified. In addition, higher mode fluctuations were also observed. These fluctuations were believed to be a harmonic of the

second mode, and were not predicted by Mack. The second mode and its harmonic occurred only at selected frequencies, and those frequencies decreased as you moved downstream on the model. Calculations showed the second mode fluctuation wavelengths were about twice the boundary layer thickness, and the harmonic mode fluctuation wavelengths were about equal to the boundary layer thickness. This correlates well with the observed decrease in the frequency-most-amplified as the boundary layer thickness increased.

The location of the maximum fluctuations was always very near the boundary layer edge, with most of the disturbance energy located in the top half of the boundary layer. Very little disturbance energy was observed at frequencies above 300 kHz.

Stetson, et al.'s experimental results closely agreed with the linear stability theory, and further verified Mack's work. (The second mode harmonic fluctuations which were observed are nonlinear and could not be predicted by linear theory.) In addition, the amplification-rate data agreed very well with the experimental work of Kendall and Demetriades (4).

With experimental techniques and analysis procedures verified for flow over a sharp cone, Stetson, et al. proceeded to analyze the boundary layer stability characteristics of hypersonic flow over small bluntness sphere-cone configurations. They presented the results of 0.15, 0.25, 0.50, and 0.70 inch nosetip configurations in 1984, and reported that the stability characteristics were completely changed from those of the sharp cone (8).

Stetson, et al. found that for the small bluntness configurations ($R_n = 0.15, 0.25$ inch) disturbances of all frequencies were damped to high local Reynolds numbers. Unlike the sharp cone, the Reynolds number at which disturbances were first amplified (the critical Reynolds number) was high for the small bluntness sphere-cones. Once disturbances began to amplify within the boundary layer, they grew rapidly, with transition occurring at a Reynolds number only slightly larger than the critical Reynolds number. This was quite different from the sharp cone which has a low critical Reynolds number, followed by a long region of moderate disturbance growth. When transition does occur on the sharp cone, it is at a Reynolds number significantly larger than the critical Reynolds number.

For the $R_n = 0.15$ inch sphere-cone the critical Reynolds number occurred at the approximate location where the boundary layer had swallowed the entropy layer, indicating that the entropy layer swallowing region is a stable region of the flow. The entire flow over the $R_n = 0.25$ inch sphere-cone was in the entropy layer swallowing region, and the boundary layer was stable over the entire model.

As the nosetip bluntness is increased further, the characteristics of the flow again change. For the larger bluntness configurations ($R_n = 0.50, 0.70$ inch), transition occurred at a lower Reynolds number than on the sharp cone. This outcome was not unexpected because transition experiments show that there is a definite limit to the benefits of nosetip bluntness (3).

However, the flow over both the $R_n = 0.50$ and 0.70 inch sphere-cones did produce some unexpected results. In both cases Stetson, et

al. found large amplitude disturbances outside the boundary layer, but within the entropy layer. These disturbances grew as the flow progressed down the model, suggesting the existence of instabilities within the entropy layer. To investigate the possible existence of such instabilities, Stetson, et al. first calculated the $\rho \partial u / \partial y$ profiles to determine if local maximums existed in the vorticity distribution within the entropy layer. Such maximums would indicate the existence of instabilities (8,10). The vorticity distribution within the entropy layer is small, and no clear local maximums were discernible. At the suggestion of Eli Reshotko, Stetson, et al. then calculated the $\partial M / \partial y$ profiles. For inviscid flow only, these local maximums approximately correlate to local maximums in the vorticity distribution (6,8). The Mach number profiles were compared with the experimental hot-wire surveys, and the local maximums in the $\partial M / \partial y$ profiles approximately corresponded to the locations of maximum fluctuation energy sensed by the hot wire (8).

As the entropy layer is swallowed by the boundary layer, these large amplitude disturbances enter the boundary layer and begin to grow rapidly. Stetson, et al. have suggested that these large amplitude disturbances could force an otherwise stable boundary layer to grow much like environmental disturbances are known to affect boundary layer flows (8).

In an effort to correlate the results of several experiments investigating the effects of nosetip bluntness, Stetson plotted the data from three different test facilities as shown in Figure 2. By nondimensionalizing sphere-cone transition-experiment data with sharp-

cone data and plotting it versus the ratio of boundary layer transition distance divided by the distance where entropy layer swallowing occurs, X_T/X_{SW} , Stetson was able to correlate data from three different facilities. This technique allowed him to show that nosetip bluntness effects were independent of the test facility.

After investigating other aspects of the boundary layer stability problem, including unit Reynolds number effects (20), facility influences (3,21), and pressure-gradient effects (22), Stetson, et al. returned to Tunnel B at AEDC to continue the investigation of the $R_n = 0.70$ inch sphere-cone configuration in 1986. A summary of all the data collected for the $R_n = 0.70$ inch sphere-cone is presented in Appendix B. The particulars of the 1986 investigation, the results of the data analysis, and the author's conclusions are presented in the following sections.

3.0 APPARATUS

When Stetson, et al. arrived at AEDC for their second stability investigation of the $R_n = 0.70$ inch sphere-cone Tunnel B seemed like an old friend (6). However, it had been five years, and several things needed to be refurbished or fabricated anew. The model used in the original investigation was not in very good shape, so an identical force and moment model was refurbished with pressure taps and thermocouples (5,9). The survey mechanism was pulled out of storage, checked out and installed in the tunnel along with the newly refurbished model (5). As before, new hot-wire, total temperature, and pitot probes were fabricated in preparation for the investigation. AEDC's constant current hot-wire instrumentation system was again used, providing consistency with the previous investigations (5,9).

3.1 Test Facility

The AEDC Tunnel B, shown in Figure 3, is a closed circuit hypersonic wind tunnel with a 50-inch-diameter test section. The axisymmetric Mach 8 contoured nozzle used allows continuous operation at stagnation pressure levels between 50 and 900 psia. The available range of freestream Reynolds number/foot is 0.3 to 4.7×10^6 . To prevent air liquefaction, a natural gas fired combustion indirect heat exchanger is used to provide stagnation temperatures up to 1350°R . The throat, nozzle, test section, and diffuser are cooled by integral, external water jackets.

Tunnel B is equipped with a model injection system, which allows the model to be removed from the test section while the tunnel remains

in operation. Further information on Tunnel B can be found in Reference (23).

3.2 Test Article

The model used for this investigation was a seven degree half-angle cone constructed at AEDC of 304 stainless steel. It is shown installed in Tunnel B in Figure 4. The cone had a 40-inch virtual length, a 9.82-inch base diameter, and a 0.70-inch radius spherical nosetip. For this investigation, an existing 10.5- inch frustrum extension was added to increase the area of entropy layer swallowing which could be surveyed with the flow field probes. This 10.5-inch extension to the model is visible in Figure 5.

The model was instrumented as shown in Figure 6 with both pressure orifices and thermocouples. The 25 pressure orifices were arranged primarily along the top centerline ray ($\text{THETA} = 0$), with orifices also being located on the $\text{THETA} = 90, 180, \text{ and } 270$ degree rays at three axial model stations. The four thermocouples were mounted internally along the $\text{THETA} = 270$ degree ray. The actual locations of both the pressure orifices and the thermocouples are presented in Appendix B.

To allow surveying the model as far downstream as possible, the model was installed as far upstream in the test section as practical. Again, this was to allow maximum surveying of the entropy layer swallowing region (9).

3.3 Flow-Field Survey Mechanism

Flow field surveys were conducted using a retractable survey system (x-z) which was designed and built at AEDC. The mechanism can

be retracted into a housing which is fitted to a 40 inch long by four inch wide air lock above the test section. The housing can be sealed from the tunnel by a pneumatically operated door, which allows the probes to be changed while the tunnel remains in operation.

The survey mechanism has a 35-inch range in axial positioning, and a ten-inch range in vertical positioning. Separate drive motors control injection, axial positioning, and vertical positioning.

The survey probes are rake mounted on a strut, which can be manually swept to any angle between five degrees upstream and 15 degrees downstream. The rake contains four tubes, each 0.10 inch I.D., which contain a hot-wire anemometer probe, a pitot pressure probe, a total temperature probe, and a touch probe. The touch probe is a safety which stops the motion of the survey mechanism when it touches the model. Figure 7 provides a detailed sketch of the probe configuration, and Figures 5 and 7 show the probes mounted in Tunnel B.

The probes are also fitted with a pneumatically operated shield which is lowered during injection and retraction through the tunnel boundary layer, during tunnel condition changes, and other times when the probes are not actually being used. The use of the shield greatly extends the life of the fragile hot-wire probes (9).

3.4 Flow-Field Survey Probes

The hot-wire probes, shown in Figure 8a, were fabricated by the von Karman Facility at AEDC. Using the Wollaston process, platinum-10% rhodium wires were drawn to either 20 or 50 micro-inch nominal diameter and approximately 140 diameters in length. These wires were then bonded, using a technique developed by Philco-Ford Corporation (24), to

sharpened three mil nickel wire supports. The wire supports were inserted in a 0.25 inch long, 0.032 inch diameter alumina cylinder, which was then glued to another alumina cylinder of 0.093 inch diameter and 3.0 inches long. This last cylinder carried the hot-wire leads through the probe holder of the survey mechanism.

The pitot pressure probe, shown in Figure 8b, was fabricated by cold-drawing a stainless steel tube through a set of wire-drawing dies until the cylindrical tip had an inside diameter of 0.007 inches. The drawn tube was then electropolished to an outside diameter of 0.015 inches to minimize flow field interference.

The total temperature probe, shown in Figure 8c, was fabricated from a length of 0.020 inch O.D. sheathed CR-AL thermocouple wire containing two 0.004 inch diameter wires. About 0.015 inches of the wires were bared, and then a thermocouple junction of approximately 0.005 inch diameter was made (9).

3.5 Hot-Wire Anemometer Instrumentation

Flow fluctuation measurements were made using constant-current hot-wire anemometry techniques. The instrumentation used is depicted in Figure 9, and described in detail in Reference (25).

The heart of the instrumentation system is a Philco-Ford Model ADP 12/13 amplifier/current control which supplies the wire-heating current to the hot-wire sensor. Push-button switches allow selection of up to 15 previously adjusted wire-heating currents, and the electronic circuitry in the amplifier will automatically compensate for the thermal lag of the hot-wire sensor. When required, a Shapiro/Edwards Model

G-50 square-wave generator is used to determine the time constant of the sensor.

The heating current and mean voltage from the hot-wire sensor are displayed on autoranging digital voltmeters and recorded on both a Bell and Howell Model VR3700B magnetic-tape machine, and the Tunnel B data acquisition system. The raw-signal a-c response of the hot-wire sensor is displayed on an oscilloscope, processed by a Hewlett-Packard Model 8553B/ 8552B wave analyzer to provide a visual display of the spectra of the fluctuating signal, and also recorded on the Bell and Howell Model VR3700B magnetic-tape machine for later analysis.

4.0 TEST DESCRIPTION

During the 1986 investigation, Stetson, et al. matched the test conditions and model configuration with those of their first investigation of the 0.70 inch radius sphere-cone (5,6,7). This allowed them to verify and further study the disturbance instabilities they observed in the entropy layer during the first investigation. Likewise, to avoid the introduction of additional or unaccounted for variables in the two investigations, the test and data acquisition procedures were identical to those of Stetson, et al.'s previous investigations in Tunnel B. The hot-wire and total-temperature-probe calibrations were also performed using the previously developed procedures (5,9).

Although the author has participated in more recent experiments with Stetson, et al., he was not present during the 1986 investigation of the 0.70-inch sphere-cone. Consequently, Reference (9), and many personal discussions with Ken Stetson and Joe Donaldson were used by the author to prepare this section.

4.1 Test Conditions

A summary of the nominal freestream test conditions is given below.

Mach number	8.0
Reynolds number	$2.6 \times 10^6/\text{ft}$
Total Temperature	1311°R
Total Pressure	575 psia
Dynamic Pressure	2.64 psi

Temperature	95°R
Pressure	0.06 psia
Velocity	3822 ft/sec

4.2 Test Procedures

The tunnel is brought up to test conditions, and the model is injected into the flow. After the model has reached equilibrium temperature, hot-wire and mean flow data are collected.

The model is sting mounted on a vertical strut in a tank below the tunnel test section. Before injection, the tank access doors are closed and the tank is vented to tunnel conditions. The fairing and safety doors are then opened and the model is injected into the tunnel flow. The fairing doors are closed, and after the model temperature reaches equilibrium data are collected using the rake-mounted probe sensors. When a model configuration change is required, the fairing doors are opened and the model is retracted into the tank. The safety and fairing doors are then closed and the tank is vented to atmosphere, allowing the access doors to be opened.

4.3 Data Acquisition

Hot-wire anemometry was the primary means of data collection. However, pitot pressures and total temperatures were also taken at several data points to provide mean-flow boundary layer profile data, and to define the flow environment around the hot-wire. Pressure and temperature data were also taken at the model surface to further define the flow.

Several separate surveys of the boundary layer were accomplished at each axial model station. For model stations 16, 30, 36, and 42 the mean flow data were collected. Next a continuous sweep was made with a constant hot-wire-sensor current. Then hot-wire data were collected with a series of increasing wire-heating currents at a single location in the profile.

Surveys of the flow field were accomplished by injecting the probes into the flow and positioning them axially at the desired station. The probes were then lowered, in a direction normal to the model surface, until the touch sensor made contact with the model. The probes were then driven down manually while observing them on a high-resolution closed-circuit TV. The telescopic lens on the closed-circuit TV camera, coupled with the electronics, produced an image on the monitor which was magnified 38 times. An image analyzer/digitizer system, which was interfaced with the video camera of the closed-circuit TV, was then used to determine the actual height of the probes above the model surface. This system automatically located the lower edge of the probe and the upper edge of the model surface, and then calculated the distance between them using computer-assisted analysis techniques. The system was calibrated using this edge-location technique on a known distance prior to the test. It was determined that the accuracy was better than ± 0.00007 inches over the range of 0.003 to 0.2 inches.

At the stations where mean flow data were collected, the probes were positioned 0.02 inches above the model surface and then marched upwards, normal to the model surface, stepping through the boundary

layer to a height of two or three times the boundary layer thickness. During this survey total temperature and pitot pressure, the mean flow parameters, were recorded at 25 to 40 heights.

The probes were then returned to within 0.02 inches of the model surface for the next survey. This time the boundary layer was probed with a continuous sweep, during which the hot-wire sensor current was held constant at the largest practical value. During this upward sweep through the boundary layer, the response (rms of the a-c voltage component) of the hot-wire sensor as a function of the distance normal to the model surface was recorded with an x-z plotter. Figure 10 shows the response of the hot-wire during these sweeps at each of the model stations surveyed.

At the rear stations the plots in Figure 10 show a definite maximum, the "maximum energy point" of References (4), (8), and (26). However, at the forward stations this definite maximum degrades into perhaps two peaks, one inside the boundary layer and one outside the boundary layer.

Influenced by the data from their 1981 experiment, Stetson, et al. opted to collect quantitative data at the measurement stations shown in Figure 10 (6,8).

After sweeping the boundary layer, the probes were returned to the measurement station and quantitative data were collected. The hot-wire response was recorded for a series of increasing wire heating currents, or overheats, to determine the respective contributions of the fluctuating flow parameters to the total fluctuations sensed by the wire. One of the overheats was a nominal zero (unheated wire), to

allow determination of the electronic noise in the system. A total of 40 measurements were taken at each wire overheat.

After obtaining both qualitative and quantitative data at a model station, the probes were raised, the shield lowered, and the rig moved to the next model station where the procedure was repeated.

During the investigation, if the hot-wire broke, the rig was retracted into an airlock above the tunnel and the safety door was closed. The airlock was then vented to atmosphere and opened. A new hot-wire sensor was installed and the process was reversed to return the sensor to the flow. A descriptive log of the wires used can be found in Table 3 of Reference (9).

4.4 Probe Calibration

Reduction of the quantitative hot-wire measurements requires a knowledge of both the thermal and physical characteristics of the sensing wire. This was accomplished with two complementary calibrations of each wire.

First the wires were placed in an oven and heated to 600°F. The resistance of the wire was then measured as the oven was allowed to slowly return to room temperature. This allowed calculation of the reference resistance, and the thermal coefficient of resistance at the reference temperature of 32°F. At this time the wire aspect ratio was also determined as a function of resistance per unit length using the manufacturer's specified parameters. Experience has shown that this first calibration also serves to screen out the weakest wire sensors (27).

The final calibration of the sensor wire was performed in the tunnel freestream, where the heat-loss coefficient (the Nusselt number), and the temperature-recovery characteristics were determined as a function of the local Reynolds number. The tunnel total pressure was varied while holding the total temperature constant to provide several local Reynolds numbers. The total-temperature probe was also calibrated as a function of the local Reynolds number at this time.

5.0 REDUCTION OF QUALITATIVE HOT-WIRE DATA

The author's intent is to compare the data from this investigation with the published results of Stetson et al's previous investigations. Therefore, the procedures used by the author to reduce the hot-wire data are the same as those previously used by Stetson, et al.

The reduction begins by processing the hot-wire signal through a frequency analyzer to digitize and increase the effective frequency range of the data. The electronic noise of the instrumentation system is then subtracted, and the data is further conditioned by compensating the signal for instrumentation deficiencies, and for the thermal lag of the sensing wire. Modal analysis of this processed signal is then used to determine which flow fluctuations are present, and to determine the magnitude of those fluctuations (4,8).

5.1 Anemometer Signal Analysis

The a-c voltage signals collected at each model station provided the total fluctuation amplitude-squared as a function of frequency. The signals were fed to an oscilloscope for immediate evaluation, and recorded on magnetic tape for later analysis.

These recorded data were analyzed using a Spectral Dynamics Corporation Model SD 360 digital signal processor with a frequency range of 0 to 150 kHz. To increase the effective frequency range, the tape was fed into the analyzer at one fourth the speed it was recorded. This provided an effective frequency range of 0 to 600 kHz. The analyzer divided the 600 kHz broadband into 600 Hz narrow bands, sampled the signal for each narrow band 128 times and averaged the result. Thus,

the analog signal was reduced to digital points, equally spaced at 600 Hz intervals, over the frequency range from 0 to 600 KHz.

This analysis was performed for each of the 12 wire-heating currents at each model station.

5.2 Anemometer Signal Restoration

The raw data signals must be processed to subtract the electronic noise of the instrumentation system, and to account for instrumentation error and the thermal lag of the sensing wire.

One of the wire-heating currents was actually a no-current situation (an unheated wire) and represents the electronic noise of the instrumentation system. Figure 11 shows the response of several wire heating currents, including the corresponding "noise," over the frequency range from 0 to 600 KHz. The bottom curve is the response of the unheated wire. This noise response (the unheated wire a-c voltage) was subtracted from each of the other corresponding eleven overheat responses at each of the discrete frequencies. The result is eleven noise-free signals at each model station. The data from the two smallest wire-heating currents were considered questionable because of their low signal-to-noise ratio (both were less than one). Therefore, these two signals were discarded. The remaining nine noise-free signals at each model station were used for all subsequent data reduction and analysis.

The instruments used to obtain the a-c voltage component of the hot-wire signal were found to suffer a roll off with frequency. This roll off was compensated using the methods of Laderman and Demetriades (17). The roll off for each instrument was mathematically defined as a

function of frequency. These math models were then applied as transfer functions to each instrument during the data reduction procedures, producing a "restored" hot-wire response signal. These restored signals were used for all subsequent data reduction and analysis.

Compensation of the hot-wire-anemometer signal for the thermal lag of the hot-wire sensor was also done mathematically. This compensation was done after the fact, and required that the time constant of the given wire be determined for one heating current at one test condition. This determination of the wire time constant was done during the anemometer calibration performed in the tunnel freestream using the square-wave technique.

At this point the digital, discrete-point hot-wire signal is "noise-free", and has been "restored" to compensate for instrumentation deficiencies, and for the thermal lag of the sensing wire. The data can now be analyzed frequency by frequency, or the 600 Hz narrow bands can be integrated to allow analysis of the broadband (summed signal) response. The following modal analysis techniques are valid for both cases (27).

5.3 Modal Analysis of Restored Anemometer Signal

The hot-wire responds to fluctuations of density, velocity, and total temperature. Modal analysis procedures are used to determine which flow fluctuations are present, and to determine the magnitude of those fluctuations. By using the mode concept and fluctuation-diagram techniques introduced by Kovasznay (28) and expanded by Morkovin (27) the a-c voltage response of the hot-wire signal can be reduced to these sensing variable components.

The instantaneous response of the hot-wire follows the equation

$$\frac{\Delta e}{\bar{e}} = -\Delta e_p \left(\frac{\Delta p}{\bar{p}} \right) - \Delta e_u \left(\frac{\Delta u}{\bar{u}} \right) + \Delta e_T \left(\frac{\Delta T_o}{\bar{T}_o} \right) \quad (1)$$

where Δe is the instantaneous fluctuation of the response, and $\bar{e}$ is the mean value of the response (8,27). (The total signal equals a mean value, or d-c component, plus a fluctuating, or a-c component. Equation (1) represents the wire response normalized by dividing the a-c component by the d-c component. This allows study of the flow fluctuations without having to determine the actual values of the mean flow parameters.) The fluctuating components of density, p , velocity, u , and total temperature, T_o are represented by Δp , Δu , and ΔT_o . The mean-value components are represented with a bar over the corresponding symbol, and Δe_p , Δe_u and Δe_T represent the corresponding wire sensitivity coefficients.

The wire sensitivities as presented in Reference (27) depend on Nusselt number, Nu , Reynolds number, Re , Mach number, M , a viscosity related parameter, m , a thermal conductivity related parameter, n , and temperature recovery factor, μ , and are given by

$$\Delta e_p = \frac{\bar{e} E'}{100} \left[A'_w \frac{Re_o}{Nu_o} \frac{\partial Nu_o}{\partial Re_o} - \frac{A'_w}{\tau_{wr}} \frac{Re_o}{\eta} \frac{\partial \eta}{\partial Re_o} \right],$$

$$\Delta e_u = \frac{\bar{e} E'}{100} \left[A'_w \left\{ \frac{Re_o}{Nu_o} \frac{\partial Nu_o}{\partial Re_o} + \frac{1}{\alpha} \frac{M}{Nu_o} \frac{\partial Nu_o}{\partial M} \right\} - \frac{A'_w}{\tau_{wr}} \left\{ \frac{1}{\alpha} \frac{M}{\eta} \frac{\partial \eta}{\partial M} + \frac{Re_o}{\eta} \frac{\partial \eta}{\partial Re_o} \right\} \right],$$

$$\Delta e_T = \frac{\bar{e} E'}{100} \left[K + A'_w \left\{ K - 1 - n_o + m_o \frac{Re_o}{Nu_o} \frac{\partial Nu_o}{\partial Re_o} + \frac{1}{2\alpha} \frac{M}{Nu_o} \frac{\partial Nu_o}{\partial M} \right\} \right] - \frac{A'_w}{\tau_{wr}} \left\{ \frac{1}{2\alpha} \frac{M}{\eta} \frac{\partial \eta}{\partial M} + m_o \frac{Re_o}{\eta} \frac{\partial \eta}{\partial Re_o} \right\} \quad (2)$$

The wire sensitivities must be determined for each test condition, because they change with both wire-heating current and unit Reynolds number. The physical and heat-transfer properties for each wire were determined using an oven and a freestream calibration (see Section 4.4, Probe Calibration), which provided the information required to determine the wire-sensitivity coefficients.

For supersonic flow, the terms $\partial Nu_o/\partial M$ and $\partial \eta/\partial M$ can be neglected. Within the accuracy of the hot-wire-fluctuation measurements, both the wire Nusselt number and the temperature-recovery factor are independent of Mach number (27).

Applying this to Equation (2), the sensitivity coefficients for density and velocity become indistinguishable:

$$\Delta e_\rho = \Delta e_u = \Delta e_m \quad (3)$$

where Δe_m is the sensitivity coefficient for mass-flux, m .

$$m = \rho u \quad (4)$$

$$\ln m = \ln \rho + \ln u \quad (5)$$

$$d \ln m = d \ln \rho + d \ln u \quad (6)$$

$$\frac{m'}{m} = \frac{\rho'}{\rho} + \frac{u'}{u} \quad (7)$$

$$\text{or } \frac{\Delta m}{m} = \frac{\Delta \rho}{\rho} + \frac{\Delta u}{u} \quad (8)$$

Therefore, Equation (1) is rewritten in terms of mass-flux and total temperature only.

$$\frac{\Delta e}{e} = -\Delta e_m \left(\frac{\Delta m}{m} \right) + \Delta e_T \left(\frac{\Delta T_o}{T_o} \right). \quad (9)$$

Next, Equation (9) is squared, and the time average is taken to yield the relation for the mean-square voltage fluctuation $\tilde{e}^2$:

$$\left(\frac{\tilde{e}}{e} \right)^2 = \Delta e_m^2 \left(\frac{\tilde{m}}{m} \right)^2 + \Delta e_T^2 \left(\frac{\tilde{T}_o}{T_o} \right)^2 - 2\Delta e_m \Delta e_T \left(\frac{\tilde{m}}{m} \right) \left(\frac{\tilde{T}_o}{T_o} \right) R_{mT} \quad (10)$$

$\tilde{m}$ and T_o are the root-mean-square (rms) values of the mass-flux fluctuation and the total temperature fluctuation, and R_{mT} is a coefficient correlating the mass-flow and total temperature fluctuations.

To apply the fluctuation diagram technique, Equation (10) is rewritten by introducing the parameters

$$r = \frac{\Delta e_m}{\Delta e_T} \quad (11)$$

and

$$Z = \frac{\tilde{e}}{e \Delta e_T} \quad (12)$$

and making the necessary substitutions:

$$Z^2 = \left(\frac{\tilde{m}}{m} \right)^2 r^2 - 2 \left(\frac{\tilde{T}_o}{T_o} \right) \left(\frac{\tilde{m}}{m} \right) R_{mT} r + \left(\frac{\tilde{T}_o}{T_o} \right)^2 \quad (13)$$

Note Equation (13) is of the form

$$Z^2 = D_1 r^2 + D_2 r + D_3 \quad (14)$$

and for all cases where D_1 is positive, the locus of Equation (13) is a hyperbola. For the special case of perfect correlation, or anticorrelation, between mass-flow and total temperature fluctuations ($R_{mT} = \pm 1$), Equation (14) reduces to a pair of straight lines:

$$\begin{aligned} Z &= (D_4 r + D_5), \\ Z &= (D_4 r - D_5). \end{aligned} \quad (15)$$

The fluctuation-diagram technique is based on the fact that the relative sensitivity of the hot-wire varies as a function of wire-heating current, or overheat. For a given location in the flow, at a given wire overheat, values for the wire sensitivity coefficients, the mean voltage, and the voltage fluctuation can be determined. In principle, if measurements were taken at six wire overheats, the resulting equations could be solved simultaneously for all the unknowns. However, the scatter in the data usually prevents such a solution.

An alternative is the fluctuation-diagram technique, where for each overheat at a given location in the flow, values are determined for r and Z using Equations (11) and (12). These pairs are then plotted in rectangular r - Z coordinates, and faired with a hyperbola or straight line, producing a mode diagram of the flow fluctuations. To correlate the diagram with the flow fluctuations, the equation of each diagram is determined using a second-order least-squares curve fit. The coefficients of the equation are then matched to the corresponding

coefficients of Equation (10) to obtain values of the mass-flow and total temperature fluctuations, and their correlation coefficient.

5.4 Determination of Disturbance Amplitudes

The amplitudes of the fluctuations were determined using an on-line RMS meter, and by processing the hot-wire signals through the digital spectrum analyzer as described in Sections 5.1 and 5.2. The RMS meter provides only broadband information, while the digital analysis of the fluctuation spectra allows both a broadband and a discrete frequency analysis.

As a quick check, each digital spectrum was integrated (the signals were summed across the frequency band) to produce the broadband disturbance amplitude of the total signal, which was then compared to the amplitude determined from the RMS meter. These values were in agreement, and represented the total disturbance amplitudes for the frequency band of 0 to 600 kHz.

The next step was to perform the modal analysis described in Section 5.3 on the broadband total signals. The modal analysis decomposed the total signals into their components of mass-flux and total temperature, again for the frequency band of 0 to 600 kHz. At this point, the entire frequency range of 0 to 600 kHz has been considered collectively as a whole, and only the broadband disturbance amplitudes are known.

In an effort to better understand the distribution of the fluctuations by frequency, modal analysis of the total signals was performed frequency-by-frequency. Each 600-Hz narrow band of frequencies was treated as a whole, and each total signal was reduced to its components

of mass-flux and total temperature using the modal analysis and fluctuation diagram techniques.

Using the maximum-overheat spectrum of the total anemometer signal, the fluctuation amplitudes were plotted as a function of frequency, for each model station, as shown in Figure 12. The amplitude is plotted on an arbitrary scale with the intent being to show which frequencies are amplified along the model and to compare the magnitudes of the fluctuations from one model station to the next.

The amplitudes of the mass-flow and total temperature fluctuations were plotted as a function of R , where $R = \sqrt{Re_x}$, for each discrete frequency between 0 and 300 kHz. (Amplitudes at frequencies above 300 kHz were negligible.) For the frequency of 12kHz, these plots are presented as Figures 13 and 14, respectively. A frequency of 12 kHz was chosen for presentation because it lies within the narrow range of peak amplitudes as shown in Figure 12. The data presented in Figures 13 and 14 are representative of the many plots generated. The points of Figures 13 and 14 represent the actual fluctuation amplitudes, as determined from the model analysis, while the curves shown represent a fourth-order least-squared fit of $\ln A$. Experience has shown that fitting $\ln A$ rather than A is mathematically more direct, and produces better results (26).

As a final check, both the mass-flux and total temperature disturbance amplitudes determined from the discrete-frequency modal analysis were integrated. This provided broadband amplitudes of the fluctuation components, which were then compared to the results of the modal

analysis performed on the broadband total signal. This procedural crosscheck found both mass-flux and total temperature in agreement.

5.5 Determination of Disturbance Amplification Rates

Once the mass-flux and total temperature disturbance amplitudes were determined at every frequency for each model station, the disturbance amplification rates, $-\alpha_i$, were determined. This was done using the equation of the fourth-order polynomial which was found to fit $\ln A$ versus R in the plots of A versus R . The slope of this polynomial is the amplification rate, with $-\alpha_i$ defined as $(1/2A)(\partial A/\partial R)$. Figures 13 and 15, taken together, illustrate this procedure. In Figure 13 the curve represents the fourth-order polynomial used to fit the mass-flux amplitude data as a function of R . As can be seen in Figure 15, the slope of this curve defines the amplification rate of the mass-flux disturbances as a function of R at 12 kHz. Likewise, Figure 14 is matched with Figure 16, and shows the amplification rate of the total temperature fluctuations as a function of R at 12 kHz.

The amplification rates of each component were also cross-plotted as a function of frequency. Figure 17 shows the mass-flux amplification rate spectra and Figure 18 shows the total temperature amplification rate spectra.

A positive amplification rate, $(-\alpha_i)$, indicates growth of the fluctuation amplitude, while a negative value of $(-\alpha_i)$ indicates fluctuation damping. The points of zero amplification rate are neutral stability points depicted on the entropy layer stability diagram in Figure 19. The Reynolds number corresponding to the maximum amplifi-

cation rate for each frequency was also noted and used in the construction of the stability diagram.

These procedures are consistent with the methods used by Stetson, et al. in References (4), (8), and (26), and are essentially the same as those used by Demetriades in Reference (17).

6.0 RESULTS AND DISCUSSION

The disturbances observed by Stetson, et al. in the entropy layer of the 0.70-inch radius sphere-cone during their 1981 investigation prompted them to collect additional data on this configuration. These additional data, which were collected by Stetson, et al. in 1986, were analyzed by the author and are presented in this section.

As before, Stetson, et al. collected mean-flow data across the boundary layer at several model stations. These data are necessary to characterize the flow around the hot-wire probes used to collect the qualitative and quantitative disturbance fluctuation measurements. From the mean-flow data total temperature, Mach number, and velocity profiles were calculated. The total temperature profiles were used to calculate the total boundary layer thickness, and these data are presented in Figure 20. The velocity profiles are presented in Figure 21 to illustrate the non-similarity of the boundary layer profiles. Unlike the velocity profiles for the sharp cone, as can be seen from Figure 21, the mean-flow velocity is not constant between the boundary layer edge and the shock layer for flow over the $R_n = 0.70$ inch sphere-cone. This is a direct result of the entropy gradient created by the curved shock upstream of the blunt nosetip.

Hot-wire anemometers were again used by Stetson, et al. in 1986 to measure disturbance fluctuation amplitudes in the flow, this time in the entropy layer. Hot-wire data were collected using two different methods. Qualitative data were collected by making a continuous sweep across the flow field while holding the wire heating current constant. To obtain quantitative data, multiple wire heating currents were used

to collect data at a single measurement station. As before, disturbances were observed in the entropy layer.

In an effort to determine if instabilities exist in the entropy layer, this author plotted $\rho (\partial u / \partial y)$ and $\partial M / \partial y$ profiles using the experimental data collected by Stetson, et al. These profiles are presented in Figure 22. The $\rho (\partial u / \partial y)$ profiles are a measure of vorticity distribution, and by definition local maximums in the profiles in the inviscid portion of the flow (i.e., the entropy layer) indicate the presence of instabilities (10). The $\partial M / \partial y$ profiles are an alternative method to locate instabilities within the entropy layer. Stetson, et al. developed this alternative method at the suggestion of Eli Reshotko in Reference (8). Both sets of profiles indicate instabilities are present in the entropy layer.

The amplitudes of the entropy layer fluctuations are presented in Figure 12 as a function of frequency. This figure was constructed using the total-signal hot-wire data and should be used only to examine the frequency band of the disturbances. Making comparisons at a given frequency of the disturbance amplitude as a function of axial model station is not advised. Because of the non-similarities of the boundary layer profiles, the local unit Reynolds number varies as a function of the measurement station. This precludes using the maximum wire current total-signal data to directly calculate disturbance fluctuation amplitudes and amplification rates. It is necessary to reduce the total-signal hot-wire data to the wire sensing variables of mass-flux and total temperature using the modal analysis and fluctuation diagram techniques described in Section 5.3.

Selected data are presented for both the amplitudes and amplification rates of both mass-flux and total temperature in Figures 13 through 18. The stability of the entropy layer flow fluctuations is summarized in the entropy layer stability diagram presented in Figure 19. This figure indicates which frequencies are amplified, and which are damped, for a given local Reynolds number or model station.

6.1 Boundary Layer Profiles

Mean-flow data were taken at model stations 16, 30, 36, and 42, which corresponds respectively with s/R_n values of 16, 36, 45, and 54. As shown in Figure 7, the three probes were configured side-by-side and were expected to generate significant wall interference. Because of this probe arrangement, meaningful data could not be obtained close to the model surface.

During the mean-flow boundary layer sweeps, both total temperature and total pressure were measured. As can be seen in Figure 20, total temperature is a constant between the edge of the boundary layer and the shock layer. For this reason the edge of the boundary layer was defined in terms of the overshoot in the total temperature profiles. The boundary layer thickness, δ , was defined to be the height, z , at which local total temperature divided by the tunnel stilling chamber temperature equals 1.0025. The total boundary layer thicknesses were calculated for all model stations where mean-flow data have been collected on the 0.70-inch radius sphere-cone, including the 1981 investigation. These data are presented in Figure 23, and compared to the theory of Patankar-Spalding (29). As can be seen, very good agreement exists between the two separate investigations. In both

cases, the boundary layer growth rate is higher than expected from theory.

The measured pitot pressures and the wall static pressures are used to calculate the local Mach number profiles across the boundary layer. Because the static pressure variation is small across the boundary layer at a given model station, it is assumed constant for the Mach number calculations. From the local Mach number profiles, the local velocity profiles are calculated. Using the boundary layer edge locations determined from the total temperature profiles, u/u_e profiles are calculated and are shown in Figure 21. Unlike the sharp-cone profiles, the mean-flow velocity is not constant between the edge of the boundary layer and the shock layer for flow over the 0.70-inch radius sphere-cone. This non-similarity in the velocity profiles results in a variation of the local Reynolds number with axial model station.

Variations in the boundary layer profiles are of interest because the hot-wire probe's sensitivity to fluctuations of velocity, density, and total temperature change with both heating current and local Reynolds number.

6.2 Qualitative Hot-Wire Data

The hot-wire response curves shown in Figure 10 were created by sweeping the hot-wire probe from 0.02 inches above the model surface up through the flow field. This was done at each model station of interest to determine the location of peak fluctuation energy sensed by the hot-wire probe.

This location is referred to as the "maximum energy point" by Stetson et al. in References (4), (8), and (26). As used by Stetson, et al., the "maximum energy point" represents the peak fluctuation energy sensed by the hot-wire probe. This is the point of maximum heat transfer in the measurement survey. It was at these points that Stetson, et al. collected the quantitative data in their earlier investigations. However, Stetson, et al. broke from their previous convention and collected quantitative data at points other than where the hot-wire signal was a maximum during the 1986 investigation of the 0.70-inch sphere-cone. To avoid confusion, the points at which quantitative data were collected are referred to as measurement stations in this study.

During the 1981 investigation Stetson, et al. observed a "maximum energy point" outside of the boundary layer. However, as they probed farther forward on the model during the 1986 investigation the "maximum energy point" in the entropy layer disappeared. Stetson, et al. wanted to follow a disturbance to determine if it was stable or unstable, so they estimated the path of the "maximum energy point" disturbance. Stetson, et al. then took quantitative measurements along this estimated streamline.

The locations of the measurement stations chosen by Stetson, et al. are shown in Figure 10 for each model station where quantitative hot-wire data were collected during the 1986 investigation of the 0.70-inch sphere-cone. At model stations 16, 17, and 18 data were collected at two measurement stations, one inside the boundary layer and one

outside. In this study, only the data outside the boundary layer are presented (i.e., Runs 744, 746, and 748 were not analyzed).

The measurement station locations are related to the total boundary layer thickness in Figure 24 for all the quantitative data collected for the 0.70-inch sphere-cone. All of the measurement stations of the 1986 investigation are located outside of the boundary layer in the entropy layer. All of the measurement stations in the 1981 investigation, and the measurement stations at model stations 40 and 42 of the 1986 investigation represent "maximum energy points". The 1981 investigation data show the peak fluctuation energy is located in the entropy layer, and first approaches, then enters the boundary layer as the boundary layer swallows the entropy layer.

As can be seen in Figure 10, the "outside" measurement stations do not correspond to a local maximum in the fluctuation energy until model station 21. At this point there is a weak local maximum which continually grows with increasing distance along the surface. At station 40 and 42 this local maximum has grown into the peak fluctuation energy location, yet remains outside the boundary layer. These local maximums indicate the presence of disturbance fluctuations outside the boundary layer but within the entropy layer. The growth of these maximums reflects the growth of the disturbance fluctuations as they progress down the model. This growth indicates the existence of instabilities in the entropy layer.

In an effort to determine if instabilities do exist in the entropy layer, the p ($\partial u / \partial y$) and $\partial M / \partial y$ profiles were calculated from the

experimental data collected by Stetson, et al. in their 1986 investigation. These profiles are shown in Figure 22.

The $\rho (\partial u / \partial y)$ profiles are a measure of vorticity distribution in the flow. Within the boundary layer, vorticity variations are large, and a definite maximum is clearly visible at all model stations. However, outside of the boundary layer the vorticity gradient is small, and the maximums are less well defined, if they exist at all. The $\rho (\partial u / \partial y)$ profiles shown in Figure 22 reveal that local maximums exist aft of model station 16. By definition, these local maximums correspond to generalized inflection points for compressible flow, and indicate the presence of instabilities (10).

The $\partial M / \partial y$ profiles are an alternative method of locating the maximums in the $\rho (\partial u / \partial y)$ profiles. As explained by Stetson, et al. in Reference (26), for inviscid flow a maximum of $\rho (\partial u / \partial y)$ will correspond approximately to a maximum of $\partial M / \partial y$. The experimental data shown in Figure 22 show that for inviscid flow, a local maximum in the $\rho (\partial u / \partial y)$ profile does correspond approximately to a local maximum in $\partial M / \partial y$. More importantly, the profiles presented in Figure 22 contain local maximums outside of the boundary layer, indicating that instabilities do exist in the entropy layer.

6.3 Quantitative Hot-Wire Data

Quantitative hot-wire data were taken at model stations 16-24, 40 and 42 during the 1986 investigation. The "hole" in the data between model stations 24 and 40 in the data collection was intentional. The intent of Stetson, et al. was to combine these data with those of the

1981 investigation to provide complete coverage of the model from station 16 to 42.

The scope of this study includes only the 1986 data. The "hole" in this data caused some difficulties in reducing the data. While calculating the curve fit of A versus R, where $R = \sqrt{Re_x}$, it was found that the fourth-order least-squares methodology could not bridge the gap between stations 24 and 40. The resulting amplitudes and corresponding amplification rates were judged unrealistic by the author.

Because of these results, the programs were rerun without the station 40 and 42 data points. Working within the imposed funding constraints, it was felt this approach would provide the most useful data. It is hoped that at some future date the data from both investigations can be combined to provide a more complete picture.

6.3.1 Fluctuation Spectra. The amplitude of the hot-wire response is plotted as a function of frequency for each model station and presented in Figure 12. The amplitude scale is arbitrary, with the intent being to show relative magnitudes of the disturbance amplitudes. These plots indicate that only very low frequency disturbances are present in the entropy layer. These low frequency disturbances are a product of the unsteadiness of the strong curved shock upstream of the nosetip. The unsteadiness of this shock is likely influenced by the tunnel freestream acoustic disturbances.

The amplitudes of the entropy layer disturbances peak at 10 kHz for model stations 16-19, with the peak shifting to 12 kHz for stations 20-24. Note that the data presented were all taken outside the

boundary layer within the entropy layer, and that the amplitude signals above 300 kHz for each spectrum are simply noise.

Because the total signal hot-wire data were used to construct Figure 12, these plots should be used only to determine the frequencies at which disturbances occur in the entropy layer. The amplitude versus R plots of mass-flux or total temperature should be used to determine how the amplitude varies with model station at a given frequency.

6.3.2 Disturbance Amplitudes versus R. Using modal analysis, the hot-wire signal was reduced to the wire-sensing components of mass-flux and total temperature. The amplitudes of these components were plotted as a function of R for the frequency range of 0 to 300 kHz at 600 Hz intervals. These curves show how the disturbance fluctuation amplitudes vary with R, or model station, at a given frequency. Plots were made for each frequency between 600 Hz and 300 kHz, at 600 Hz intervals. The 12 kHz frequency data were chosen for presentation in Figures 13 and 14 because they represent the peak disturbance amplitude, as seen in Figure 12. As discussed in Section 5.4, the points on these figures represent the digital data from the discrete-frequency modal analysis, while the curves are a fourth-order least-squared curve fit of $\ln A$.

The amplitude of the mass-flux disturbances is plotted as a function of R in Figure 13 for a frequency of 12 kHz. The variation of amplitude with R seen in Figure 13 is characteristic of all the mass-flux disturbances below 300 kHz. Likewise, the largest disturbances are seen at frequencies below 30 kHz, and range in magnitude from 0.16-0.22 percent of the mean value of the hot-wire signal. As frequency is

increased, the amplitude curve flattens and the disturbances become negligible above 100 kHz.

The amplitude of the total-temperature disturbances is plotted as a function of R in Figure 14 for a frequency of 12 kHz. The total temperature disturbances are small in comparison to the mass-flux disturbances. As can be seen in Figure 14, the disturbance amplitude ranged from 0.03-0.05 percent of the mean value. The disturbances increase with increasing R , and this trend continues as frequency is increased, up to a frequency of 75 kHz. Above 75 kHz the curves are flat with the disturbance amplitude essentially zero.

6.3.3 Disturbance Amplification Rates versus Frequency. The amplification rates of the mass-flow and total temperature disturbance fluctuations are plotted as a function of frequency at each model station to determine the stability of the fluctuations. The mass-flux data are shown in Figure 15 and the total temperature data are shown in Figure 16. The amplification rate curves for model stations not shown follow the trends of the data presented in Figures 15 and 16.

A positive amplification rate, $(-\alpha_j)$, indicates growth of the fluctuation amplitude, while a negative value of $(-\alpha_j)$ indicates fluctuation damping. In all cases, the value of the amplification rate has gone into the noise by 150 kHz.

The curves of mass-flux amplification rate presented in Figure 15 show that frequencies of 0-100 kHz are lightly damped forward of model station 21, experience neutral damping at station 21, and are slightly amplified aft of model station 21. The amplification rate trend of frequencies of 100-150 kHz are similar. Forward of model station 21

disturbances are strongly damped, and aft of model station 21 they are strongly amplified.

Figure 16 shows the amplification rate of the total temperature fluctuations is very small across all model stations for frequencies of 0-100 kHz. For frequencies of 100-150 kHz, the amplification rate is essentially neutral across all model stations.

6.3.4 Comparison of 1986 Data with 1981 Data. The disturbance-fluctuation amplitudes and amplification rates of both investigations were compared at model stations 23 and 24. These two stations represent the edge of the downstream "hole" in the data. A quantitative comparison was not made, due to the differences in the arbitrary scales, as explained below, but an effort was made to compare qualitatively the amplitudes and amplification rates.

Because the hot-wire probes are very small, no two are exactly alike. When the probes are used to collect data, the gains in the instrumentation are chosen to provide the largest hot-wire signal. Because of the differences in the wires, the gains selected may vary from wire to wire. These differences result in the differences seen in the arbitrary scales of the disturbance amplitudes and amplification rates.

For the mass-flux disturbances, the amplitude trends of the two data sets match, and the slopes of the curves are compatible. The total temperature amplitude trends match those of the 1981 data with only a small difference. The 1986 total temperature data show a continuous decrease in disturbance amplitude with increasing frequency. The 1981 data agrees until frequency equals 175 kHz where it shows a

rise, and then another decrease. This amplitude bulge is nonexistent in the 1986 data. In addition, the slopes of the total temperature curves only match in the frequency range of 75-150 kHz.

Excellent correlation exists between the two data sets for mass-flux disturbance amplification rates. As with amplitude, there are some differences in total temperature. The 1981 data shows significant damping of both mass-flux and total temperature at model stations 23 and 24 for all frequencies. However, as Figures 17d and 18d show, the 1986 data indicate neutral amplification for frequencies of 100-150 kHz, and even a very slight amplification for frequencies of 0-100 kHz.

6.4 Entropy Layer Stability Diagram

The entropy layer stability diagram shown in Figure 19 summarizes the frequency and local Reynolds number conditions which cause disturbance fluctuations to be amplified within the entropy layer on the 0.70-inch nosetip-radius sphere-cone. This stability diagram was constructed by the author using the experimental data of this study. Within the unstable region represented by the shaded portion of the stability diagram, disturbances are amplified. The boundary of the shaded region represents the points of neutral stability, where fluctuations are neither amplified nor damped. The neutral boundaries represented by the dashed lines were approximated because the disturbances are small at these higher frequencies. The unshaded region of the stability diagram represents areas where the disturbances are damped.

Using the stability diagram, the growth or damping of a disturbance within the entropy layer at a given frequency can be determined

as it progresses down the model. In addition, for a given Reynolds number, or model station, the stability diagram indicates which frequencies are amplified, and which are damped within the entropy layer.

7.0 SUMMARY AND CONCLUSIONS

Stetson, et al. conducted stability experiments on slender cones in hopes of learning what causes the forward shift in transition at large R_n , and to gain a better understanding of the transition reversal with increased R_n (4,5,6,7). Local Reynolds-number reduction had been shown to shift transition downstream (2,3), but the displacement reversal, and continuing forward displacement were not understood.

While investigating the 0.70-inch radius sphere-cone, Stetson, et al. discovered disturbances in the entropy layer outside the boundary layer during their 1981 investigation. (5,6,7,8). Disturbances were also observed in the entropy layer during this study. These disturbances are a result of the unsteadiness of the strong detached shock upstream of the nosetip. Currently the influence of the tunnel freestream disturbances on the detached shock and the observed entropy layer disturbances is unknown. The amplitude and frequency of the tunnel freestream disturbances need to be determined with a hot-wire stability investigation. Such data would allow a much needed direct comparison of the freestream disturbances with the entropy layer disturbances.

The local maximums in the hot-wire profiles of Figure 10 show that disturbances exist in the entropy layer and that the amplitudes of these disturbances increase with axial model station. The disturbances at the aft end of the model are larger than those closer to the nosetip, indicating a growth in the disturbances as the flow progresses downstream. This growth suggests instabilities exist in the entropy layer which are amplifying the disturbances.

The experimental $\rho(\partial u/\partial y)$ and $\partial M/\partial y$ profiles shown in Figure 22 were plotted to determine if such instabilities exist in the entropy layer. Examination of the experimental $\rho(\partial u/\partial y)$ and $\partial M/\partial y$ profiles revealed local maximums in both, confirming the existence of inviscid instabilities in the entropy layer. The observed growth of the disturbances in the entropy layer is likely caused by the instabilities in the entropy layer.

No disturbances were observed in the entropy layer of the small-bluntness investigations (4,5,6,8). Such disturbances may not exist, or they may be too small to measure with the hot-wire probes used by Stetson, et al. Without further investigations it is not possible to determine whether instabilities exist in the entropy layer of the small-bluntness flows. It seems reasonable to assume that disturbances and instabilities both exist in the entropy layer regardless of the bluntness size.

As can be seen in Figure 24, Stetson, et al.'s first large-bluntness investigation shows the maximum energy points, which are located in the entropy layer, first approach, and then enter the boundary layer as the entropy layer is swallowed. These peaks in the measured fluctuation energy grow rapidly once they enter the boundary layer, and the flow quickly undergoes transition. The small-bluntness investigations showed no corresponding growth of disturbances within the boundary layer after it has swallowed the entropy layer. In fact, the boundary layer remained stable downstream of the entropy layer swallowing location (8).

It seems reasonable to conclude that the large bluntness flow undergoes transition as a result of the disturbances present in the entropy layer. However, there is currently no boundary layer stability data to support this conclusion.. To conclusively show that the entropy layer disturbances are the same disturbances being amplified downstream in the boundary layer, a boundary layer stability diagram needs to be constructed and compared to the boundary layer stability diagram presented in Figure 19. If the frequency of the entropy layer disturbances and the disturbances amplified in the boundary layer downstream of the swallowing location match, then a relationship will be firmly established.

The boundary layer flow undergoes transition shortly after swallowing the large bluntness entropy layer, yet remains stable for small bluntness flows. Understanding this difference is key to understanding what causes the transition reversal and the continuing forward displacement.

The transition Reynolds number provides a clue. Experiments have shown that transition occurs at the same local Reynolds number for small bluntness sphere-cones. This results in a rearward displacement of transition, due to the reduced local Reynolds number caused by the pressure losses across the bow shock. However, for large bluntness, the transition Reynolds number decreases with increasing bluntness. In fact, at sufficiently large bluntness the transition Reynolds number is actually less than that of a sharp cone (2,3). A reduction in transition Reynolds number equates to a forward shift of the transition location. From the available transition and stability experiment data,

it appears that local Reynolds number reduction and entropy layer instabilities are competing for dominance in blunted sphere-cone flow (2,3,8).

The entropy-layer-swallowing location may be the factor that determines which effect will dominate the flow. If the flow mechanisms are the same for both large and small bluntness, then the entropy-layer-swallowing location is a function of the entropy layer thickness, which is in turn a function of the nosetip bluntness. The thicker entropy layers generated by large bluntness are not swallowed as quickly as the thinner entropy layers generated by smaller bluntness. For small bluntness, perhaps the entropy layer is swallowed before disturbances in the entropy layer have time to grow to sufficient size to cause transition. Whereas for large bluntness flows, the longer distance required to swallow the entropy layer allows the instabilities to amplify the disturbances to a size sufficient to cause transition when they enter the boundary layer.

It is important to note that the boundary layer is stable as it is swallowing the entropy layer (2,3,8). Thus, if disturbances from the entropy layer are not sufficiently large to cause transition, they will be damped by the stable boundary layer. For large bluntness flows, the disturbances entering the boundary layer may be so large that they are causing an otherwise stable boundary layer to undergo transition (8,11,16). This would explain the wide variance in transition Reynolds number seen for large-bluntness flows (2,3). In contrast, the disturbances entering the small-bluntness boundary layer may be

sufficiently small that they are damped out by the stable boundary layer, making them inconsequential to the transition process.

The data of the present study, although not sufficient to be conclusive, does support the ideas presented above, and is in agreement with the previously published data.

Although the transition-displacement reversal, and the continuing forward shift in transition location were discovered years ago during transition experiments, their causes were not known (2,3). It now appears that instabilities in the entropy layer cause transition to shift forward by amplifying disturbances in the entropy layer which then enter the boundary layer and cause transition in the flow. As discussed in the Introduction, the rearward shift in transition is known to be caused by the local Reynolds number reduction due to the pressure losses across the bow shock (2,3). These two effects, entropy-layer instabilities and local Reynolds-number reduction, appear to be struggling for dominance. It now appears the entropy-layer-swallowing location, or entropy-layer thickness is the factor that determines which effect will dominate the flow. However, further investigation is needed to better define this causal relationship.

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APPENDIXES

APPENDIX A
FIGURES

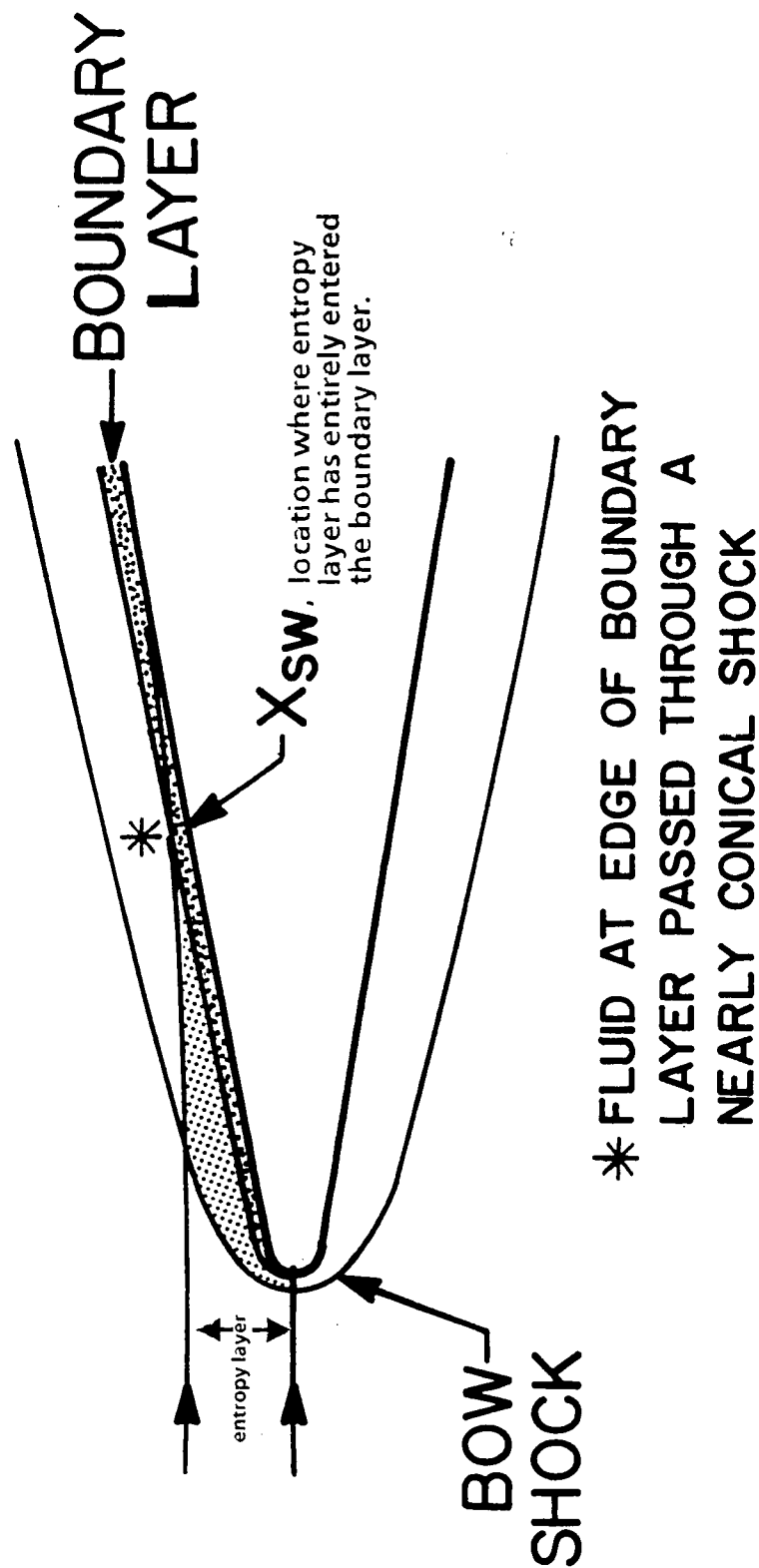


Figure 1. Schematic Illustration of Flow Over a Slender, Blunt Cone

Source: Adapted from Stetson, K. F., "Hypersonic Boundary Layer Transition Experiments", AFWAL-TR-80-3062, October 1980.

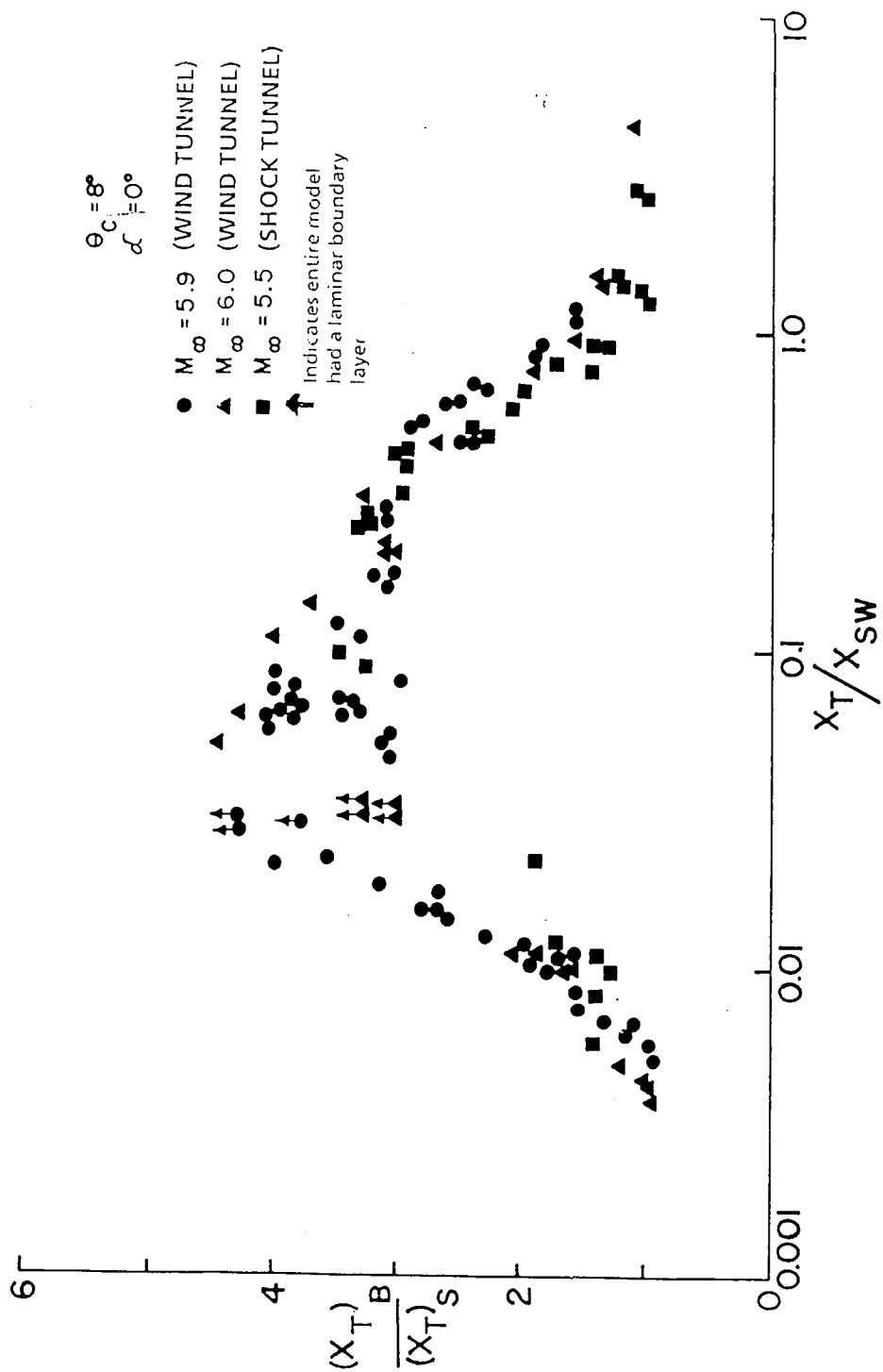
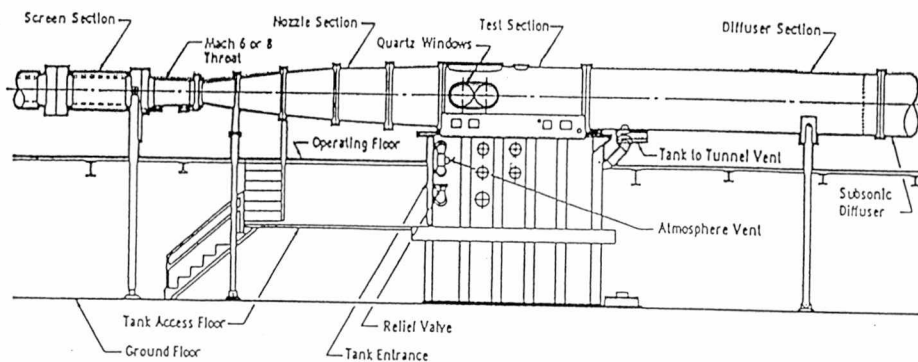
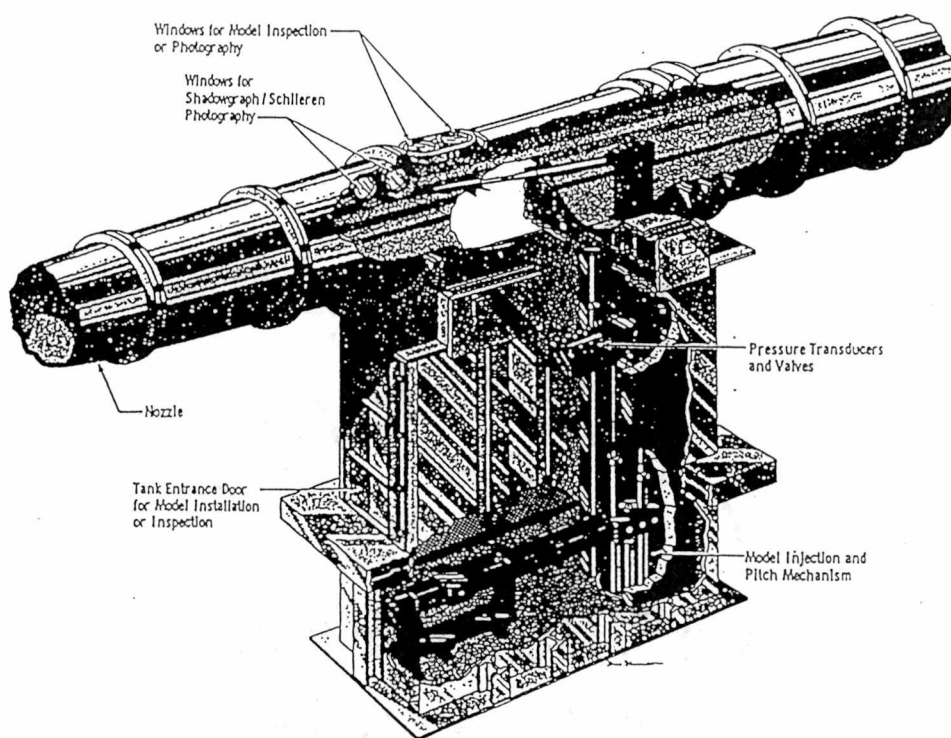


Figure 2. A Comparison of Nosetip Bluntness Effects on Cone Frustum Transition

Source: Adapted from Stetson, K. F., "Hypersonic Boundary Layer Transition Experiments", AFWAL-TR-80-3062, October 1980.



a. Tunnel assembly



b. Tunnel test section

Figure 3. AEDC Tunnel B

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

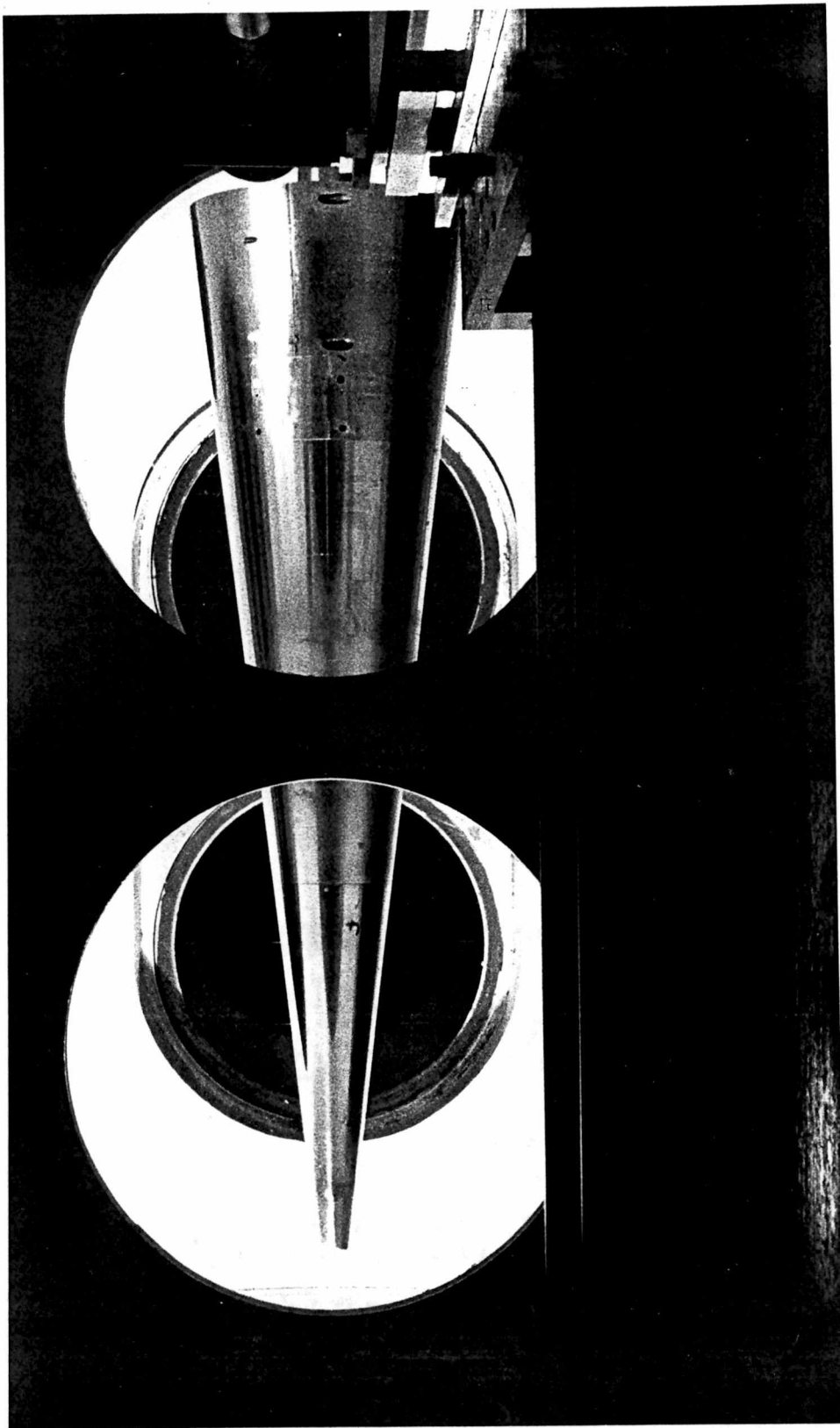
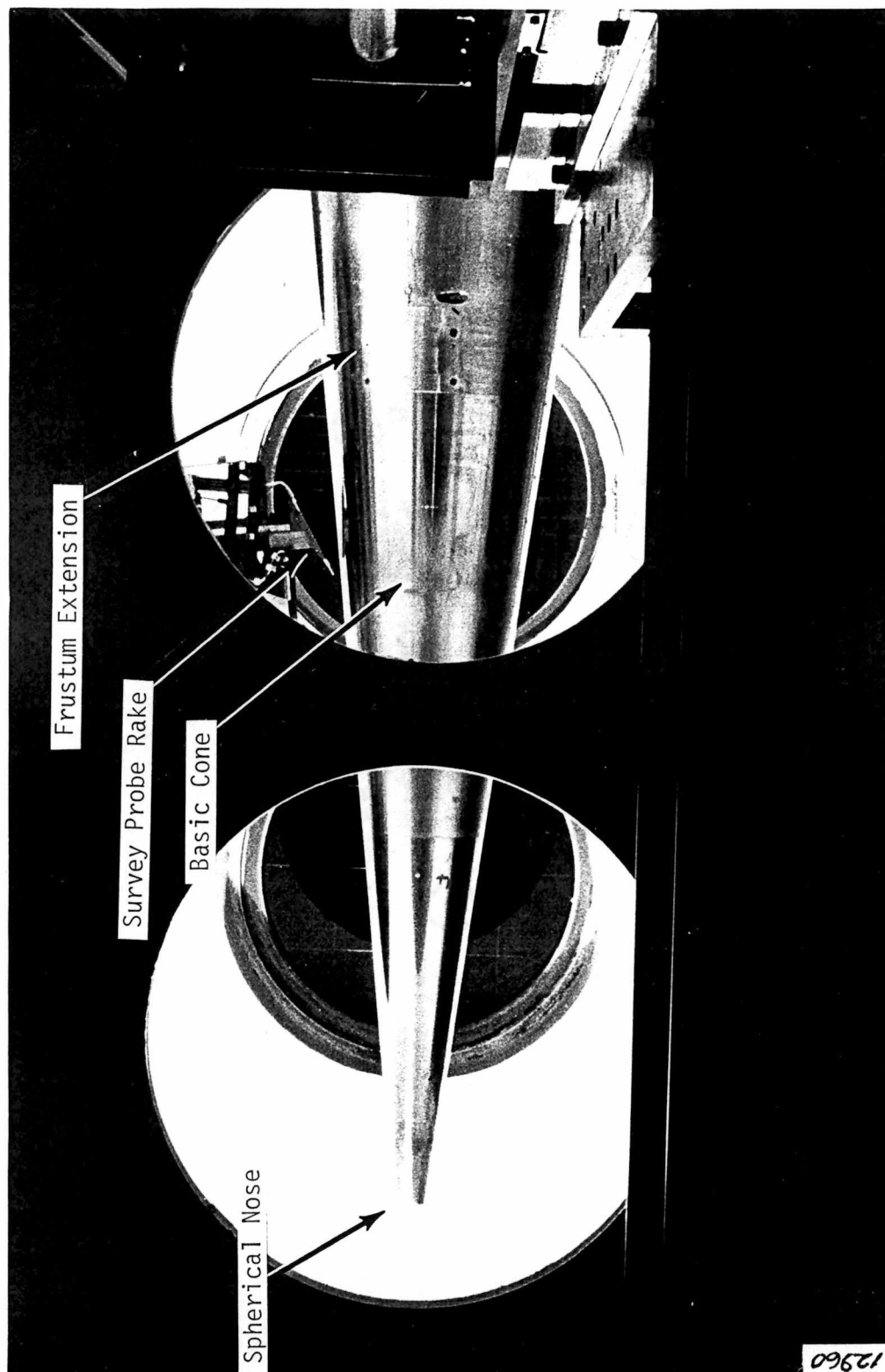
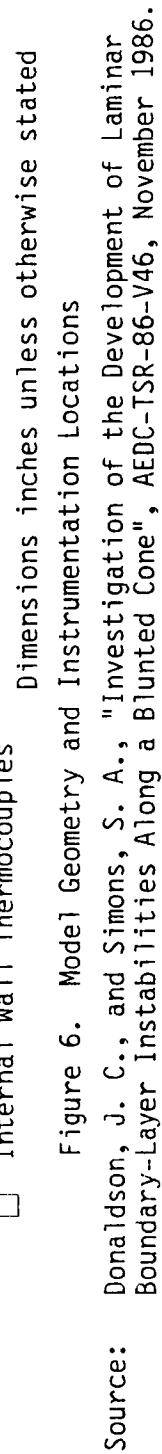
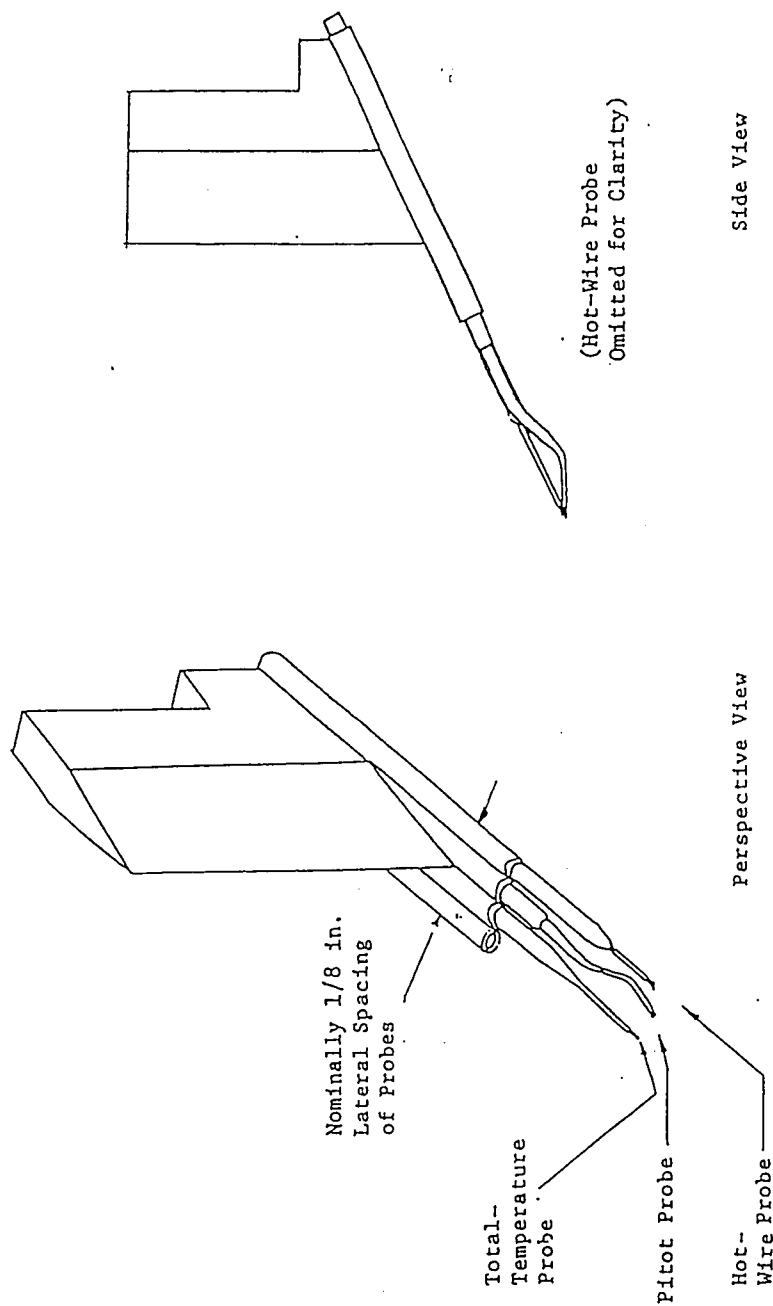


Figure 4. Model Installed in Tunnel B



Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

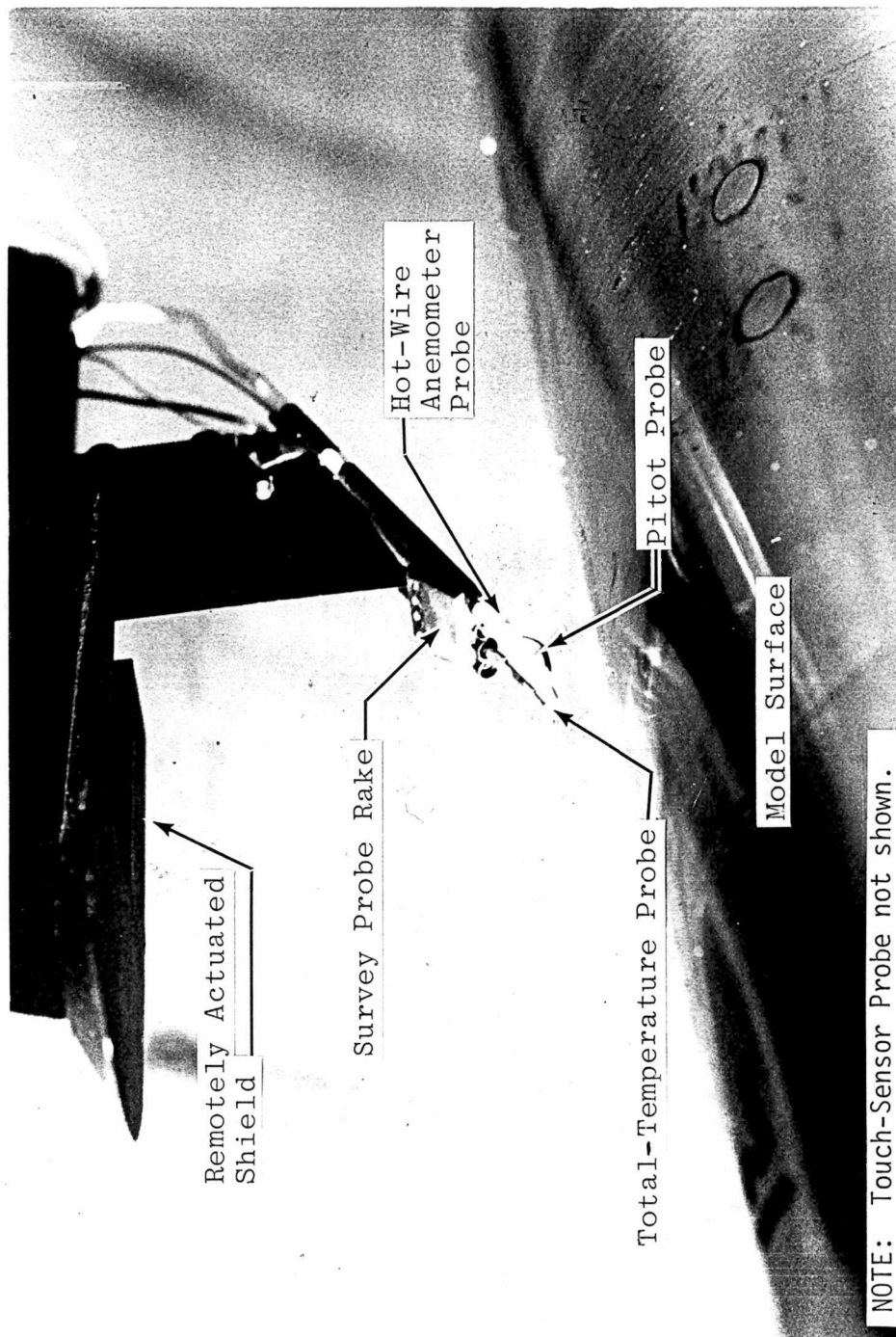




a. Rake and Probe Installation

Figure 7. Survey Probe Configuration

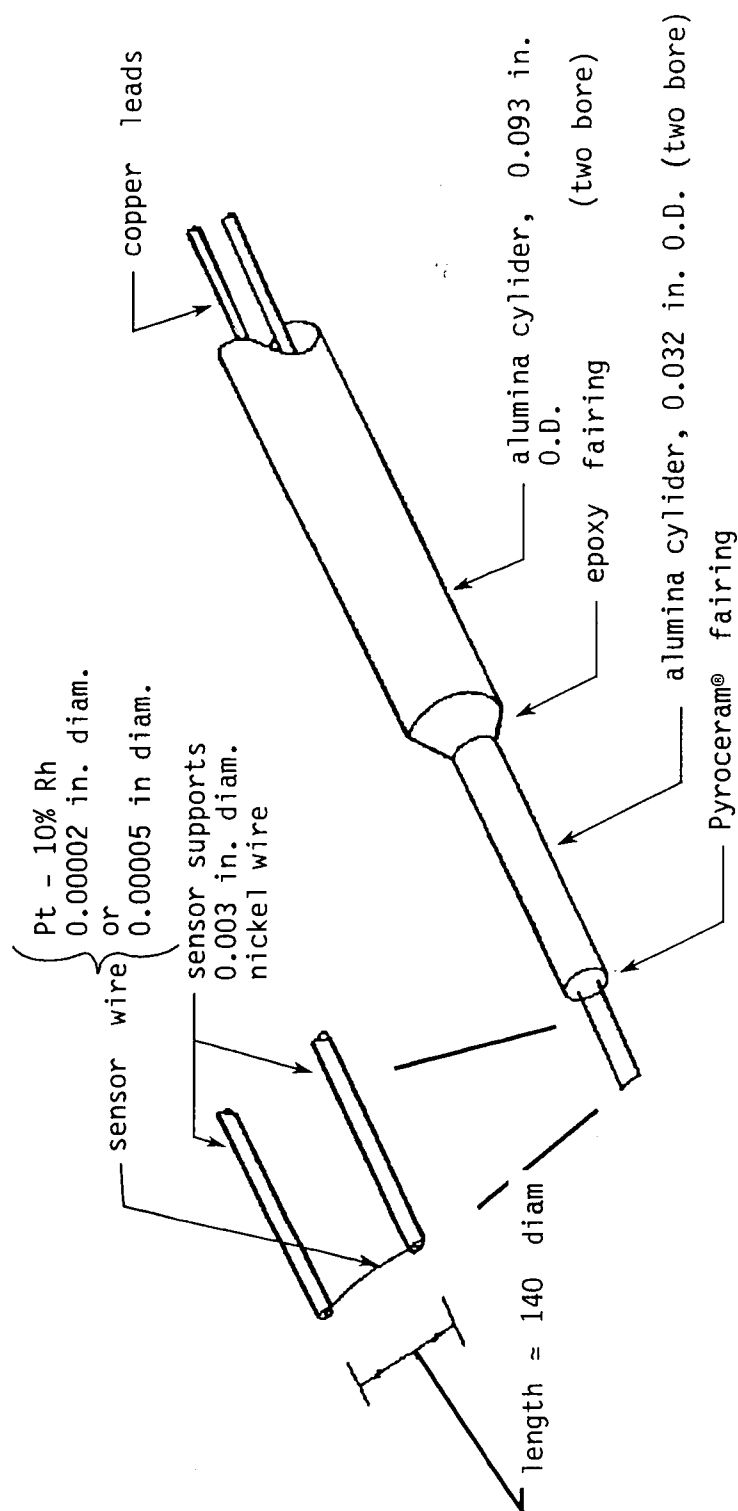
Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.



b. Rake/probe mounted above Model Surface

Figure 7. Concluded

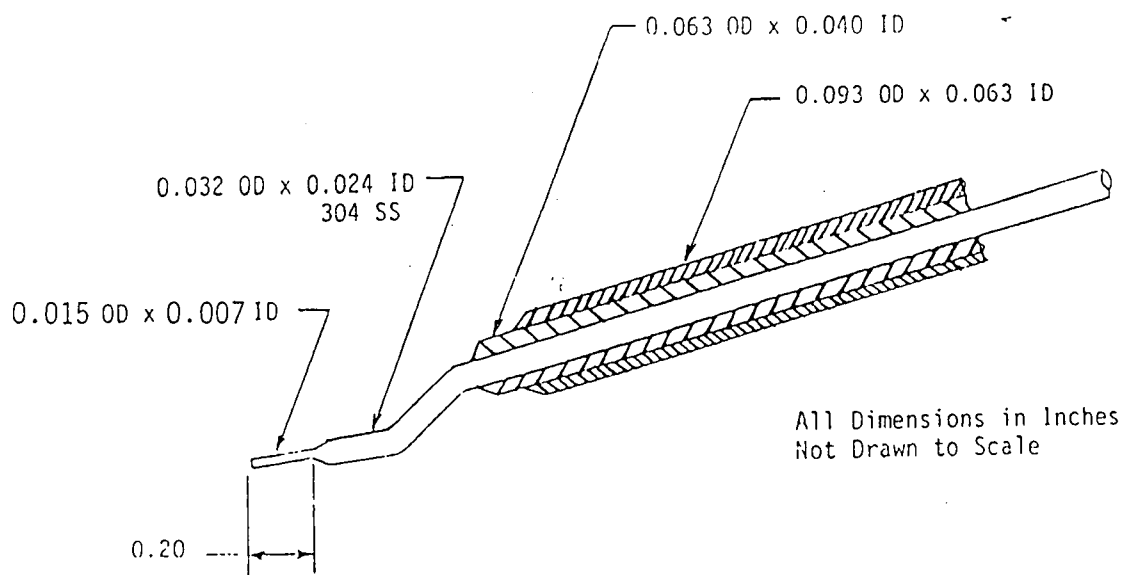
Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.



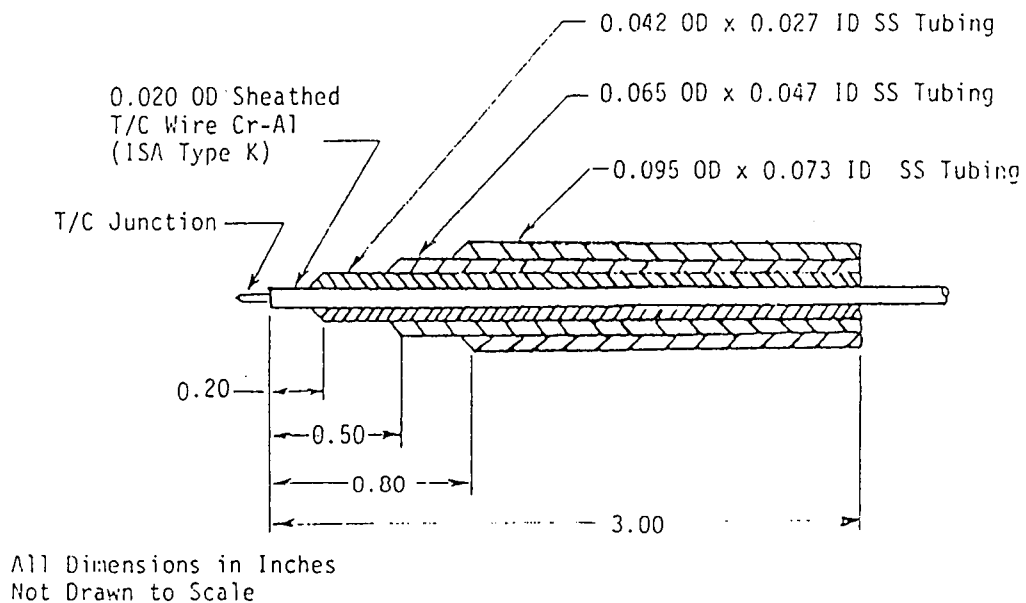
a. Hot-wire anemometer probe

Figure 8. Survey Probe Details

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.



b. Pitot probe



c. Total-temperature probe

Figure 8. Concluded

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

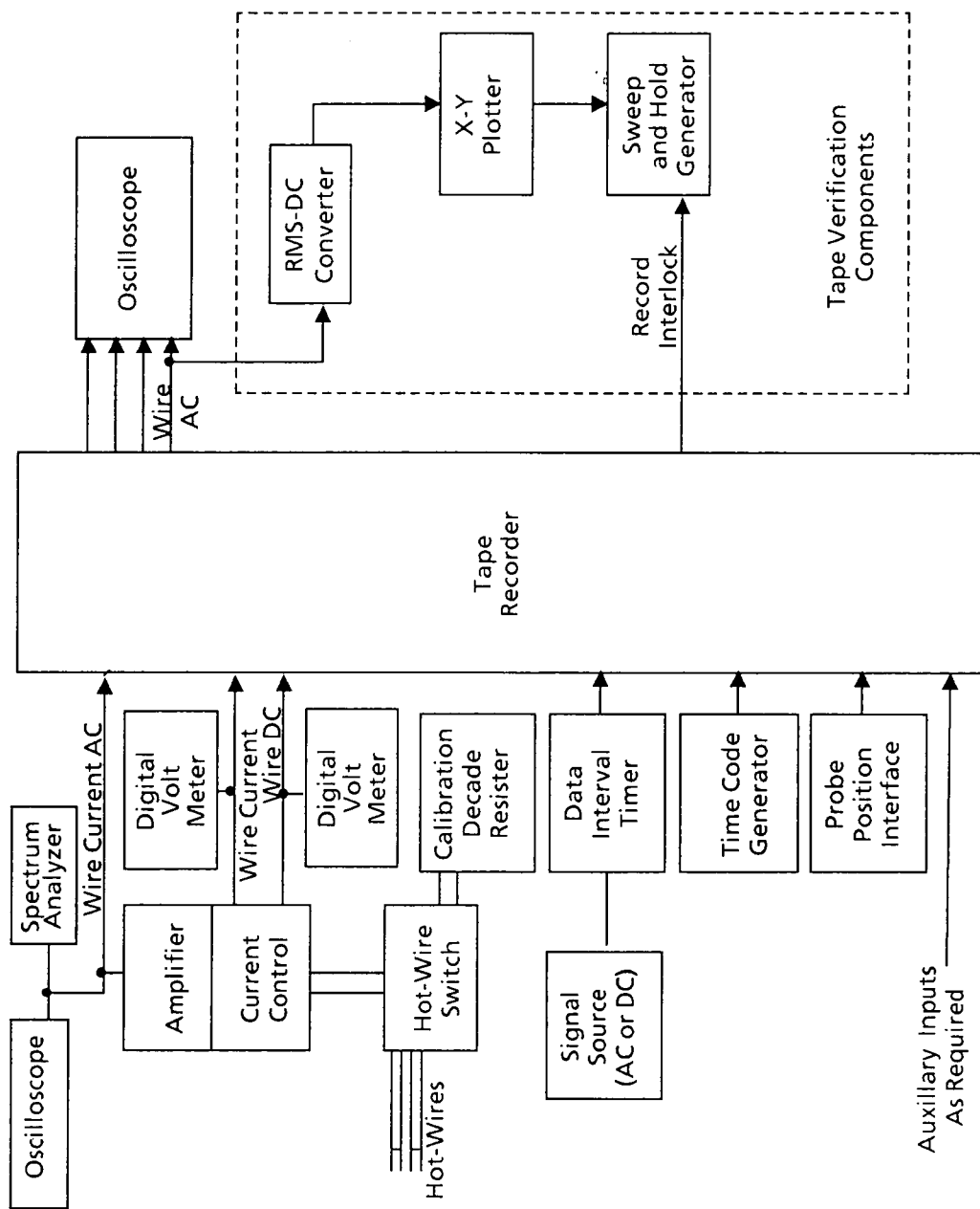


Figure 9. Hot-wire Instrumentation

SOURCE: Adapted from Donaldson, J. C., Nelson, C. G., and O'Hare, J. E., "The Development of Hot-Wire Anemometer Test Capabilities for $M = 6$ and $M = 8$ Applications," AEDC-TR-76-88 (AD A029570), September 1976.

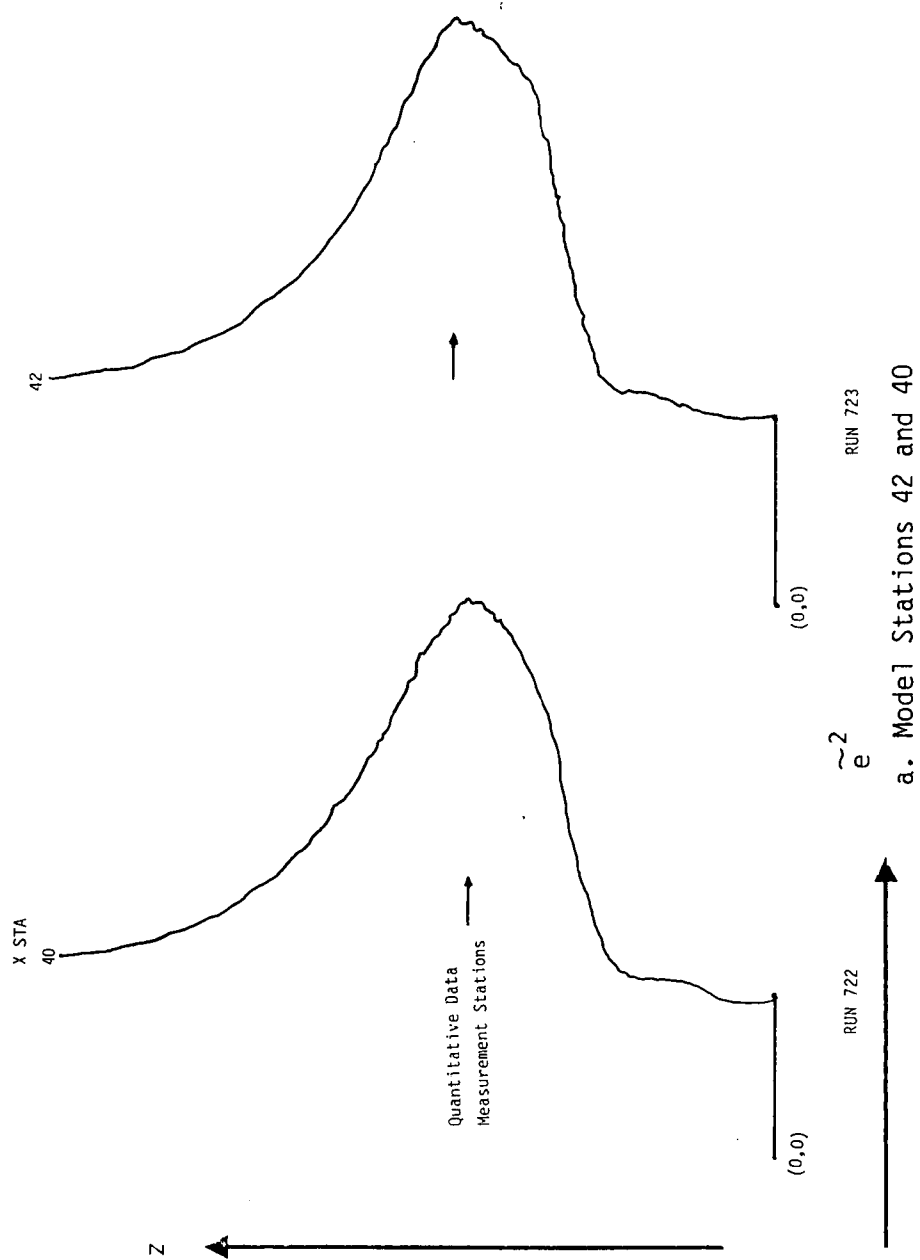
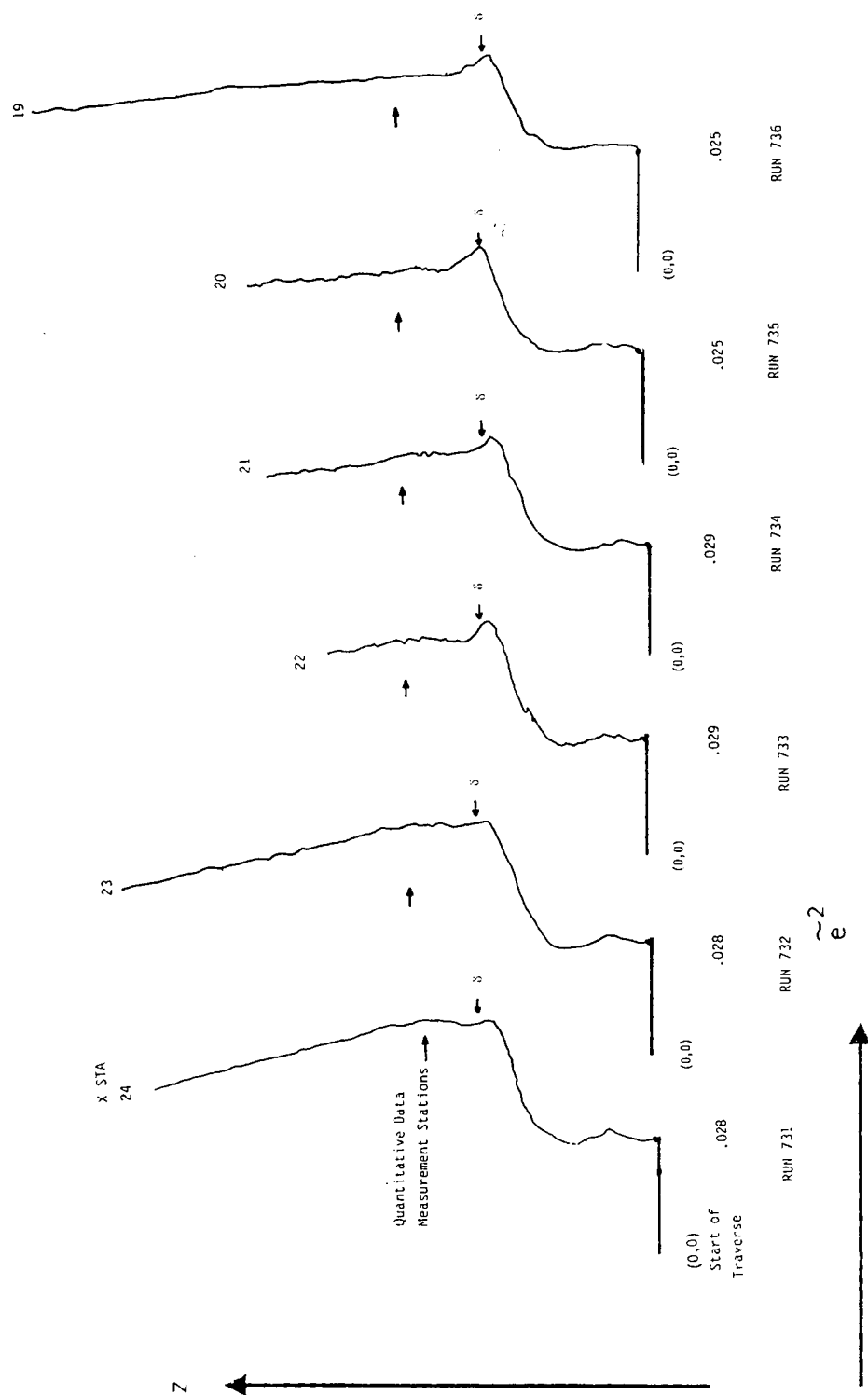
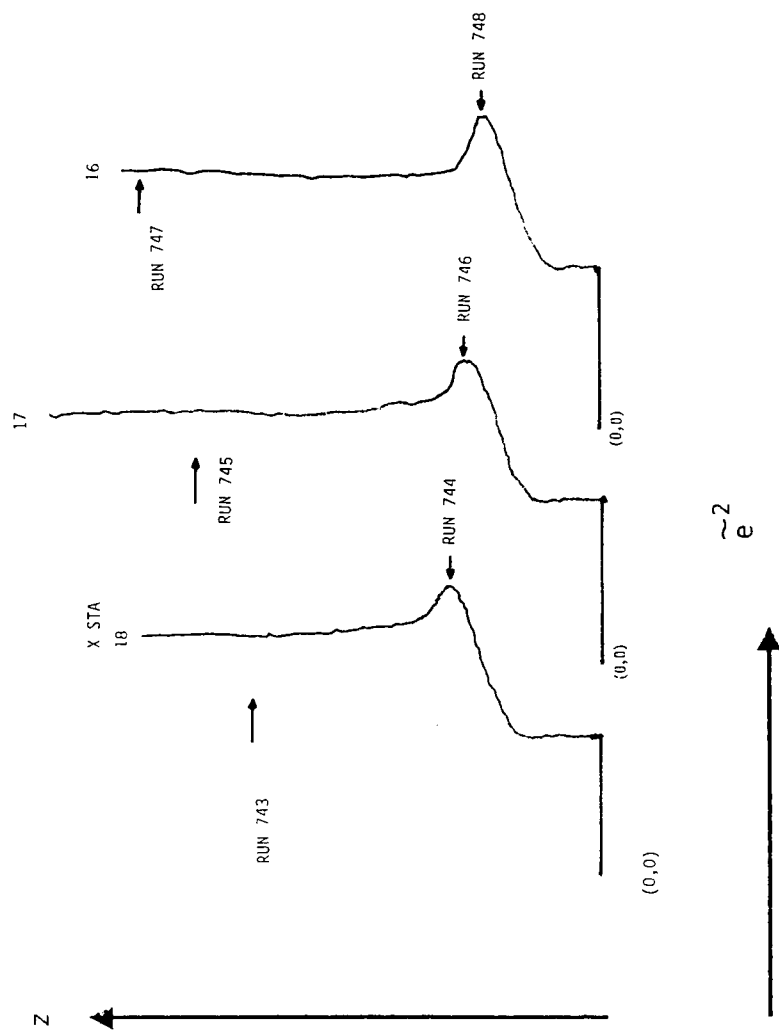


Figure 10. Square of the Hot-Wire Voltage Obtained in Continuous Sweeps of the Probe Across the Cone Flow Field, at Different Stations Along the Length of the Cone



b. Model Stations 24, 23, 22, 21, 20, and 19

Figure 10. Continued



c. Model Stations 18, 17, and 16

Figure 10. Concluded

Model Station 21

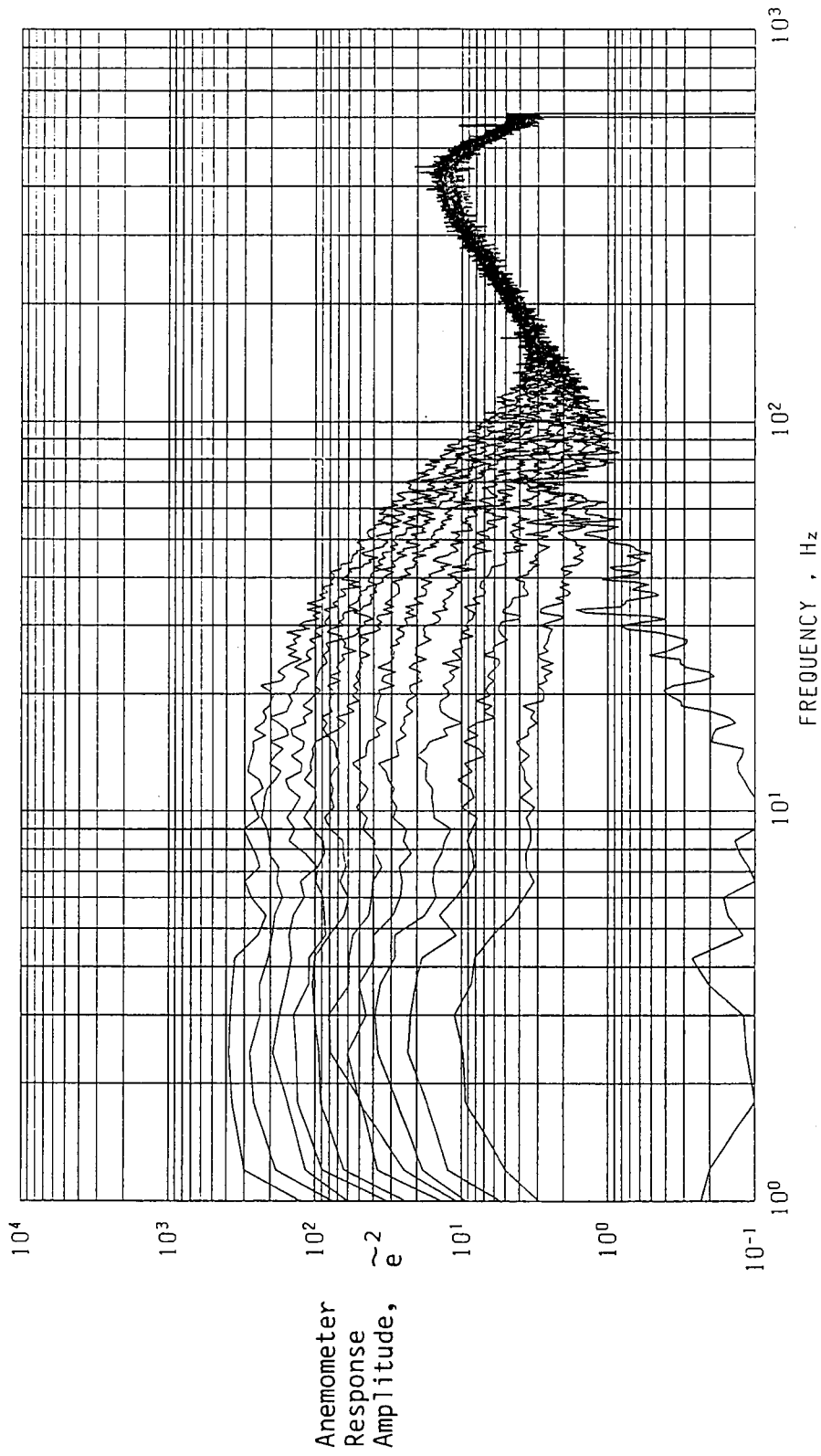


Figure 11. Representative Spectrum of Hot-Wire Data and Corresponding Noise

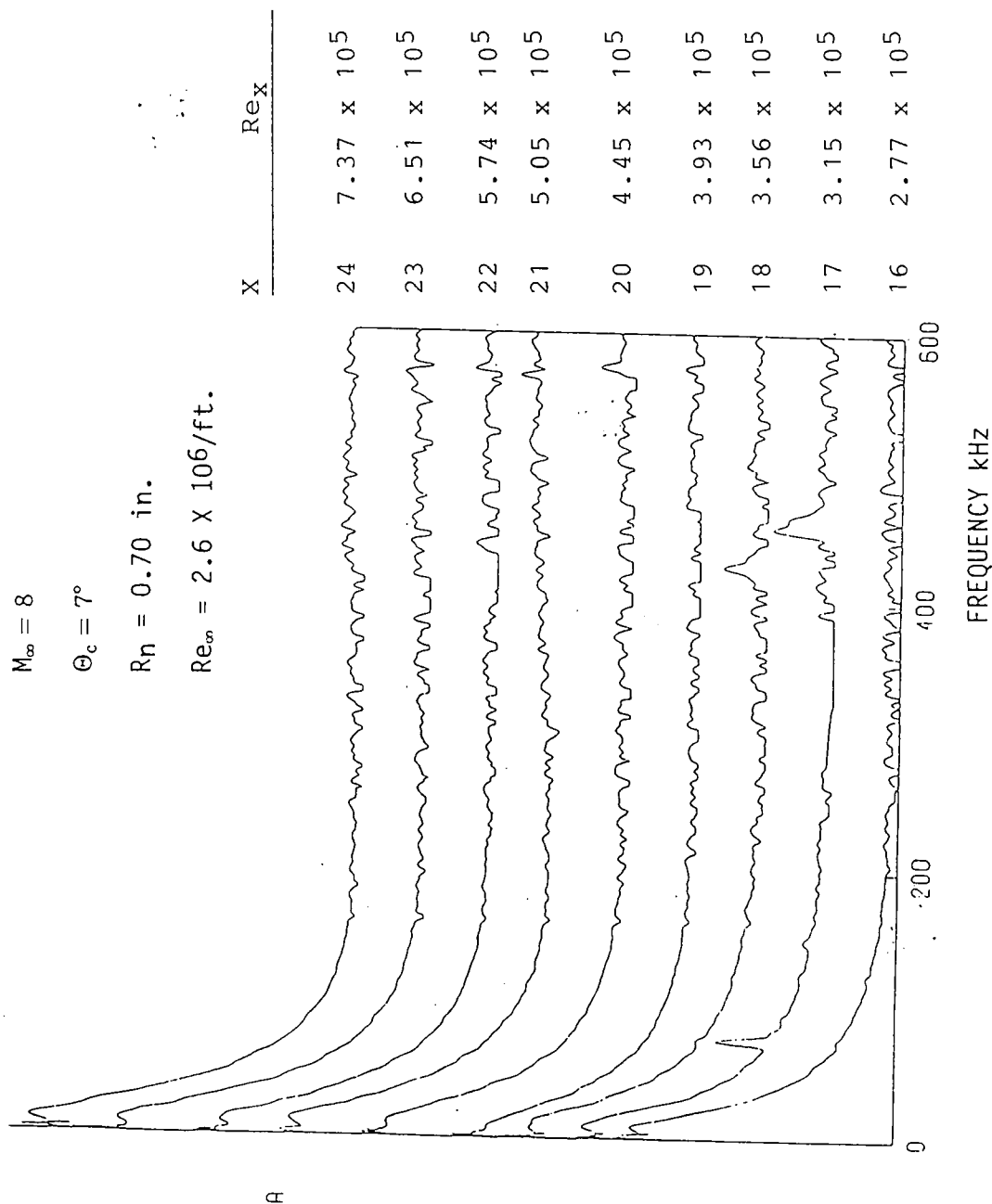


Figure 12. Entropy Layer Fluctuation Spectra

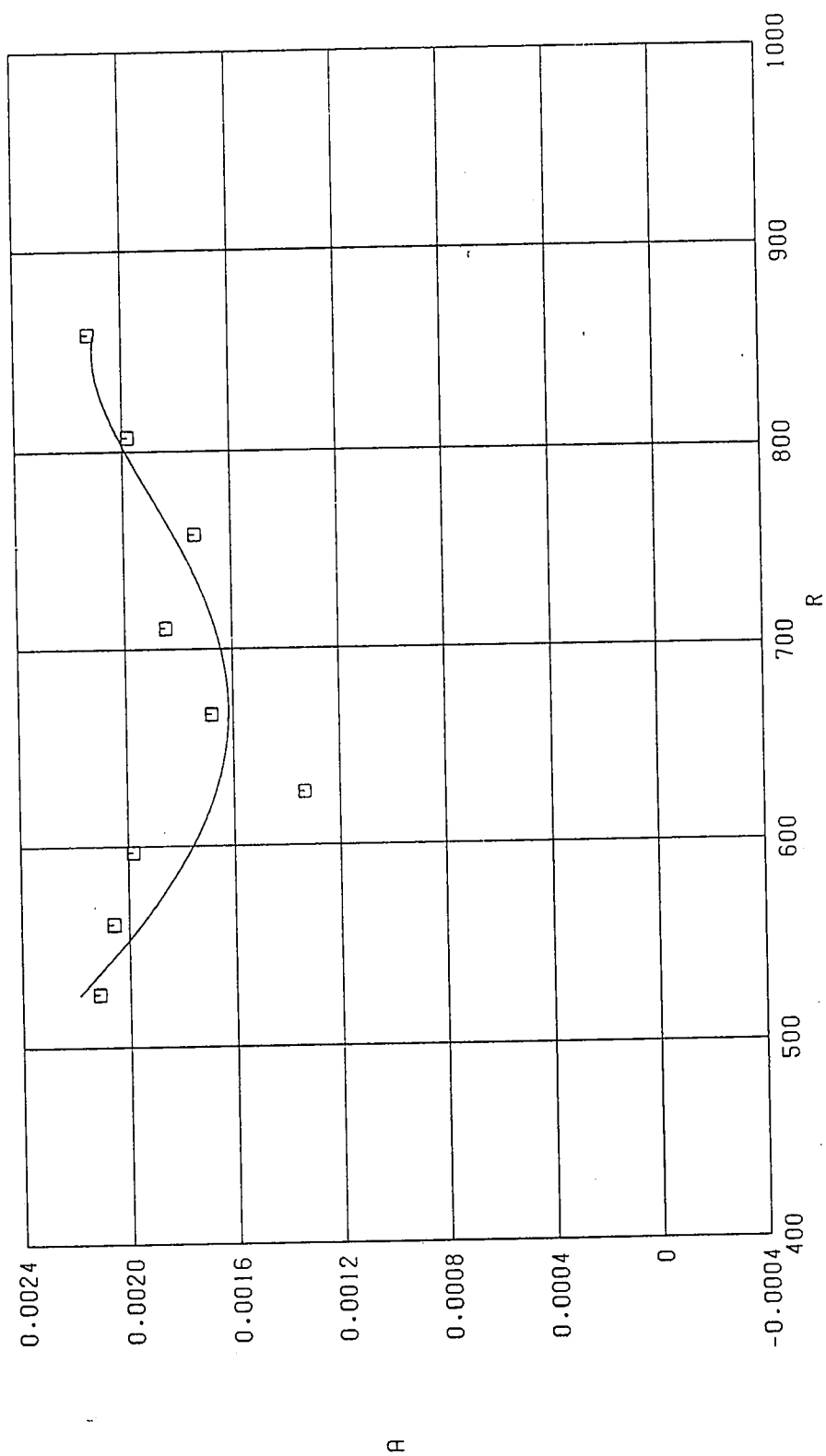


Figure 13. Mass-Flow Fluctuation Amplitudes at 12kHz

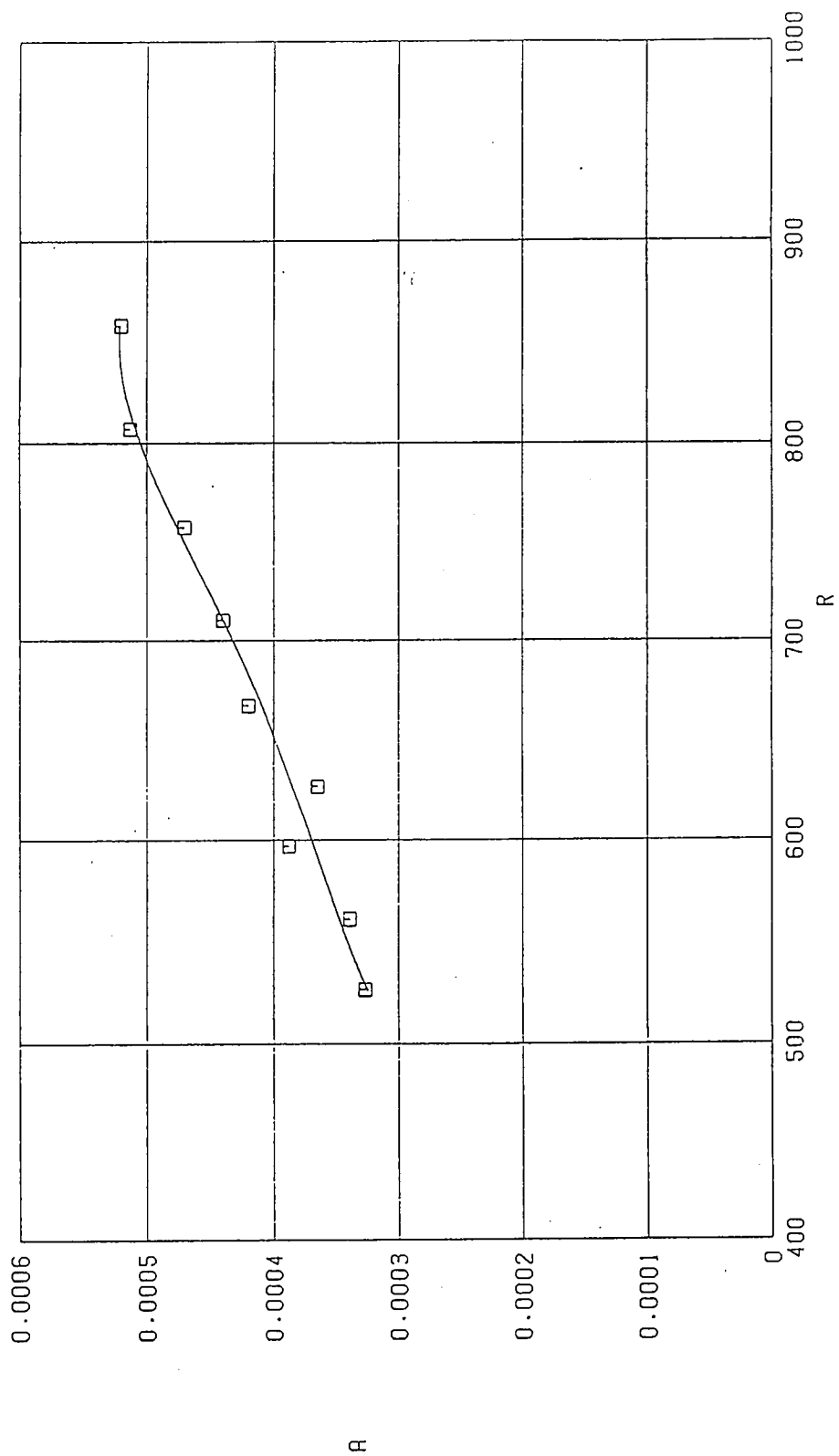


Figure 14. Total Temperature Fluctuation Amplitudes at 12kHz

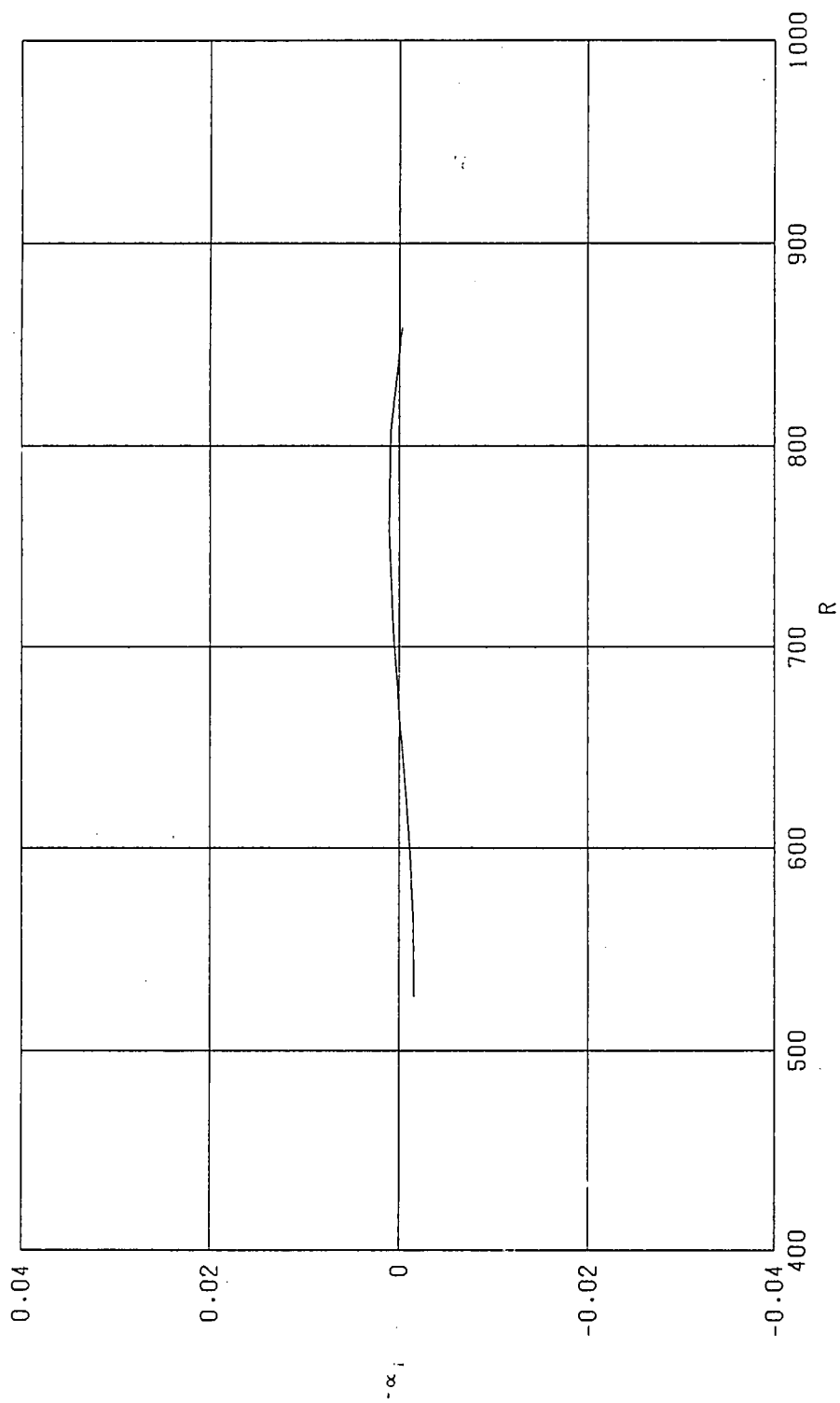


Figure 15. Mass-Flow Fluctuation Amplification Rates at 12 kHz

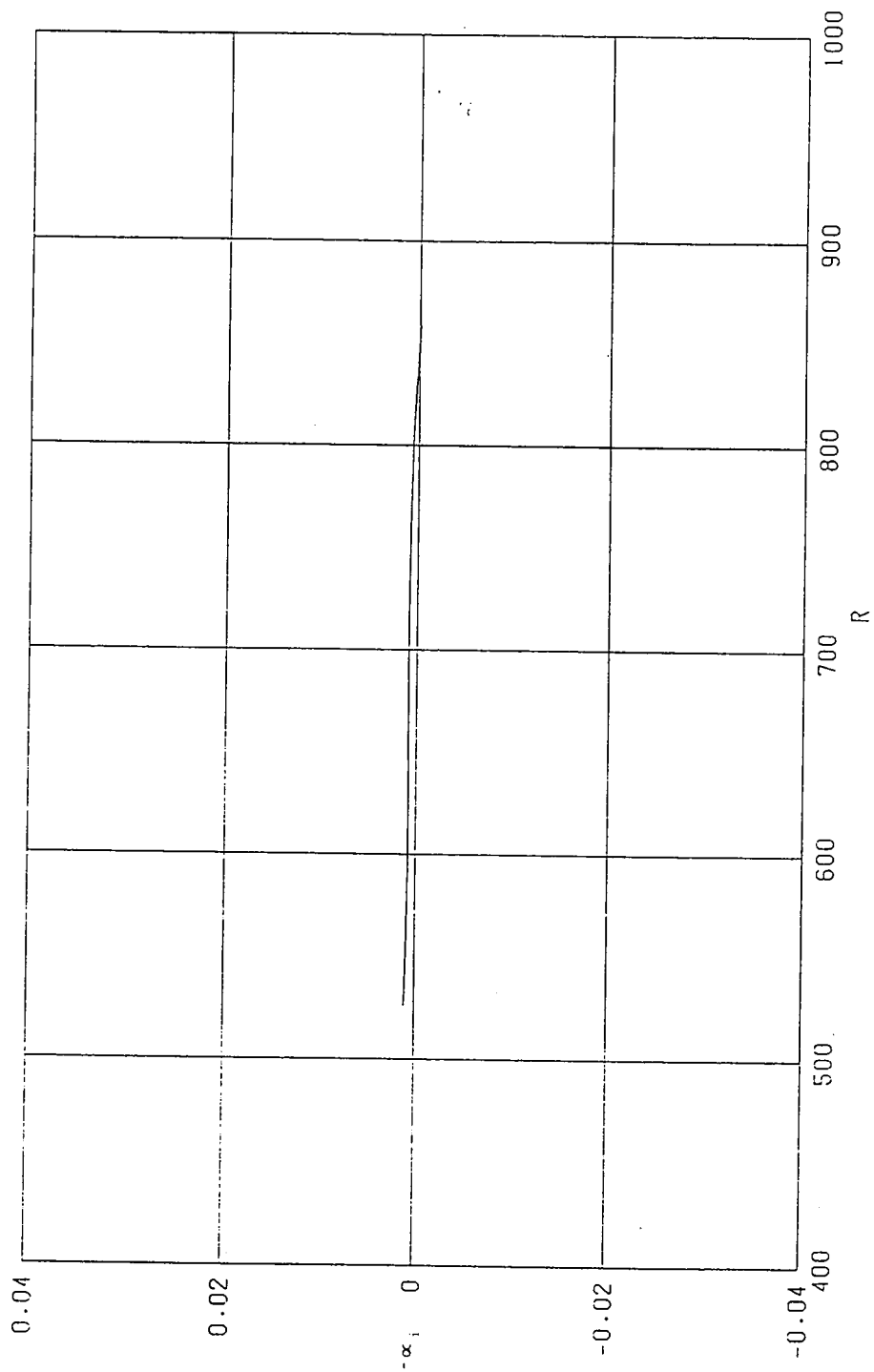
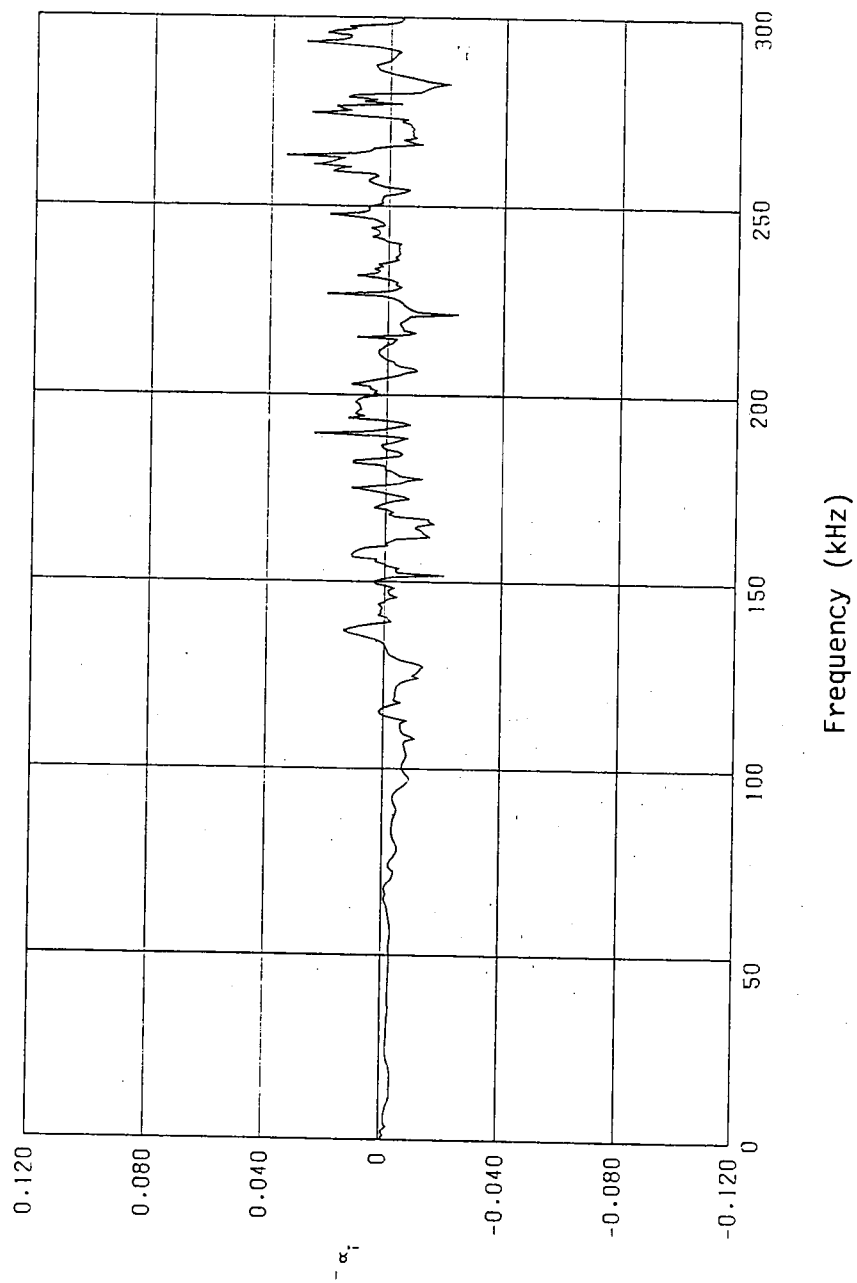
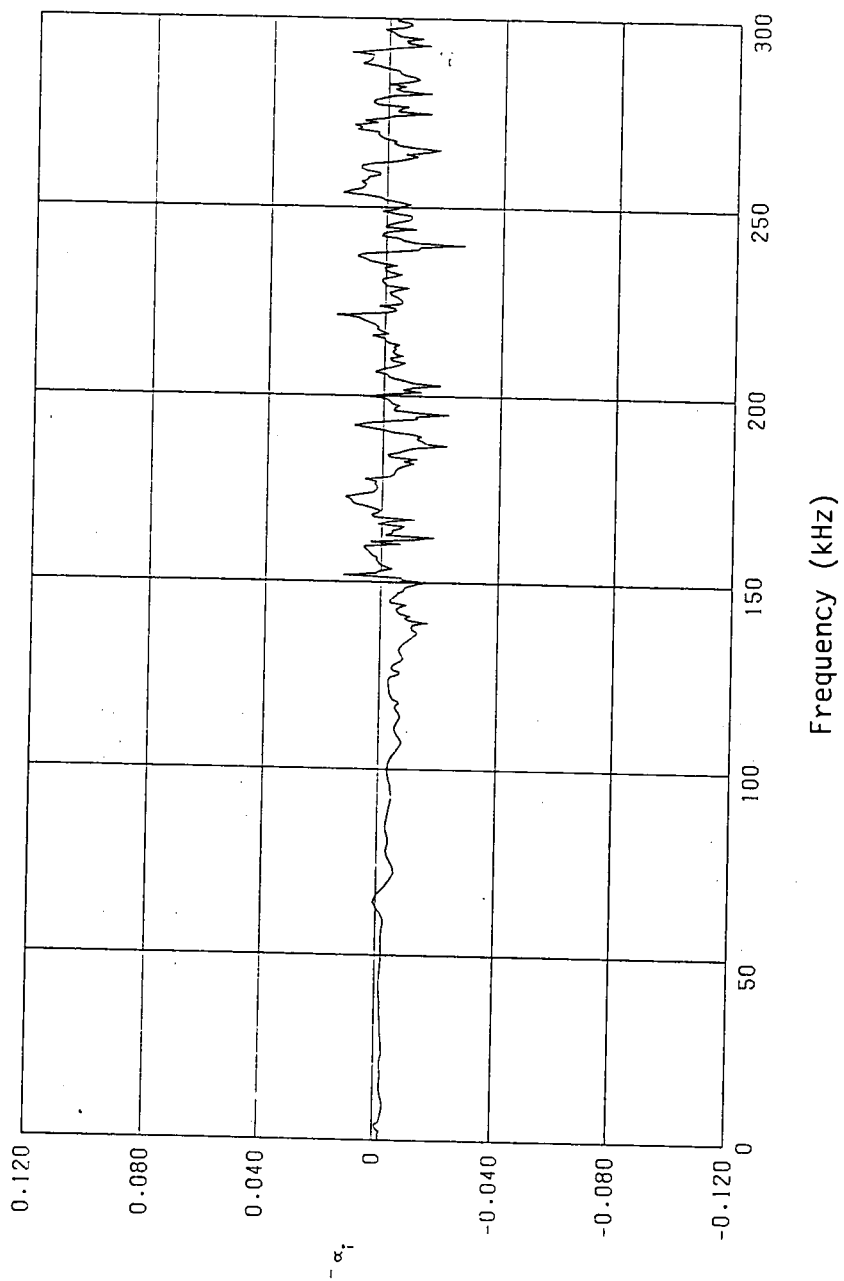


Figure 16. Total Temperature Fluctuation Amplification Rates at 12kHz



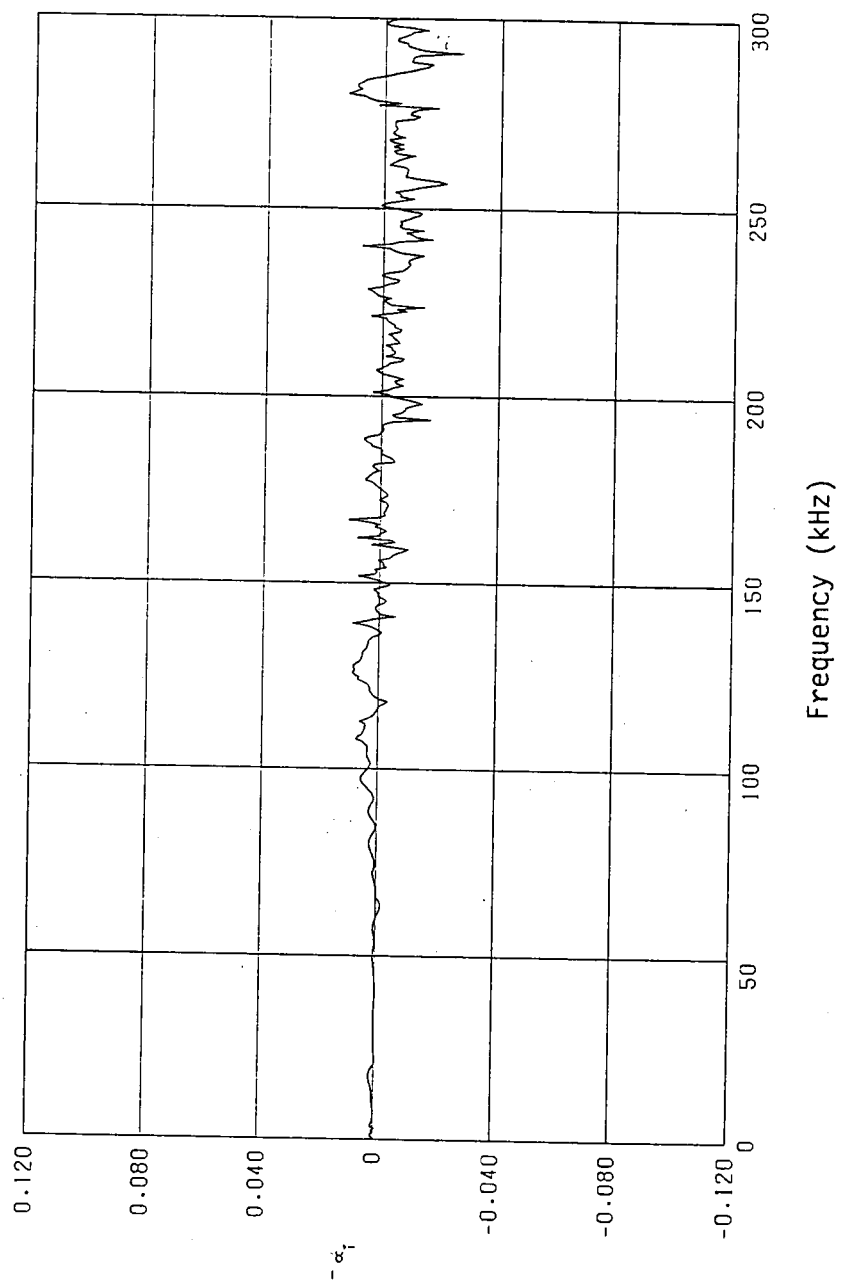
a. Model Station 17

Figure 17. Amplification Rate Spectra of Mass-Flow Fluctuations



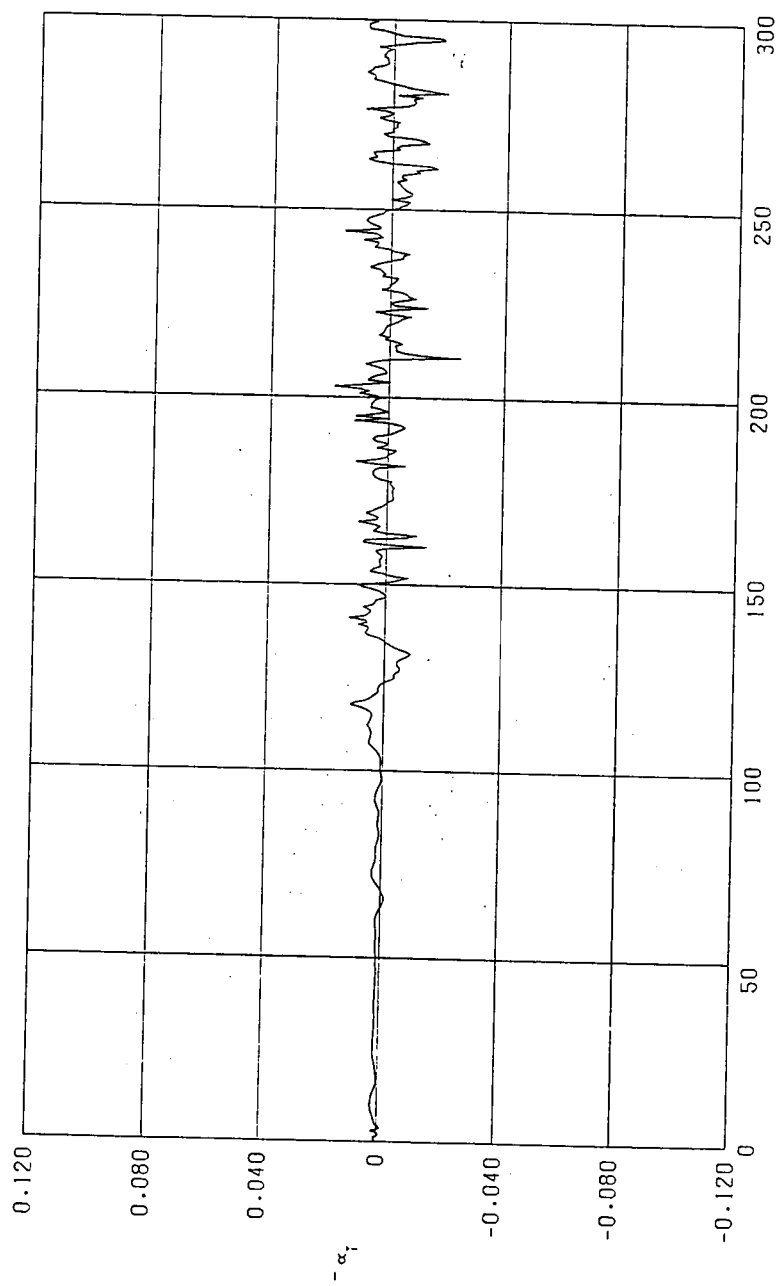
b. Model Station 19

Figure 17. Continued



c. Model Station 21

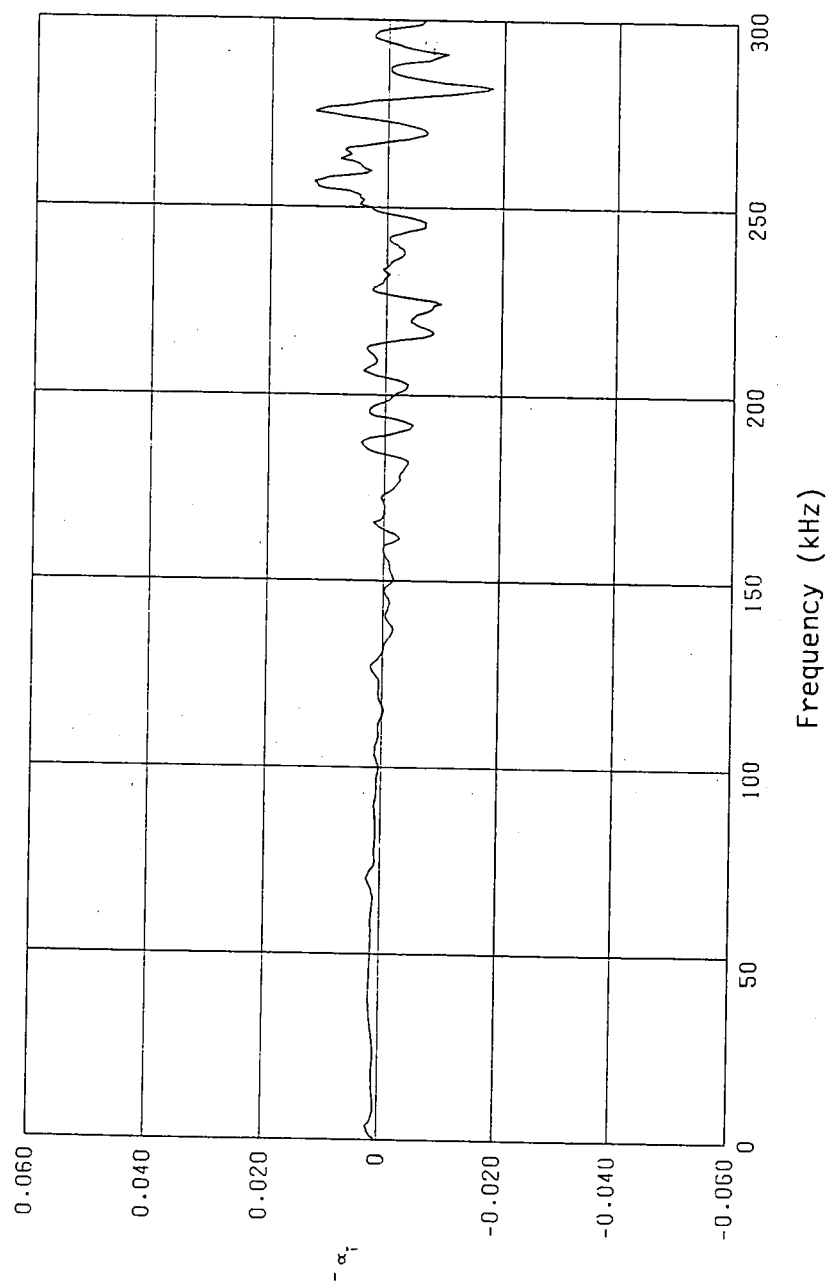
Figure 17. Continued



Frequency (kHz)

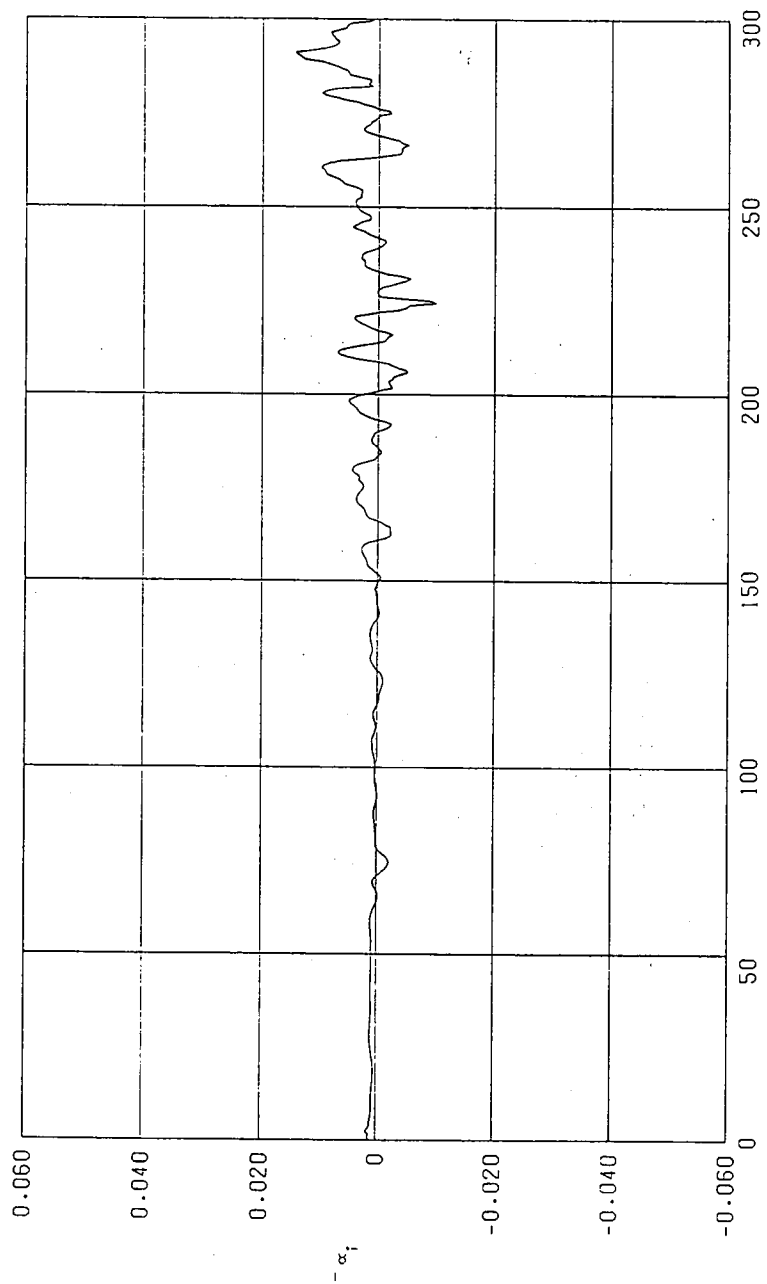
d. Model Station 23

Figure 17. Concluded



a. Model Station 17

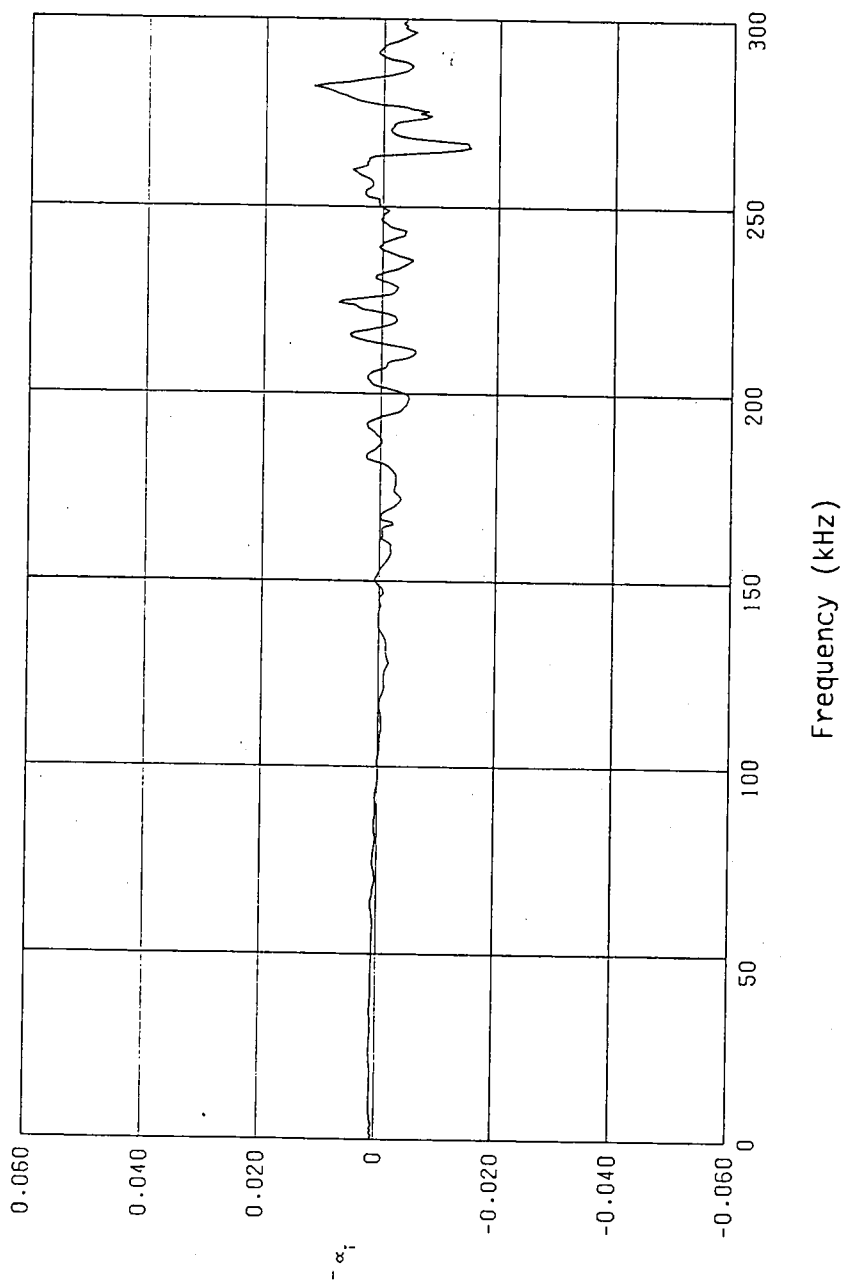
Figure 18. Amplification Rate Spectra of Total Temperature Fluctuations



Frequency (kHz)

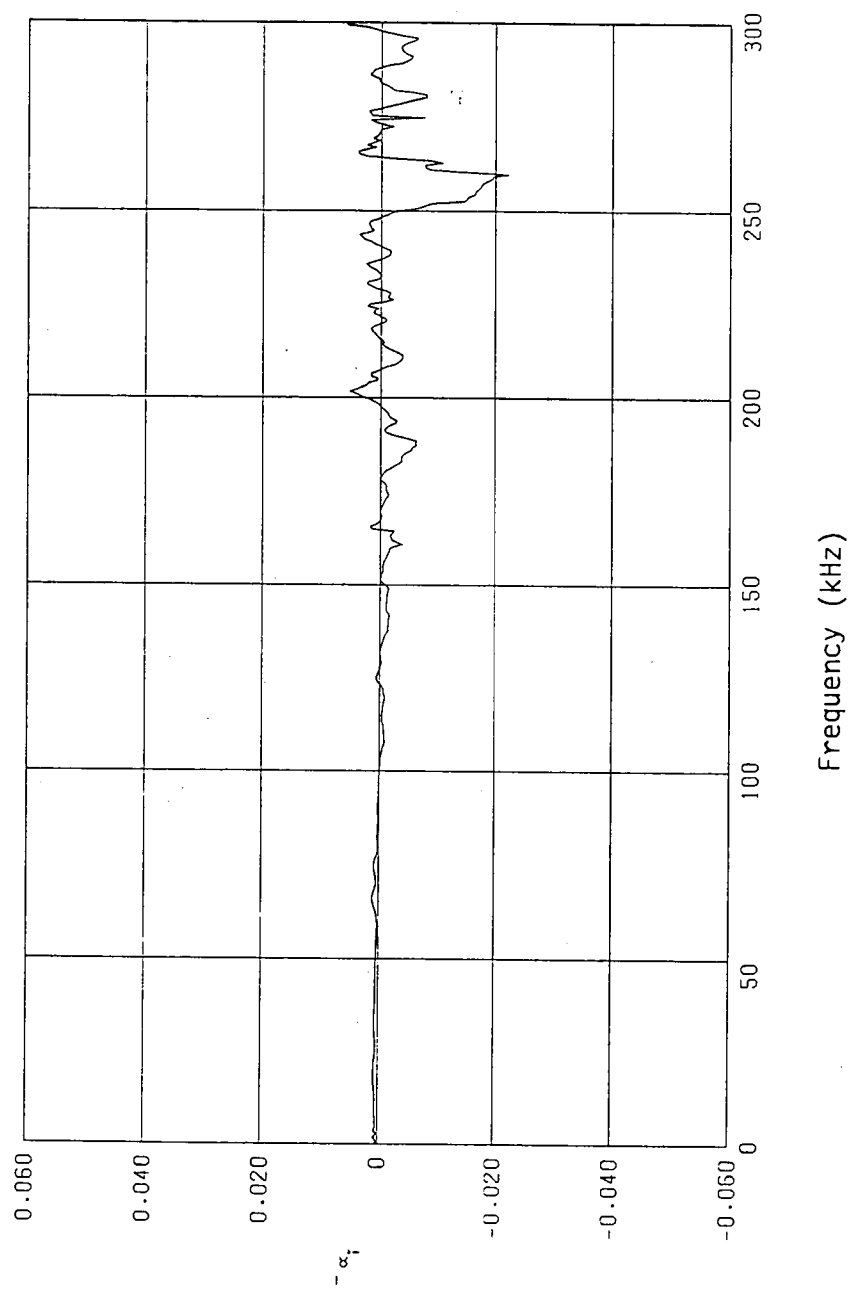
b. Model Station 19

Figure 18. Continued



c. Model Station 21

Figure 18. Continued



d. Model Station 23

Figure 18. Concluded

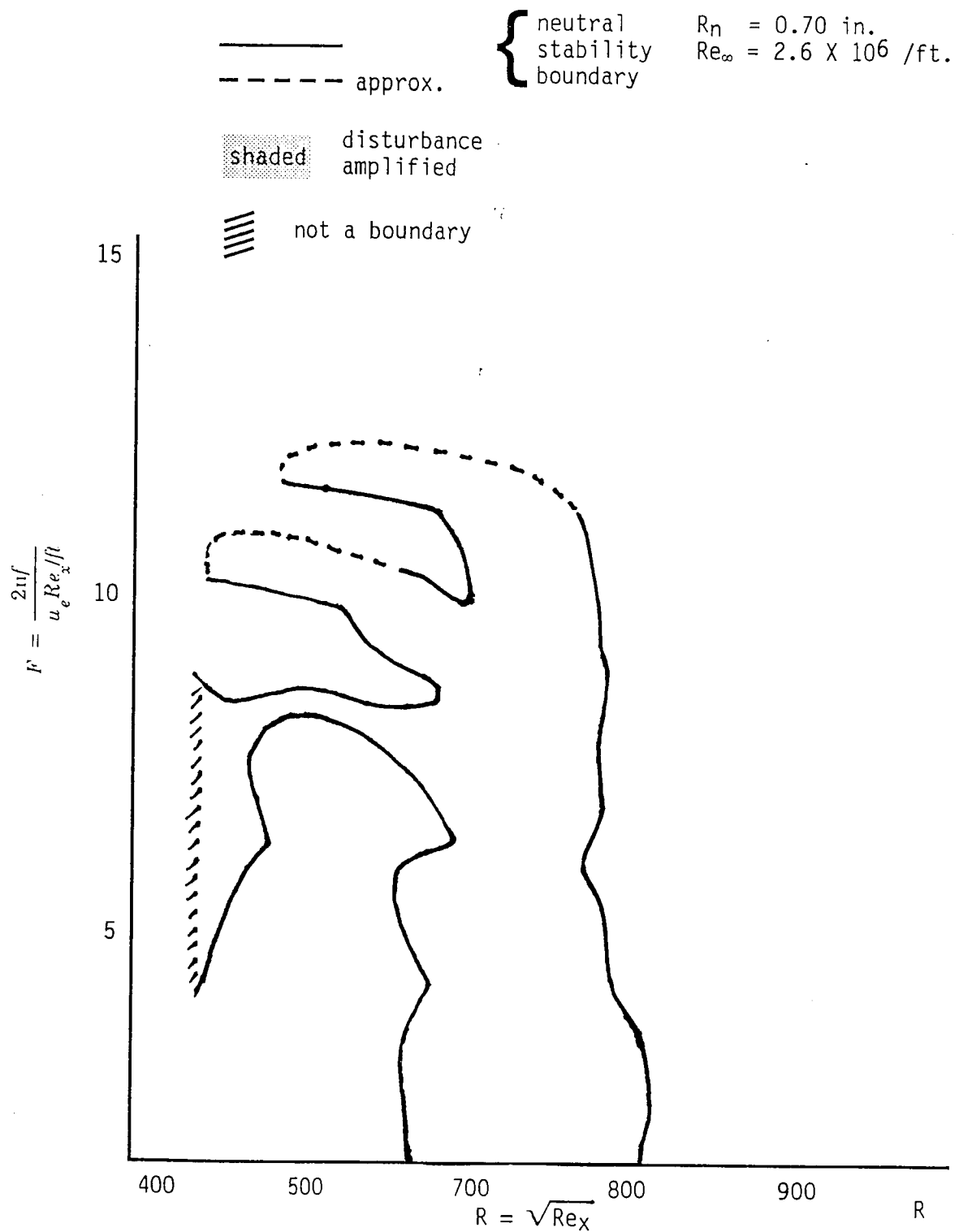
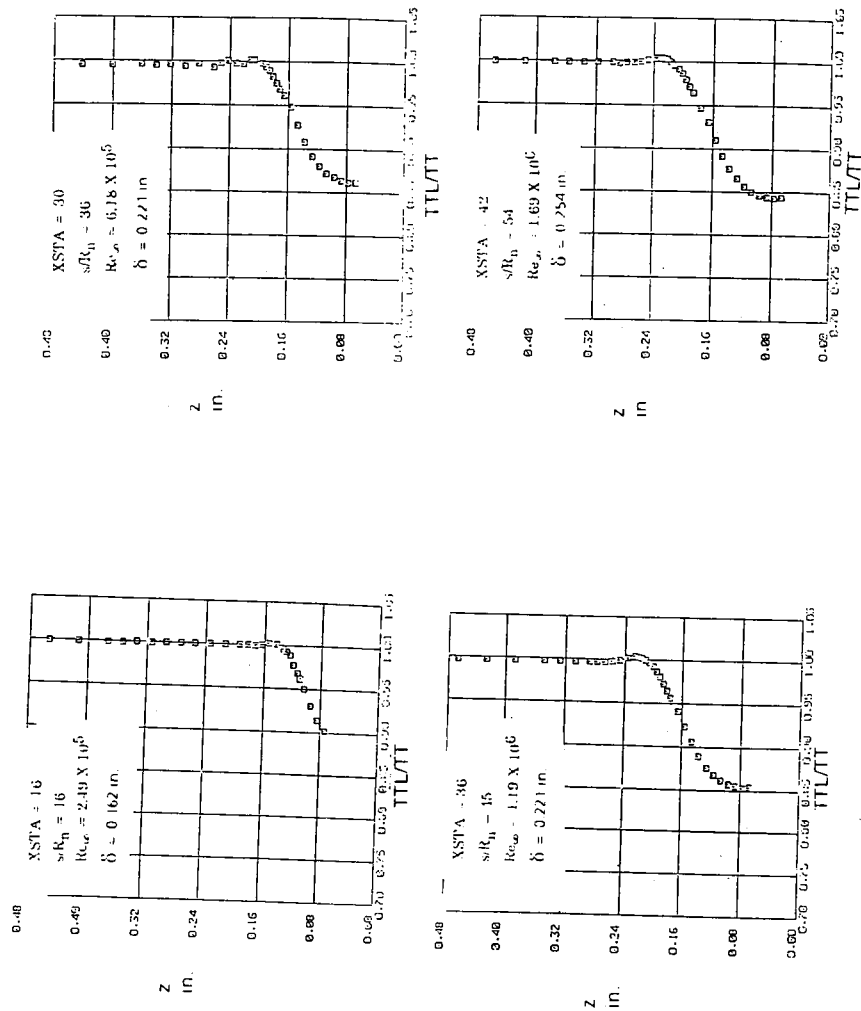


Figure 19. Entropy Layer Stability Diagram Based on the Variation of Dimensionless Frequency, F , versus the Square Root of the Local Reynolds Number, R

$$Re_{\infty} = 2.61 \times 10^6 \text{ /ft}$$

$$M_{\infty} = 8$$

$$R_n = 0.70(\text{in.})$$



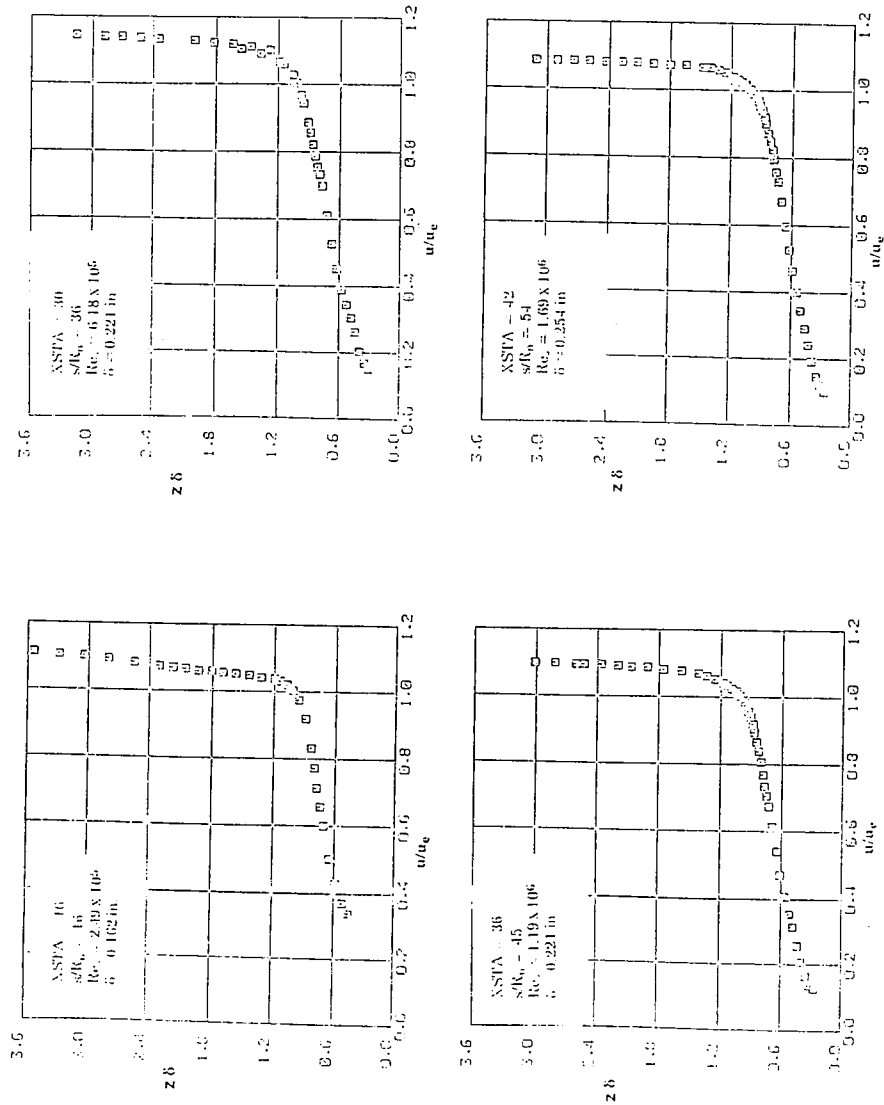
Blunt 0.70 inch Nosetip Radius Cone Data

Figure 20. Mean Total Temperature Boundary Layer Profiles

$$Re_{\infty} = 2.61 \times 10^6 \text{ /ft}$$

$$M_{\infty} = 8$$

$$R_n = 0.70(\text{in.})$$

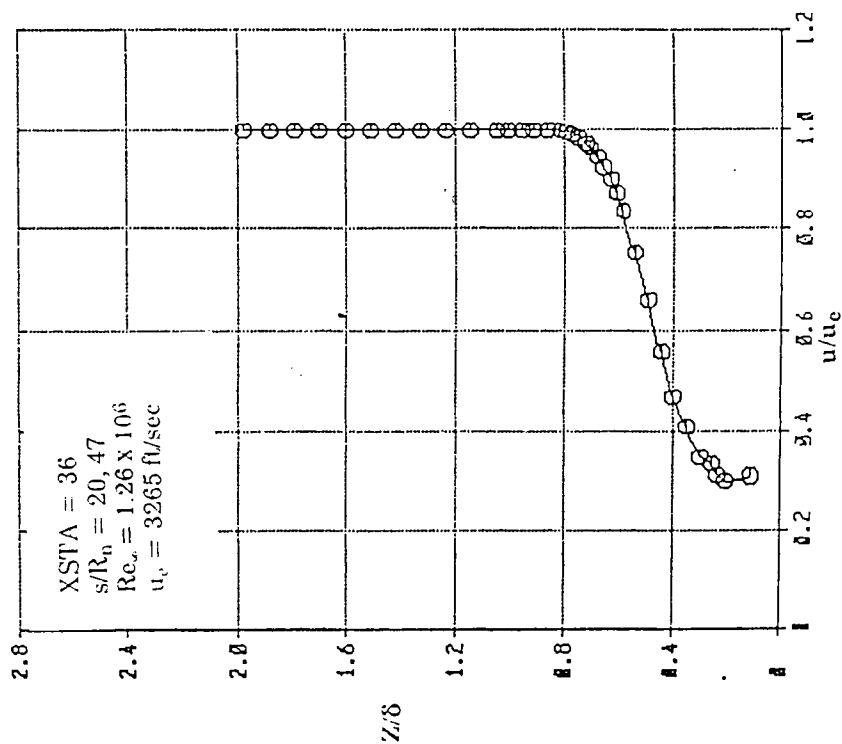
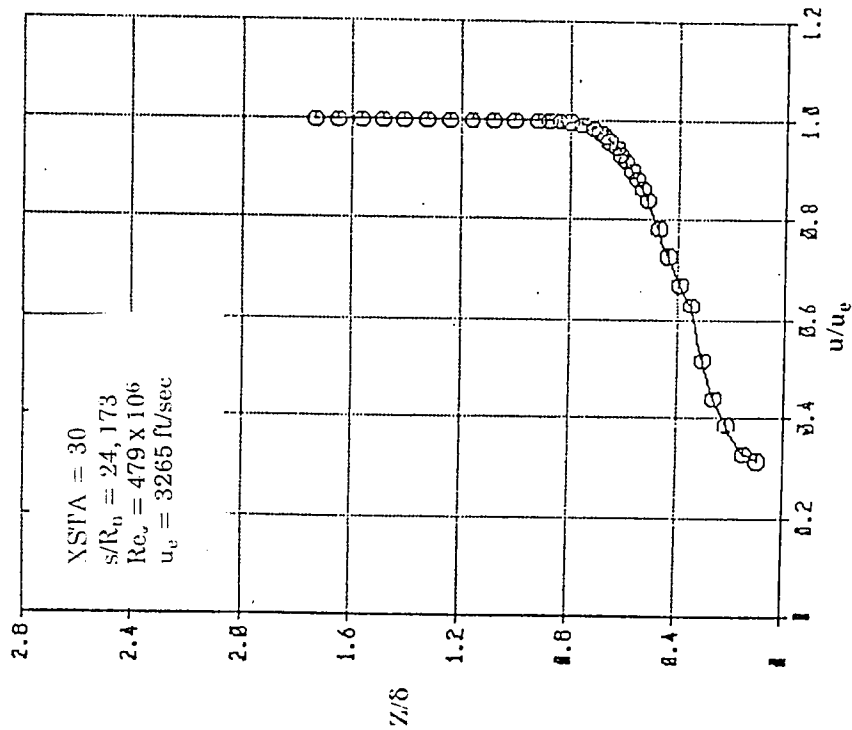


a. 0.70 inch Blunt Cone

Figure 21. Mean Velocity Boundary Layer Profiles

Re_∞ 1.30 X 10⁶ /ft

M_∞ = 8
R_n = 0.0015(in)



b. Sharp Cone

Figure 21. Concluded

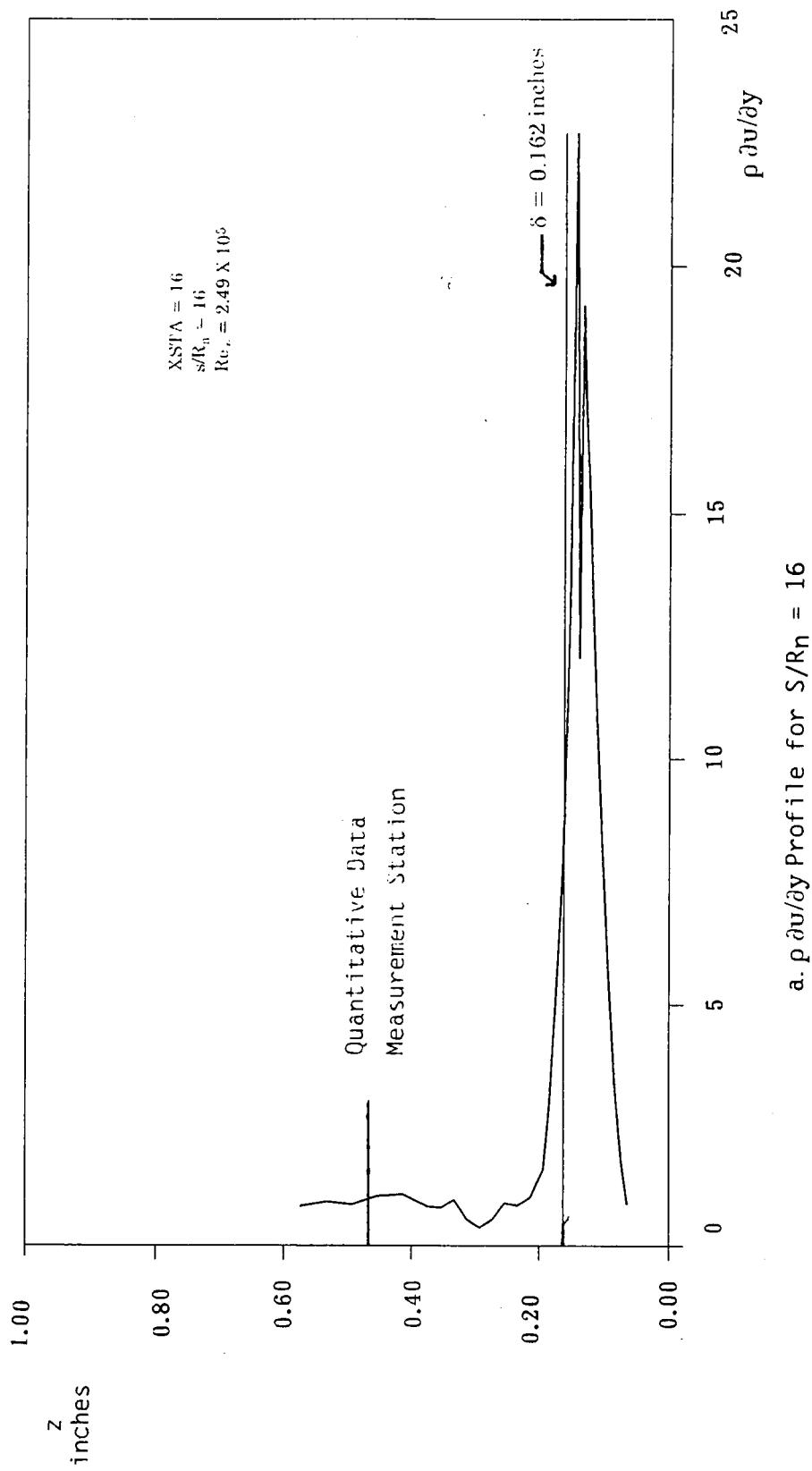
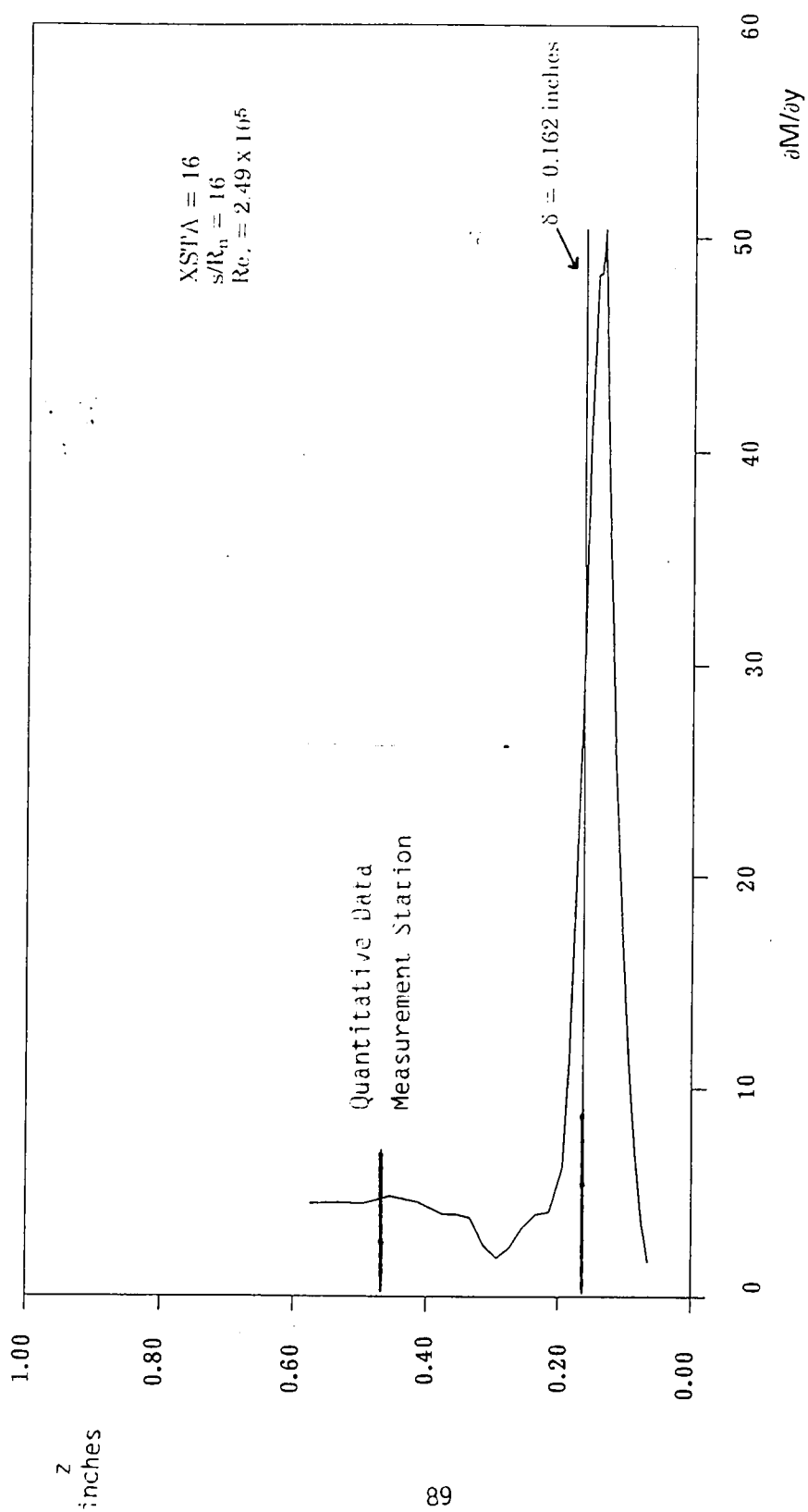
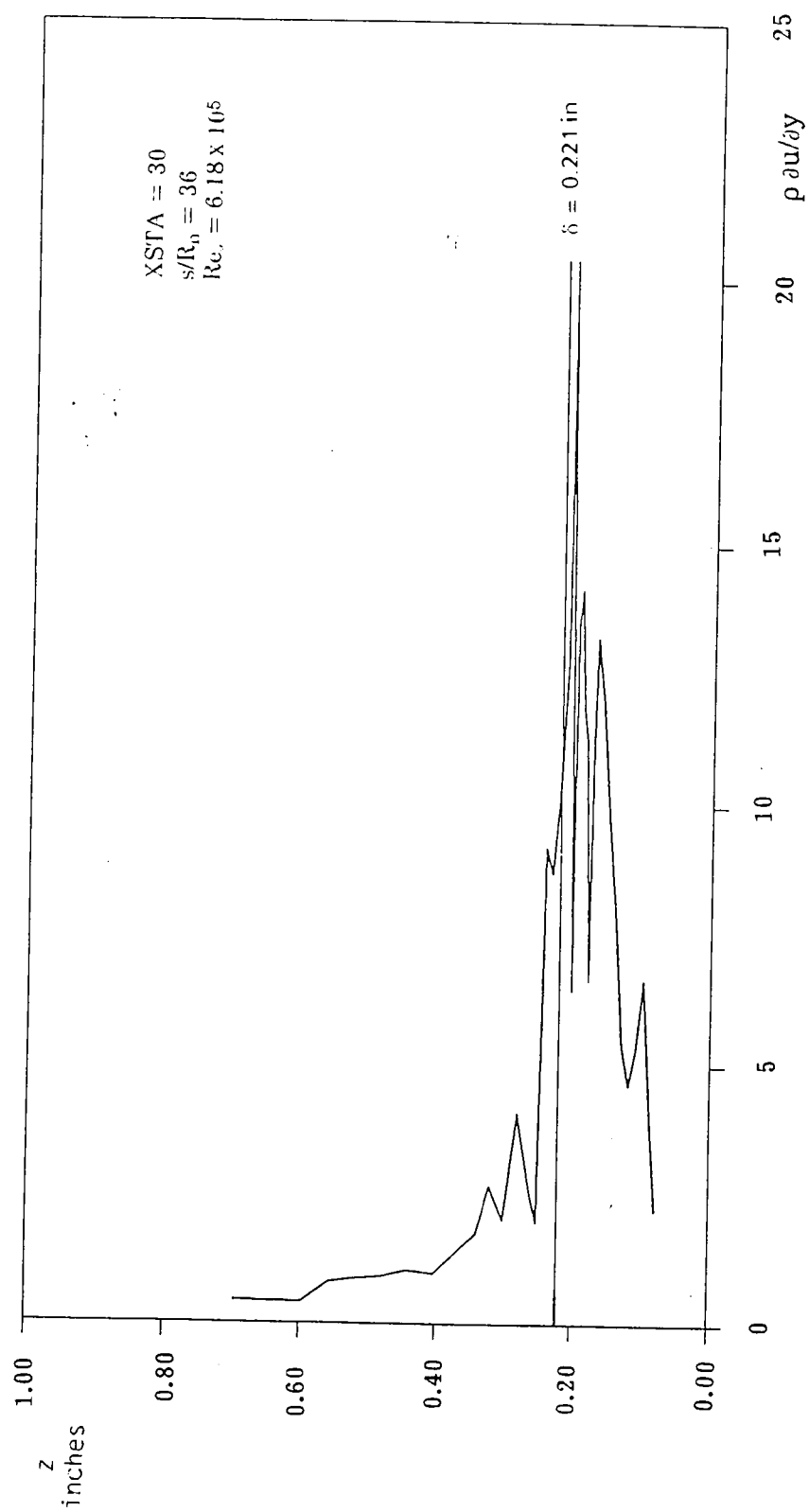


Figure 22. Transverse Profiles of $\rho \frac{du}{dy}$ and $\frac{dM}{dy}$ Across the Boundary Layer and External Flow on $R_n = 0.70$ in Cone



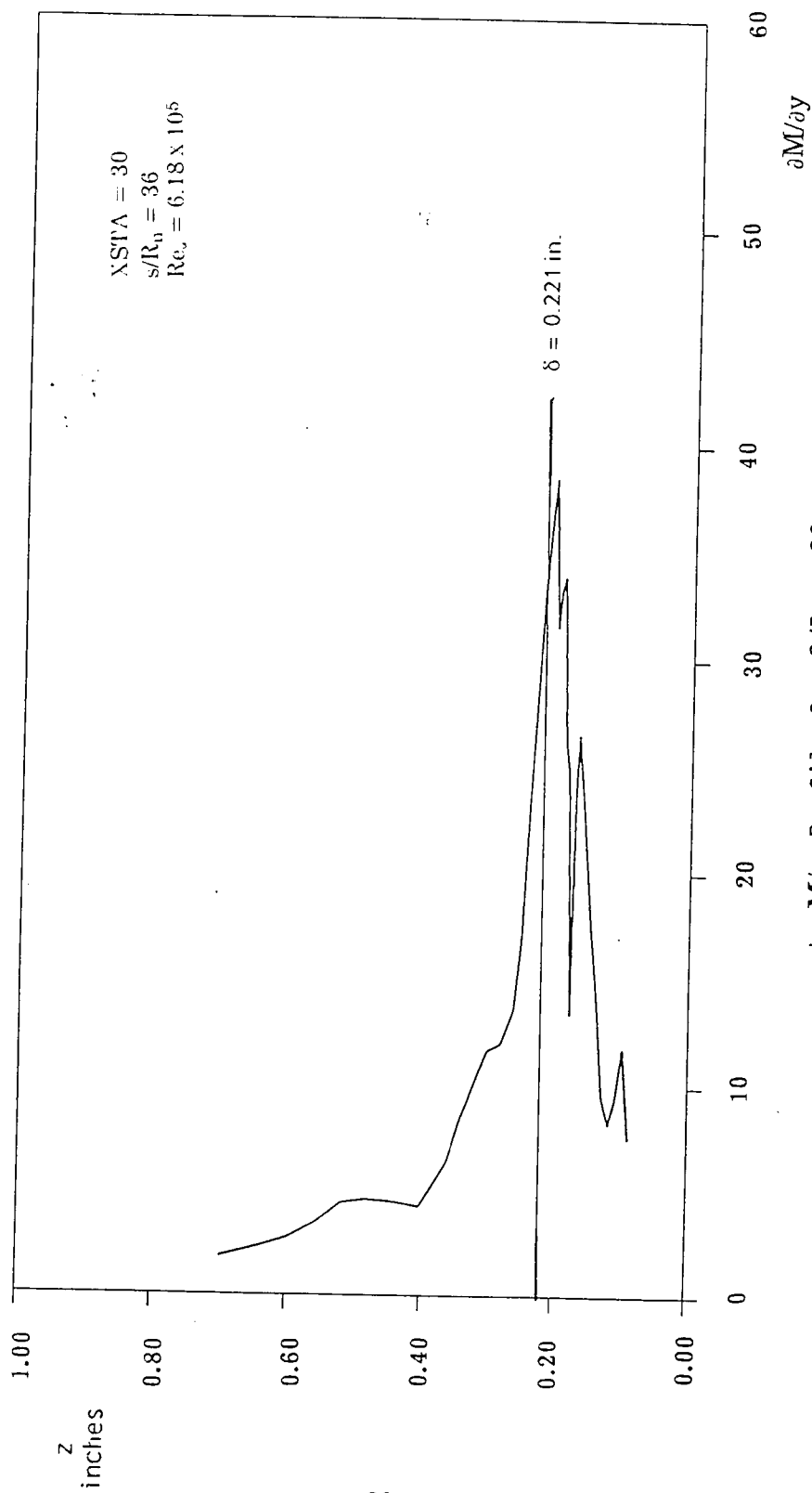
b. aM/ay Profile for $S/R_\eta = 16$

Figure 22. Continued



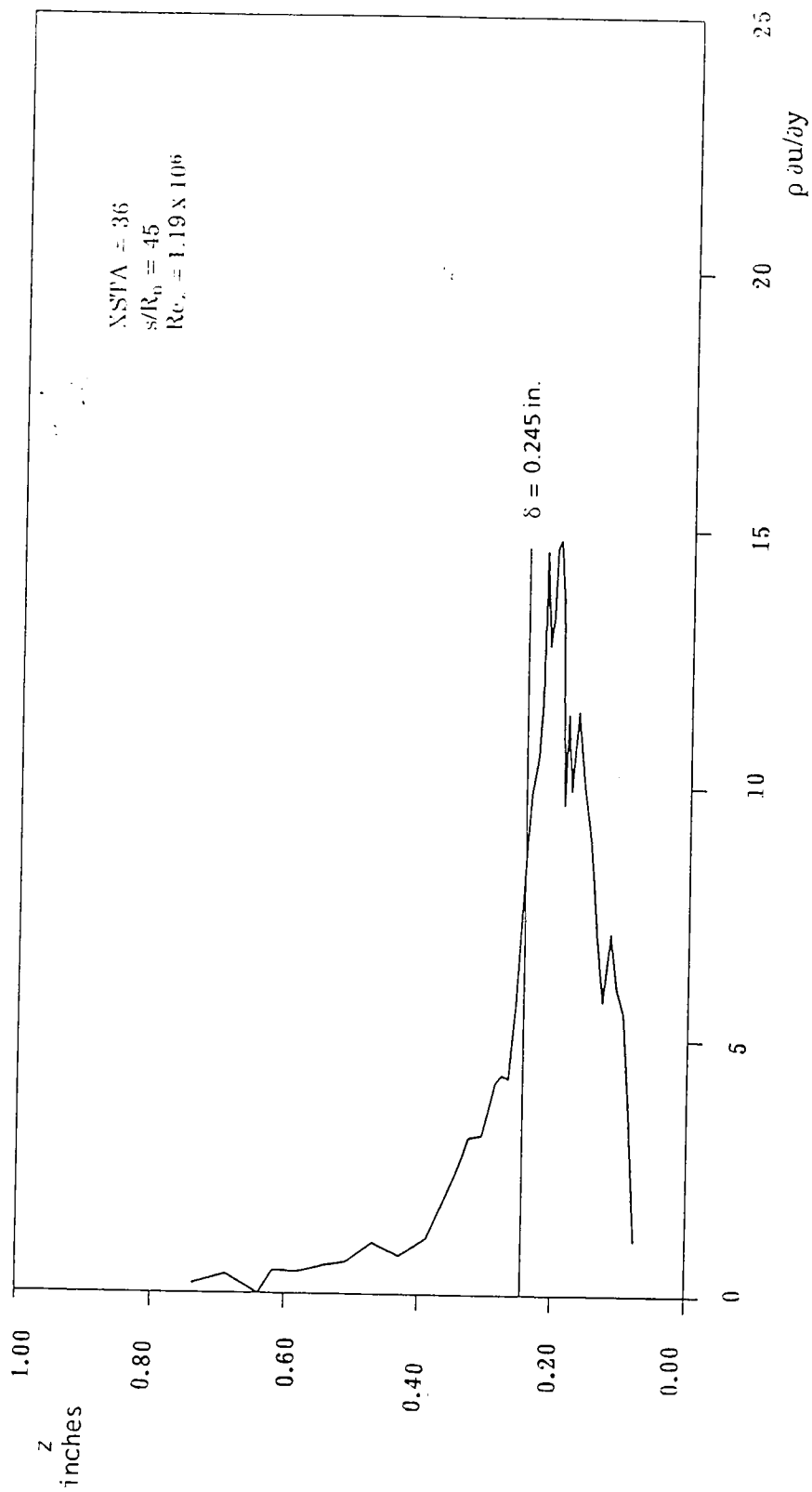
c.p. $\partial u / \partial y$ Profile for $S/R_0 = 36$

Figure 22. Continued



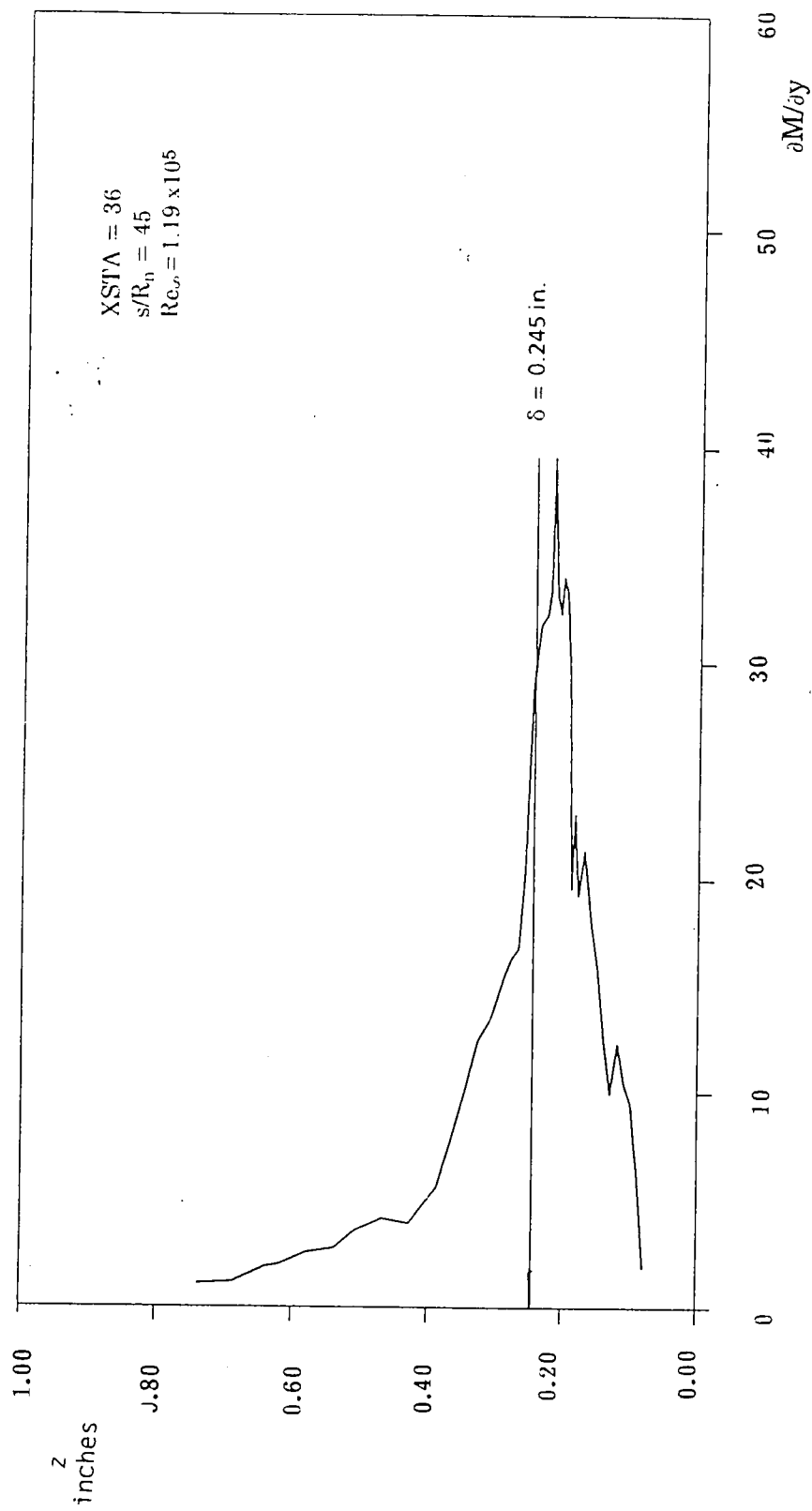
d. dM/ay Profile for $S/R_n = 36$

Figure 22. Continued



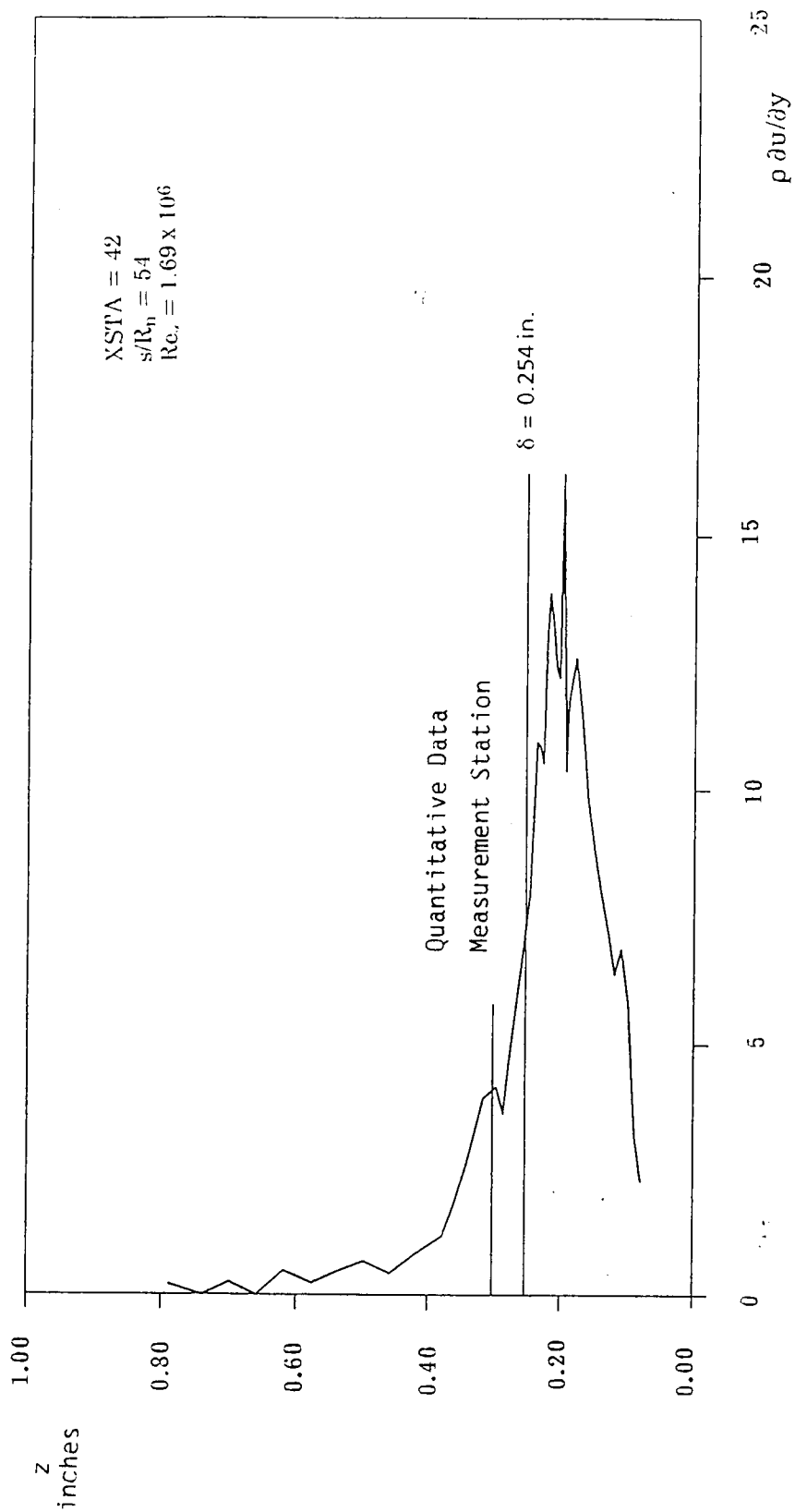
e. $p \text{ au/ay}$ Profile for $S/R_n = 45$

Figure 22. Continued



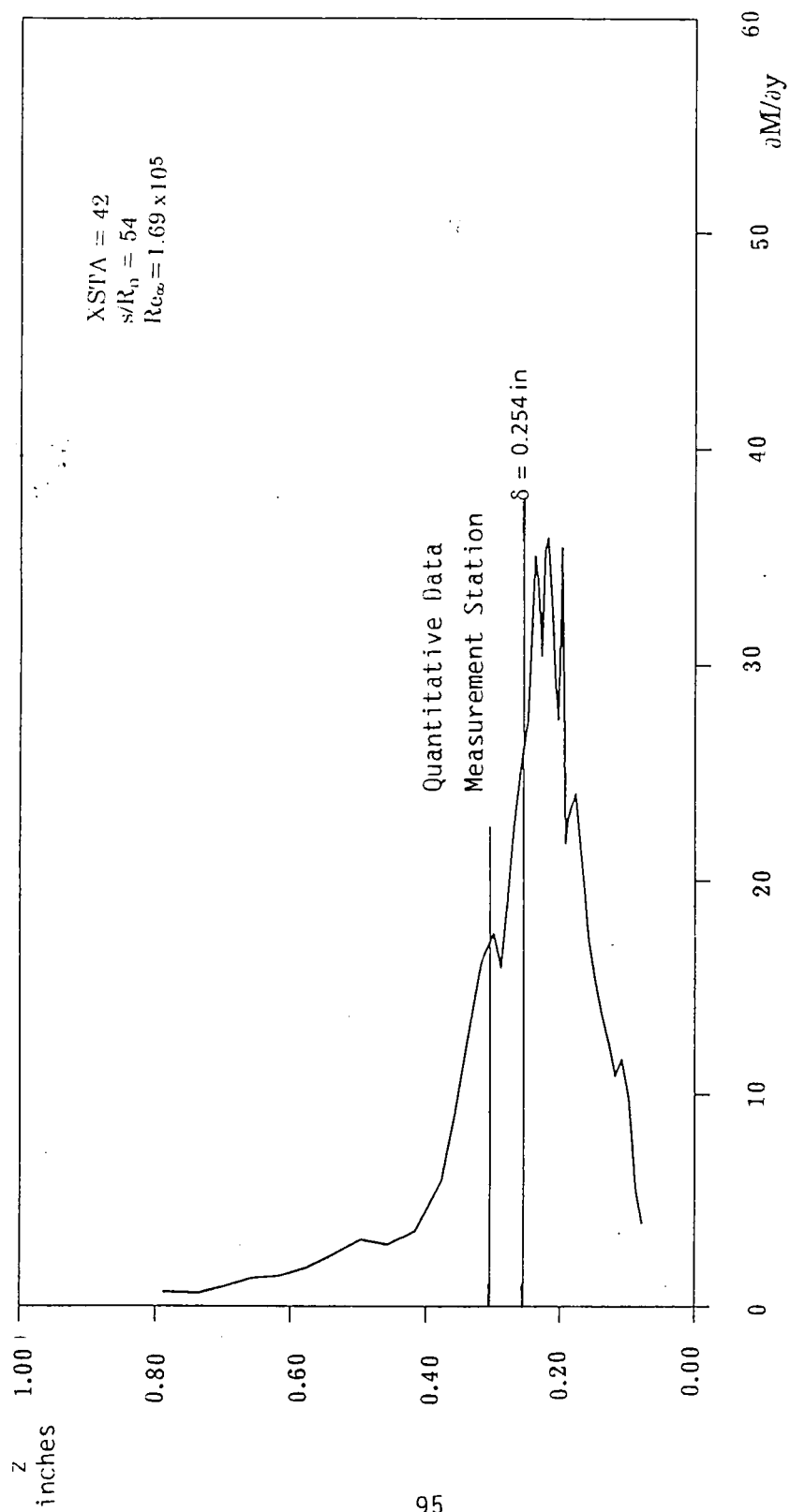
f. aM/ay Profile for $S/R_n = 45$

Figure 22. Continued



g.p. $\partial u / \partial y$ Profile for $S/R_n = 54$

Figure 22. Continued



h. aM/ay Profile for $S/R_\eta = 54$

Figure 22. Concluded

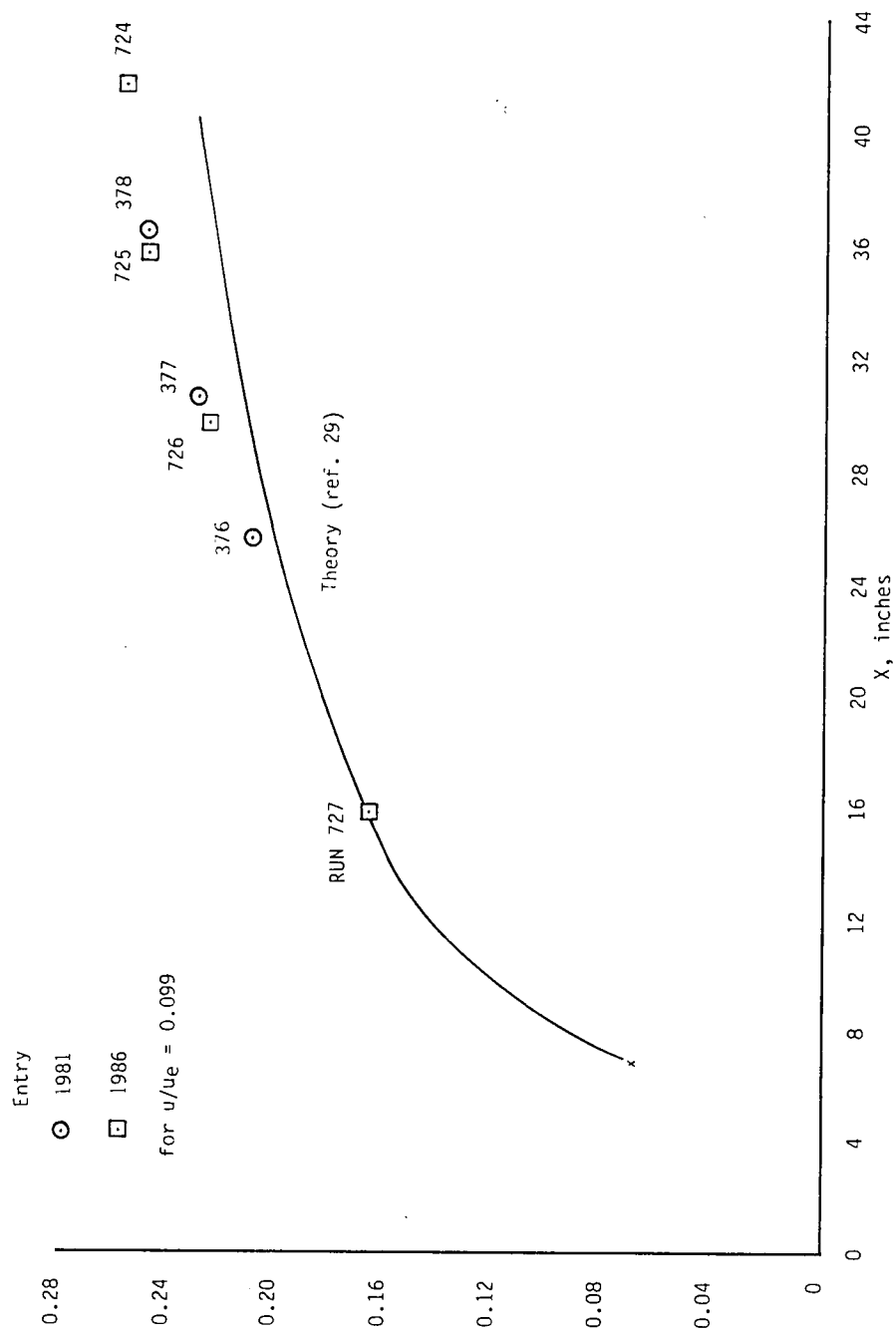


Figure 23. Boundary Layer Total Thickness as a Function of Distance Along Cone Surface

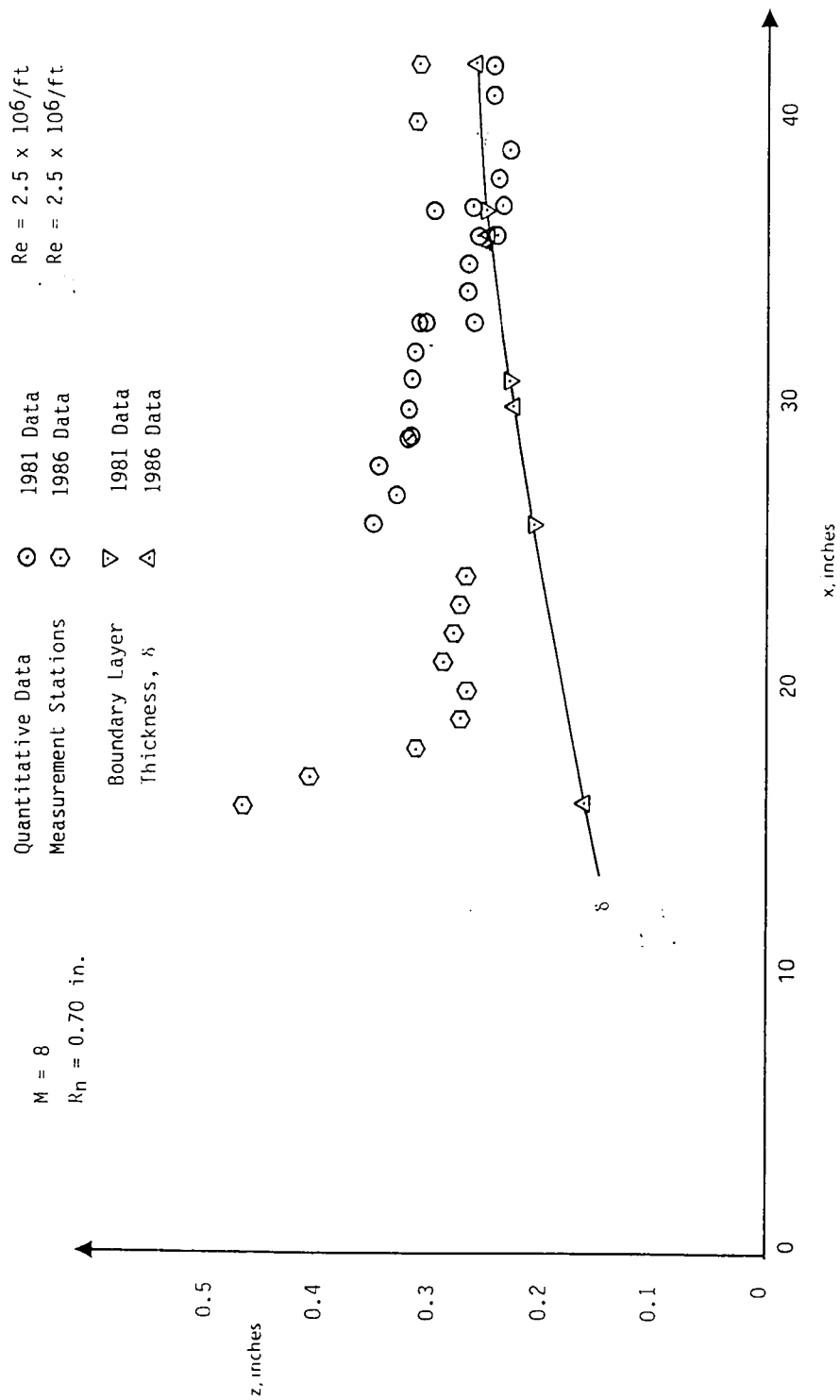


Figure 24. Comparison of Spatial Locations of the Points where Quantitative Data was Measured Compared to the Boundary Layer Thickness

APPENDIX B
SUPPLEMENTARY INFORMATION

R ₀₀ in.		Re _{eff} ×10 ⁻⁶	ALPHA deg	X STATION (NOMINAL)																		
				6	8	10	11	15	16	18	20	24	25	26	28	30	31	32	35	36	37	42
0.0015	0.5	0																			272	
	1.0	0																			286 ^a	
	1.0	+2			111						109							107				
				459 ^b			458 ^b													456 ^c		
	1.3	0																		457 ^{b,c}		
	2.0	0	601																			
	3.0	0	600																			
	2.5	0																				
0.15																						
0.25	2.5	0																				
0.70	2.5	0																				
0.90	2.5	0																				
2.00	3.5	0																				

1. PHI = 30 deg or 45 deg. Extrapolated

2. Superscripts

a. ALPHA = -2.0 deg. PHI = 0 deg windward surface.

c. Cold wall data. TWL = 525, 640, 540 deg R. for Runs 207, 208, 242, respectively.

All other data obtained at hot wall conditions (TWL $\geq$ 860 deg R).

e. Extended survey of preceding Run, all outside boundary layer. f. PHI = 45 deg

Matrix of Mean-Flow Boundary Layer Survey Data Collected by Stetson et al.

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

R _n , in.	Re/ft x10 ⁻⁶	ALPHA deg.	X STATION (NOMINAL)																	
			10	14	15	17	19	20	25	26	27	28	30	31	32	33	34	35	36	37
0.0015	1.0	0	51	46		42		34			26		21			16	15	12	11	8
	1.3	0										373	372		371				370	
0.15	2.5	0	96	88		84		79	67		64		60			57				54
0.25	2.5	0	255 ^e 254										208 ^c 207 ^c					240 242 ^c		
0.50	3.5	0	140		141	142		139	138									134		
0.70	2.5	0									376			377						378
0.90	2.5	0								257 ^e 256										
2.00	3.5	0																129 132		

Notes: 1. RUN numbers < 200 obtained qualitative boundary layer data; RUN numbers > 200 obtained mean flow boundary layer data
 2. Superscripts: c -- Cold Wall data, $TWL \approx 525^\circ$, 640° , 540° deg R. for RUNS 207, 208, 242, respectively. All others at hot wall conditions ($TWL \geq 860^\circ$ deg R).
 e -- Extended survey of preceding run, all outside boundary layer.

Matrix of Hot-Wire Qualitative Survey Data Collected by Stetson et al.

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

R _n (m)	Re f: (x 10 ⁻⁶)	ALPHA (deg)	X STATION																															
			10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37				
	0.5	2.0		432	433		434		436		437		438		439		440		441		442		443		444		445							
0.0015	1.0	-2.0				427	426		425		424		423		422		421	285	284	283	420	282	281	280	279	418	277	278	277	276	275	274		
		-4.0							474	470		473		469	468		467		466		465		464		463	452	460		451					
	2.0	-4.0	612	613	611	614	610		615																									
0.70	2.5	-2.0							616																							475		
																																476		

NOTES: 1 Roll attitude: PHI = -90 deg for RUN < 500; PHI = -110 deg for 500 < RUN < 700; PHI = 45 deg for RUN > 700.

2 Superscripts: s - Single sensitivity for RUN numbers so noted. For all other RUNs, data were obtained on 11 wire sensitivities.

e - No "inner peak" observed; data obtained at approximate height where peak was previously observed.

Matrix of Hot-wire Quantitative Data for ALPHA # 0 Collected by Stetson et al.

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

PRESSURE ORFICE NO.	THETA, deg.	X, in.	S, in.
1	0	39.494	35.103
2	↓	38.500	34.102
3		37.999	33.597
4		36.023	31.606
5		34.038	29.606
7		30.064	25.602
8		28.078	23.602
9		26.093	21.602
10		24.112	19.606
11		22.127	17.606
12		20.474	15.940
13		19.473	14.932
14		16.994	12.434
15		15.014	10.439
16		13.028	8.439
17		11.043	6.439
18		9.058	4.439
19		8.094	3.467
20	90	20.478	15.944
21	180	20.478	15.944
22	270	20.474	15.944
23	90	19.489	14.948
24	180	19.483	14.942
25	270	19.489	14.948
26	180	11.043	6.439
INTERNAL THERMOCOUPLE NO.			
101	270	15.0	10.4
102	↓	24.1	19.6
103		34.0	29.6
104		45.0	41.0

Model Instrumentation Locations

Source: Donaldson, J. C., and Simons, S. A., "Investigation of the Development of Laminar Boundary-Layer Instabilities Along a Blunted Cone", AEDC-TSR-86-V46, November 1986.

VITA

Norman Harold Patnode was born in Millington, Tennessee on 11 February 1961. He attended elementary schools in Millington, Tennessee and Norfolk, Virginia. He graduated valedictorian from Norview Senior High School in Norfolk in June 1979. The following September he entered Virginia Tech in Blacksburg and in May, 1983 received the degree of Bachelor of Science in Aerospace and Ocean Engineering. He worked in NASA Langley's Spin Tunnel as a tunnel operator for Birle Applied Research for a year before attending Officer Training School and receiving his commission in the U. S. Air Force in September 1984. He was then assigned to Wright-Patterson Air Force Base, Ohio, where he worked as a stability and control engineer for two years before being selected to attend Undergraduate Pilot Training at Reese Air Force Base, Texas in November 1986. He was then assigned to Arnold Engineering Development Center, Arnold Air Force Base, Tennessee in October 1987, where he managed test projects for the Reentry Systems Division, Deputy for Flight Dynamics. In June of 1990, he was installed as the Director of Quality for Arnold Engineering Development Center. In May of 1991, he was transferred to the Rocket Propulsion Division, Deputy for Propulsion, and again served as a test manager at the Arnold Engineering Development Center. Concurrently, he studied at The University of Tennessee Space Institute and received a Master of Science Degree in Aerospace Engineering in May 1992.