Progress in the Lewis Research Center Altitude Wind Tunnel (AWT) Modeling Program

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NASA

PROGRESS IN THE LEWIS RESEARCH CENTER ALTITUDE WIND TUNNEL (AWT) MODELING PROGRAM

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Abstract

The rehabilitation of the AWT at the NASA Lewis Research Center is under study with the goal of providing a modern subsonic wind tunnel for conducting propulsion system/airframe integration, isolated propulsion system, propulsion acoustics and adverse weather tests. Because of the increased Mach number capability (from Mach 0.6 to 0.9 plus) and the incorporation of acoustic and adverse weather capabilities into an existing tunnel, the AWT rehabilitation represents a significant technical challenge. In order to reduce the risk associated with such an undertaking, an extensive AWT modeling program is being conducted to guide and verify the tunnel design. Significant findings and progress in this modeling program are the subject of this paper.

Introduction

The proposed modification of the AWT is intended to provide a modern and versatile wind tunnel with the capability for testing a wide range of propulsion system types and for conducting a number of types of performance tests. The capabilities of the AWT will include:

1. Concurrent pressure and temperature altitude simulation.
2. Large scale test articles.
3. Full subsonic speed range.
4. Propulsion system operation/simulation.
5. Acoustic measurement capability.
6. Icing; heavy rain testing capability.

A layout showing the major features of the proposed AWT rehabilitation is shown in Fig. 1 along with its specific operational capabilities. In Fig. 2, a comparison of the altitude and Mach number operational envelop for which true altitude temperature is simulated is shown for the AWT and existing larger U.S. propulsion wind tunnels. As noted, the AWT will provide a broad and unique capability for testing propulsion systems over the full range of subsonic speeds. Expanded discussion of AWT uses and capabilities including the acoustic and adverse weather capabilities has been reported.[1,2]

Because of the significant increase in maximum tunnel Mach number, approximately 50 percent, in an existing tunnel and due to the additional complexity of providing acoustic and adverse weather testing capability, an extensive modeling program at Lewis was undertaken to confirm the adequacy of the design and assure the attainment of the desired tunnel capabilities. The modeling effort was essentially an independent check of the AWT design in those areas considered to be critical to obtaining the desired tunnel capabilities. In addition to being directly beneficial to the AWT, the modeling program was recognized as providing design tools and an engineering data base that could be used in the design and rehabilitation of other wind tunnels.

AWT Modeling Program

The modeling program contains both analytical and physical modeling efforts in the areas of aerothermodynamics, acoustics, icing and system dynamics. The results of the system dynamics activity are reported in another paper in this conference. Elements of the aerothermodynamic, acoustics and icing modeling efforts are shown in Fig. 3.

The analytical modeling employed the latest computer codes and prediction techniques modified as necessary to address the specific characteristics of the AWT design. The analytical modeling (Fig. 4) emphasized potential problem areas or unique features. The major accomplishments of the analytical modeling, which was an extensive effort, have been reported[3,4] and will not be repeated here.

The major effort in the physical modeling consists of building 1/10th-scale models of most of the tunnel components and then assembling them into a high-speed leg, a fan leg and corners as shown in Fig. 5. The fan leg model has been modified from earlier plans. It will now be run with a clean inlet (bellmouth) and with simulated real inlet flow using screens to adjust the inlet flow profile. The AWT fan diffuser has been replaced with nominal exit ducting. Eventually a complete 1/10th-scale loop was to be built, but this effort has since been dropped. The scale of these models was a compromise between the resources required to build and test them and the uncertainty associated with scaling the model results to the full size tunnel. It is believed that the scale selected is reasonable and it is also consistent with previous experience. The acoustic modeling associated with the anechoic test section will be performed in the high-speed leg. In addition, several other Lewis tunnels, including the 8- by 6-ft Supersonic Wind Tunnel and the 6- by 9-ft Icing Research Tunnel (IRT), along with other facilities were used to conduct the remaining acoustic and icing physical modeling efforts. The following discussion presents the significant results obtained in the physical modeling program.

Modeling Program Results

Aerodynamics

Corners. Two types of corner turning vanes were investigated. These vanes were designed using recently developed computer codes. One design technique referred to as controlled diffusion, calculates unique vane cross sections using an inverse design approach and includes a boundary layer analysis for purposes of avoiding flow separation[5]. The second design technique[6] calculates the vane aerodynamics with an inviscid panel code and uses more conventional circular arc type vane cross sections. Both techniques use two-dimensional analysis codes.

A comparison of the loss coefficients for these two vane designs at the design inlet Mach number of 0.35 for the corner immediately downstream of the test section (corner 1) is shown in Fig. 6. The loss coefficient is defined as the loss in area weighted total pressure through the corner divided by the corner inlet dynamic pressure. The circular-arc vanes have a loss coefficient 25 percent higher than that for the controlled diffusion vanes. Furthermore, the higher loss is associated with the two-dimensional portion of the flow which is that portion of the flow towards the center of the duct where the corner walls have little influence[7] and the flow approximates a two-dimensional cascade.

The addition of the exhaust scoop and fairing adds about 25 percent to the corner losses. For the same inlet flow, the exhaust scoop blockage raises the inlet Mach number to 0.4. While this higher Mach number contributes to the added losses, the major contribution is associated with losses introduced by the exhaust scoop itself.

Data in the literature on corner losses are both sparse and relatively old. Nevertheless, it can be seen in Fig. 6 that the corner losses for the controlled diffusion vanes are somewhat less than the range of those reported in spite of the fact that the inlet Mach number for the controlled diffusion vanes is significantly higher. If the controlled diffusion vane loss coefficient is extrapolated to an inlet Mach number of 0.1,[7] the loss would be reduced to 0.1 or about 26 percent less than the best reported in the literature.

Selection of the best vane type for a given application will depend on a number of factors. While reductions in pressure loss contribute to reduced tunnel operating cost due to reduced drive power and cooling requirements, the cost of fabrication must also be considered. The controlled diffusion vanes are probably more costly to build because of their more complex airfoil geometry, but the number required is reduced by 1/6 due to lower solidity requirements. Therefore, a number of competing factors must be evaluated before a selection can be made for any specific application.

Pressure loss coefficient results for the corner immediately upstream of the fan (corner 2) are shown in Fig. 7. Data for the corner are shown with the fan shaft fairing installed. For this type of corner penetration, the losses for the controlled diffusion turning vanes are about equal to that for the circular-arc. This is a result of significantly higher three-dimensional losses since the two-dimensional losses for each vane type are about the same as the level shown in the previous discussion.

Of interest are the results obtained when the two corners are combined, including the modest diffuser section between them. As shown in Fig. 7, there is a substantial reduction (about 1/3) in loss coefficient. Again, there is only a modest advantage for the controlled diffusion vanes. The explanation for the large reduction in loss coefficient is believed to be that the high loss regions of the upstream corner repositions the high energy flow into those regions of the downstream corner that are more efficient in turning the flow. Expanding on this point, the high loss vane/end wall region of the upstream corner creates a low energy flow which persists to the downstream corner. Thus, the high loss vane/end wall region of the downstream corner sees a much lower energy flow and therefore the losses for this area are reduced. A similar argument can be made for the shaft fairing of the downstream corner since it is in the same horizontal plane as the exhaust scoop and its fairing.

High-speed leg. Analytical analysis of the contraction section[3] indicated the possibility of flow separation from the wall at the very beginning of the contraction. This could lead to a problem with flow quality in the test section. Contributing to this condition was the relatively short length of the contraction section; it had a length to max diameter ratio of 0.935. However, measurements of wall static pressure profiles in the contraction section and observation of flow tufts did not show any separation over the full Mach number range. Typical flow Mach numbers in the vicinity of the wall as determined with wall static pressure data are shown in Fig. 8 for a test section Mach number of 0.916. The gradual, well behaved surface Mach number profiles at the entrance to the contraction section do not show any sign of separation. Results obtained at other circumferential locations were similar and therefore are not presented here. The figure also shows a slightly faster acceleration for streamlines aligned with the center of the flat wall section as opposed to streamlines aligned with the edges of the flat. This is a result of the higher wall curvature associated with the transition from circular to octagonal cross section which is initiated at about the -0.816 X/L position.

Results of turbulence intensity measurements are presented in Fig. 9. Measurements of the longitudinal turbulence were made in the model AWT settling chamber with four 34-mesh screens installed in the plenum tank upstream of the settling chamber. The table indicates no significant variation in turbulence with tunnel Mach number or circumferential position. The turbulence numbers are defined as the rms of the fluctuating longitudinal velocity divided by the average velocity. An overall average turbulence of about 4 percent is indicated from the data. Estimates of test section turbulence made by extrapolating from the measurements made in the settling chamber are also shown in Fig. 9. Three different methods for conducting this extrapolation,[8-10] were employed. While there is some variation in the resulting estimates, a reasonable assumption is that the turbulence will be towards the center of the estimated band and thus, the prospects for achieving the AWT turbulence intensity goal of 0.5 percent in the high-speed leg model test section appears to be very good. Two additional factors need to be addressed, however, before a final assessment can be made. One is the added turbulence associated with including the two transverse fluctuating velocity components along with the longitudinal component measurements, and the second is the reduction in turbulence to be obtained by adding screens and a honeycomb to the settling chamber in future tests. However, these adjustments to the turbulence are in opposition and will tend to cancel each other out.

Measurements of the total pressure at the test section inlet of the high-speed leg are shown in Fig. 10. The total pressure profile is very flat. For the 0.8 test section Mach number shown, the maximum local total pressure variation is less than 0.3 percent which is equivalent to about the same percentage variation in Mach number assuming a constant static pressure profile. The total pressure loss coefficient for the contraction section was found to be 0.0021 (based on test section dynamic pressure). This low value also implies that there was no flow separation in the contraction section.

Thus, preliminary results obtained with the high-speed leg model indicate that the flow quality at the test section inlet appears to be quite good even though the contraction length is relatively short and the contraction ratio (6.503/1) is very modest. Considerable calibration effort on the test section remains to be done, however. Included in this effort is an evaluation of tunnel wall interference effects associated with test section axisymmetric models with blockages up to 12 percent. Additionally, pressure loss coefficients for all model components will be determined.

Acoustics

In the AWT design and the physical models, a number of sonic chokes are planned to be employed. The effect these chokes will have on overall system acoustics is being investigated. One type of choke that will be in both the AWT and physical models is the butterfly valve which will be used for controlling exhaust flows. Measurements were made to determine their effectiveness in restricting downstream background or self-generated noise from propagating back into the tunnel and compromising acoustic measurements. The results of measuring noise levels upstream of a 54 in. diameter butterfly valve is shown in Fig. 11. The upstream noise level is substantially less than the downstream fluctuating pressure levels, by as much as 30 dB; however, the noise level still exceeds the tunnel background noise level goal of 120 dB overall sound pressure level. As a consequence, both in the AWT and in the physical models, acoustic treatment will be employed upstream of all exhaust valves in order to control background noise in the tunnel test section. An alternate way to possibly reduce this valve noise was to develop a more aerodynamically streamlined valve design. However, this approach was considered to be more expensive and also to have a higher degree of risk.

An acoustic choke is proposed to be used at the end of the test section to limit downstream noise from propagating into the tunnel test section. Because several mechanical means for doing this are possible, the acoustic suppression characteristics of several concepts are being evaluated along with their pressure loss levels. Results to date have been encouraging. Acoustic attenuation in the range of 20 dB, as shown in Fig. 12, at the lower frequencies has been obtained. A more powerful acoustic driver will be used to complete the evaluation at higher frequencies. Several acoustic choke concepts will also be evaluated. In summary, the acoustic choke appears to be a viable means for attenuating downstream noise enough to meet the AWT test section background noise level goals.

Icing

An investigation of the effect of spray bar shape on nozzle spray dispersion has been completed. These tests were conducted in the Lewis 6- by 9-ft Icing Research Tunnel (IRT). Spray dispersion was obtained by measuring ice accretion on a downstream grid as shown in Fig. 13. Results obtained for three spray bar geometries are shown in Fig. 14 for a relatively low tunnel test section velocity of 35 mph. The spray dispersion, which was measured 19 ft. downstream of the nozzle/spray bar, is not materially affected by the spray bar shape. The relatively blunt IRT spray bar has only slightly better dispersion than the other more streamlined types. Along with spray dispersion, turbulence measurements were obtained. The turbulence is the same as previously defined and includes only the longitudinal component. The transverse components were generally within 10 percent of the longitudinal. It can be seen that the turbulence is about the same immediately downstream of the nozzle, and is probably dominated by the high pressure air/water flow through the nozzle which was constant in each case. The effect of the spray bar on turbulence is more apparent in the region about 15 in. from the nozzle centerline. The relatively blunt IRT spray bar has, as expected, the highest turbulence level.

For higher tunnel velocities, Fig. 15, the spray dispersion is generally reduced; however, the spray bar influence is more pronounced. Comparisons are in process between these measured spray dispersion results and an analytical computer code. The code is a two-dimensional, stochastic type and also accounts for turbulence. This code will eventually be available for assessing spray uniformity for spray nozzle systems.
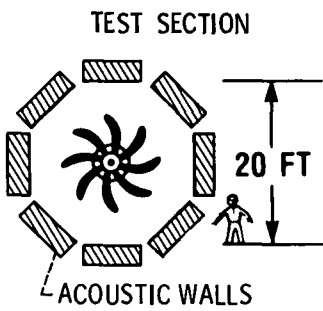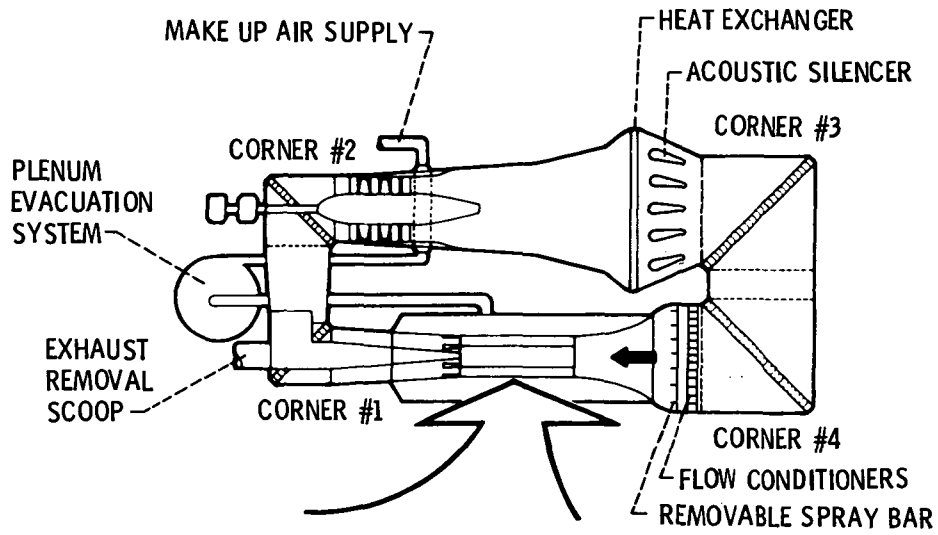
Concluding Remarks

Significant progress has been made in the physical modeling phase of the AWT modeling program. Modeling results obtained in the area of aerodynamics, acoustics, and icing are providing a data base, not only for the design of AWT, but also for other tunnels that may have similar capability requirements. It is anticipated that the remaining activities, a major one of which is the fan, will also provide important design information for advanced tunnel components. The remaining efforts should be completed in about 1 yr.

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MAKE UP AIR SUPPLY

HEAT EXCHANGER

ACOUSTIC SILENCER

CORNER #3

CORNER #2

PLENUM
EVACUATION
SYSTEM

EXHAUST
REMOVAL
SCOOP

CORNER #1

CORNER #4

FLOW CONDITIONERS

REMOVABLE SPRAY BAR

TEST SECTION

20 FT

ACOUSTIC WALLS

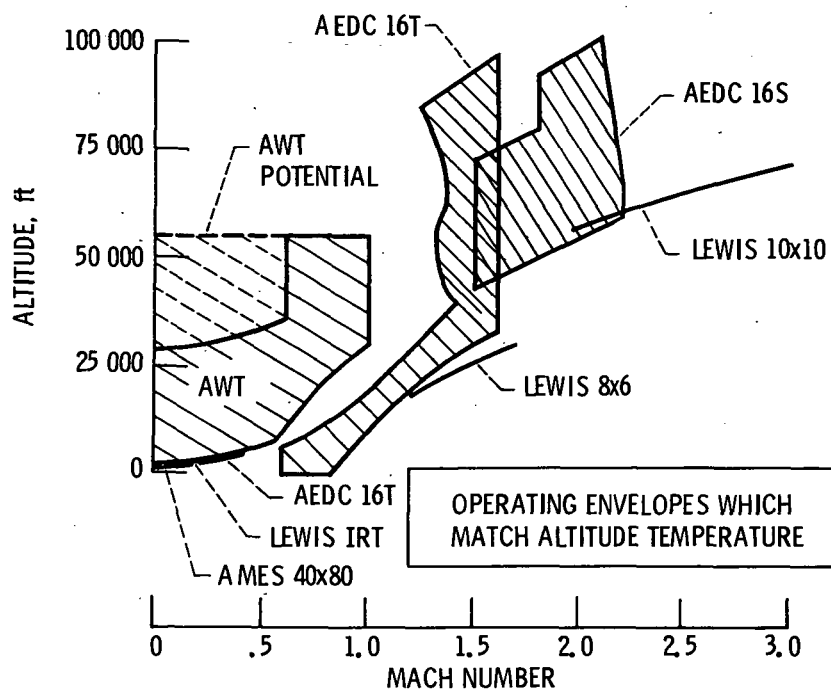| CAPABILITIES	
MACH NUMBER	0 TO 0.9 +
ALTITUDE	0 TO 55000 FT +
TOTAL TEMPERATURE	-60° TO 60 °F
TEST SECTION ACOUSTIC LEVEL	120 dB (OASPL)

Figure 1. -Features and capabilities of rehabilitated AWT.

Figure 2. - Propulsion wind tunnel operating envelopes.

AEROTHERMODYNAMICS

- COMPONENT AERODYNAMIC
  AND THERMODYNAMIC
  PERFORMANCE

- COMPONENT AERODYNAMIC
  LOADS

- OVERALL SYSTEM PERFORMANCE -
  STEADY STATE

ACOUSTICS

- ANECHOIC TEST SECTION

- BACKGROUND ACOUSTIC LEVELS

ICING

- TUNNEL SYSTEMS FOR PROVIDING
  ICING/HEAVY RAIN/FREEZING
  RAIN/SNOW

- EFFECT OF ICING ON TUNNEL
  COMPONENTS

Figure 3. - Modeling program elements.

RETURN AND
MAKE-UP
AIR FLOWS

RAPID DIFFUSER AND
HEAT EXCHANGER

FAN

ACOUSTIC TREATMENT
VANES AND RINGS

CORNERS WITH
TURNING VANES

DIFFUSER
WITH EXHAUST
SCOOP AND
RE-ENTRY AIR

ACOUSTIC
TREATMENT

TEST SECTION
WITH BLEED AND
BLOCKAGE
MODELS

CIRCULAR TO
OCTAGONAL
TRANSITION

————— AERO   — — — — ACOUSTIC
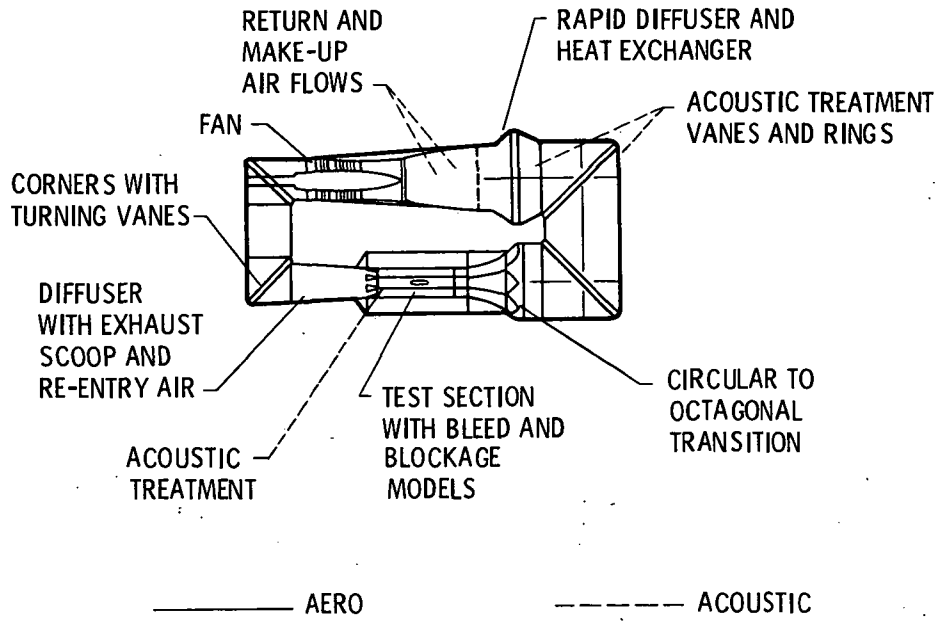
Figure 4. - Areas analyzed using existing or modified computer codes /prediction
techniques.

FAN

CORNERS

SETTLING
CHAMBER

FLOW

CONICAL
DIFFUSER

TEST SECTION

CONTRACTION
SECTION

PLENUM TANK
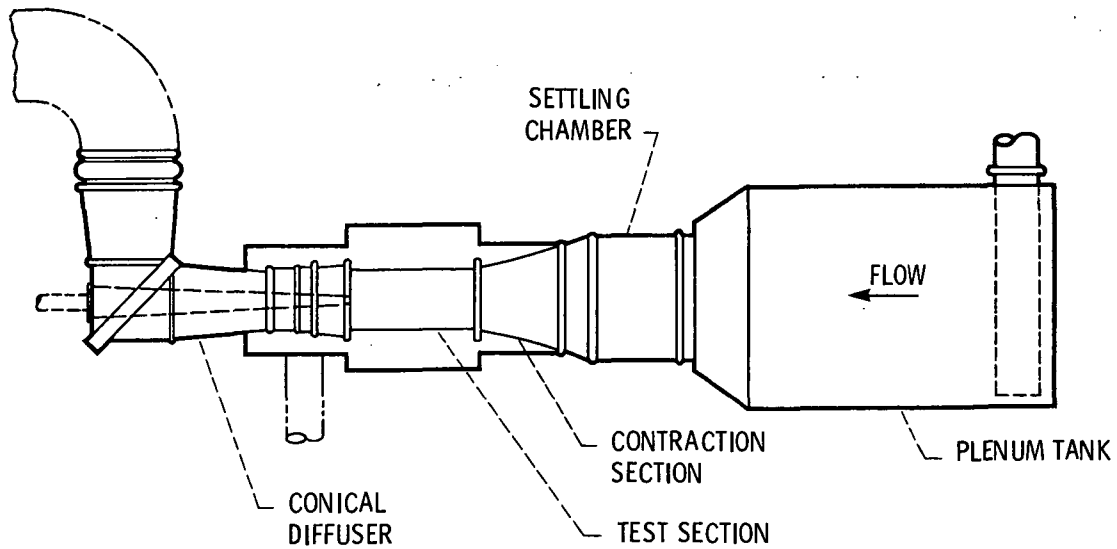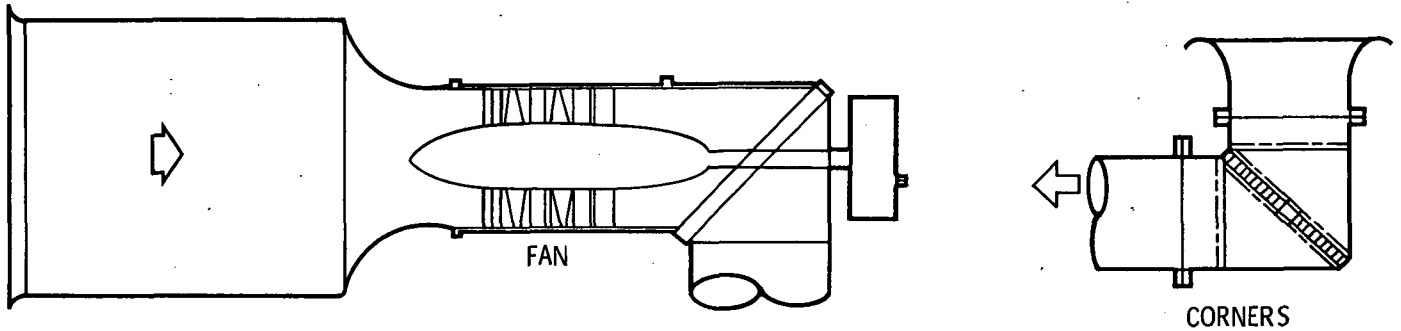
Figure 5. - One-tenth scale AWT aerodynamic models.
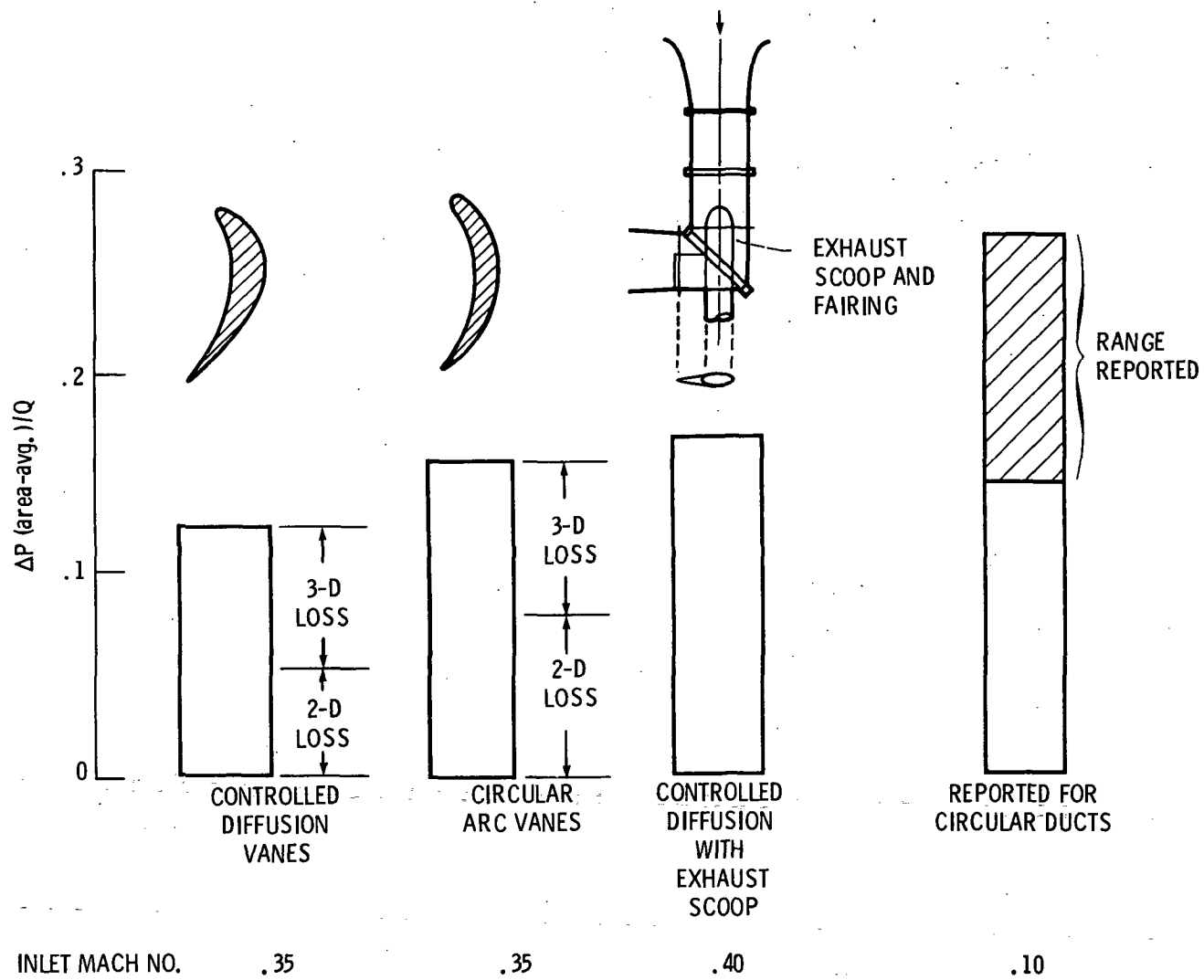
Figure 6. – Pressure losses for corner downstream of test section.

FAN POSITION

Δp
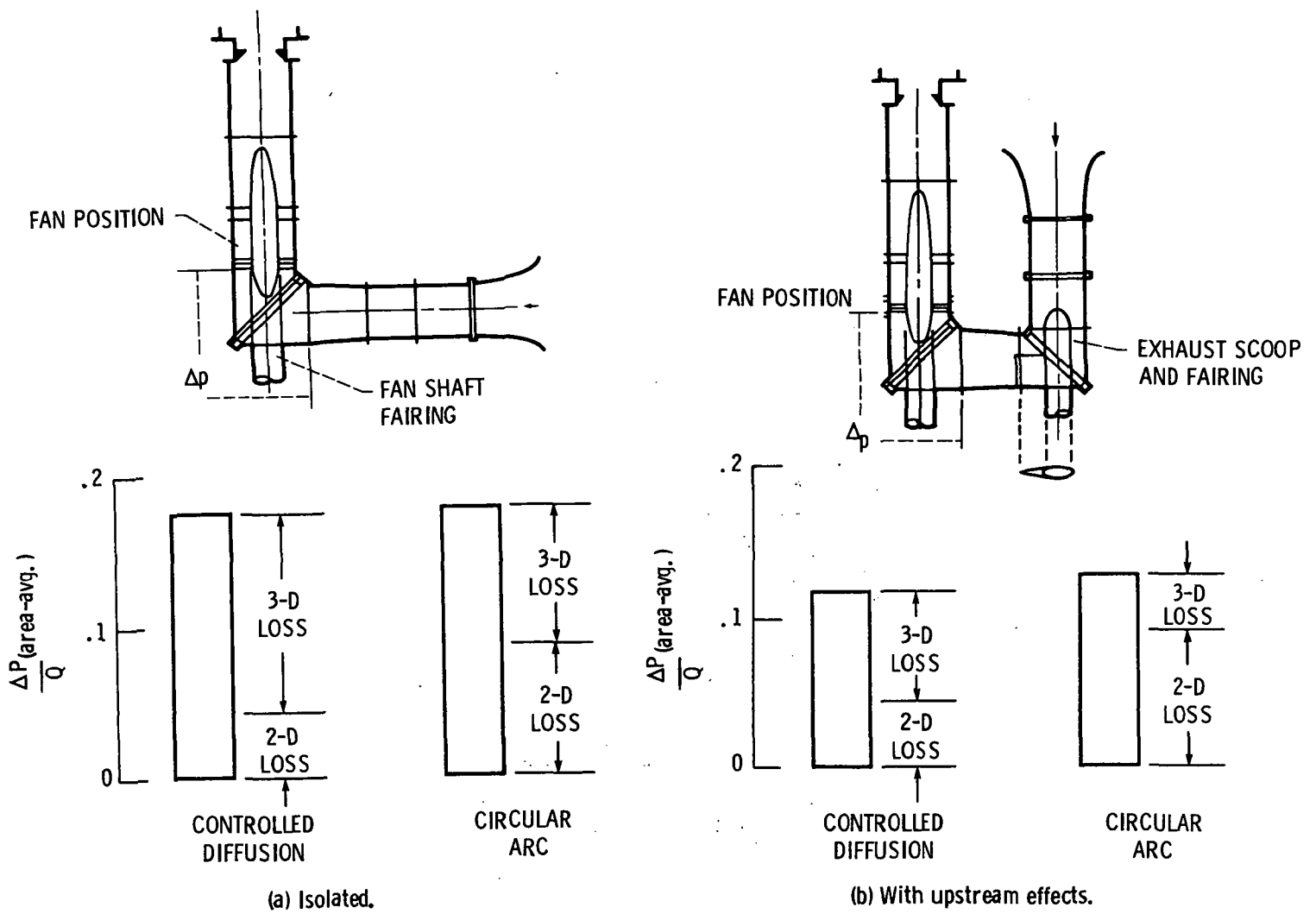
FAN SHAFT
FAIRING

$\frac{\Delta P \text{(area-avg.)}}{Q}$

.2

.1

0

3-D
LOSS

2-D
LOSS

CONTROLLED
DIFFUSION

3-D
LOSS

2-D
LOSS

CIRCULAR
ARC

(a) Isolated.

FAN POSITION

Δp

EXHAUST SCOOP
AND FAIRING

$\frac{\Delta P \text{(area-avg.)}}{Q}$

.2

.1

0

3-D
LOSS

2-D
LOSS

CONTROLLED
DIFFUSION

3-D
LOSS

2-D
LOSS

CIRCULAR
ARC

(b) With upstream effects.

Figure 7. – Pressure losses for corner upstream of fan. De-
sign inlet Mach no. of 0. 24.
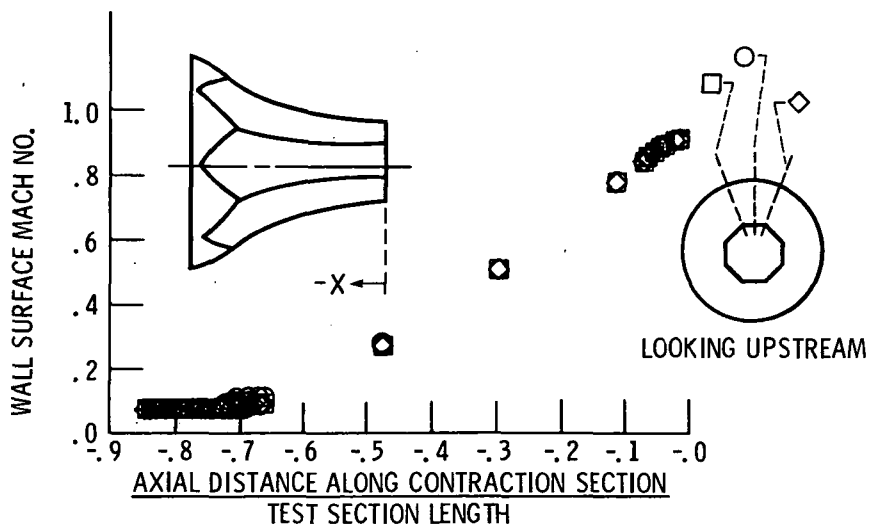
Figure 8. - Wall Mach number distribution along contraction section, M_T = 0.916.

TUNNEL MACH NO.	CIRCUMFERENTIAL LOCATION, deg											
	56 1/4			146 1/4			236 1/4			326 1/4		
	AXIAL LOCATION, inches											
	-96	-72	-56	-96	-72	-56	-96	-72	-56	-96	-72	-56
0.2	3.9	2.9	3.1	4.4	4.0	4.2	3.2	4.0	3.8	2.2	5.0	2.9
0.4	2.5	3.5	4.5	3.5	3.1	3.5	3.2	4.1	4.5	3.4	2.7	2.3
0.6	3.7	6.0	4.3	3.9	5.2	5.7	3.5	3.9	3.9	2.0	2.1	2.8
0.8	4.0	4.3	4.9	3.8	4.3	4.5	2.8	3.5	3.3	1.9	2.6	2.3
0.916	3.0	3.2	4.3	5.7	5.0	5.1	3.6	2.8	2.7	3.2	2.0	4.3
AVG.	3.4	4.0	4.2	4.3	4.3	4.6	3.3	3.7	3.6	2.5	2.9	2.9
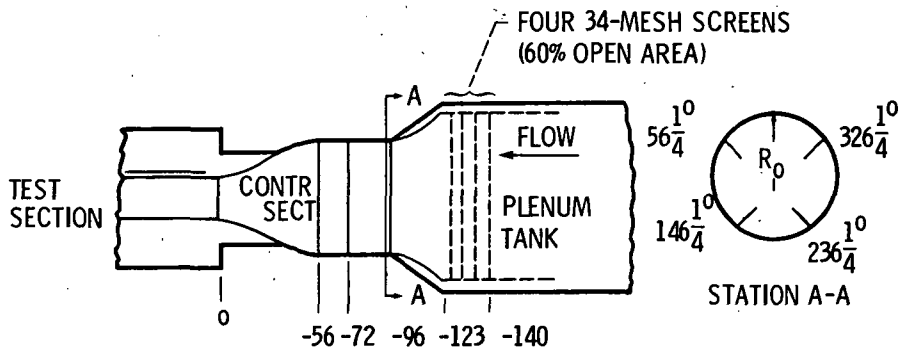
(a) Longitudinal measurement ahead of contraction section.
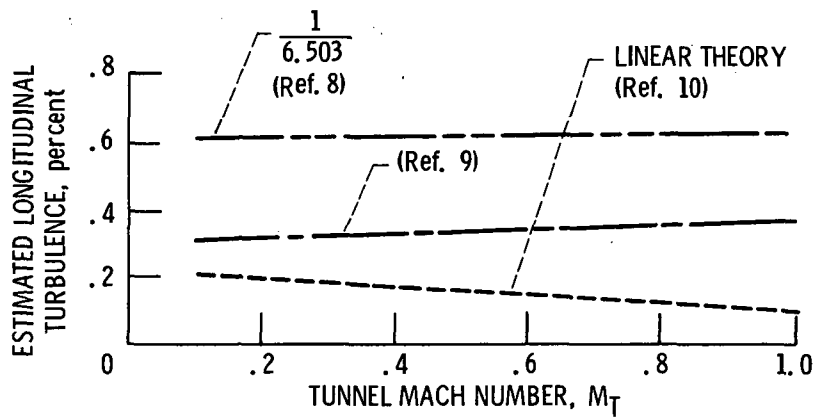
(b) Estimated for test section.
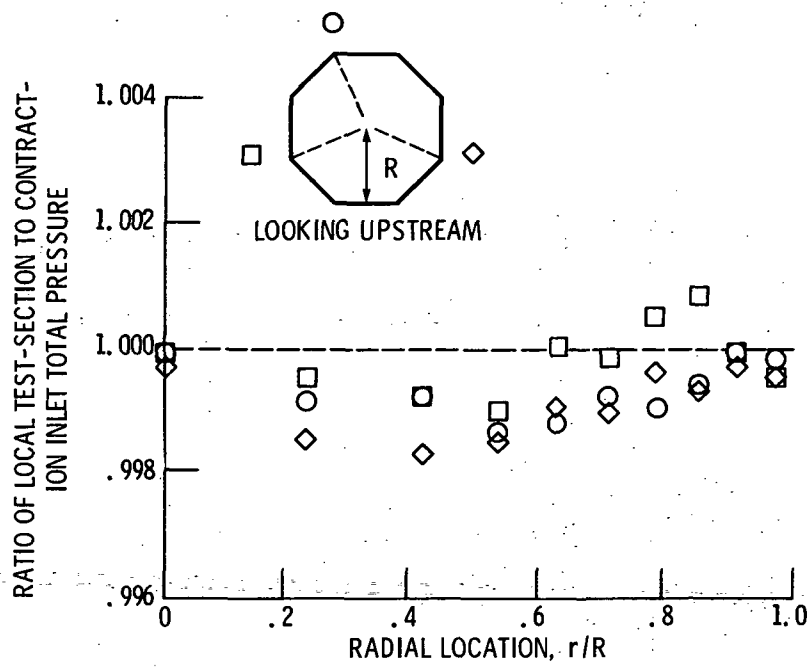
Figure 9. – Turbulence levels in high speed leg.

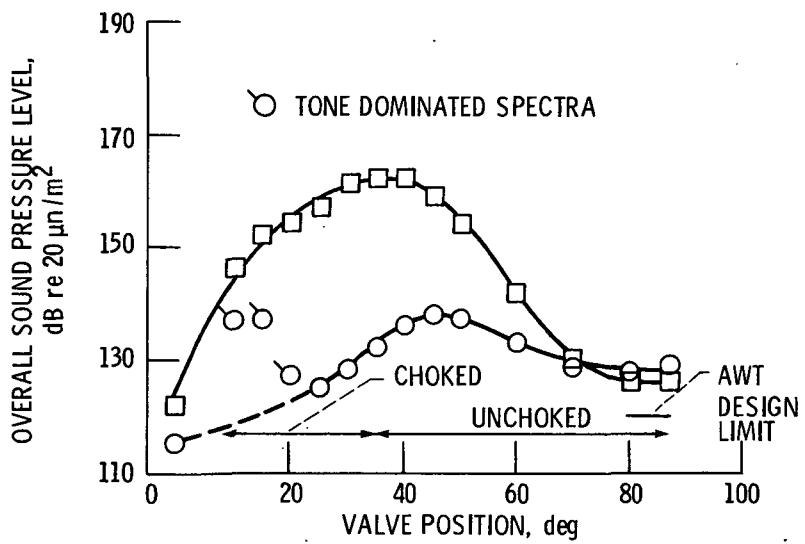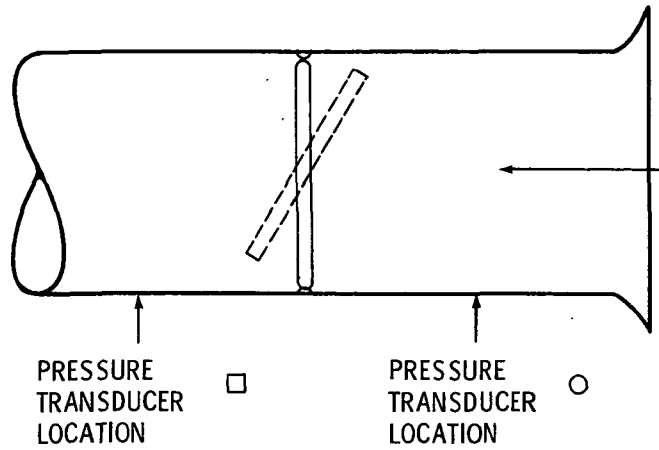Figure 10. - Typical test-section total-pressure distribution. Tunnel Mach number = 0. 8.

PRESSURE
TRANSDUCER   □
LOCATION

PRESSURE
TRANSDUCER   ○
LOCATION

Figure 11. - Valve noise measurements.

MICROPHONE LOCATIONS

FLOW →

FINGER FLAP

ACOUSTIC DRIVER

CROSS-SECTION

160

150

140

130

120

110

21. 4 dB

NOISE FLOOR

(a) 2025 Hz Tone.

150

140

130

120

110

19. 0 dB

NOISE FLOOR

.5   .7   .9   1. 1

THROAT SURFACE MACH NUMBER

(b) 4025 Hz Tone.

TONE PEAK SPL, dB
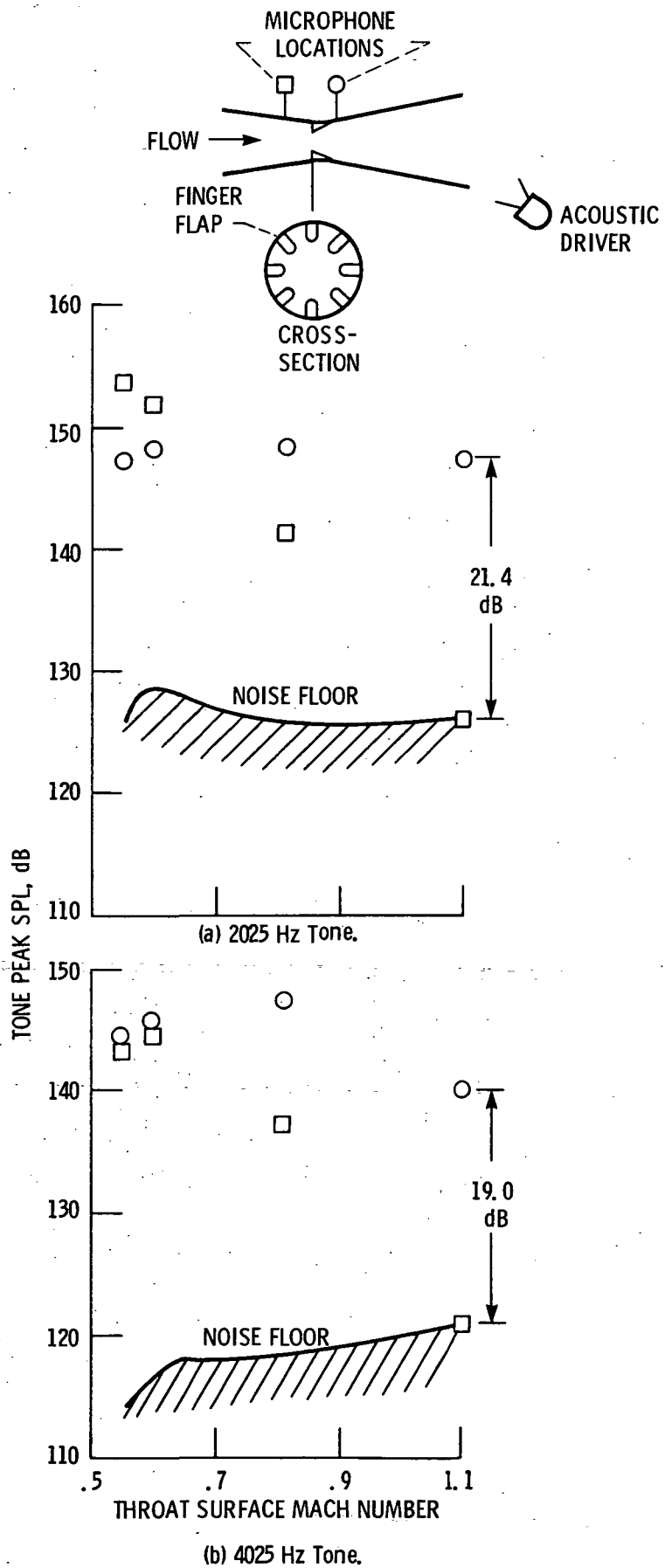
Figure 12. - Variation of noise attenua-
tion with hroat Mach number.

ICING RESEARCH TUNNEL

TEST
SECTION

SPRAYBAR   ICE COLLECTION GRID

NOZZLE

19 ft
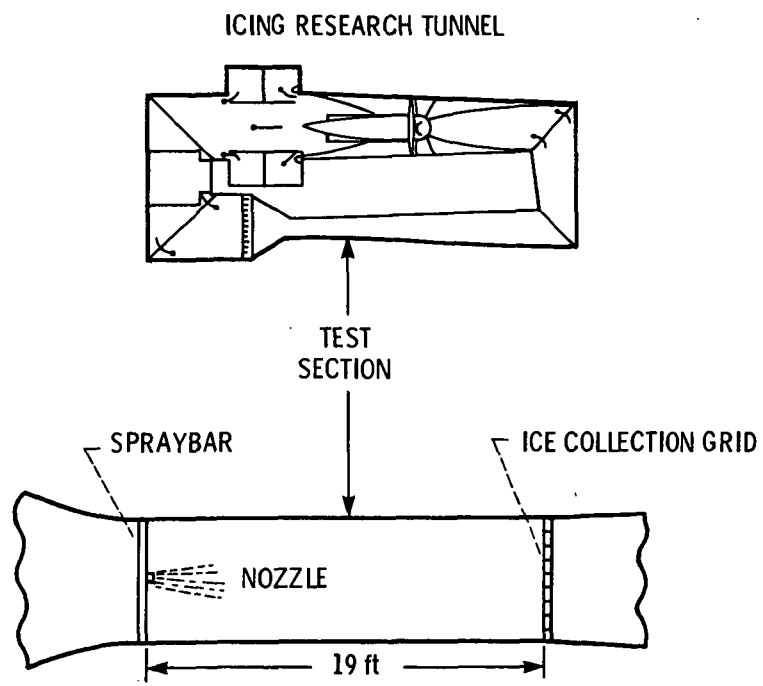
Figure 13. - Spray dispersion test set-up.

SPRAY VOLUME MEDIAN
DIAMETER 12 μm
TEST SECTION
VELOCITY 35 MPH

IRT

ICE ACCRETION, inches

TURBULENCE, percent

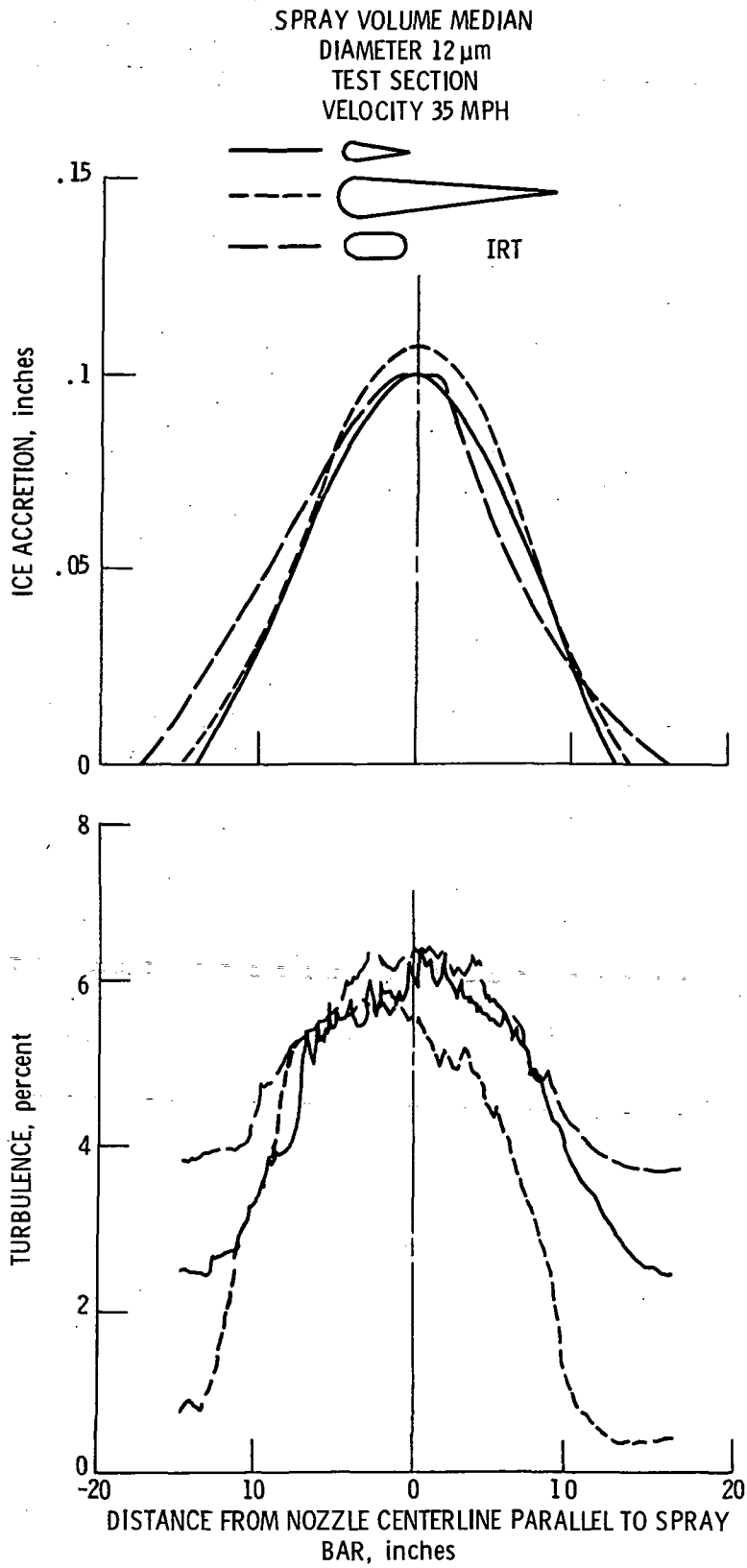DISTANCE FROM NOZZLE CENTERLINE PARALLEL TO SPRAY
BAR, inches

Figure 14. - Effect of airfoil shape on spray dispersion.

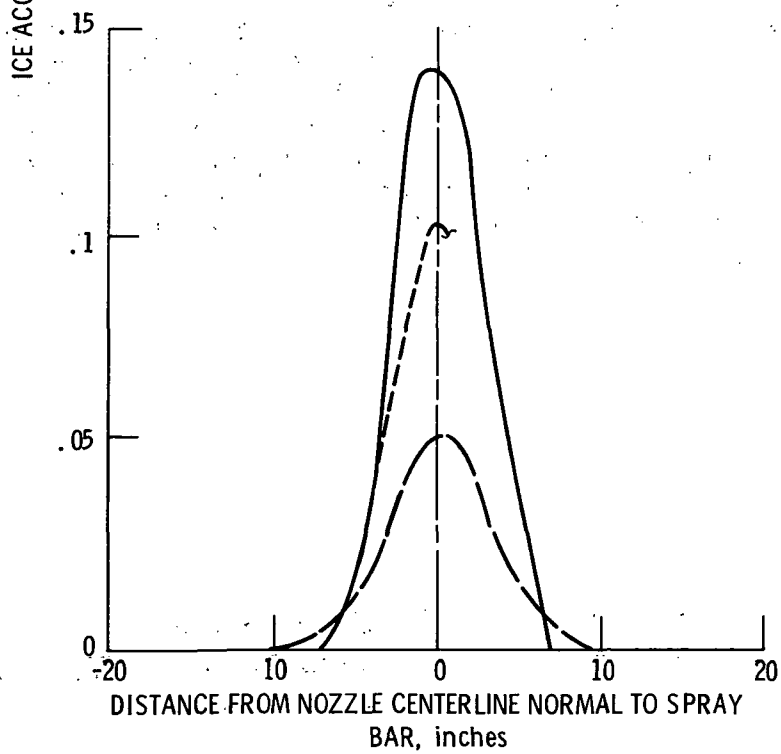SPRAY VOLUME MEDIAN DIAMETER 12 μm TEST SECTION VELOCITY
105 mph

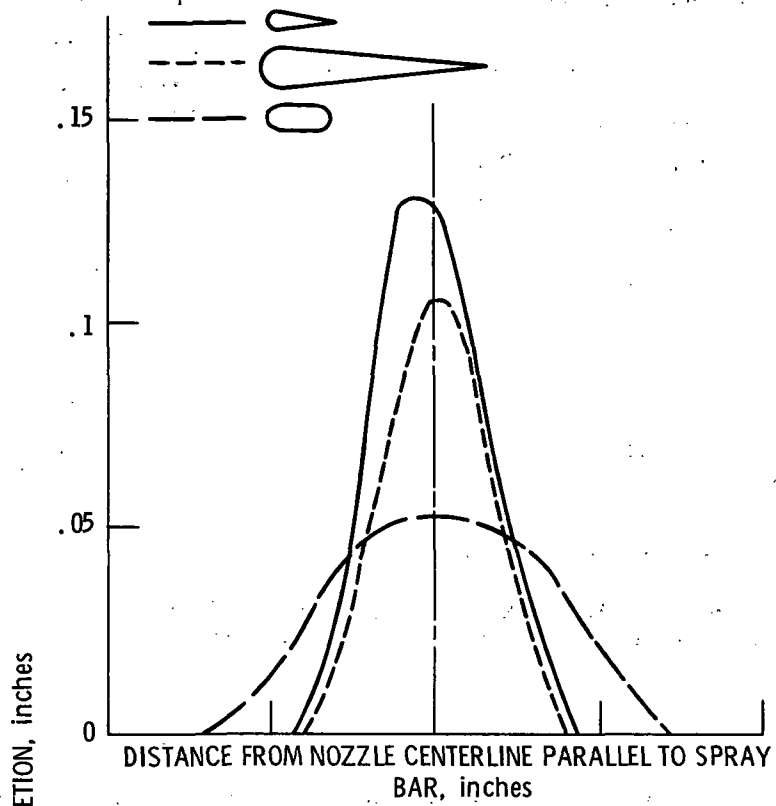Figure 15. - Effect of airfoil shape on spray dispersion.

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16. Abstract

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