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INITIAL CALIBRATION RESULTS FROM THE AEDC-PWT 4-FOOT TRANSONIC TUNNEL

M. S. Hartley and J. L. Jacocks

ARO, Inc.

August 1968

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 6540223F/876A, Project G226.

The results of research presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the AEDC, AFSC, under Contract F40600-69-C-0001. The research was conducted from December 6, 1967, to February 23, 1968, under ARO Project No. PC4635, and the manuscript was submitted for publication on June 7, 1968.

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This technical report has been reviewed and is approved.

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ABSTRACT

Tests were conducted in the AEDC Aerodynamic Wind Tunnel, Transonic (4T), to determine the tunnel calibration, Mach number distributions, and boundary-layer thicknesses. During the tests, Mach number was varied from 0.1 to 1.4, test section wall angle from -0.5 to 0.5 deg, and test section wall porosity from 0 to 10 percent. Data were obtained at various stagnation pressure levels from 500 to 2500 psf. Considerable development of the flow expansion region was required to obtain uniform supersonic Mach number distributions. Good Mach number distributions are obtainable up to and including Mach number 1.2. The distributions from Mach number 1.25 to 1.4 are suitable only for very limited testing. The results show that the tunnel calibration is a function of test section wall porosity and wall angle. Boundary-layer thicknesses on the contoured walls and parallel walls at the nozzle exit are nearly equal.

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NOMENCLATURE

M	Mach number
M_c	Equivalent plenum Mach number
M_∞	Average free-stream Mach number
p_c	Plenum pressure, psfa
p_e	Diffuser exit pressure, psfa
p_t	Stagnation pressure, psfa
q	Dynamic pressure, psfa
Re	Reynolds number
T_t	Stagnation temperature, °F
x	Tunnel station, in.
θ_w	Test section wall angle, deg (positive for diverged walls)
λ	Tunnel pressure ratio (p_t/p_e)
σ	Standard deviation
τ	Wall porosity, percent
τ_m	Maximum porosity, percent
w	Specific humidity (lb water/lb dry air)

SECTION I

INTRODUCTION

The PWT Aerodynamic Wind Tunnel, Transonic 4T, was designed to provide the United States Air Force with an economic testing capability for conventional weapons development. Its test section size permits testing of relatively large models while maintaining the flexibility and ease of operation of much smaller wind tunnels. By virtue of its being a continuous-flow tunnel, it is possible to obtain maximum utilization of available run time.

There are several features of 4T which make it suitable for many varied types of testing. The first of these features is the flow-conditioning system to reduce the airstream turbulence level. This system consists of eight screens and a silencer section. The silencer is made up of several panels of acoustical material encased in perforated sheet metal. A second feature of Tunnel 4T is the captive trajectory store separation support system. This system allows testing of external stores in the vicinity of the parent aircraft as they are released from the aircraft. The system is controlled by the PWT digital computer which may use the equations of motion to predict succeeding points in the trajectory from the forces measured at each point, or the forces may be obtained in a preselected grid pattern from which the trajectory can be determined. This system may be completely removed from the tunnel to permit conventional testing with the standard model support system. The third special feature of 4T is the variable porosity test section. It is generally recognized that a fixed porosity test section does not reduce wall interference effectively at all transonic Mach numbers. Accordingly, 4T was equipped with variable porosity walls to reduce wall effects, thus providing more reliable data.

Shakedown and calibration of Tunnel 4T was conducted from December 13, 1967, to January 11, 1968, and from February 9 to February 23, 1968. The results presented in this report include the influence of variation of wall configuration in the flow expansion region, centerline Mach number distributions for the final wall configuration, nozzle exit boundary-layer data, and centerline-plenum calibration relations.

SECTION II

APPARATUS

2.1 BASIC TUNNEL

Tunnel 4T is a continuous-flow, closed-loop tunnel capable of operation at Mach numbers from 0.1 to approximately 1.4. The location of 4T

with respect to the PWT complex is shown in Fig. 1, Appendix I, and the general arrangement is given in Fig. 2. The operating envelopes (stagnation pressure, dynamic pressure, and unit Reynolds numbers) are presented in Fig. 3. Subsonic flow in 4T is generated through a fixed sonic block nozzle. The sidewalls of the nozzle are parallel. Supersonic flow is generated by expansion through approximately the first 6 ft of the porous test section walls. Details of the wall geometry are given in Fig. 4. The 4- by 4-ft test section has an overall length of 12.5 ft, including the 6-ft flow expansion region. Each test section wall has variable porosity with a porosity range from 0 to approximately 10 percent. During the calibration, every third hole was plugged and the wall travel reduced, resulting in a maximum porosity of 6 percent. The test section sidewalls are fixed parallel, and the top and bottom walls may be converged or diverged 0.5 deg. Downstream of the test section is a 5-ft-long diffuser section with movable sidewalls to alleviate blockage of the model support system. The diffuser wall actuators may be disconnected and the walls moved to an extreme open position, allowing access to the test section for minor model changes. For major model changes, the south test section sidewall may be raised. The model support system consists of a half-sector sting support with an angle-of-attack range from 28 to -12 deg. The model pitch center is 3.5 ft upstream of the end of the test section.

Tunnel 4T is driven by a portion of the existing 178,000-hp PWT Plenum Evacuation System (PES). A complete description of this system is given in the Test Facilities Handbook.*

The tunnel instrumentation consists of the standard tunnel pressures and temperatures plus 100 channels of pressure readouts, 25 channels of temperature readouts, and 10 channels of force and moment readouts. The standard tunnel pressures are measured using servo-driven mercury manometers, and standard temperatures are measured using Chromel®-Alumel® thermocouples. On-line data are obtained using the PWT data acquisition system.

2.2 CALIBRATION EQUIPMENT

Static orifices located on a centerline pipe were used to determine the Mach number distributions. The pipe was supported at its downstream

*Test Facilities Handbook (Seventh Edition). "Propulsion Wind Tunnel Facility, Vol. 5." Arnold Engineering Development Center, July 1968.

end by the model support sector and at its upstream end by forward-swept strut rods attached to the nozzle sidewalls. A tensile load of approximately 10,000 lb was applied to the pipe by tightening the forward support rods. A sketch of the pipe installation including the orifice spacing is given in Fig. 5. A photograph of the installation with the south test section wall raised is shown in Fig. 6.

Boundary-layer data at the sonic nozzle exit were obtained using two 21-tube boundary-layer rakes. Static orifices on the wall adjacent to the rake were used to determine local velocity. A sketch of the boundary-layer rakes is presented in Fig. 7.

SECTION III PROCEDURE

3.1 TUNNEL OPERATION PROCEDURE

Operation of Tunnel 4T requires control of three basic variables: stagnation pressure, tunnel pressure ratio, and plenum pressure ratio. At present, the stagnation temperature is a function of the PES coolant water temperature, and no control is available.

The test section Mach number is normally set by establishing a given ratio of plenum pressure to stagnation pressure, utilizing the calibration surfaces developed in Appendix II. Tailoring of subsonic Mach number distributions is accomplished by varying the tunnel pressure ratio, λ , and auxiliary PES suction; no reentry flap suction is used. For operating convenience, two analog pressure ratio computers yield digital displays on the operating console of the plenum and tunnel pressure ratios.

Tunnel humidity is controlled by air exchange utilizing the PWT silica-gel drier.

3.2 TEST PROCEDURE

The primary variables during the Mach number calibration were wall porosity, wall angle, tunnel pressure ratio, and plenum suction. The approximate test section Mach number was set using a series of wall static pressures manifolded to read an average value in the downstream region of the test section. Generally a wall porosity was set, and the Mach number was varied through the entire range at various wall angles.

At subsonic Mach numbers, the tunnel pressure ratio and plenum suction were adjusted to obtain a good distribution at the downstream end of the test section. For supersonic Mach numbers, the tunnel pressure ratio was maintained at approximately $\lambda = 1.4$. Boundary-layer data were obtained at tunnel station-12 on the north nozzle sidewall and the bottom wall.

A tunnel stagnation pressure of 1 atm (approximately 2040 psfa) was maintained throughout most of the calibration. Special runs were made at various stagnation pressures to check the Reynolds number effect on the data. The stagnation temperature varied from 50 to 80°F.

3.3 DATA REDUCTION PROCEDURE

Mach number calibration data were obtained on-line using the PWT digital computer and data acquisition system. Local Mach numbers were calculated from the static pressure measurements and were displayed on the cathode ray tube display plotted as a function of tunnel station. Average test section Mach number was determined from the average of the values downstream of station 72. The data reduction program was written to reject bad values before taking the average. The 2σ Mach number deviation downstream of station 72 was also calculated after the bad points were rejected. The equivalent plenum Mach number was calculated from the ratio of plenum pressure to tunnel stagnation pressure. The average test section Mach number, the equivalent plenum Mach number, the test section wall porosity, and the test section wall angle were all used as functions in three-dimensional surface fits for test section Mach number determination. The details of this surface fit procedure and its use are included in Appendix II. The surface fits were determined off-line. All on-line data were tabulated using the PWT line printers.

The boundary-layer displacement and momentum thicknesses were calculated on-line assuming a constant stagnation temperature through the boundary layer.

3.4 ACCURACY OF THE RESULTS

Based on a confidence level of 95 percent, estimates of the errors in the data resulting from instrumentation errors are as follows:

ΔM	± 0.002
$\Delta \tau$	± 0.02 percent
$\Delta \theta_w$	± 0.03 deg
$\Delta \lambda$	± 0.001
$\Delta(p_c/p_t)$	± 0.001

These Mach number deviations do not include the deviation from the mean in the test section. The accuracy of the surface fit is discussed in Appendix II. During the early portion of the calibration, difficulties were experienced with the wall angle and wall porosity readouts. As a result, the above error estimates are not applicable to wall configurations A and B.

SECTION IV RESULTS AND DISCUSSION

4.1 DEVELOPMENT OF FLOW EXPANSION REGION CONFIGURATION

The original test section wall design utilized a 3-ft tapered porosity flow expansion region, denoted as configuration A in Fig. 8a. Supersonic Mach number distributions obtained with this wall configuration are shown in Fig. 9a. For wall porosities above about 3 percent, an overexpansion occurred near the end of the tapered porosity region followed by a compression and subsequent reflection of the disturbances. The flow quality with configuration A was considered unacceptable, and attempts were made to eliminate the overexpansion by physically modifying the flow expansion region.

Details of the significant configurations tried with the 10-percent porosity walls are given in Fig. 8a, and the resulting Mach number distributions are shown in Figs. 9b through e. A scaled sketch of each configuration appears in the upper margin of Fig. 9. Little improvement was obtained and, in general, the degree of overexpansion was a function only of the number of holes plugged.

A major modification was then made by plugging one out of every three holes throughout the test section, thereby reducing the maximum wall porosity from 10 to 6 percent. The resulting hole pattern is shown in Fig. 6. The Mach number distributions obtained with this 6-percent wall and the basic 3-ft tapered region are shown in Fig. 9f. Comparison with Fig. 9a shows some improvement, although the overexpansion still existed.

After several modifications of the flow expansion region, configuration G (Fig. 8b) was developed with the results shown in Fig. 9g. The overexpansion had finally been eliminated at $M_\infty = 1.1$. In order to obtain reasonable distributions at $M_\infty = 1.2$, the maximum porosity was increased back to 10 percent upstream of station 30 with the results shown in Fig. 9h. The final modification consisted of removing the first 3 in. of the solid inserts to obtain configuration I with the results given in Fig. 9i.

4.2 CENTERLINE MACH NUMBER DISTRIBUTIONS

All the wall configurations yielded essentially identical subsonic Mach number distributions. The distributions obtained with configuration I at $\tau = 6$ percent are given in Fig. 10a. The tunnel pressure ratios shown are not necessarily optimum, as evidenced by the slight gradients downstream of station 120. It is noted that plenum suction was used for all Mach numbers.

Detailed supersonic calibration results with configuration I are given in Figs. 10b through g for all wall porosities at which data were obtained. The distributions obtained at $M_\infty = 1.25$ and above (Fig. 10g) are suitable only for very limited testing applications.

A useful measure of the uniformity of a Mach number distribution is the standard deviation statistic 2σ . The Mach number deviation in terms of this parameter is given in Fig. 11 for configuration I.

All of the data presented have been for zero wall angle. The effect of wall angle is quite similar to that of porosity, as shown in Fig. 12 for configuration G. Comparisons with Fig. 9h show that a wall angle change from $\theta_w = 0$ to 0.25 deg is roughly equivalent to a porosity change from $\tau = 3.0$ to 4.0 percent at $M_\infty = 1.1$.

Water vapor condensation was found to have a noticeable effect upon the centerline Mach number distributions. Presented in Fig. 13 are distributions obtained with configuration A at $M_\infty = 1.2$ and $\tau = 2.0$ percent for several values of specific humidity. The visible condensation point occurred at $\omega = 0.0022$ which corresponds with the apparent critical value. With this exception, all data presented herein were obtained with no visible condensation.

Stagnation pressure level was found to have little effect upon the centerline Mach number distributions, as shown in Fig. 14.

4.3 BOUNDARY LAYER

Boundary-layer data obtained in the two planes near the nozzle exit, station - 12, are given in Fig. 15. For all practical purposes, the thicknesses on the contoured walls and parallel walls are equal.

SECTION V CONCLUSIONS

The following conclusions were reached as a result of the Tunnel 4T calibration:

1. Overexpansions created by developing supersonic Mach numbers with suction can be eliminated by proper design of the wall geometry in the flow expansion region.
2. Operation of Tunnel 4T is feasible in the Mach number range from 0.1 to 1.4.
3. Good Mach number distributions were obtained up to and including Mach number 1.2.
4. Poor Mach number distributions limit the testing capability above Mach number 1.2.
5. Boundary-layer thicknesses on the contoured walls and parallel walls at the nozzle exit are nearly equal.

APPENDIXES

- I. ILLUSTRATIONS**
- II. PLENUM-STREAM MACH NUMBER CALIBRATION**

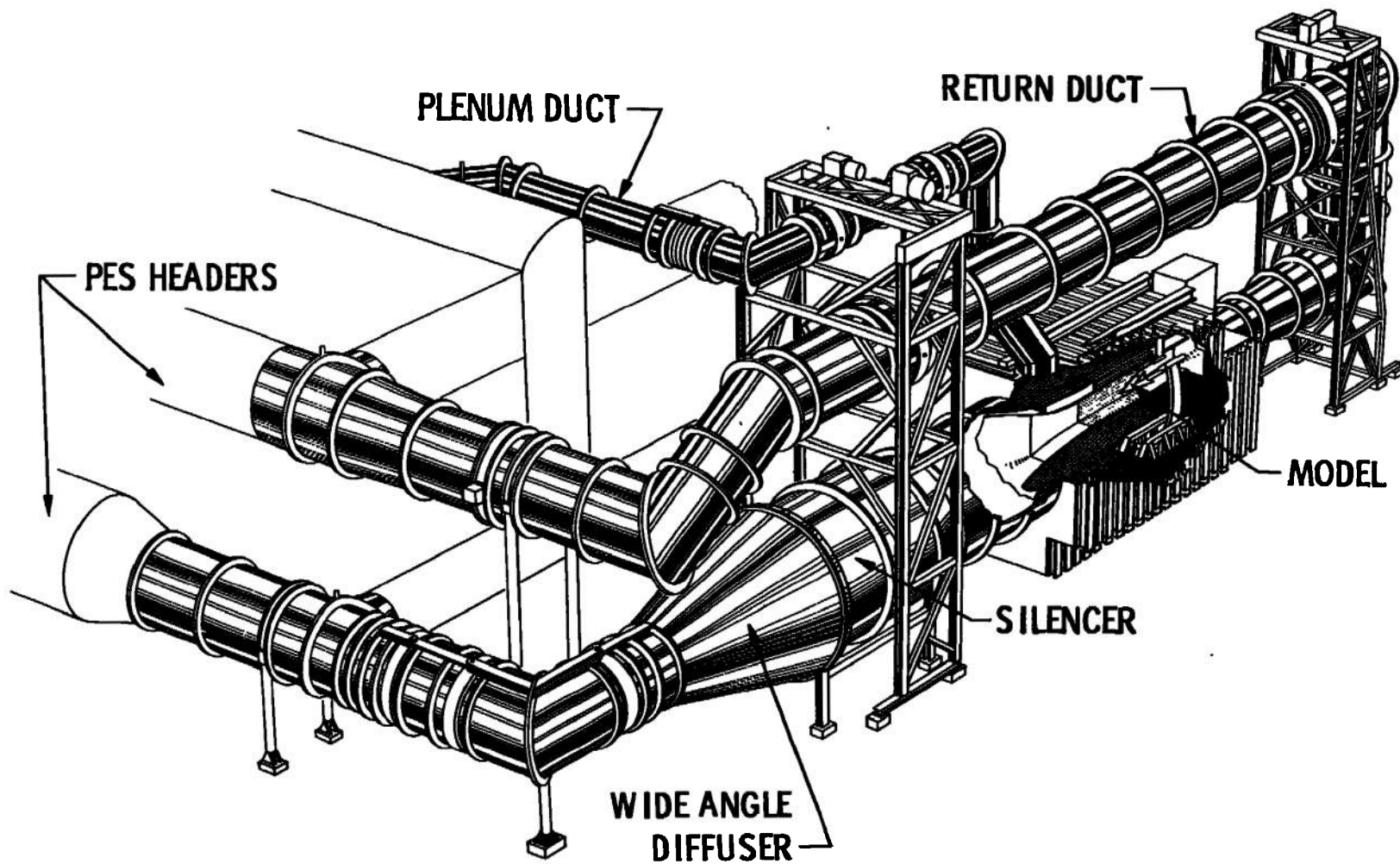
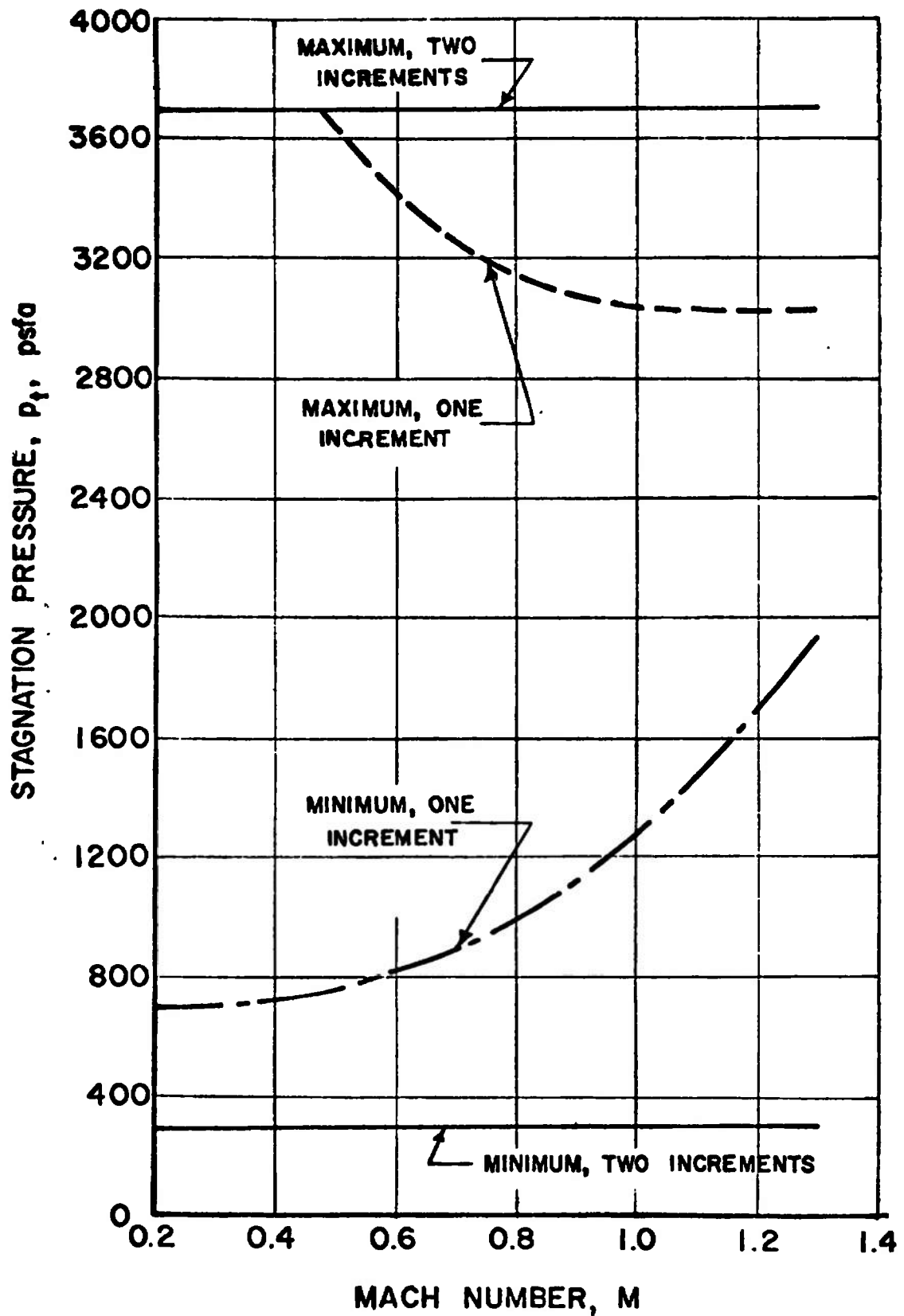
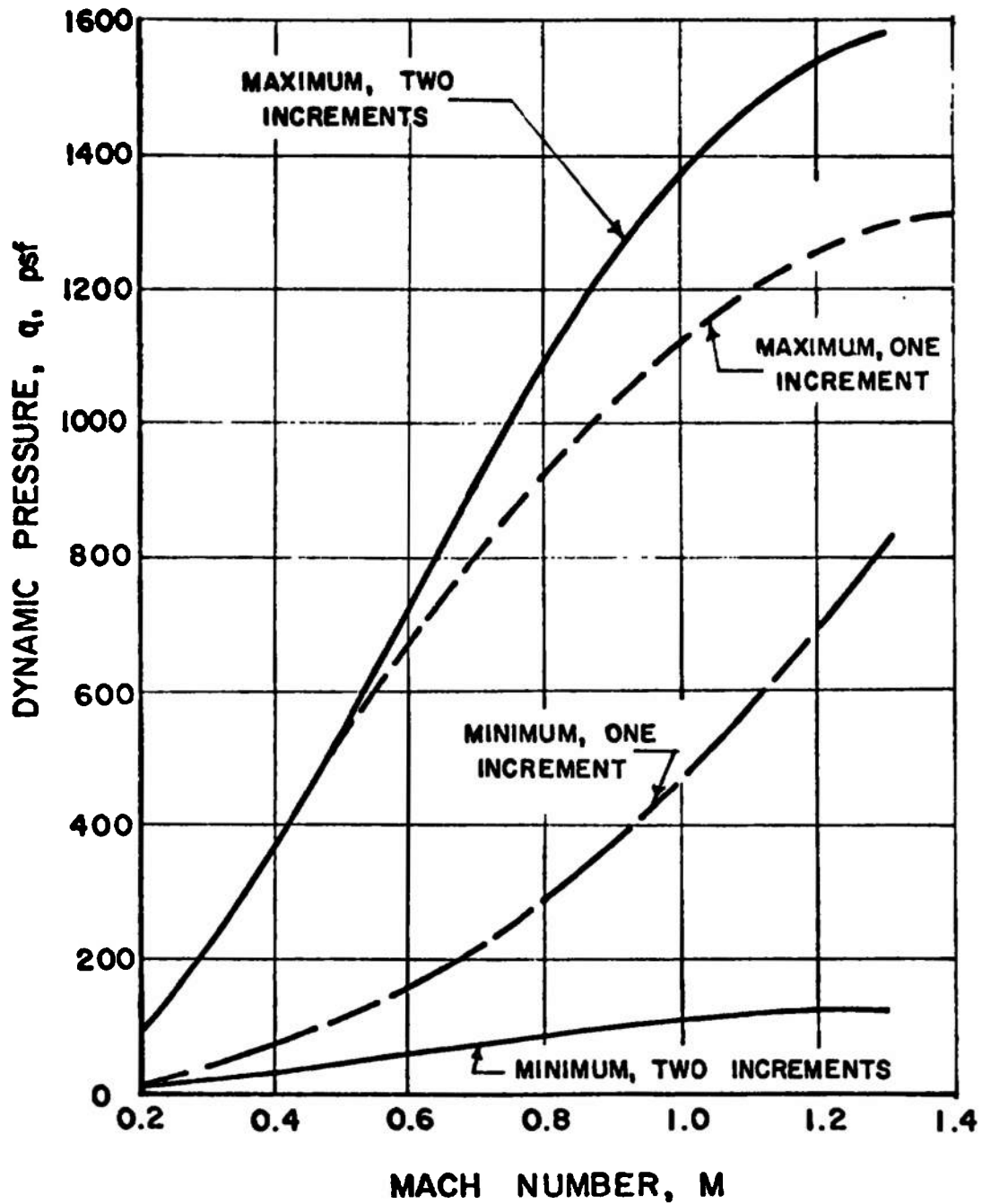


Fig. 2 Tunnel 4T General Arrangement



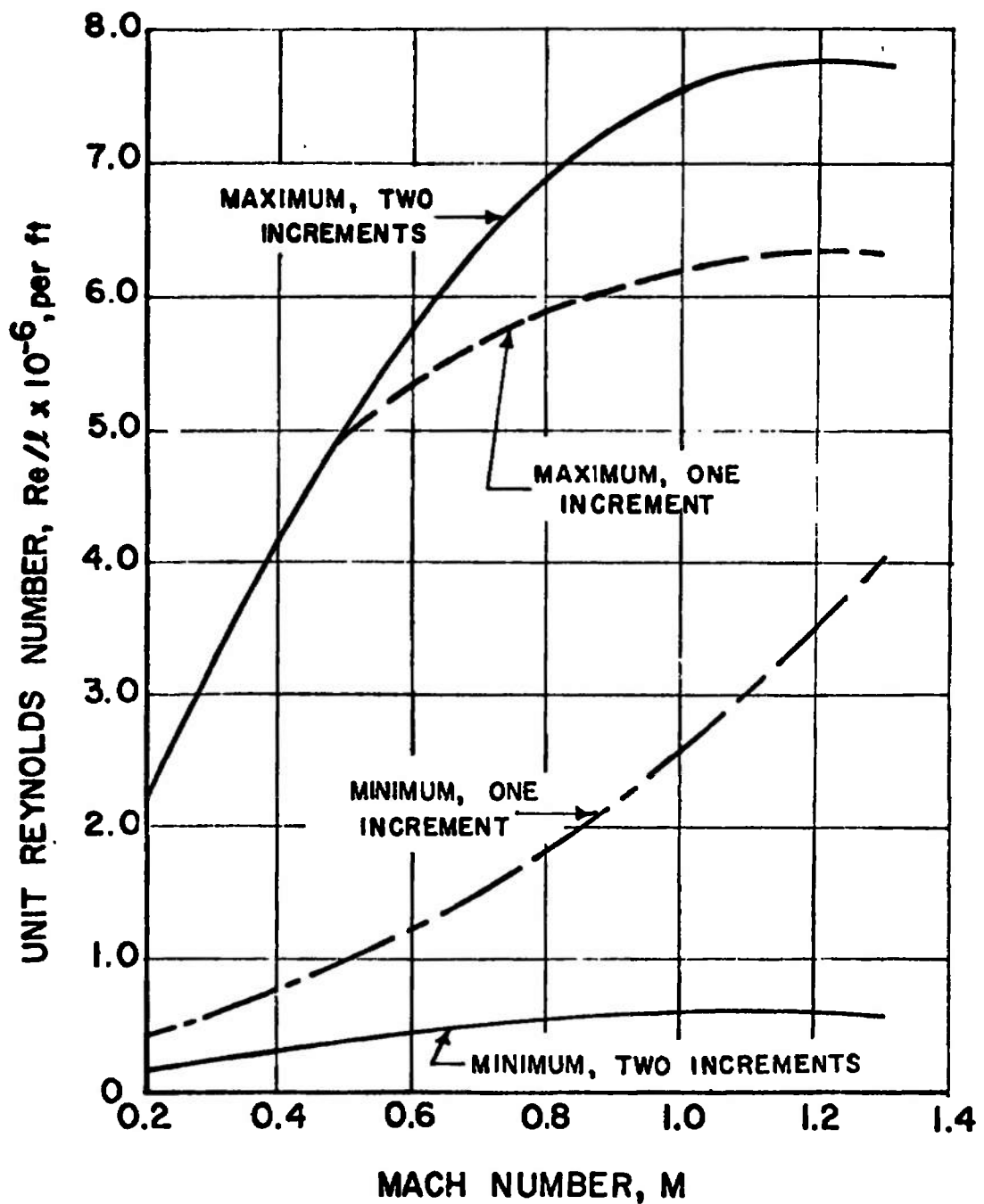
a. Stagnation Pressure

Fig. 3 Tunnel 4T Operating Envelopes



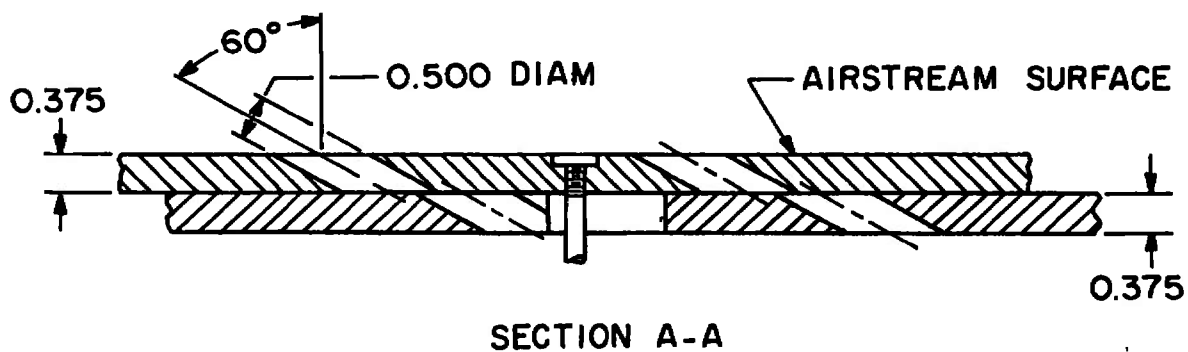
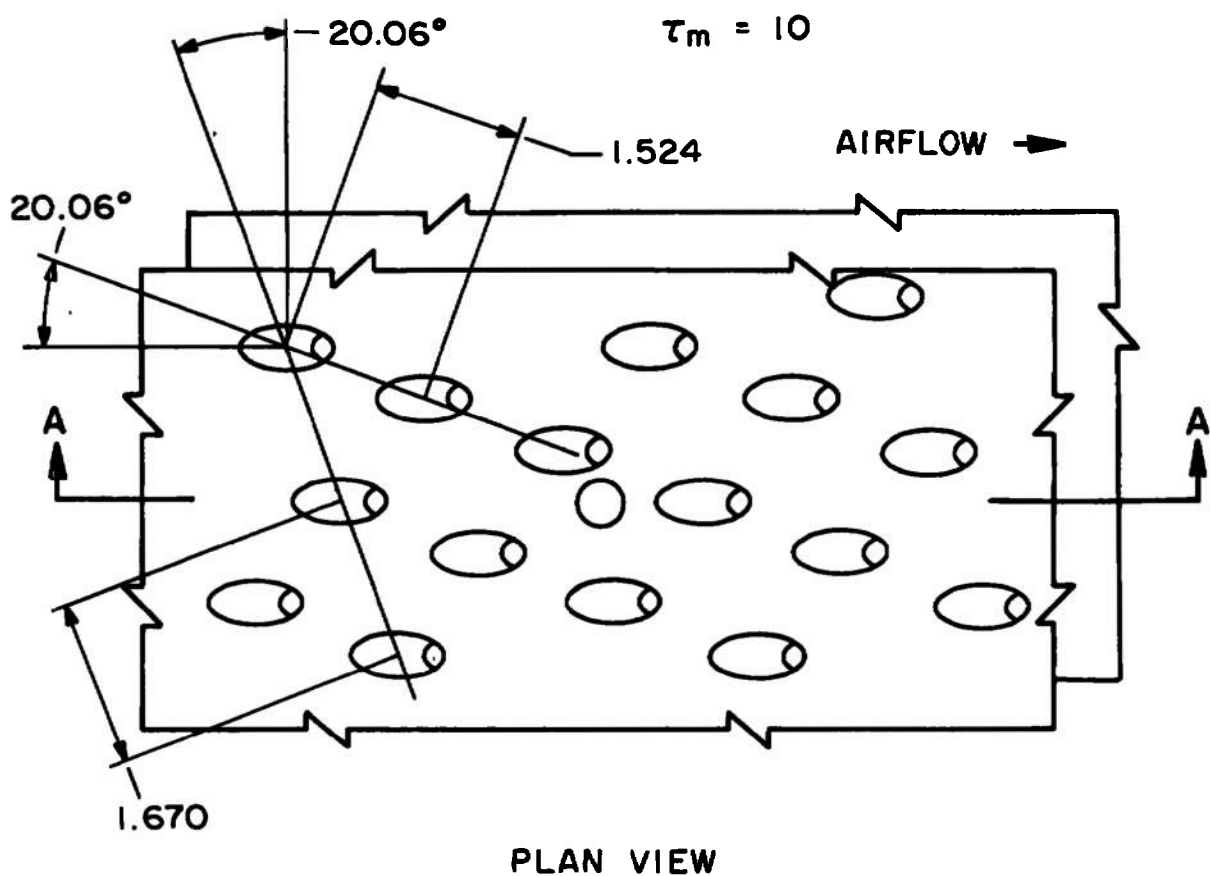
b. Dynamic Pressure

Fig. 3 Continued



c. Unit Reynolds Number

Fig. 3 Concluded



ALL DIMENSIONS IN INCHES

Fig. 4 Test Section Wall Geometry

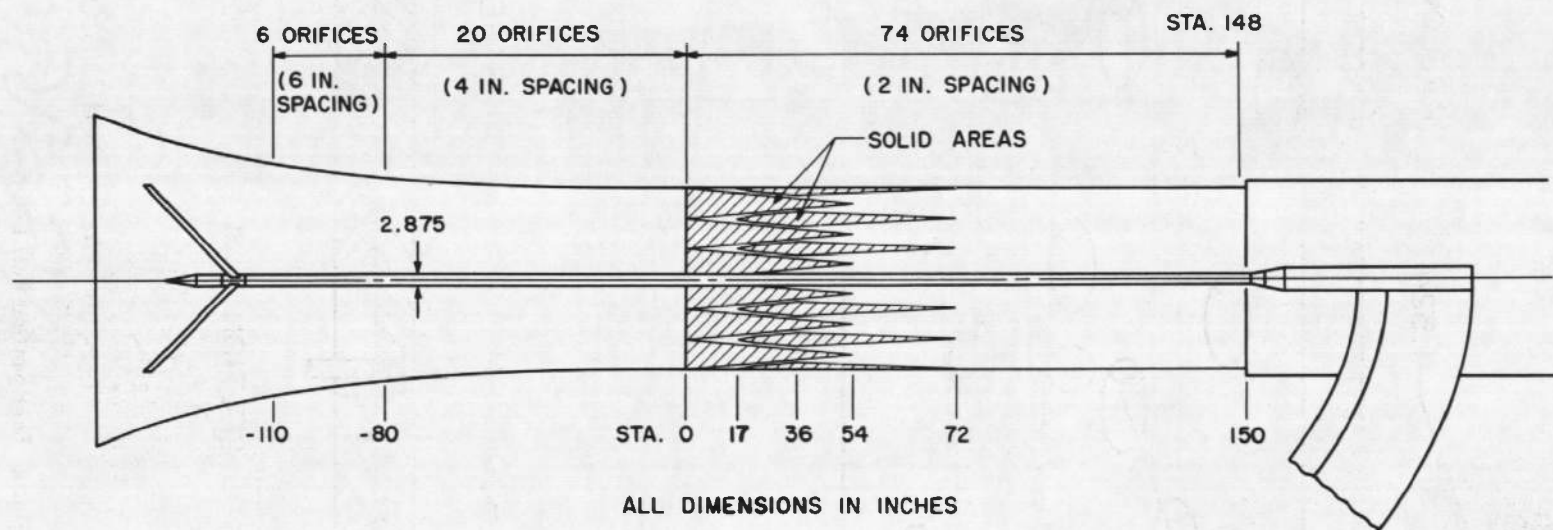
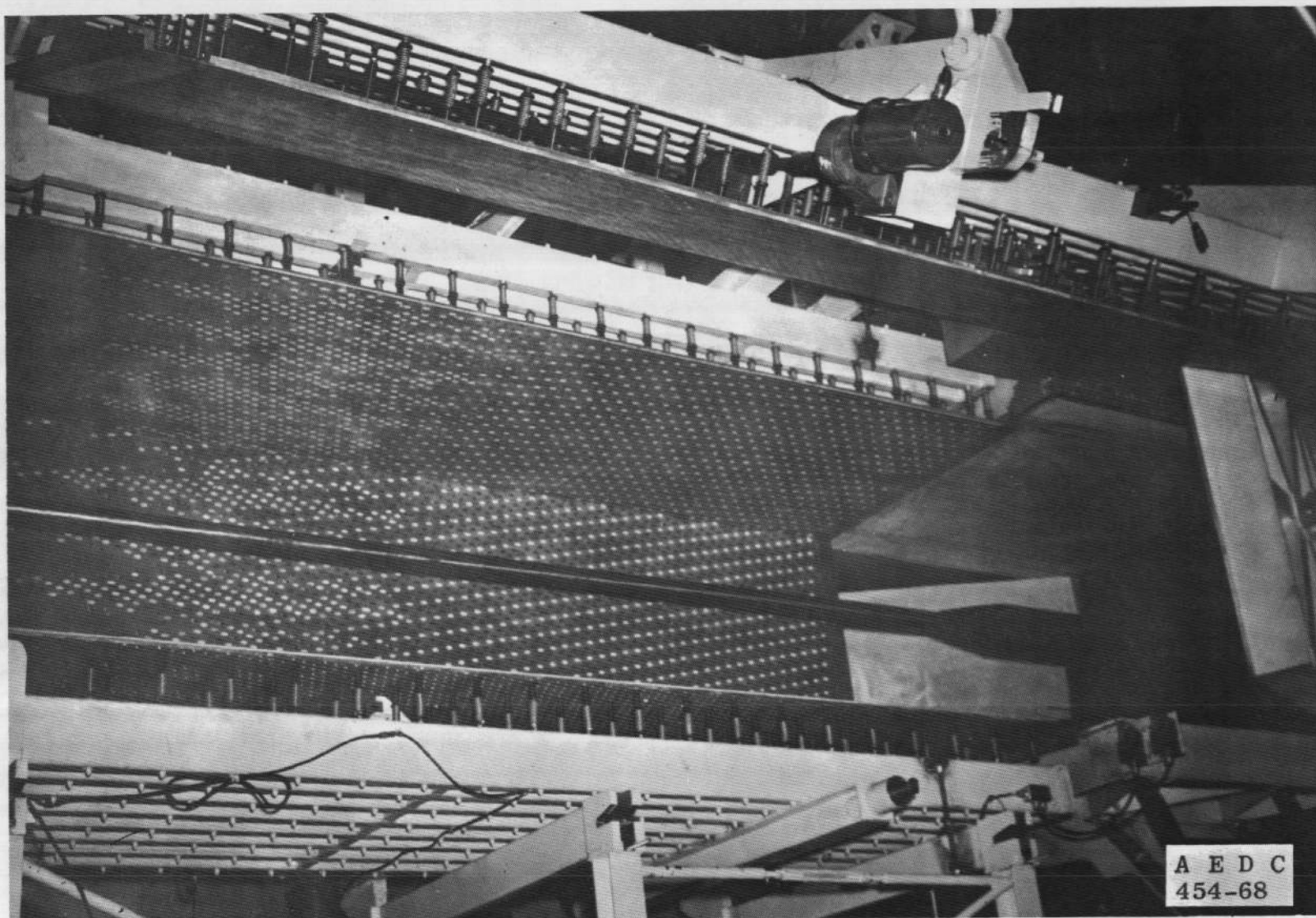
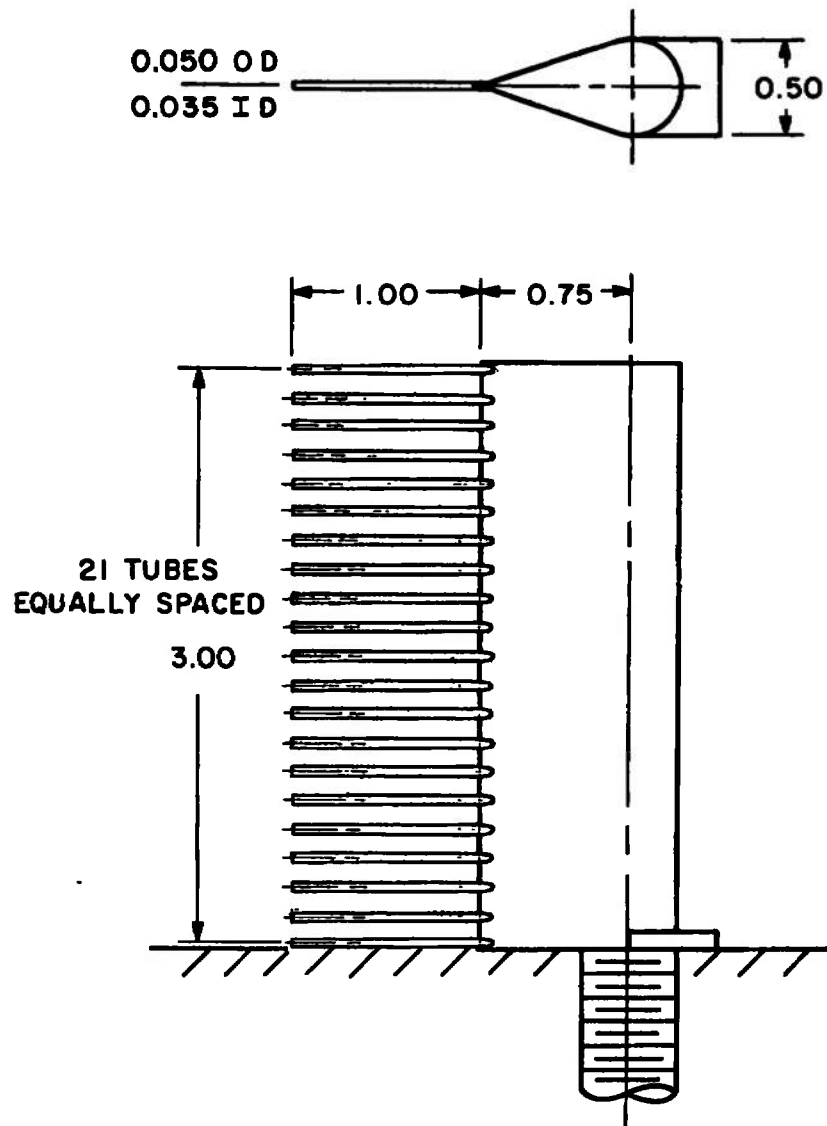


Fig. 5 Centerline Static Pipe Installation



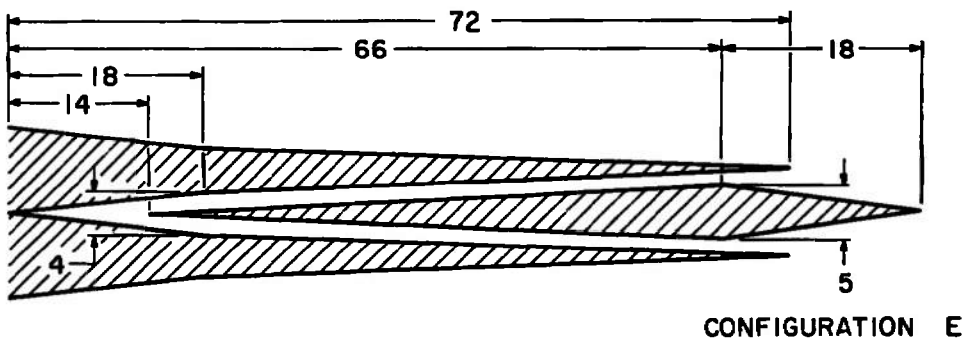
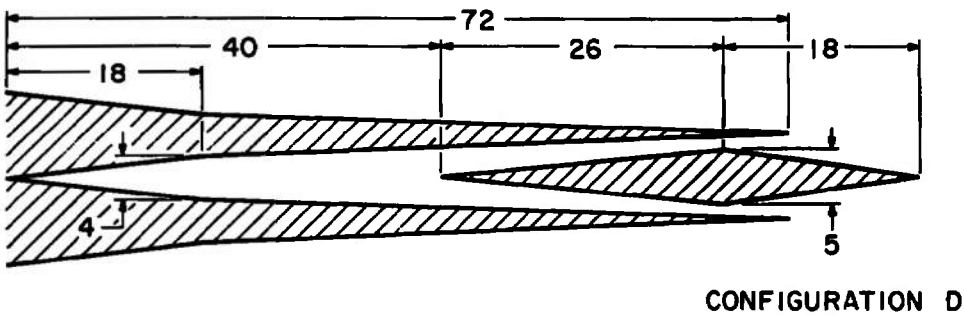
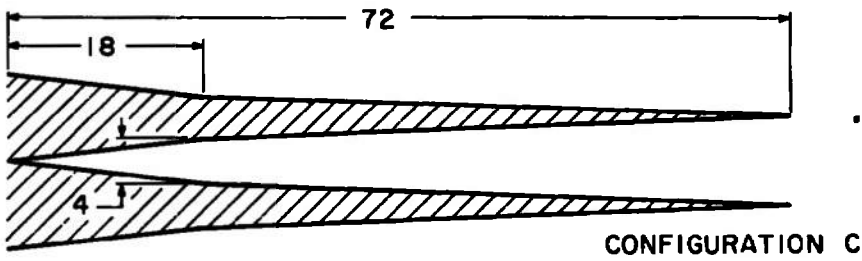
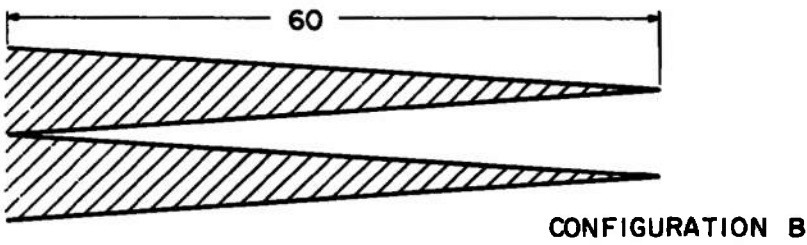
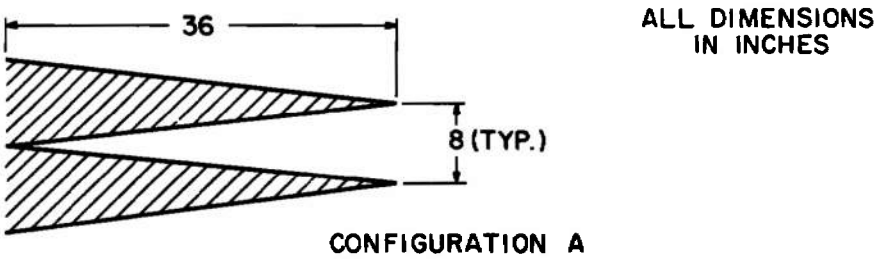
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Fig. 6 Photograph of Centerline Static Pipe

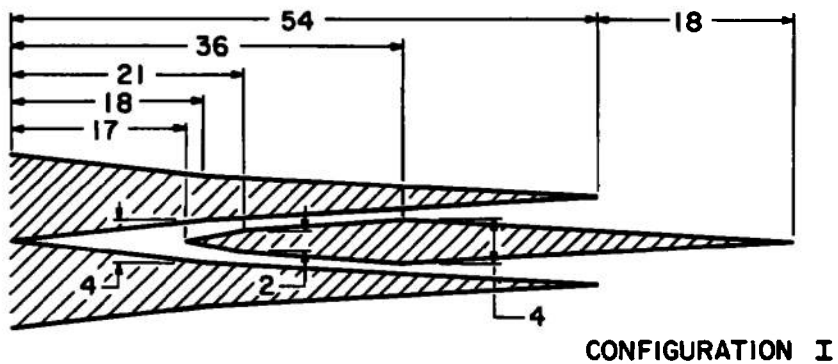
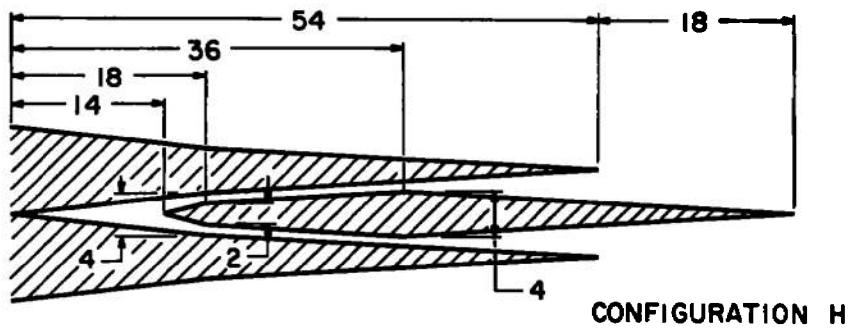
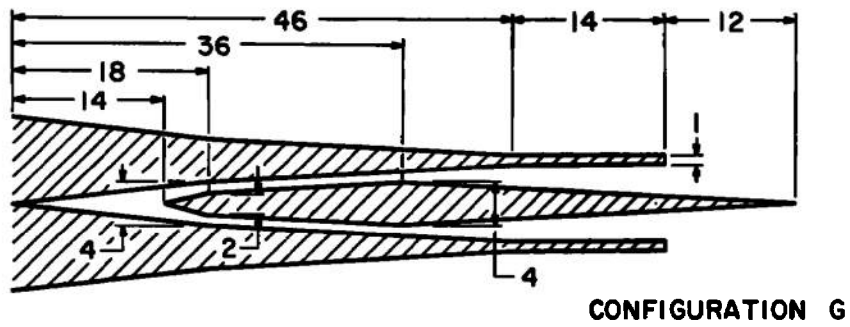
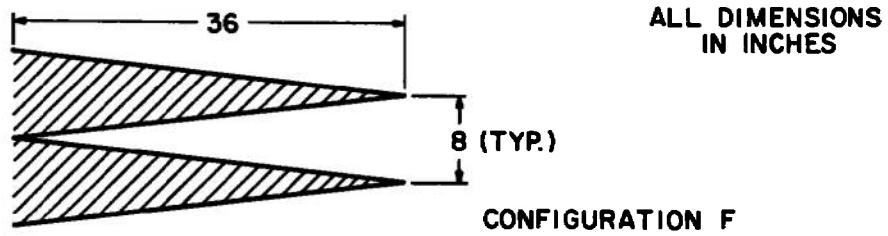


ALL DIMENSIONS IN INCHES

Fig. 7 Boundary-Layer Rake Details



a. 10-percent Maximum Wall Porosity
Fig. 8 Details of the Flow Expansion Region Configurations



b. 6-percent Maximum Wall Porosity
Fig. 8 Concluded

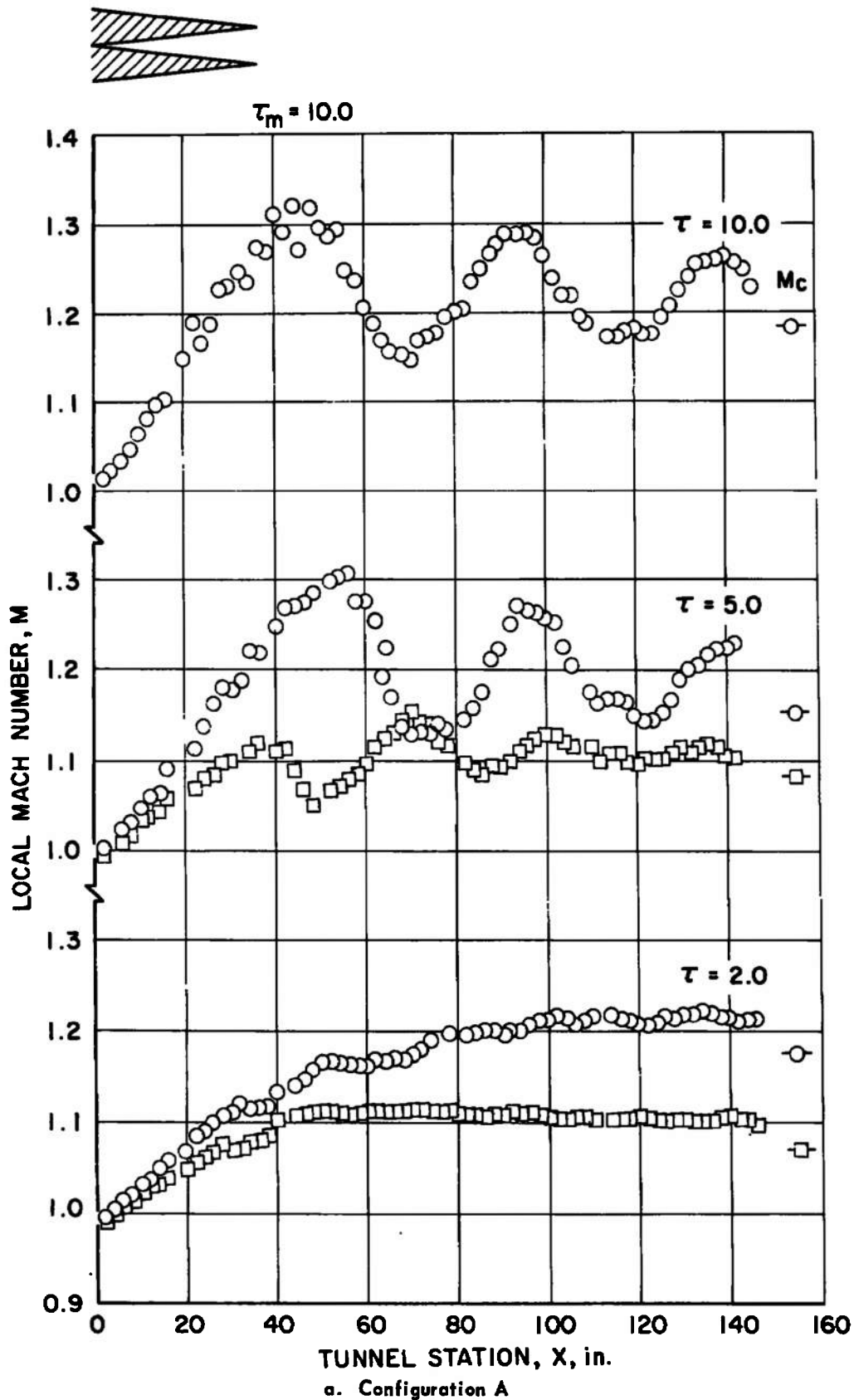
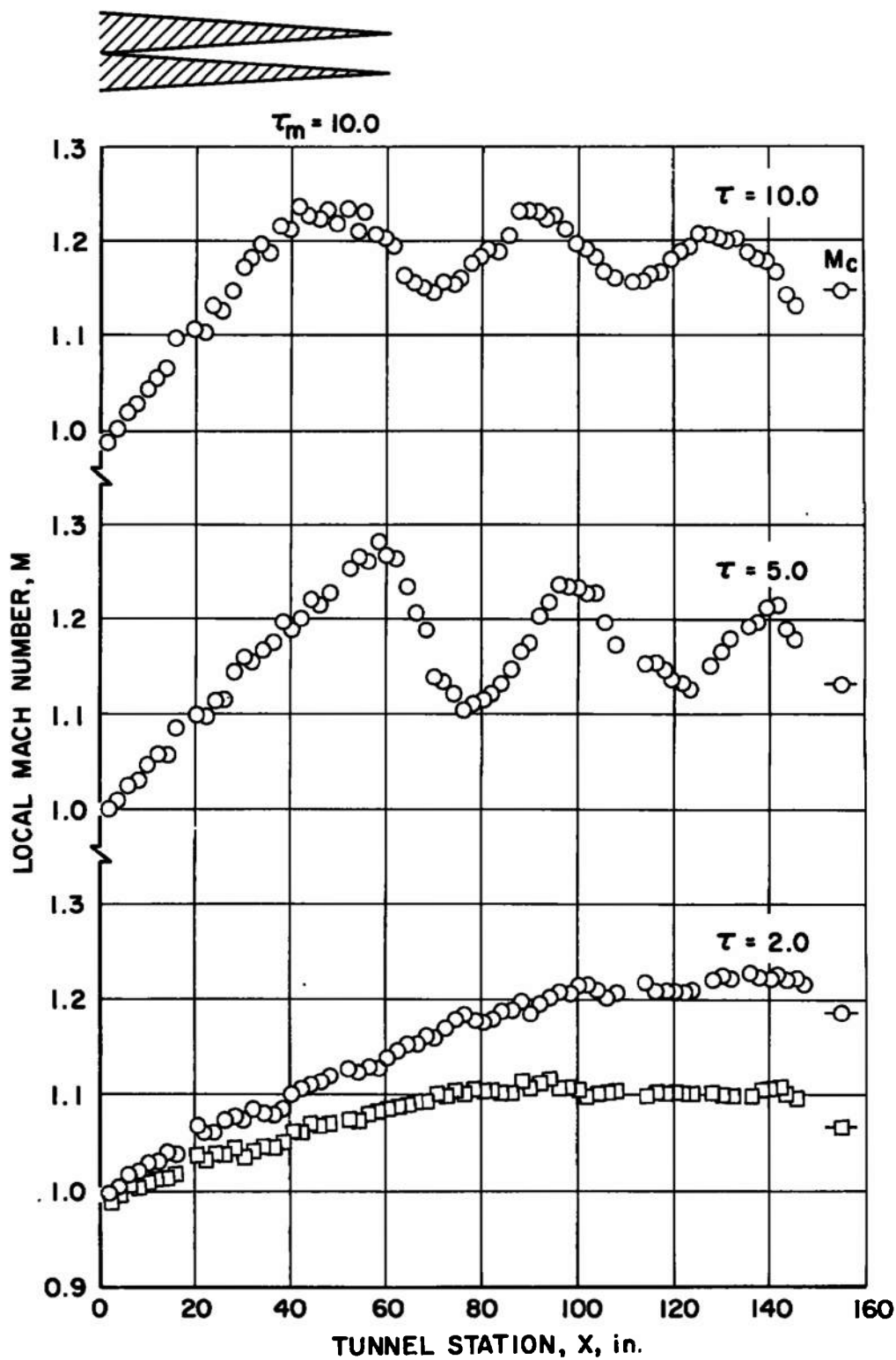
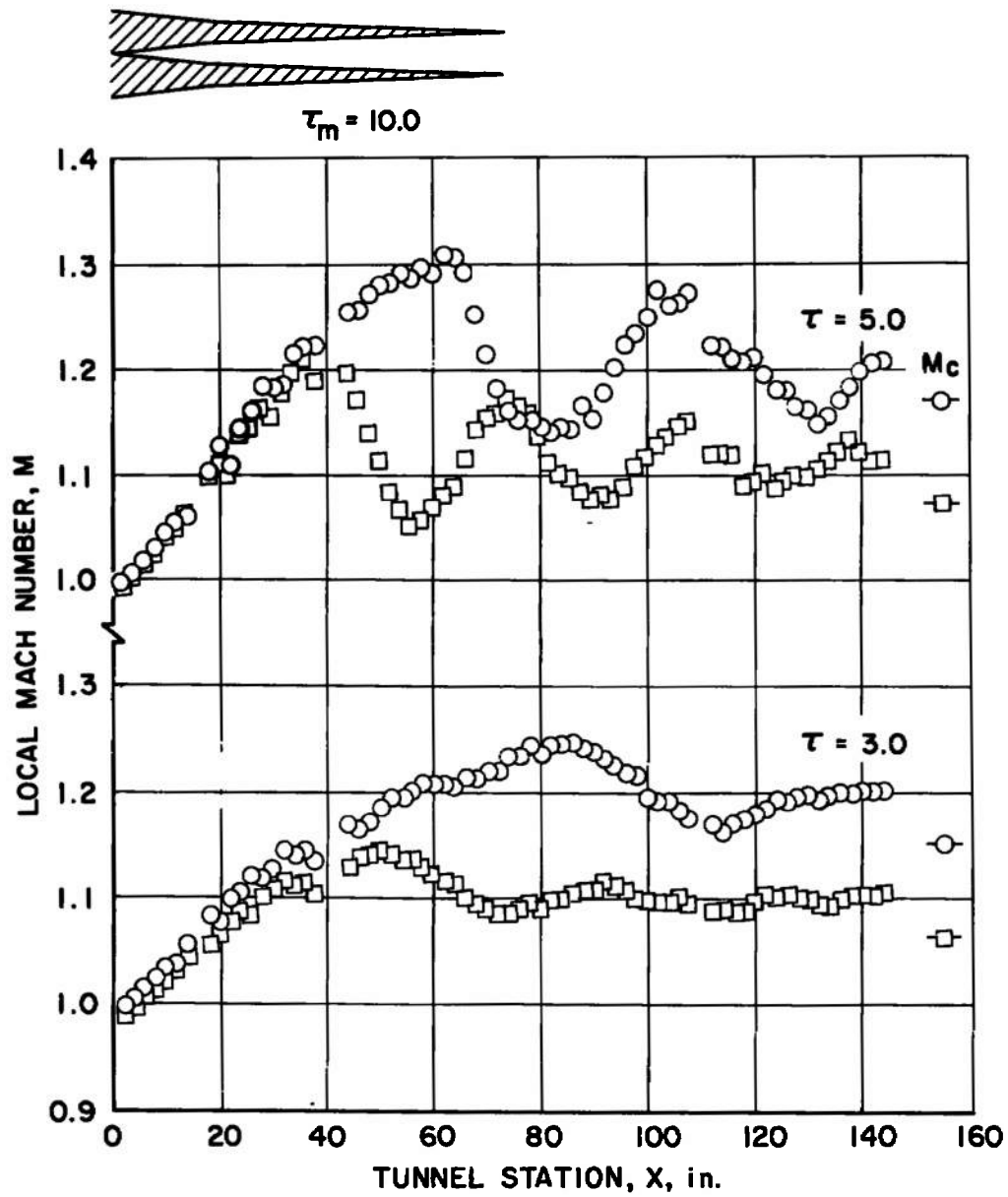


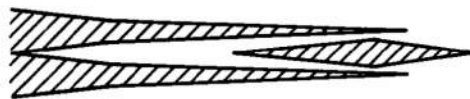
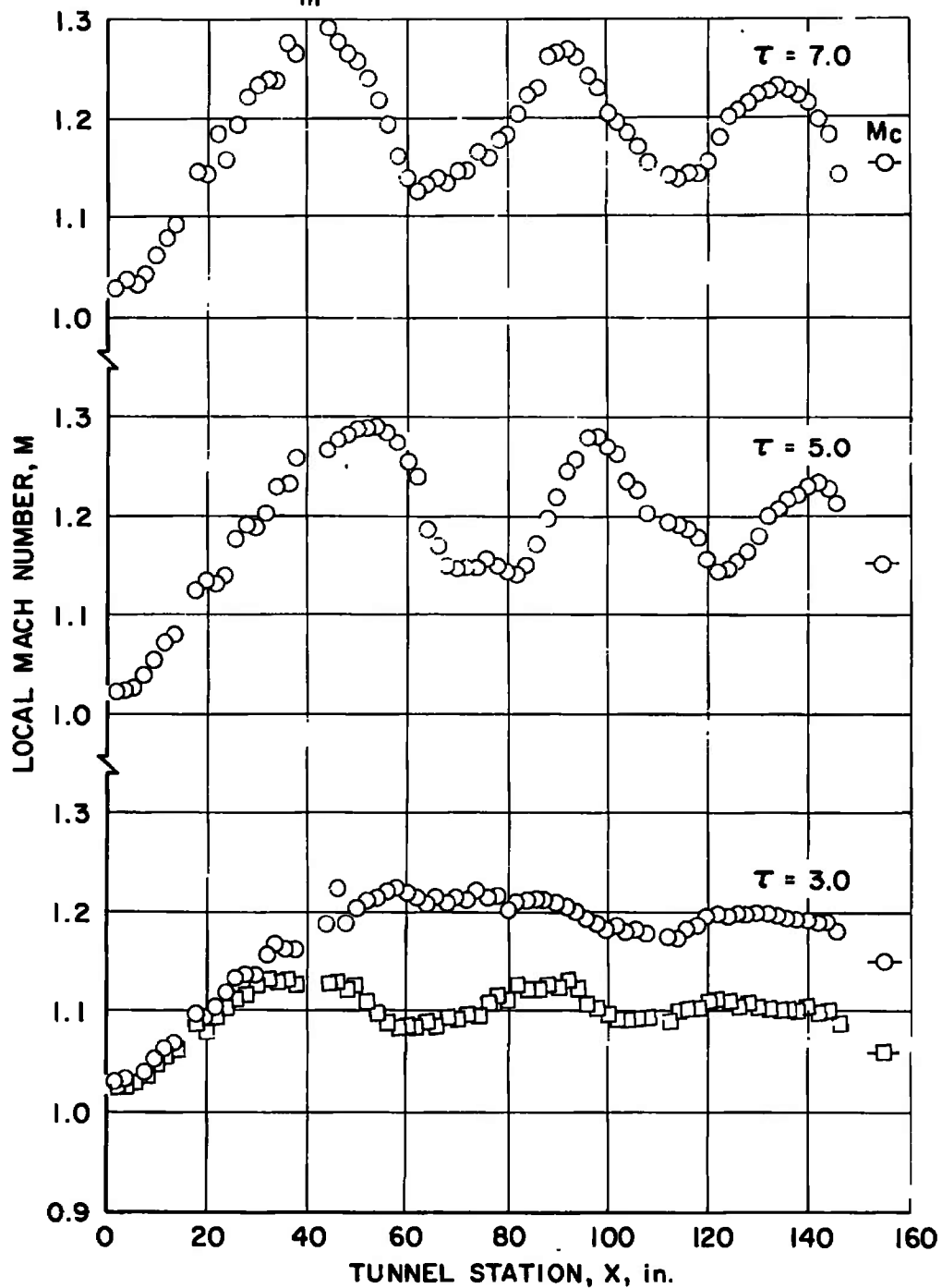
Fig. 9 Supersonic Mach Number Distributions for Different Wall Configurations and Wall Porosity, $\theta_w = 0$



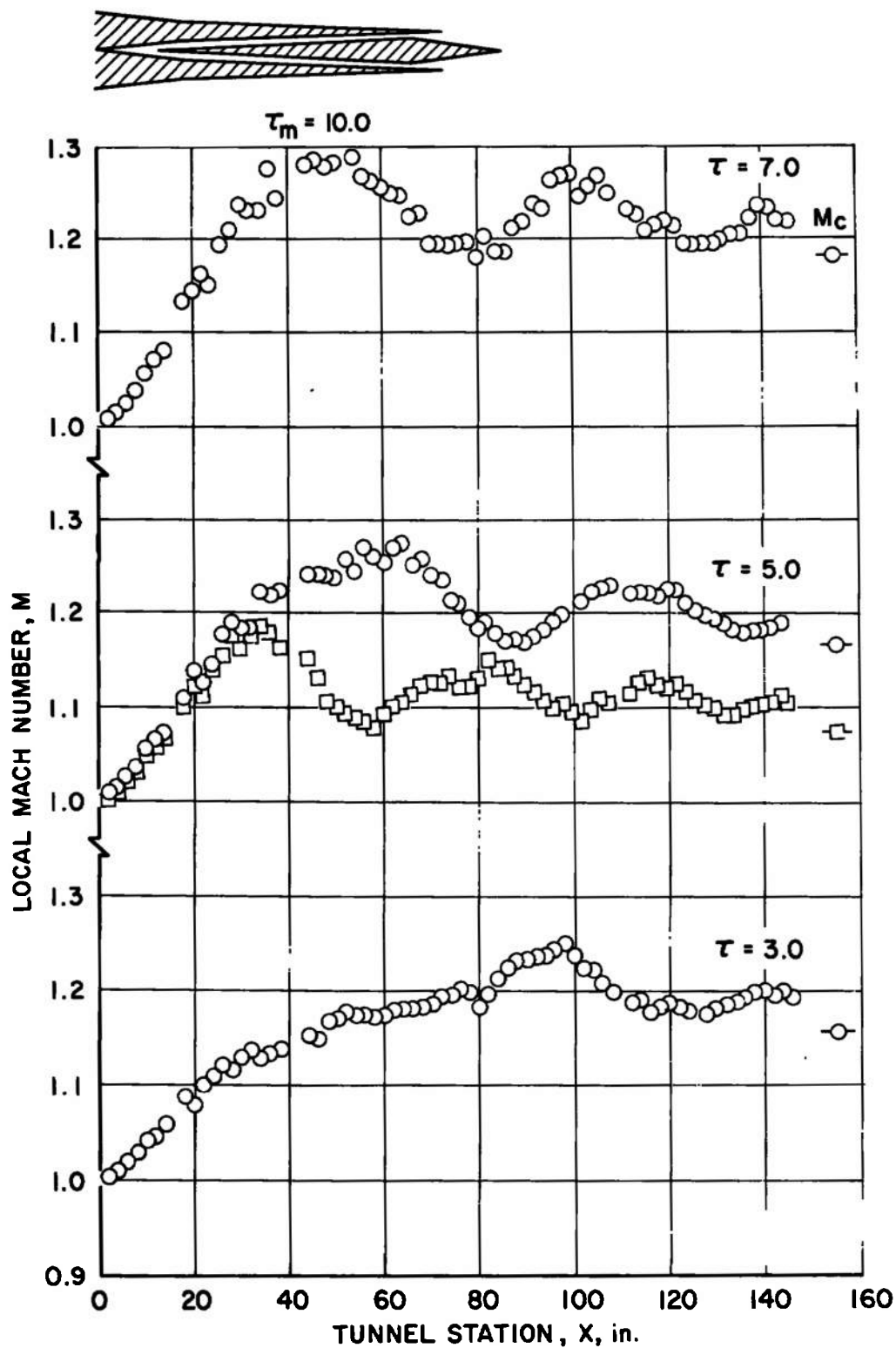
b. Configuration B
Fig. 9 Continued



c. Configuration C
Fig. 9 Continued

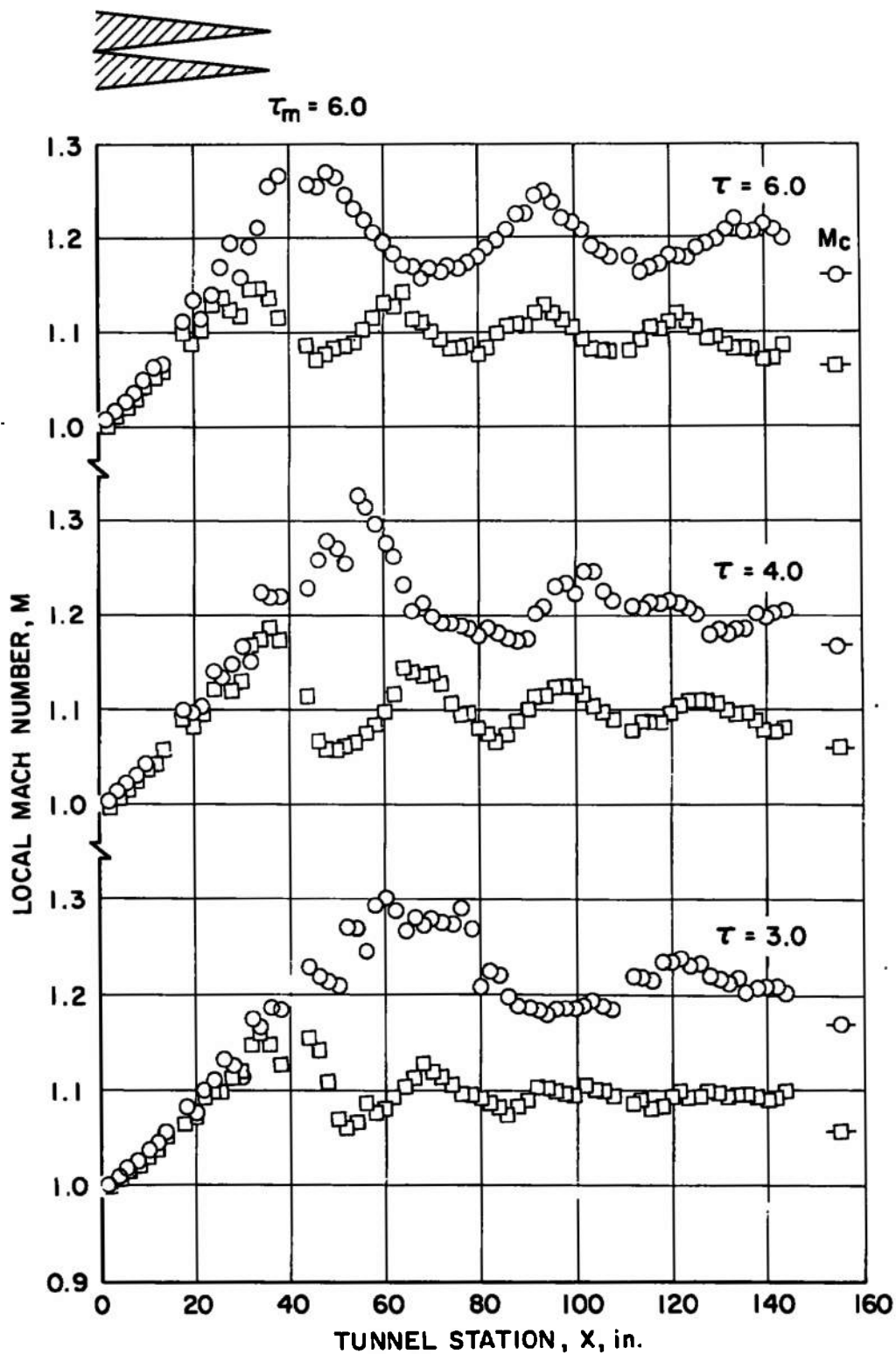

 $\tau_m = 10.0$


d. Configuration D
Fig. 9 Continued



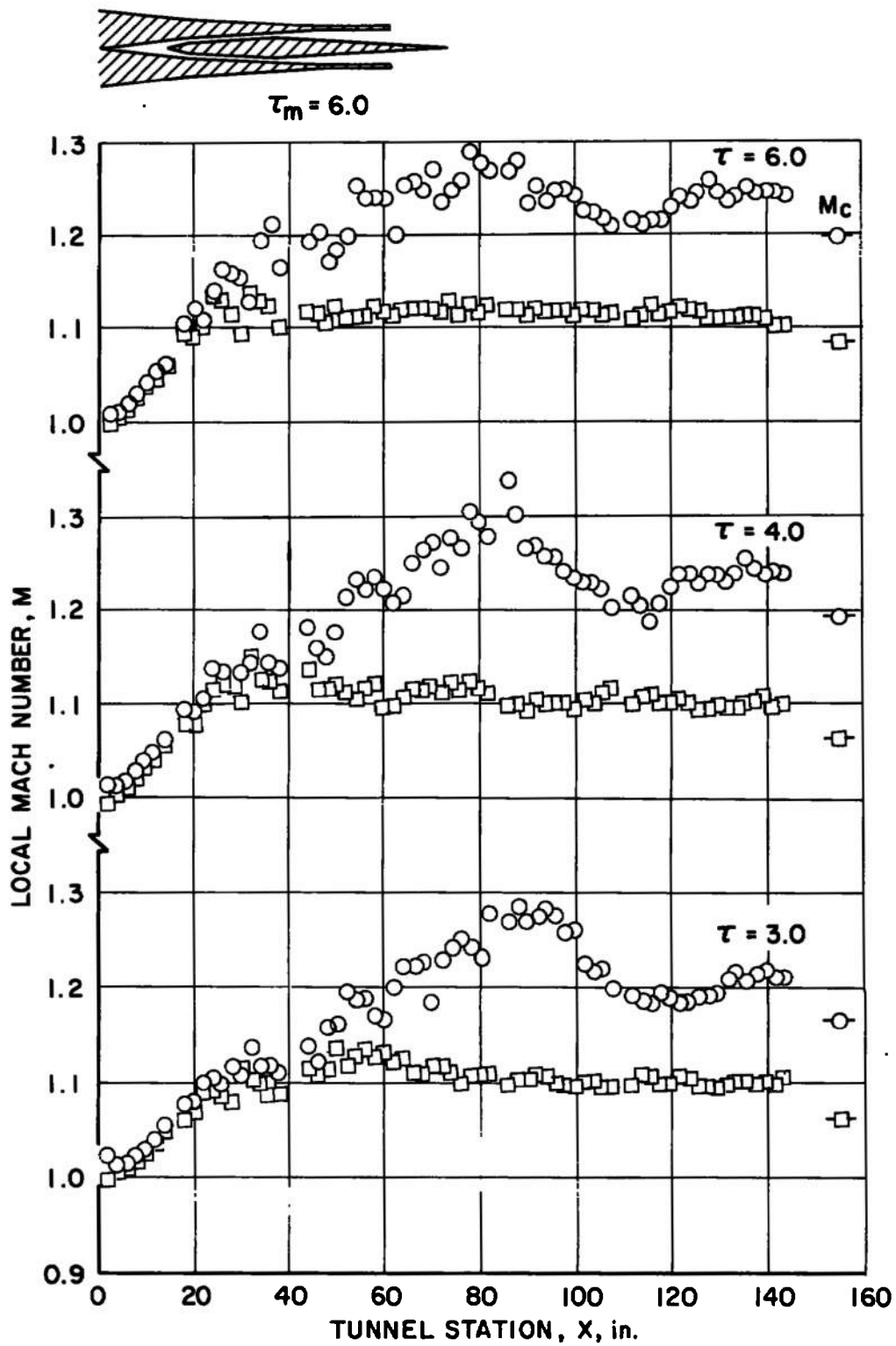
e. Configuration E

Fig. 9 Continued



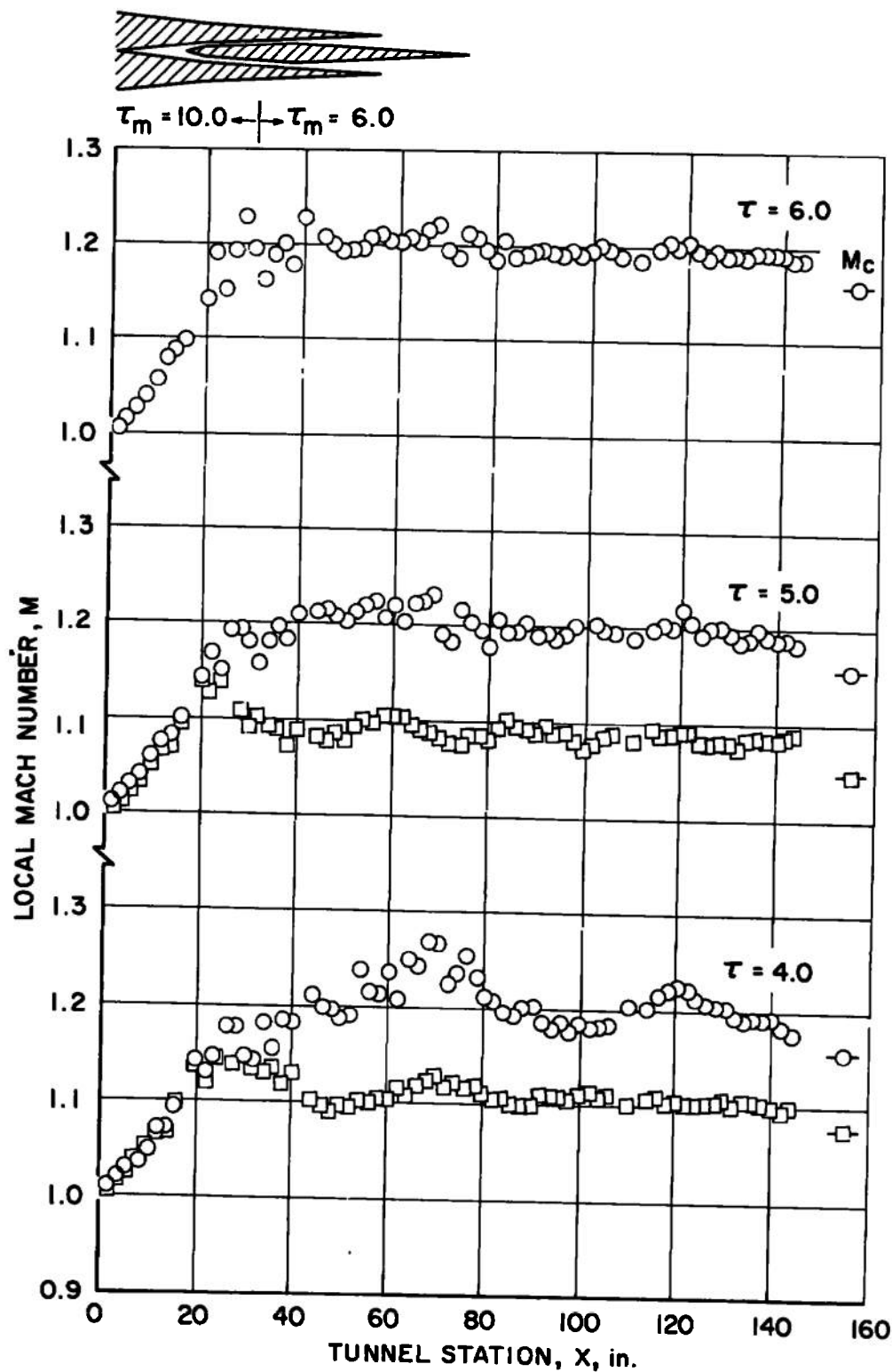
f. Configuration F

Fig. 9 Continued



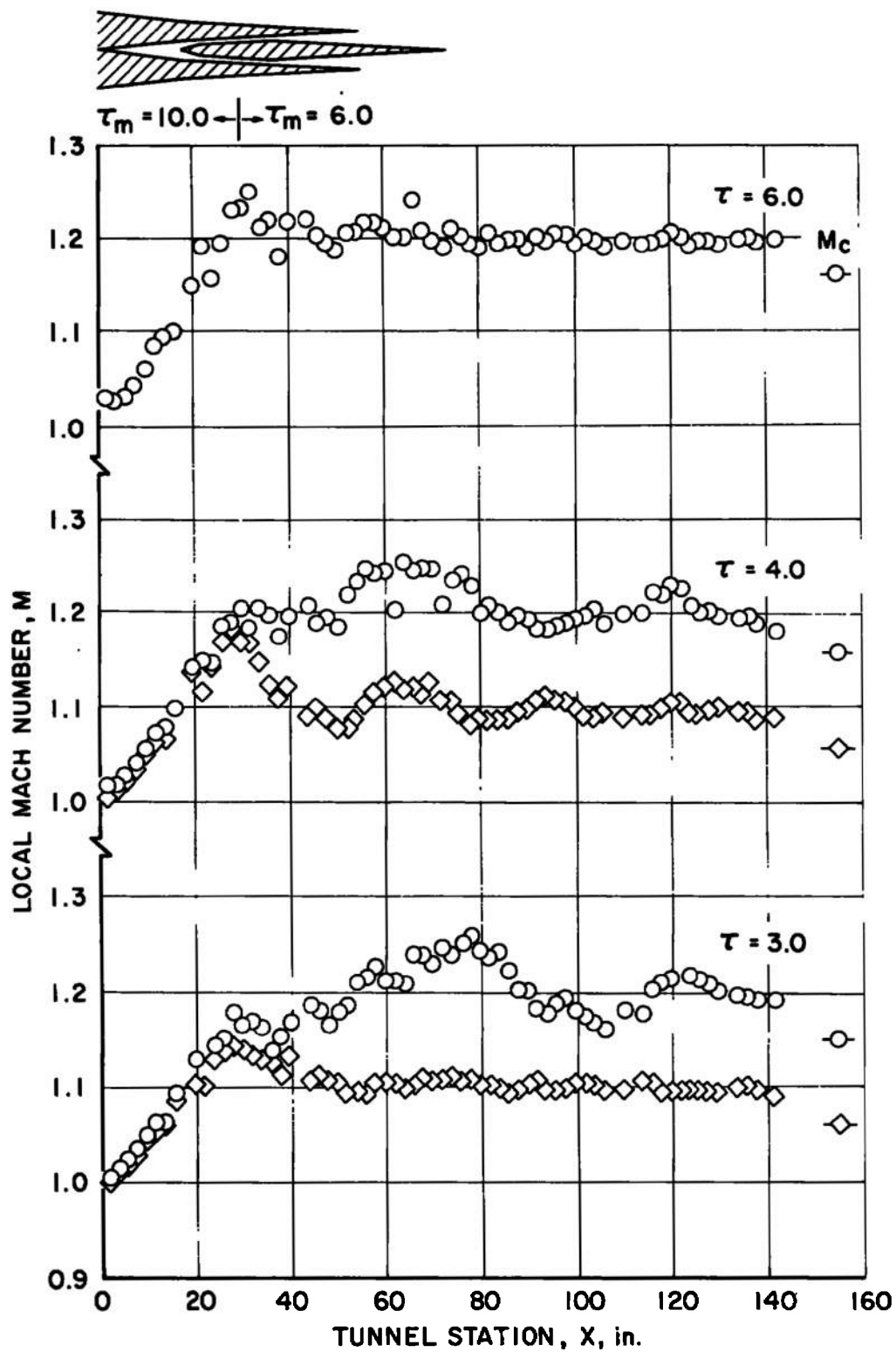
g. Configuration G

Fig. 9 Continued



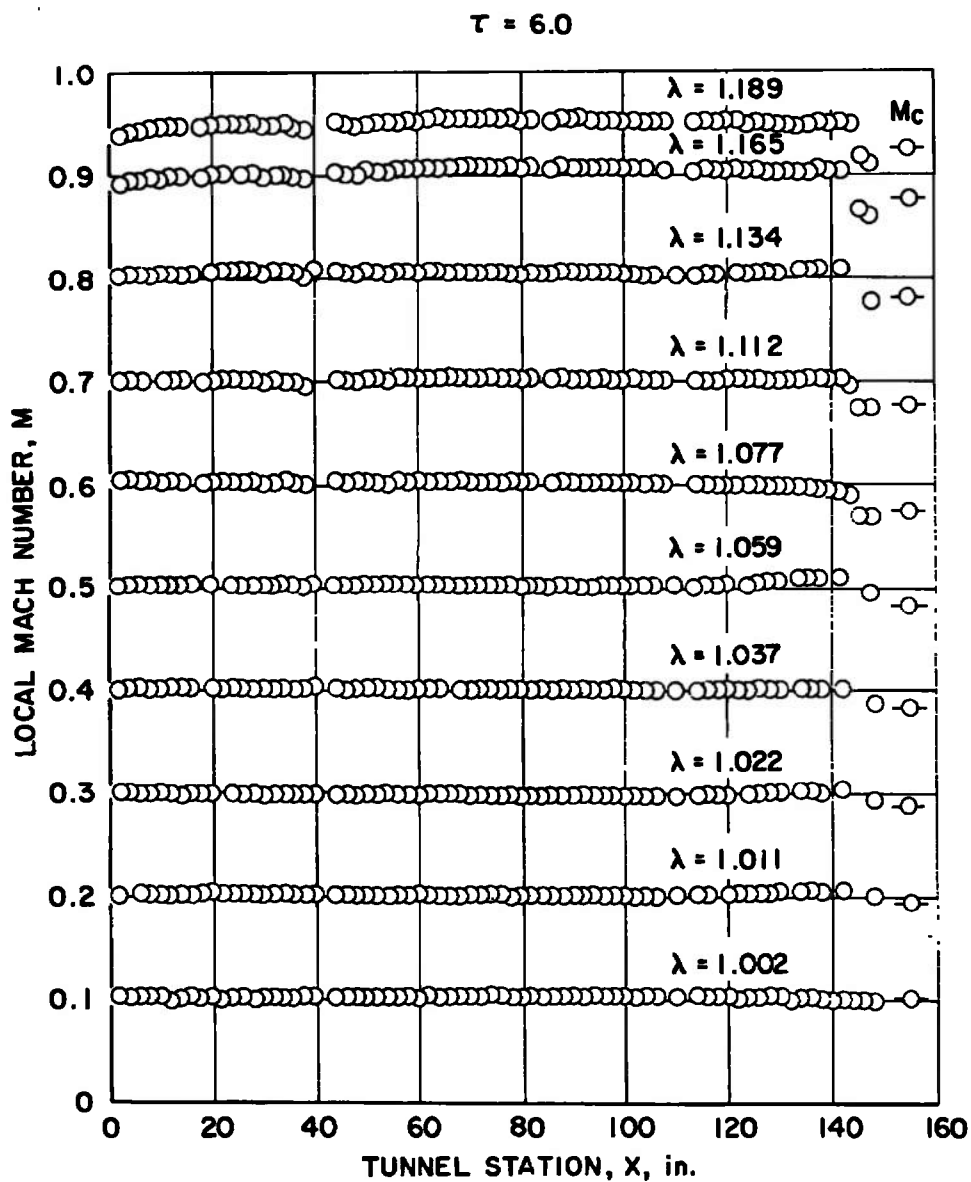
h. Configuration H

Fig. 9 Continued



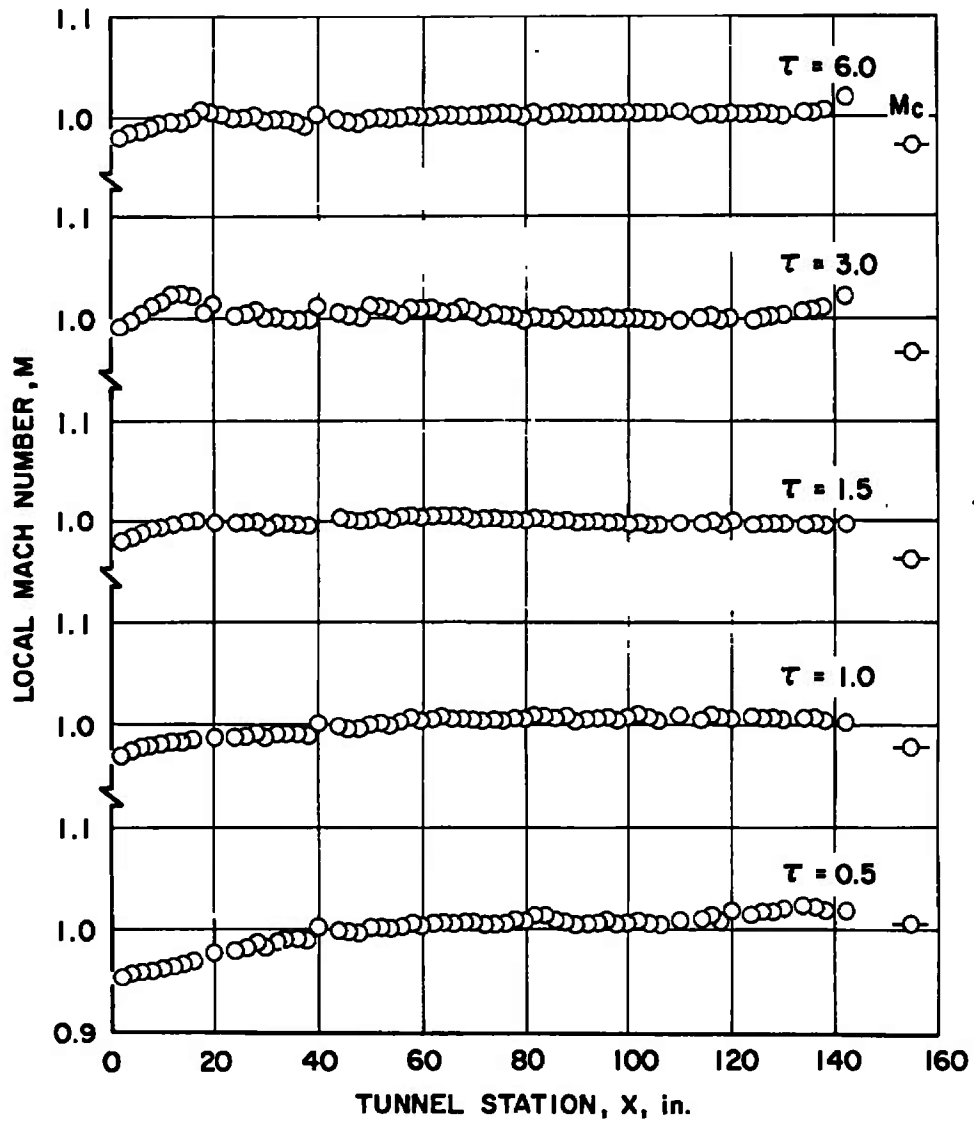
i. Configuration I

Fig. 9 Concluded



a. $M_{\infty} = 0.10$ through 0.95

Fig. 10 Mach Number Distributions for Wall Configuration 1, $\theta_w = 0$



b. $M_\infty = 1.00$
Fig. 10 Continued

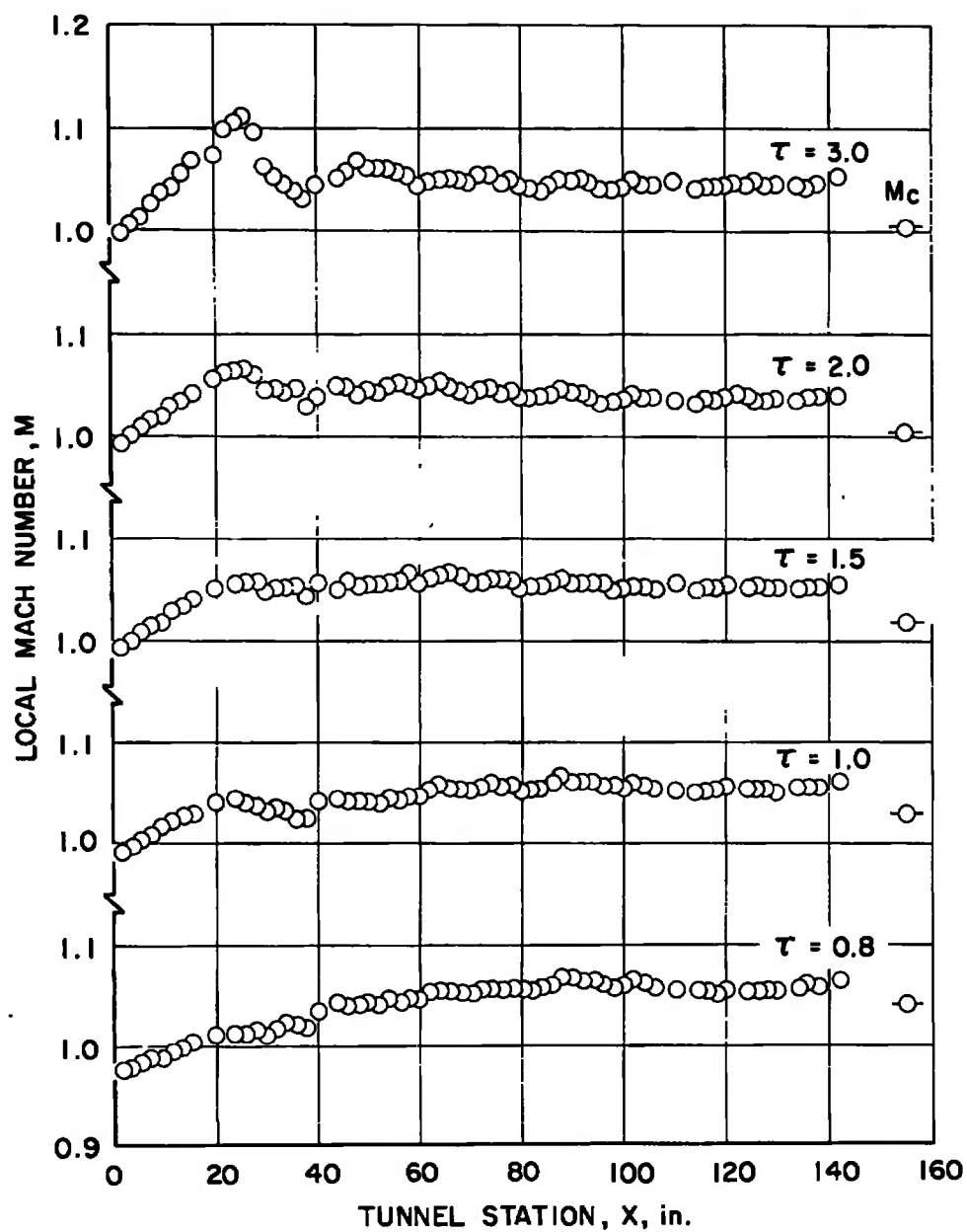
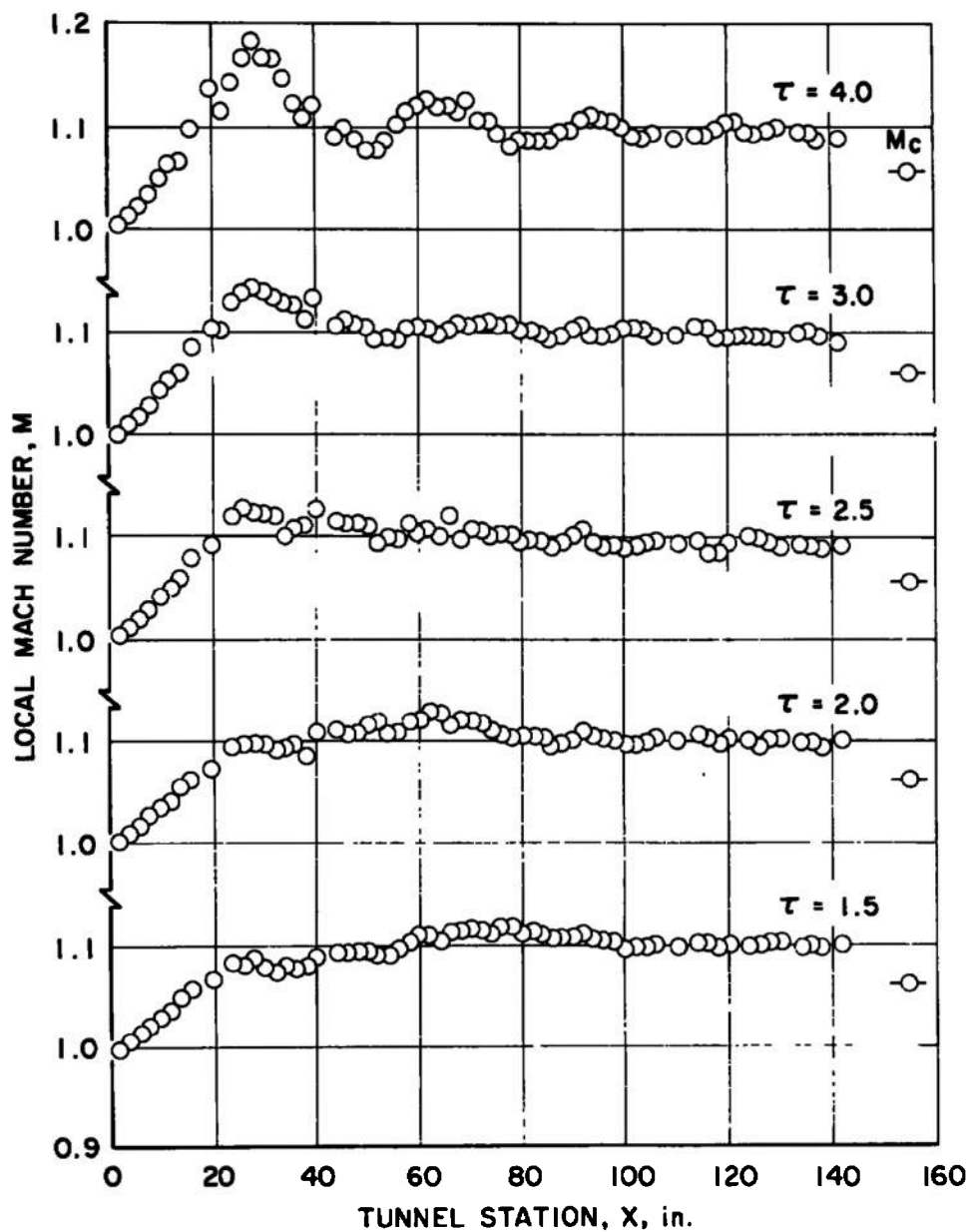
c. $M_\infty = 1.05$

Fig. 10 Continued



d. $M_{oc} = 1.10$
Fig. 10 Continued

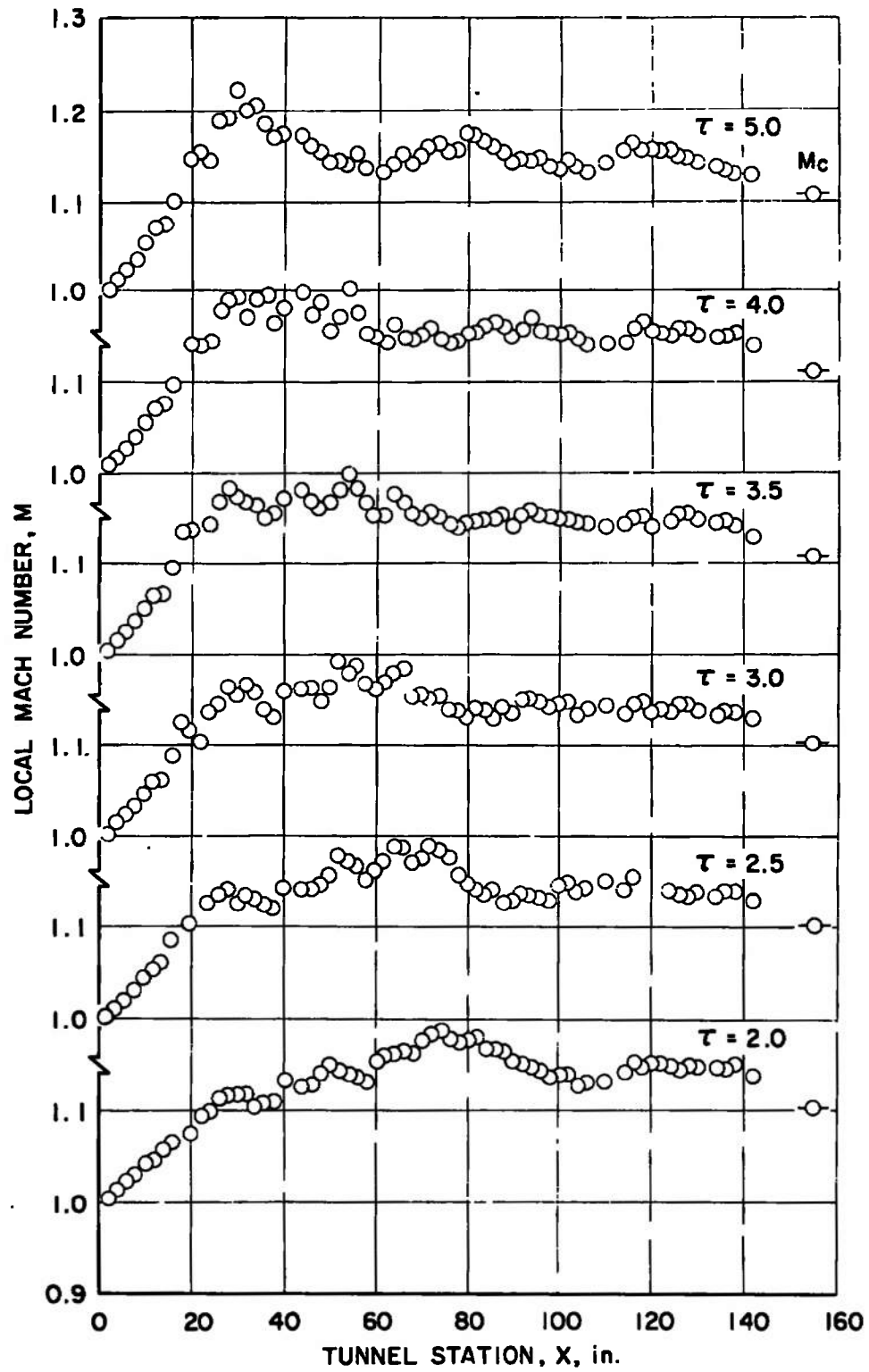
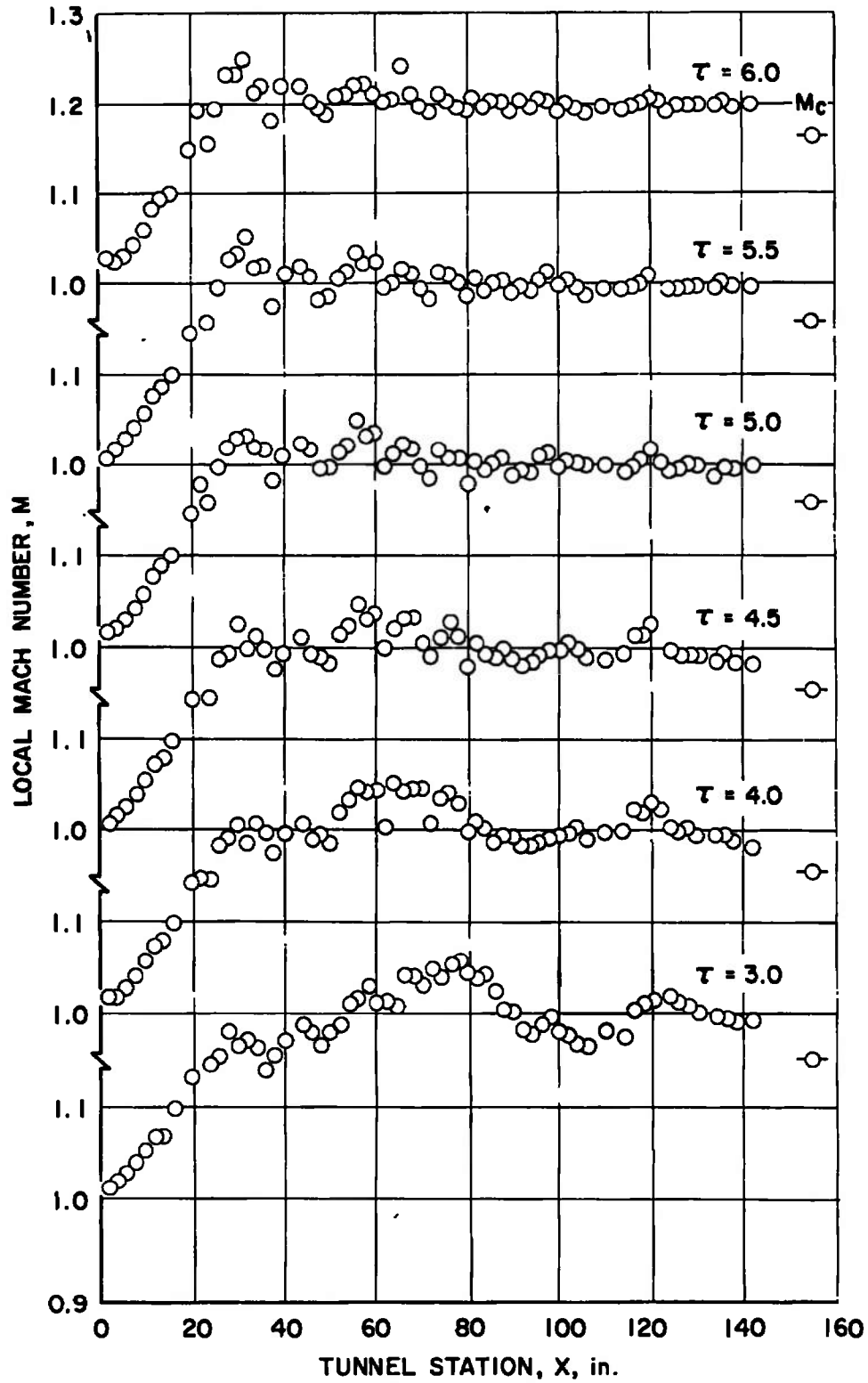
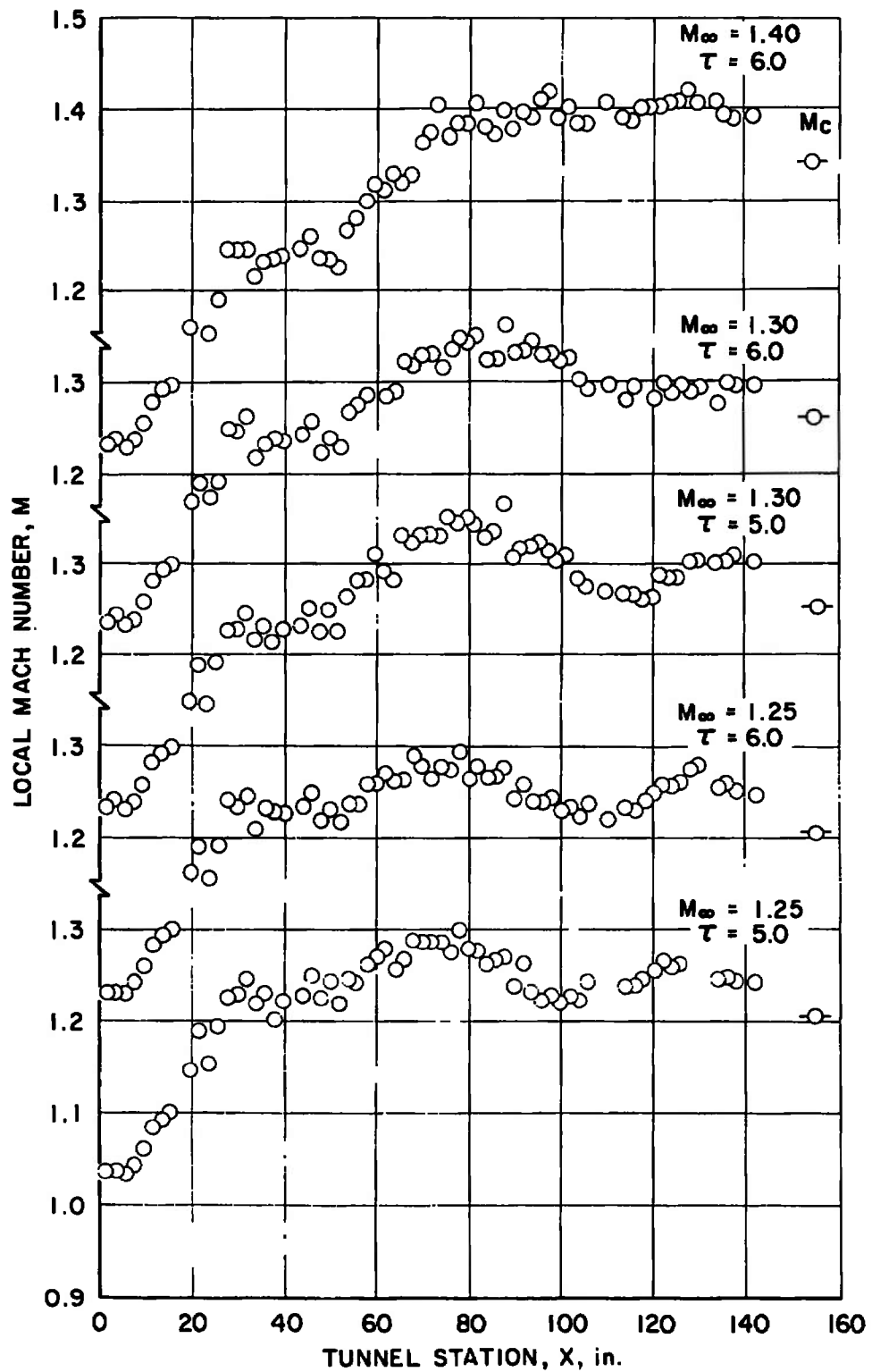
e. $M_\infty = 1.15$

Fig. 10 Continued



f. $M_{\infty} = 1.20$
Fig. 10 Continued



g. $M_{\infty} = 1.25, 1.30$, and 1.40

Fig. 10 Concluded

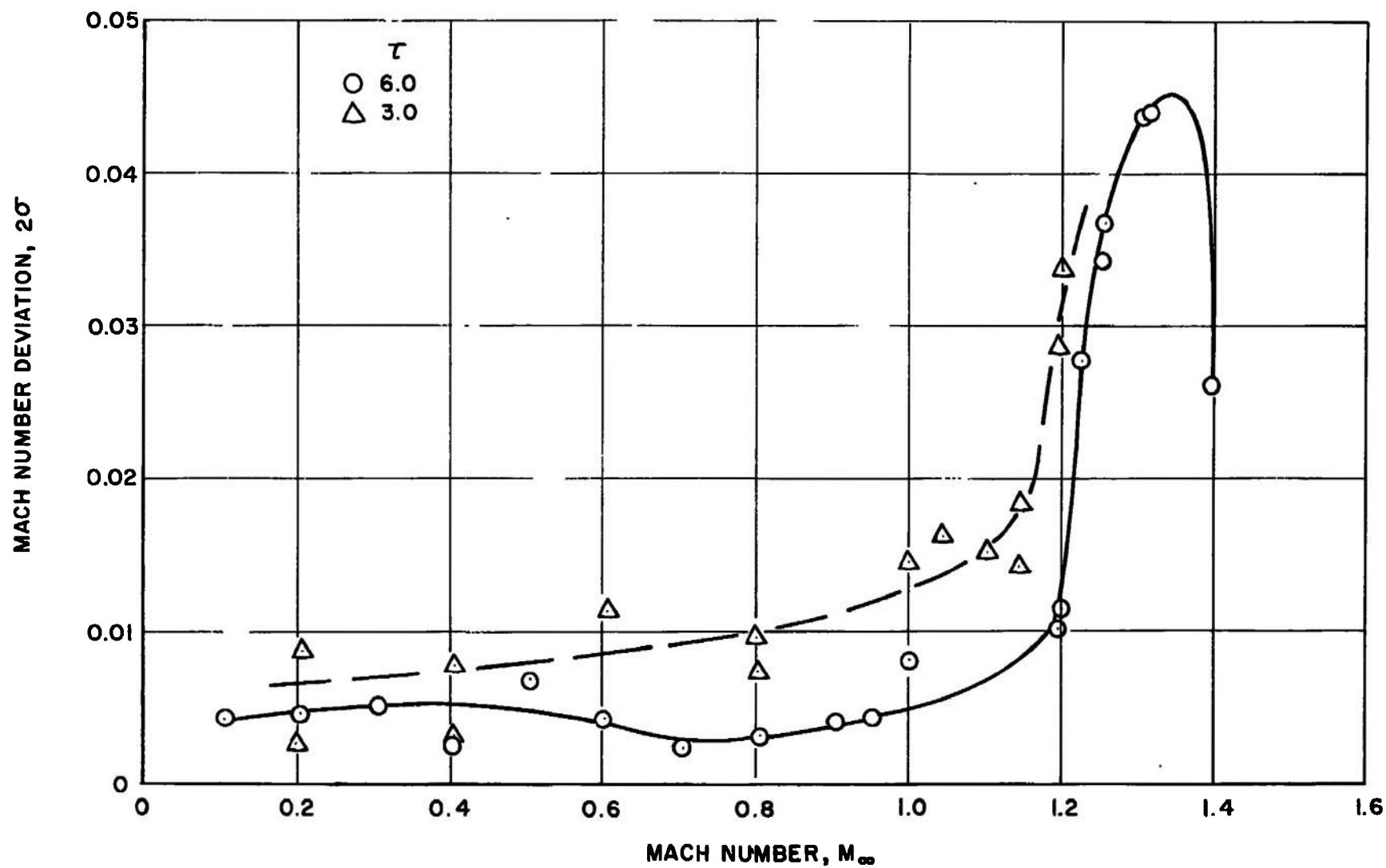


Fig. 11 Mach Number Deviations for Wall Configuration I

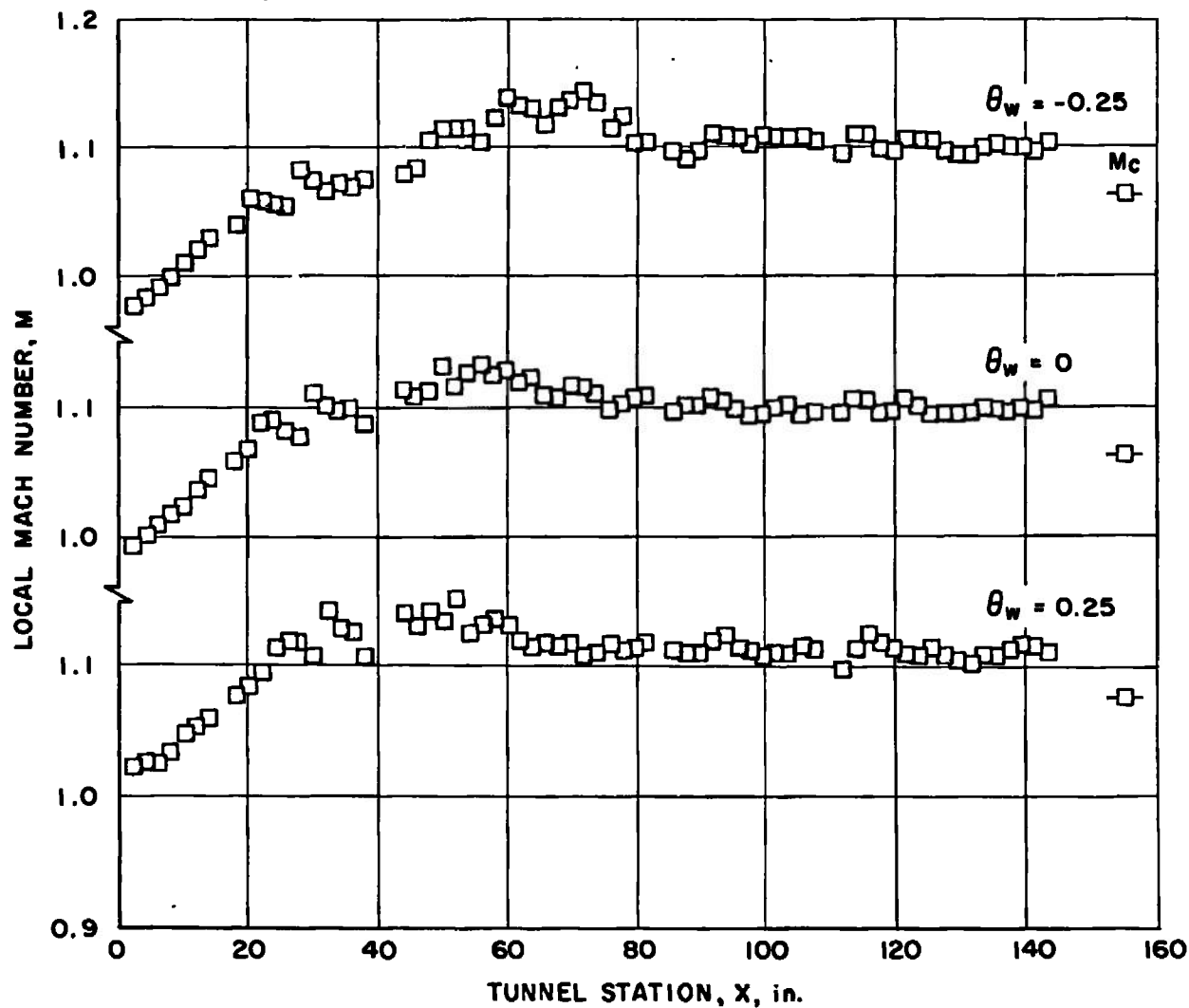


Fig. 12 Effect of Wall Angle upon the Mach Number Distribution at $M_\infty = 1.10$ for Configuration G, $r = 3.0$

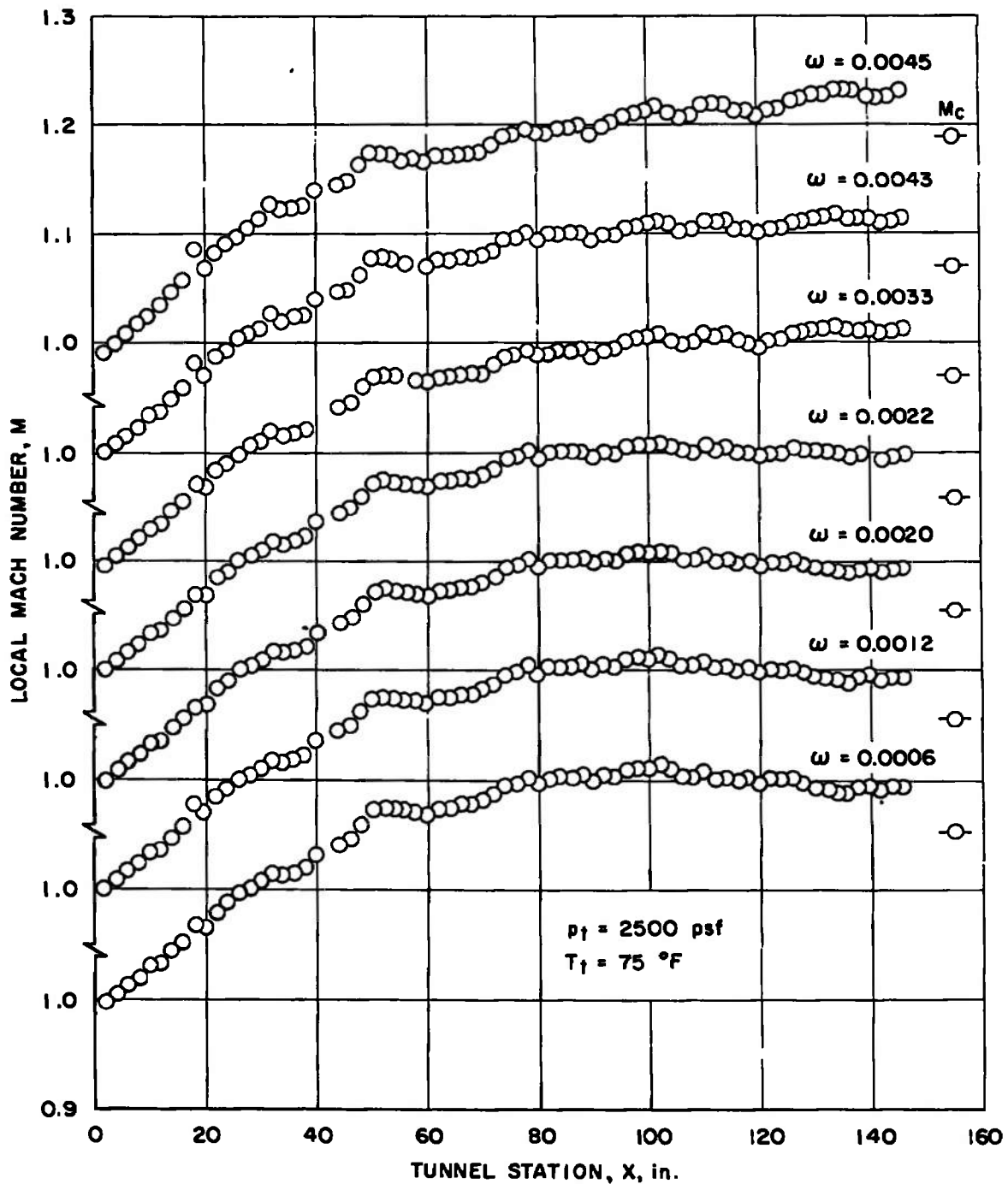


Fig. 13 Effect of Water Condensation upon the Mach Number Distribution
 at $M_\infty = 1.20$ for Configuration A, $\tau = 2.0$

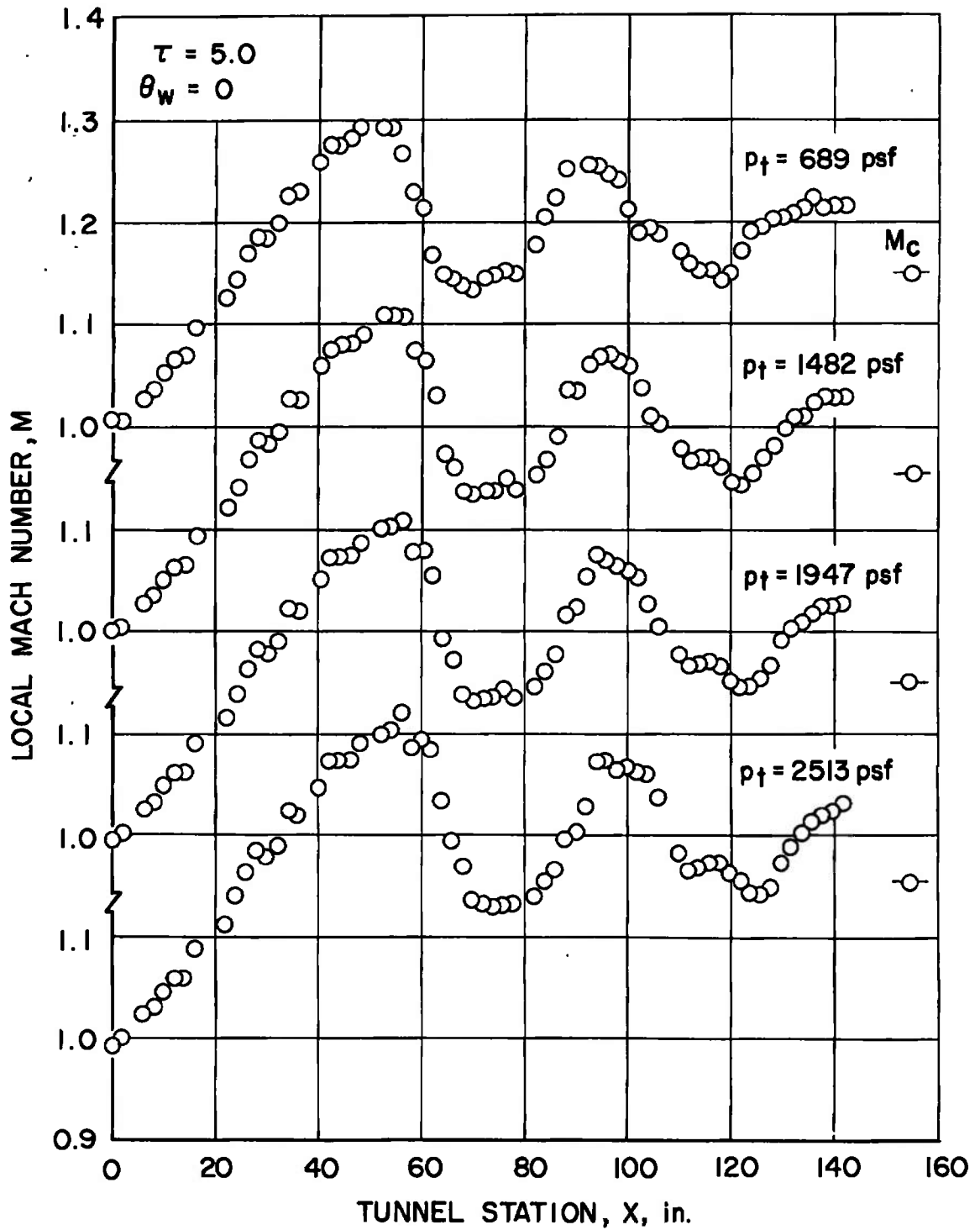


Fig. 14 Effect of Stagnation Pressure Level upon the Mach Number
 Distribution at $M_\infty = 1.20$ for Configuration A, $r = 5.0$

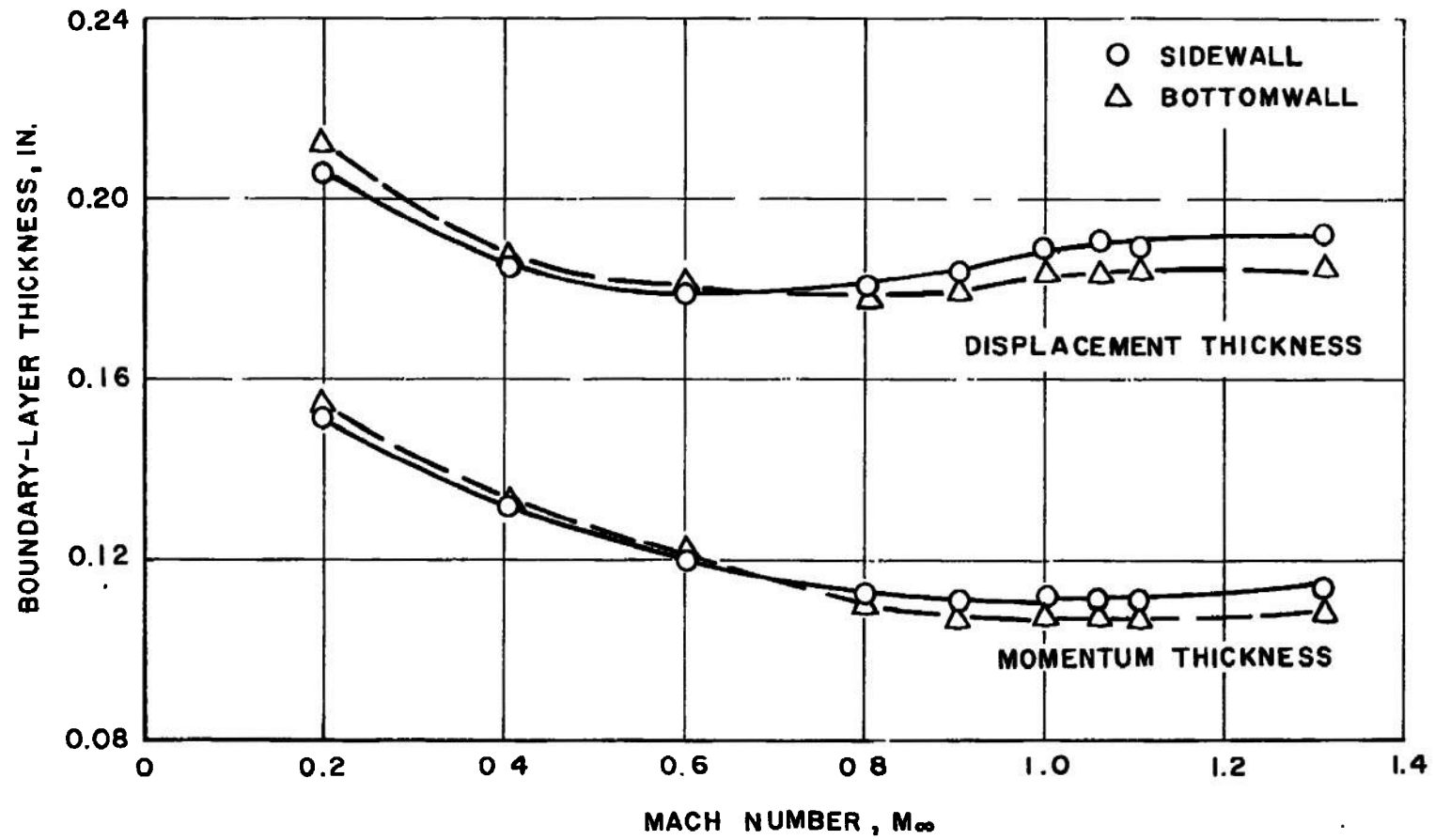


Fig. 15 Boundary-Layer Thicknesses at Tunnel Station-12

APPENDIX II

PLENUM-STREAM MACH NUMBER CALIBRATION

It is generally accepted that the plenum pressure-to-free-stream pressure relationship is invariant with respect to model blockage. This assumption allows the setting and determination of the free-stream Mach number from measurements of the stagnation and plenum pressures.

The Tunnel 4T plenum-stream Mach number relationship was determined to be a function of Mach number, wall porosity, and wall angle. To facilitate on-line data reduction, analytic expressions of the calibration relationship were determined using a least-squares, multiple-regression surface fitting program. Three surface fits were required to adequately specify the relationship, one for each discrete wall angle of $\theta_w = -0.25, 0$, and 0.25 deg. The data and analytic surfaces are given in Fig. II-1. The surfaces are of the form:

$$M_\infty - M_c = \sum_{i,j=0}^5 a_{ij} M_c^i \tau^j$$

where the a_{ij} are listed in Table II-I. The probable error in the surface fits is ± 0.003 . However, errors as large as ± 0.01 exist for small wall porosities. In actual use each surface is applied to a range of wall angle which results in known errors as large as ± 0.01 for $\theta_w = \pm 0.5$ deg. Insufficient data were obtained at the extreme wall angles and porosities to allow improvement of these accuracies.

Tunnel operating tables were prepared by evaluating the surfaces over the full range of all variables. These tables are in the form of plenum pressure ratio, p_c/p_t , as a function of M_∞ , τ , and θ_w .

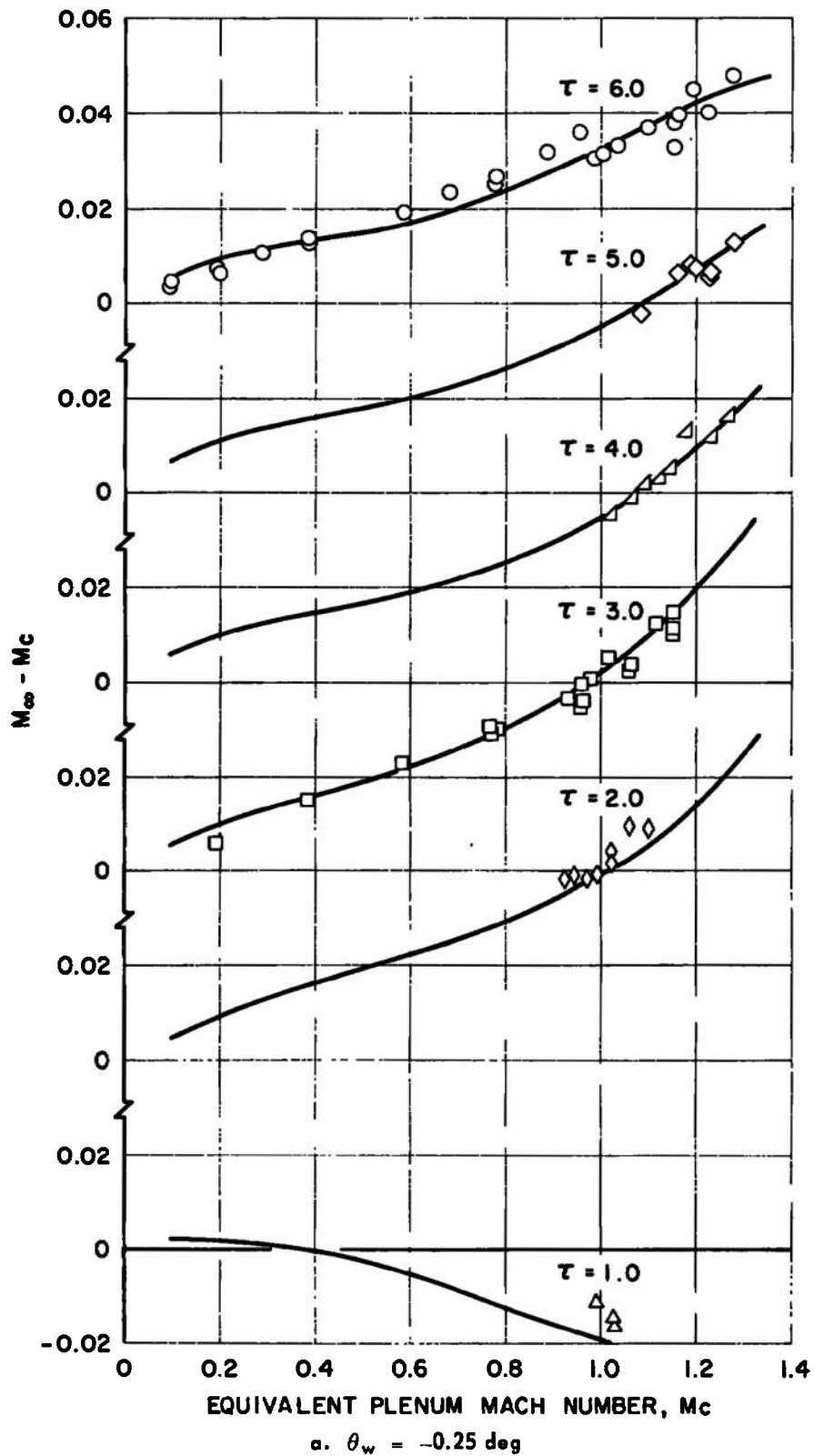
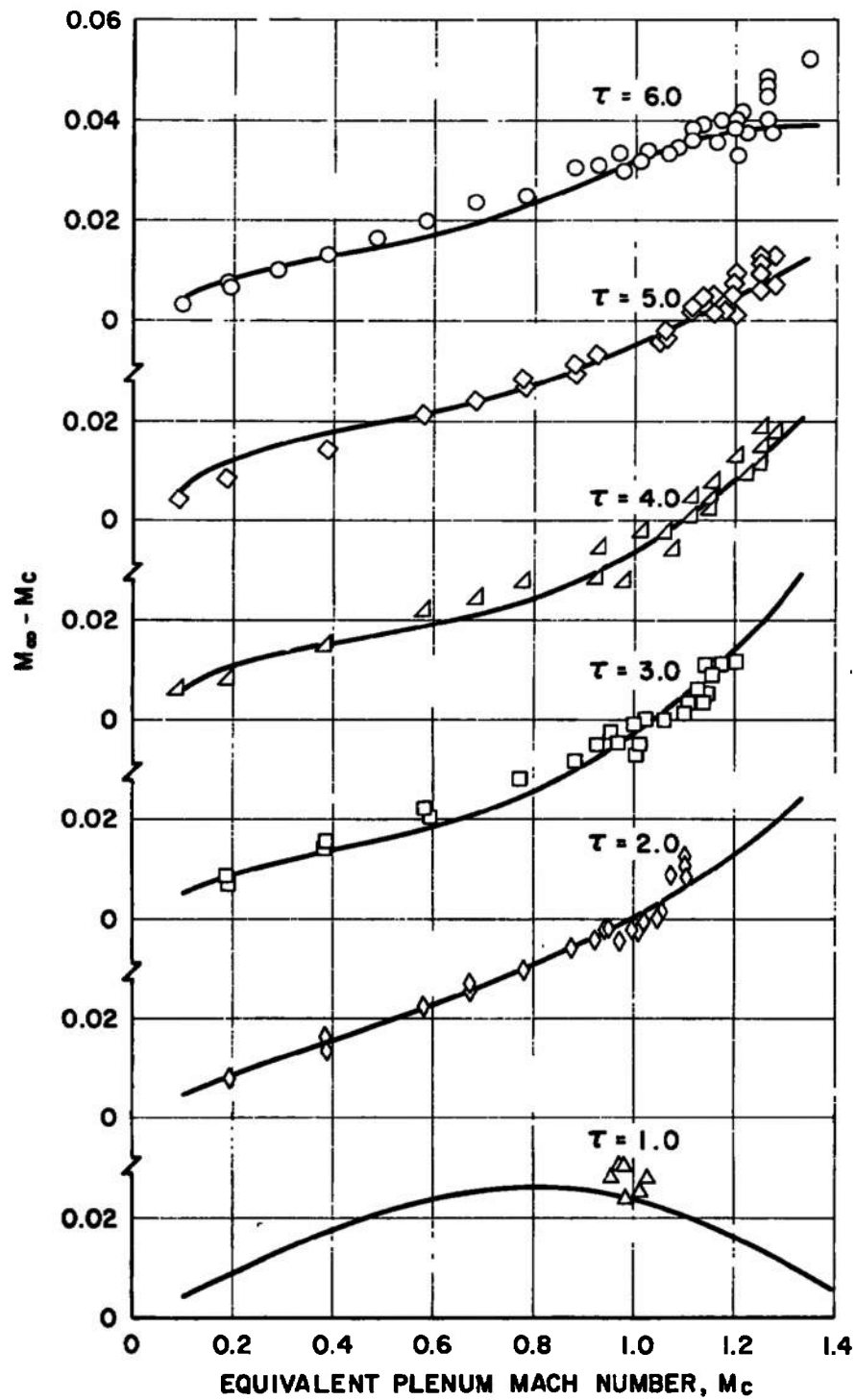
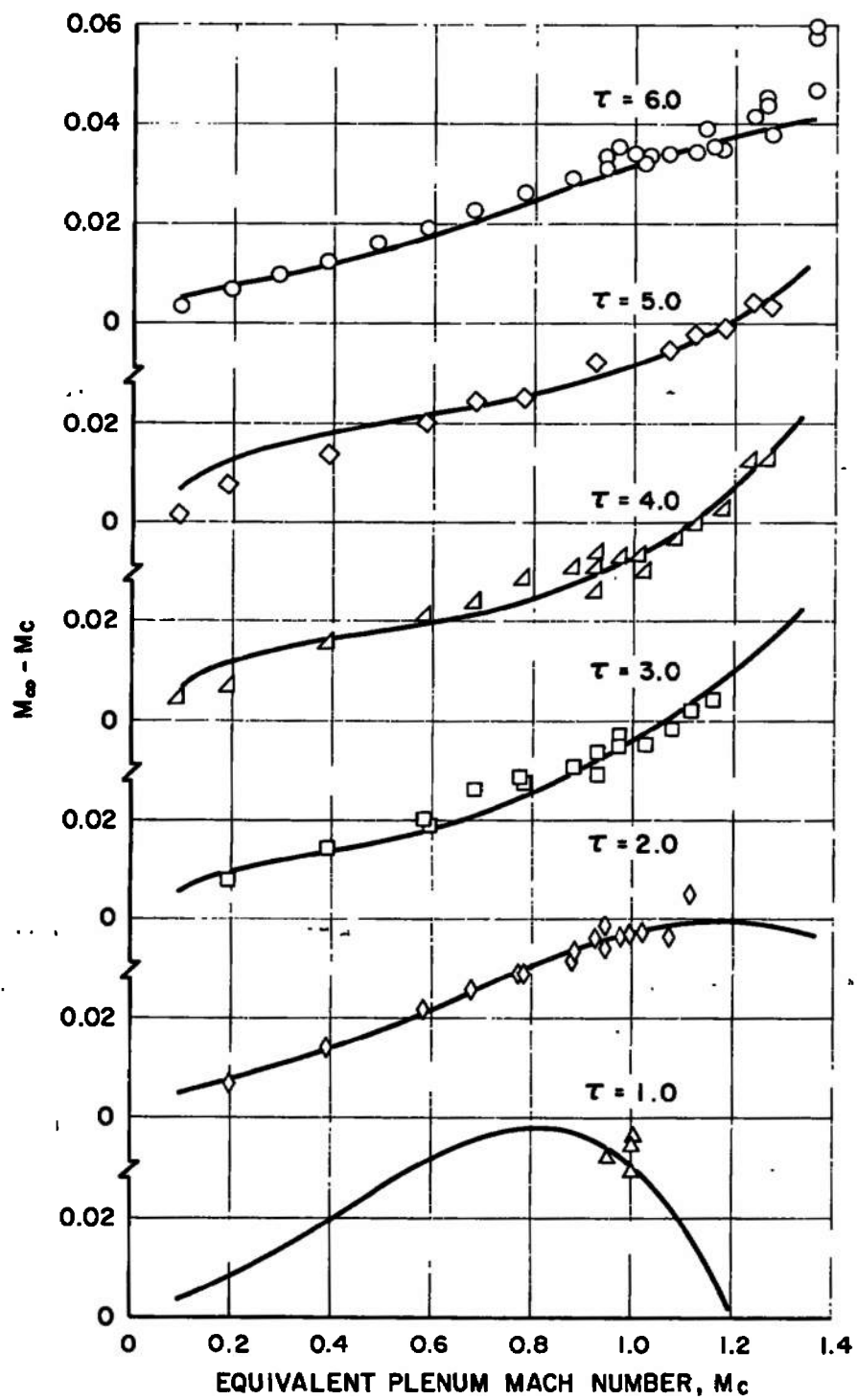


Fig. II-1 Plenum-Stream Mach Number Relationship



b. $\theta_w = 0^\circ$

Fig. II-1 Continued



c. $\theta_w = 0.25$ deg
Fig. II-1 Concluded

TABLE II-1
COEFFICIENTS OF THE PLENUM-STREAM
MACH NUMBER SURFACE FITS

i	j	a_{ij}		
		$A_w = -0.25$	$A_w = 0$	$A_w = 0.25$
0	0	8.8162-03	-1.4182-03	-3.2803-03
1	0	-1.4814-01	3.8602-02	6.4839-02
0	1	-1.1500-02	1.1847-03	4.2549-03
2	0	-5.0331-02	3.0062-02	1.0161-01
1	1	2.4648-01	1.9089-02	-5.5552-02
0	2	4.7414-03	0	0
3	0	0	-1.2475-01	0
2	1	0	0	-8.4591-02
1	2	-1.0264-01	-1.7029-02	2.9193-02
0	3	-7.8087-04	-1.2922-04	-8.8654-04
4	0	-4.7303-02	0	-2.0694-01
3	1	6.8461-02	1.0869-01	1.6803-01
2	2	-1.3508-02	-2.4771-02	-2.0411-02
1	3	1.8639-02	6.1570-03	-2.6103-03
0	4	4.3887-05	2.3079-05	2.1618-04
5	0	2.9912-02	1.0163-02	5.1541-02
4	1	-1.9618-02	-1.6077-02	1.1582-03
3	2	-2.8543-03	-8.9183-03	-2.0552-02
2	3	1.4330-03	3.2586-03	4.6276-03
1	4	-1.2142-03	-6.1716-04	-1.2886-04
0	5	0	-1.0930-06	-1.4096-05

NOTE: 8.8162-03 $\equiv$ 0.0088162

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13. ABSTRACT Tests were conducted in the AEDC Aerodynamic Wind Tunnel, Transonic (4T), to determine the tunnel calibration, Mach number distributions, and boundary-layer thicknesses. During the tests, Mach number was varied from 0.1 to 1.4, test section wall angle from -0.5 to 0.5 deg, and test section wall porosity from 0 to 10 percent. Data were obtained at various stagnation pressure levels from 500 to 2500 psf. Considerable development of the flow expansion region was required to obtain uniform supersonic Mach number distributions. Good Mach number distributions are obtainable up to and including Mach number 1.2. The distributions from Mach number 1.25 to 1.4 are suitable only for very limited testing. The results show that the tunnel calibration is a function of test section wall porosity and wall angle. Boundary-layer thicknesses on the contoured walls and parallel walls at the nozzle exit are nearly equal. This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of Arnold Engineering Development Center (AETS), Arnold Air Force Station, Tennessee 37389. This document has been approved for public release its distribution is unlimited. <i>Per A.F. Letter 20 Sept. 72 William O. Cole</i>			

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14	KEY WORDS	LINK A		LINK B		LINK C	
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	tunnel calibration						
	centerline Mach number distributions						
	boundary-layer thicknesses						
	wall porosity						
	wall angle						
	flow expansion region						
	1. Transonic wind tunnels -- Calibration						
	2 " " " " -- PWT						
	3 " " " " -- Boundary layer						
	4 " " " " -- Mach number						
	5 Boundary layer -- Thickness						
	6 Mach Numbers -- Des						
	7 Flow Velocity -- Distribution						
	8 Flow -- Velocity Distribution						
	17-3						