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DETERMINATION OF OPTIMUM OPERATING PARAMETERS FOR THE AEDC-PWT 4-FT TRANSONIC TUNNEL WITH VARIABLE POROSITY TEST SECTION WALLS

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ARO, Inc.

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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 65401F/06RB.

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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 optimum operating parameters which minimize tunnel interference effects. The tunnel is equipped with inclined hole, variable porosity, test section walls. Pressure distributions on a 20-deg cone-cylinder model having a blockage ratio of 1 percent were used to select optimum test section wall porosity, wall angle, and tunnel pressure ratio through the Mach number range from 0.1 to 1.3. Practically interference-free results were achieved at the optimum conditions for all Mach numbers except for the range from 0.95 to 1.05 where noticeable compression waves impinged upon the model. The recommended schedule for wall porosity ranges from 1.5- to 7.0-percent open area, dependent upon Mach number.

CONTENTS

APPENDIX
Illustrations

NOMENCLATURE

C_p	Pressure coefficient, $(p - p_1)/q_1$
$C_{p_{tr}}$	Interference-free pressure coefficient
d	Model diameter, 5.416 in.
M	Nominal Mach number
M_c	Equivalent plenum Mach number
M_1	Test section Mach number as defined by tunnel calibration
M_∞	Test section Mach number as indicated by model pressures
p	Model static pressure, psfa
p_e	Diffuser exit static pressure, psfa
p_t	Tunnel stagnation pressure, psfa
p_1	Test section static pressure, psfa
q_1	Test section dynamic pressure, psf
x	Model station measured from apex, in.
θ_w	Test section wall angle, deg (positive diverged)
λ	Tunnel pressure ratio, p_t/p_e
σ	Standard deviation, see Eq. (1)
τ	Wall porosity, percent

SECTION I
INTRODUCTION

The Propulsion Wind Tunnel Facility (PWT) Aerodynamic Wind Tunnel, Transonic (4T) at the Arnold Engineering Development Center (AEDC) is equipped with a variable porosity, variable wall angle, perforated test section which allows virtual cancellation of model-induced disturbances for supersonic Mach numbers. The development of the wall configuration is described in Ref. 1.

The present tests were conducted with the objective of defining the optimum wall porosity, wall angle, and tunnel pressure ratio schedule throughout the Mach number range from 0.1 to 1.3. These optimum settings were determined by examining static pressure distributions on a 20-deg (total-angle) cone-cylinder model of 1-percent blockage. For subsonic Mach numbers the criteria for selecting the optimum porosity was that which minimized the forebody drag error, and the optimum pressure ratio criteria was a uniform pressure on the model afterbody. Wall angle variations were not considered for subsonic Mach numbers. The criterion for optimum wall porosity and wall angle determination at supersonic Mach numbers was a minimum deviation from interference-free pressure distributions.

SECTION II
APPARATUS

2.1 TUNNEL 4T

Tunnel 4T is a closed-loop, continuous flow tunnel with a Mach number range from 0.1 to 1.35, a stagnation pressure range from 300 to 3700 psfa, and a stagnation temperature range from 80 to 130°F. The general arrangement of Tunnel 4T is sketched in Fig. 1, Appendix.

The test section flow is generated through a two-dimensional, fixed, sonic-block nozzle with parallel sidewalls. Supersonic speeds are obtained by expansion through the upstream portion of the test section. The top and bottom test section walls may be converged or diverged 0.5 deg.

The perforated test section walls are of the variable porosity type with an available porosity range from 0- to 10-percent open area. Two plates with identical hole geometry are utilized, the airside plate being fixed and the backside or cutoff plate sliding upstream for decreasing porosity. The wall geometry and general test section arrangement are sketched in Fig. 2.

The tunnel is equipped with two model support systems: a conventional sector for sting-mounted models and a captive trajectory store separation support system. A more detailed description of the tunnel and the supporting equipment is given in Ref. 2.

2.2 CONE-CYLINDER MODEL

A 20-deg total-angle cone-cylinder model of 1-percent blockage was sting mounted at zero angle of attack; the installation is shown in Fig. 2. A photograph of the installation is presented as Fig. 3. For this test, nominally 100 static pressure orifices on the bottom ray of the model were used. Further description of the model is available in Ref. 3.

2.3 INSTRUMENTATION

The standard tunnel pressures were measured using servo-driven -mercury manometers. The model pressures were measured using 5- and 15-psid self-balancing transducers referenced to the tunnel plenum pressure.

SECTION III
PROCEDURE

3.1 TEST CONDITIONS

Data were obtained throughout the Mach number range at a nominal stagnation pressure of 2000 psfa and a stagnation temperature of 100°F. For a few Mach numbers, data were obtained utilizing the full range of wall angle, ±0.5 deg, and wall porosity, from 0 to 10 percent.

In general, a desired Mach number was set and the effect of varying wall porosity, wall angle, and tunnel pressure ratio was determined. Mach numbers were not set precisely on the nominal values because of problems with the tunnel instrumentation. However, the data accuracies were unaffected since duplicate backup instrumentation was used for data reduction purposes.

3.2 DATA REDUCTION AND PRECISION

All of the model and tunnel data were processed on line utilizing the PWT data acquisition system. Real-time displays of the model pressure distributions on a cathode ray tube allowed rapid determination of the optimum values for the basic tunnel parameters: wall porosity, wall angle, and tunnel pressure ratio.

The model pressures were converted to pressure ratios, p/p_t, and computer plotted as a function of body station, x/d. These plots were traced for this presentation.

A statistical description of the magnitude of tunnel interference on the model pressures was obtained using the standard deviation, σ, defined by

$$\sigma^2 = \frac{1}{N-1} \sum \left[\left(C_p - C_{p_{tr}} \right) - \frac{1}{N} \sum \left(C_p - C_{p_{tr}} \right) \right]^2 \qquad (1)$$

where the summations extend over the entire model, and N is the number of pressure orifices. This somewhat unusual formulation was considered necessary because the interference-free data (Ref. 3) were available at only discrete Mach numbers, whereas the present data deviate from these nominal values as much as $\Delta M = 0.02$.

Based on a confidence level of 95 percent, estimates of the random errors in the data are:

ΔM_l	±0.003
$\Delta(p/p_t)$	±0.001
$\Delta\tau$	±0.1
$\Delta\theta_w$	±0.03
$\Delta\lambda$	±0.001

SECTION IV
RESULTS AND DISCUSSION

4.1 SUBSONIC INTERFERENCE EFFECTS

Representative subsonic model pressure distributions are shown in Fig. 4 along with empirical interference-free curves based upon the results of Ref. 3. With decreasing porosity, the data show progressive deviation from the interference-free curves. This deviation is more clearly seen in Fig. 5 where pressure coefficient is used instead of pressure ratio to eliminate the influence of slight variations in Mach number.

This type of tunnel interference has not been noted in any of the open literature. Extrapolation of the afterbody data to the solid wall condition (τ = 0) indicates a pressure coefficient correction of ΔC_p = -0.07. The classical solid blockage correction based upon model volume is ΔC_p = 0.04, (Ref. 4), which is the wrong direction, whereas the classical wake blockage correction based upon model drag is insignificant, ΔC_p = -0.0005, although in the desired direction.

The measured interference is fundamentally a simple change in the test section Mach number. The interference errors are plotted as a function of model station in Fig. 6 for two wall porosities. The curves drawn are the pressure coefficient errors which result from the given assumed Mach number error:

$$C_p - C_{p_{t.f}} = \frac{dC_p}{dM}\left[M_l - M_\infty\right] \quad (2)$$

where

$$\frac{dC_p}{dM} = \frac{10}{M(M^2+5)} + \frac{5M^2-10}{M(M^2+5)}C_p \quad (3)$$

The Mach number differences, $M_l - M_\infty$, are those necessary to match the measured afterbody pressure errors.

The test section Mach number in 4T is determined by calibration (Ref. 5) which relates the ratio of plenum pressure and tunnel stagnation pressure (expressed by M_c) to the average centerline Mach number. This plenum-stream calibration is a function of Mach number, wall porosity, and wall angle. The calibration data for M = 0.60 and 0.95

along with the analytic fit of the data used for data reduction are reproduced in Fig. 7. These data were obtained utilizing a centerline static pipe of 2.9-in. diameter which extended from the strut sector all the way upstream through the nozzle. Subsequent completely empty-tunnel calibrations utilizing static pressure orifices in the test section walls essentially duplicated the data shown. It is, therefore, concluded that the measured deviations in model pressures are truly model-induced interference and not related to the tunnel calibration.

The model-induced Mach number errors are also given in Fig. 7. The data at M = 0.60 represent the scatter for the entire model length whereas those for M = 0.95 are limited to the cone pressures. The data indicate that a wall porosity of τ = 8 to 9 at M = 0.60 provides zero interference. However, insufficient tunnel calibration data were obtained at these higher wall porosity settings to allow complete confidence in the measurements. For M = 0.95, it appears that interference-free conditions are obtained with τ = 6, although the effect is small for $\tau \geqslant 2$.

It is expedient to use a constant wall porosity setting for subsonic Mach numbers and, therefore, it is recommended that τ = 6 be utilized for M < 1.0. Adequate calibration data are available throughout the Mach number range at this porosity setting, and the interference effects are small.

The true measure of the detected subsonic interference effects is totally dependent on acceptance of the interference-free data of Ref. 3, including the Mach number setting accuracies in the Propulsion Wind Tunnel, Transonic (16T). These data were reexamined for the present application and were determined to be sufficiently accurate, although the precision of any single model pressure measurement was not as good as for the present data. The Mach number setting error in 16T at M = 0.6 (Ref. 6) is small, $\Delta M < 0.003$ at most, and in the same direction as 4T so that $M_1 - M_\infty$ for the present data is considered quite accurate at M = 0.6.

In conclusion, it is possible that the subsonic interference effect detected in Tunnel 4T is simply a function of the somewhat unique model geometry. As a result of the model extending practically to the rear of the test section, being mounted on a rather large sting, and in proximity to the sector boom, the model is effectively of infinite length insofar as the test section flow is influenced. The classical wall interference theories do not consider this specific geometry and one should not expect agreement of these theories with the data. However, since the interference can be significantly large, it is highly desirable that applicable theoretical and additional experimental work be done. Similar interference effects are to be expected with engine-inlet integration tests that use model geometries which are also effectively of infinite length.

4.2 MODEL PRESSURE DISTRIBUTIONS

The effects of wall porosity and wall angle on the model pressure distributions for M = 0.95 through 1.10 are presented in Figs. 8 through 14. The interference-free curves, drawn for nominal Mach numbers, are based upon theory and upon empirical results from Ref. 3.

A threefold reduction in wall interference was obtained in the vicinity of M = 1.1 with variable porosity compared to that obtained with a constant wall porosity of τ = 6.0. The recommended wall porosity schedule provides practically interference-free results above M = 1.15, the deviation being only twice that present in the free stream, and it is doubtful that any significant improvements could be made. However, the interference effects in the vicinity of M = 1.0 are not insignificant and further wall development is recommended.

SECTION V
CONCLUSIONS

The investigation of optimum operating parameters for the PWT Aerodynamic Wind Tunnel, Transonic (4T) utilizing a 1-percent blockage cone-cylinder model has resulted in the following conclusions:

1. Practically interference-free data are obtainable throughout the Mach number envelope except for the range of M = 0.95 through 1.05. Within this range, the shoulder expansion reflects from the wall and impinges on the model as a compression.

2. The recommended wall porosity settings range from 1.5 to 7.0 percent open, dependent upon Mach number, with parallel test section walls.

3. Utilization of wall angle variations as a supplement to the recommended wall porosity schedule produces data somewhat closer to interference-free values than that obtainable with parallel walls. However, wall angle variations are not recommended because of the added test complexity.

4. Significant subsonic interference effects were detected which are not presently explainable in terms of classical interference theory. Although the interference could be practically eliminated with variable porosity, further study of the effects is required.

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

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Selection of the optimum wall porosity and wall angle settings within the Mach number range from M = 0.95 to 1.10 is difficult because of conflicting requirements. The flow over the cone is subsonic and, particularly for the lower Mach numbers, wall variations directly affect the cone pressures. However, within the shoulder expansion from the model to the wall the flow is completely supersonic and a different wall boundary condition is required for interference-free conditions. The tunnel 4T wall geometry is such that optimum wave cancellation occurs with lower wall porosity settings ($\Delta\tau \approx 1$) than those required to achieve the correct cone pressures. Since forebody drag measurements are usually considered the most important in the transonic range, the recommended wall porosity settings are a compromise favoring those which provide the correct cone pressure.

Within the Mach number range from 0.95 to 1.05, the shoulder expansion reflects from the wall and impinges on the model as a compression for all wall settings. This interference indicates that the wall is effectively too open to cancel the model disturbances, and yet the interference is basically unaffected by wall changes, particularly within the Mach number range from 0.95 to 1.0. Wall angle variation as a supplement to wall porosity variation provides slight improvements in the model pressure distribution relative to the parallel wall setting above M = 1.0.

The model pressure distributions obtained at M = 1.15, 1.2, and 1.3 are shown in Figs. 15, 16, and 17, respectively. The data are practically interference free at the optimum porosity settings with zero wall angle. Wall angle variation in this Mach number range provides no significant improvement in the interference effects.

4.3 OPTIMUM OPERATING PARAMETERS

The optimum tunnel pressure ratio for a given Mach number is defined as that which minimizes the pressure gradient over the downstream portion of the model. The recommended pressure ratio settings for parallel walls are shown in Fig. 18. This curve represents a fairing of data obtained throughout the subsonic Mach number range. For supersonic Mach numbers the tunnel pressure ratio must be high enough to stabilize the shock system from the model support sector, and $\lambda = 1.4$ has proved to be adequate.

The recommended wall porosity settings at $\theta_w = 0$ are given in Fig. 19. Some improvements in the model pressure distributions are obtainable with both wall porosity and wall angle variations. However, the improvement shown in the model pressure distributions using variable wall angle is small, and it is difficult to justify the increased tunnel operating complexity. Further, as discussed in Ref. 5, the Mach number setting accuracies are poor with nonzero wall angles; therefore, it is recommended that variable wall angle not be utilized.

A quantitative description of the magnitude of wall interference in Tunnel 4T is presented in Fig. 20. The 2 σ deviation of the pressure coefficients from interference-free values is a statement that 95 percent of the data are within $\pm 2\ \sigma$ of interference-free values (provided one assumes a normal distribution). The bottom curve in Fig. 20 is the tunnel centerline nonuniformity which, of course, is included in the model data.

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APPENDIX
ILLUSTRATIONS

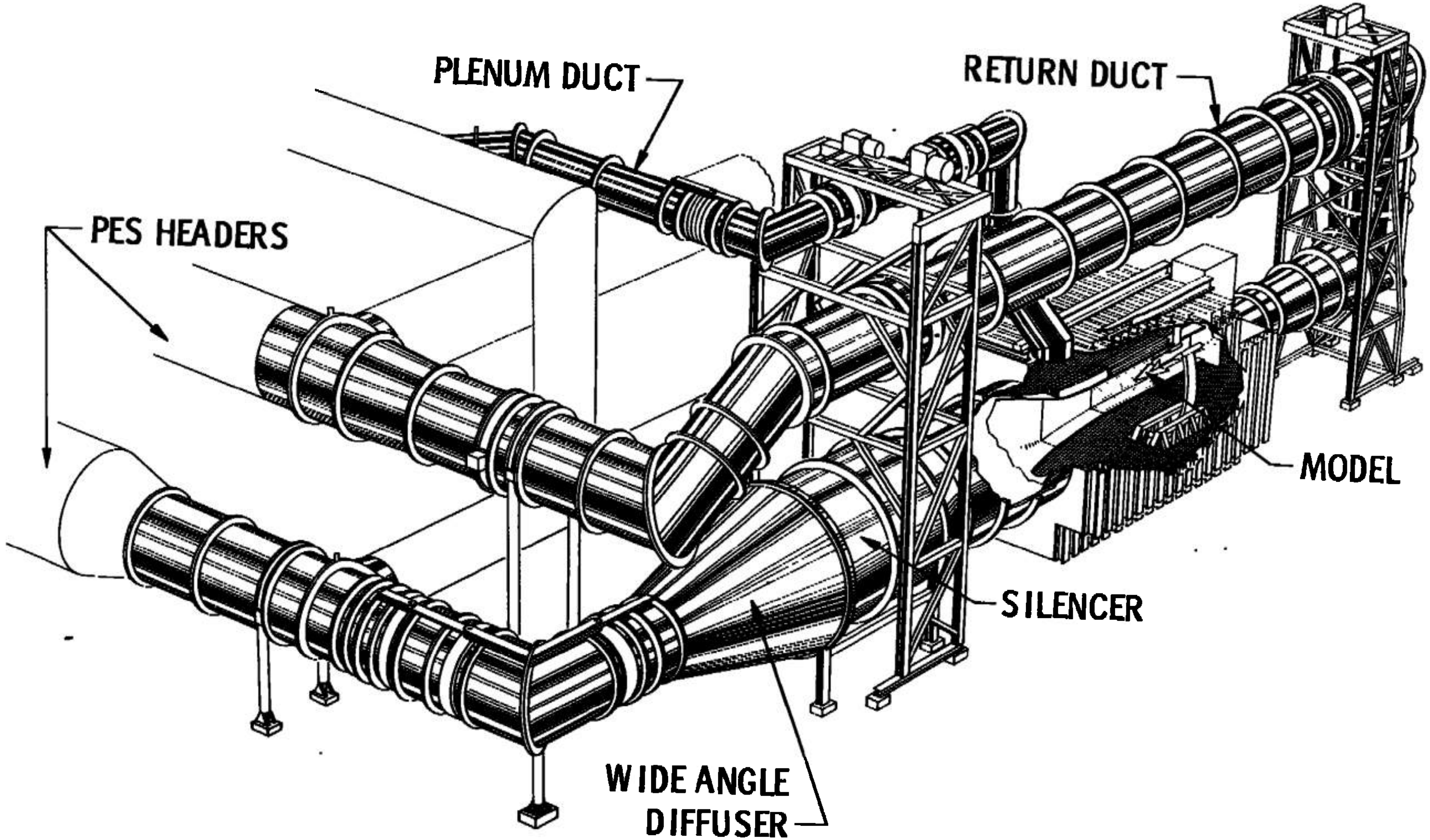


Fig. 1 Tunnel 4T General Arrangement

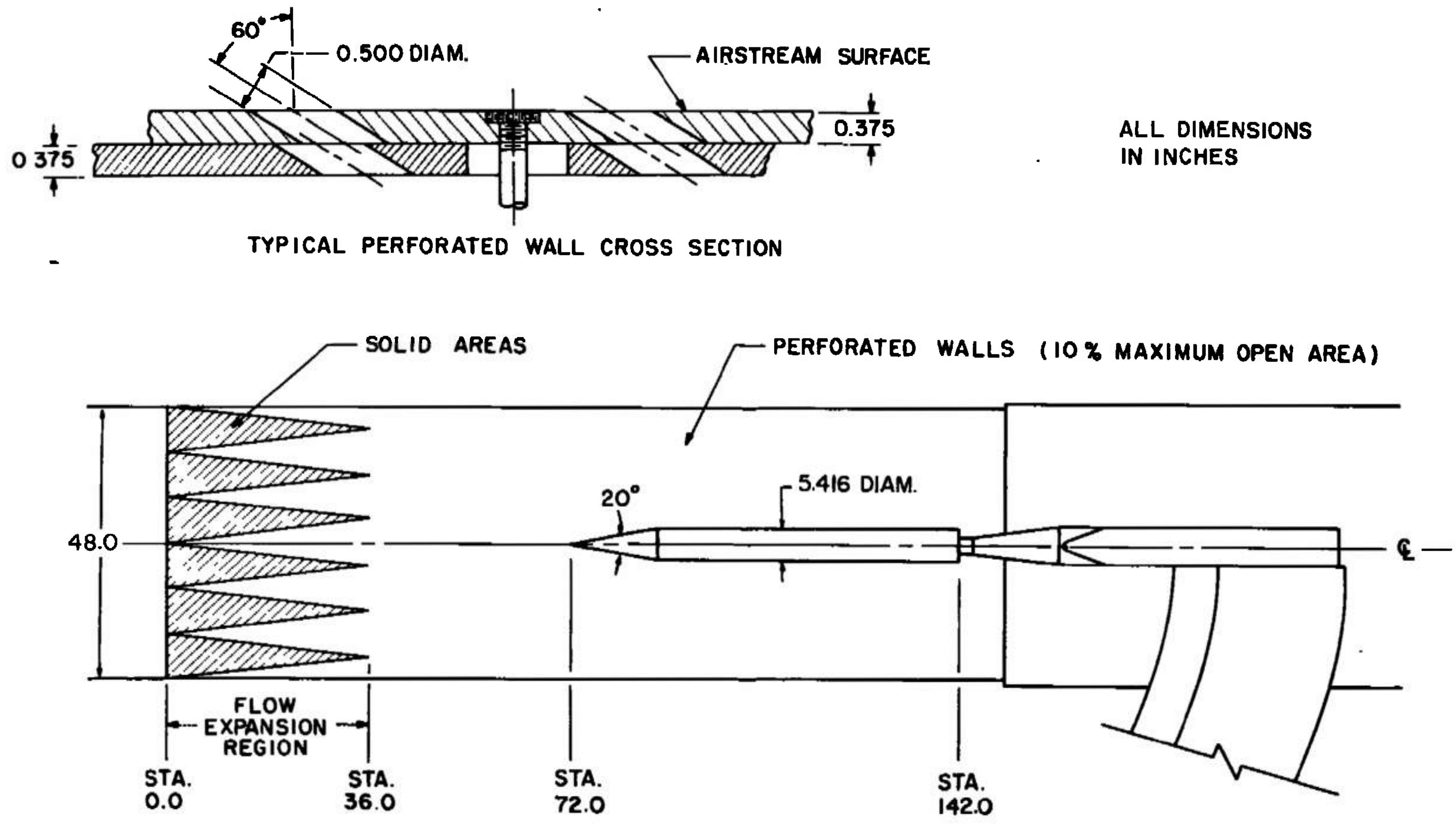


Fig. 2 Model Installation Sketch

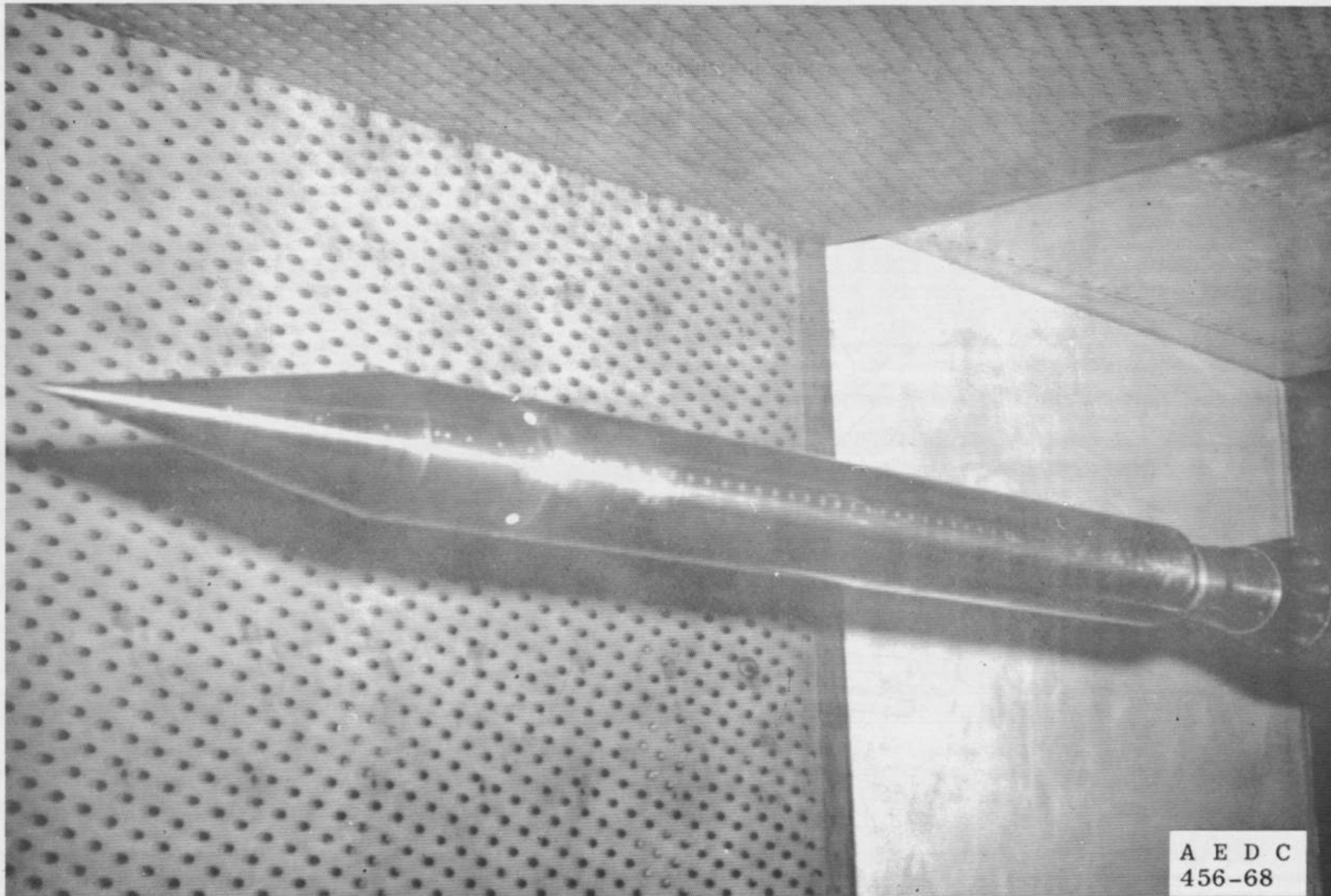


Fig. 3 Photograph of Model Installation

SYM	M_l	τ	θ_w	λ
○	0.582	8.0	0	1.072
□	0.599	6.0	0	1.058
△	0.585	4.0	0	1.055
◊	0.589	2.0	0	1.053
▽	0.585	0.5	0	1.052

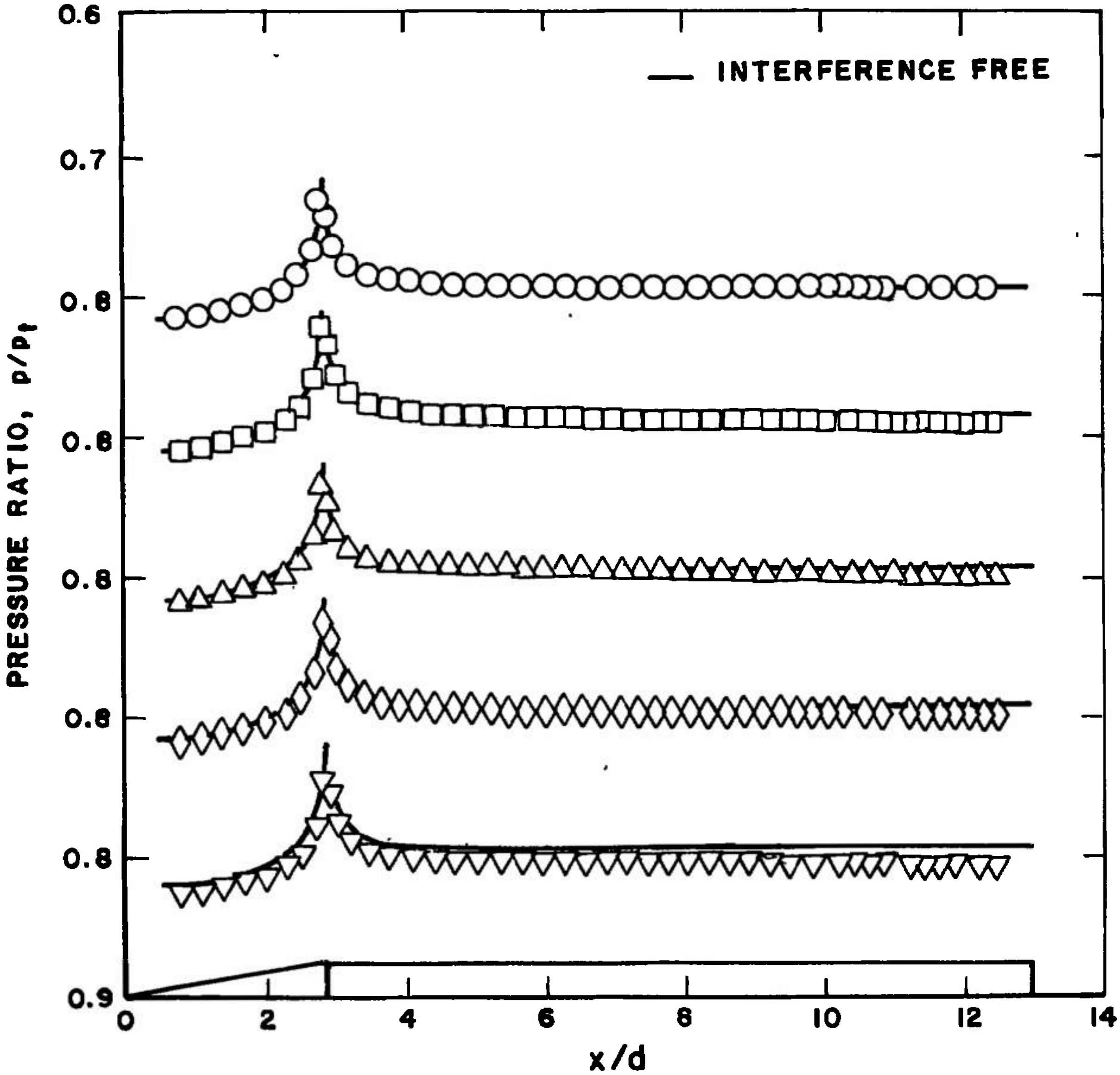


Fig. 4 Model Pressure Distributions at M = 0.60, θ_w = 0

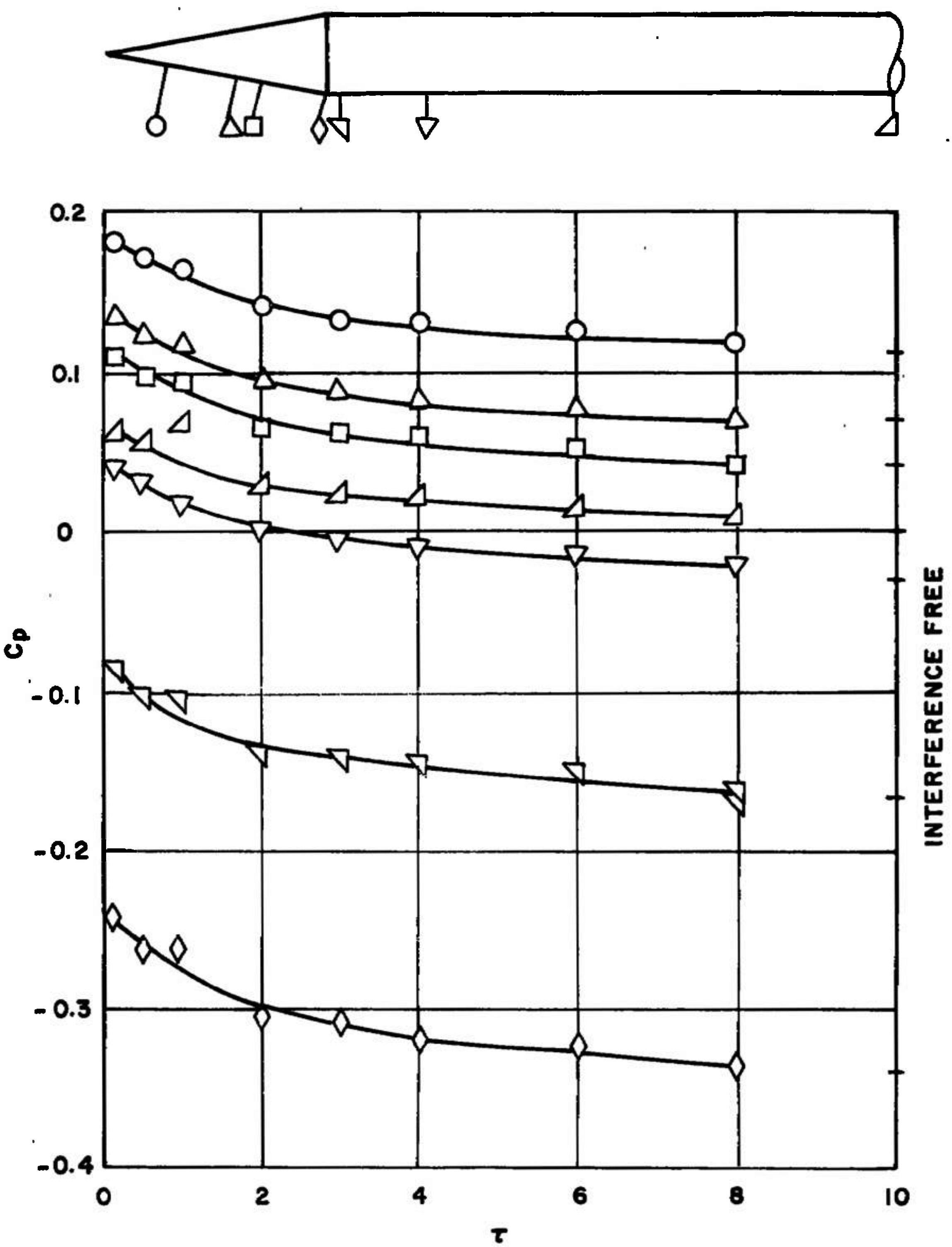


Fig. 5 Effect of Wall Porosity upon the Model Pressures at M = 0.60, θ_w = 0

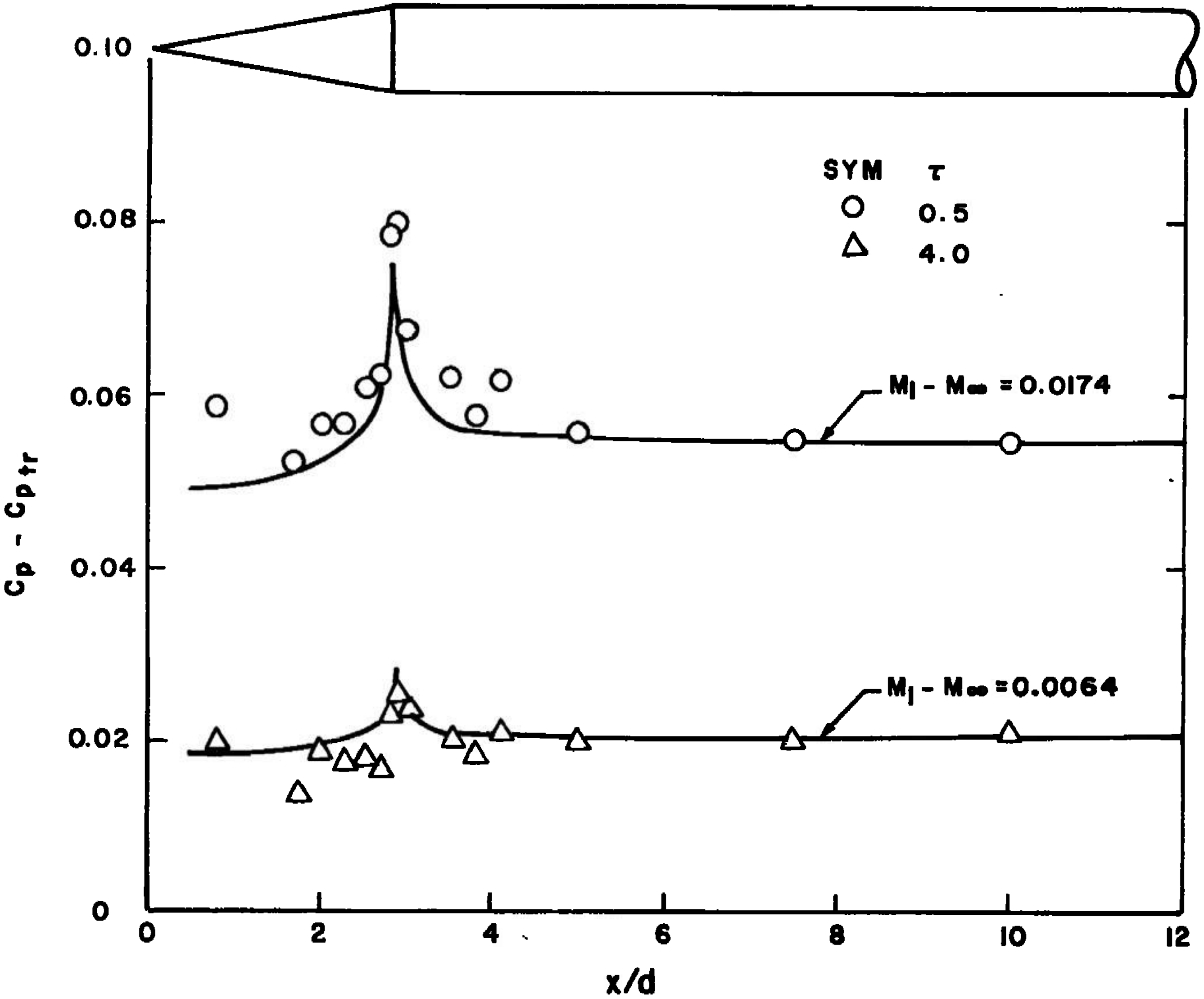


Fig. 6 Model Pressure Coefficient Errors at M = 0.60, θ_w = 0

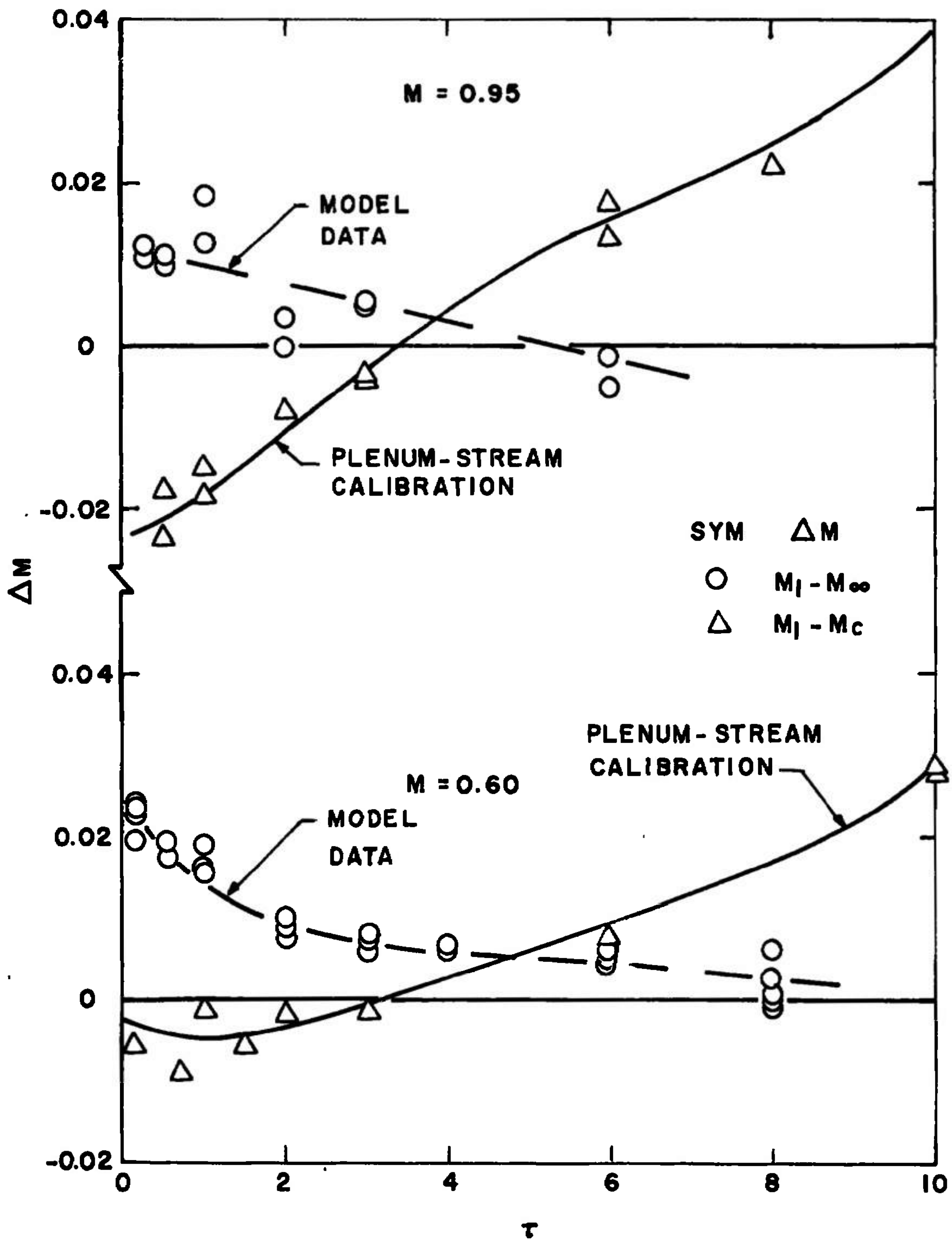


Fig. 7 Mach Number Differences at M = 0.60 and 0.95, θ_w = 0

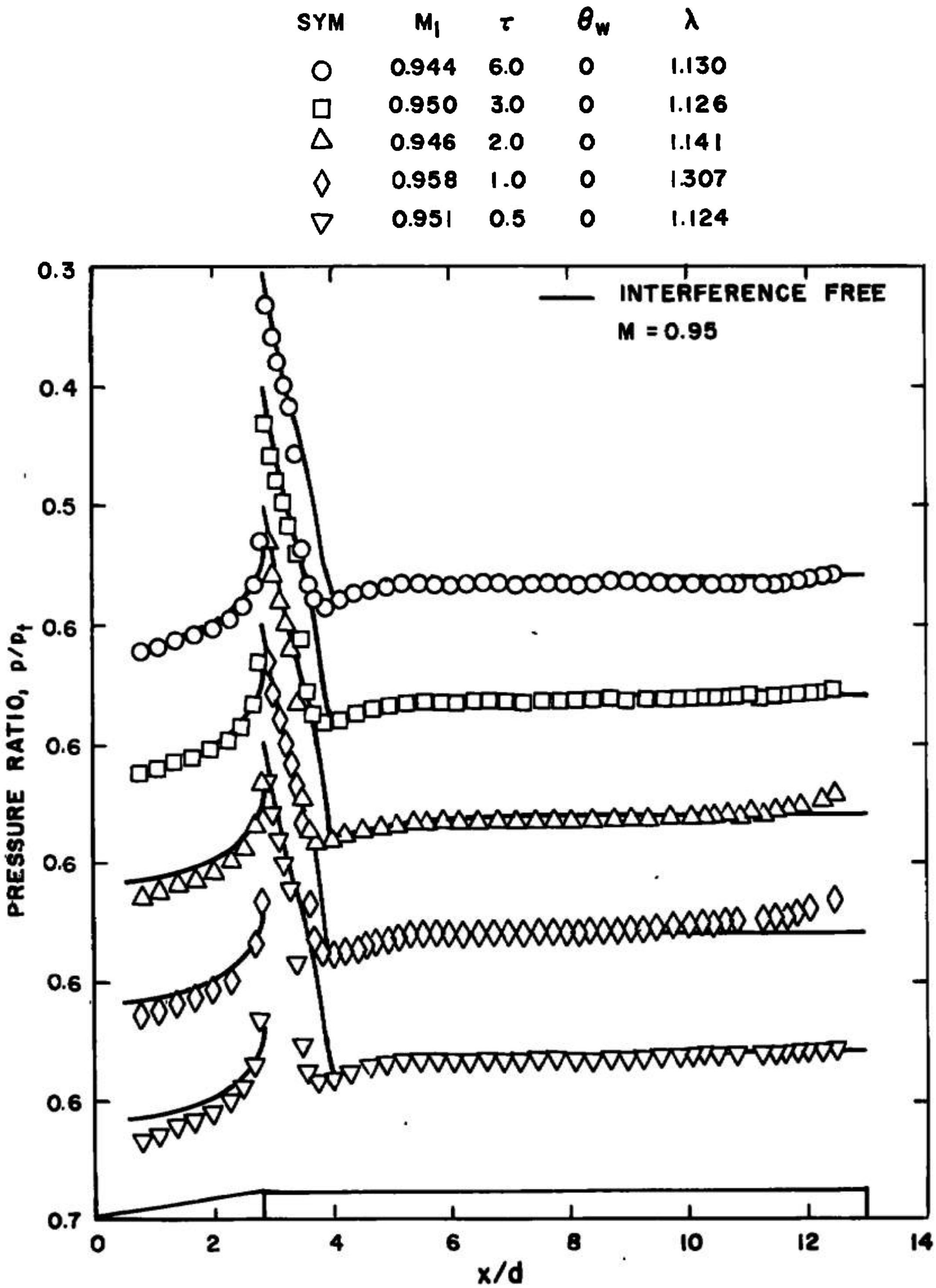


Fig. 8 Model Pressure Distributions at M = 0.95, θ_w = 0

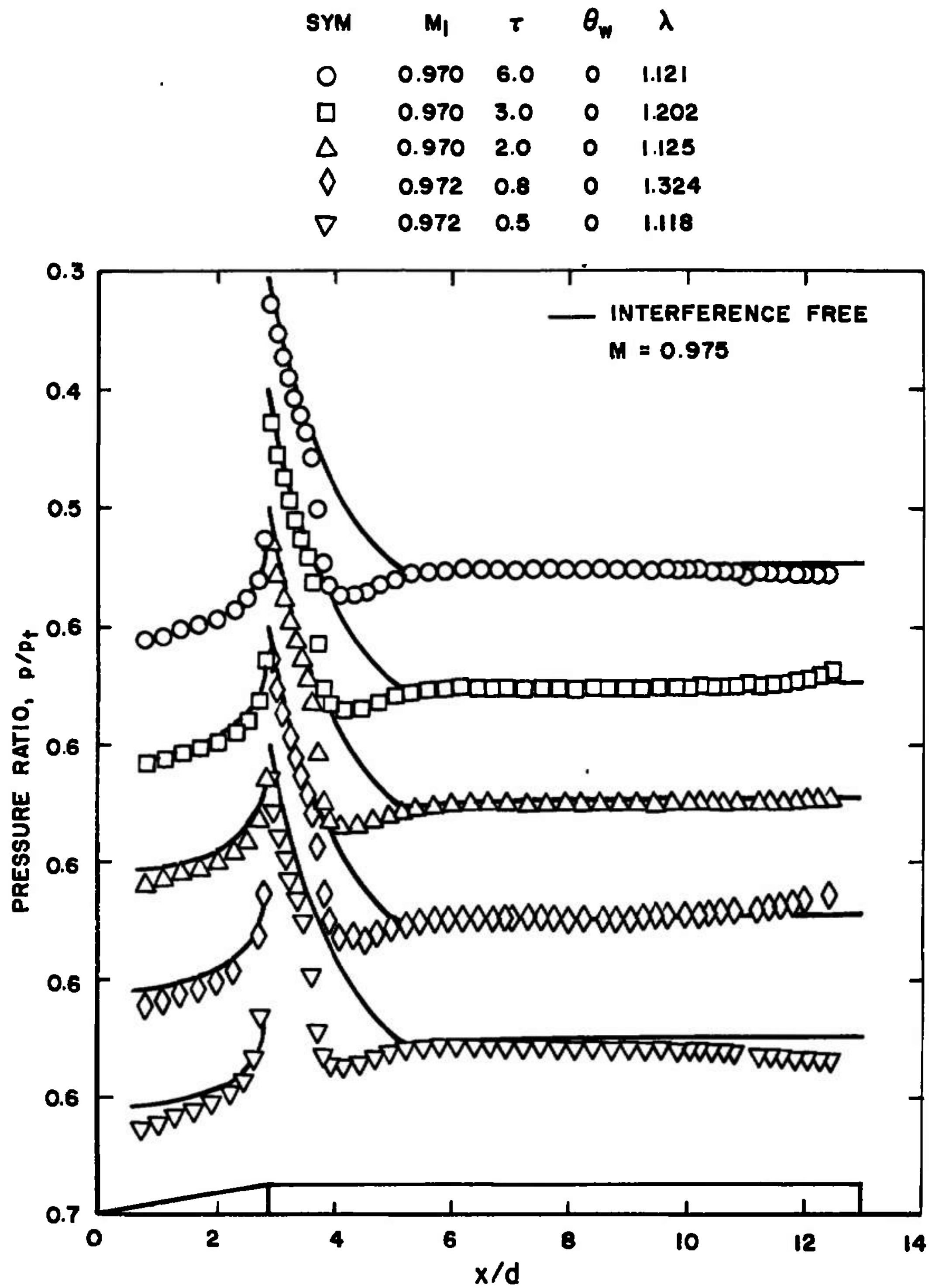
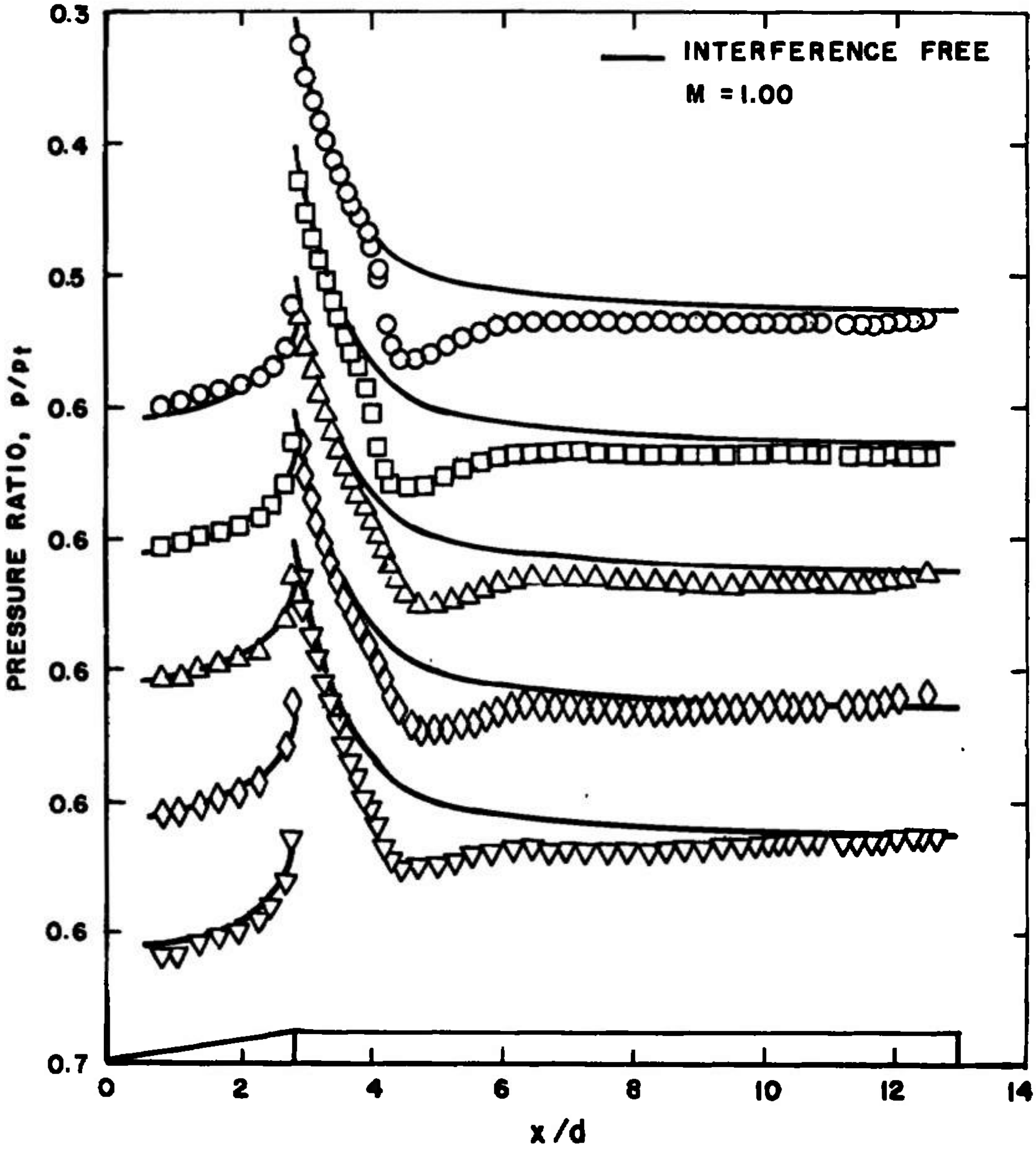


Fig. 9 Model Pressure Distributions at M = 0.975, θ_w = 0

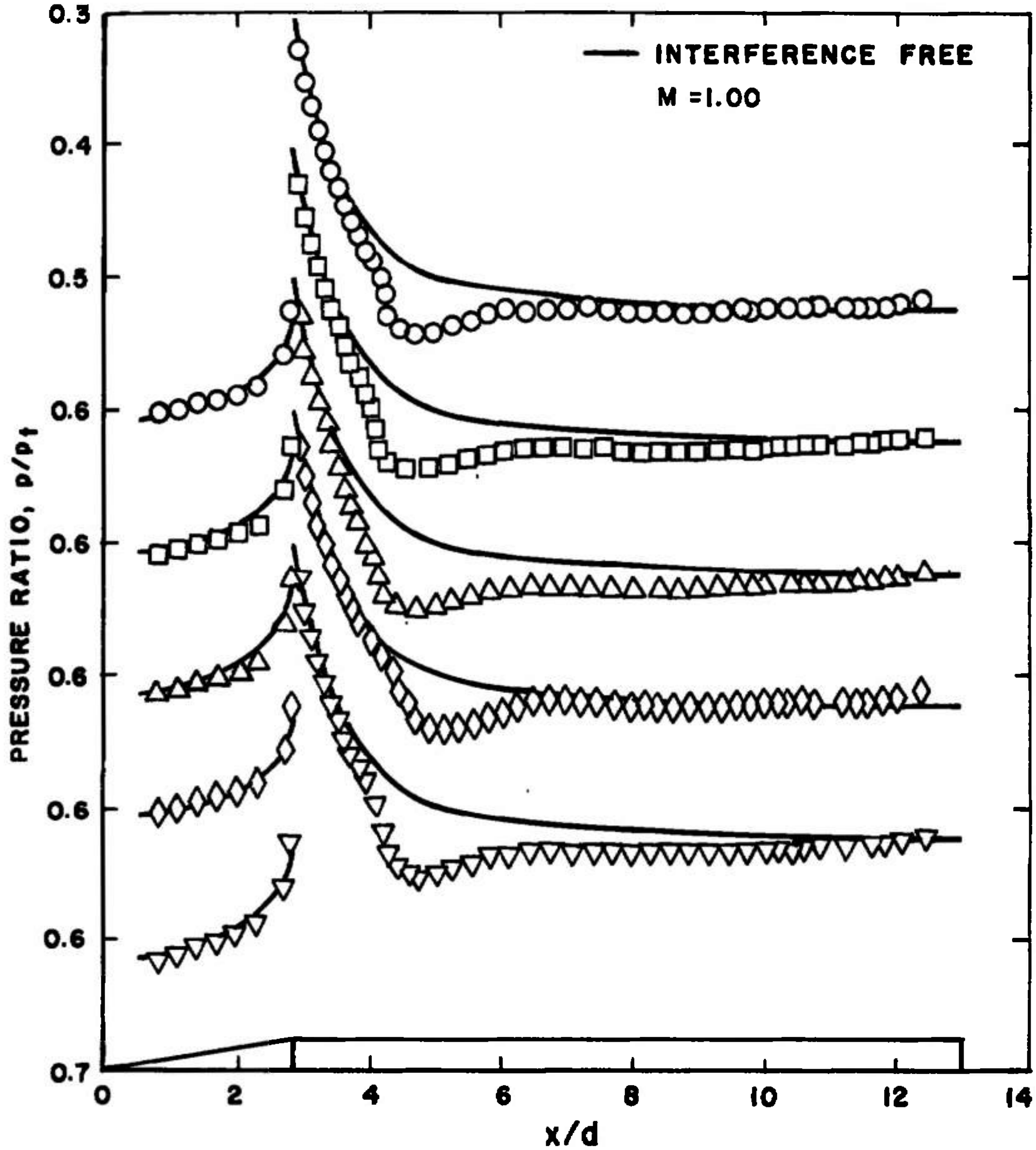
SYM	M_l	τ	θ_w	λ
○	0.999	6.0	0	1.203
□	0.997	3.0	0	1.125
△	0.996	1.5	0	1.406
◊	1.001	1.0	0	1.328
▽	1.000	0.5	0	1.134



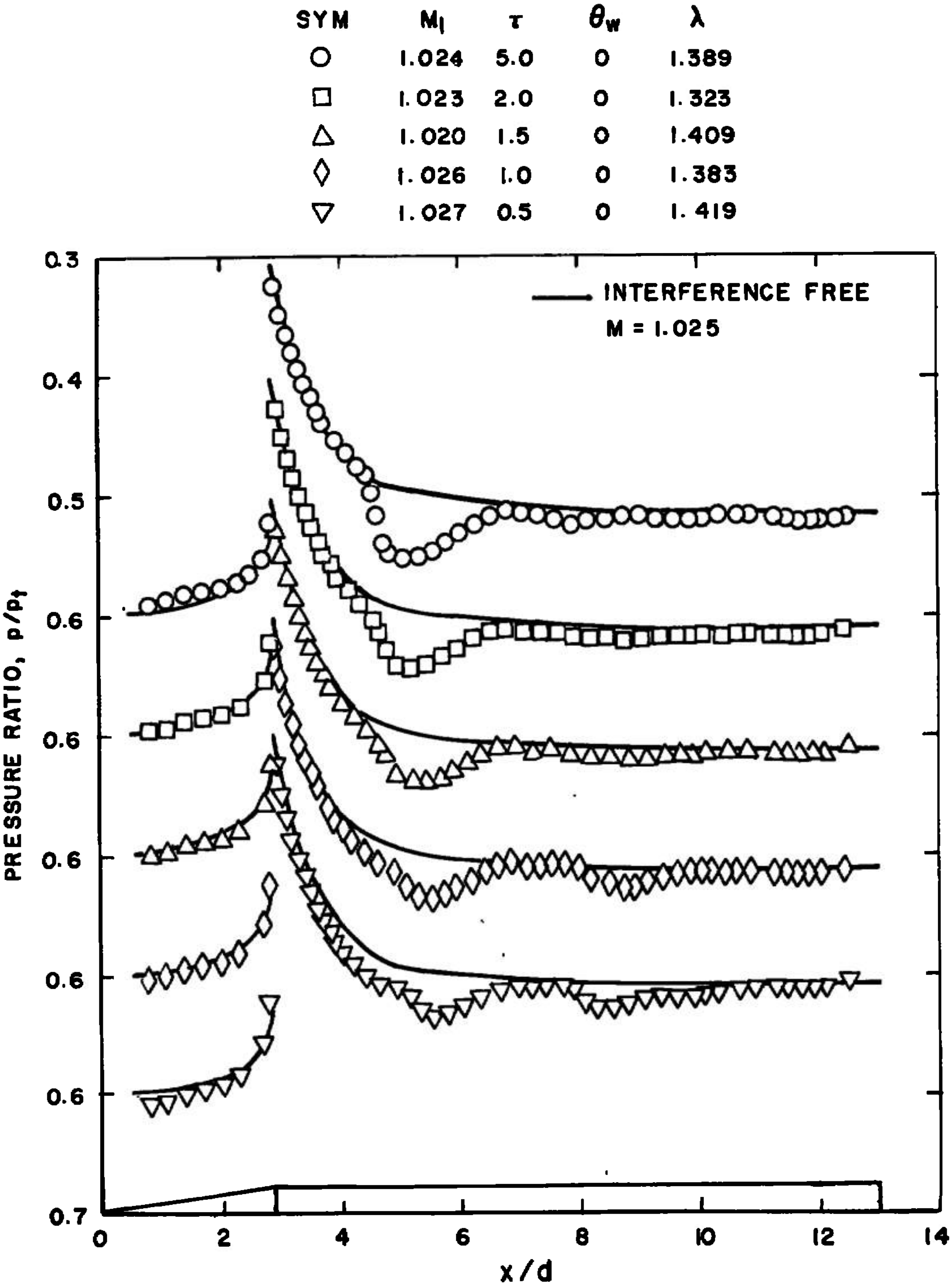
a. $\theta_w = 0$

Fig. 10 Model Pressure Distributions at M = 1.00

SYM	M_l	τ	θ_w	λ
○	1.007	2.0	-0.50	1.460
□	0.998	1.5	-0.50	1.362
△	1.000	1.0	-0.25	1.342
◇	1.007	1.0	0.25	1.193
▽	0.995	0.5	0.25	1.143



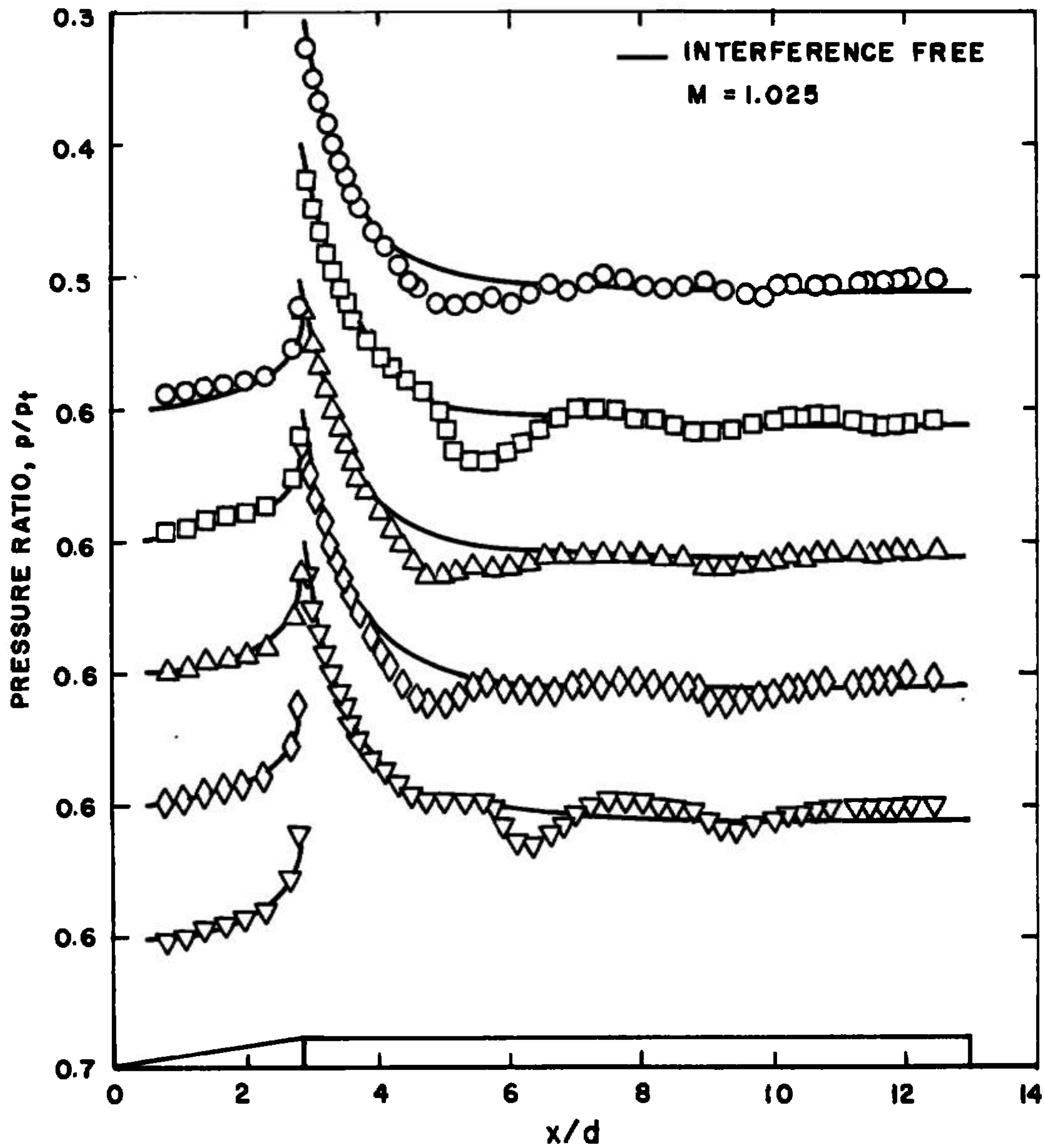
b. θ_w = variable
Fig. 10 Concluded



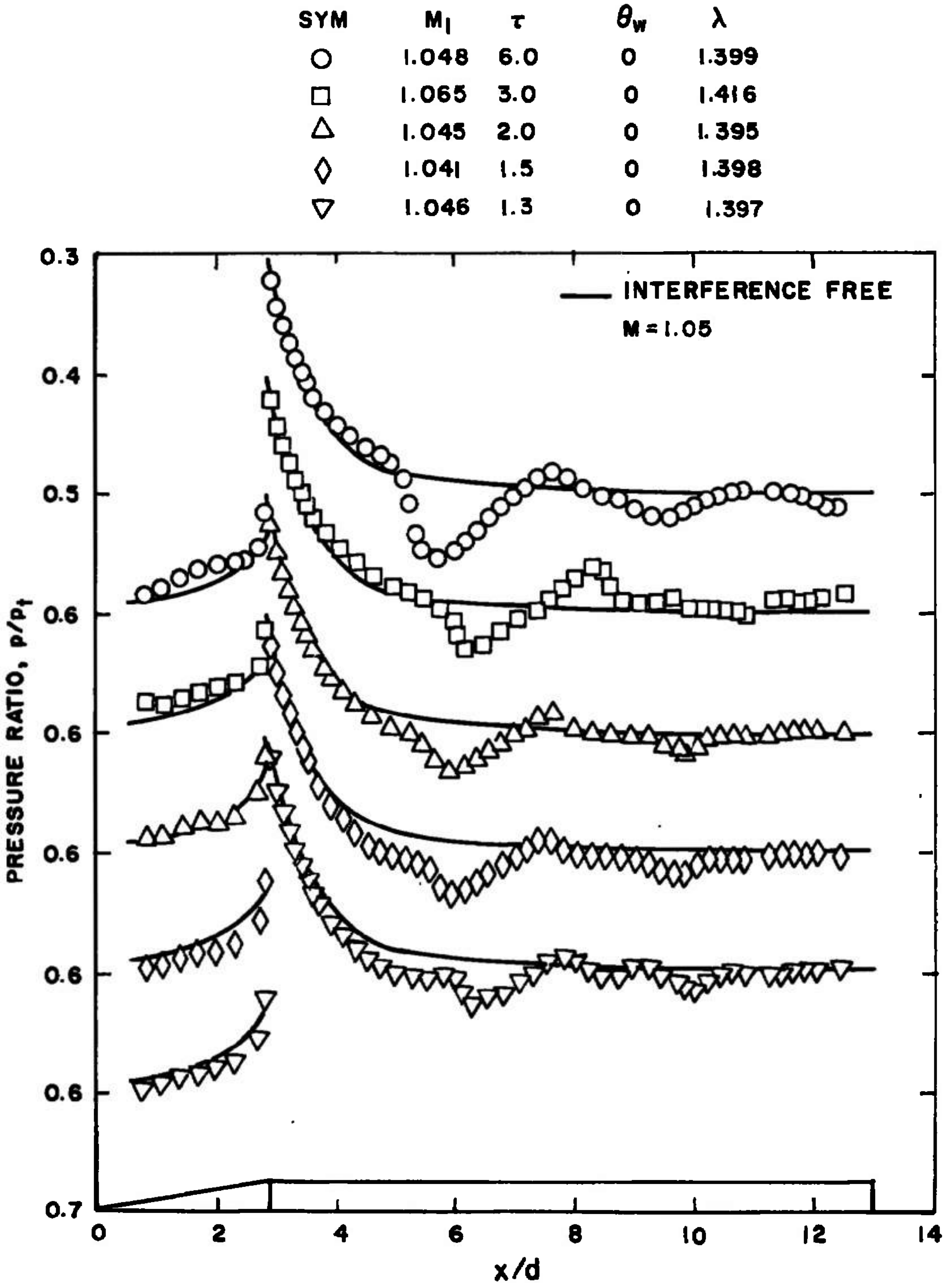
a. $\theta_w = 0$

Fig. 11 Model Pressure Distributions at M = 1.025

SYM	M_l	τ	θ_w	λ
○	1.034	2.0	-0.50	1.464
□	1.031	2.0	0.25	1.389
△	1.020	1.5	-0.50	1.465
◇	1.025	1.0	-0.50	1.369
▽	1.031	0.5	0.25	1.315

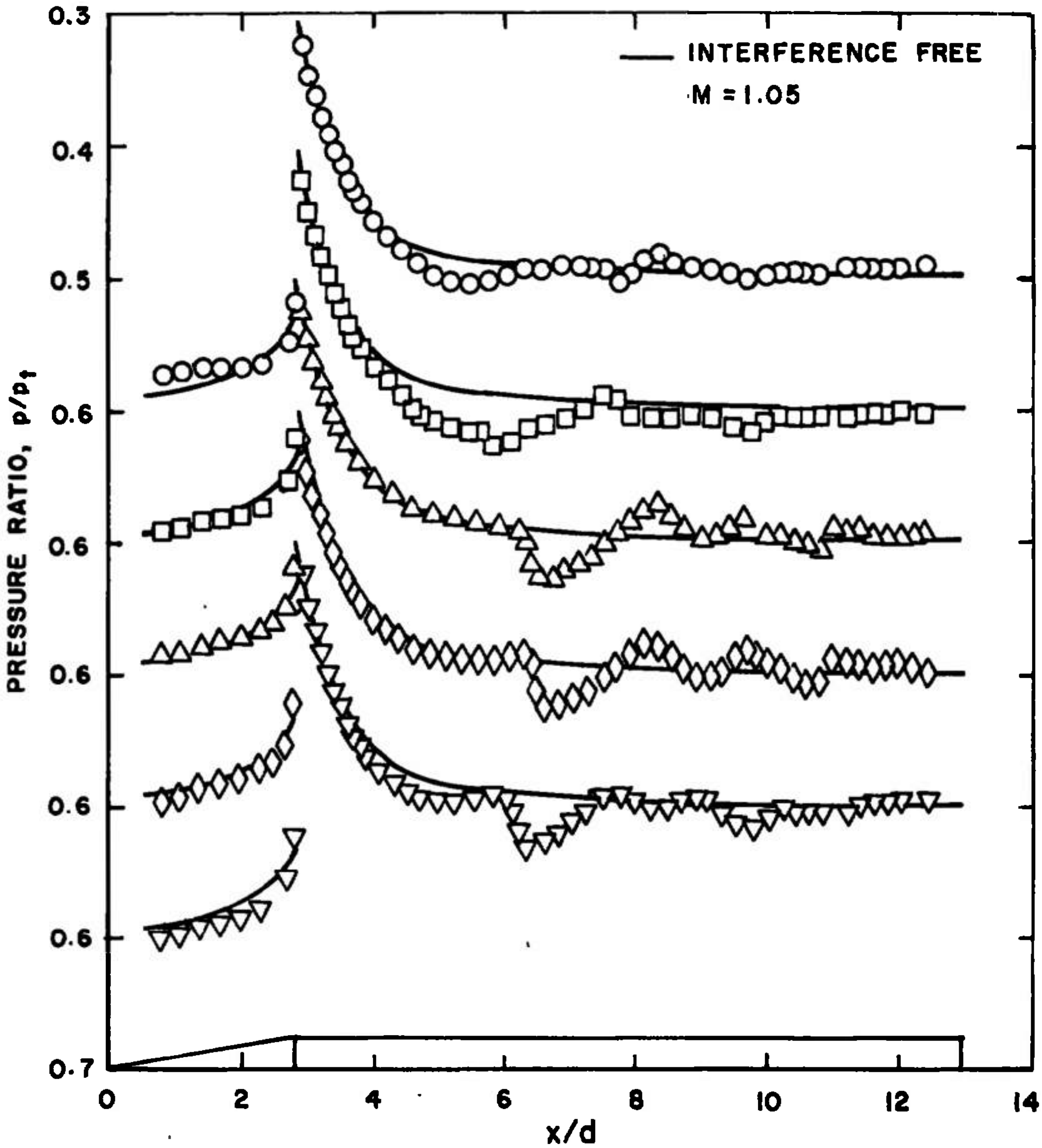


b. θ_w = variable
Fig. 11 Concluded

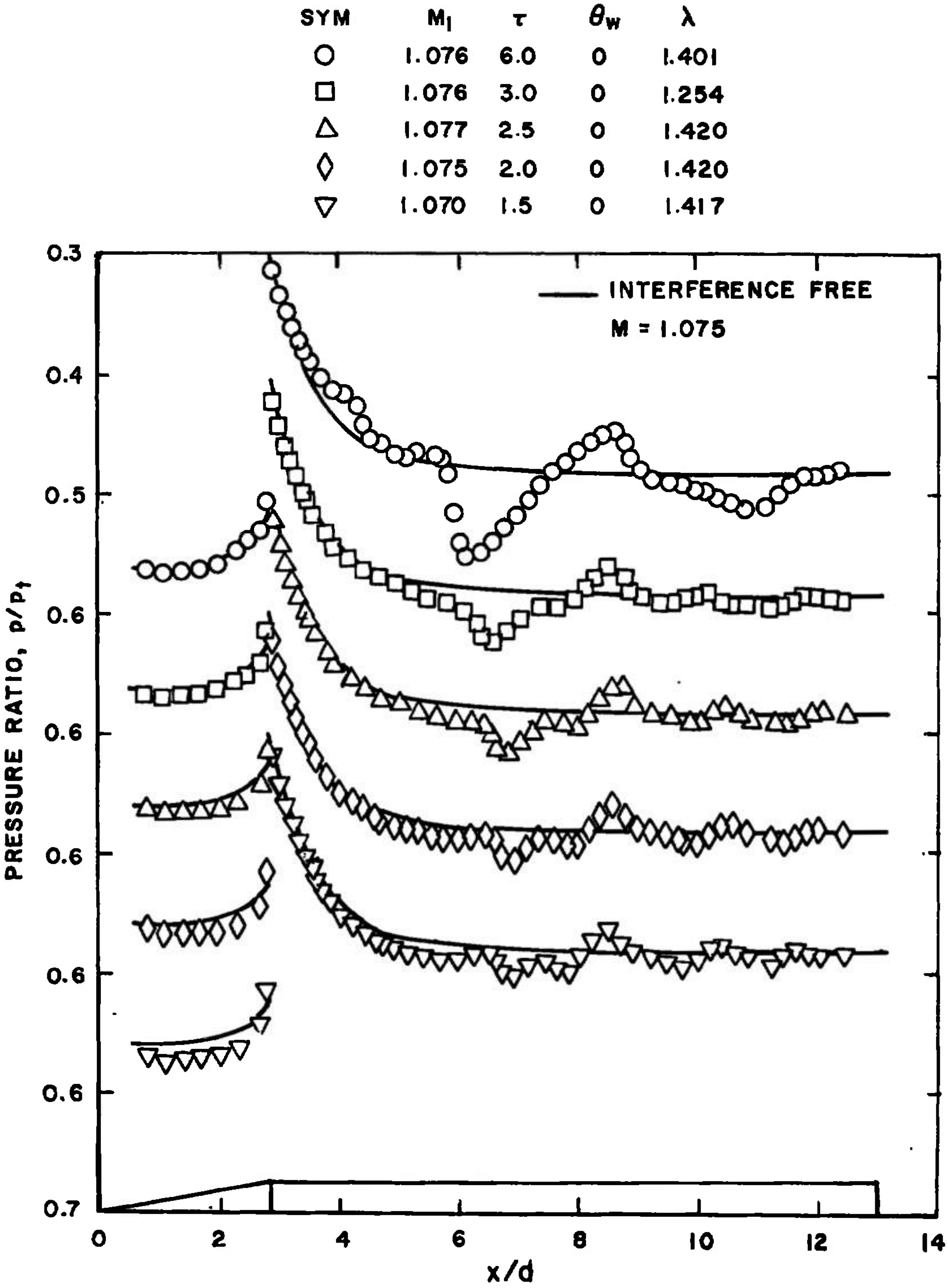


a. θ_w = 0
Fig. 12 Model Pressure Distributions at M = 1.05

SYM	M_l	τ	θ_w	λ
○	1.056	2.0	-0.50	1.478
□	1.041	2.0	-0.25	1.422
△	1.058	1.5	0.25	1.390
◊	1.054	1.0	0.25	1.387
▽	1.043	0.5	0.25	1.161



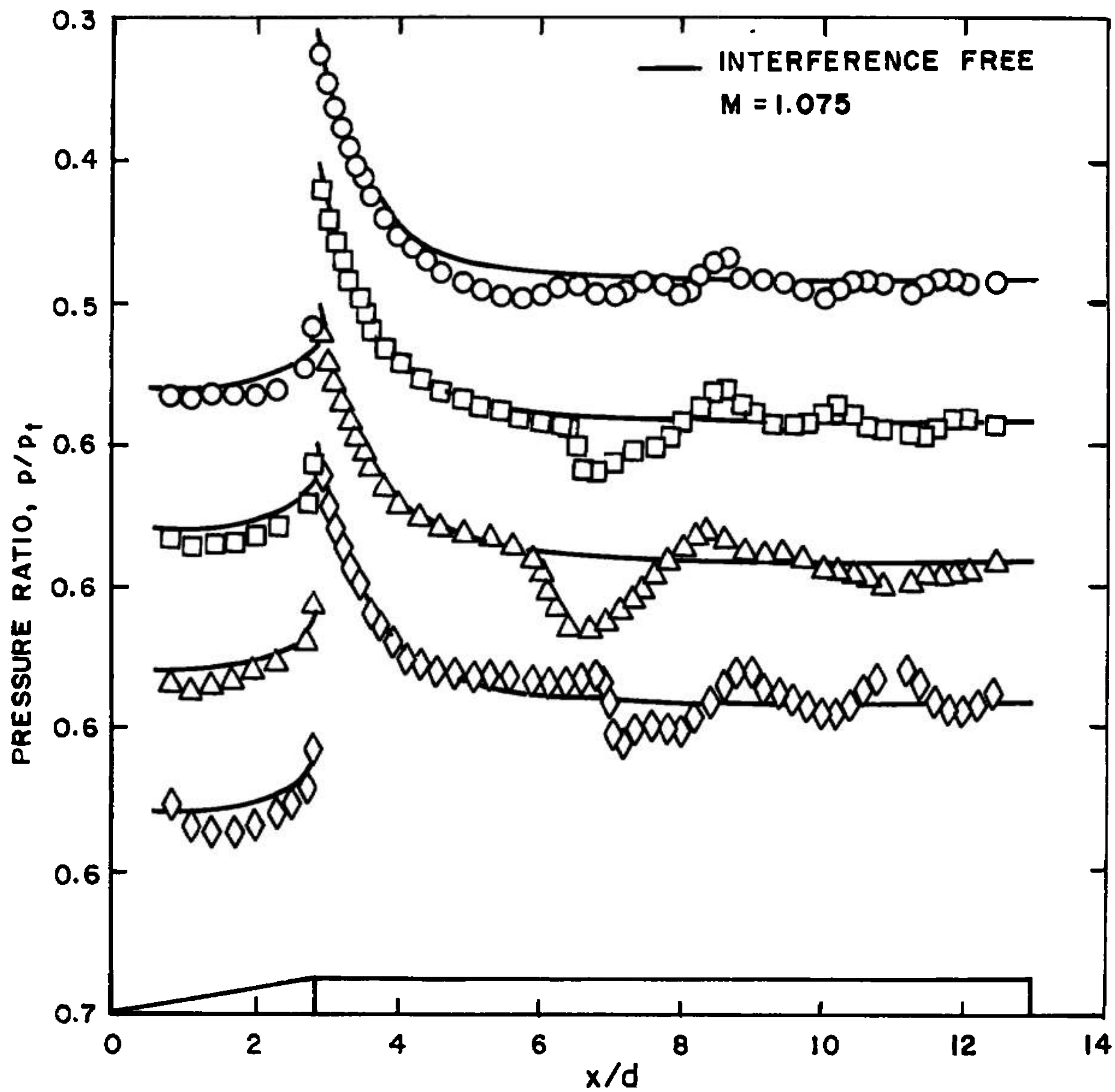
b. θ_w = variable
Fig. 12 Concluded



a. $\theta_w = 0$

Fig. 13 Model Pressure Distributions at M = 1.075

SYM	M_l	τ	θ_w	λ
○	1.071	2.0	-0.25	1.446
□	1.073	2.0	0.25	1.393
△	1.067	2.0	0.50	1.399
◇	1.083	1.0	0.50	1.380



b. θ_w = variable
Fig. 13 Concluded

SYM	M_l	τ	θ_w	λ
○	1.101	5.0	0	1.403
□	1.109	3.0	0	1.411
△	1.102	2.0	0	1.399

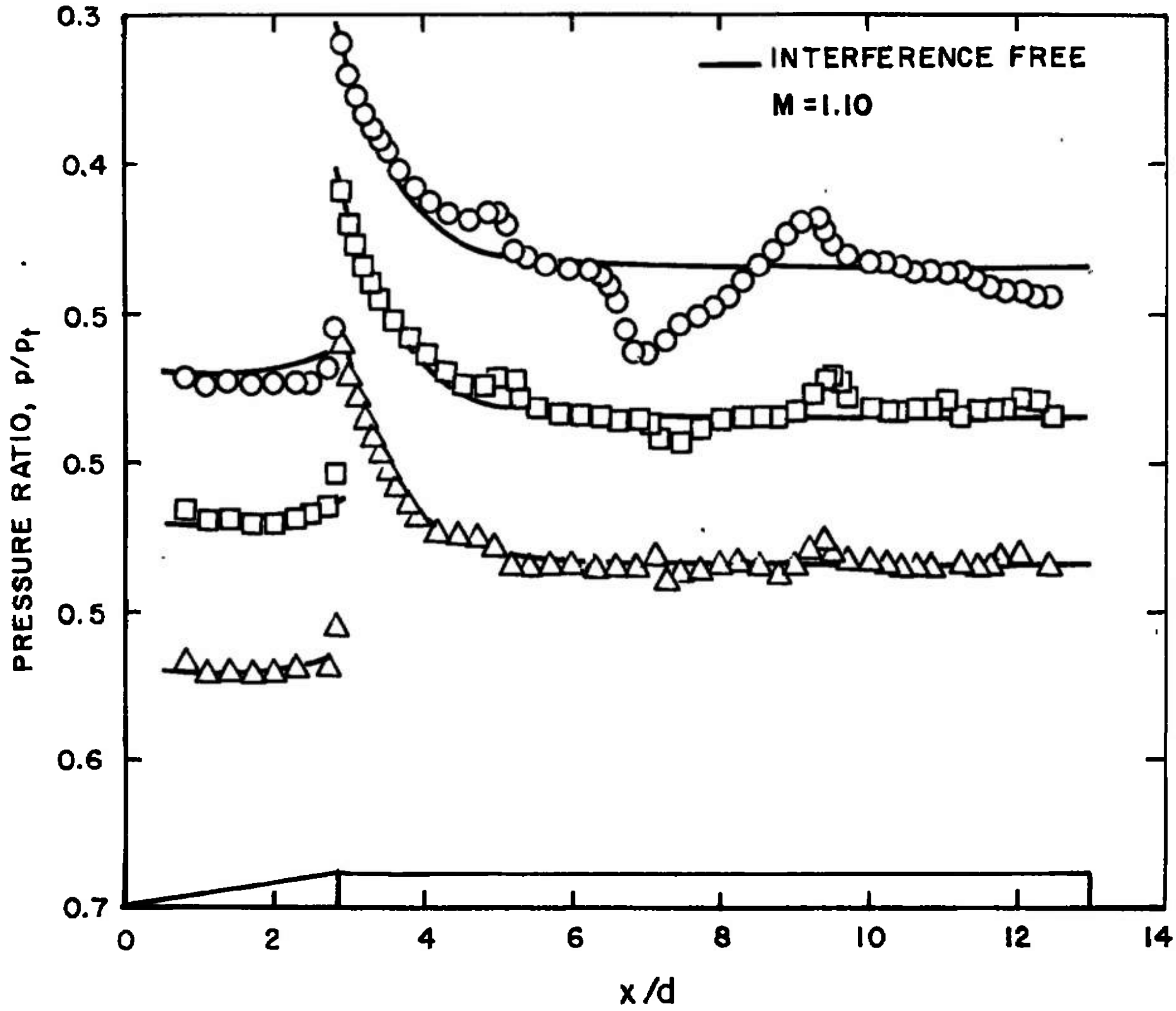
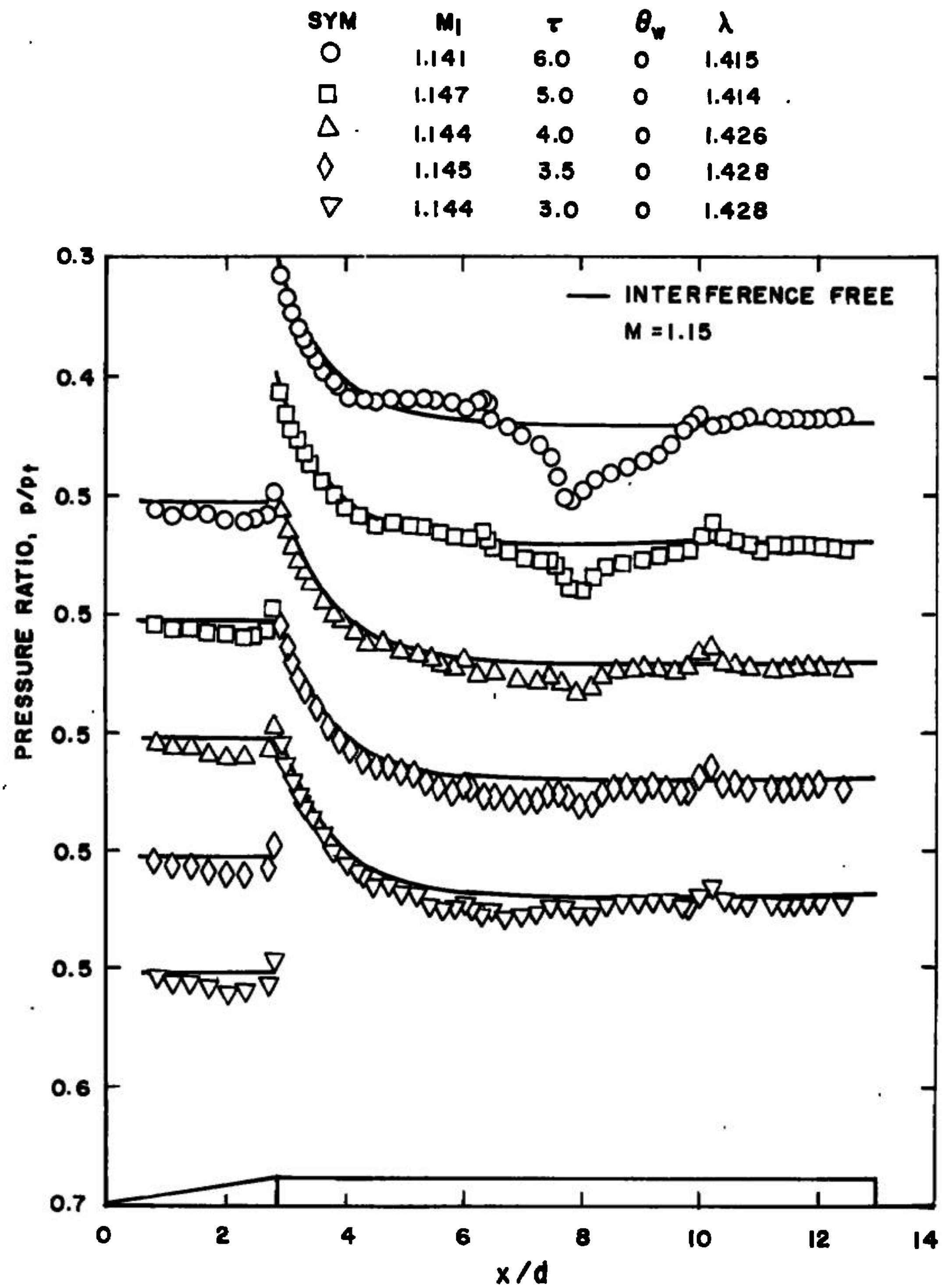
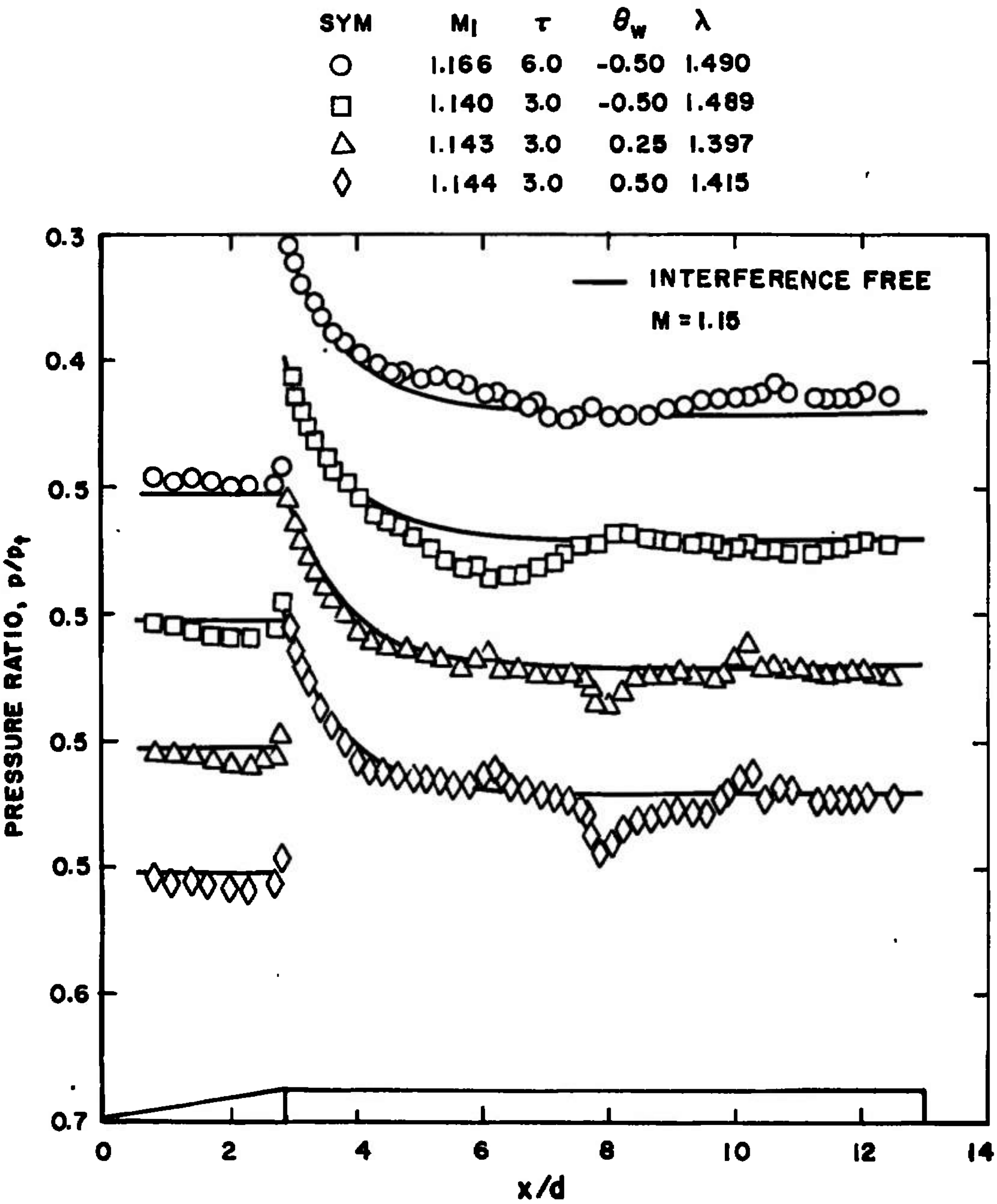


Fig. 14 Model Pressure Distributions at M = 1.10, θ_w = 0



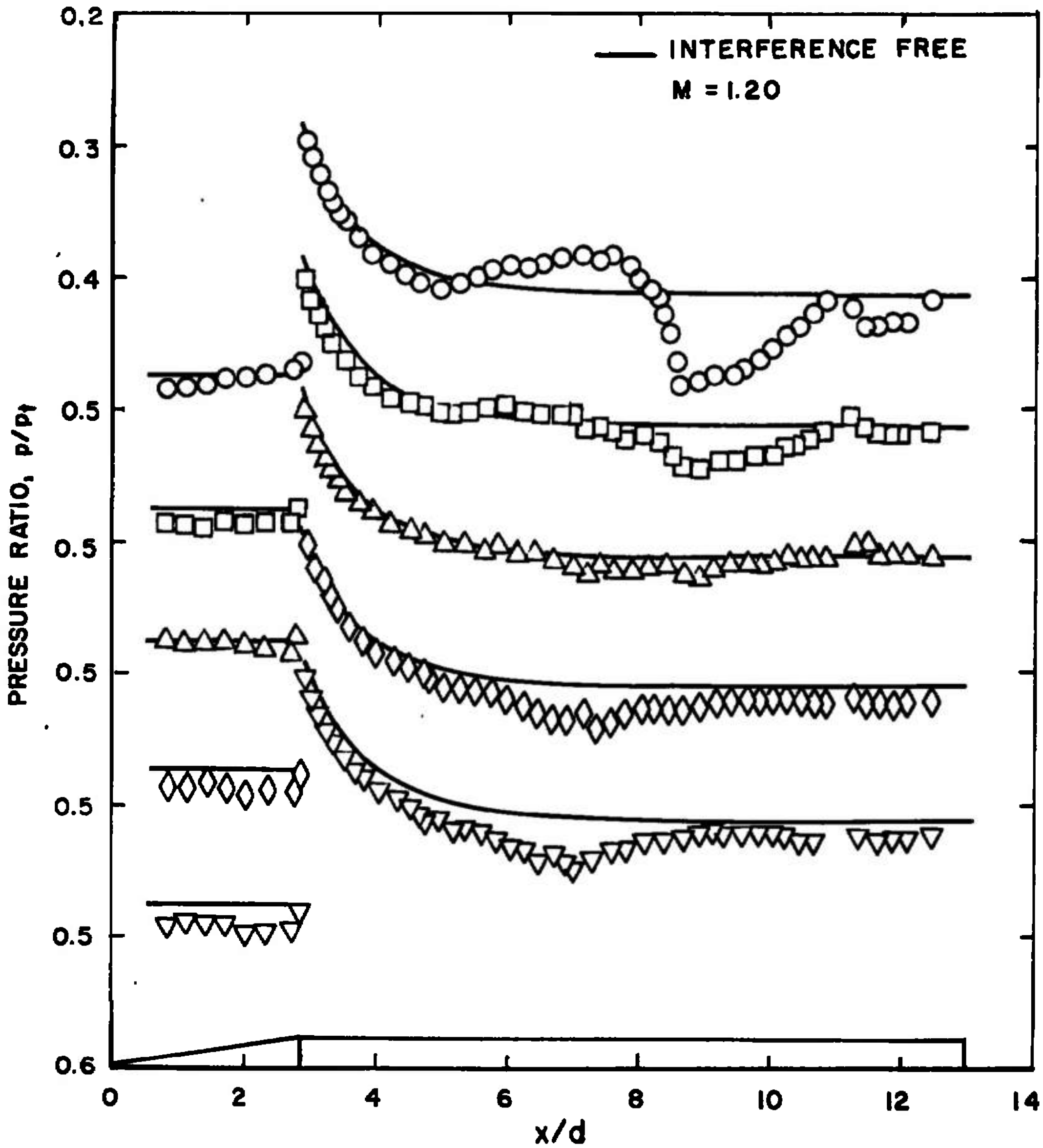
a. $\theta_w = 0$

Fig. 15 Model Pressure Distributions at M = 1.15



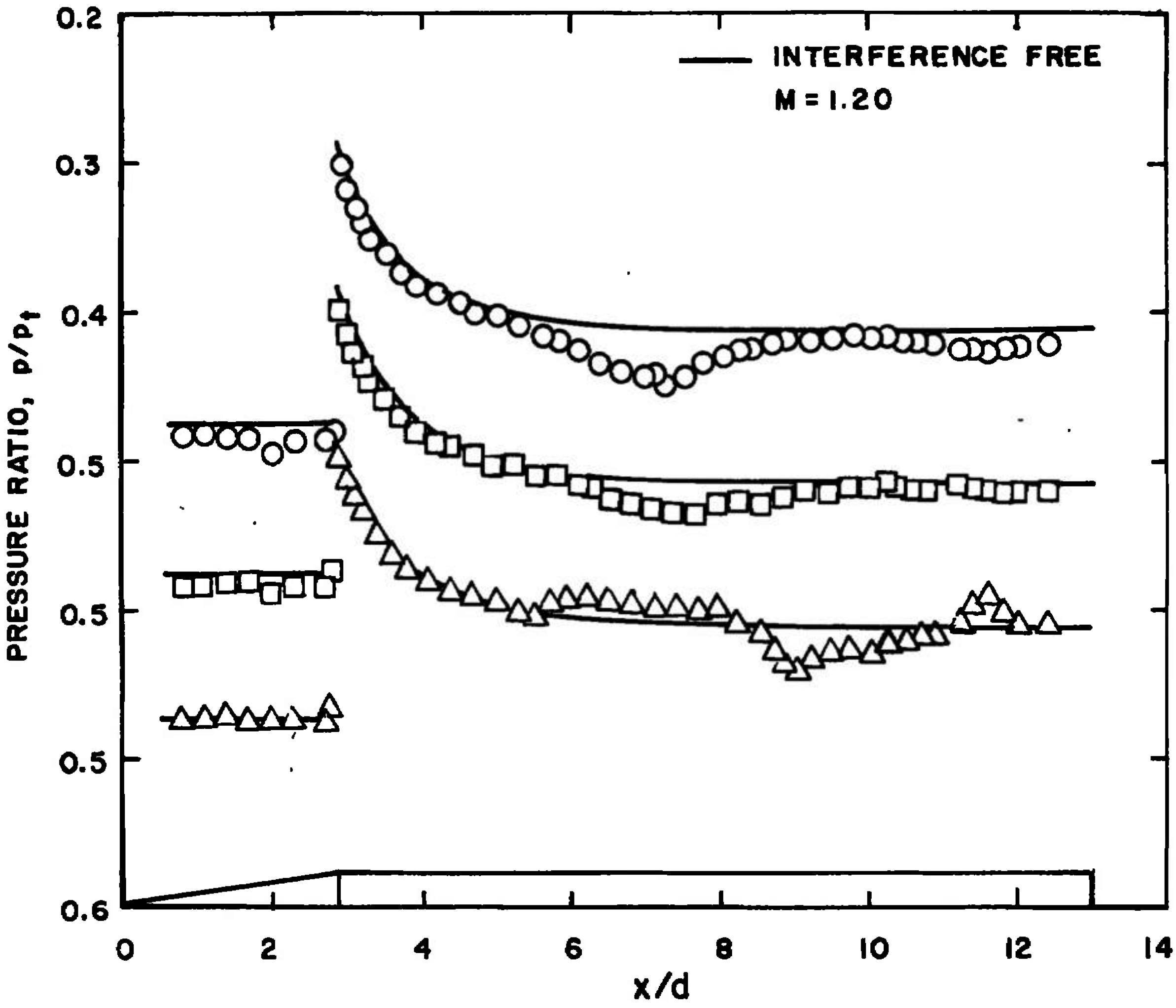
b. θ_w = variable
Fig. 15 Concluded

SYM	M_l	τ	θ_w	λ
○	1.192	8.0	0	1.397
□	1.198	6.0	0	1.390
△	1.202	5.0	0	1.418
◇	1.191	4.0	0	1.414
▽	1.175	3.0	0	1.408

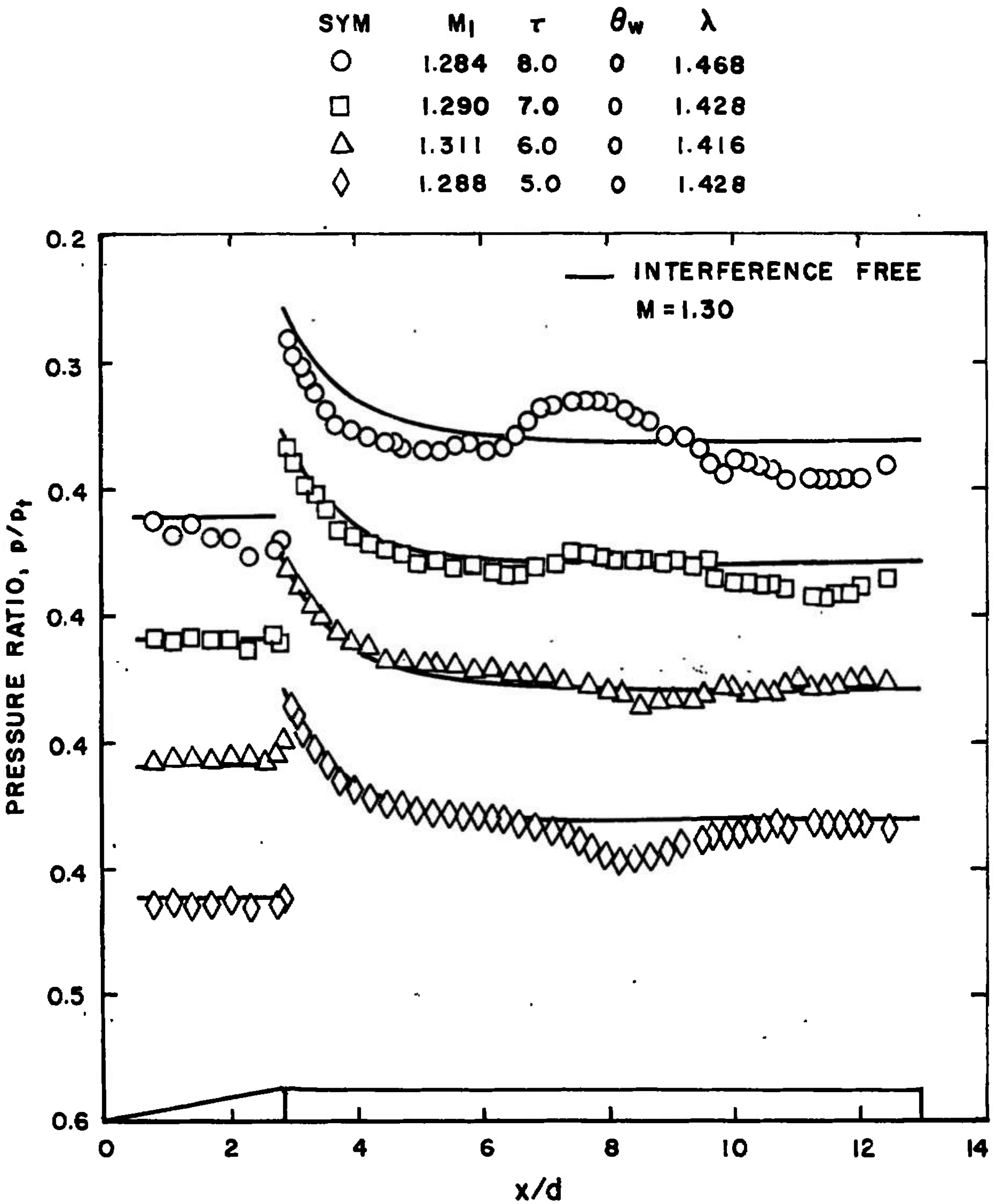


a. $\theta_w = 0$
Fig. 16 Model Pressure Distributions at M = 1.20

SYM	M_l	τ	θ_w	λ
○	1.188	5.0	-0.50	1.494
□	1.198	5.0	-0.25	1.471
△	1.217	5.0	0.50	1.409

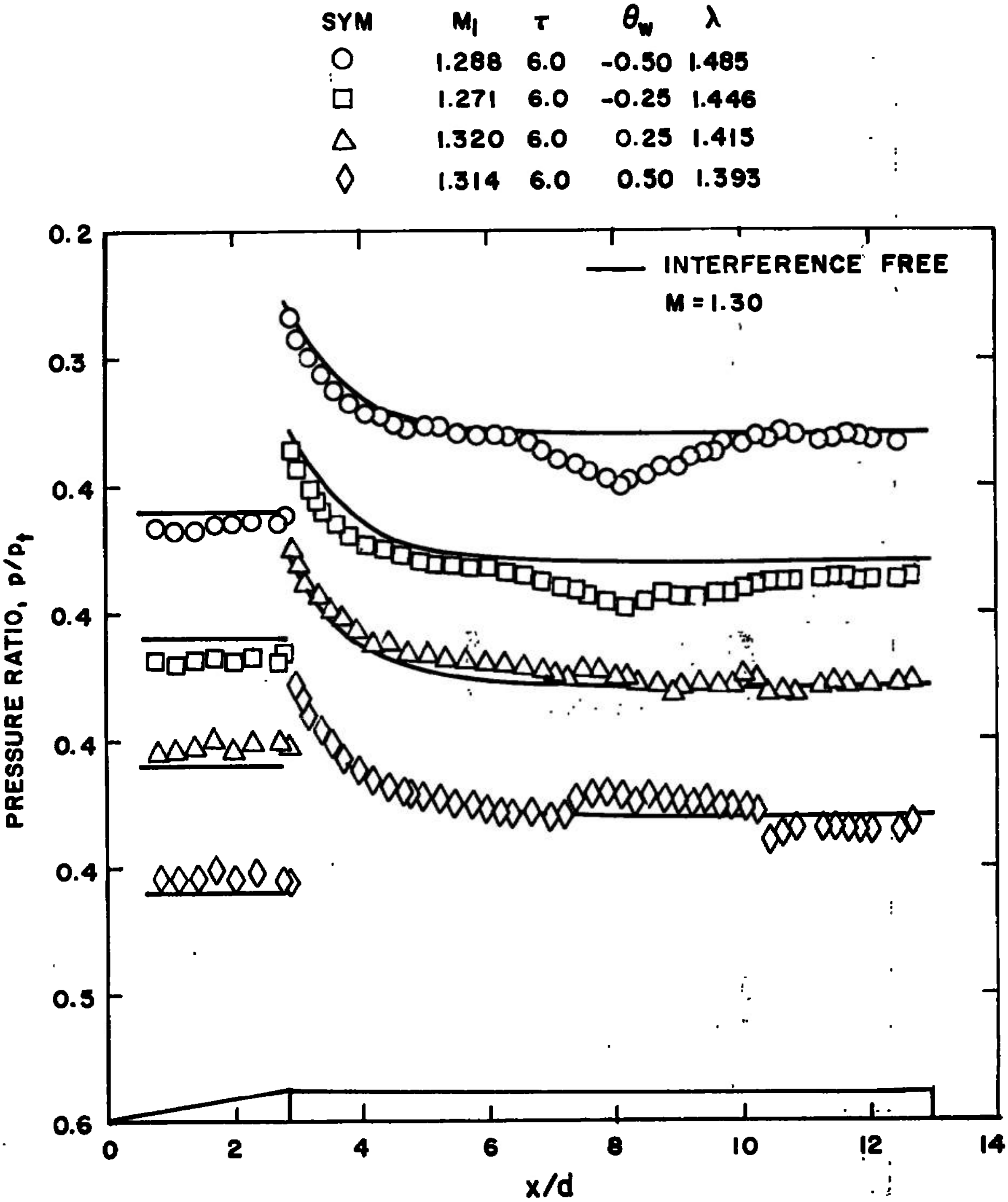


b. θ_w = variable
Fig. 16 Concluded



a. $\theta_w = 0$

Fig. 17 Model Pressure Distributions at M = 1.30



b. θ_w = variable
Fig. 17 Concluded

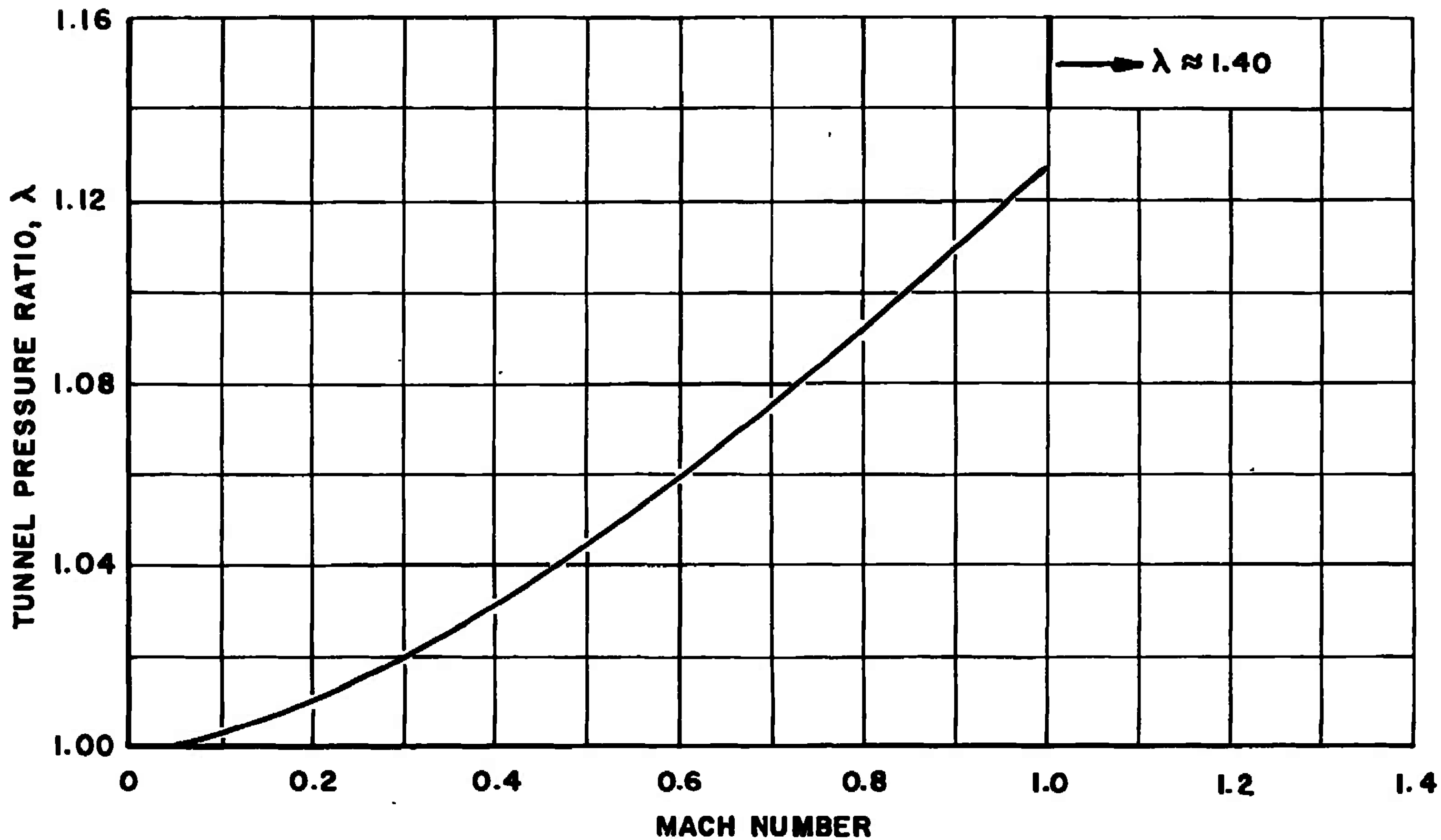


Fig. 18 Recommended Tunnel Pressure Ratio Settings, $\theta_w = 0$

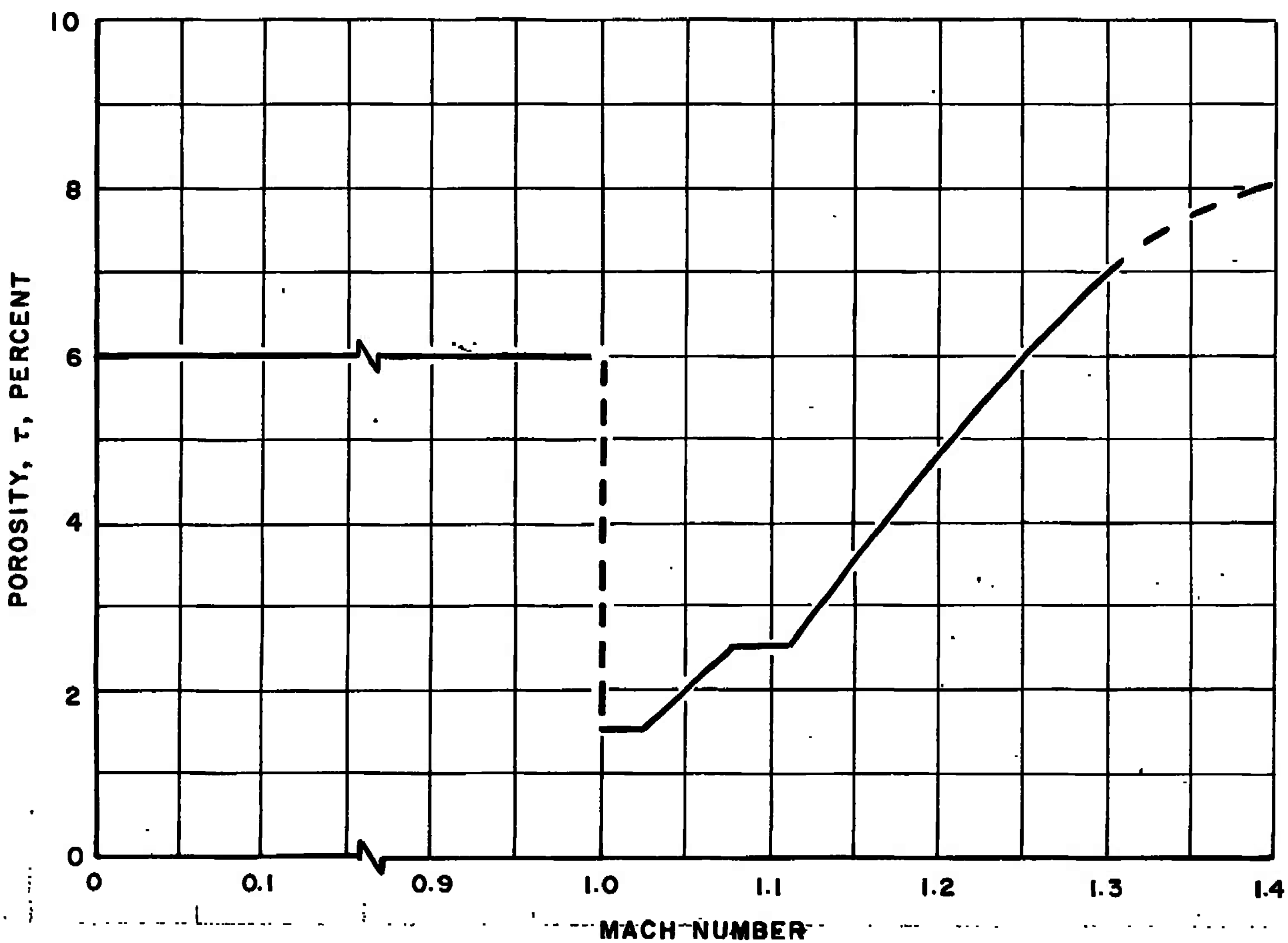


Fig. 19 Recommended Wall Porosity Settings, $\theta_w = 0$

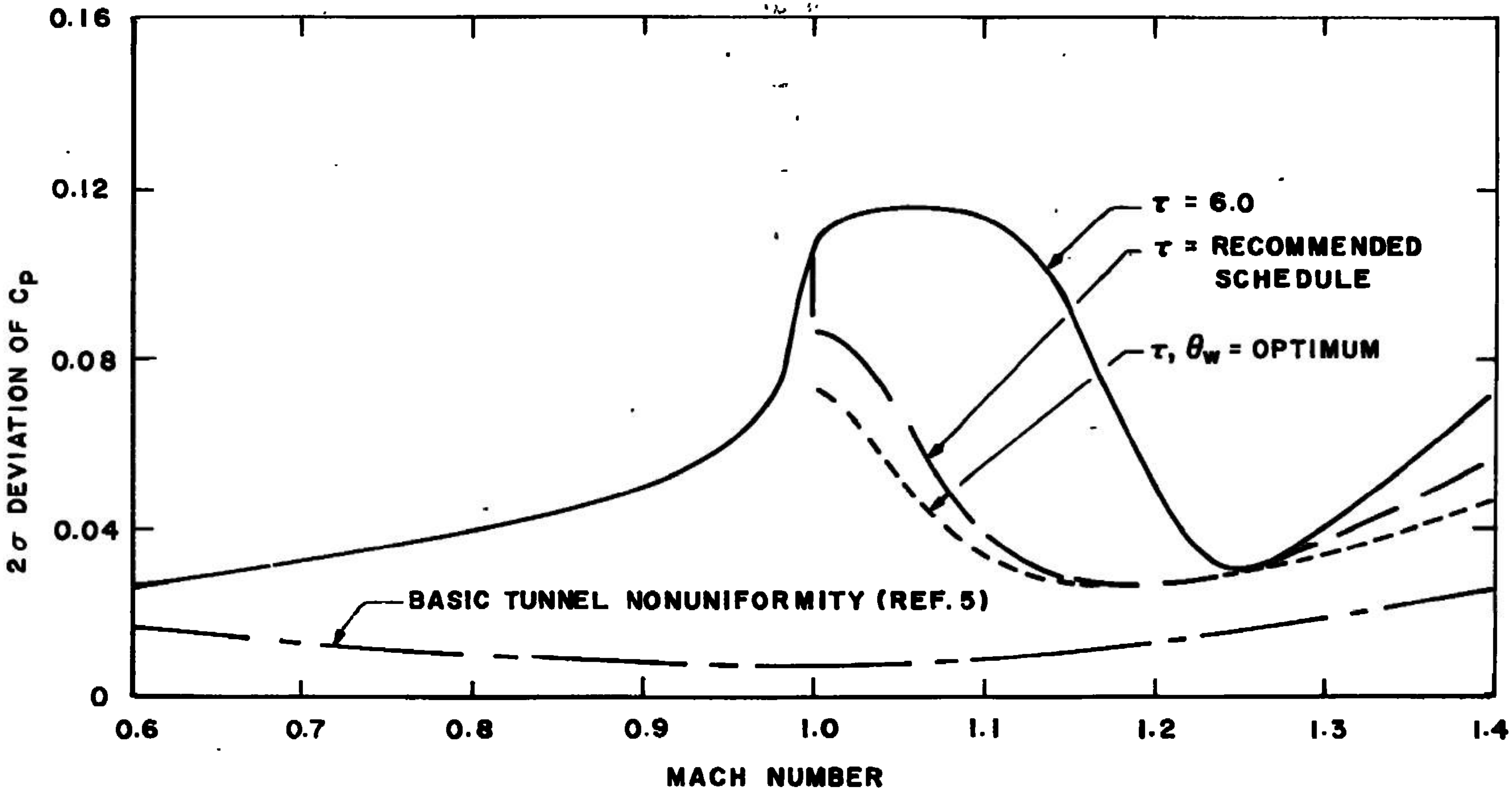


Fig. 20 Quantitative Description of the Wall Interference Reduction Obtained with Variable Wall Porosity

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13. ABSTRACT

Tests were conducted in the AEDC Aerodynamic Wind Tunnel, Transonic (4T), to determine optimum operating parameters which minimize tunnel interference effects. The tunnel is equipped with inclined hole, variable porosity, test section walls. Pressure distributions on a 20-deg cone-cylinder model having a blockage ratio of 1 percent were used to select optimum test section wall porosity, wall angle, and tunnel pressure ratio through the Mach number range from 0.1 to 1.3. Practically interference-free results were achieved at the optimum conditions for all Mach numbers except for the range from 0.95 to 1.05 where noticeable compression waves impinged upon the model. The recommended schedule for wall porosity ranges from 1.5- to 7.0-percent open area, dependent upon Mach number.

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1. Transonic wind tunnels -- Performance

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3 " " " -- Interference

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