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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF A VARIABLE MACH NUMBER TWO-DIMENSIONAL SUPERSONIC TUNNEL OF FIXED GEOMETRY

By

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Variable Mach number supersonic flows have been generated in a $2\frac{1}{4}$- by $4\frac{1}{2}$-inch fixed-geometry rectangular tunnel by removal of air through longitudinal slots of several profiles and proportions. The nature of the flow over a range of Mach numbers up to 1.45 is shown in schlieren photographs and pressure distributions along the tunnel. The most uniform flow was produced by removal of air through a single slot in a flat surface.

INTRODUCTION

The utility of a conventional fixed-geometry wind tunnel for testing is seriously restricted in the supersonic regime because of its limitation to a single Mach number. This limitation has been overcome, to a certain extent, by the use of interchangeable nozzle blocks, but this system is complicated by difficulties in construction, assembly, and storage of many sets of blocks; and with each set of blocks the tunnel operates at a single Mach number. Several systems of continuously varying the tunnel geometry have been tried and continuous variations in Mach number obtained. One solution involves the use of elastic walls which are flexed to the desired shape. Other methods use nonelastic blocks the position of which is variable either by translation or rotation. Examples of these latter systems are found in references 1 and 2. A different approach to the problem of obtaining a continuous range of Mach number involves variation of the amount of air flowing through a fixed-geometry system. The advantages of a fixed-geometry supersonic tunnel with a continuous Mach number are obvious. In the subsonic regime, it has been found possible to eliminate wind-tunnel boundary corrections and to avoid tunnel-constriction effects at Mach numbers close to unity by the use of multiple longitudinal slots in the tunnel walls (reference 3). The present research was conducted in a rectangular slotted tunnel with glass side walls to permit visual observation of the flow as well as pressure measurements. A limited range of slot shapes has been studied to determine the influence of slot area ratio, depth, profile, and distribution on the flow. In each configuration, slot profile was constant throughout the length of the channel. The size and proportions of the tunnel were determined by the equipment available at the Langley induction aerodynamics laboratory and are not necessarily optimum from the aerodynamic viewpoint. This work was initiated in November 1947 and is continuing with investigations of the fundamentals of flow into slots from supersonic streams and of the flow inside the slots. Other work is in progress to determine the effect of the slotted walls on tunnel choking and shock reflection.

APPARATUS

The general arrangement of the experimental equipment used in this investigation is shown in figure 1. The air is accelerated to sonic velocity in an entrance bell with a contraction ratio of approximately 70:1. The tunnel tested was a $2\frac{1}{4}$- by $4\frac{1}{2}$-inch constant-cross-section rectangular tube approximately 17 inches long with the slots in one wall. The use of only one slotted wall corresponds approximately to the use of an asymmetrical nozzle resulting from replacing the plane of symmetry of a symmetrical nozzle with a solid surface. This simplification in design greatly reduces the construction required and eliminates the complication of coordinated removal of air from two surfaces to obtain axial flow along the plane of symmetry. The slotted walls were assembled as individual units of bars separated to form the slots of constant cross section. The slots in the original installation were divided into 12 compartments by transverse bulkheads $\frac{1}{8}$ inch below the surface of the slotted wall and fitted with individual butterfly valves in an effort to obtain longitudinal control of the rate of air flow into the slots. Early tests indicated that the throttling action of the valves in the critical region at the front of the slots was negligible because of the low air velocity through these compartments. Severe disturbances of the flow resulted from an abrupt change in stream direction ahead of each bulkhead. Therefore, the bulkheads were cut to a point $\frac{1}{2}$ inch below the base of the slots and the valves were held in the open position throughout these tests. A typical slotted-wall assembly is shown in figure 2(a) and details of the individual bar profiles in figure 2(b). Air flow into the slots was effected by reducing the pressure in the plenum chamber below the slots. A short diffuser following the test section was used to reduce the power required to generate a given Mach number.

Pressure orifices 0.050 inch in diameter were installed in the surface opposite the slotted wall and also in the plenum chamber below the slots. A total-pressure tube and thermocouple were installed ahead of the inlet bell to determine the stagnation conditions. The pressure data were recorded photographically from mercury manometers which precluded the measurement of stream-pressure fluctuations. Wet- and dry-bulb temperatures measured at the blower intake were used in determining absolute humidity of the air supply. A schlieren optical system of conventional design, using 6-inch mirrors, and a spark light source producing intermittent flashes of approximately 10 microseconds were used as an aid for visualization of the flow. A rake of nine conical tipped probes was installed $6\frac{1}{4}$ inches downstream from the leading edge of the slots to facilitate visual observation. These probes were located both on the vertical center line and laterally across the tunnel, with the lateral probes displaced enough vertically to facilitate individual identification.

SYMBOLS

A	cross-sectional area of channel
A_s	minimum area of slot
A_w	area of slotted wall
a_o	sonic velocity at stagnation conditions
H_o	stagnation pressure
h	height of channel
m	mass flow
p	static pressure along reflection plane
p'	static pressure below slots
x	distance along axis of channel from slot lip, inches
δ	angle of flow relative to porous wall

γ ratio specific heats

ν deviation of stream at test section from direction at $M = 1.0$

ρ_o density at stagnation point

RESULTS AND DISCUSSION

In a generalized discussion of one-dimensional steady flow through channels it has been shown by Taylor and Maccoll (reference 4) that the flow rate and stream pressure are related as follows:

$$\frac{\gamma - 1}{2} \frac{m^2}{A^2 a_o^2 \rho_o^2} = \left(\frac{p}{H_o}\right)^{\frac{2}{\gamma}} - \left(\frac{p}{H_o}\right)^{\frac{\gamma+1}{\gamma}}$$

For air $\gamma = 1.4$, the mass-flow term reaches a maximum at a value of $\frac{p}{H_o} = 0.528$ which corresponds to sonic velocity. Thus, supersonic flow $\frac{p}{H_o} < 0.528$ can be obtained at constant $\rho_o a_o$ by (1) increasing cross-sectional area A of the channel, (2) reduction of mass flow m by withdrawal of air through "porous" walls, or (3) by a combination of both methods. Charts for designing minimum-length shockless nozzles have been calculated and are reported by Shames and Seashore (reference 5). Similar calculations have been applied to a tube of constant-cross-sectional area, equal to that at the point of sonic velocity, to determine the angle of flow δ relative to the "porous" wall and the portion of air flow across this surface (fig. 3). The initial turn, equal to one-half of the total stream deviation, was taken abruptly at x/h equal to zero. The second family of characteristic lines was assumed not to reflect from the "porous" surface.

Calculated pressures along the center line of a symmetrical, two-dimensional nozzle of minimum length are presented in figure 3(d) for two values of initial stream deflection. In the experimental setup, air removal was effected through only one wall; the solid wall opposite the "porous" surface therefore corresponds to the plane of symmetry in the theoretical nozzle. Comparison of experimental pressure data from a representative configuration with the calculated pressure distributions along this plane shows close agreement in the initial rate of expansion. To facilitate this comparison, the theoretical pressure curves have been displaced upstream equally on all pressure plots in this paper.

Effect of free-area ratio.- The results of several tests with single-wall free-area ratios of $\frac{1}{9}$, $\frac{1}{5}$, and $\frac{1}{3}$ are presented for comparable values of chamber-pressure ratio $\frac{p'}{H_o}$ in figure 4. These floors were constructed of rectangular bars of $\frac{1}{2}$-inch depth. From the schlieren photographs one gains the general impression of smoother flow in those cases where air removal was through slots for which the total area was one-fifth of the wall area. In comparing these photographs, it should be noted that the field of view varies somewhat from one configuration to another. For comparable values of chamber-pressure ratio, the Mach number of the flow, as indicated by the slope of the disturbance lines, is greater for the larger slots. The velocity distribution in the direction of flow is indicated by the pressures measured along the reflection plane (figs. 4(b) to 4(d)). The acceleration at the front of the slotted section in all cases follows closely that calculated from the Prandtl-Meyer turn.

For comparable values of chamber-pressure ratio, the compression following the initial expansion increases with reduction of slot width. This is not surprising since the pressure at the front of the slot, which controls the extent of the initial expansion, is influenced less by the slot pressure losses than points further downstream. The pressure at the forward edge of the slots approaches the chamber pressure since the air velocity in this part of the slot is undoubtedly low. The compression following the initial expansion was observed in all tests in which (1) the capacity of the slots was too small to handle the air turned in the initial expansion at the pressure ratio available, or (2) the flow expanded abruptly to a pressure corresponding to an initial deviation of more than one-half the total deviation represented by the chamber-pressure ratio. This latter phenomenon was observed with slotted walls that had a large free-area ratio. All reported free-area ratios were calculated as the ratio of minimum slot area to total wall area of the slotted wall.

At comparable values of chamber-pressure ratio one also observes a marked decrease in maximum Mach number attained as the ratio of slot area to wall area is decreased. This is attributed to the higher pressure loss through the smaller slots.

The effect of increasing the absolute stagnation pressure from 55 to 70 inches of mercury at comparable values of $\frac{p'}{H_o}$ is shown in figure 4(b). The reduced magnitude of the pressure variation following the initial expansion suggests that the loss characteristics of the slots are not independent of the Reynolds number; the improvement may also be influenced by the increase in stagnation temperature and decrease in relative humidity of the air.

Effect of slot depth.- Data taken in tests of three surfaces with slots of equal width but of different depth are presented in figures 5 to 7. A rake of conical-tipped survey probes has been installed at a downstream station to facilitate analysis of the schlieren photographs as well as to provide a visual means of observing Mach number gradients in the flow. The intensity of the wave image from these probes is indicative of the sensitivity of the schlieren system.

At Mach numbers close to unity, the flow is spanned by multiple shocks whose intensity and concentration is considerably lower with air removal between the deeper bars. The fluctuation of the stream Mach number that occurred near unity, as measured from schlieren motion pictures, became smaller as the stream Mach number was increased, and at Mach numbers above $M = 1.1$ the flow appeared stable. At Mach numbers above 1.25 the uniform spacing and slope of Mach lines indicates satisfactory flow over the entire length of the schlieren pictures for all configurations. Parallelism of the shocks from the probes indicates very uniform Mach number across the tunnel as well as along the vertical center line. Examination of the flow close to the slotted wall shows that the subsonic layer above the slots persists to much higher Mach numbers in those tests with air removal through the $\frac{1}{8}$-inch-deep slots.

The initial expansion at the front of the slotted section is observed to follow the calculated curve quite closely for the $\frac{1}{2}$-inch slot depth (fig.6(b)). With the 1-inch slots (fig. 7(b)), the experimental pressure distribution is essentially parallel to the theoretical curve but is displaced downstream. The downstream displacement of the experimental curves suggests the existence of a vortex flow at the front of the slots which would reduce the rate of turning of the flow at the extreme forward edge of the slots. For the $\frac{1}{8}$-inch slot depth, the difference between the theoretical and the experimental curves is not considered significant because of the large variation in Mach number in the region ahead of the slots. The compression following this premature expansion also appears to originate from a point ahead of the slot entrance. A detailed study of the flow on the nozzle surface in this region indicates that the boundary layer in the corners of the chamber moved upstream, in some cases reaching points as much as 2 inches ahead of the slots proper, whereas no evidence of reverse flow could be found on the central part of the wall. It will be noted at this point that the pressures ahead of the slotted section are consistently lower in these figures than in figure 4. This difference is attributed to differences in the inlet flow produced by small differences in the entrance-bell profile resulting from a modification of the entrance bell and from the fairing required to obtain a smooth contour at the joint between the bell and the test channel.

From a comparison of the curves, following the initial expansion, it was found that the chamber-pressure ratio required to generate a given stream Mach number was consistently smaller with $\frac{1}{8}$-inch slots throughout the range of these tests. Below $M = 1.2$ $\left(\frac{p}{H_o} = 0.412\right)$ slightly larger chamber-pressure ratios were required with the deep bars, but at higher Mach numbers the bar depth made little difference. The influence of the survey tubes at the downstream end of the test channel precludes evaluation of the effect of slot depth on the length of channel over which uniform flow could be obtained.

Effect of slot profile.- The shape of the slot entrance has been altered by changing the cross-sectional profile of the individual bars making up the slotted wall. The influence of changes in crown of the bars from flat to semicylindrical and triangular is found in a comparison of figures 8 and 9 with figure 6. At comparable values of chamber-pressure ratio $\frac{p'}{H_o}$, one observes considerably greater intensity of the disturbances ahead of the probes with air removal between bars with triangular crowns. The appearance of the flow in the immediate vicinity of the probes shows little influence of slot entry on the Mach number attained at a given value of $\frac{p'}{H_o}$.

The most significant difference in the pressure distribution along the reflection plane is the increase in intensity of the compression following the initial expansion with the triangular crowned bars. Minor differences are also observed in the chamber-pressure ratios required to attain a given Mach number.

Tests using bars of lenticular cross section provide additional information regarding the influence of slot profile. In these tests other parameters, that is, slot width, depth, and spacing, were also altered (fig. 2(b)); the free-area ratio based upon minimum slot area, however, was not changed. With this configuration, the flow disturbances are sharply concentrated (fig. 10(a)), with almost complete absence of Mach lines through the remainder of the flow. The pressure distribution along the reflection plane (fig. 10(b)) is very similar to that measured with the air flow between bars with triangular crowns.

Analysis of the flow through the slotted sections of the channel indicates that the differences associated with changes in slot profile originate very close to the leading edge of the slots. In all cases, the rate of expansion is similar to that calculated for the theoretical flow around a sharp corner. The extent of the initial flow deflection increases with reduced obstruction at the entrance level, but because the slots converge, part of the flow must return toward its original path. The latter turning is accomplished through multiple compressions, the spacing of which is determined by the depth of the convergent section of the slot and by the rate of convergence of the slot. Thus it appears unlikely that satisfactory flow will be generated by the flow of air between triangular crowned or lenticular bars with abrupt transition from the closed throat to the slotted section. The flat and the circular crowned bars, on the other hand, generate equally satisfactory flows under the same conditions. The flat bars appear to be more desirable from a construction standpoint.

Effect of slot distribution.- Tests of a wall with the entire open area concentrated in a single slot at the center of the channel are presented in figure 11 for comparison with the results obtained with air removal through multiple rectangular slots of the same depth (fig. 6). The main flow in each case appears equally smooth from the schlieren photographs with but minor differences existing in the subsonic layer adjacent to the slotted wall. The pressure distributions are, in general, more uniform with the single slot at the higher Mach numbers, but in the range below $M = 1.15$ the pressure variations along the channel are somewhat lower with multiple slots. The chamber-pressure ratios required to obtain a given Mach number were somewhat lower with the single slot.

The influence of slot spacing can best be discussed by considering the individual slots as lines of pressure disturbances, the intensity of which decreases in the direction of flow. Since, in the ideal case, all of these disturbances produce expansion, their influence is confined to cones lying within the Mach cone. Each disturbance for which the intensity decreases with increasing distance from the axis of the cone produces a change in flow whose direction is always toward the axis. The influence of parallel disturbances will produce additive changes in flow in the region of intersection of the cones. Thus, a plane midway between parallel cones of equal strength will define the region in which the net lateral change in the flow is zero. At all points in this plane the flow will be directed toward the intersection of this plane with the wall containing the axis of the cones. The required change in direction of the air between the slots to planes parallel to the wall is accomplished through compression waves which reinforce to produce finite disturbances in the stream. Because increasing the distance between parallel cones decreases both the magnitude of the mutual interference and the space rate of change of the flow direction, it seems apparent that at corresponding points in the flow more uniform velocity will be obtained with a single slot.

Influence of instrumentation.- The presence of the survey tubes in the channel has previously been observed to reduce the distance over which uniform velocity could be obtained. The magnitude of this effect is indicated by the difference between the pressures measured above the single slot with the probes installed (fig. 11(b)) and without the probes (fig. 11(c)). The influence of the probes at Mach numbers below 1.15 extended far upstream, but at higher Mach numbers was confined to the vicinity of the probes themselves. The magnitude of this influence is probably determined by the ratio of slot width to total channel periphery rather than by the ratio of open to closed area of the slotted wall.

CONCLUSIONS

The results of this investigation of a variable Mach number two-dimensional supersonic tunnel of fixed geometry indicate that:

1. Controlled variable Mach number supersonic flows can be generated in a fixed-geometry slotted channel by varying the pressure ratio across the slots.

2. The initial rate of expansion at the front of the slotted section is approximately equal to that calculated from the Prandtl-Meyer expansion for supersonic flow around a sharp corner.

3. Decreasing the ratio of slot area to wall area in a given test section reduces the stream Mach number which can be generated at a given ratio of chamber pressure to stagnation pressure.

4. For given operating conditions, increasing slot depth from $\frac{1}{8}$ inch to 1 inch increased the Mach number attained below $M = 1.2$; at higher Mach numbers the slot depth made little difference.

5. If the air directed into the slots by the initial expansion exceeds that which will flow through the narrowest section of the slot at the pressure difference available, the resultant change in flow direction produces compressions and corresponding irregularities in Mach number distribution along the channel.

6. Increasing the distance between adjacent slots effected substantial improvement in the velocity distribution along the direction of flow.

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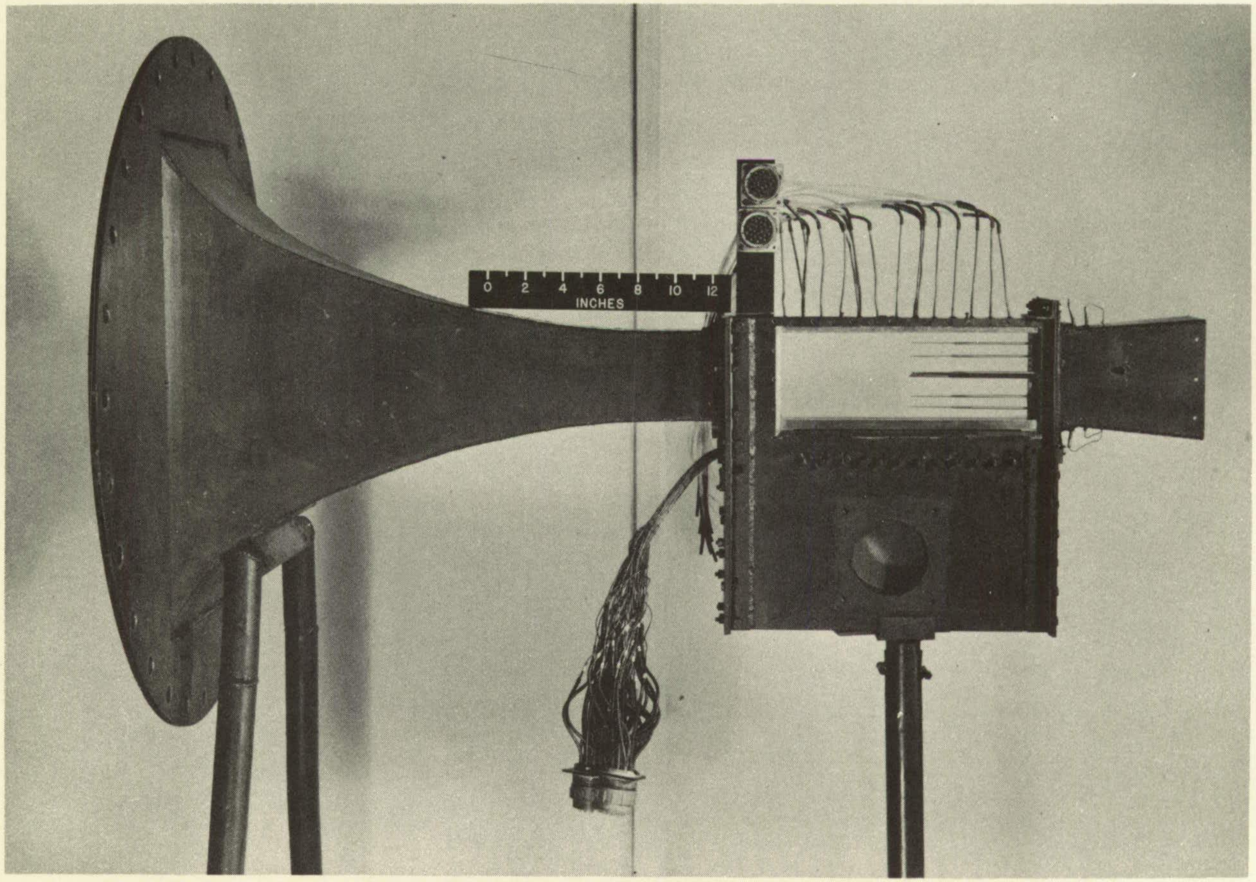

(a) General arrangement.

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Figure 1.– Test equipment.

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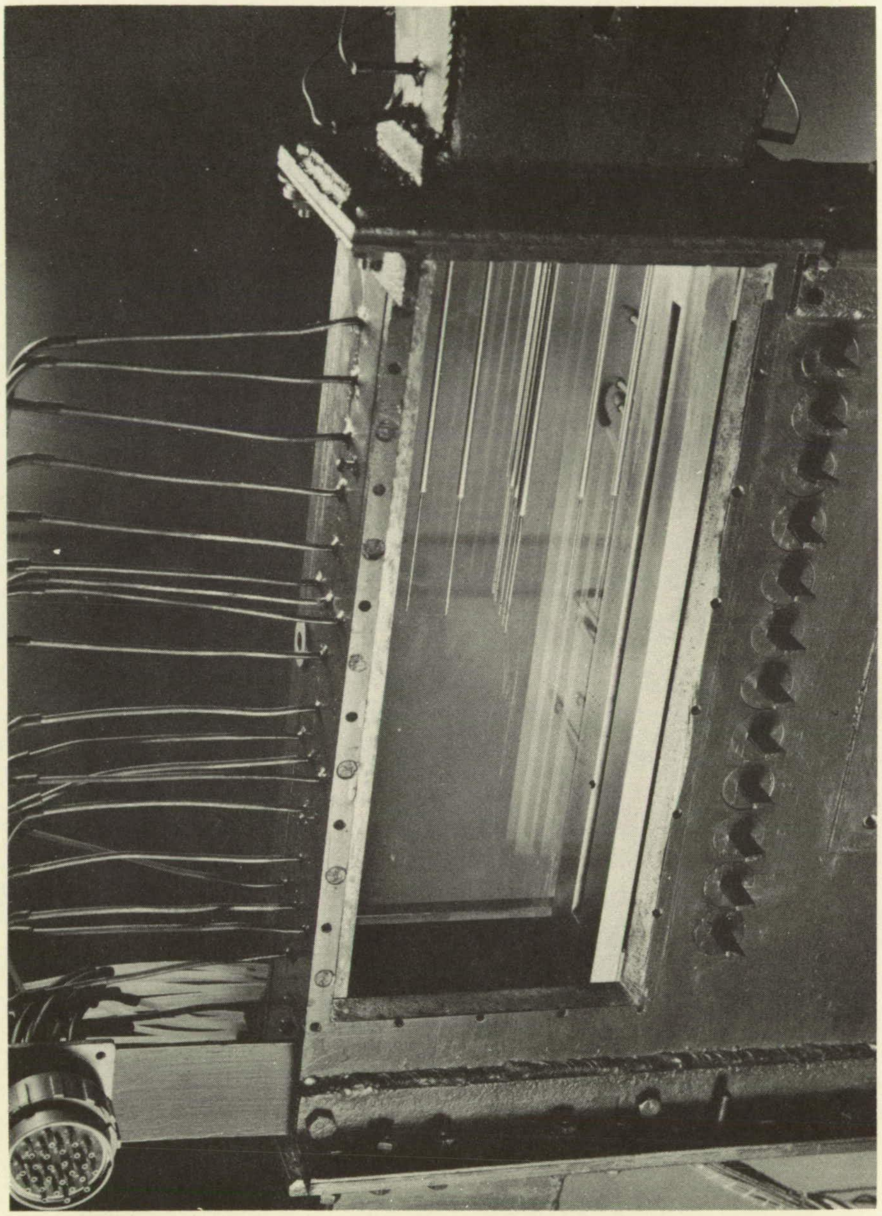

(b) Instrumentation, single-slot configuration shown.

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Figure 1.- Concluded.

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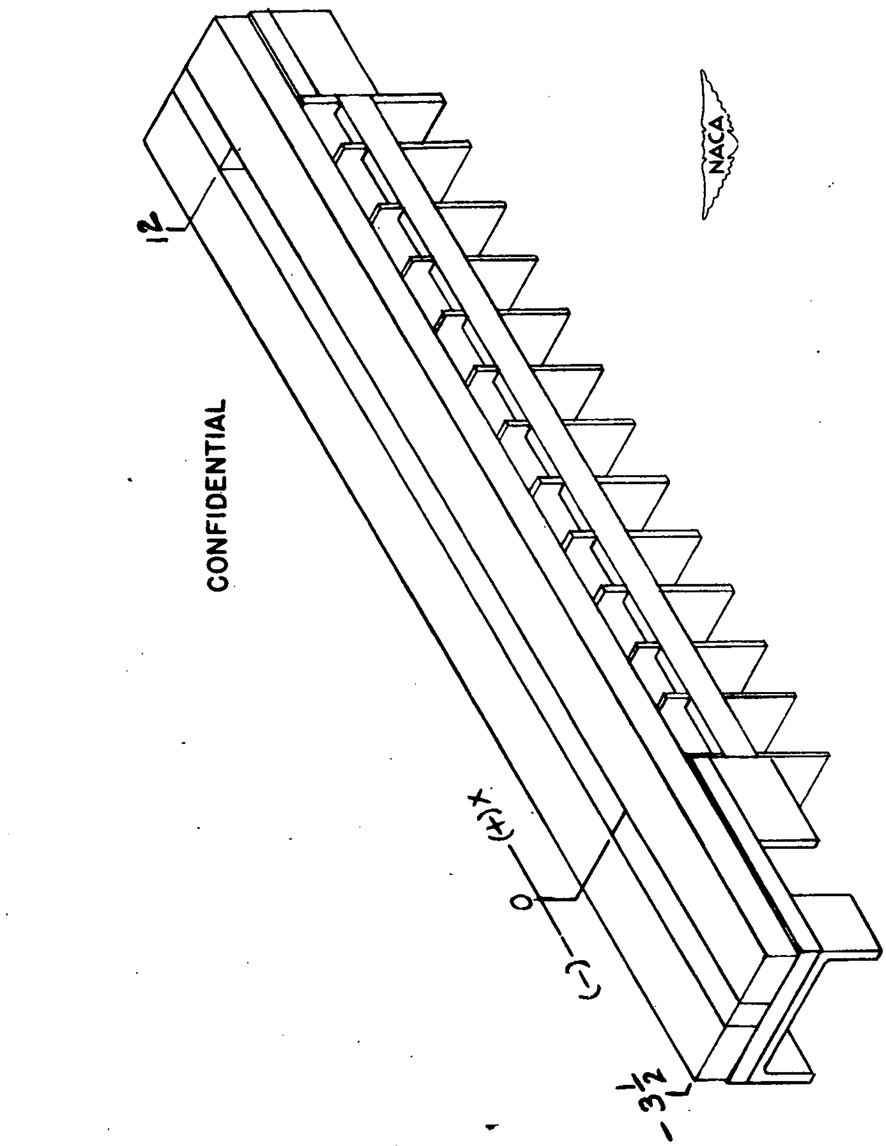

(a) Assembly, single slot configuration shown.

Figure 2.- Slotted walls. (All dimensions are in inches.)

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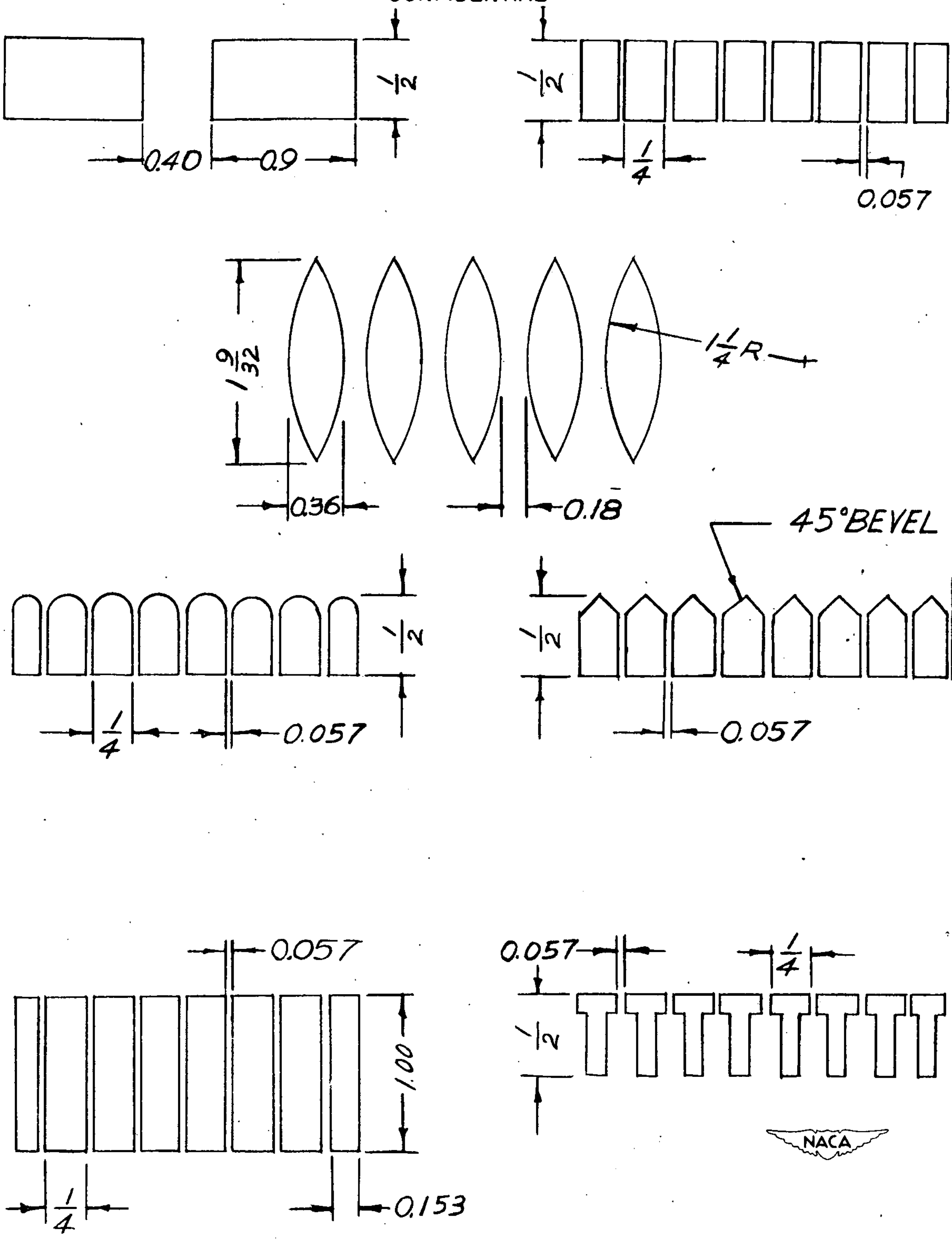

(b) Slot profiles.

Figure 2.— Concluded.

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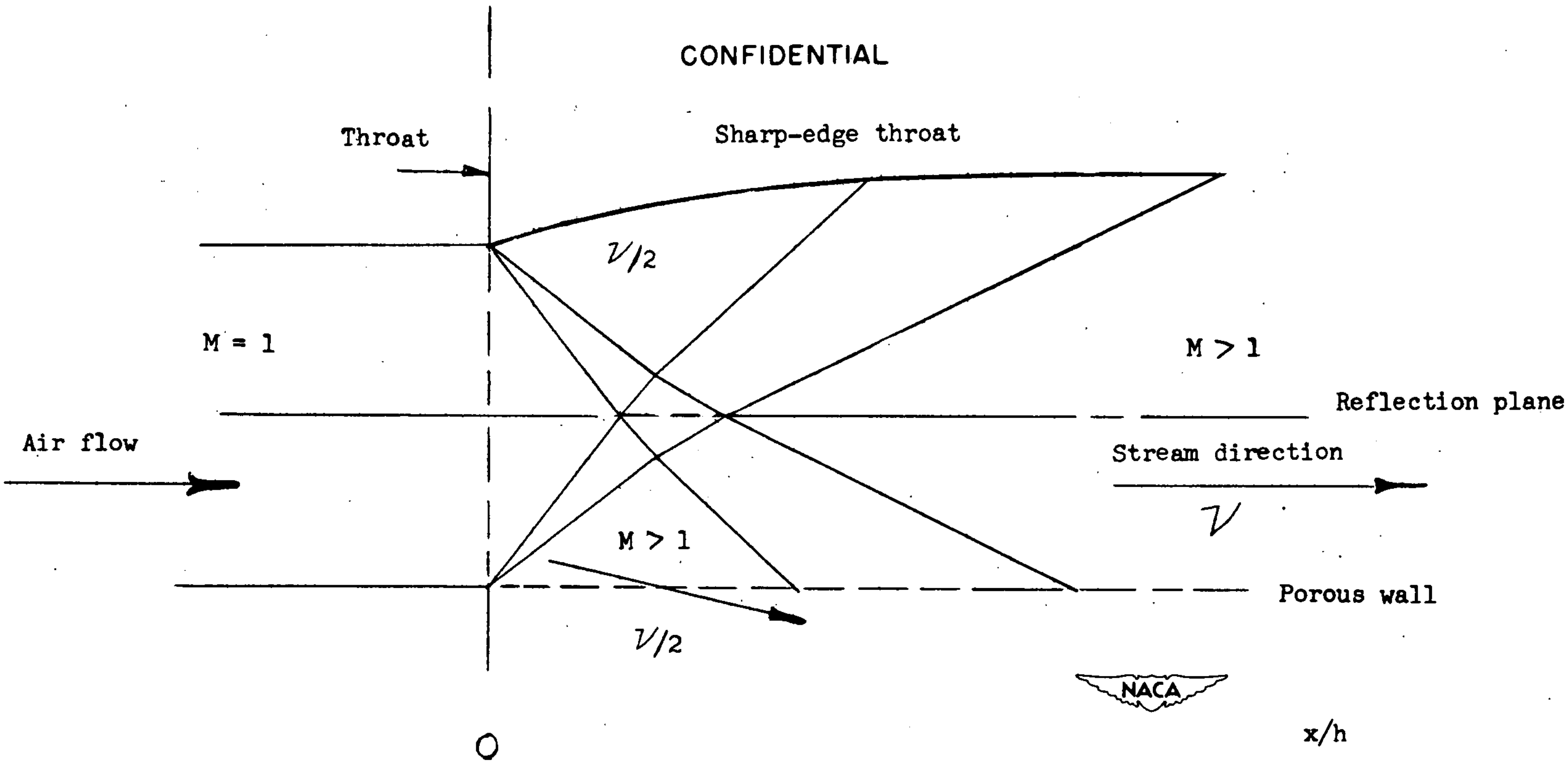

(a) Minimum length nozzles.

Figure 3.– Theoretical curves for a minimum-length nozzle.

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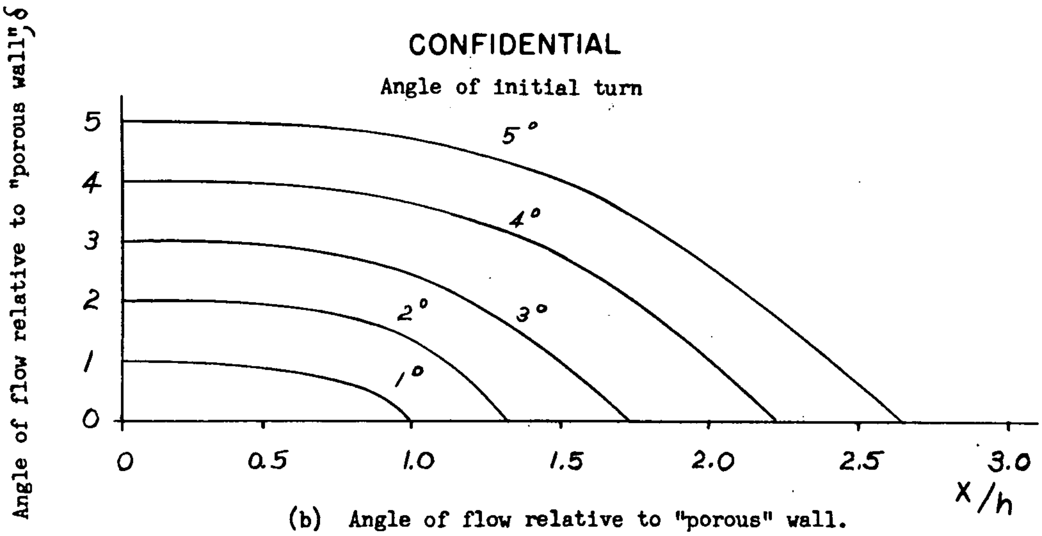
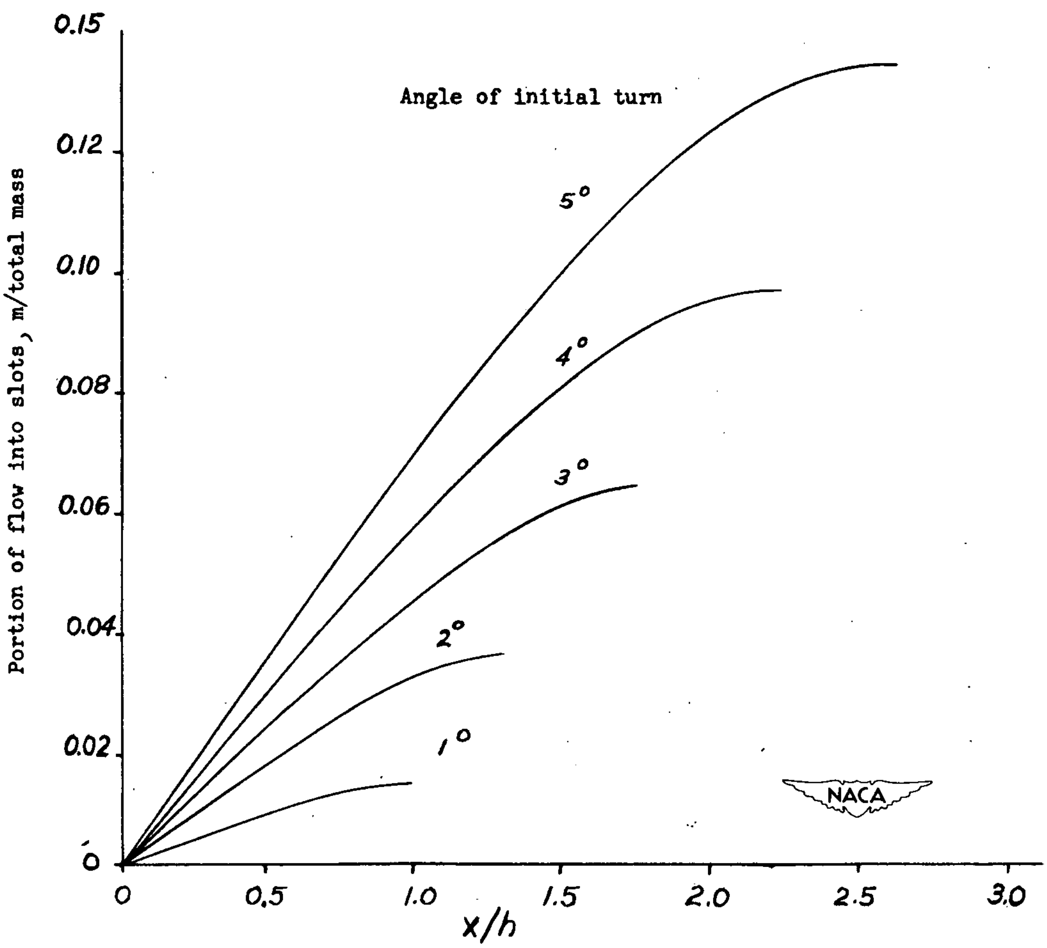


(b) Angle of flow relative to "porous" wall.



(c) Air flow into "porous" wall.

Figure 3.- Continued.

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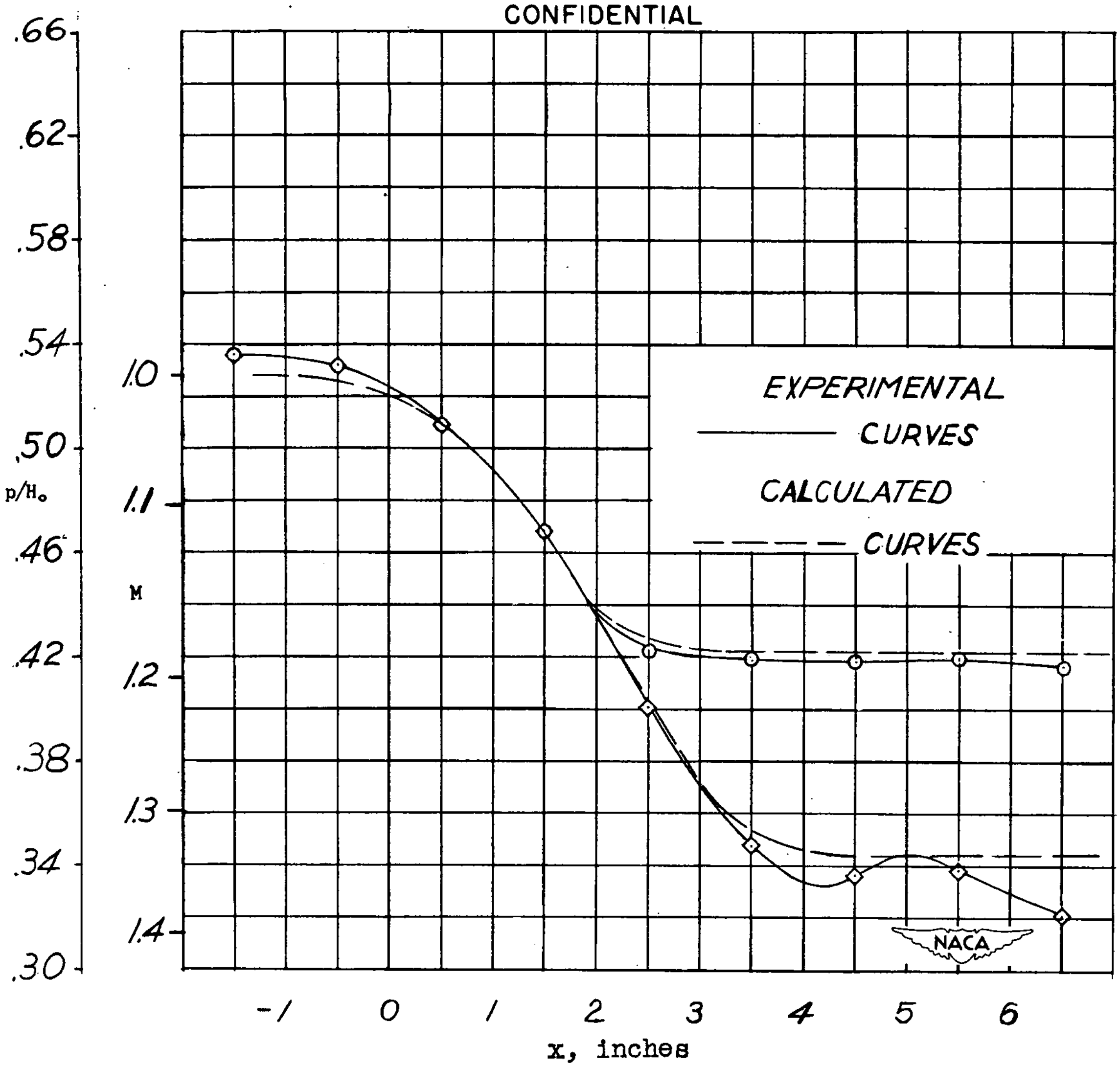

(d) Pressure distribution along plane of symmetry.

Figure 3.– Concluded.

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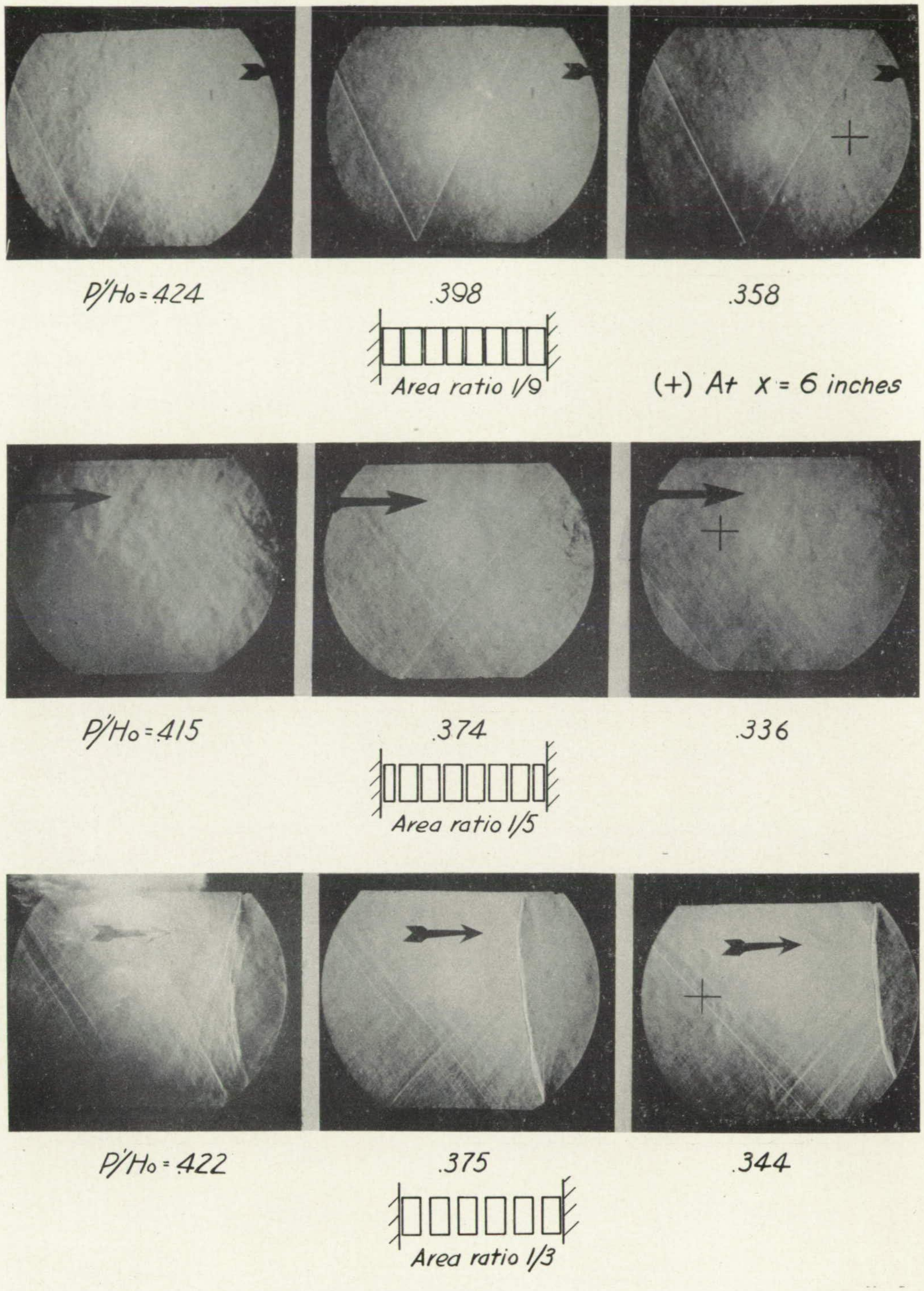

(a) Schlieren photographs. $\frac{A_s}{A_w} = \frac{1}{9}, \frac{1}{5},$ and $\frac{1}{3}$. Slotted wall at bottom.

Cross (+) indicates where $x = 6$ inches.

Figure 4.- Flow through rectangular tunnel with uniform longitudinal slots of different widths.

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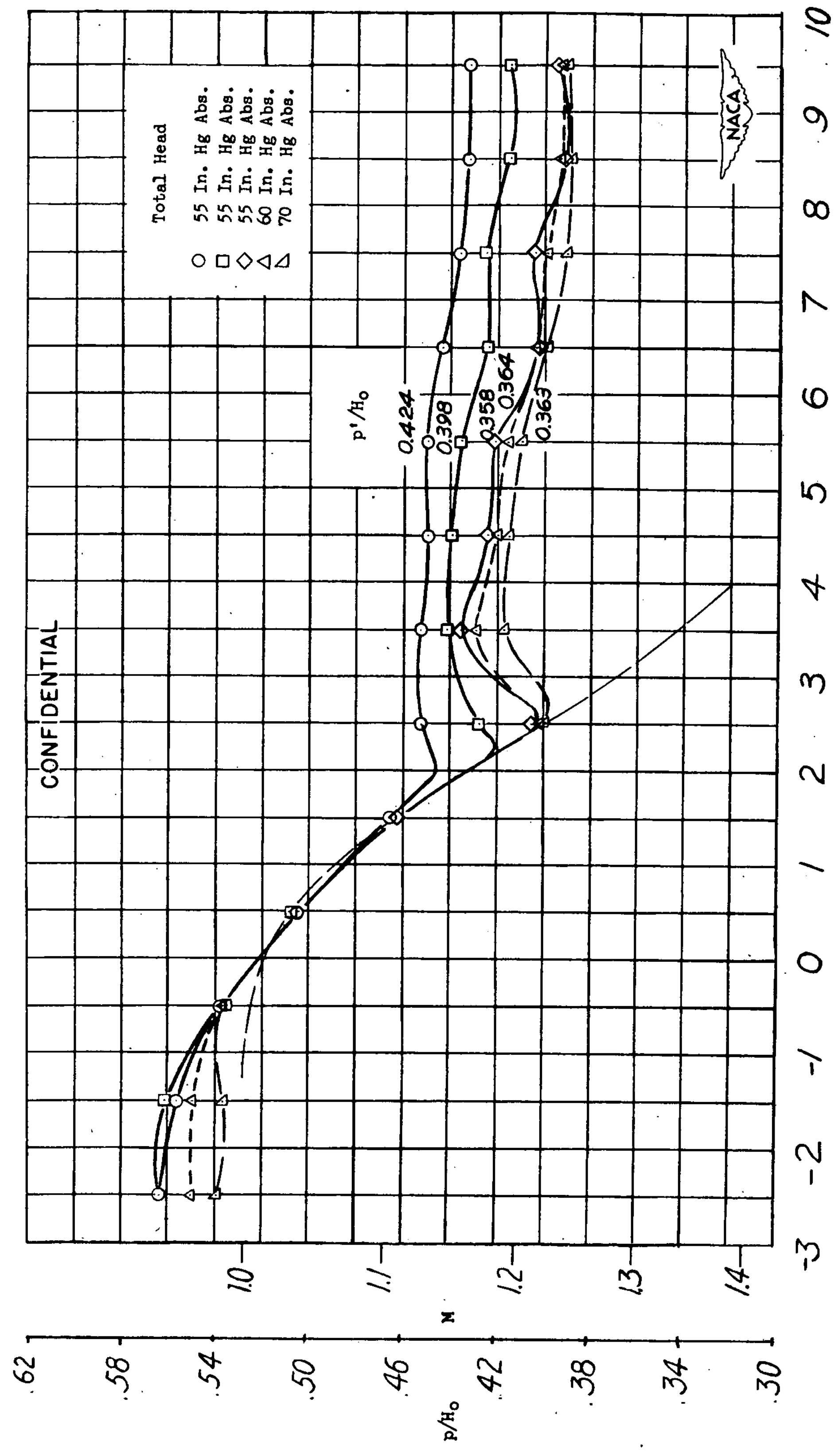

(b) Pressure distribution along reflection plane. $\frac{A_s}{A_w} = \frac{1}{9}$.

Figure 4.– Continued.

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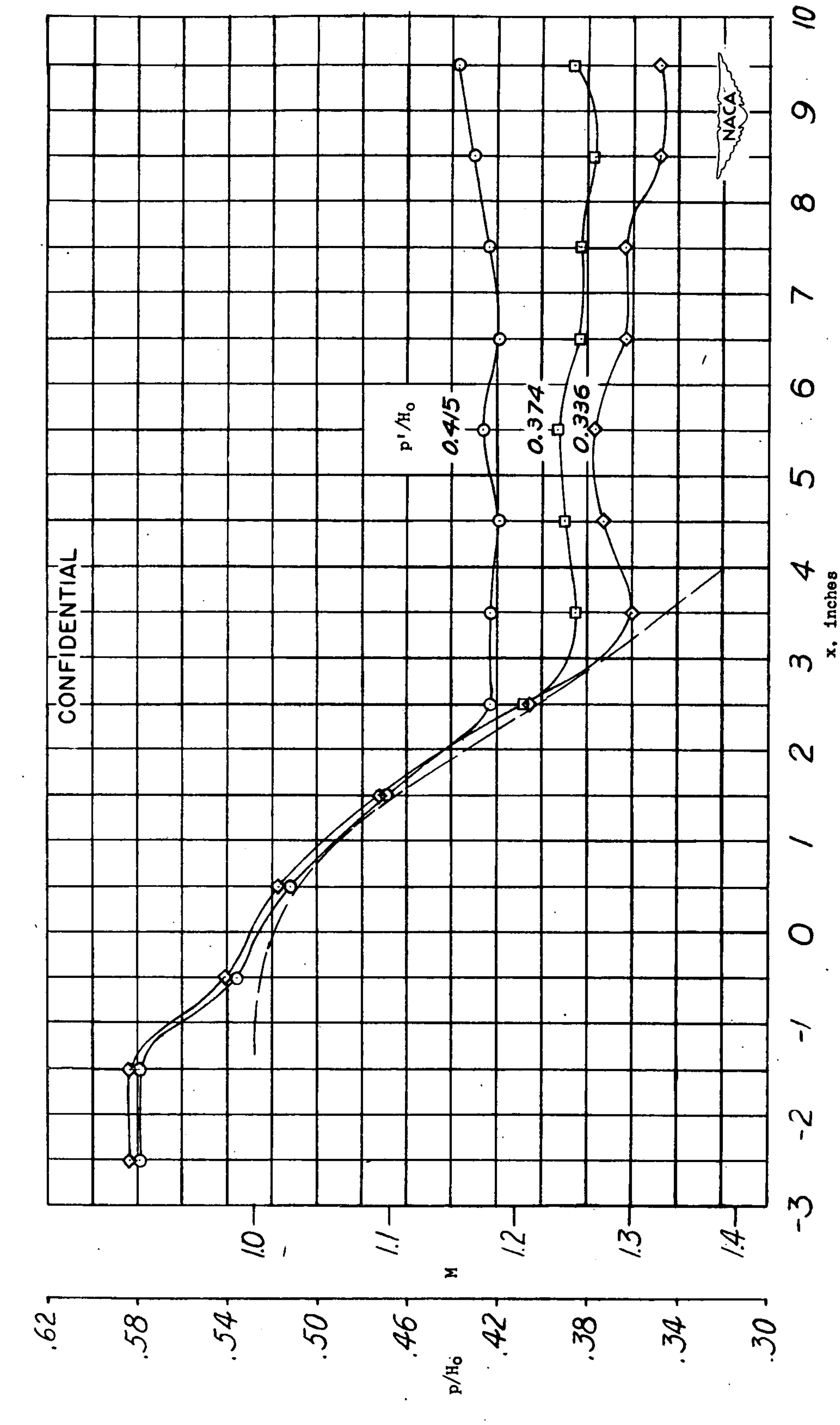

(c) Pressure distribution along reflection plane. $\frac{A_B}{A_W} = \frac{1}{5}$; H_o = 53 inches of mercury absolute.

Figure 4.- Continued.

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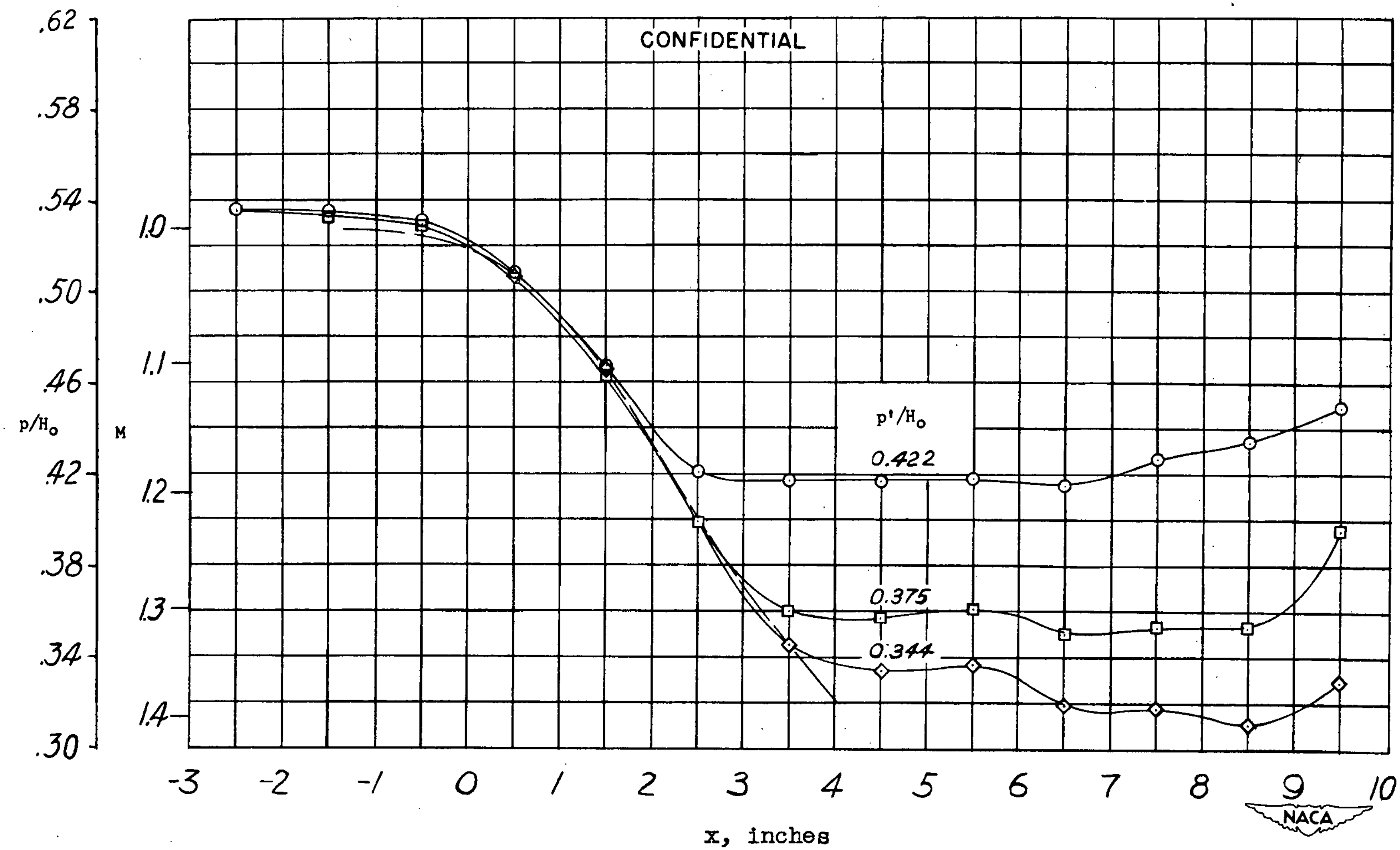

(d) Pressure distribution along reflection plane. $\frac{A_s}{A_w} = \frac{1}{3}$; H_o = 52.7 inches of mercury absolute.

Figure 4.– Concluded.

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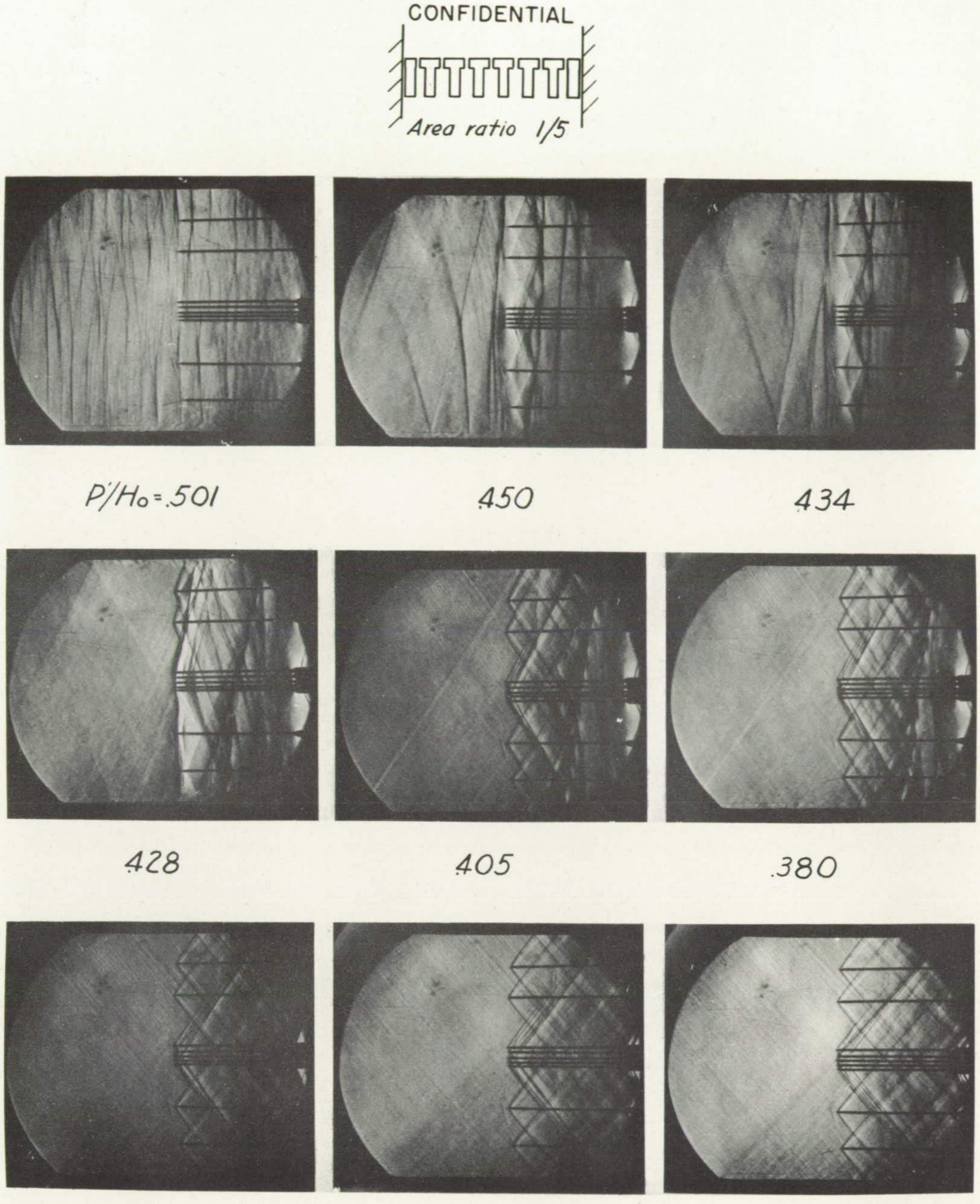

(a) Schlieren photographs. Slotted wall at top.

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Figure 5.- Flow through rectangular tunnel with uniform longitudinal slots of $\frac{1}{8}$-inch depth.

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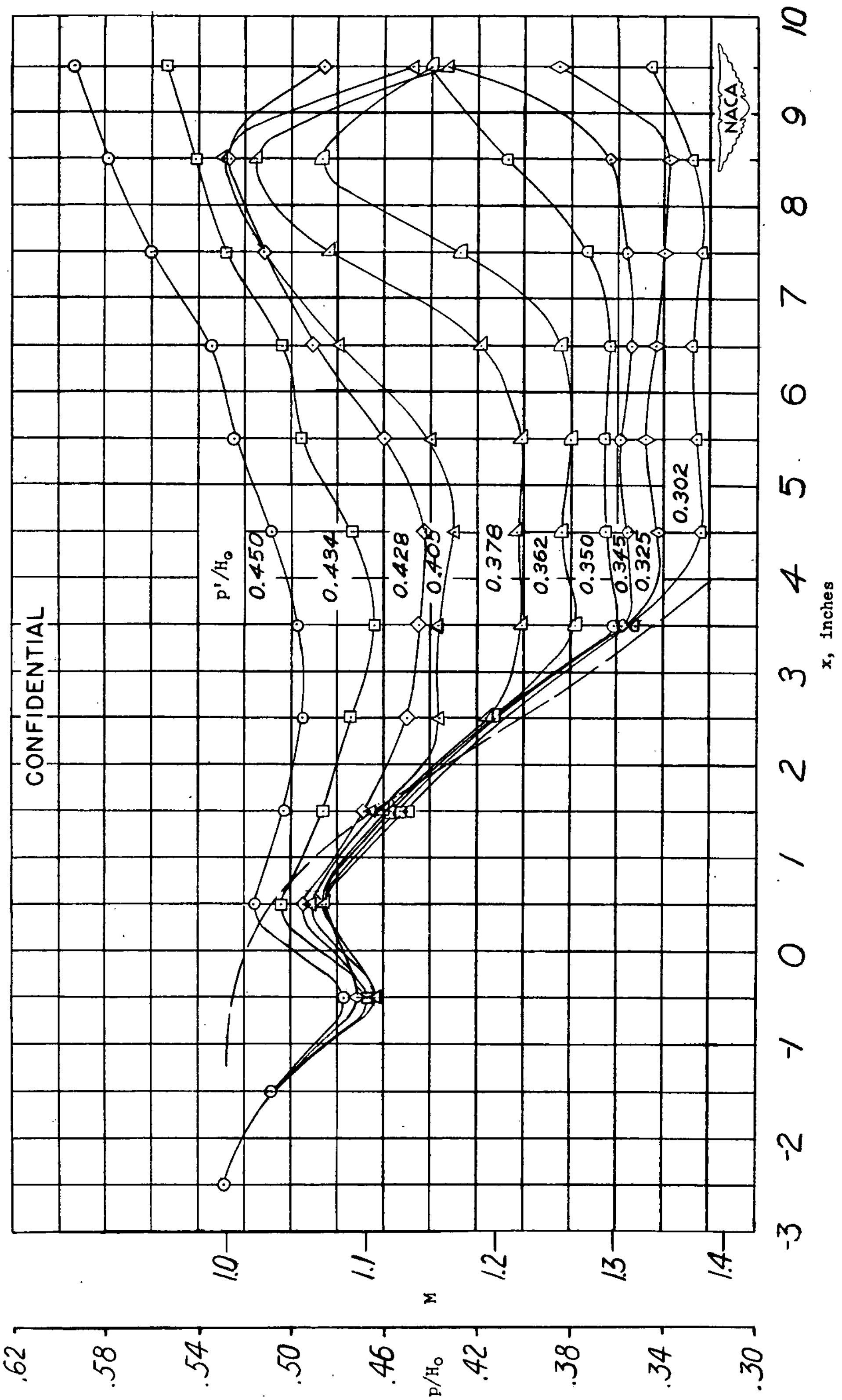

(b) Pressure distribution along reflection plane.

Figure 5.– Concluded.

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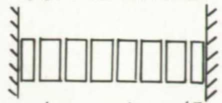
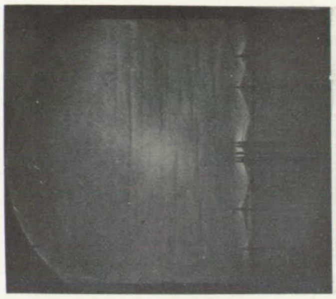
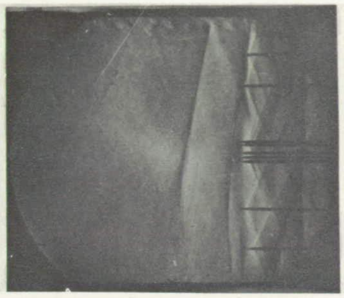


Area ratio 1/5



$P'/H_o = .497$



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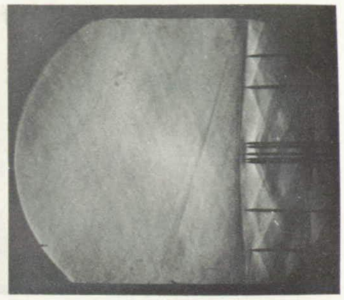

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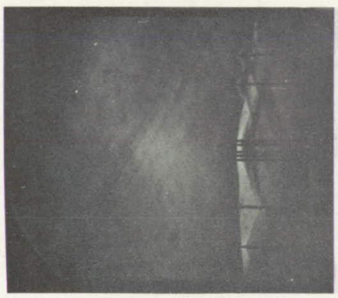

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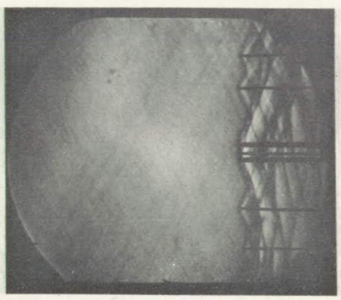

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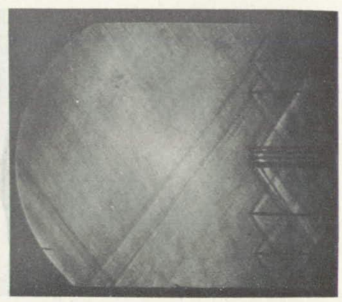

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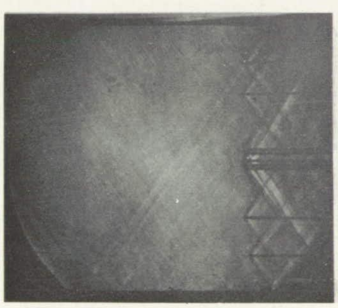

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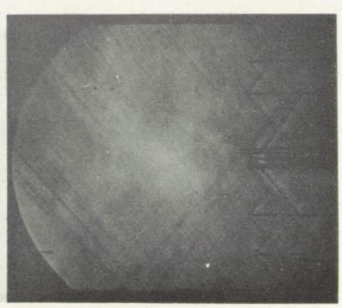

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(a) Schlieren photographs. Slotted wall at top.

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Figure 6.- Flow through rectangular tunnel with uniform longitudinal slots of $\frac{1}{2}$-inch depth.

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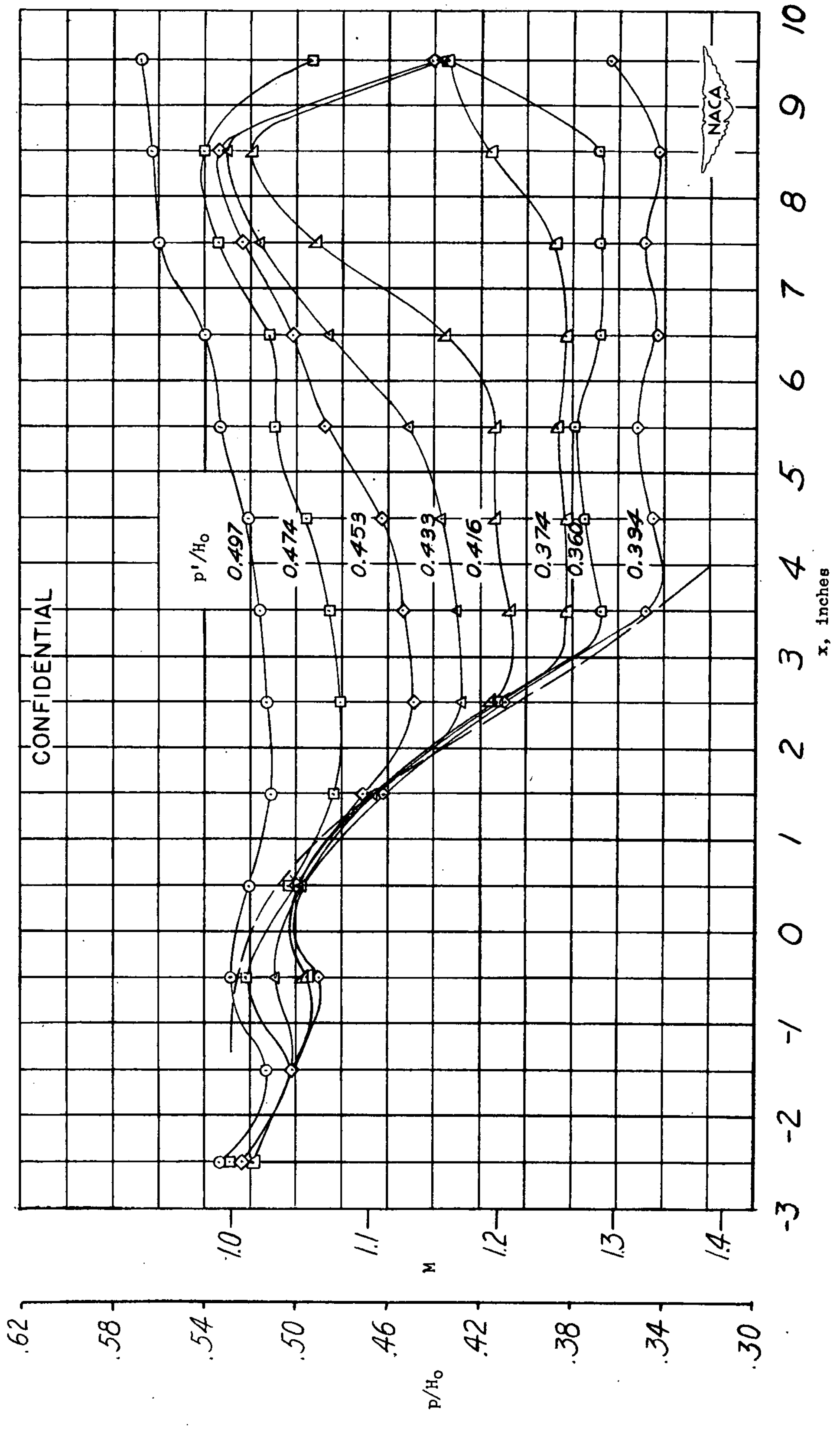

(b) Pressure distribution along reflection plane.

Figure 6.– Concluded.

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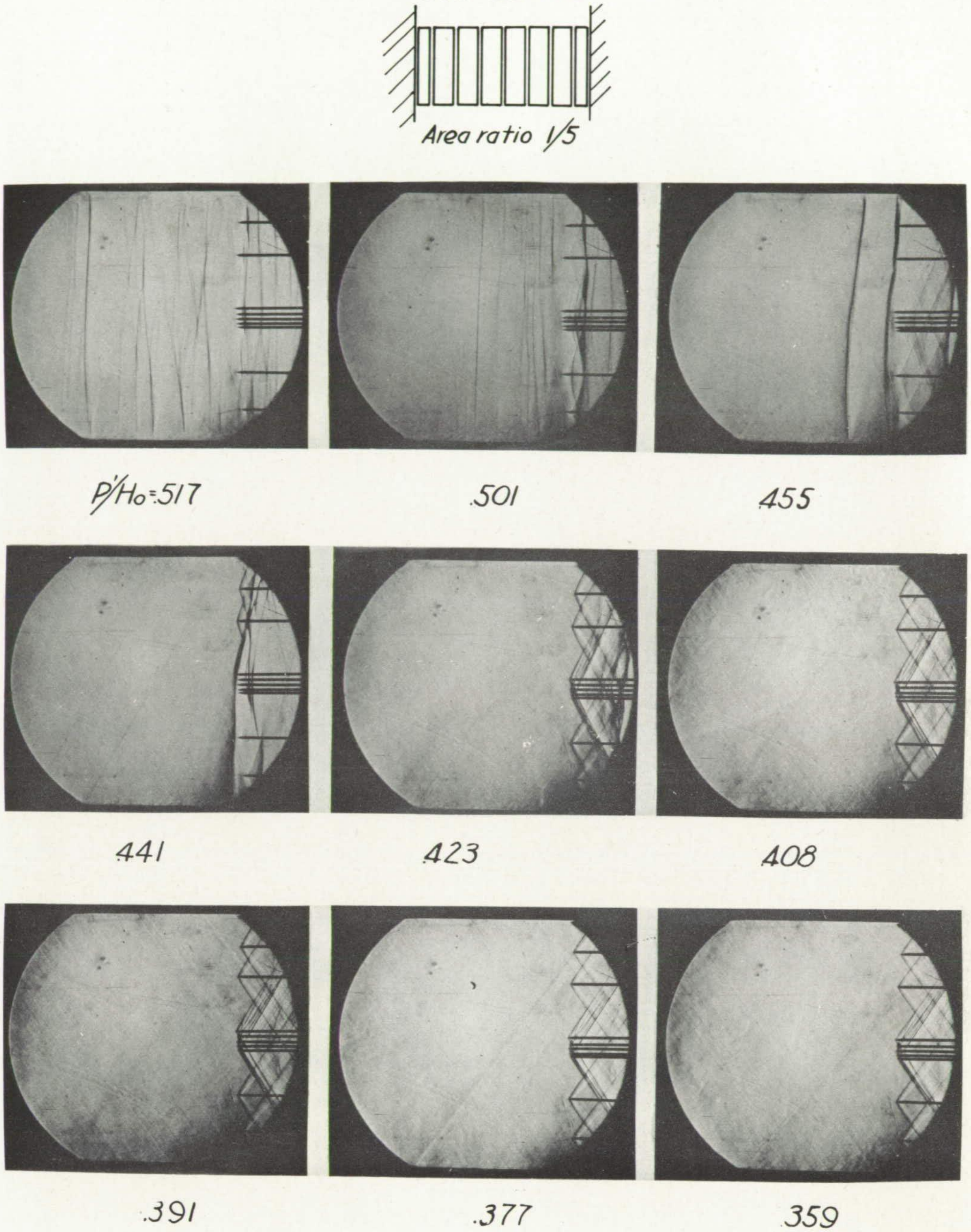

(a) Schlieren photographs. Slotted wall at top.

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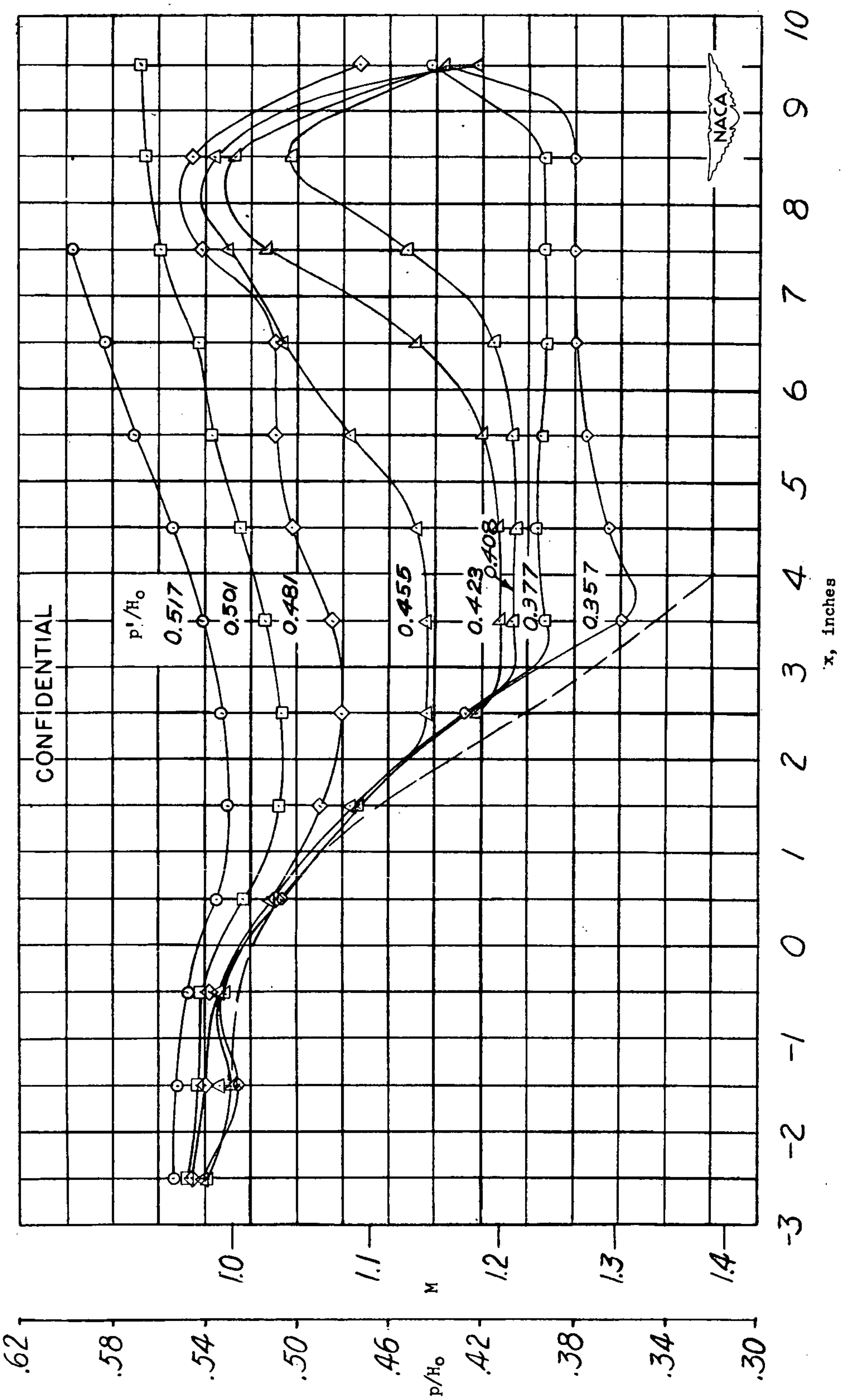
Figure 7.- Flow through rectangular tunnel with uniform longitudinal slots of 1-inch depth.



(b) Pressure distribution along reflection plane.

Figure 7.— Concluded.

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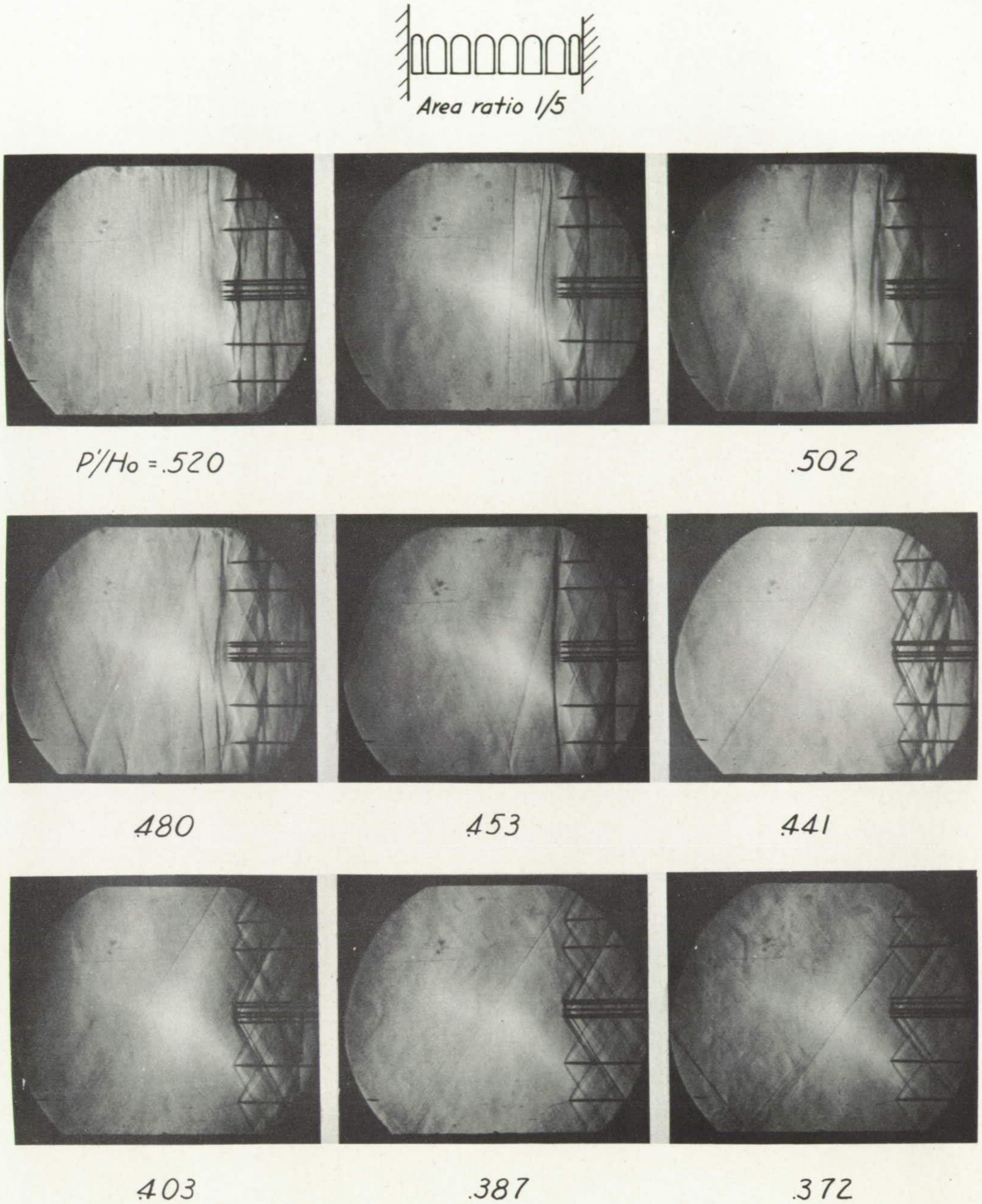
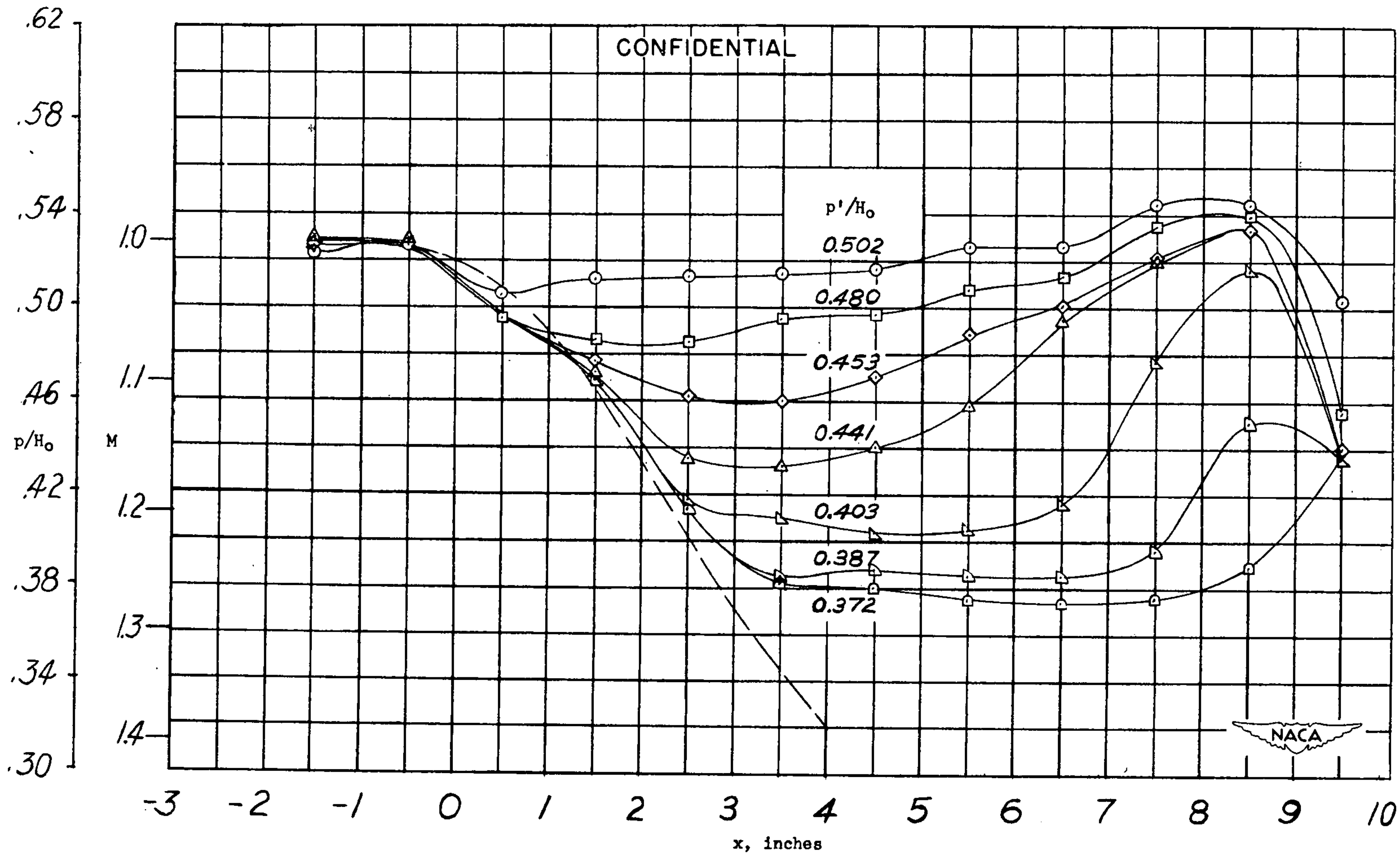


(a) Schlieren photographs. Slotted wall at top. L-59014

Figure 8.- Flow through rectangular tunnel with uniform longitudinal slots formed by cylindrical crowned bars.

CONFIDENTIAL



(b) Pressure distribution along reflection plane.

Figure 8.– Concluded.

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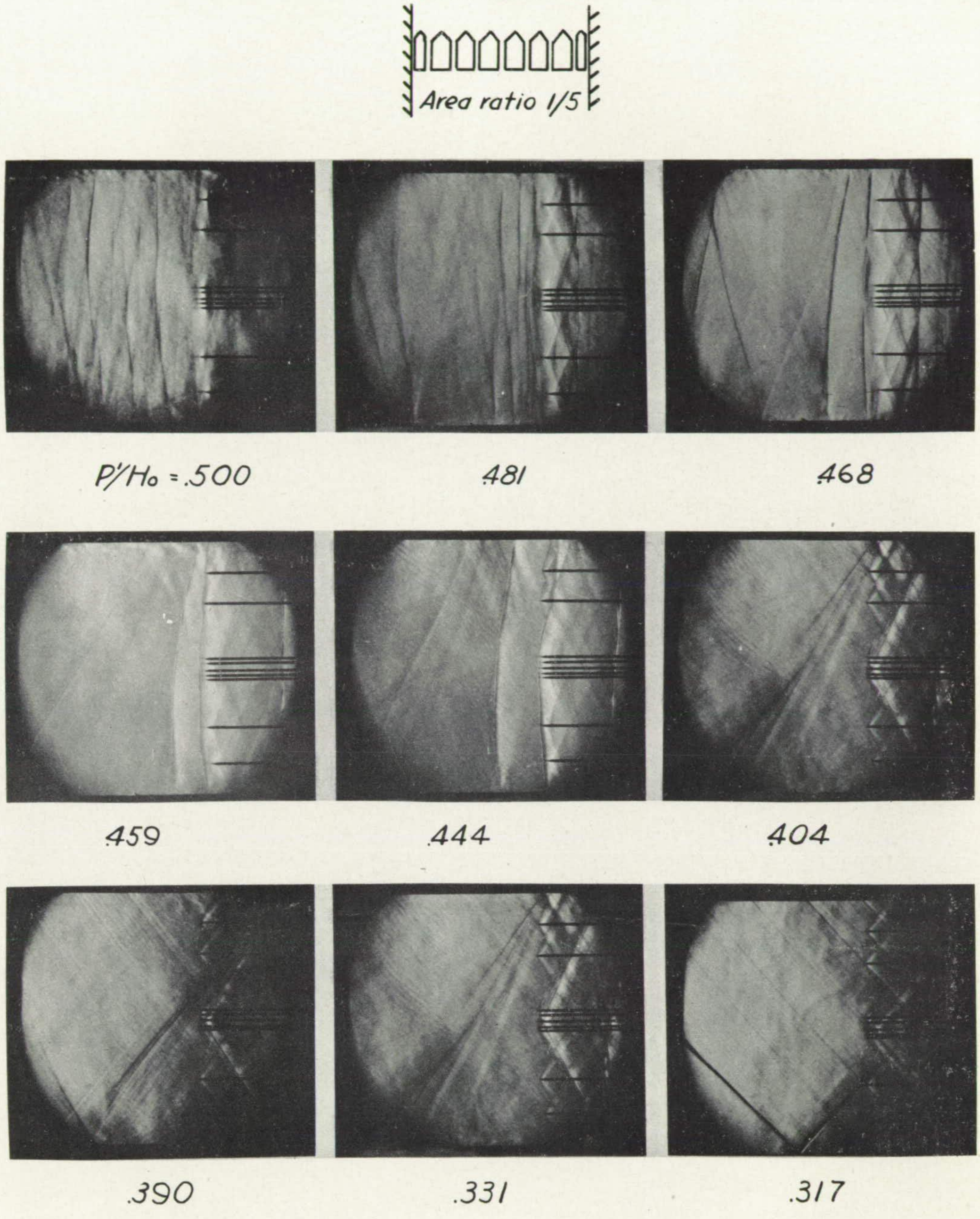

(a) Schlieren photographs. Slotted wall at top.

L-59011

Figure 9.– Flow through rectangular tunnel with uniform longitudinal slots formed by triangular crowned bars.

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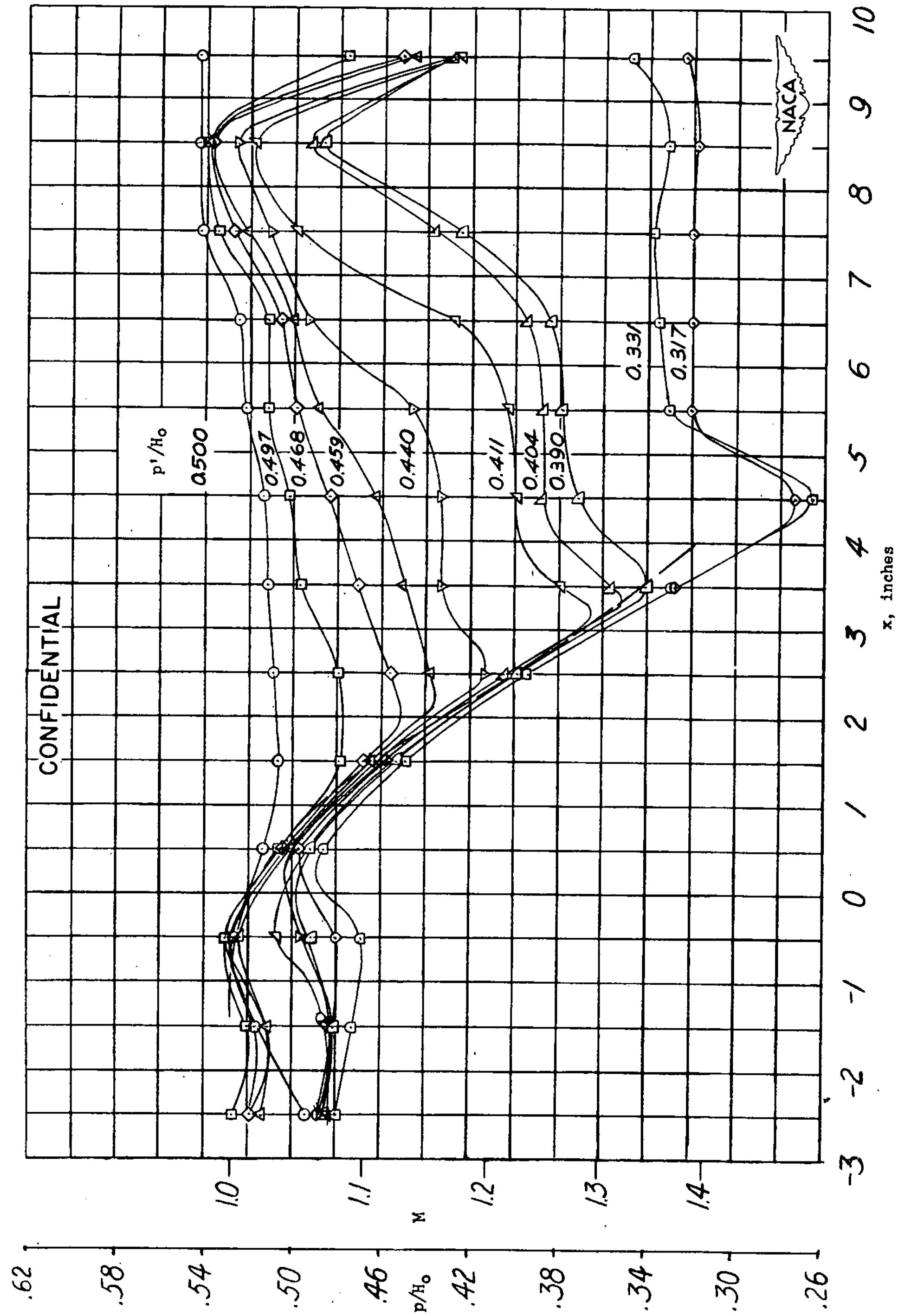

(b) Pressure distribution along reflection plane.

Figure 9.- Concluded.

CONFIDENTIAL

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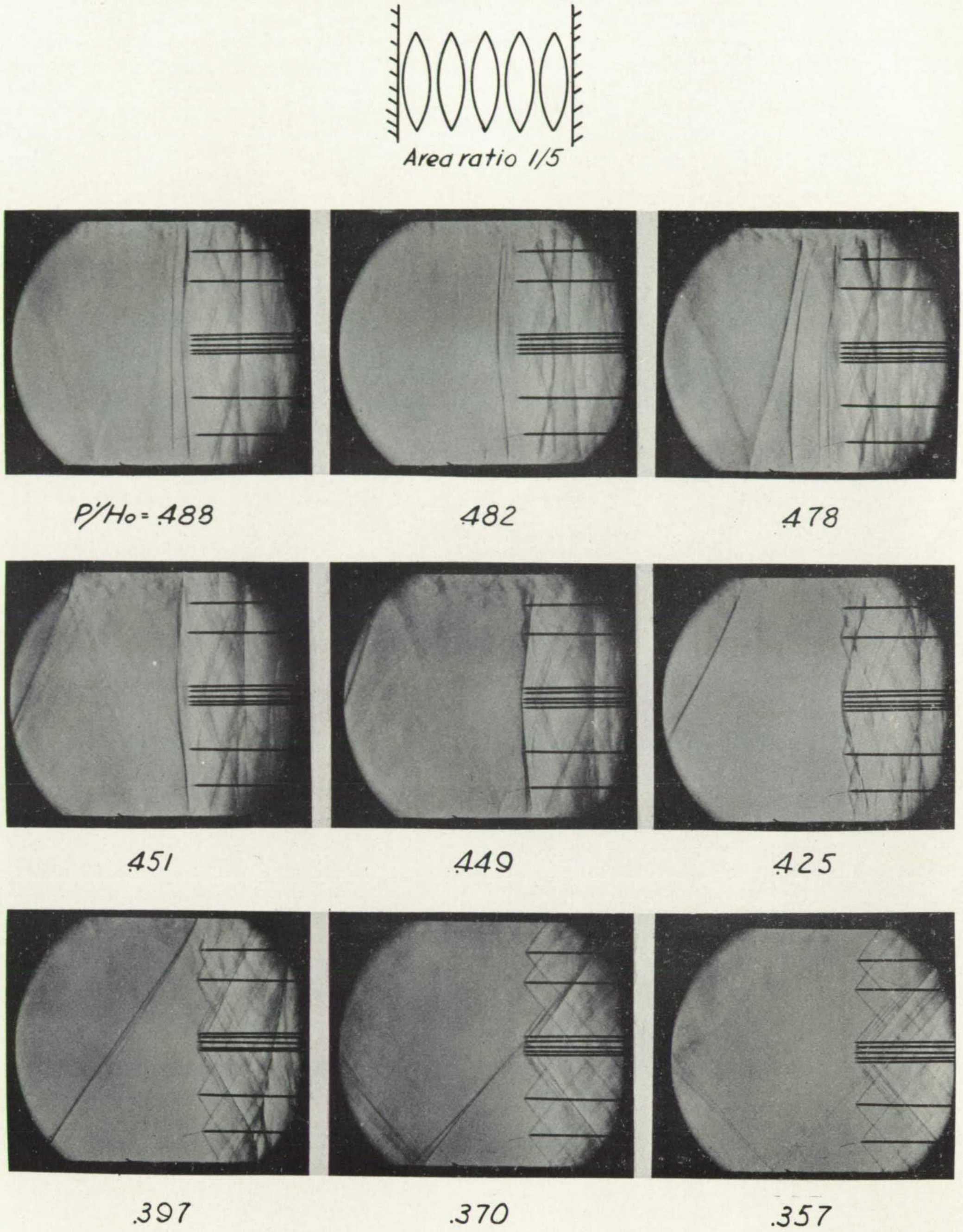

(a) Schlieren photographs. Slotted wall at top.

Figure 10.- Flow through rectangular tunnel with uniform longitudinal slots formed by lenticular bars with 45° apex angle.

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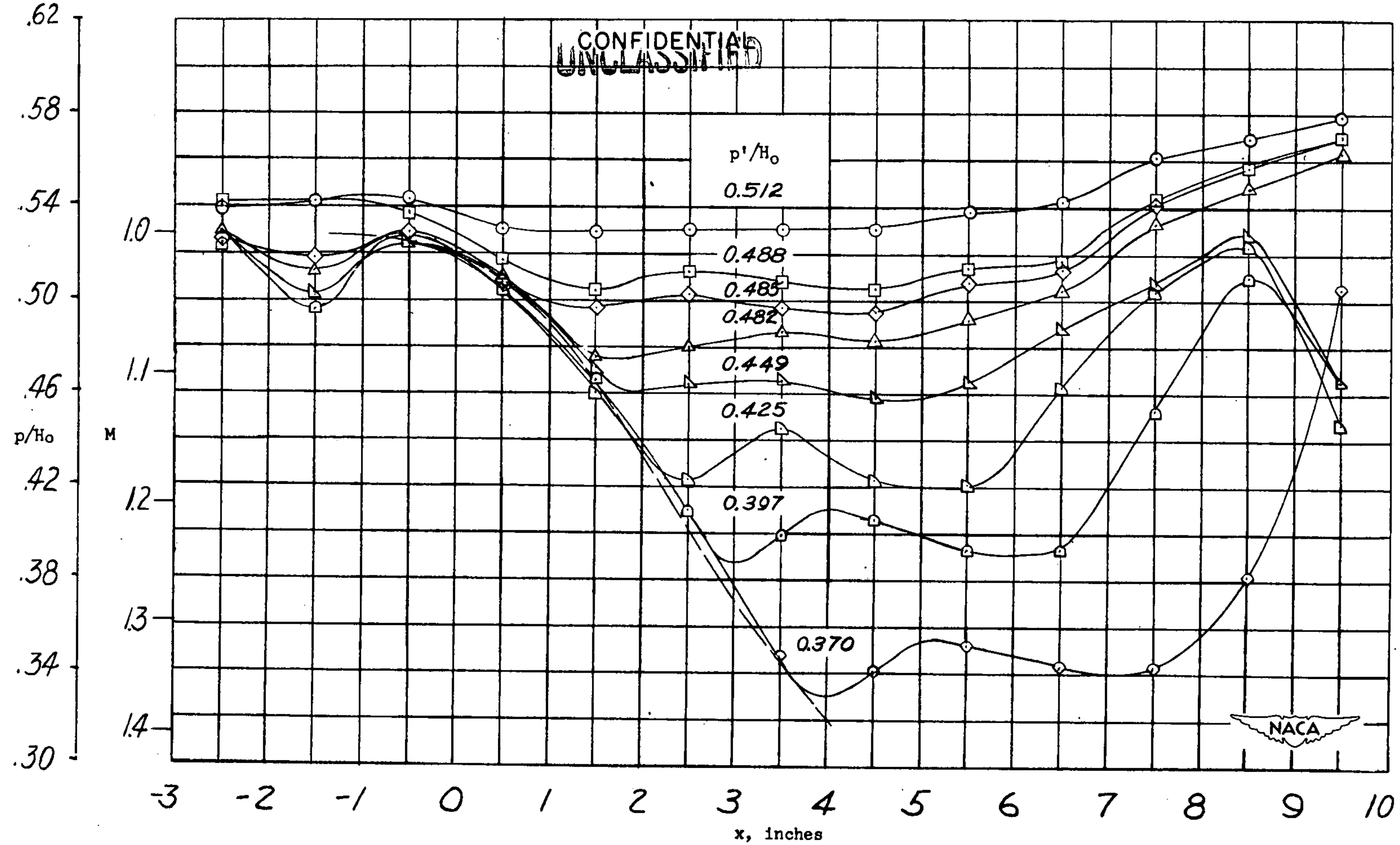
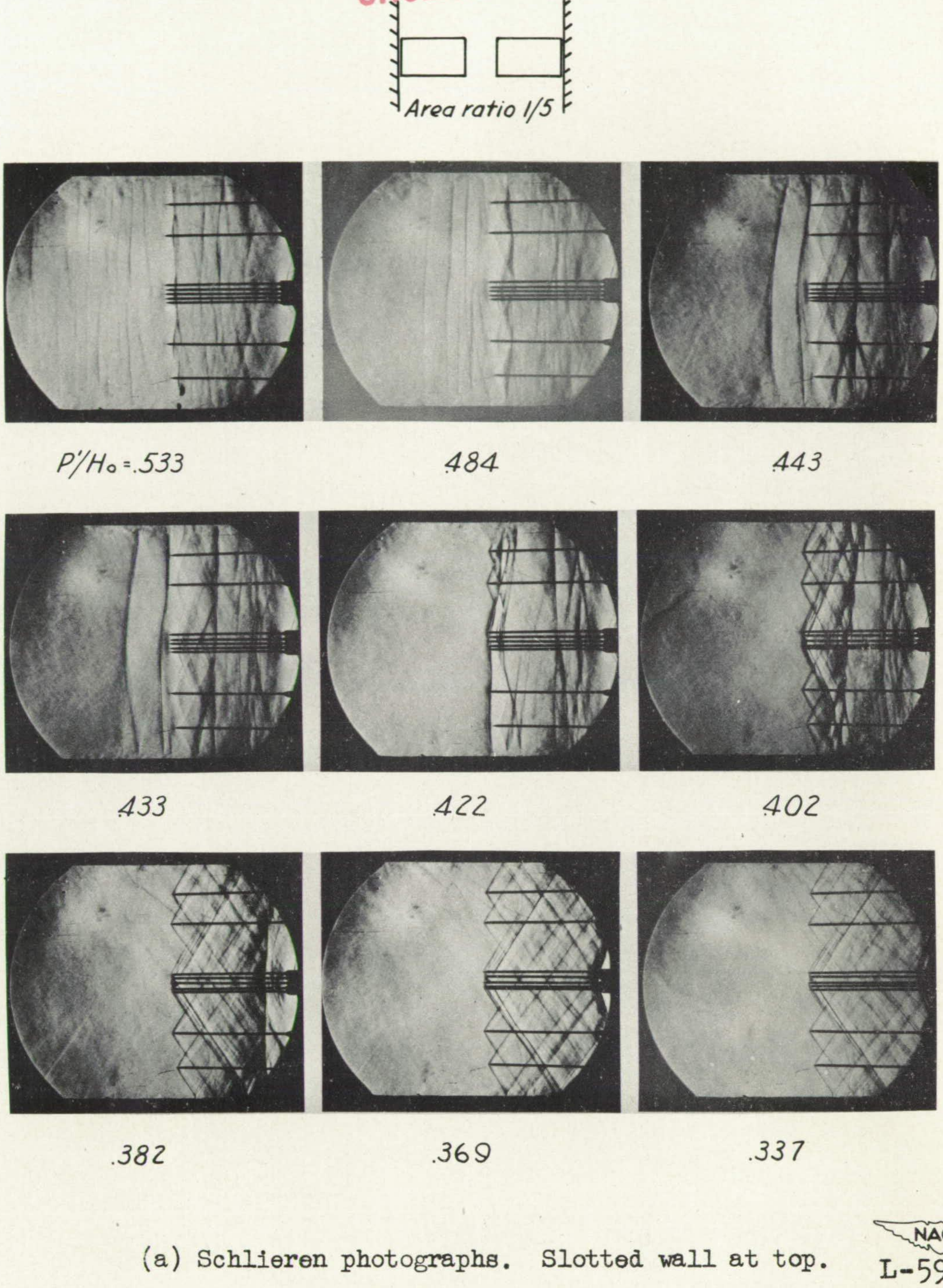


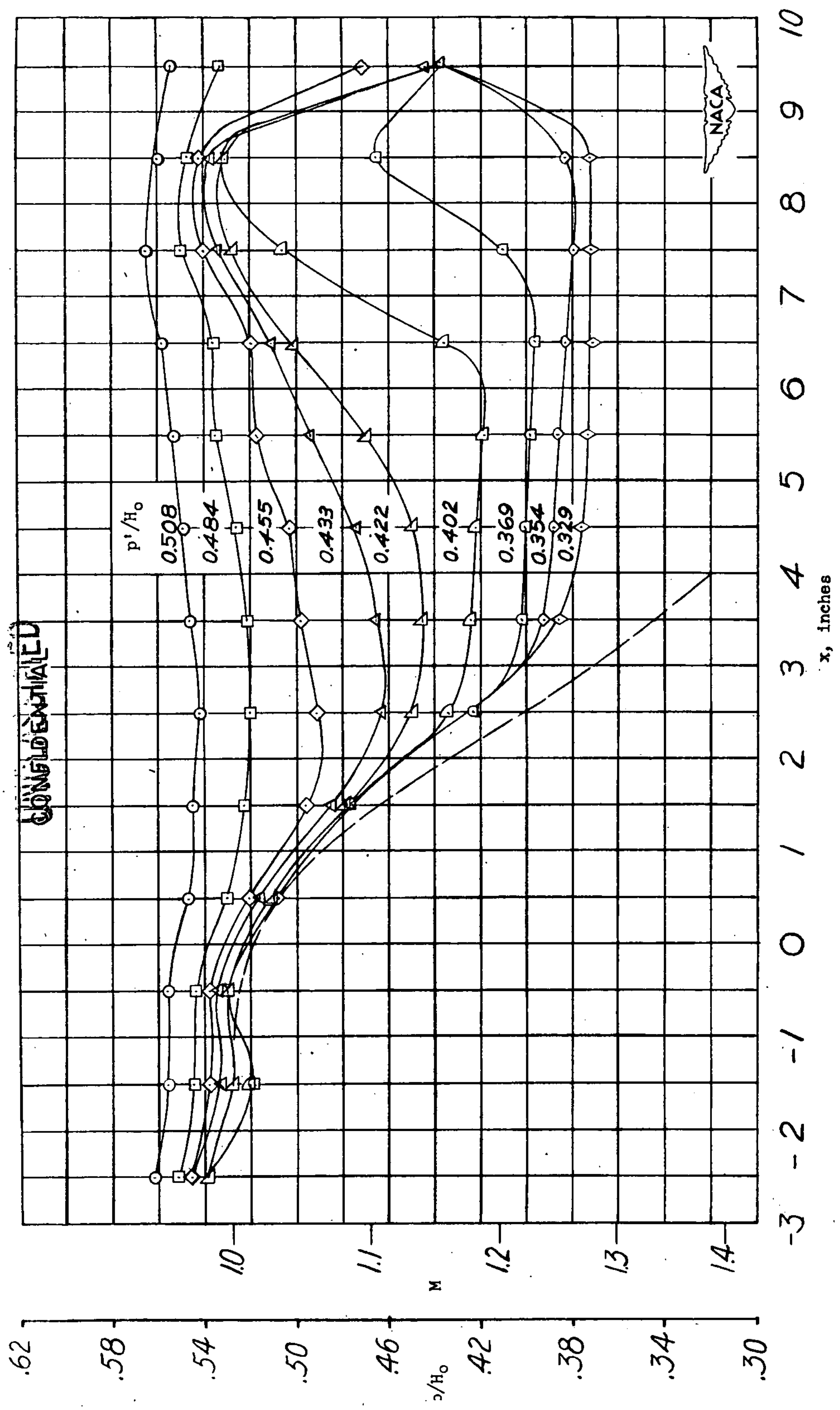
(b) Pressure distribution along reflection plane.

Figure 10.— Concluded.



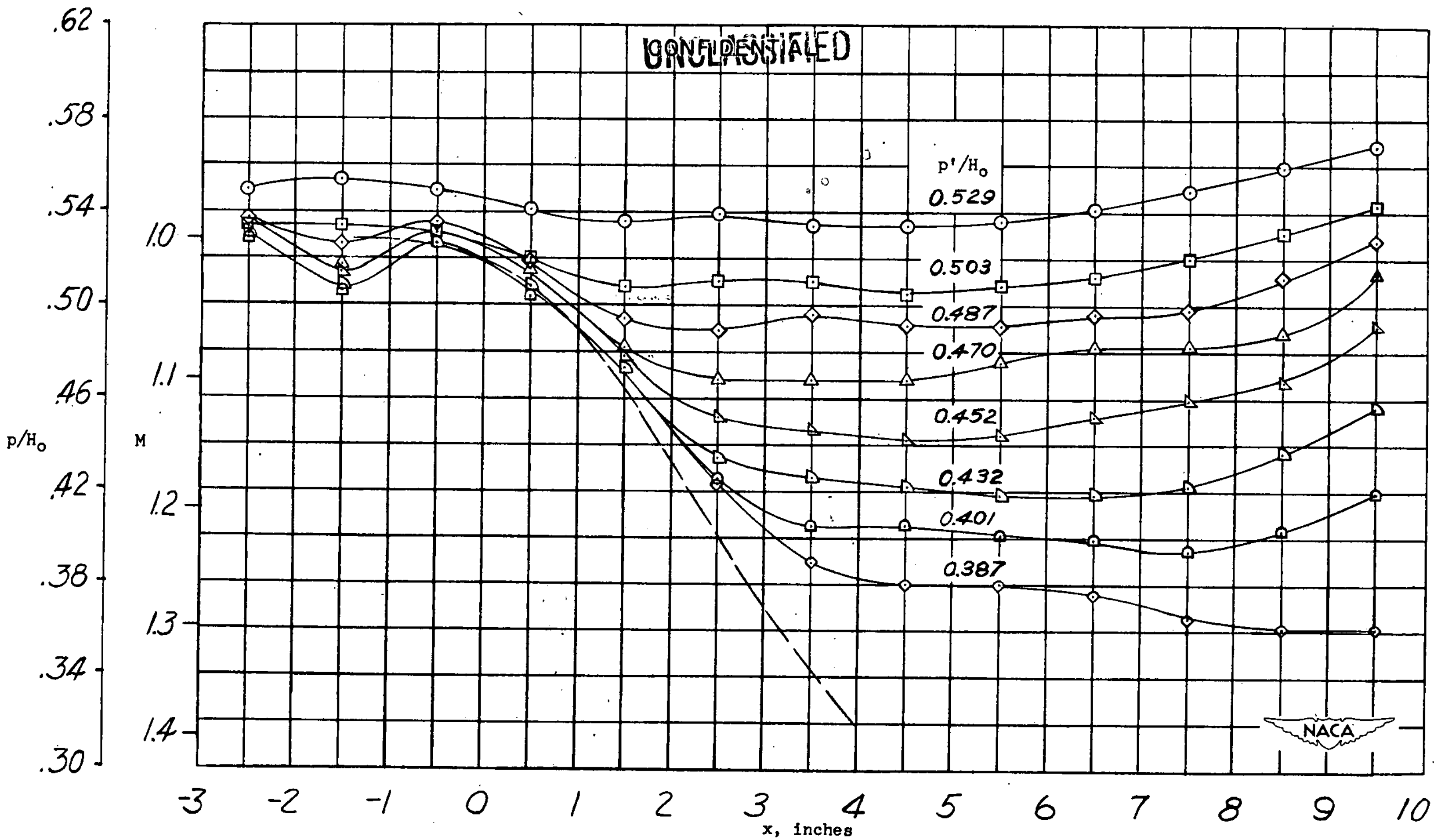
(a) Schlieren photographs. Slotted wall at top. L-59009

Figure 11.– Flow through rectangular tunnel with a uniform longitudinal slot of rectangular profile.



(b) Pressure distribution along reflection plane.

Figure 11.- Continued.



(c) Pressure distribution along reflection plane without survey probes.

Figure 11.- Concluded.