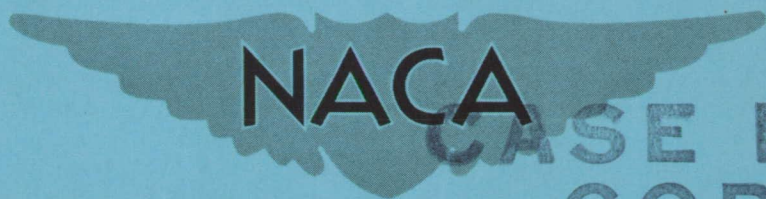


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RESEARCH MEMORANDUM

THE AERODYNAMIC DESIGN AND CALIBRATION OF AN ASYMMETRIC
VARIABLE MACH NUMBER NOZZLE WITH A SLIDING BLOCK
FOR THE MACH NUMBER RANGE 1.27 TO 2.75

By Paige B. Burbank and Robert W. Byrne

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

A method of designing an asymmetric, fixed-geometry, variable Mach number nozzle has been developed by using the method of characteristics. A small nozzle conforming to the analytically determined ordinates was constructed and calibrated over a range of Mach numbers extending from 1.27 to 2.75. The results show the variation in Mach number to be ± 0.02 or less and in the flow direction to be $\pm 0.2^\circ$ within the test section. The range of Mach numbers from 1.27 to 2.75 was obtained by translating the lower block in a straight line parallel to the test-section center line for a distance of 2.17 test-section heights.

INTRODUCTION

Interest in the design and operation of variable Mach number nozzles has increased considerably recently due to the planning and designing of a large number of large-scale supersonic research and development facilities. A scheme which permits the Mach number in the test section to be changed by changing the relative position of two nozzle blocks, each of which has fixed geometry, was first investigated at the Ames Aeronautical Laboratory and is reported in reference 1. This type of variable Mach number nozzle has several features which make it most suitable for rapid supersonic testing of aircraft and aircraft components which operate over a moderately large Mach number range. The most important features are the following: With a nozzle of this type it is possible to change the test Mach number continuously during the test run. Low starting compression ratio is obtainable for this tunnel since it can be started while in the low Mach number position and later moved to a high Mach number setting. This latter advantage also eases the structural problem connected with models and model



supports in that the starting loads can be reduced considerably. A simple variable second-minimum section can be combined with the translational movement of the block and low running pressure ratios obtained over the Mach number range. Since the Mach number is changed by a straight-line translation of one part, the mechanism required is simple. The time-consuming process of changing nozzle blocks with the fixed-block, single Mach number design, or of changing the nozzle contour with flexible walls, is eliminated.

In the experimental investigation reported in reference 1, a nozzle was obtained which gives fairly constant velocity at the axis of the test section in the range of Mach numbers between 0.8 and 2.0. However, an appreciable variation of velocity in a direction normal to the stream was found with a consequent curvature of the streamlines for supersonic Mach numbers. The turning of the test-section stream, corresponding to the data presented in reference 1, was of the order of 2° in the high Mach number range. The results of reference 1 were later duplicated on a large scale and reported in reference 2.

In 1948 work was begun at the Langley Aeronautical Laboratory on a program of developing a variable Mach number nozzle of the asymmetric, fixed-geometry type. The general arrangement was similar to that considered in reference 1. The upper and lower blocks of the nozzle are of fixed geometry (not flexible); one block is translated in a straight line with respect to the other and in this way a continuous variation of test-section Mach number is obtained. The translation is in the direction parallel to the direction of the stream in the test section, and, therefore, the dimensions of the test section are maintained constant while the Mach number is changed. However, in contrast with the design procedure used in reference 1, the program described herein began with an analytical determination of the nozzle shape by using a characteristic-net construction in designing the nozzle over the design Mach number range and basic design criteria given later, which are due to Dr. Antonio Ferri of the Langley Laboratory. The first step was the determination of a method of obtaining a satisfactory characteristic net over the range of Mach numbers considered. After the principles had been established and shown to give satisfactory nozzle designs, various methods of application, together with experimental investigations, were initiated at both the Ames and Langley Laboratories.

This paper presents the basic design method and experimental results of a calibration of a nozzle which was constructed to conform to the analytically determined ordinates. The range of Mach numbers over which the nozzle was calibrated extended from 1.27 to 2.75.

SYMBOLS

h_{min}	height of first minimum
h	height of test section
d	longitudinal positioning dimension for relative block positions
M	Mach number

NOZZLE DESIGN

A Mach number range extending from 1.7 to 2.6 was selected as being representative of a range which would be of most immediate interest. The actual Mach numbers were 1.71 and 2.63, which were selected to avoid interpolation in existing supersonic-flow tables. It was first assumed, and later checked analytically, that if a nozzle shape giving uniform flow in the test section could be determined for these two limits of the Mach number range, then good flow could be expected at the intermediate Mach numbers and also for a limited range of Mach numbers above and below the design range.

Three design criteria were set up to be followed throughout the design. The first criterion was that the nozzle contour was to have the second derivative of the same sign (without inflection points) in the supersonic-flow region. The second criterion was that the variation of the first derivative of the nozzle contour should be continuous and smooth throughout the nozzle length. The third criterion was that no compression waves were to be used in the characteristic design of the nozzles. The nozzle contour was to be designed without inflection points in order to eliminate flow discontinuities which, as will be apparent from the following discussion, are difficult to handle in the characteristic-net construction used in the nozzle design. The necessity of introducing compression waves into the characteristic net is thereby avoided and the third design criterion partially satisfied. It was desired to make the first derivative of the nozzle contour continuous and smooth so that a continuous variation of the flow phenomena could be expected over the Mach number range when one block is translated with respect to the other. This continuous variation of flow properties would also tend to insure uniform flow in the test section. The third criterion of not introducing compression waves into the net was chosen because compression waves tend to produce local thickening of the boundary layer and because these compression waves tend to collect and form a shock wave as they travel downstream.



In order to start the characteristic-net construction for the method presented herein, the shape of the sonic line must first be determined. In order to simplify the net construction it was decided that the subsonic entrance section should be designed in such a manner that the sonic line would be straight and perpendicular to the wall at the first minimum section. The analysis presented in reference 3 and experimental results of reference 4 show that, if the nozzle walls in the vicinity of the minimum section are parallel with zero curvature and the converging subsonic section approaching this region very gradual, a straight sonic line can be obtained. The subsonic portion of the nozzle and the minimum section were designed to respect these conditions throughout the Mach number range and a straight sonic line was used in the characteristic-net construction, thus eliminating the shape of the sonic line as a parameter in the nozzle design. Since one block was to remain fixed and the Mach number varied by translating the other block in a straight line, the position of the sonic line on one had to be kept fixed, while the sonic-line position on the other block moved along a portion of the surface which, therefore, had to be straight.

The details of the design procedure will be described by presenting it as it was applied to the particular problem of designing a nozzle for the previously mentioned Mach number range. The method can, of course, be applied to other Mach number ranges close to the one selected in this paper.

The first step in analytically determining the shape of the nozzle was to design a nozzle shape which would satisfy the conditions of uniform flow in the test section at the two design Mach numbers of 1.71 and 2.63. Since the amount of flow turning required to obtain a Mach number of 1.71 was reasonably small (18°), it was desirable to construct a characteristics net for this Mach number which was free of reflected waves. This procedure simplified the net construction and, as will be seen later, permitted a more accurate determination of the nozzle contour and kept the relative movement of the blocks to a minimum. Since the Mach number 1.71 net was to have 18° of turning to obtain the condition of no reflected waves and since the same nozzle shape had to develop a uniform flow at a Mach number of 2.63 (equivalent to 42° of turning) by simple translation in a straight line of one of the blocks, the net resulting from a Mach number 2.63 setting of the blocks would require 24° of flow expansion to be obtained by reflected expansions in the characteristic net for the higher Mach number. The procedure then was to first design the part of the 2.63 nozzle near the first-minimum section. For a first approximation to the nozzle shape, a characteristic net was constructed graphically for both Mach numbers with 2° expansion lines. The upper surface of the nozzle was maintained straight (A-B, fig. 1(a)) until a 24° difference in required expansion between the Mach numbers of 1.71 and 2.63 was made up by reflected waves. With

a 2° net, six reflections were required to make up the differences in flow expansion required (see fig. 1(a)). The lower-nozzle surface from point C to point D is used to create enough expansion waves for the required number of reflections in the region A-B on the upper surface. The initial selection of point spacing of the expansion waves from C-D is arbitrary; however, considerations of over-all nozzle length and the criterion of smooth changes in curvature make it desirable to limit the point spacing to small intervals of nearly uniformly changing length from the minimum to the test section. After the attainment of the required number of expansions in the region A-B, the upper-surface design was continued to point E which was the first point at which the upper surface had to curve in order to cancel an expansion wave. When point E was reached on the upper surface, the design of the net for the Mach number 2.63 nozzle was temporarily stopped. The first part of the lower surface (C-D) was then moved along a line inclined at an angle of 18° with respect to the straight line (A-B) on the first part of the upper block until the first 2° expansion line for $M = 1.71$ from point C hit the upper surface at the point E (see fig. 1(b)). In figure 1, the positions of the two Mach number settings are shown removed from each other for clarity. Expansion lines were then drawn (fig. 1(b)) from each of the points from C to D to the upper surface where they were canceled by curvature of the upper surface. Points of curvature for the upper surface were, therefore, established between the points E and F. The design of the Mach number 1.71 net was then stopped and the construction of the Mach number 2.63 net resumed. The curvature just determined from points E to F was placed in its proper position in the Mach number 2.63 net (fig. 1(c)). From the newly determined points of curvature between E and F, expansion lines were drawn with slopes suitable for the Mach number 2.63 net, down backwards to the lower nozzle surface. Some of these expansion lines, in addition to having to pass through the points between E and F determined from the Mach number 1.71 net construction (fig. 1(b)), had to also agree with the lines originating in the region C-D previously drawn for the $M = 2.63$ net, (fig. 1(a)). The lines which did not have to meet these requirements fell in the region D-G and determined a new portion of the lower surface contour (fig. 1(c)). For this particular example, expansion lines which fell in the region D-G could either be designed to originate in this region or designed as reflected waves in this region. The final choice in the design in this region was dictated by meeting the conditions set up in the design of the first set of expansion lines in figure 1(a). A cut-and-try process was necessary in order to make the $M = 1.71$ and $M = 2.63$ contours so far determined agree. This process consisted in adjusting the locations of the points of expansion in the two nets. The construction of the $M = 2.63$ net was temporarily stopped again and the newly determined portion of the lower surface, D-G, was then moved to its proper location on the Mach number 1.71 net, figure 1(d), and the shape of the upper surface from F to H was determined in the same

manner as the shape from E to F was determined in figure 1(b). A new portion of the upper surface was obtained (F-H) and the design of the Mach number 1.71 net was stopped and the design of the Mach number 2.63 net resumed. The portion of the upper surface (F-H) was then placed in its proper position on the Mach number 2.63 net (fig. 1(e)) and the shape of the lower surface between points G and I was determined in the same manner as the surface shape between points D and G in figure 1(c). This process of alternating between the designs of the two Mach number nets with point-spacing adjustments made to match up the expansion lines was continued until the 18° of turning required was obtained. The design was considered correct when the last expansion line from each net met at the same point on the upper surface and the upper and lower surfaces downstream of this last line were parallel and inclined at an angle of 18° with respect to the initial direction of the flow.

As mentioned previously, the method of design involves a process of cutting and trying between each step to obtain agreement between the two nets. A point-by-point correspondence between the two nets is not necessary and small variations in point spacing from one net to the other can be allowed. However, the difference between the slopes at any pair of corresponding points must remain within the precision to which the net is designed. After the first approximation to the nozzle shape was obtained by the construction of a 2° net for the two Mach numbers, an equivalent 1° net was constructed, figure 2. In the construction of the 1° net, adjustments in the location of the points of expansion were made, but they were small compared to those found necessary in the initial attempts made with the 2° nets shown in figure 1.

Characteristic nets were then constructed for three intermediate Mach numbers and Mach numbers of 1.6 and 2.8 by using the shape of the lower surface, as determined before, and finding the shape of the upper surface required to give uniform flow in the test section for the Mach number chosen. It was found that for a Mach number range between 1.6 and 2.8 the shape of the upper block agreed within the precision of the construction with the shape for the two design Mach numbers of 1.71 and 2.63. Characteristic nets were not constructed for Mach numbers lower than 1.6 because at the lower Mach numbers the nozzle becomes much longer than that required to produce uniform flow with the usual type of nozzle. It was thought, therefore, that the expansion process would be so gradual that fairly uniform velocity would be obtained in the test section.

Since the net for the lower design Mach number 1.71 was constructed so that each expansion wave originating from the lower surface was canceled by suitable curvature of the upper surface, it can be seen that the flow between any two of the characteristic lines of this net can be considered as the flow between two lines in a Prandtl-Meyer expansion

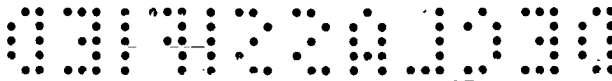
around a corner. The nozzle contour between these two lines then corresponds to two streamlines of the flow around that corner. Each pair of adjacent characteristic lines will, of course, have its own corner (see fig. 3); however, continuity of the first derivative can be maintained by setting the tangents to the streamlines (nozzle contour) at the beginning of the flow for any one corner (determined by a pair of characteristic lines) the same as that at the end of the preceding corner flow. Two corner locations are left undetermined in this process, the corner for the expansion from 0° to 1° (corner 0,1 fig. 3) and the corner for the expansion from 17° to 18° . The corner (0,1) can be determined by plotting the tangent of the nozzle contour for each point between the 1° and 17° points of expansion as a function of the length and fairing the curve to zero and 18° slope, respectively. The point of zero slope will then be point 0 in figure 3. The corner 0,1 can be determined by drawing a vertical line from point 0 until it intersects the line drawn from 1. The corner for the expansion from 17° to 18° can be treated in the same manner. Following this procedure, the entire shape of the nozzle can be calculated.

In applying this method to the design of nozzles for Mach number ranges much different from that considered in this paper, it may not be possible to follow exactly the procedure presented step by step. In fact, in a later design for a nozzle to cover the range from 2.5 to 5.0, it was found most practical to design a complete net for the higher Mach number, and while the upper surface is kept fixed, work backwards to design a new lower surface for the lower Mach number. The point spacings on the two lower surfaces were then compared and point spacings adjusted until the two curves agreed.

APPARATUS AND TESTS

The tests on the variable Mach nozzle were made in one of the blow-down jets of the Langley Gas Dynamics Branch. High-pressure air was throttled to the desired stagnation pressure and discharged through the two-dimensional asymmetric nozzle to the atmosphere.

The nozzle consisted of two solid dural nozzle blocks with a width of 3 inches and test-section height of 3 inches. The 3-inch test section was designed to begin at the point where the last line of the 1° net met the upper wall. No second-minimum section was provided (fig. 4). The ordinates for the blocks are given in tables I and II. The coordinate centers for these ordinates are given in the assembly drawing of figure 5. The Mach numbers shown on this figure for each position of the block are the theoretical Mach numbers for which the block was set. No correction was made to the nozzle to allow for the



boundary-layer-displacement thickness. Previous experience with symmetrical nozzles in this Mach number and Reynolds number range showed that neglecting the boundary layer resulted in a flow in the test section which was uniform within the precision of measurements but at a Mach number slightly less than the theoretical. The sonic and supersonic portions of the nozzle blocks were machined to a tolerance of ± 0.001 inch. The tolerance of the subsonic portion was ± 0.005 inch.

The Mach number was changed by simple translation of the lower block along a line parallel to the direction of the flow in the test section. The translation necessary to change the block setting for a Mach number of 1.27 to that for 2.75 amounted to 2.17 test-section heights. The dimensions used to set the relative position of the nozzle blocks for a given Mach number are shown in figure 5 and table III. These dimensions are h_{\min} , h , and the horizontal displacement of the lower nozzle block relative to the upper block d . The dimension h was maintained at a constant value of 3 inches for all Mach numbers.

Aerodynamically, it does not make any difference whether the lower or the upper block is moved. However, for practical testing considerations where a constant test-section position is to be maintained, the lower block has to be moved, while the upper-block position is kept fixed.

In the nozzle tests reported herein, a filler block was necessary to fair the lower block into the settling-chamber aperture. The side walls were bolted rigidly to the nozzle blocks. When the block setting (Mach number) was to be changed, one side wall was removed, the lower block shifted to the new position, and, together with the filler block corresponding to the new position, doweled and bolted into place between the two walls.

A nozzle (similar to the one described) in which the Mach number is to be changed during the test run and in which aerodynamic tests are to be performed could have the test-section axis horizontal and the entire subsonic geometry fixed for all Mach numbers.

The side walls used in the preliminary survey had windows which permitted the flow to be visualized along most of the supersonic section of the nozzle. The nozzle Mach number and direction surveys presented in this paper were made with solid side walls (without windows) to eliminate any disturbances which might originate at the window - side-wall juncture. The nozzle-block side-wall joint was metal to metal. A circular rod of rubber in a groove located on the block side wall $1/8$ inch below the nozzle surface was used for sealing (see fig. 4).

The Mach number distribution in the test section was determined by a static-pressure survey in the vertical center plane of the nozzle with a single static-pressure probe (fig. 6). Using a single probe was insurance against the necessity of calibrating each tube of a multitube rake in order to establish the Mach number level in the test section. A multitube rake small enough to fit in the 3- by 3-inch test section was subject to relatively large construction errors and deflections due to air loads during the test. In order to avoid choking at $M = 1.27$, a smaller probe was used (fig. 7). The static pressure was measured every $\frac{1}{12}h$ along the test-section center line in the vertical center plane and $\frac{1}{6}h$ above and below the test-section center line. The Mach number was calculated from the ratio of the settling chamber and local static pressures.

The direction of the flow was measured with a wedge probe (fig. 8) which had a static-pressure orifice on each side of the wedge. Measurements were taken every $\frac{1}{12}h$ along the tunnel center line. The wedge included angle (20°) was too great for an attached shock at $M = 1.25$. The method of determining the flow direction from the wedge measurements is outlined in reference 5.

An attempt was made to maintain the same Reynolds number at each Mach number from 1.27 to 2.75. However, since the nozzle was operated without a second minimum, the Reynolds number increased for the higher Mach numbers (see table IV) because high stagnation pressures were required in the tunnel running condition. The equivalent test-section height for a tunnel operating with atmospheric stagnation pressure is included in table IV. The Reynolds number of the table is referred to the test-section height.

RESULTS AND DISCUSSION

The summary of the results of the Mach number and flow-direction surveys are shown in figures 9 and 10. In these figures, the Mach number and flow direction at the center line are shown in the region of best flow near the end of the nozzle. The region of best flow was found to exist in a region upstream of the designed test-section region. This region (of the same dimensions of the designed test section) was chosen as that which had the least Mach number and flow deviation over the entire Mach number range. The region of best flow was found to be located at a distance $0.75h$ upstream of the designed test section (fig. 5). The displacement of the usable test region is believed partially due to the existence of a boundary layer on the nozzle surfaces



for which no correction was made and possibly due to the conditions existing at the end of the test section. The ambient pressure at the end of the test section was atmospheric, while the pressure of the jet at this point was below atmospheric pressure. Under these conditions it is possible for the boundary layer to separate upstream of the end of the test section and cause irregularities to occur in the flow at this point. With a closed tunnel it may be possible to extend the test region downstream. Except for the lowest test Mach number, the measured Mach number in the test section was less than the design Mach number for all Mach number settings. This is also probably due to the existence of the boundary layer.

The complete results of the tunnel calibrations are shown in figure 11. In this figure the test section for which good flow was found is indicated by solid vertical lines and the corresponding test rhombus by dashed lines. A compilation of the nozzle calibration results is given in table V where the Mach number and flow deviations are shown for all Mach numbers. It is possible, owing to the relatively large size of the wedge probe, that any concentrated disturbances striking the wedge ahead of the orifice would give twice the value of the actual variation in pressure existing at that point because of its reflection on one surface of the wedge and thus affect the flow angle measurements.

The results of the Mach number survey for a Mach number of 1.25 cannot be analyzed in the same manner as the results for the other Mach numbers, because when the probe was in the $\frac{1}{6}h$ position off the center line, the shock from the cone apex was reflected from the nozzle surface back onto the probe at a position very close to the static orifices. These readings, however, can be used to determine the variation in Mach number along each of the three longitudinal lines along which the survey was made. In table V it will be seen that the measured Mach number 1.27 was greater than the Mach number for which the block was set. For this case, the blocks were moved so far off the lower design condition that the sonic line cannot be assumed straight. When the blocks were set with the same criteria used to set the other block positions there was a section downstream of the position of the first minimum which had a cross-stream dimension slightly less than the h_{min} value used to set the nozzle blocks. A higher test-section Mach number than expected can be justified from these considerations.

The accuracy of measuring the Mach number and flow direction was determined from the scatter of test points obtained from several tests made under the same conditions. The accuracy of the flow direction was $\pm 1.0^\circ$ and the accuracy of the Mach number measurement was ± 0.01 .

Typical schlieren photographs taken during the preliminary runs are shown in figure 12 for Mach numbers of 1.54, 1.87, and 2.75. It can be seen that no large disturbances exist in the flow. The multitube rake shown in the photographs was that used in the preliminary surveys.

CONCLUSIONS

A method of designing an asymmetric, fixed-geometry, variable Mach number nozzle has been developed using the method of characteristics. A small nozzle conforming to the analytically determined ordinates was constructed and calibrated over a range of Mach numbers extending from 1.27 to 2.75. The results show the variation in Mach number to be ± 0.02 or less and in the flow direction to be $\pm 0.2^\circ$ within the test section. The range of Mach numbers from 1.27 to 2.75 was obtained by translating the lower block in a straight line parallel to the test-section center line for a distance of 2.17 test-section heights.

The length of the nozzle from the minimum section to the beginning of the experimental test section for $M = 2.75$ was 4.87 test-section heights.

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TABLE I
VARIABLE MACH NUMBER NOZZLE - UPPER BLOCK ORDINATES

X	Y	X	Y	X	Y	X	Y
1.039	9.760	6.750	7.999	12.375	6.926	22.875	6.768
1.125	9.732	6.875	7.967	12.500	6.913	23.000	6.765
1.250	9.692	7.000	7.935	12.625	6.900	23.125	6.762
1.375	9.651	7.125	7.903	12.750	6.889	23.250	6.756
1.500	9.610	7.250	7.872	12.875	6.877	23.375	6.748
1.625	9.570	7.375	7.840	13.000	6.867	23.500	6.736
1.750	9.529	7.500	7.810	13.125	6.857	23.625	6.723
1.875	9.489	7.625	7.780	13.250	6.848	23.750	6.708
2.000	9.448	7.750	7.750	13.375	6.839	23.875	6.691
2.125	9.407	7.875	7.720	13.500	6.831	24.000	6.672
2.250	9.367	8.000	7.691	13.625	6.824	24.125	6.652
2.375	9.326	8.125	7.662	13.750	6.817	24.250	6.626
2.500	9.286	8.250	7.633	13.875	6.811	24.375	6.596
2.625	9.245	8.375	7.605	14.000	6.805	24.625	6.531
2.750	9.205	8.500	7.577	14.125	6.800	24.875	6.459
2.875	9.164	8.625	7.550	14.250	6.796	25.125	6.382
3.000	9.123	8.750	7.523	14.375	6.792	25.375	6.296
3.125	9.082	8.875	7.496	14.500	6.789	25.625	6.200
3.250	9.042	9.000	7.470	14.625	6.787	25.875	6.089
3.375	9.001	9.125	7.444	14.750	6.785	26.125	5.972
3.500	8.961	9.250	7.419	14.875	6.783	26.375	5.844
3.625	8.921	9.375	7.394	15.000	6.782	26.625	5.699
3.750	8.880	9.500	7.369	15.125	6.781	26.875	5.514
3.875	8.840	9.625	7.345	15.250	6.780	27.125	5.279
4.000	8.800	9.750	7.321	15.375	6.779	27.375	4.970
4.125	8.760	9.875	7.298	15.500	6.779	27.625	4.558
4.250	8.721	10.000	7.275	15.625	6.779	27.875	4.042
4.375	8.681	10.125	7.252	15.750	6.779	28.125	3.560
4.500	8.642	10.250	7.230	15.875	6.778	28.375	3.175
4.625	8.604	10.375	7.208	16.000	6.778	28.625	2.890
4.750	8.565	10.500	7.187	16.125	6.778	28.875	2.692
4.875	8.528	10.625	7.166	16.250	6.778	29.125	2.570
5.000	8.490	10.750	7.146	16.375	6.778	29.375	2.512
5.125	8.453	10.875	7.126	16.500	6.778	29.625	2.500
5.250	8.417	11.000	7.106	16.625	6.778	29.875	2.500
5.375	8.379	11.125	7.087	21.625	6.778	30.125	2.500
5.500	8.343	11.250	7.069	21.750	6.778	30.375	2.500
5.625	8.308	11.375	7.051	21.875	6.777	30.625	2.478
5.750	8.272	11.500	7.033	22.000	6.776	30.875	2.438
5.875	8.237	11.625	7.016	22.125	6.776	31.125	2.381
6.000	8.202	11.750	7.000	22.250	6.775	31.375	2.299
6.125	8.168	11.875	6.984	22.375	6.774	31.625	2.186
6.250	8.133	12.000	6.969	22.500	6.773	31.875	2.021
6.375	8.100	12.125	6.954	22.625	6.772	32.125	1.771
6.500	8.066	12.250	6.940	22.750	6.770	32.375	1.440
6.625	8.033					32.500	1.250





TABLE II
VARIABLE MACH NUMBER NOZZLE - LOWER BLOCK ORDINATES

X	Y	X	Y	X	Y
0	5.055	11.875	8.912	17.625	10.264
.375	5.177	11.976	8.945	17.750	10.279
.625	5.258	12.125	8.993	17.875	10.294
.875	5.340	12.250	9.032	18.000	10.308
1.125	5.421	12.375	9.071	18.125	10.320
1.375	5.502	12.500	9.109	18.250	10.329
1.625	5.583	12.625	9.147	18.375	10.337
1.875	5.664	12.750	9.185	18.500	10.343
2.125	5.746	12.875	9.223	18.625	10.349
2.375	5.827	13.000	9.260	18.750	10.354
2.625	5.908	13.125	9.296	18.875	10.359
2.875	5.989	13.250	9.332	19.000	10.360
3.125	6.070	13.375	9.368	19.125	10.361
3.375	6.152	13.500	9.403	19.250	10.362
3.625	6.233	13.625	9.437	19.375	10.363
3.875	6.314	13.750	9.471	19.500	10.364
4.125	6.395	13.875	9.504	19.625	10.365
4.375	6.476	14.000	9.537	19.750	10.365
4.625	6.558	14.125	9.570	19.875	10.365
4.875	6.639	14.250	9.602	21.125	10.361
5.125	6.720	14.375	9.634	21.375	10.359
5.375	6.801	14.500	9.666	21.625	10.358
5.625	6.882	14.625	9.698	21.875	10.357
5.875	6.964	14.750	9.729	22.125	10.354
6.125	7.045	14.875	9.760	22.375	10.351
6.375	7.126	15.000	9.789	22.625	10.340
6.625	7.207	15.125	9.817	22.875	10.325
6.875	7.288	15.250	9.845	23.125	10.305
7.125	7.370	15.375	9.873	23.375	10.277
7.375	7.451	15.500	9.900	23.625	10.243
7.625	7.532	15.625	9.926	23.875	10.198
7.875	7.613	15.750	9.952	24.125	10.145
8.125	7.694	15.875	9.978	24.375	10.085
8.375	7.776	16.000	10.002	24.625	10.013
8.625	7.857	16.125	10.026	24.875	9.923
8.875	7.938	16.250	10.049	25.125	9.823
9.125	8.019	16.375	10.072	25.375	9.698
9.375	8.100	16.500	10.094	25.625	9.537
9.625	8.182	16.625	10.115	25.875	9.343
9.875	8.263	16.750	10.136	26.125	9.113
10.125	8.344	16.875	10.157	26.375	8.813
10.375	8.425	17.000	10.177	26.625	8.467
10.625	8.506	17.125	10.197	26.875	8.099
10.875	8.587	17.250	10.215	27.125	7.668
11.125	8.668	17.375	10.232	27.375	7.185
11.375	8.750	17.500	10.248	27.625	6.683
11.625	8.831			27.720	6.500

TABLE III
POSITIONING DIMENSIONS FOR NOZZLE BLOCKS

Theoretical Mach number	h_{\min}/h	d/h
1.25	0.96	1.73
1.60	.80	1.26
1.71	.74	1.07
1.90	.64	.77
2.20	.50	.33
2.63	.34	-.17
2.80	.29	-.33



TABLE IV
TEST REYNOLDS NUMBERS

Measured Mach number	Test Reynolds number	Equivalent test-section height for atmospheric stagnation pressure (ft)
1.27	5.25×10^6	1.185
1.54	5.39	1.270
1.66	5.54	1.355
1.87	5.16	1.355
2.15	5.47	1.610
2.57	6.32	2.290
2.75	6.13	2.460



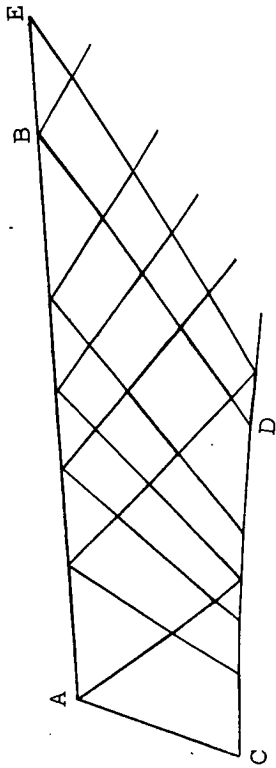
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TABLE V
SUMMARY OF NOZZLE-CALIBRATION RESULTS

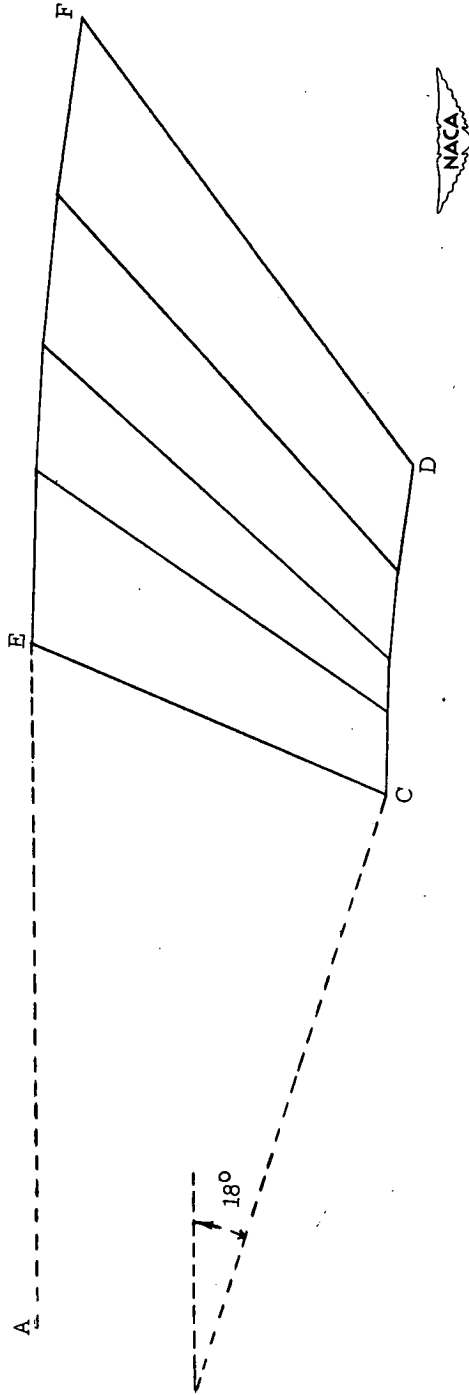
Theoretical Mach number	Measured Mach number	Mach number variation, experimentally determined test region	Mach number variation, test rhombus	Flow-direction variation, test-region center line (deg)	Flow-direction variation, test-rhombus center line (deg)
1.25	1.27	±0.020	±0.020	-----	-----
1.60	1.54	±.015	±.015	±0.18	±0.25
1.71	1.66	±.015	±.015	±.17	±.17
1.90	1.87	±.010	±.010	±.22	±.37
2.20	2.15	±.020	±.020	±.15	±.23
2.63	2.57	±.010	±.015	±.11	±.17
2.80	2.75	±.017	±.025	±.08	±.235



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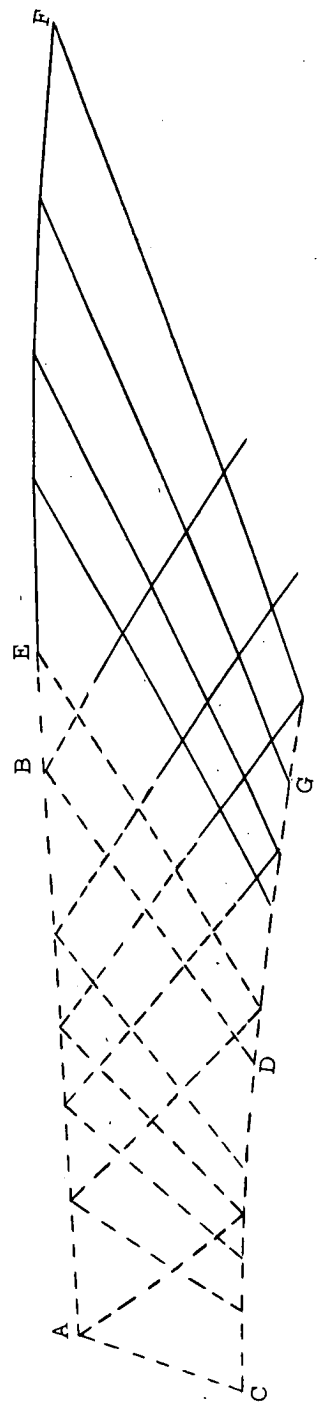


(a) $M = 2.63$.

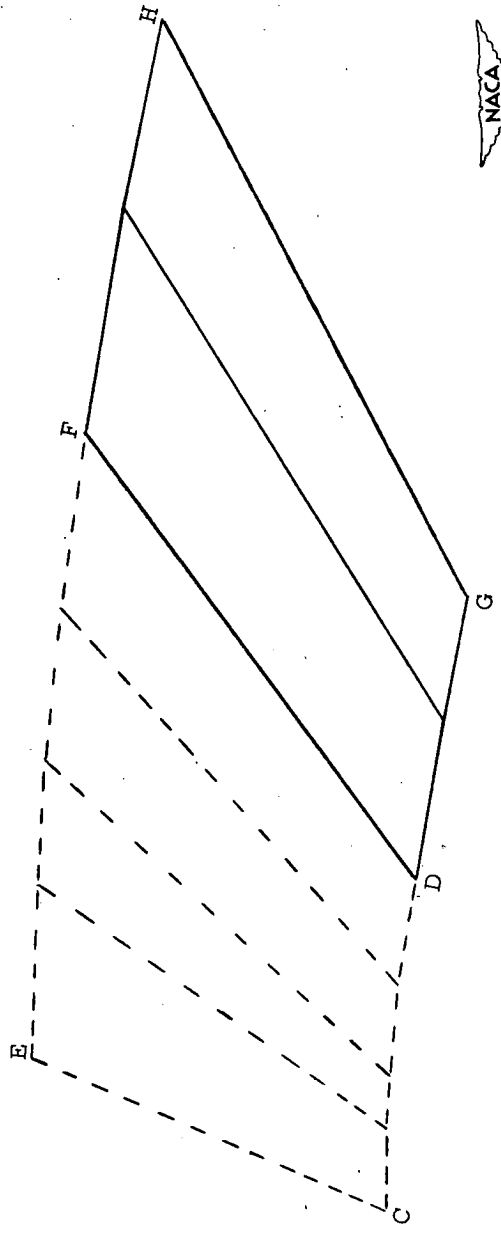


(b) $M = 1.71$.

Figure 1.- 2° characteristic-net construction.



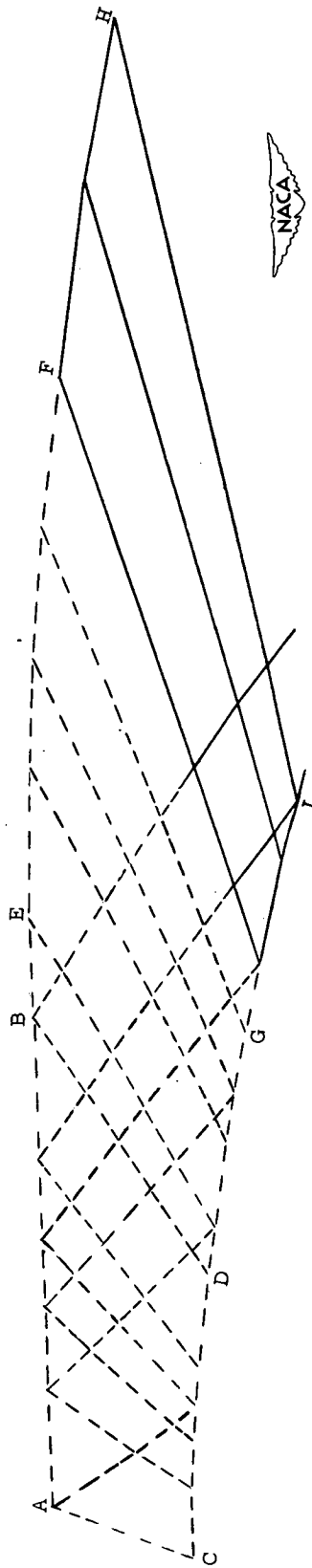
(c) $M = 2.68$.



(d) $M = 1.71$.



Figure 1.- Continued.



(e) $M = 2.63$.

Figure 1.- Concluded.

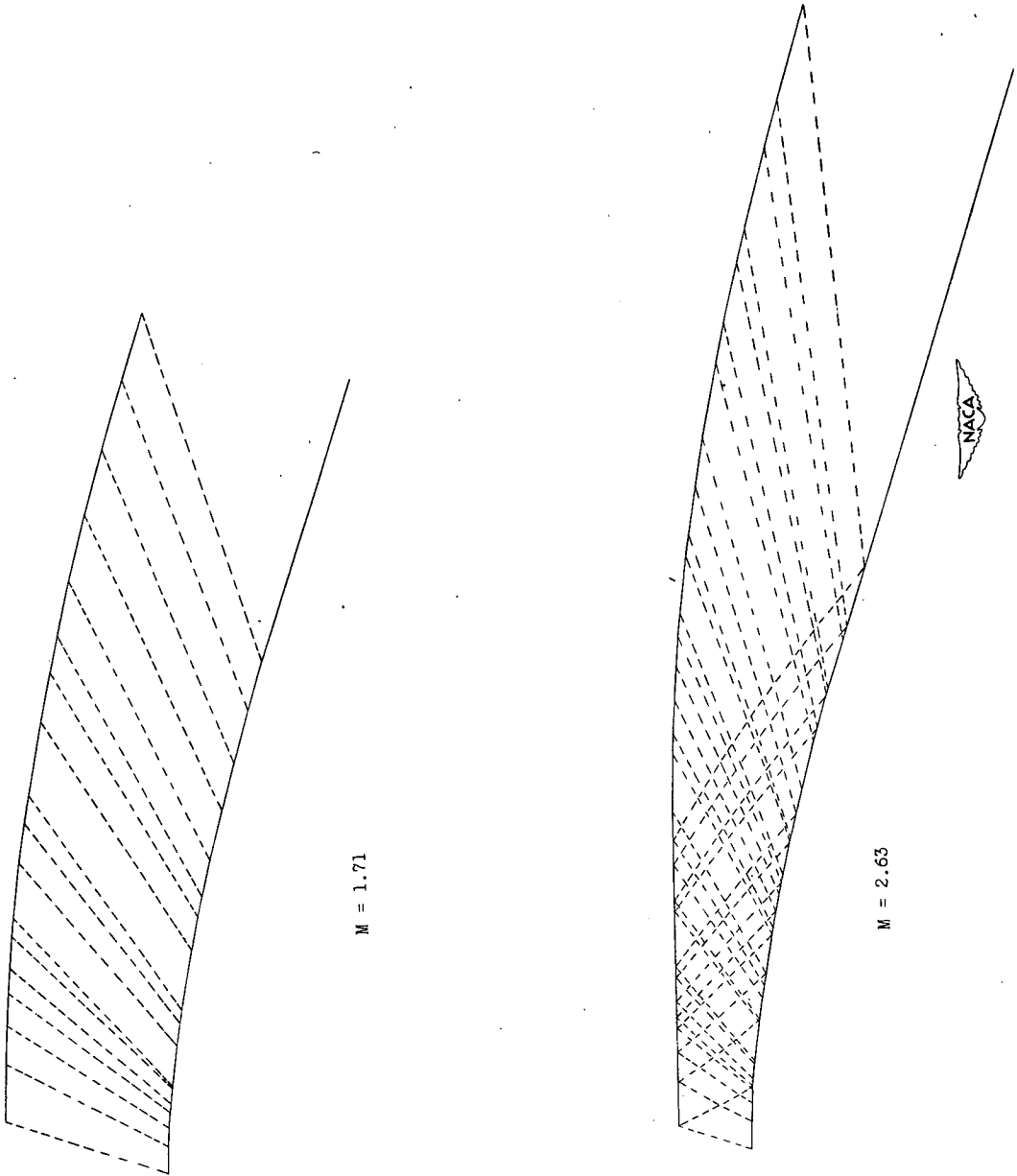


Figure 2.- 1° characteristic-net construction.

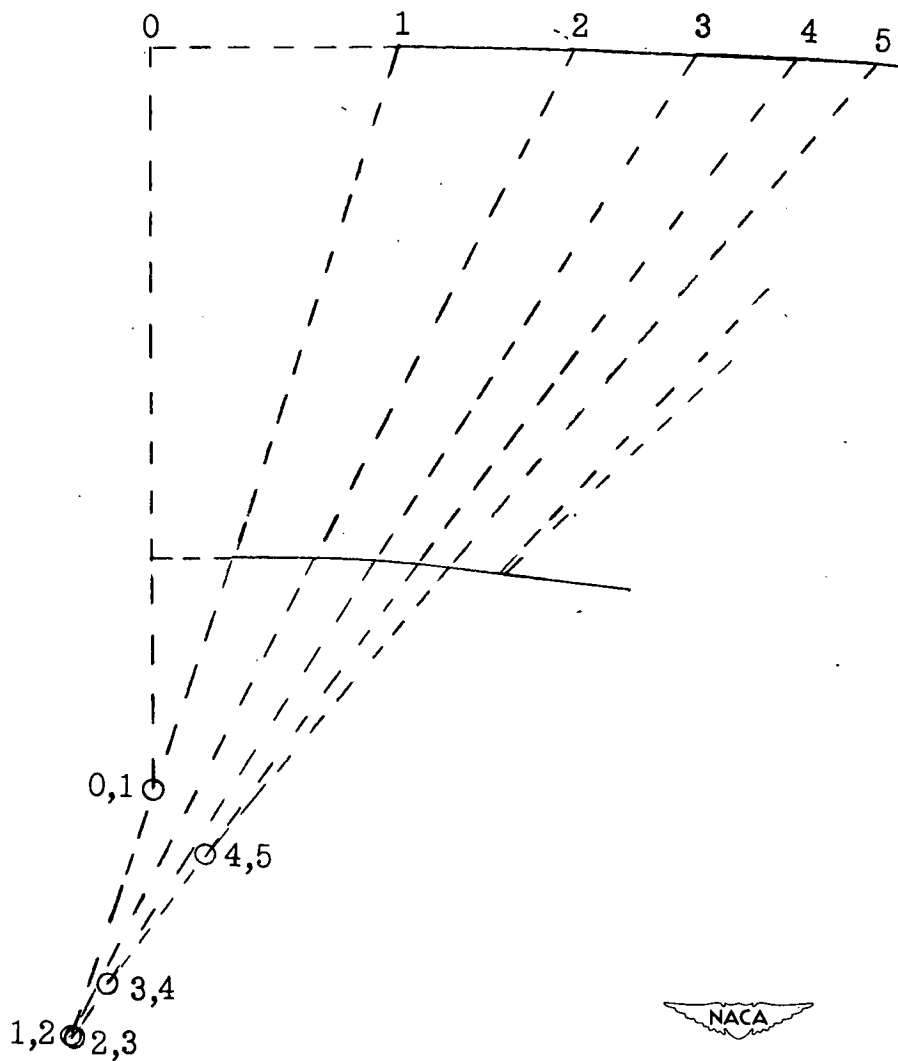


Figure 3.- Corner flow construction. $M = 1.71$.



Figure 4.- Photograph of nozzle assembly.

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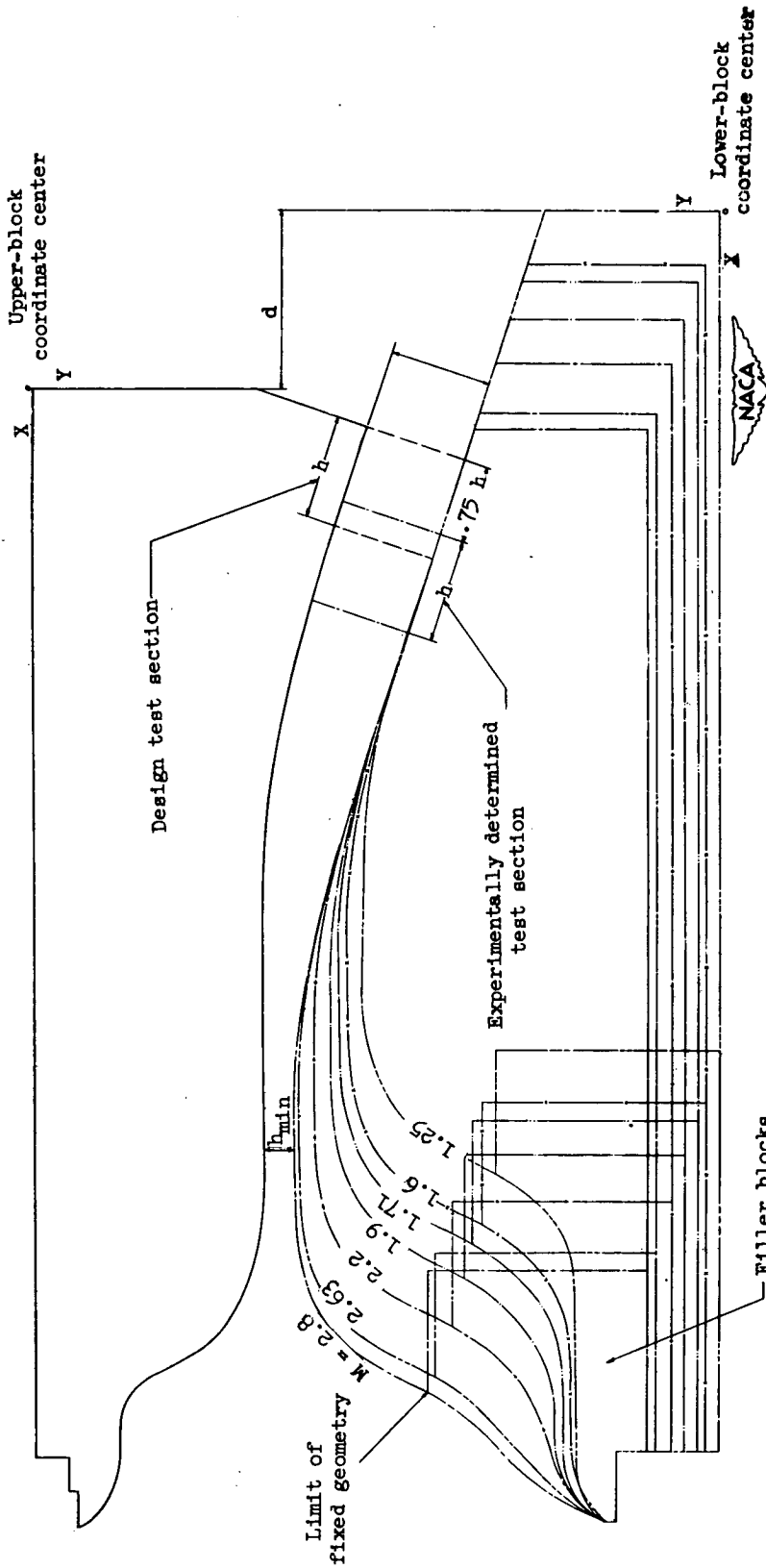


Figure 5.- Assembly drawing of nozzle blocks.

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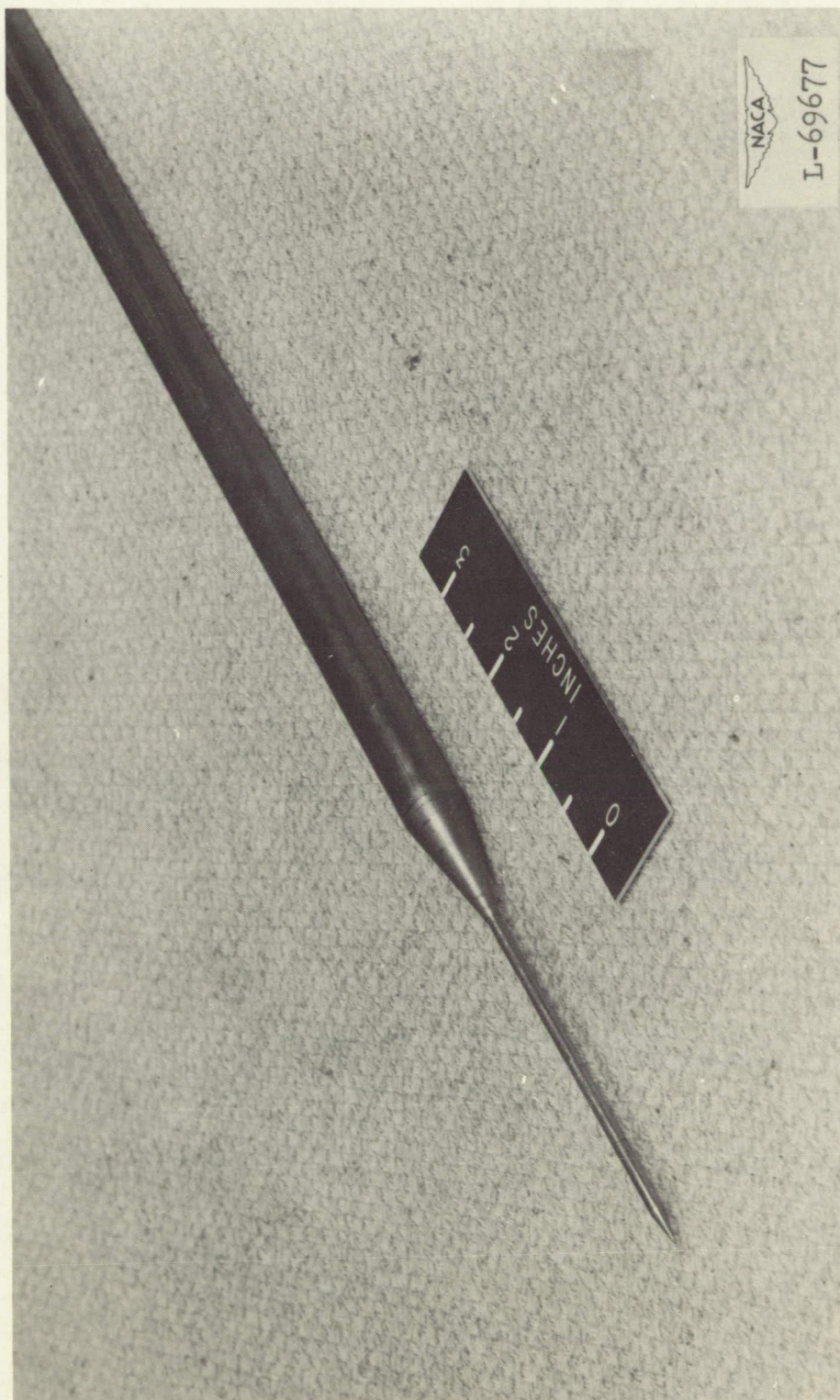


Figure 6.- Static-pressure probe.

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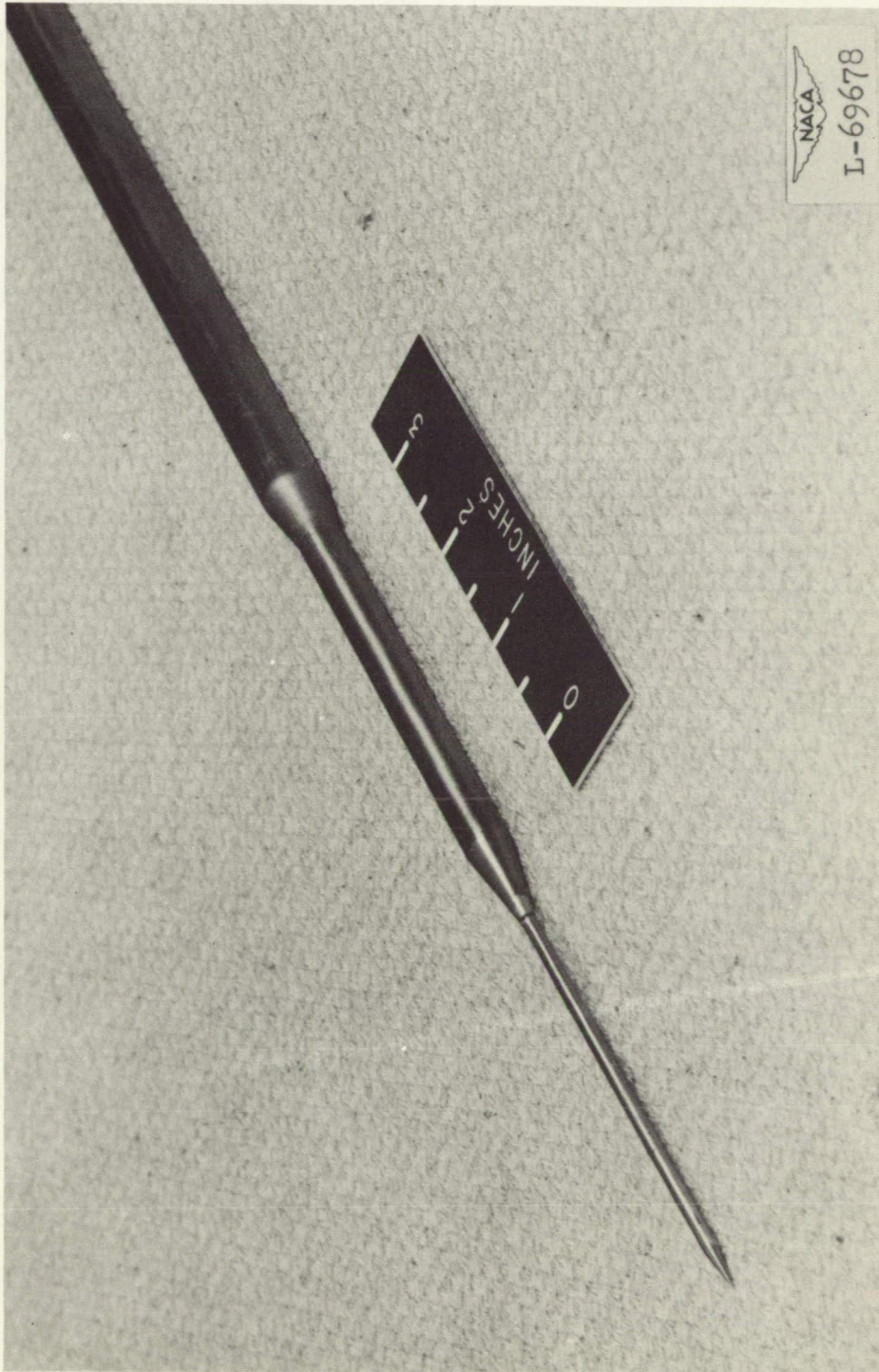


Figure 7.- Static-pressure probe used at $M = 1.27$.

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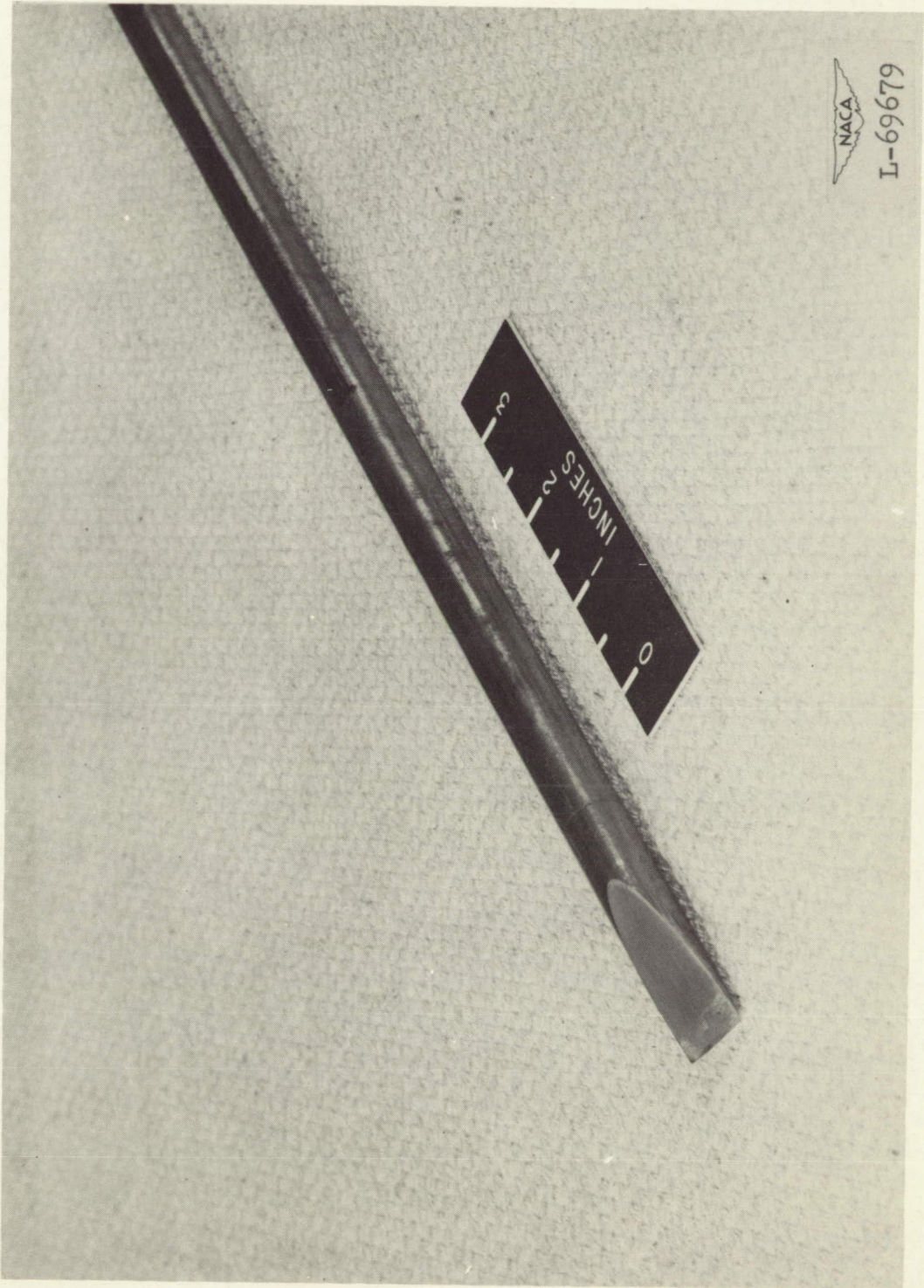


Figure 8.- Wedge probe.

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Average measured Mach number

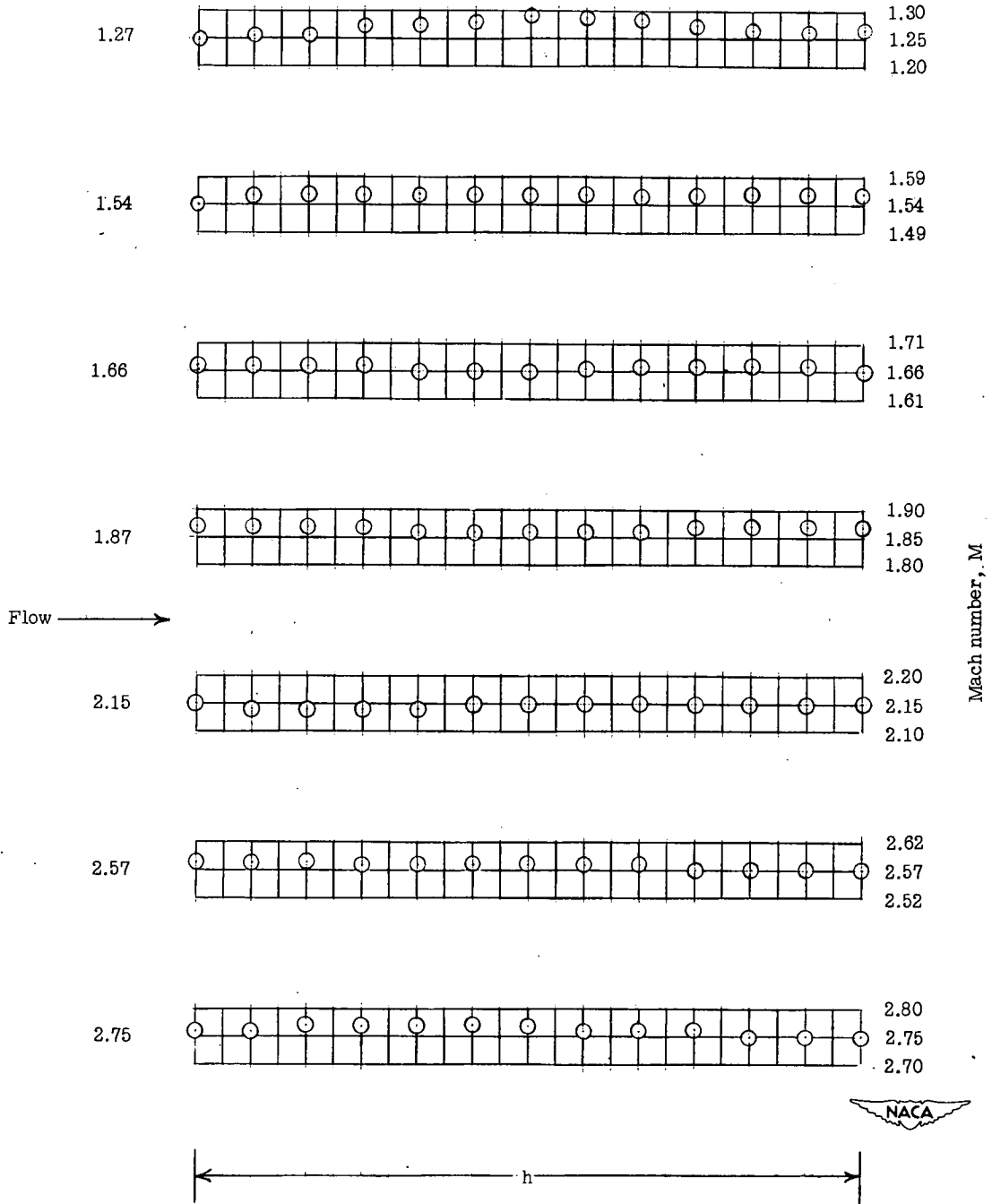
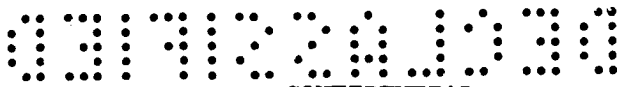


Figure 9.- Distribution of Mach number M along the tunnel center line in the experimentally determined test section.



Average measured Mach number

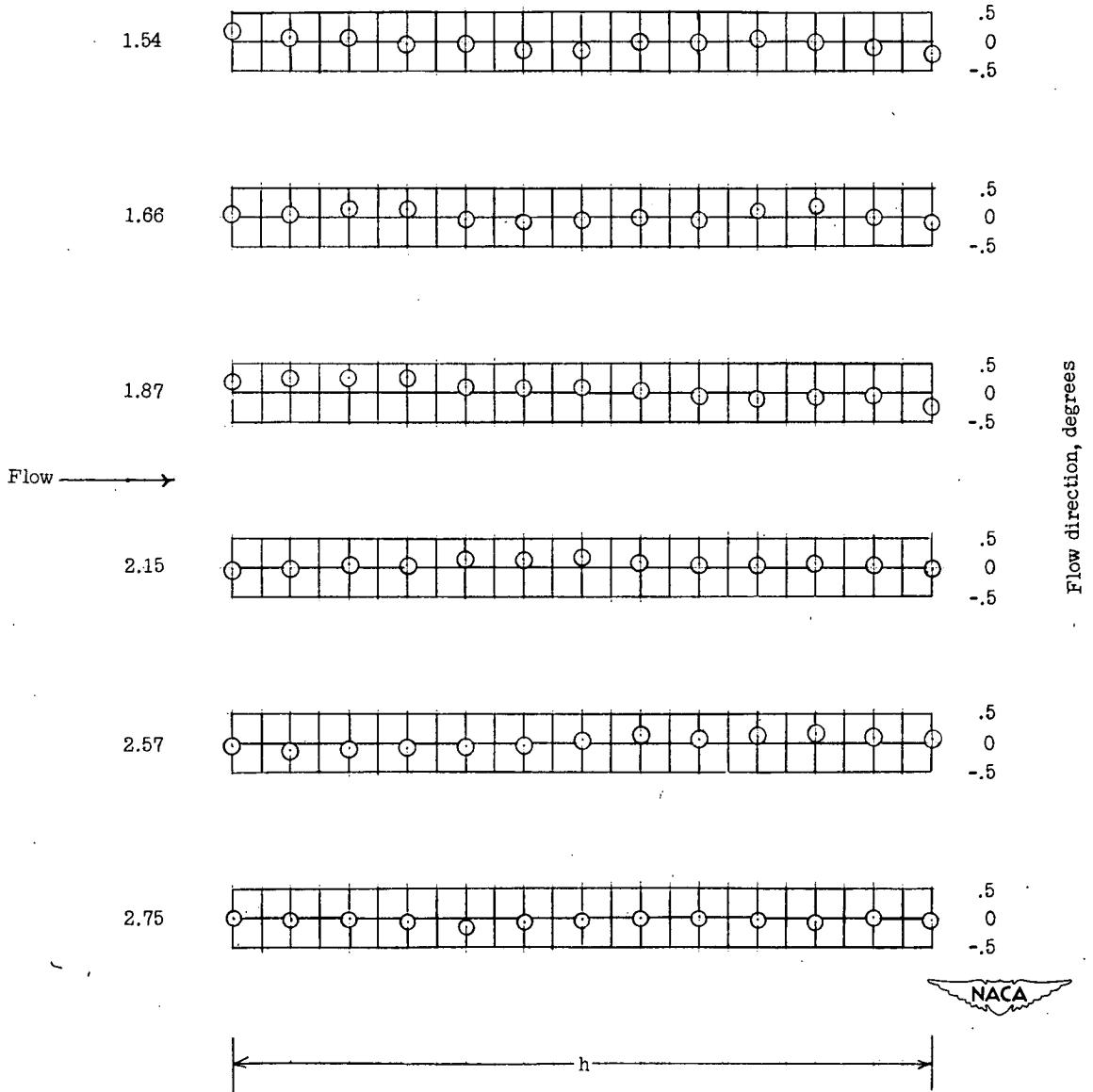
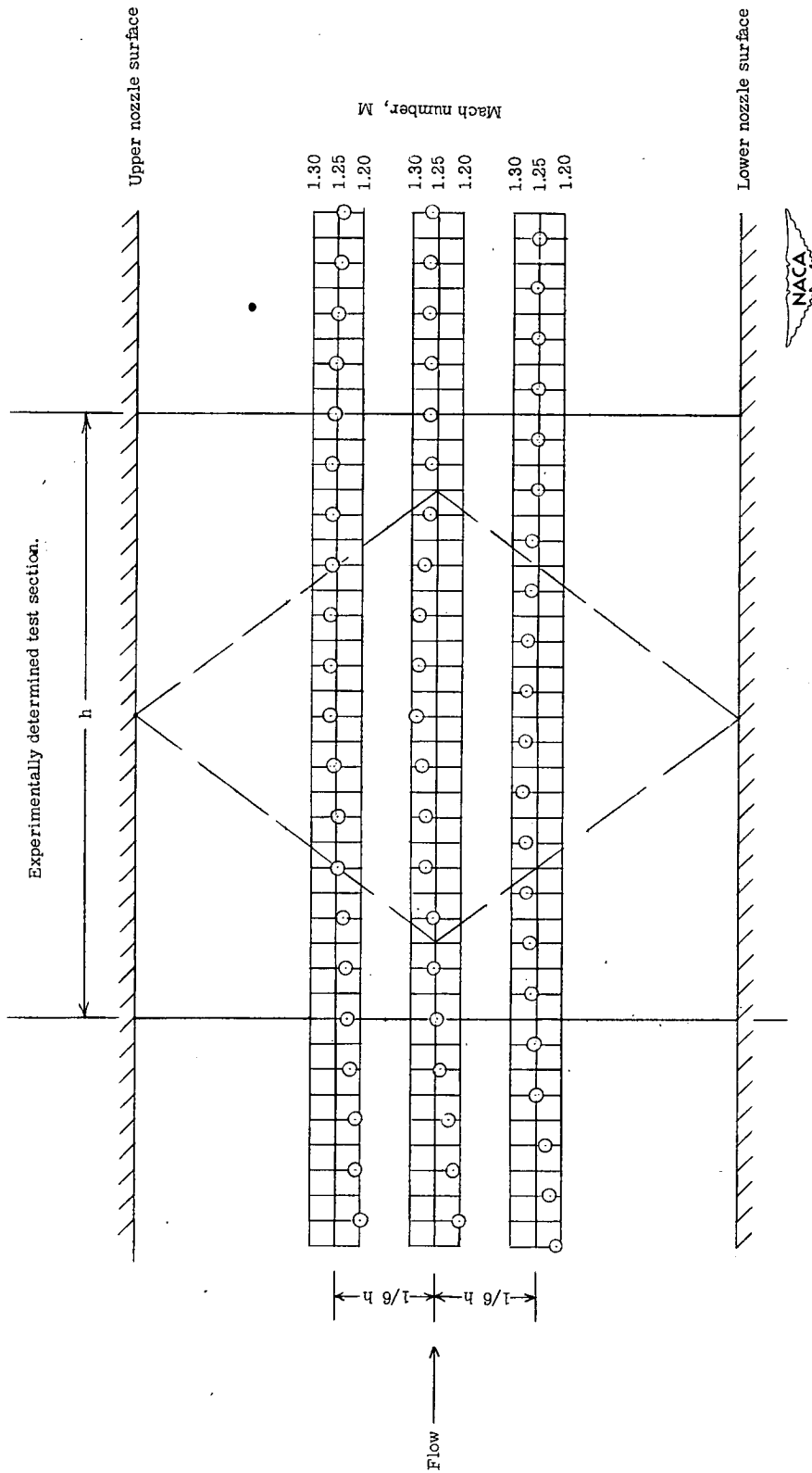


Figure 10.- Variation flow direction along the tunnel center line in the experimentally determined test section.



(a) $M = 1.27$

Figure 11.- Complete calibration results.

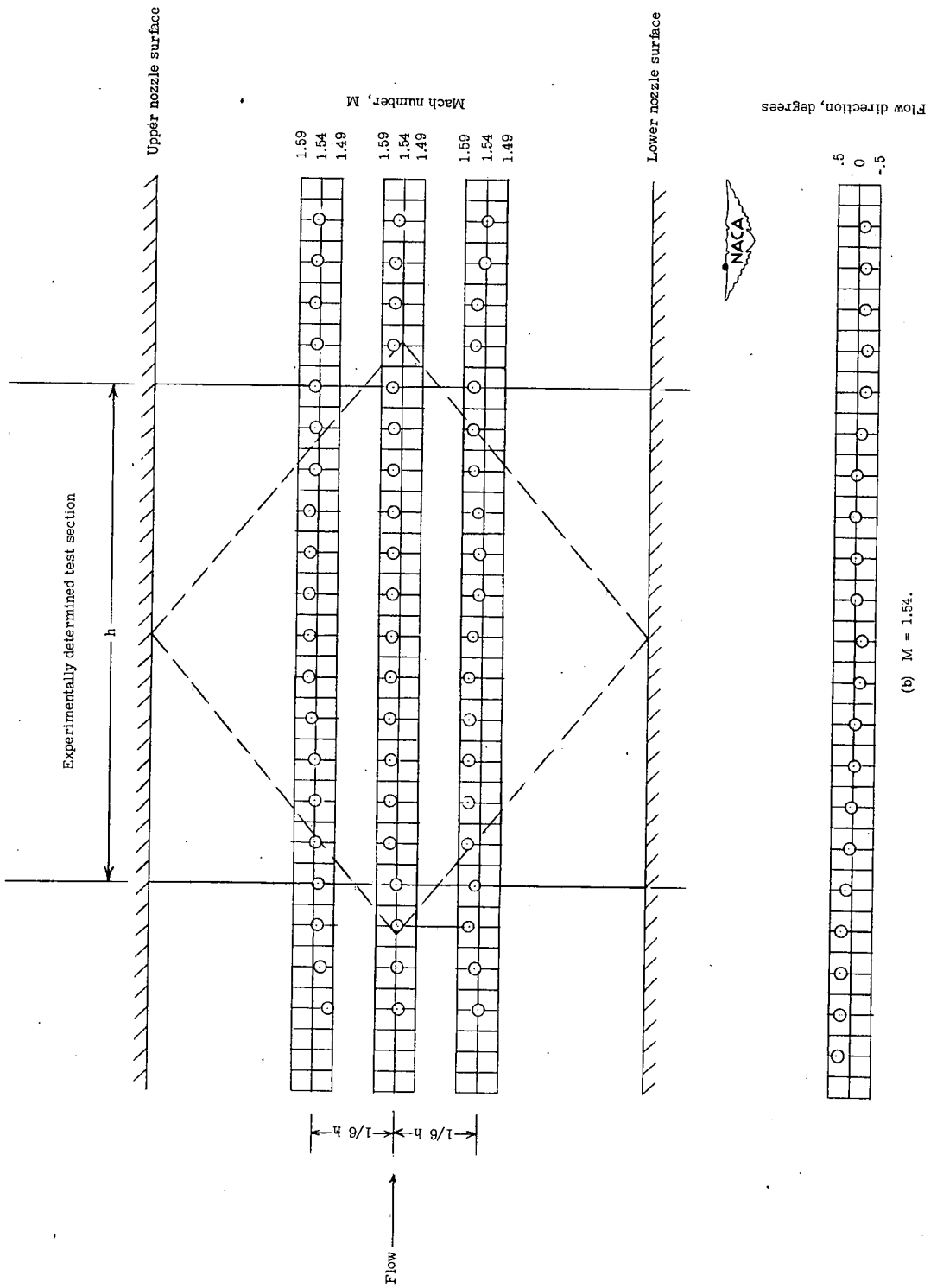
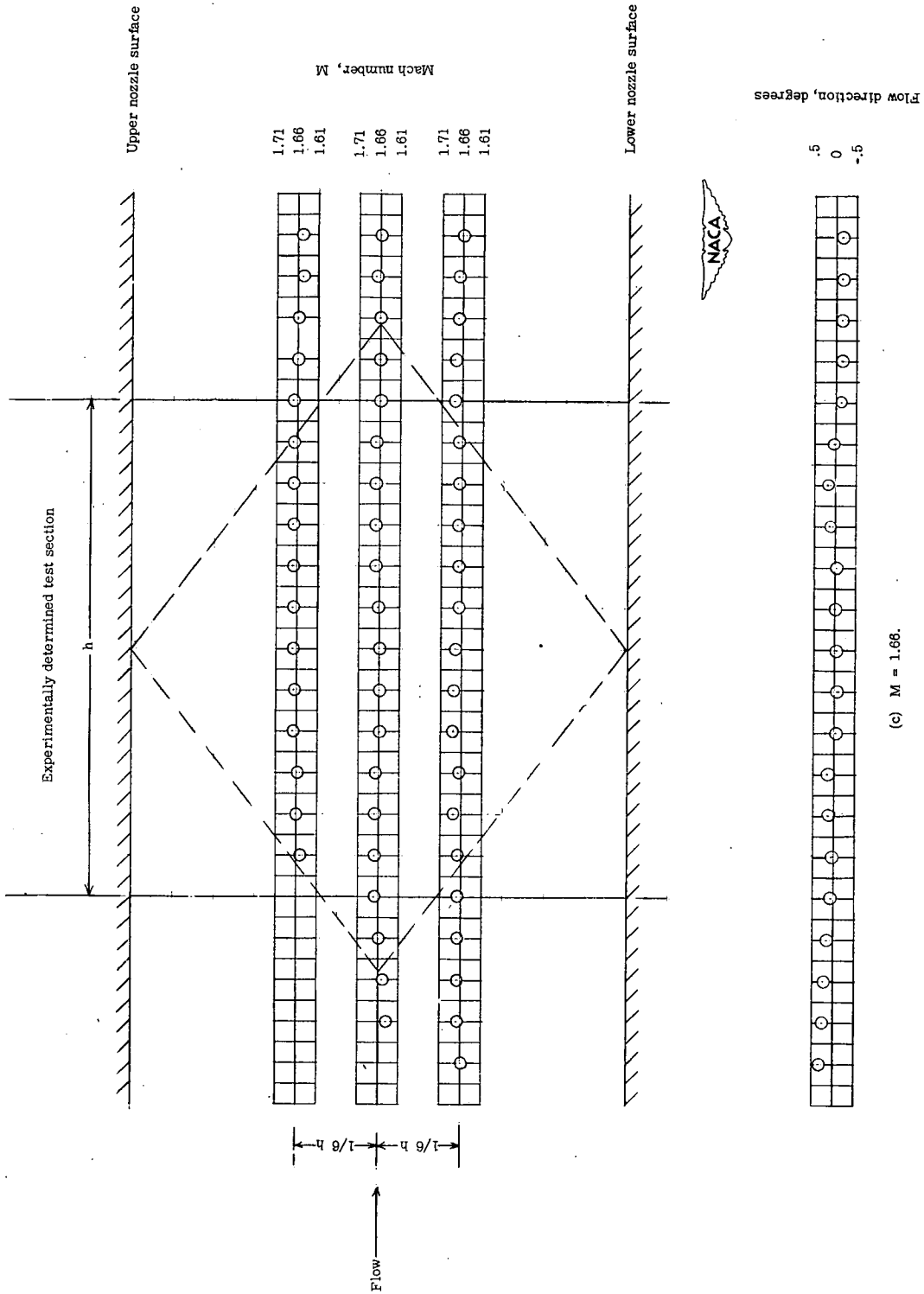
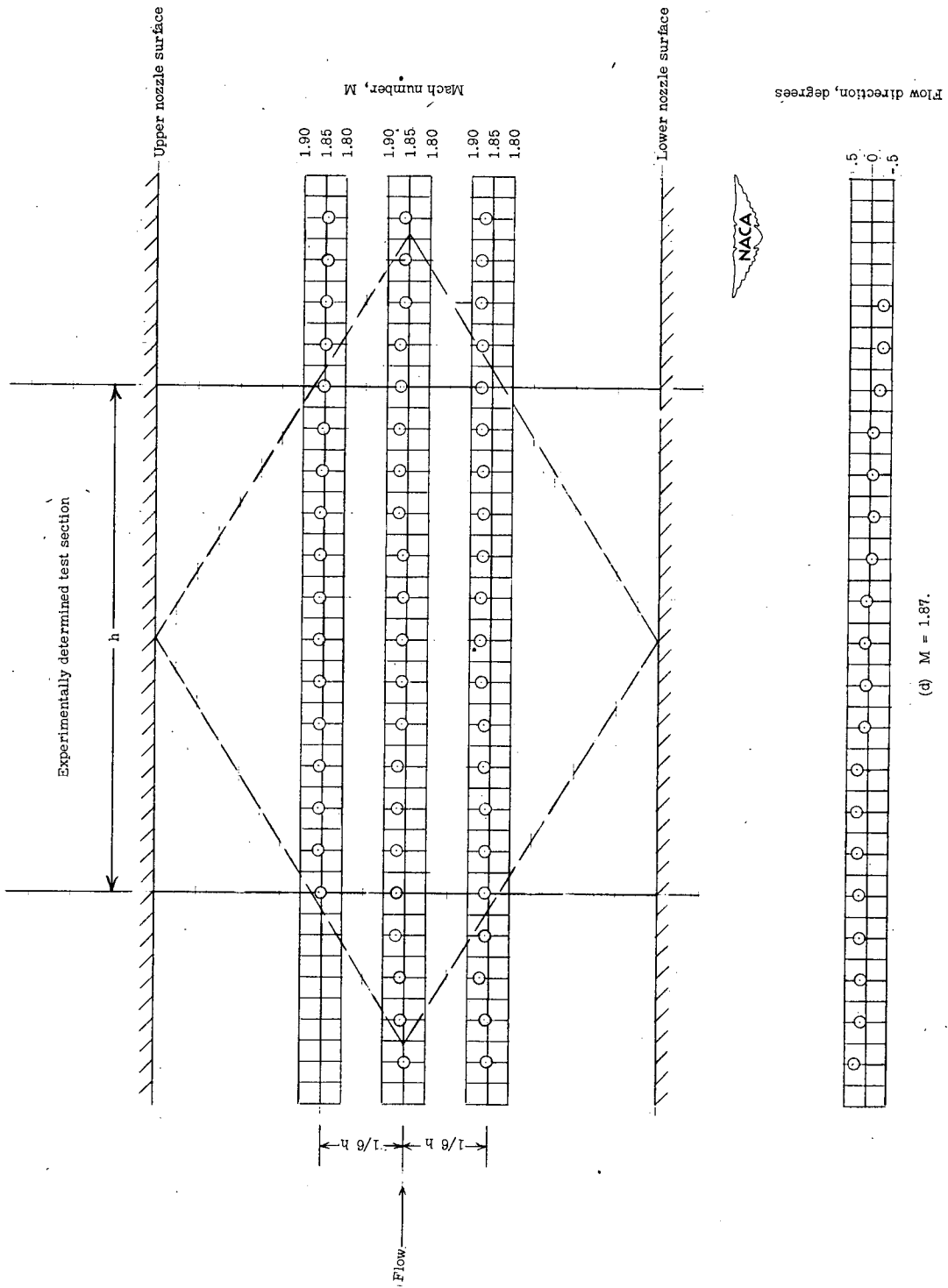


Figure 11.- Continued.



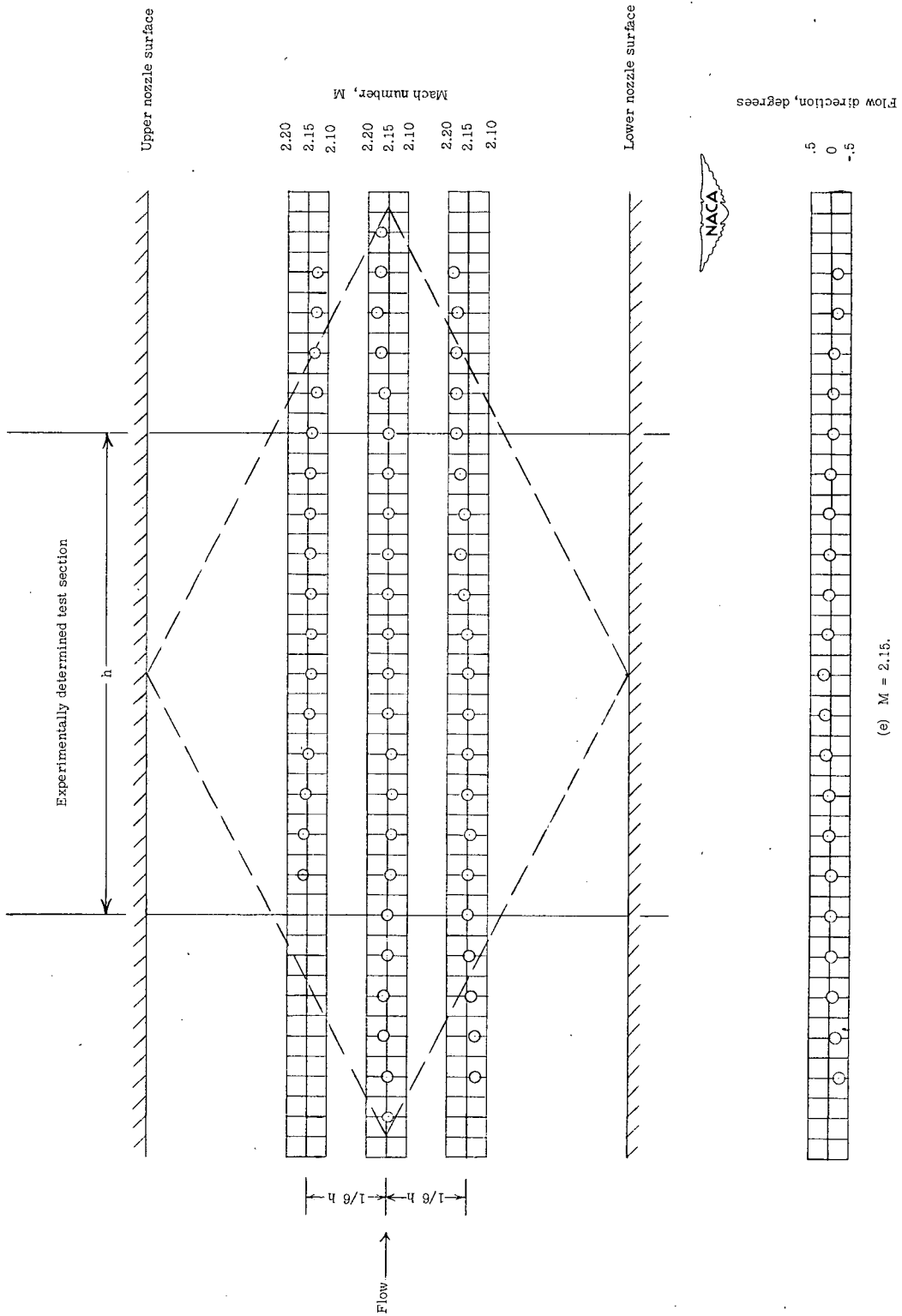
(c) M = 1.66.

Figure 11.- Continued.



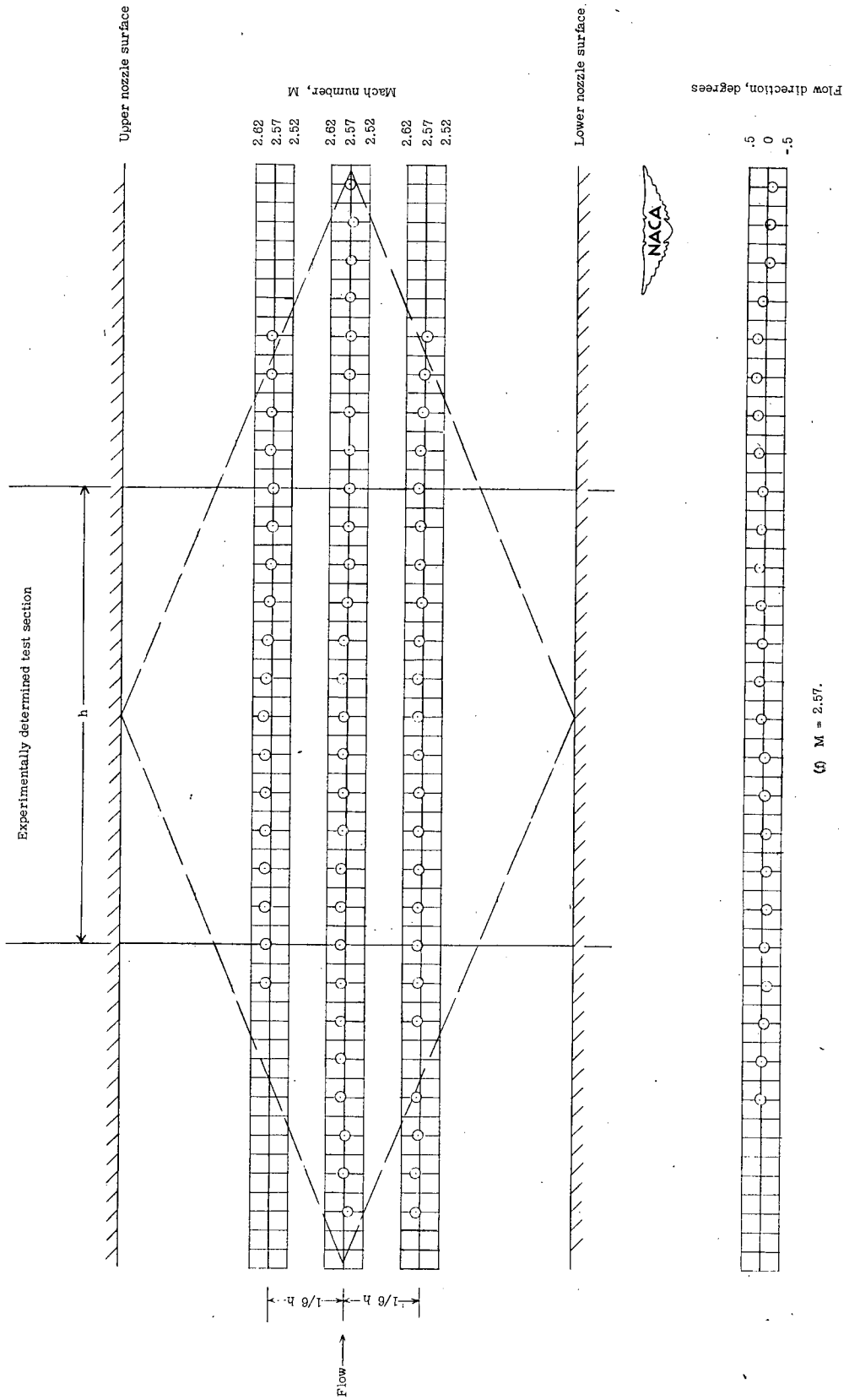
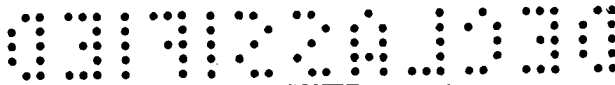
(c) $M = 1.87$.

Figure 11.- Continued.



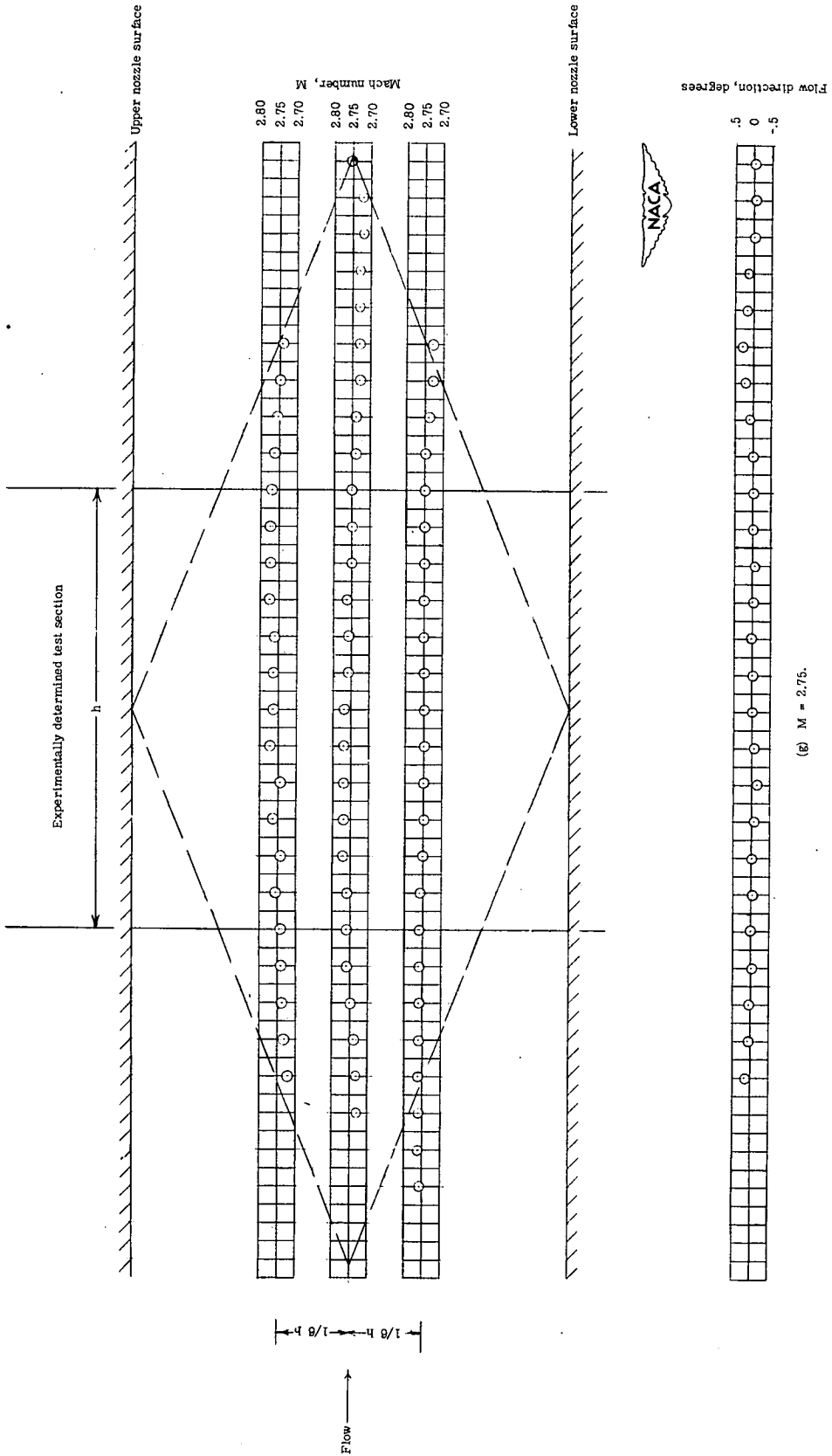
(e) $M = 2.15$.

Figure 11.- Continued.



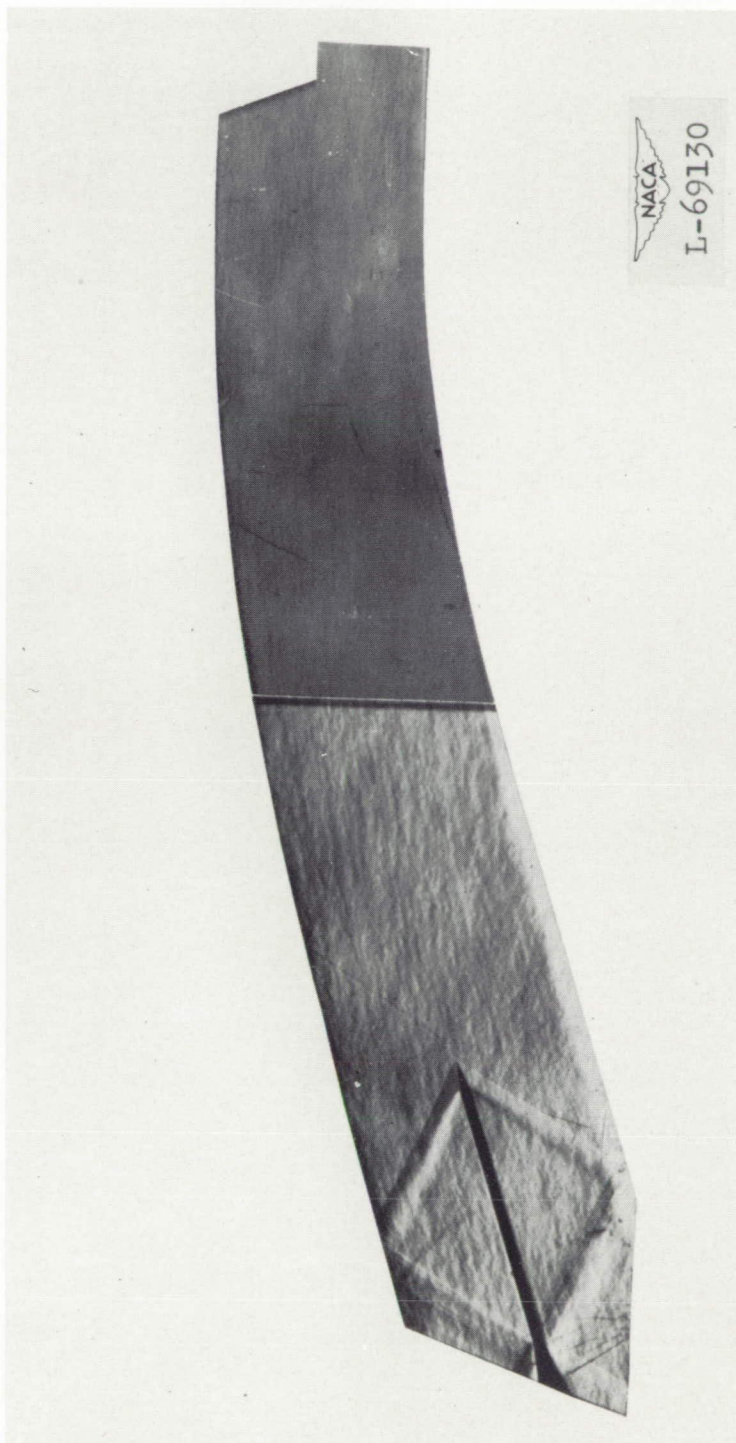
① M = 2.57.

Figure 11.- Continued.



(e) M = 2.75.

Figure 11.- Concluded.



(a) $M = 1.54$.

Figure 12.- Schlieren photograph of flow in the nozzle.

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(b) $M = 1.87$.

Figure 12.- Continued.

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(c) $M = 2.75$.

Figure 12.- Concluded.