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CORNELL AERONAUTICAL LAB., INC., BUFFALO, N.Y. (REPORT NO. AD-706-A-5)

AN EXPERIMENTAL INVESTIGATION OF THE PERFORATED-WALL TRANSONIC WIND TUNNEL - PHASE I

WILDER, JOHN G., JR. AUG'51 59PP PHOTOS, DIAGR, GRAPHS

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CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO 21, NEW YORK

Report No. AD-706-A-5
C. A. L. Service Contract SCD-10
(AF 33(038)-9928)

AN EXPERIMENTAL INVESTIGATION OF THE PERFORATED-WALL TRANSONIC WIND TUNNEL
PHASE I

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AUGUST 1951

FOREWORD

The work contained in this report was performed for Sverdrup & Parcel, Inc. under C.A.L. Service Contract SCD-10, as part of Air Force Contract AF 33(038)-9928. The work constituted research directed toward the design of the Propulsion Wind Tunnel of the A.E.D.C.

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SUMMARY

Experiments have been carried out on a small-scale perforated-wall transonic wind tunnel over a range of Mach numbers from .8 to 1.3 to determine flow uniformity length of tunnel required to attain uniform flow, shock cancellation characteristics and suction power requirements. The results show that satisfactory flow uniformity is attainable in tunnel lengths comparable to the tunnel depths. In particular, it is observed that the discrete disturbances arising from individual holes in the wall do not produce marked effects on the flow except in the immediate vicinity of the wall. Qualitative analysis of schlieren photographs discloses powerful shock cancellation capabilities of a perforated wall for a wide range of shock strengths. Suction power required to change tunnel Mach number in the supersonic range is in fair agreement with theory, but suction power required to bring the tunnel to sonic speed cannot be predicted by any presently available theory, and is considerable. Scale effects may be important in this phenomenon, and larger scale experiments would be desirable.

INTRODUCTION

It has been recognized for some time that the conventional solid wall wind tunnel is inadequate in the high subsonic and transonic speed range. This inadequacy is primarily due to the choking phenomenon which occurs when the area increase in the test section, caused by the presence of the model, is great enough to cause an acceleration of the mean tunnel flow to a Mach number of one, which limits the equivalent free-stream velocity to a lower value. This limit on test section Mach number prohibits tests in the transonic region and makes the problem of correcting tunnel data to free flight conditions a very difficult one[1,2].

Work on the alleviation of the choking phenomenon by the NACA led to the development of the slotted transonic tunnel[3,4]. The fundamental idea behind the slotted test section is the alleviation of the choking condition by allowing some of the tunnel stream to flow out of the test section at or near the model through longitudinal slots. This is roughly analogous to increasing the test section size in relation to the model size, and thereby extending the usable Mach number range of the tunnel. In fact it was found that operation through the transonic into the supersonic range was possible. Continued work on the slotted test section over the past several years has resulted in attainment of very satisfactory tunnel flows and in reduction of initially high power requirements. One further major problem which must be considered is the reflection of model-induced disturbances from the wall in supersonic operation. A consideration of this problem leads to the conclusion that longitudinal slots of large width and spacing compared to the tunnel lateral dimension cannot lead to satisfactory alleviation of such disturbances, since the discrete reflected shock and expansion waves from successive open and closed sections of the tunnel wall cannot combine in such a way as to cancel before striking the model. At low supersonic Mach numbers the reflected waves from the model nose will strike even models of extremely short lengths.

A logical extension of the slotted-wall tunnel is the ideal porous-wall tunnel. In such a tunnel, the passage of mass flow out of the working section could still be accomplished, but the uniform properties of the wall would theoretically permit selection of a porosity value such that shocks and expansions striking the wall could be completely cancelled to the first order. For waves of finite strength, complete cancellation is theoretically possible only for waves of one particular strength, but substantial reduction of the strength of the reflected waves is possible over a considerable range of incident-wave strengths[7,10].

Tests of tunnel-wall materials closely approximating ideal homogeneous porosity, such as sintered metals and fine mesh screens are reported herein and have also been conducted by the NACA[5,6,7]. In general, the results show that the theoretical advantages of such materials as regards wave cancellation are actually realized, at least qualitatively. There are, however, considerable structural difficulties involved in the utilization of such materials in large tunnel construction and, in addition, they are highly susceptible to clogging with grease and dirt.

Studies at C.A.L. led to the conclusion that ideal porosity might not be necessary, in the sense that the porous wall might have a finite-size-grain structure, provided the size of such structure were small compared to the tunnel dimensions. In particular, perforated metal sheet was deemed to be suitable because of its eminent practicability for large tunnel construction.

The nature of the losses through a perforated wall is such that use of main stream power to force the flow through the wall and then back into the tunnel with resultant low total head at the entry to the tunnel diffuser, appeared to be inefficient. It was, therefore, proposed to induce the flow through the porous wall by the use of suction power at the working section rather than by means of main stream drive power, as had been done in all the previous transonic tunnels. The air removed could then be reinjected into the diffuser at high total head in the case of a closed-return tunnel. The tunnel used in the present experiments was not a return type so that reinjection problems were not investigated.

Since some of the virtues of the slotted-wall tunnel first became apparent from the fact that it appeared theoretically capable of giving zero blockage interference corrections on the tunnel axis in subsonic flow, it was deemed worthwhile to investigate this problem for the perforated-wall tunnel. This was done first in Ref. 11 for a two-dimensional body in a two-dimensional tunnel, and it was found that a condition for zero-interference also existed for a tunnel with perforated walls.

On the basis of preliminary analytical studies of length of tunnel required to reach a given Mach number, power requirements, shock cancellation, and subsonic interference characteristics, it was concluded that the perforated-wall tunnel offered considerable promise as a transonic research tool, and should be investigated experimentally. A contract was then undertaken for Sverdrup and Parcel under their Air Force prime contract AF 33(038)-9928 to conduct small-scale experiments on a perforated-wall tunnel. This report presents the results of the first phase of this work, which was concerned with tunnel length required to produce a given supersonic Mach number, transonic blockage characteristics, and suction power requirements, as affected by various wall materials and configurations.

DESCRIPTION OF MODEL AND TEST APPARATUS

The model tunnel constructed for this investigation was a suction type non-return tunnel with a test section 2 1/4 x 4 x 12 inches (Fig. 1). The vertical walls were made of glass to permit schlieren observations while the horizontal walls were made of various porous materials mounted on removable specimen holders to facilitate change. Static pressure taps were located in the porous walls and provision was made for surveys laterally through a metal vertical wall which replaced one of the glass walls for this purpose. The primary tunnel stream exited through a diffuser, which was adapted from a previous supersonic wind-tunnel model to the suction pumps. The air that was removed through the porous walls passed through relatively large plenums located above and below the test specimens and finally through a gate valve (used for control of the plenum pressure) to a vacuum pump. The mean velocity in these plenums was always essentially zero. Pressure taps were located in each plenum. Air was fed to the tunnel from the air dryer through a large plenum chamber built onto the tunnel intake to receive the air from the air dryer. Airfoil models were supported by Lucite discs which fitted into metal rings mounted in the vertical glass walls of the tunnel.

The main tunnel drive consisted of electric motors totaling 600 horsepower while the suction plenum pump was driven by a 40 horsepower electric motor. These powers are mentioned as a matter of record and have no bearing on the ideal power required to operate the test section tested, since the adapted tunnel diffuser was known to be very inefficient (this was unimportant for this application, since excess power was available) and since a long run of piping between the suction plenums and the vacuum pump plus losses through manifolding and the control valve produced an appreciable total head loss.

Instrumentation consisted of the static pressure taps located on the porous walls and pressure taps located in the suction plenums mentioned above as well as a pitot-static probe used for surveys within the stream. The pitot-static probe was mounted on a double wedge airfoil of a small enough included angle to give an attached shock at a Mach number in excess of 1.20. Mass flows sucked through the porous wall were measured by means of calibrated venturi meters. Mercury and water manometers were used to measure all pressures.

The porous walls were adjustable from 0° to about 30' divergence from the tunnel center line. However, when the walls were diverged a bump at the test section exit (due to the fixed diffuser intake) formed a second throat. This was not an ideal arrangement but was accepted for expediency as an adjustable diffuser would have necessitated the design and construction of a complete new diffuser instead of the adaptation of an existing one. The second throat in itself served the desirable purpose of stabilizing the tunnel flow in the transonic range.

Photographs of the tunnel test section, suction plenums and piping arrangement, dry air plenum, tunnel diffuser and vacuum pump are presented in Figs. 2 through 5. Pertinent physical and air flow characteristics of the wall specimens tested are described in Ref. 9.

DISCUSSION OF RESULTS

Longitudinal Mach Number Distribution

Wall pressure taps provided a very rapid indication of Mach number distribution but the readings were not very satisfactory from the standpoint of accuracy. It will be noted in any of Figs. 6 to 13 that for a given wall configuration, the peaks and valleys of the wall pressures remained at the same geometrical location for all supersonic Mach numbers tested. This would seem to indicate the presence of local disturbances in the wall at the pressure tap rather than a general non-uniformity of the flow. The method of soldering the pressure tap to the thin-sheet walls was such as might be expected to produce local irregularities in the wall. The very uniform Mach number distributions found laterally and vertically by means of probe surveys over most of the tunnel (see Figs. 19 and 21) provide further evidence that tunnel flow is considerably better than indicated by wall pressure taps.

The first wall specimen tested was made up of two IT Erdle sheet, with holes aligned, on each wall. The perforated walls were set up parallel and runs were made for various plenum pressures resulting in a range of terminal Mach numbers from about 0.8 to 1.3. The results are presented as Mach number variation with tunnel length in Fig. 6. As may be seen from an examination of this figure, the Mach number distribution for the lower terminal Mach numbers is within tolerable limits but deteriorates rapidly as the terminal Mach number approaches 1.3.

In an attempt to improve the flow the perforated walls were diverged to an included angle of one degree and the above outlined procedure was repeated. The results of this series of tests are presented in Fig. 7. It is apparent that the longitudinal Mach number distribution was improved. Time did not permit the determination of the optimum value of included angle for Mach number distribution. It would be of questionable value to spend much time in determining this anyway, in the exploratory phase, as it probably would be different for every wall material, and very much a function of tunnel scale. Experimental evidence of this will be discussed below.

The number 00 Erdle sheet wall specimen gave a better longitudinal Mach number distribution than did the two IT sheets for zero degrees included angle, as may be seen from Fig. 8. With this wall specimen, diverging the walls to a one degree included angle actually resulted in a poorer longitudinal Mach number distribution than with parallel walls although the terminal Mach number for the same tunnel power was increased slightly (Fig. 9). This would indicate that the most desirable divergence angle is probably a function of the wall porosity, length of test section, tunnel Reynolds number, etc.

To compare a truly porous wall (one approaching ideal porosity) with the perforated sheet walls (which are only an approximation to a porous wall as they contain discrete holes) sintered bronze sheet was used for one series of tests. The longitudinal Mach number distributions obtained with the sintered bronze walls are presented in Fig. 10. As may be seen from this figure the distributions are quite as good as those obtained with the perforated sheet for comparable terminal Mach numbers. However, it is plain from a comparison of the above mentioned figures that the terminal Mach number is achieved in a much shorter length with the perforated sheet walls. As a matter of fact, for the higher terminal Mach numbers, the maximum Mach number is not achieved in twelve inches (or three tunnel depths) with the sintered bronze, as may be deduced from the continually increasing Mach number with the tunnel length. More porous sintered bronze, which would have reduced the length required to produce a given Mach number was not found to be commercially available. Diverging the sintered bronze walls one degree appeared to shorten slightly the length necessary for achieving a given Mach number (Fig. 11), but did not improve the longitudinal Mach number distribution.

To further extend the comparison of the perforated wall with walls approaching ideal porosity, tests were run using fine mesh screen or woven wire cloth as walls. The walls were made up of six layers of 200 mesh wire cloth per wall. Static pressure taps were installed along the screen wall as in the other walls tested. This resulted in a comparatively "sloppy" joint around the pressure taps as it was found quite difficult to solder tubing to six layers of very flexible wire cloth. The wire cloth wall itself was quite flexible and waves were noted in the walls during experimentation. In view of this inherent quality, the Mach number distributions presented in Fig. 12 are surprisingly good. The screen walls allowed the attainment of terminal Mach number in about the same length as the perforated sheet walls (approximately one tunnel depth). As with the sintered bronze sheet, diverging the screen walls increased the terminal Mach number slightly, but did not improve the longitudinal Mach number distribution (Fig. 13).

Schlieren photographs of the flow in the test section with the four wall materials discussed above are presented in Figs. 14 through 17. All photographs were made with walls diverged and for the maximum terminal Mach numbers attainable and so represent the poorest flows for all materials except the IT walls (in which case the flow was improved by the diverging walls over the parallel wall case, as discussed above). The schlierens are significant inasmuch as they indicate a rapid decay of the discrete discontinuities generated by the holes in the perforated walls as these discontinuities propagate into the stream (Figs. 14 and 15). The flow in the test section, discounting the flow in close proximity to the walls, for the perforated sheets appears to be as free from discontinuities as that for sintered bronze walls (Fig. 16) and superior to that for screen walls (Fig. 17). A more positive check on this was the vertical total head survey discussed below.

In all the photographs discussed above the flow is from right to left and the normal shock which appears is due to the physical second throat formed by the divergent walls as described in the section Description of Model and Test Apparatus.

Lateral and Vertical Mach Number and Stagnation Pressure Distribution

Lateral surveys of total and static pressures were made at two stations, 6 3/8- inches and 10 7/8-inches downstream of the beginning of the porous wall. From these measurements Mach numbers were computed and plots of lateral Mach number and total pressure distributions for the 6 3/8-inch station are presented in Figs. 18 and 19. The peculiar "valley" on one side of the plots is believed due to a probe interference effect as shown in Fig. 20 where wall pressures were used to compute Mach numbers near the wall for three probe positions. Apparently the probe spanning the tunnel has an appreciable effect on Mach number distribution and so would lead to erroneous values of static pressure in the stream. In view of this, it is suggested that the lateral surveys be considered only to the center line of the tunnel; in other words, as half surveys. These values should be essentially correct.

A cross plot of the lateral survey on the tunnel center line results in the graph presented in Fig. 21. It is obvious from this figure that discontinuities from the discrete holes in the perforated sheet are cancelled rapidly as they propagate into the stream and have a negligible effect on total pressure beyond about one-quarter of an inch from the walls.

Considering the fact that a minimum of effort was expended on improving the flow in the tunnel, the vertical Mach number distribution appears to be excellent.

The lateral surveys for the second station are not presented in this report because, as the wall statics indicate, the flow at the end of the test section is poor probably partially due to some flow reentry from the plenum and partially due to the effects of the physical discontinuity caused by the diffuser and test section wall joint, as discussed on page 5 .

Control of Test Section Mach Number Through Transonic Range with 6 Per Cent Biconvex Airfoil in Test Section

To investigate the blockage characteristics and controllability of test section Mach number through the transonic range with a typical test model mounted in the test section, schlieren photographs and longitudinal Mach number distributions were obtained with a 6 per cent biconvex airfoil model at 0° and 2° angle of attack for various tunnel Mach numbers from about 0.8 to 1.25. These tests were made with the parallel No. 00 Erdle sheet walls. The schlieren photographs of the flow around the airfoil at 0° angle of attack and the corresponding Mach number distributions as determined from wall static pressure measurements for the range of Mach numbers of 0.8 to 1.25 are given in Figs. 22, 23 and 24. In these tests the model center line was located 10 inches from the test section entrance and the model chord was 1.5 inches. As may be seen by the progressive wave formations on the model as the Mach number increased, the model was not perfectly aligned with the flow, but was at a very slight angle of attack.

It is interesting to compare the Mach number distributions for given terminal Mach numbers with the corresponding schlieren photographs. The formation of waves on the airfoil, the approach of the detached shock and its final attachment to the airfoil as the stream Mach number increased and the effect of the waves on Mach number distributions through the transonic into the supersonic range may be studied from this series of figures. All conditions pictured here were easily repeated in the tunnel, tested approaching from either the high or low Mach number side.

Figs. 25 through 31 present the longitudinal Mach number distributions and schlieren photographs of the flow about the airfoil at a 2° angle of attack. Here again, the wave formations on the airfoil as the flow passes through the transonic range into the supersonic range are clearly shown. Again all conditions were easily duplicated.

Although the walls were not of the correct porosity for complete cancellation of the waves from the model, it is apparent from the photographs that only very weak disturbances were reflected throughout the Mach number range tested. Listed below are the ideal porosities for complete wave cancellation and the actual porosities for the three Mach numbers corresponding to the schlierens of Fig. 24. The ideal porosities were computed according to the theory of Ref. 10, and the actual porosities were measured[9].

Mach No.	Ideal Porosity	Actual Porosity
1.12	.00611	.0309
1.20	.00628	.0240
1.25	.00986	.0245

Power Requirements for Suction

In an attempt to establish the order of magnitude of suction powers required for various terminal Mach numbers, actual mass flows through the porous walls were measured by means of a calibrated venturi meter while the tunnel was in operation and the pressure ratio through which this mass of air had to be compressed was measured. The true weight flow variation for various terminal Mach numbers for this specific tunnel using six wall configurations is presented in Fig. 32. From these data ideal powers per square foot of test section area were computed and are given in Fig. 34. It should be noted that the powers given are for atmospheric test section stagnation pressure; the power required is proportional to stagnation pressure. The data presented in Fig. 32 reveal that in accelerating the flow from a Mach number of approximately 0.80 to about 1.25 about 35 per cent of the total mass removed by suction is used in accelerating the flow to a Mach number of unity whereas according to simple one-dimensional theory[8], a Mach number of one should be attainable with no suction.

The suction power required to achieve a Mach number of unity cannot be predicted on the basis of any presently available theory, nor is the mechanism involved very clearly understood. It may be seen in Fig. 32 that, with no mass-flow removal, the tunnel Mach number attained is somewhere between .75 and .85 depending on the wall material and the wall divergence. With wall divergence, the presence of a physical second throat at the entrance to the diffuser, as discussed previously under Description of Model, tends to overshadow other effects. For the parallel-wall cases, it appears that the lower the porosity of the wall, the higher the Mach number attained. At first it was thought that the limitation on Mach number without suction power was entirely due to boundary layer and friction choking of the tunnel. Since the ratio of boundary-layer thickness to tunnel depth is quite large in a solid wall tunnel of the size used in these experiments, this appeared to be a plausible explanation. The tunnel with solid parallel walls choked at a Mach number of .78. If this were the case, the choking Mach number would be very much higher in a large scale tunnel as the ratio of boundary-layer thickness to tunnel depth decreased. An examination of the longitudinal Mach number distribution for subsonic flow in the tunnel (for example, Fig. 6) showed no progressive increase in Mach number with distance downstream of the throat, such as would be expected with ordinary boundary-layer thickening. In fact the Mach number remained virtually constant over the tunnel length, and showed a slight tendency to rise only near the end of the porous section. This clearly indicated that flow through the porous wall was modifying the mechanism of boundary-layer choking as observed in the tunnel with solid walls. A further evidence of this effect was the fact that the limiting Mach number was a function of wall porosity as discussed above.

A simple one-dimensional theory is not adequate to handle the problem of subsonic flow in a porous-wall tunnel as discussed in Ref. 8. There it is shown that a mass-flow increase (or flow into the tunnel from the plenum) is required to raise the Mach number to unity. On the other hand the pressure of the main stream must decrease with increasing Mach number, and the plenum would be at the pressure corresponding to a terminal Mach number of unity, or lower than it is at the start of the porous section. Thus, the flow would be out of the tunnel rather than into it. These two requirements on plenum pressure and mass flow are obviously contradictory, so that the assumed mechanism of operation must be in error. A possible explanation of what is occurring may be made on the basis of a branched-flow hypothesis. According to this hypothesis, the flow branches into two circuits on entering the porous section of the tunnel; one circuit is along the tunnel itself, while the other is out through the wall, through the plenum and then back through the wall into the tunnel near the end of the porous section. Since there are losses in the main circuit, and consequently a pressure drop, there will necessarily be flow through the plenum circuit with the same pressure drop. When no suction is applied, this flow through the plenum circuit reenters the main tunnel stream near the end of the porous section. The reentering flow is at low total head, due to losses in entering the plenum, and causes a pressure loss in the main stream. In addition, the reentering flow has a blocking effect. When suction is applied to the plenum, a controlled amount of the flow is prevented from reentering, and when, finally, all reentry is prevented, a Mach number of unity is attained, if the withdrawn air near the beginning of the plenum includes most of the boundary-layer air. The actual power to bring the main stream up to a Mach number of unity in this case comes from the main tunnel drive; the suction power serves only to prevent losses and blockage due to low-head air reentering from the plenum. Quite obviously, this qualitative approach leaves many questions unanswered and provides no means of estimating suction power requirements or the effects of scale. The need for further research on the subsonic operation of porous wall tunnels is apparent.

It is of some interest to compare the mass-flow ratio to bring the flow to a Mach number of unity from a subsonic Mach number with the equivalent area ratio required if a geometrical blockage were causing the limitation. The mass-flow ratio is the ratio of mass flow through the suction pump to total mass flow at the tunnel entrance. The geometrical area ratio is the ratio

$$\frac{A(M)}{A^*} - 1$$

These ratios are compared in Figs. 36 through 38 for six wall configurations, the area ratio analogy being labeled "One-Dimensional Flow" and the actual measured mass-flow ratio labeled "Experimental." An inspection of these figures shows the two ratios are of the same order of magnitude.

It is of interest to consider the incremental mass removal necessary to accelerate the flow from a Mach number of unity to a given supersonic value rather than the total mass actually removed for purposes of comparison with theory. The incremental mass flows versus Mach number for six wall configurations are presented in Fig. 33. Using these incremental mass-flow data, incremental horsepowers per square foot of test section area for various terminal Mach numbers were computed and are graphed in Fig. 35. Also included in this figure is a curve of ideal power loss through the porous wall as determined from the theory presented in Ref. 8. It should be stated that all curves are "ideal" power loss, i.e., power required for suction with a 100 per cent efficient machine, but all curves except the one determined from theory were computed from measured mass flows and pressure ratios for the specific wall materials listed. It is significant that all incremental power curves determined from experiment show greater power losses than the theoretical curve although the theory assumes total dynamic head loss when the removed mass passes through the porous walls. It is also a salient fact that at the higher end of the Mach number scale there is a remarkable difference in power loss for different wall materials as determined experimentally. The power curve most closely approaching the theoretical curve was obtained using the No. 00 Erdle sheet diverged one degree. All wall specimens tested showed an increase of slope of the power required curve with increasing Mach number and each specimen showed a decrease in power required at a given Mach number for the diverged wall configuration compared to the parallel wall case. This phenomenon may be due to a number of factors such as effect of diverging walls on boundary layer growth, nozzle effect due to diverging walls and the formation of a geometric second throat at the end of the test section due to diverging walls (as discussed in the section Description of Model and Test Apparatus).

It appears impossible to isolate single effects from the available data.

Comparison of Theory and Experiment for Longitudinal Mach Number Distribution

One-dimensional theory for predicting longitudinal Mach number distribution[8] is compared with experimentally determined longitudinal Mach number distributions in Figs. 39 through 41. In these figures the Mach number distribution predicted by theory are shown by solid curves while the experimental Mach numbers as computed from wall static pressure readings are shown as symbols. The comparisons for four terminal Mach numbers using the two IT Erdle sheets as walls are presented in Figs. 39 and 40. The theoretical predictions are quite good considering that the theory assumes a linear variation of Δp across the wall with normal velocity, whereas it is known that for the materials used this assumption is not true[9]. The actual variation falls between a linear and a square law. For these comparisons an experimentally determined $\Delta p/V$ was selected for each material that fell about in the middle of the extreme Δp range encountered in a given case. This value of $\Delta p/V$ was substituted for $k/\mu t$ as defined in Eq. (7) of Ref. 8 for the determination of the theoretical Mach number distributions.

The comparison of theory and experiment for sintered bronze sheet and for No. 00 Erdle sheet walls is given in Fig. 41. For these cases the theory is not in as good agreement with experiment as for the two IT Erdle sheets. The sintered bronze sheet is less porous, and the No. 00 Erdle sheet is more porous than the No. IT Erdle sheet. It appears that the simple theory assuming one-dimensional flow and linear wall characteristics is adequate to show the order of magnitude of tunnel length required to produce a given supersonic Mach number. More accurate calculations can be made by using the method of characteristics and the actual wall properties in specific cases.

CONCLUSIONS AND RECOMMENDATIONS

As a result of Phase I experimentation the following conclusions are made:

1. The perforated wall tunnel with suction appears to offer a very satisfactory configuration for a transonic wind tunnel at this time based on considerations of test section Mach number controllability, uniformity of flow, wave cancellation, choking characteristics, and power required.

2. The test section flow appears good although no exhaustive development was undertaken to improve the flow.

3. The one-dimensional theory of Ref. 8 appears to be adequate for predicting longitudinal Mach number distribution at low supersonic Mach number for the porous materials tested.

4. Supersonic power requirements for suction are of the order of magnitude predicted by one-dimensional theory.

5. Suction power and mass flow required to raise the tunnel Mach number to unity are considerable, and the mechanism involved is not well understood.

It is recommended that:

1. A combination Laval perforated wall tunnel be investigated for higher supersonic Mach numbers in order to reduce the suction powers required.

2. Pressure distributions over test models measured in a perforated wall tunnel be compared with free flight data to determine how closely free flight conditions are simulated.

3. A more comprehensive program be run to determine the effect of divergent walls on flow conditions.

4. A more detailed study be made of the effect on the suction power and mass flow required to reach a Mach number of unity.

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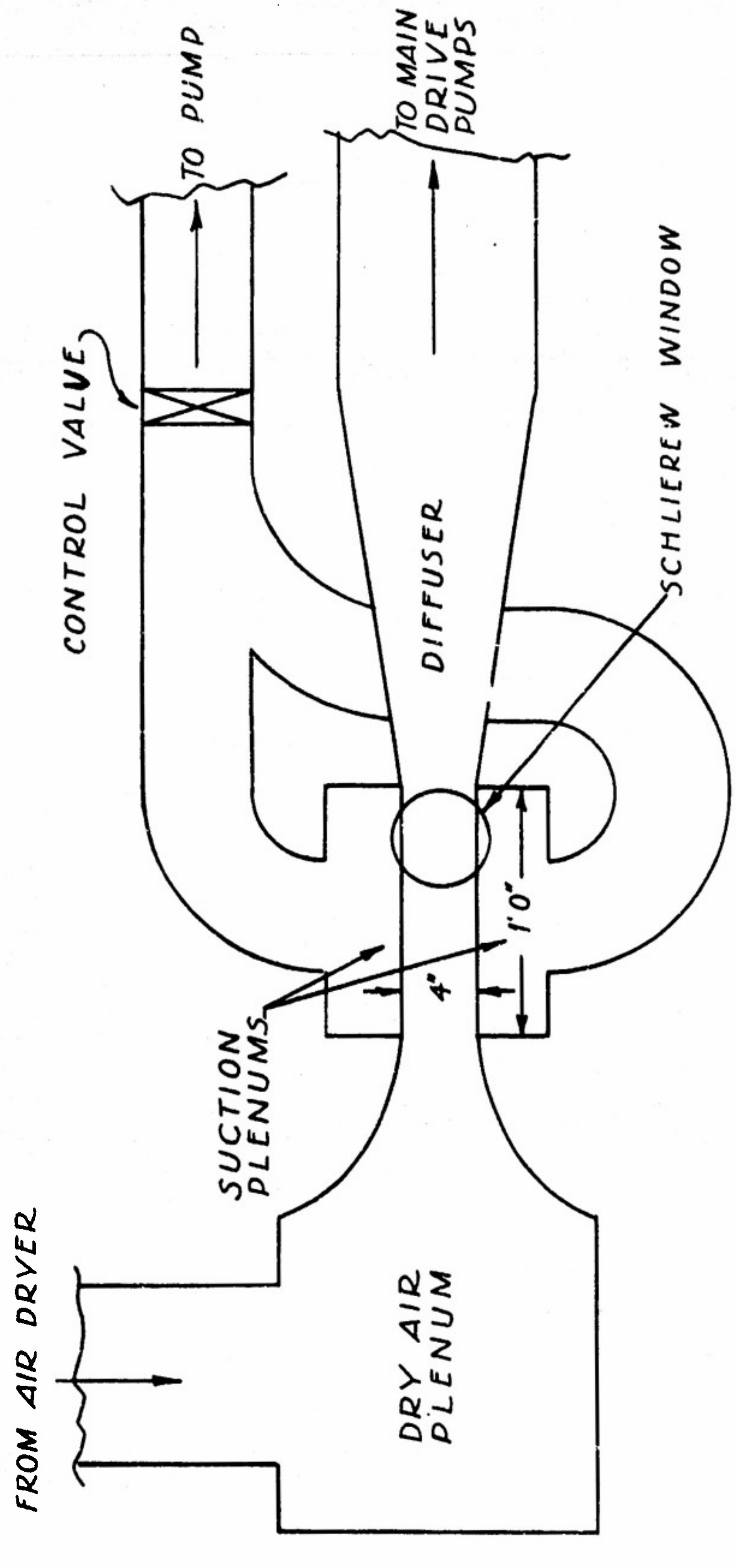

SCHEMATIC OF PERFORATED WALL WIND TUNNEL
Fig. 1

VERTICAL - SURVEYS ~ CENTER LINE AT STATION #4

2-IT ERDLE SHEETS

O-STAGNATION PRESSURE
Δ-MACH NUMBER

WALLS 1° DIVERGENT

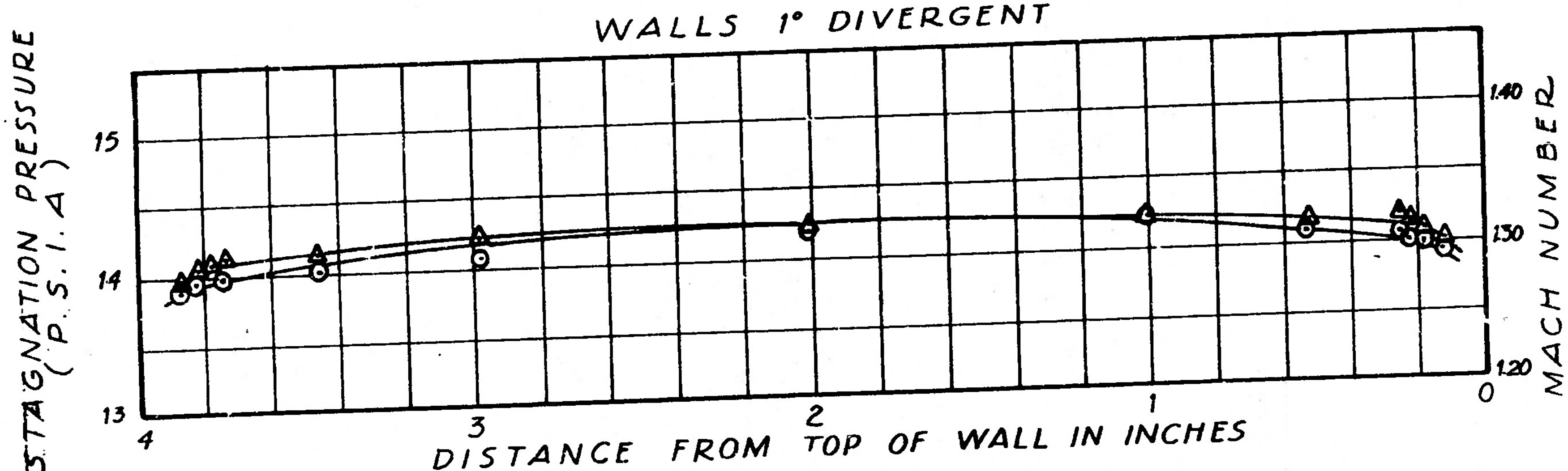

Fig. 21

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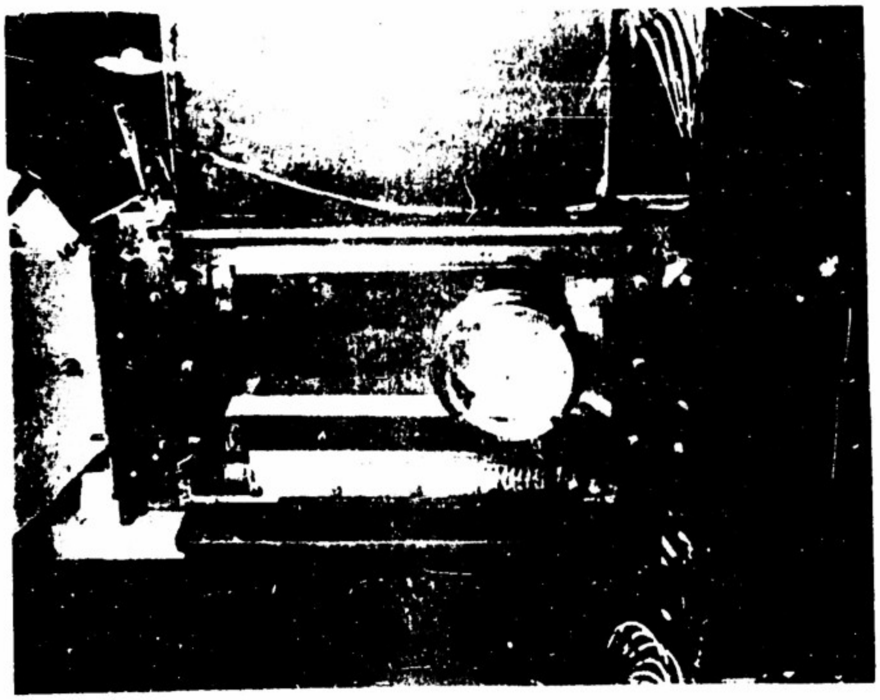

Fig. 2
TEST SECTION

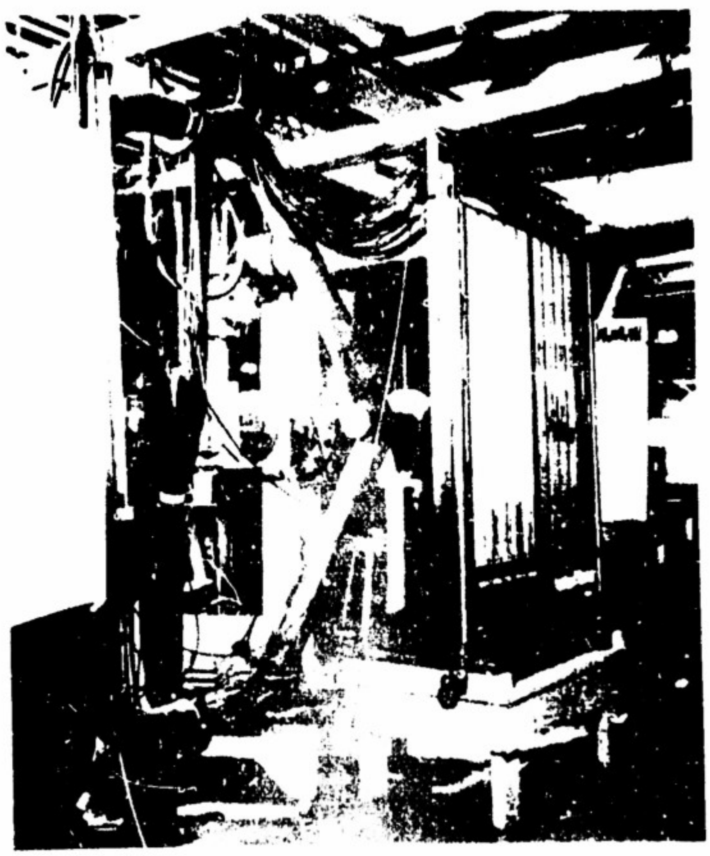

Fig. 3
SUCTION PLENUM & PIPING ARRANGEMENT

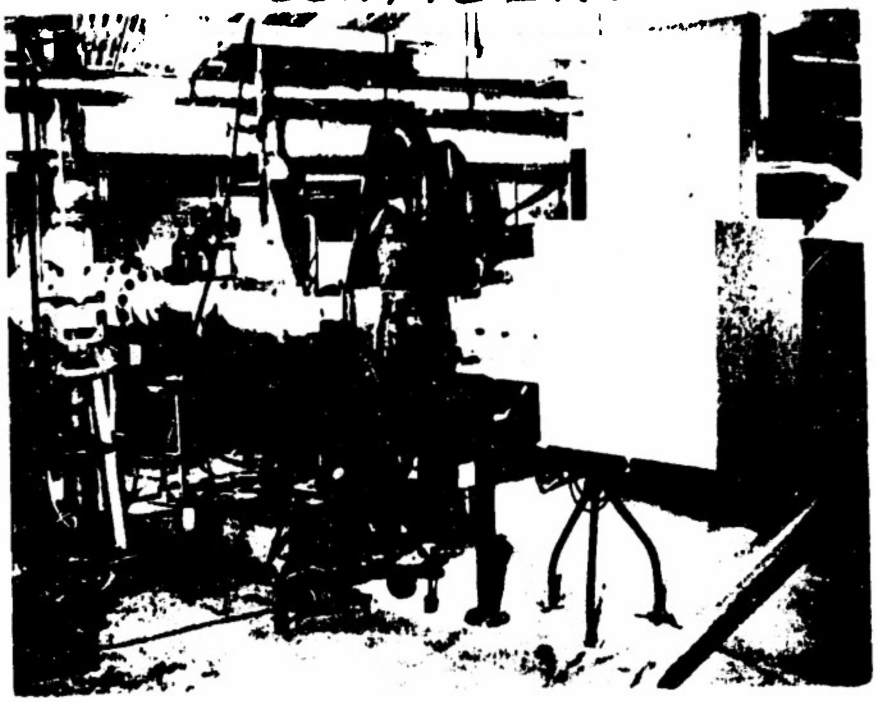

Fig. 4
DRY AIR PLENUM, TEST SECTION SUCTION PLENUMS & DIFFUSER

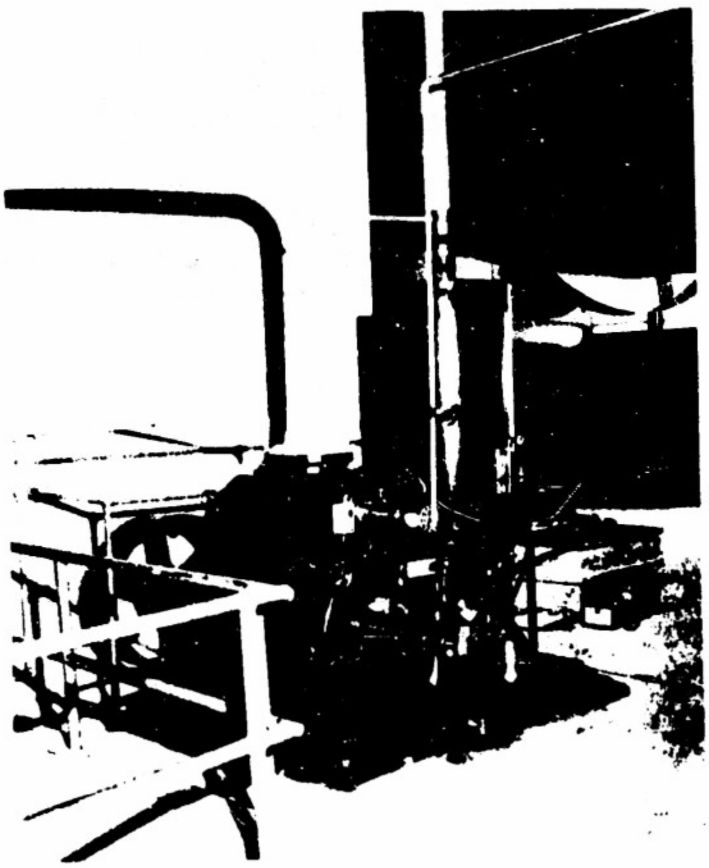

Fig. 5
VACUUM PUMP INSTALLATION

CONFIDENTIAL

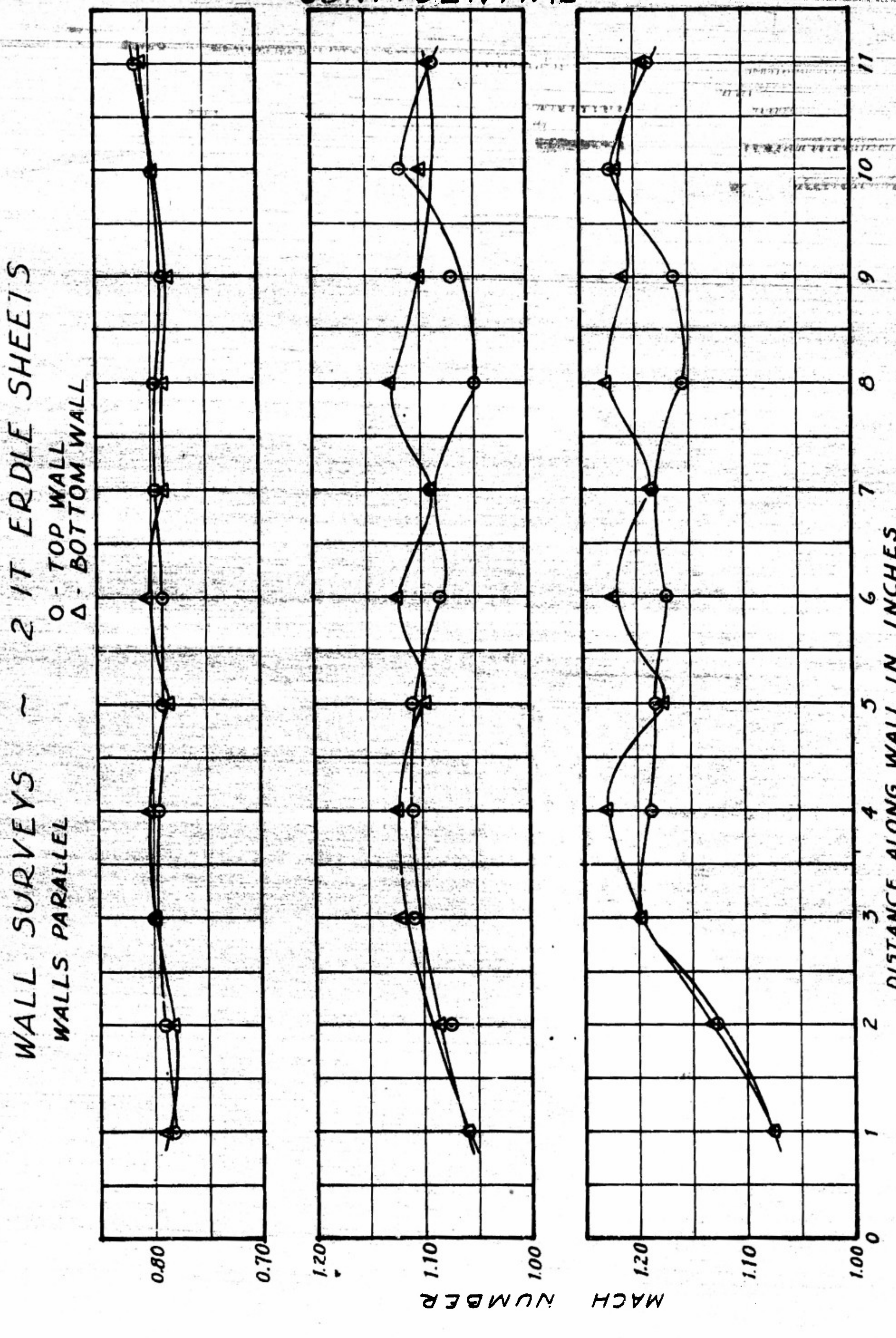

Fig. 6 a

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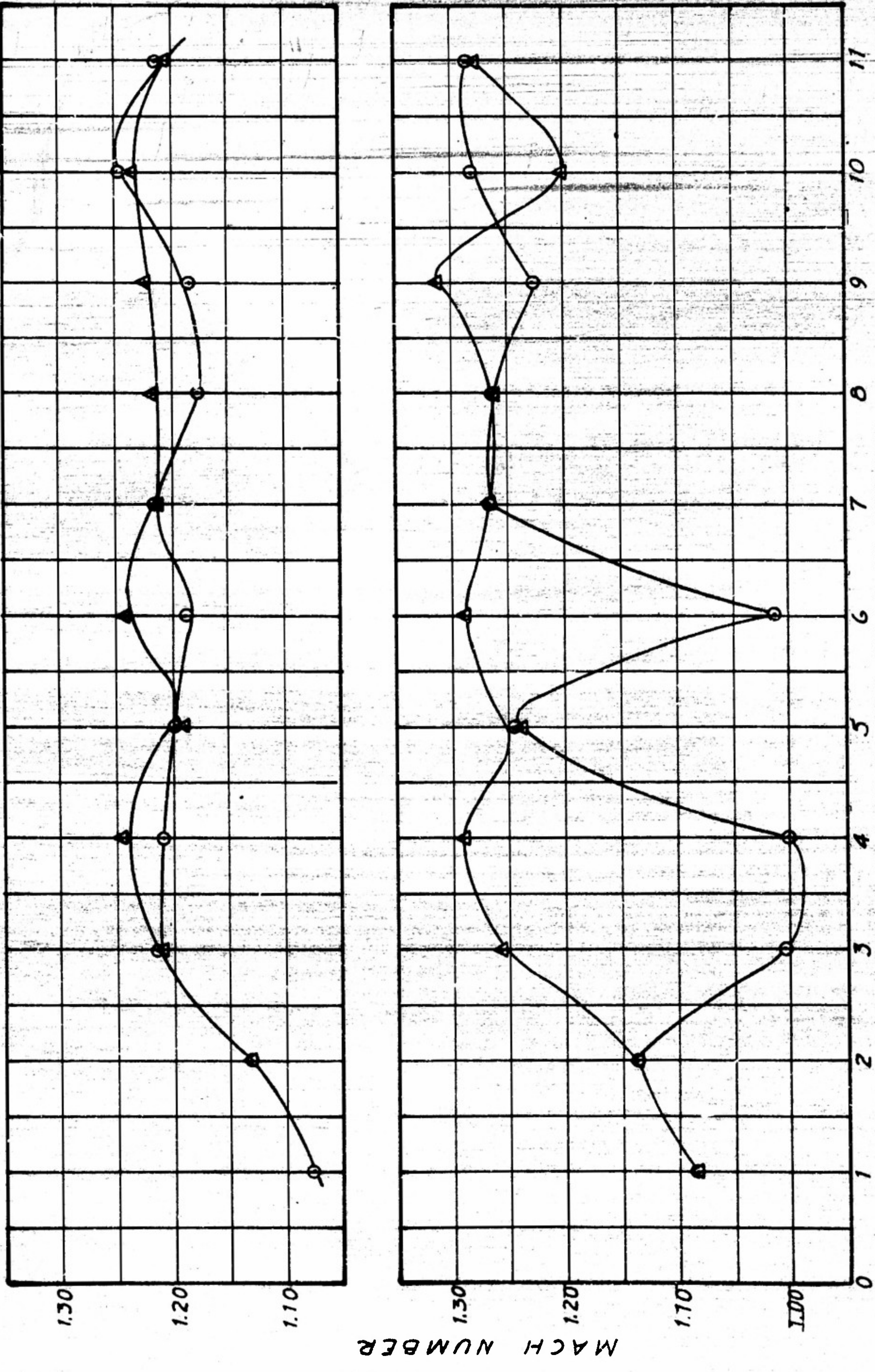
WALL SURVEYS ~ 2 IT ERDLE SHEETS

WALLS PARALLEL

O - TOP WALL
Δ - BOTTOM WALL



DISTANCE ALONG WALL IN INCHES

Fig. 6 b

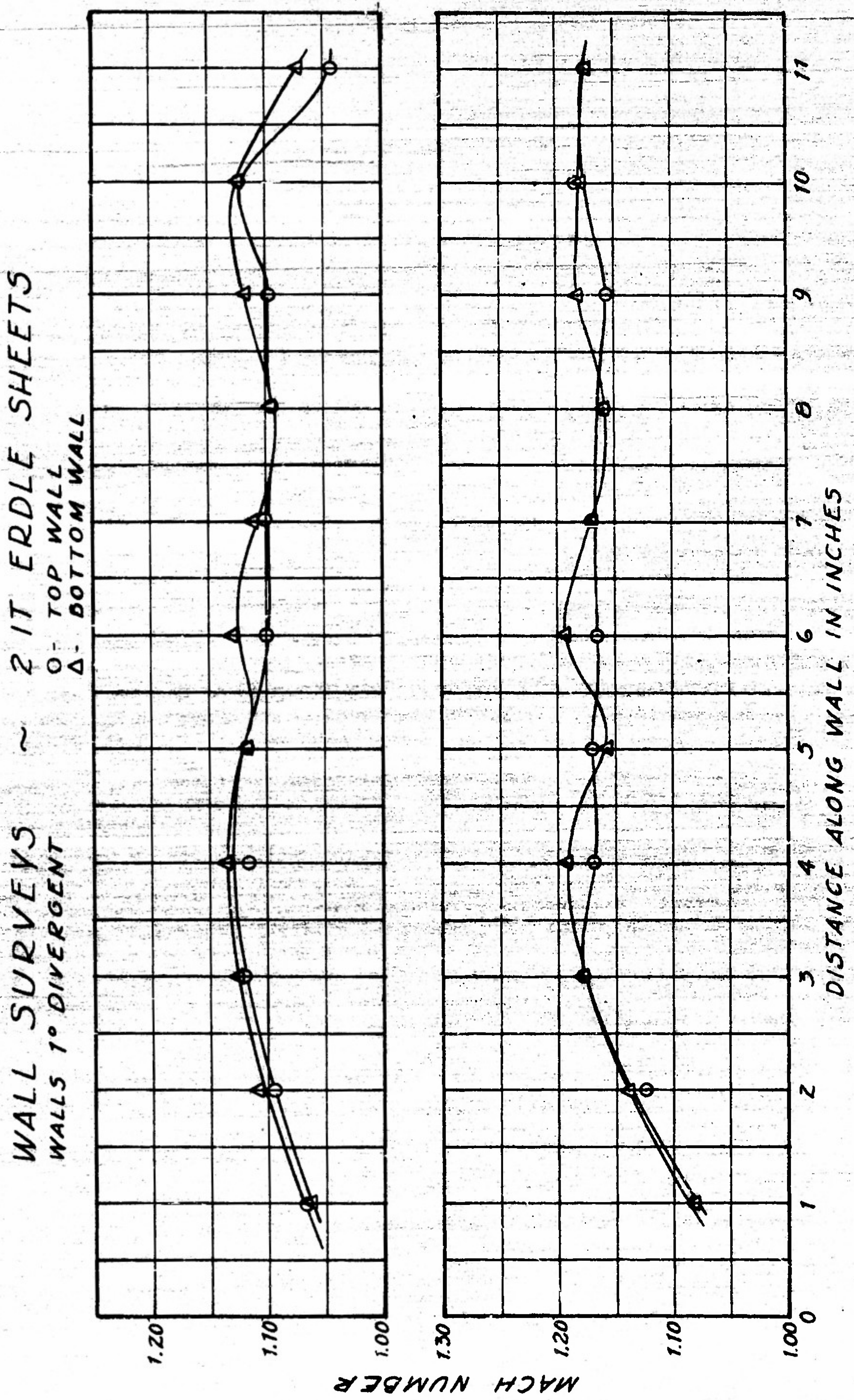

WALL SURVEYS ~ 2 IT ERDLE SHEETS
WALLS 1° DIVERGENT
O- TOP WALL
Δ- BOTTOM WALL
DISTANCE ALONG WALL IN INCHES
0
1
2
3
4
5
6
7
8
9
10
11
1.20
1.10
1.00
1.30
1.20
1.10
1.00
MACH NUMBER

Fig. 7a

WALL SURVEYS ~ 2 IT ERDLE SHEETS

WALLS 1° DIVERGENT

O- TOP WALL
Δ- BOTTOM WALL

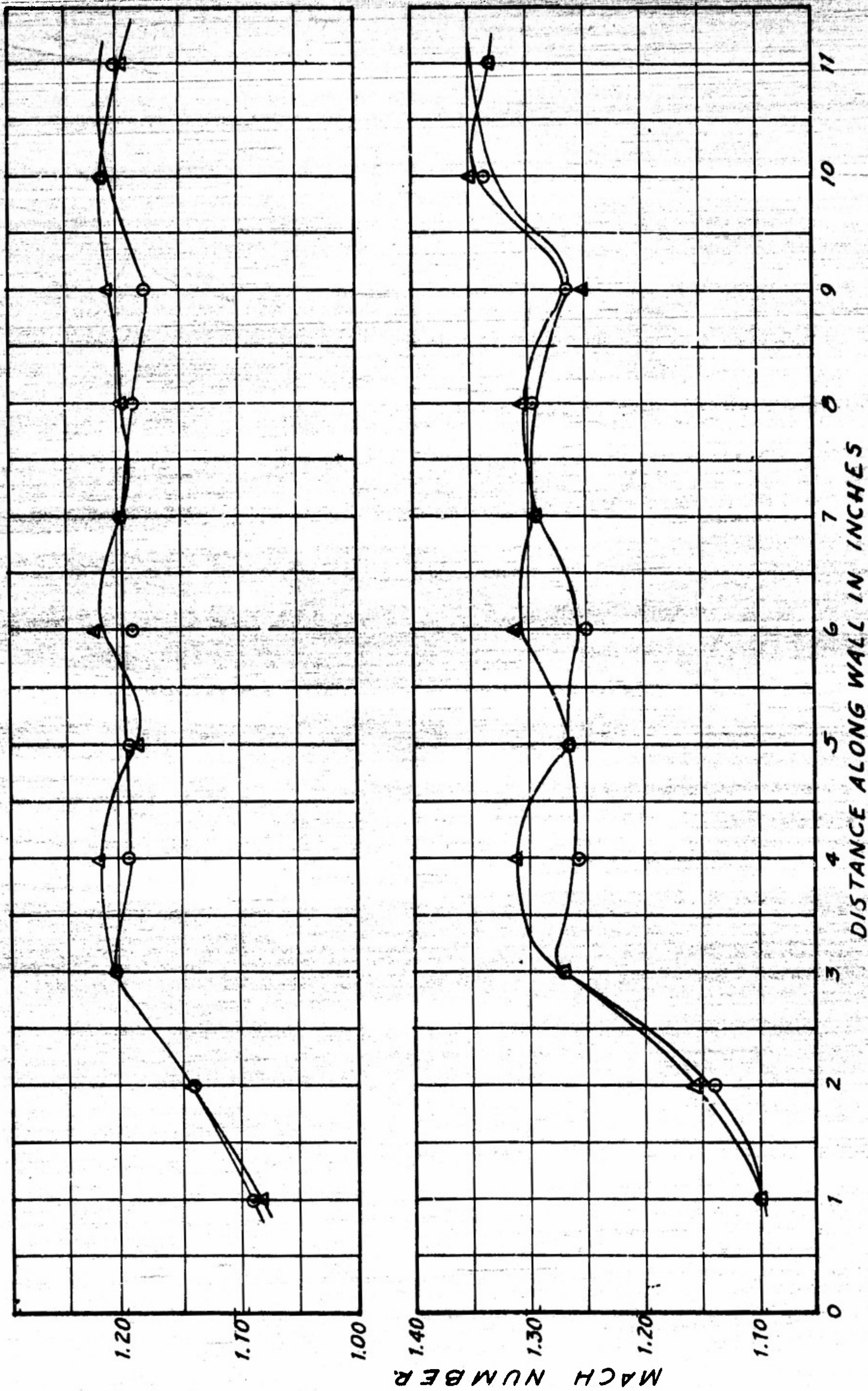


Fig. 7 b

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WALL SURVEYS ~ # 00 ERDLE SHEETS

WALLS PARALLEL

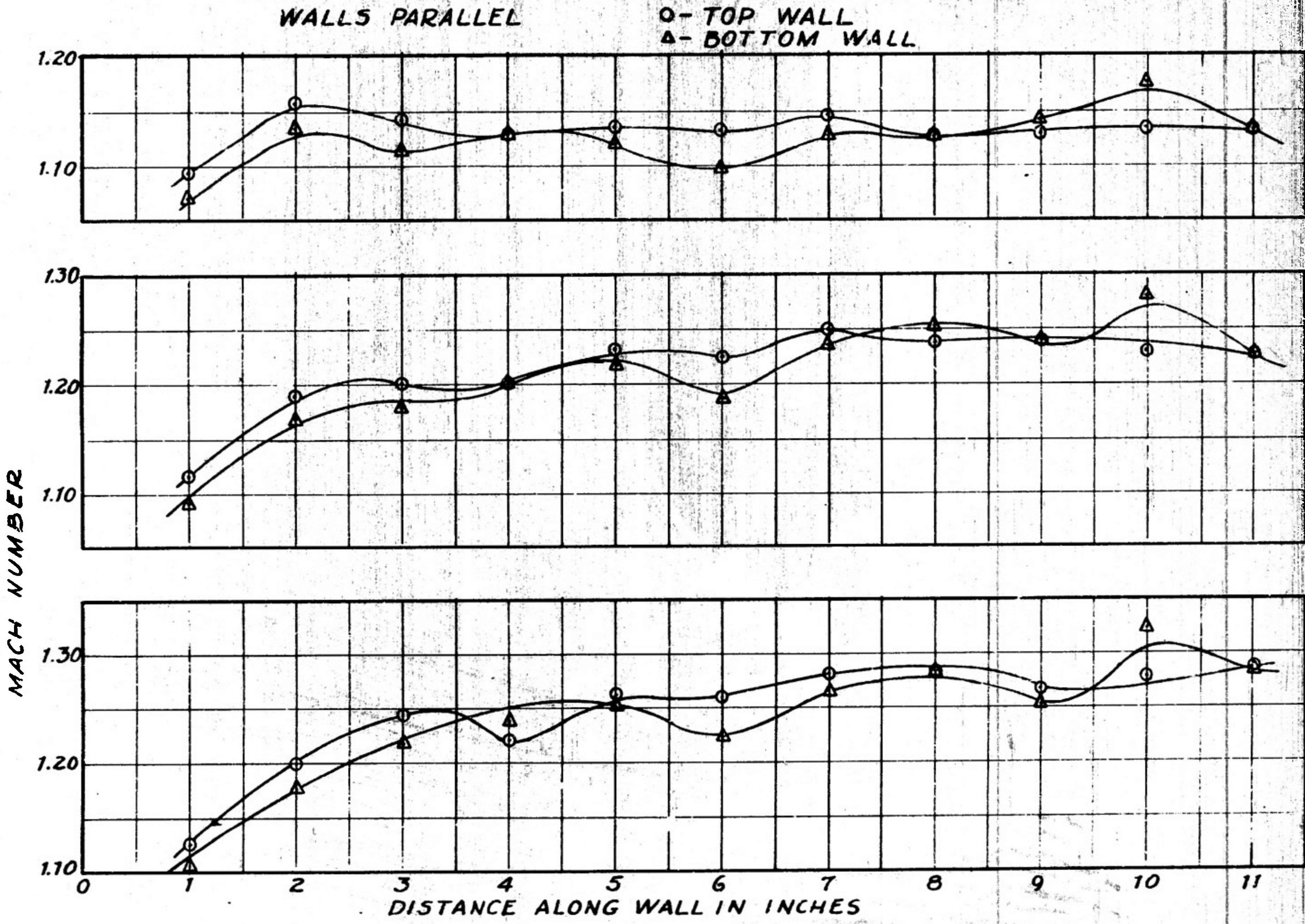

Fig. 8

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WALL SURVEYS ~ # OO ERDLE SHEETS

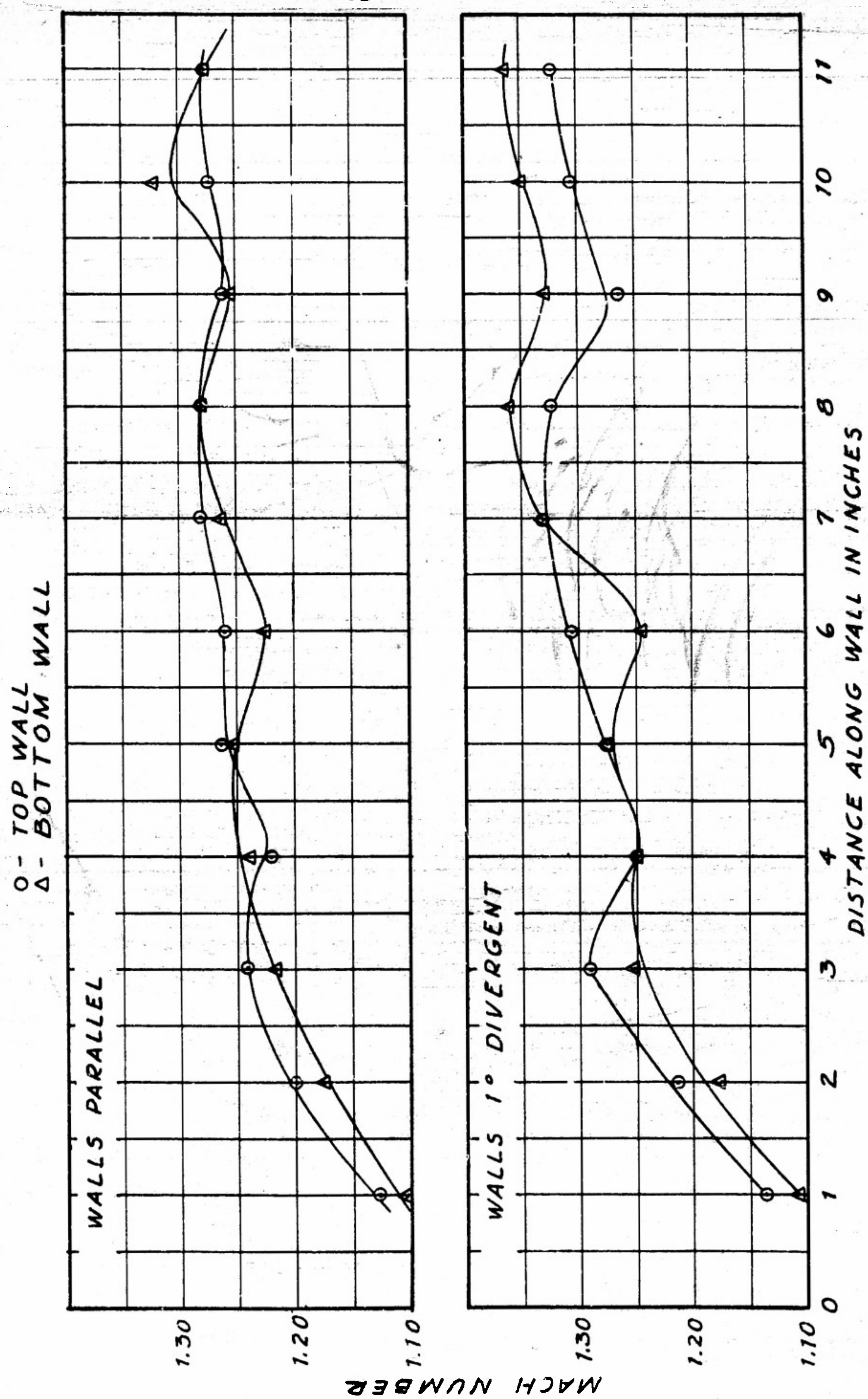


Fig. 9

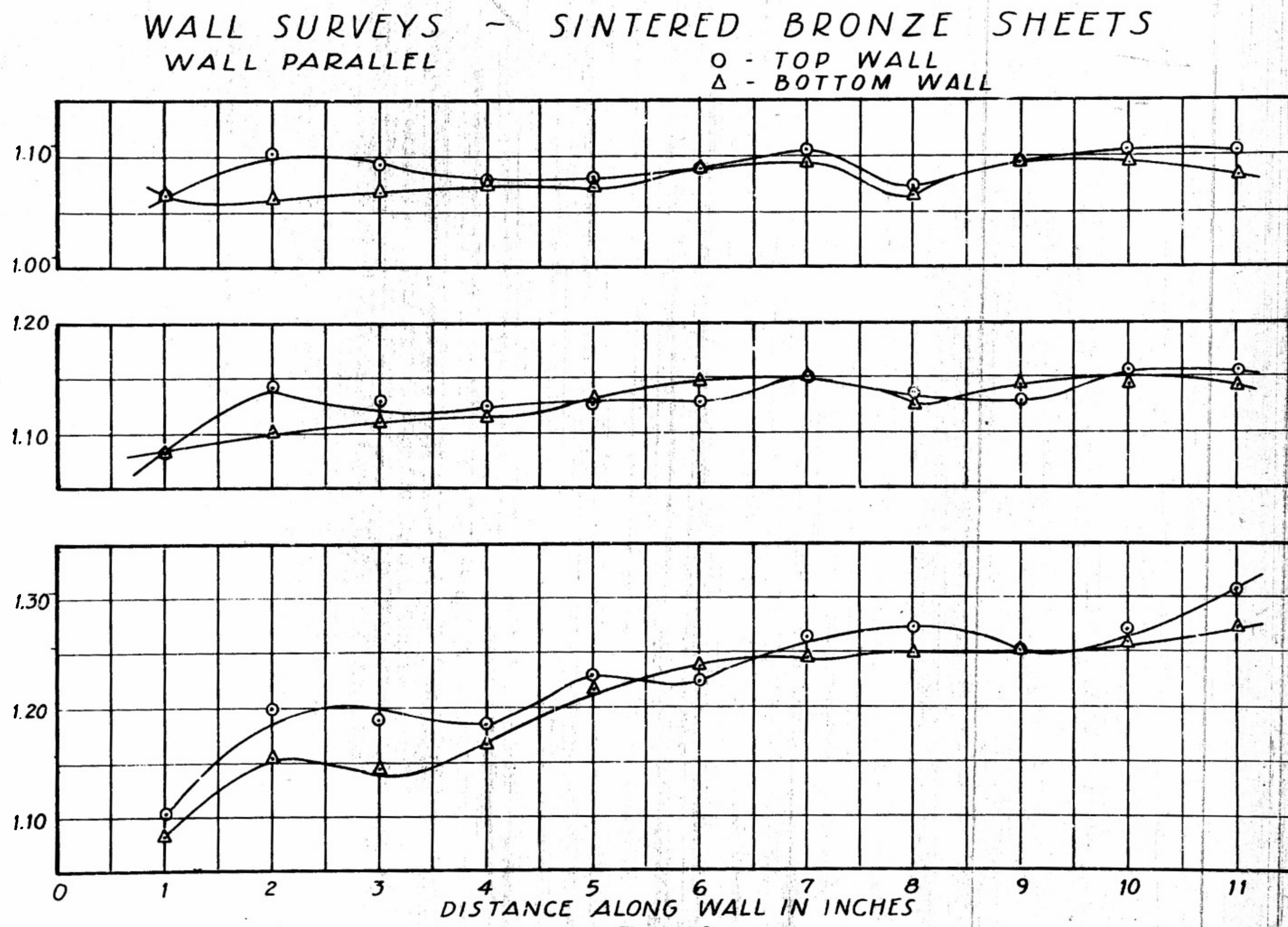


Fig. 10

CONFIDENTIAL

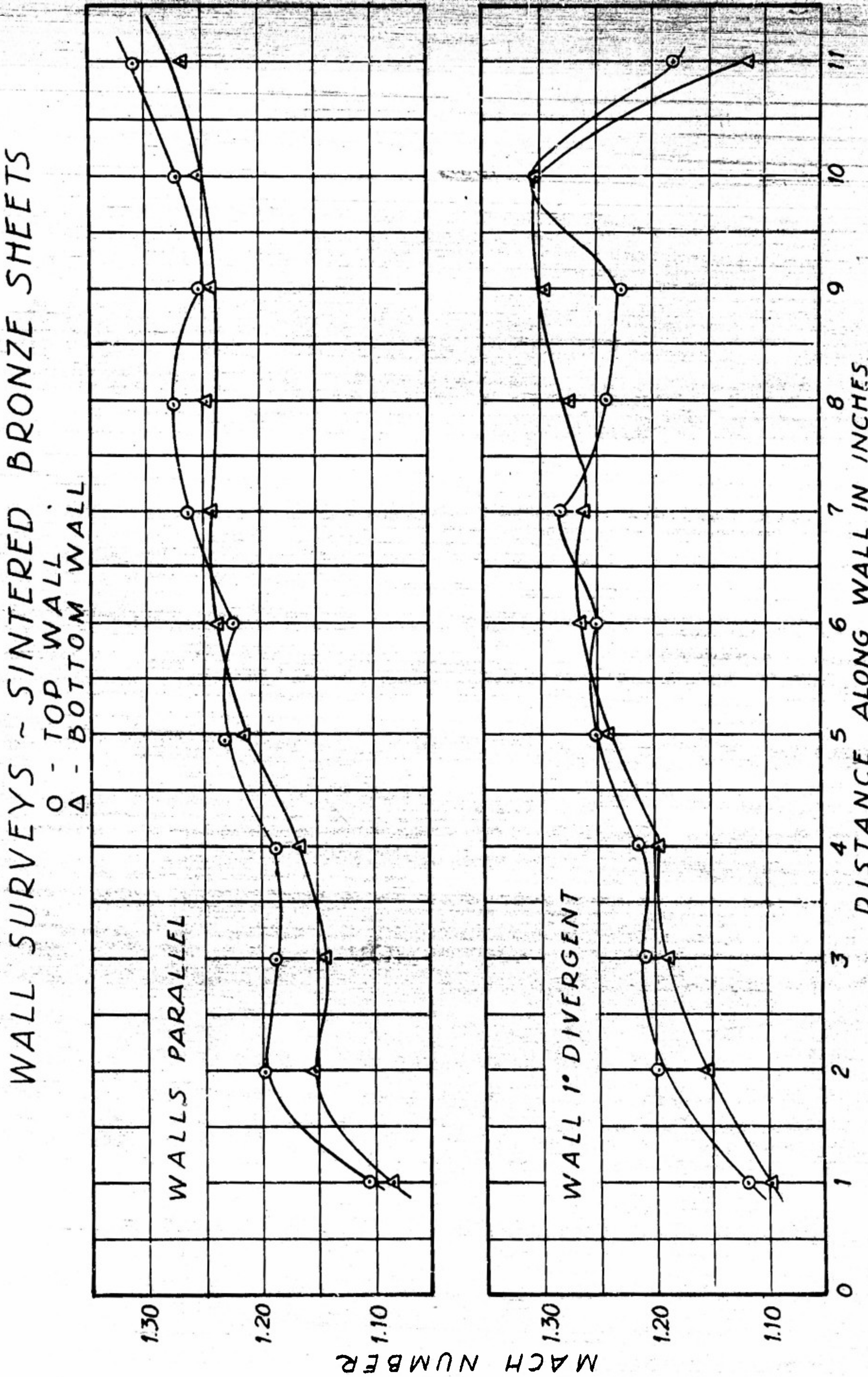

WALL SURVEYS - SINTERED BRONZE SHEETS
O - TOP WALL
Δ - BOTTOM WALL
WALLS PARALLEL
WALL 1° DIVERGENT
MACH NUMBER
1.30
1.20
1.10
DISTANCE ALONG WALL IN INCHES
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 11

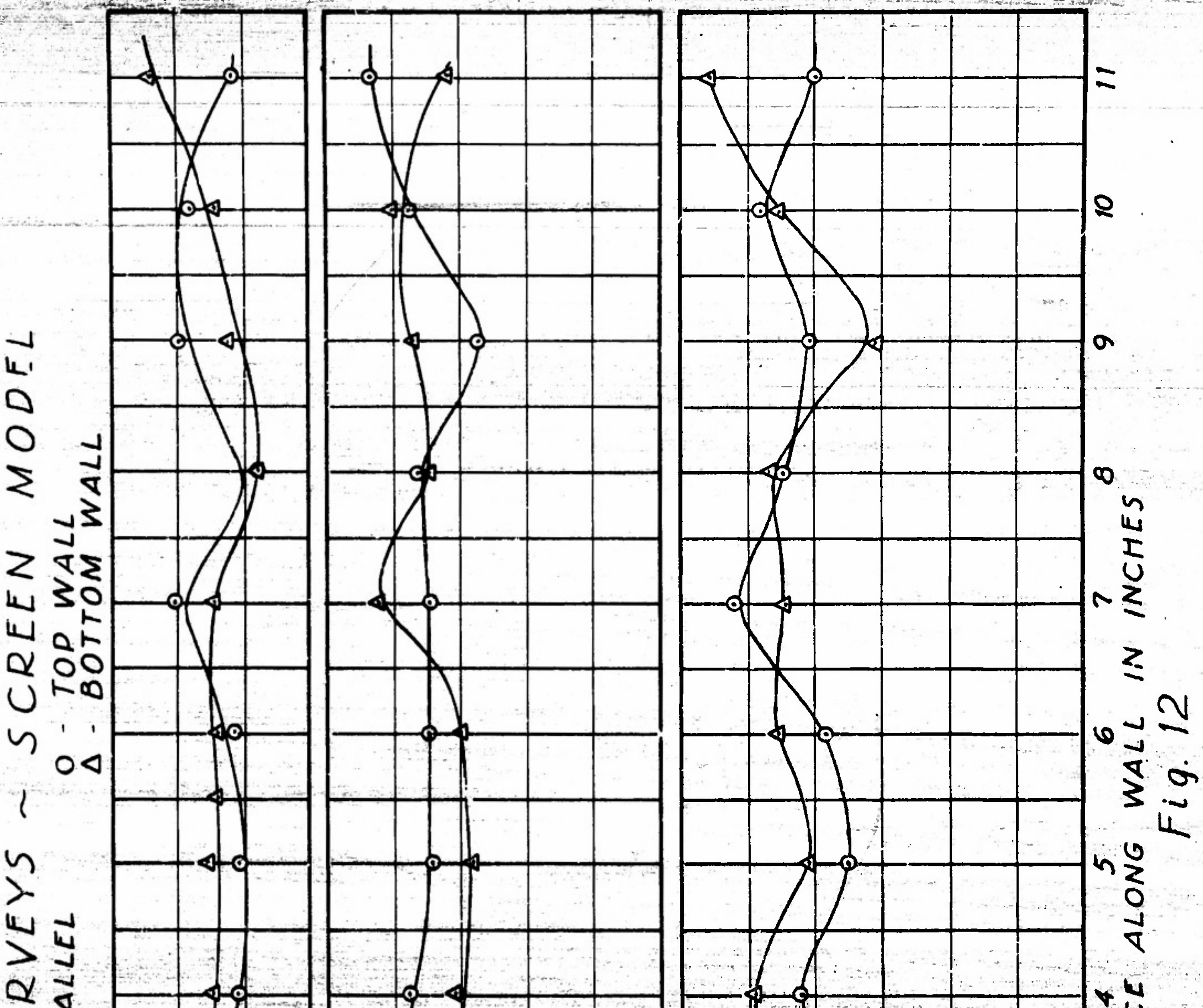

WALLS SURVEYS ~ SCREEN MODEL
WALLS PARALLEL
O - TOP WALL
Δ - BOTTOM WALL
DISTANCE ALONG WALL IN INCHES
0 1 2 3 4 5 6 7 8 9 10 11
MACH NUMBER
1.20 1.10
1.30 1.20 1.10
1.30 1.20 1.10

Fig. 12

CONFIDENTIAL

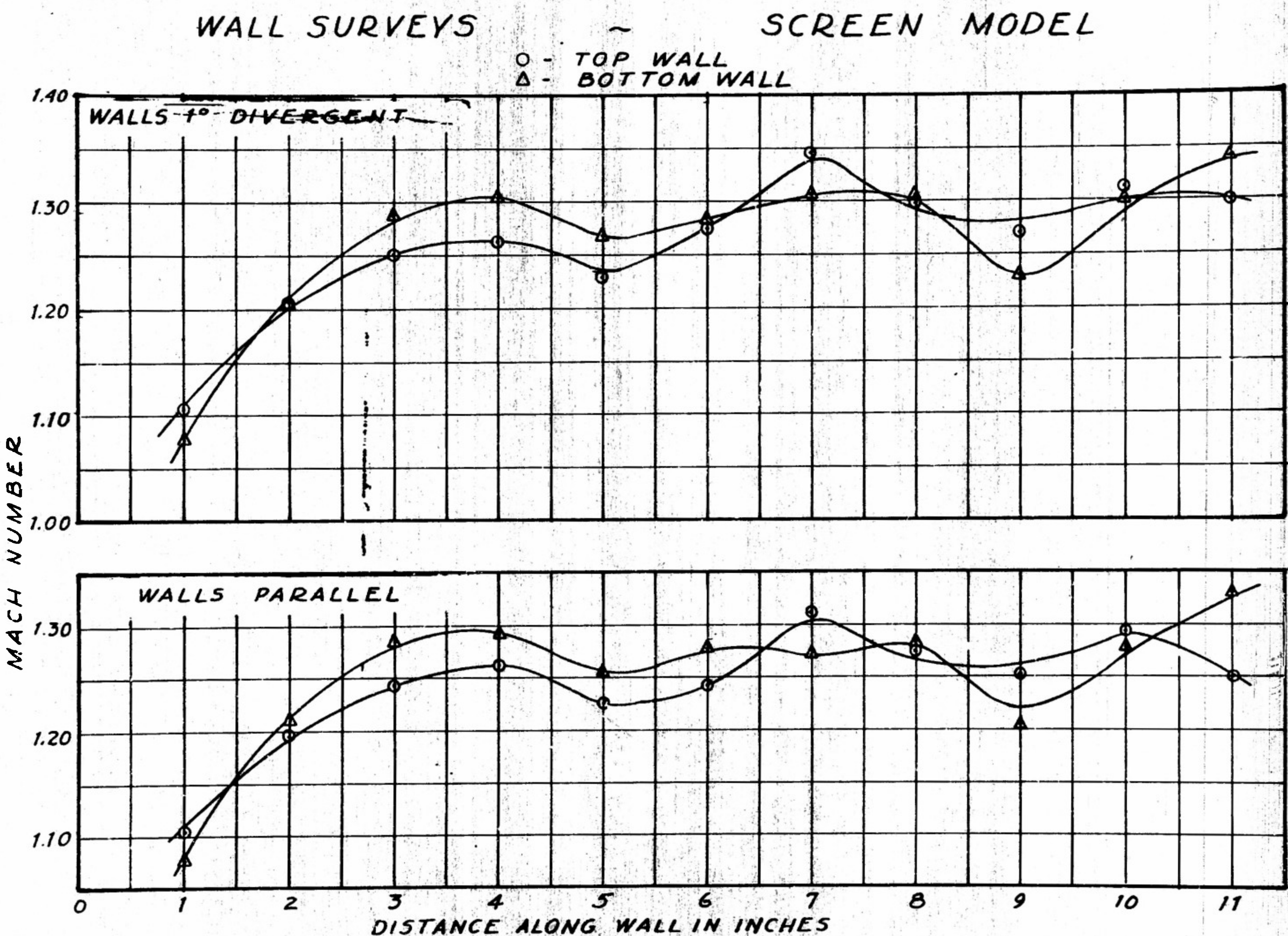


Fig. 13

CONFIDENTIAL

Fig. 14
TWO IT ERDLE SHEETS
PER WALL

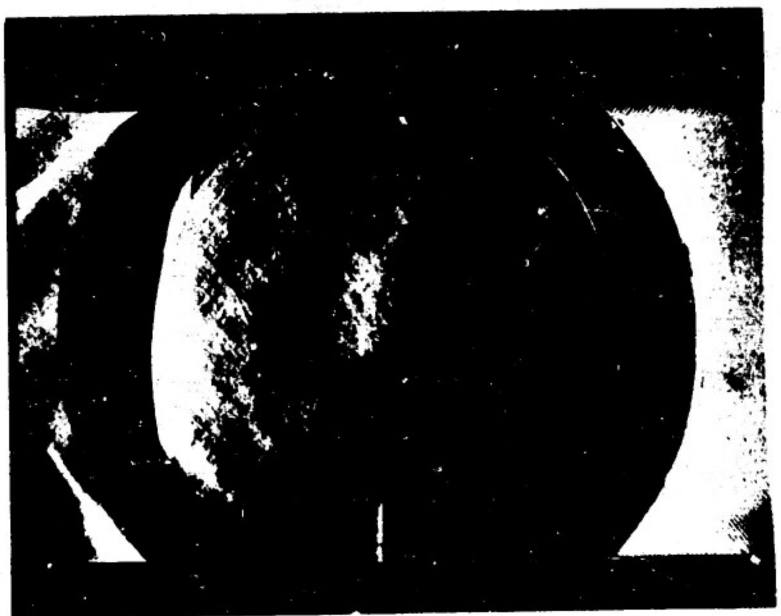


Fig. 15
NO. 00 ERDLE SHEETS

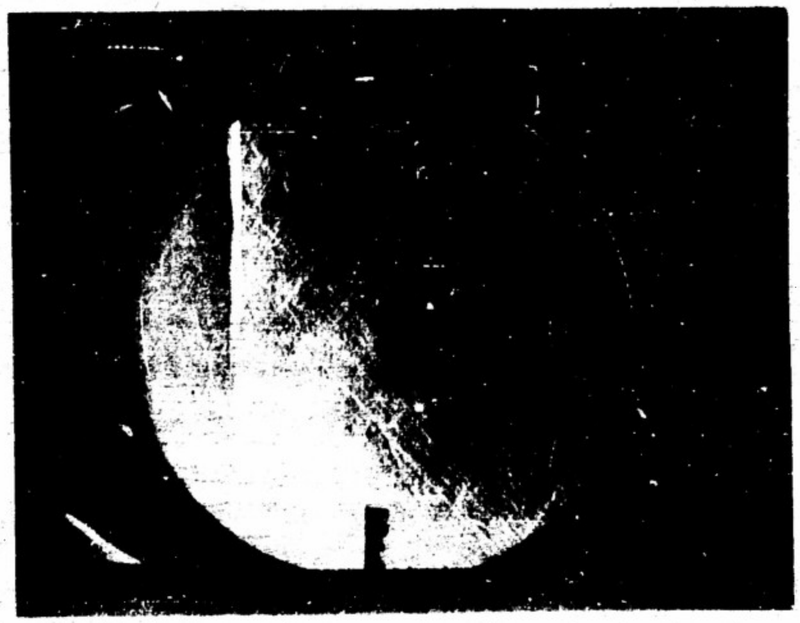


Fig. 16
SINTERED BRONZE SHEET

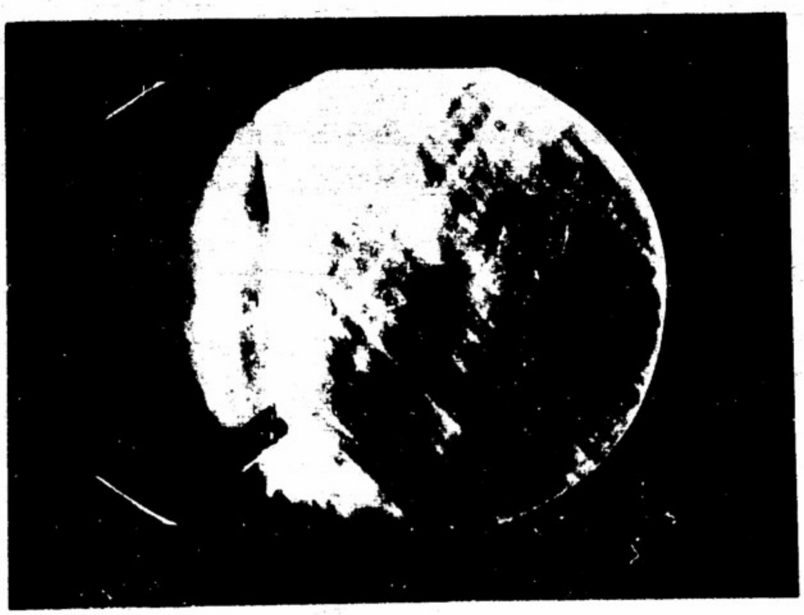
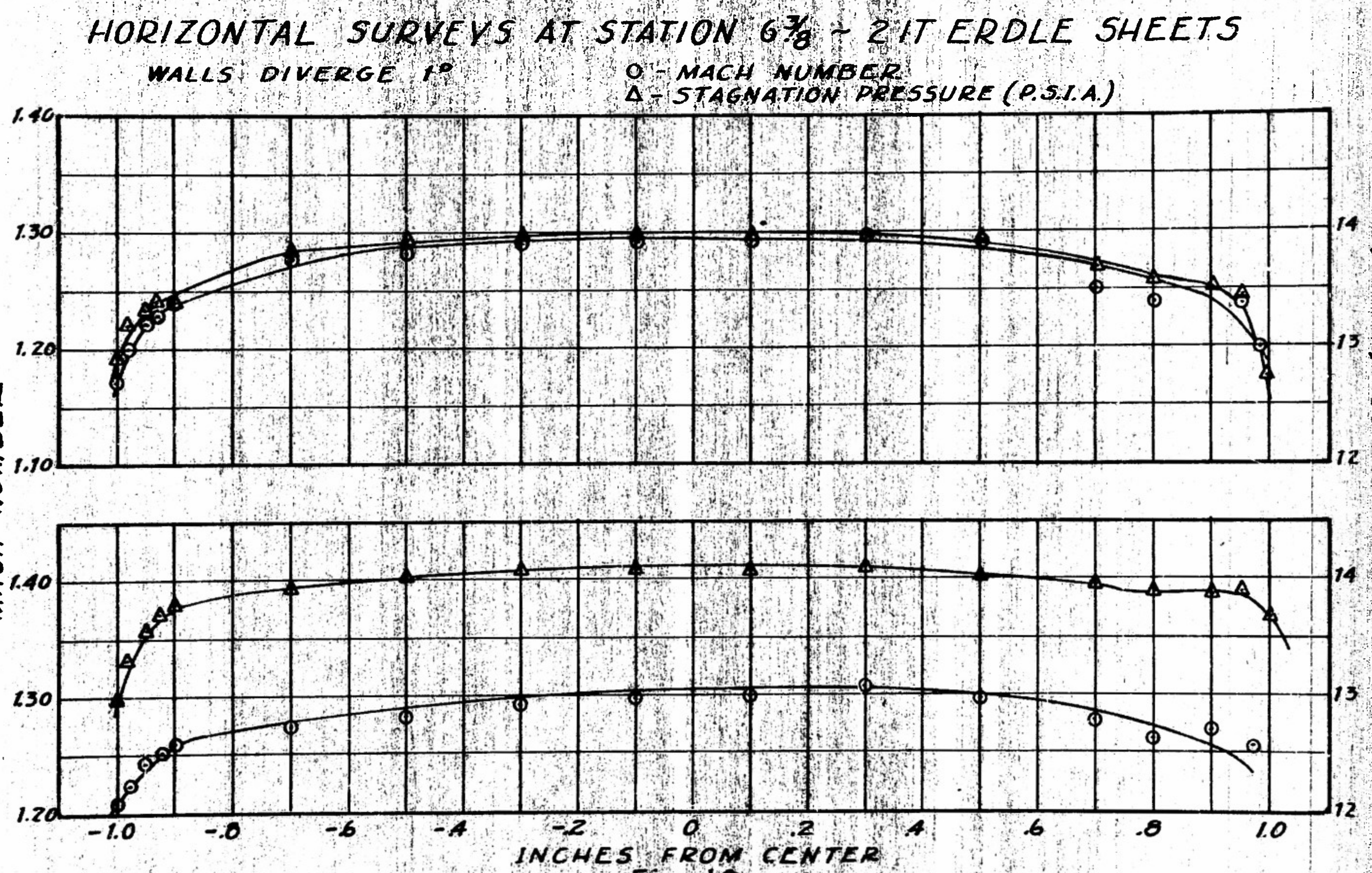


Fig. 17
WIRE CLOTH (SCREENING)


HORIZONTAL SURVEYS AT STATION 6⅜ ~ 2 IT ERDLE SHEETS
WALLS DIVERGE 1°
O - MACH NUMBER
Δ - STAGNATION PRESSURE (P.S.I.A.)
FROM TOP .128"
FROM TOP .187"
MACH NUMBER
STAGNATION PRESSURE (P.S.I.A.)
1.40
1.30
1.20
1.10
14
13
12
-1.0
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8
1.0
INCHES FROM CENTER
Fig. 18 a

HORIZONTAL SURVEYS AT STATION 6⅜ ~ 2 IT ERDLE SHEETS

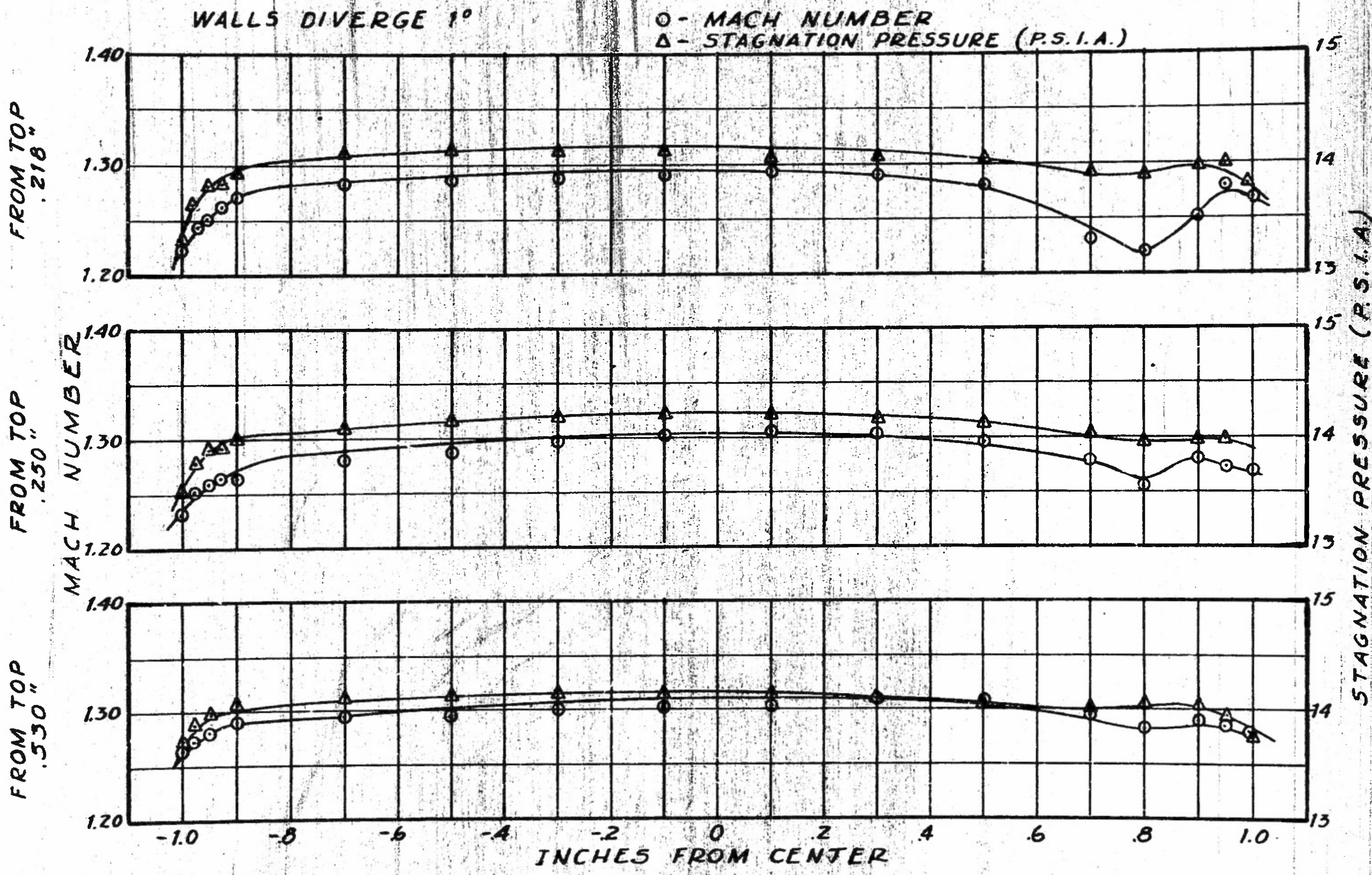


Fig. 18 b

CONFIDENTIAL

HORIZONTAL SURVEYS AT STATION 6⅜ ~ 2 IT ERDLE SHEETS

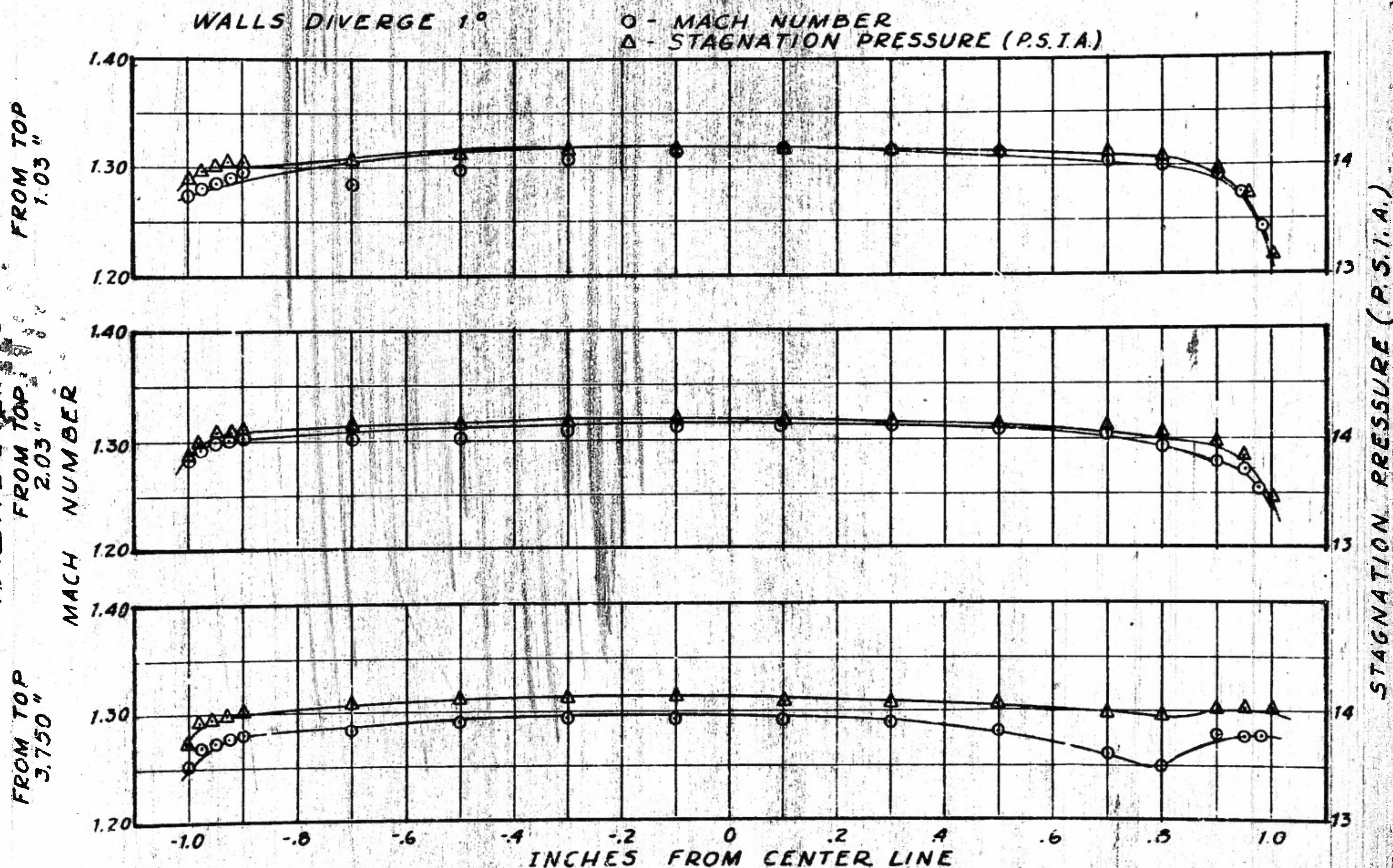


Fig. 19 a

CONFIDENTIAL

HORIZONTAL SURVEYS AT STATION 6⅜ ~ 2 IT ERDLE SHEETS

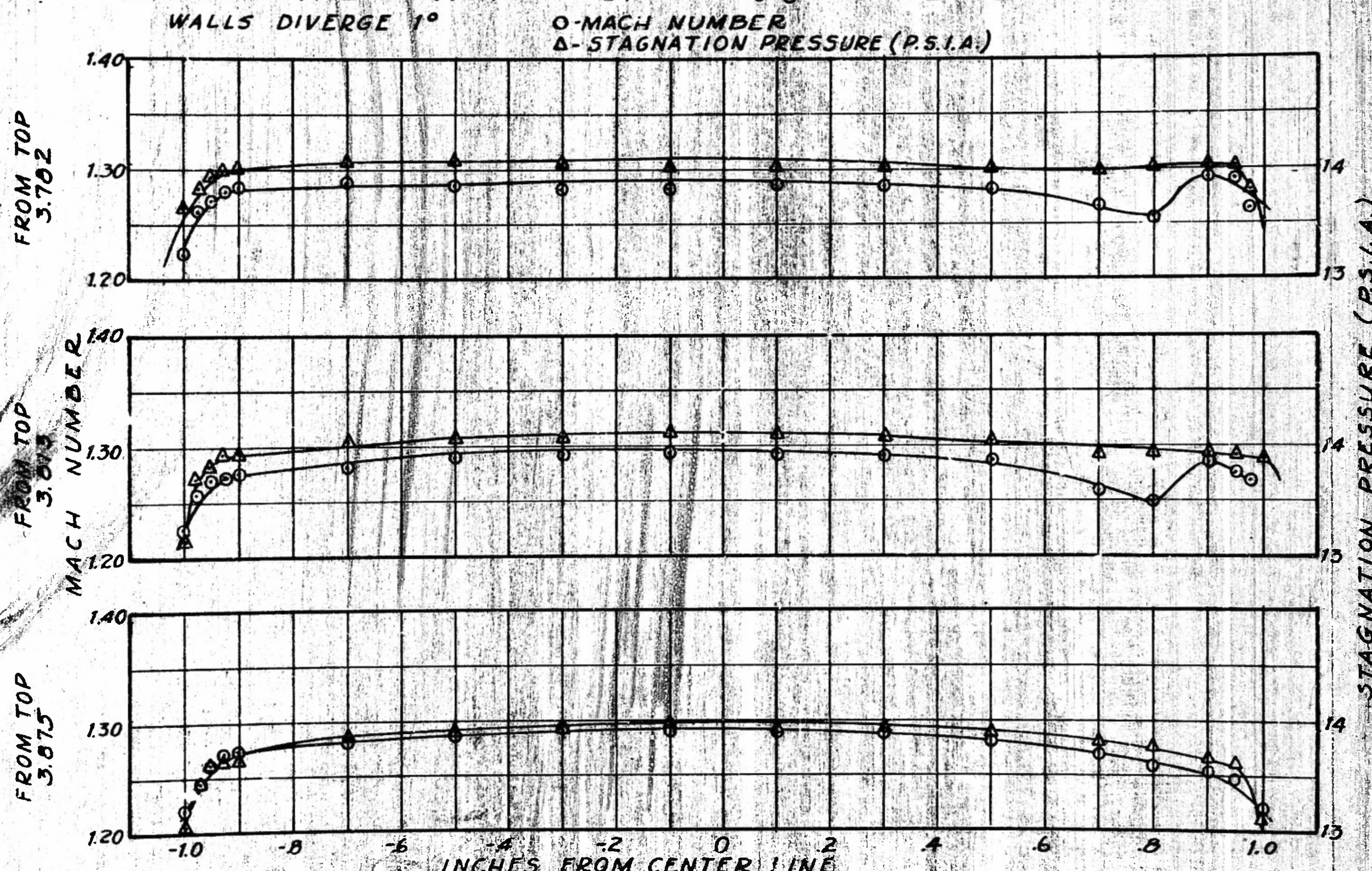


Fig. 19 b

EFFECT OF PROBE ON WALL STATIC PRESSURES

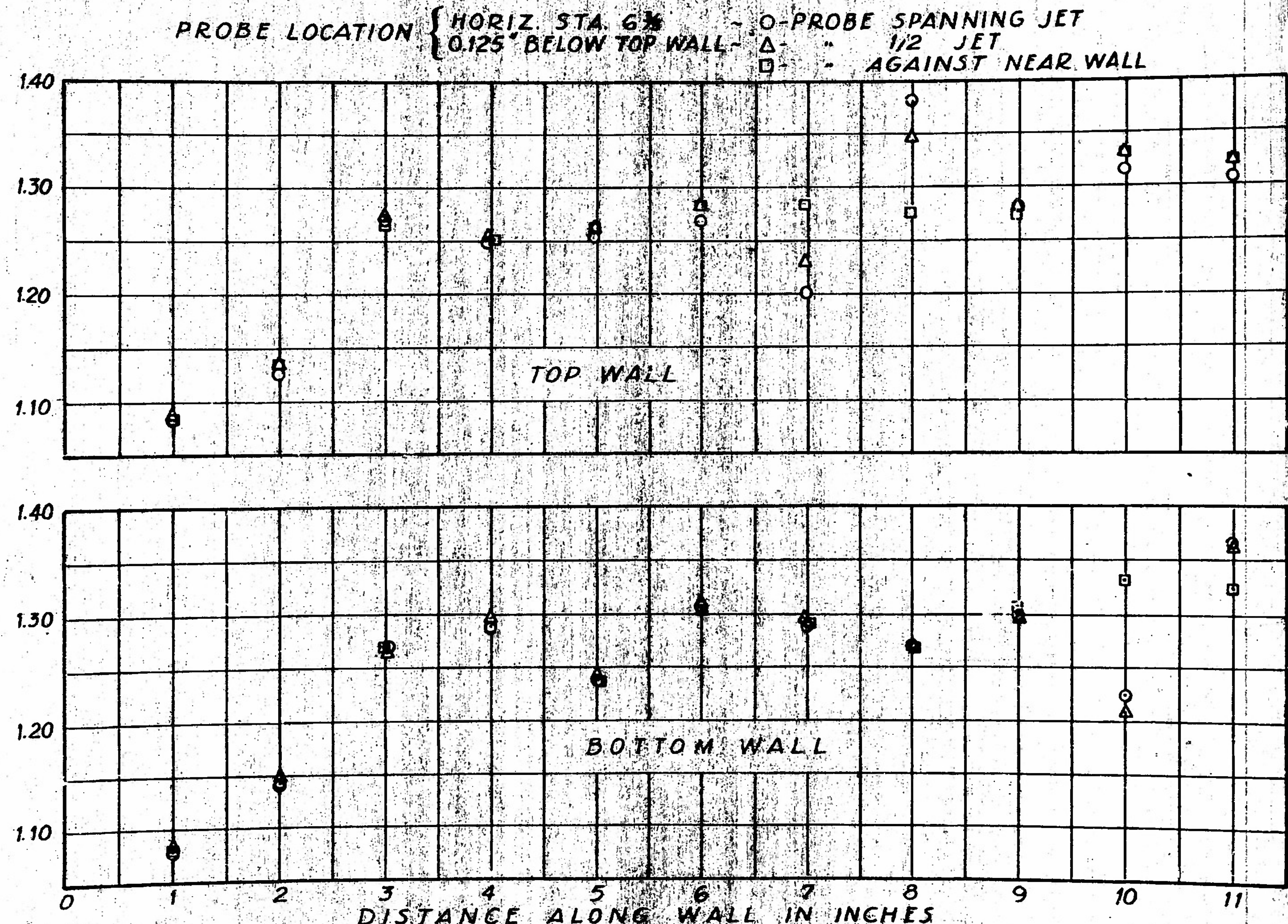


Fig. 20

VERTICAL - SURVEYS - CENTER LINE AT STATION #4

2 - IT ERDLE SHEETS

WALLS 1° DIVERGENT

O-STAGNATION PRESSURE
Δ-MACH NUMBER

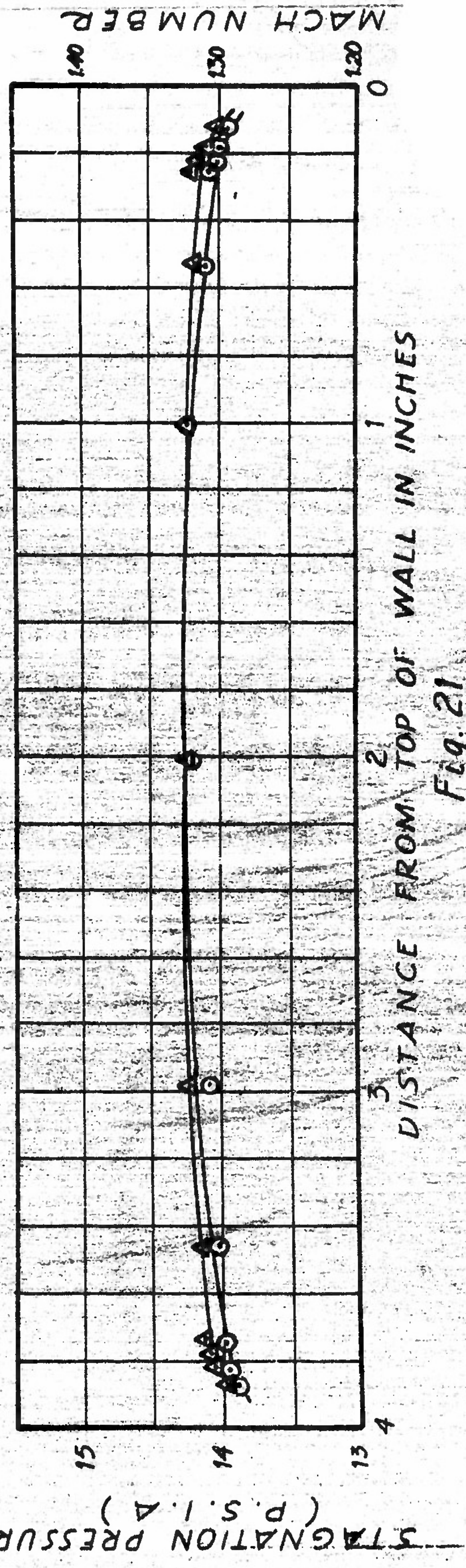


Fig. 21

C.A.L. PERFORATED WALL WIND TUNNEL

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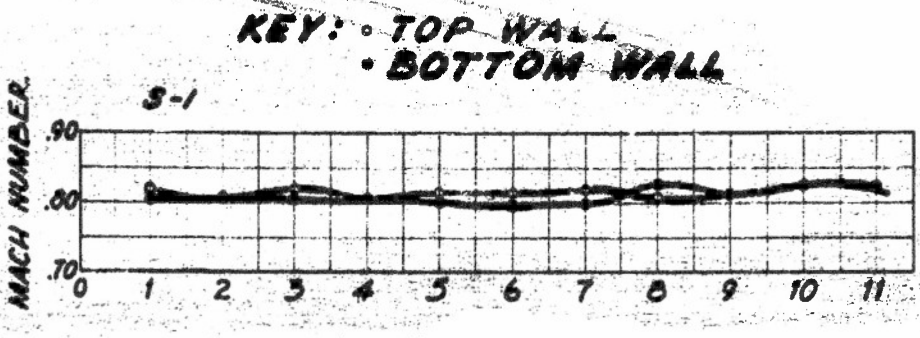
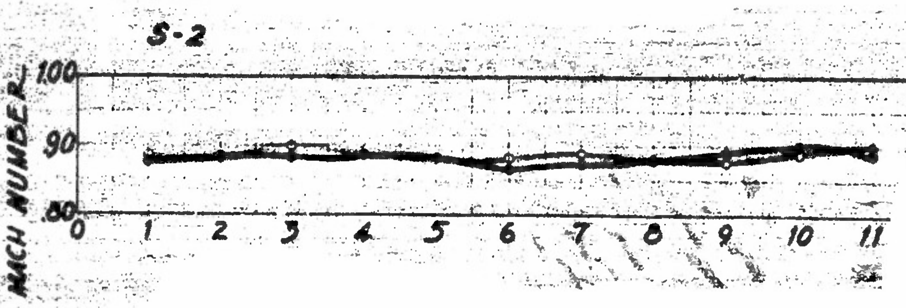
FLOW ABOUT 6% BICONVEX AIRFOIL, $\alpha = 0°$
#00 ERDLE SHEET
WALLS PARALLEL

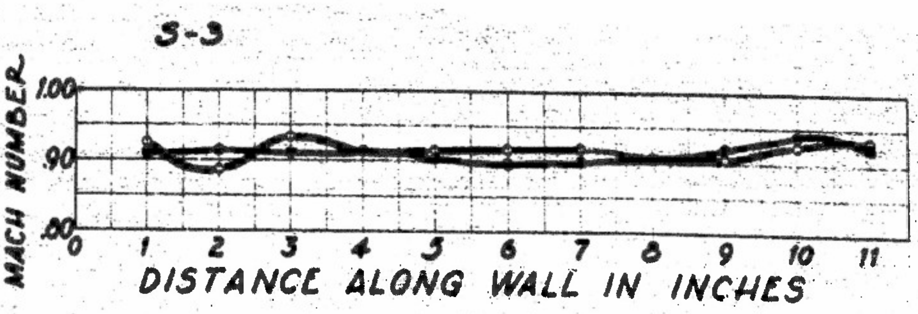
M ≈ 0.8



M ≈ 0.86



M ≈ 0.91



CONFIDENTIAL

FIG. 22

C.A.L. PERFORATED WALL WIND TUNNEL.

CONFIDENTIAL

FLOW ABOUT 6% BICONVEX AIRFOIL, $\alpha = 0°$
#00 ERDLE SHEET
WALLS PARALLEL

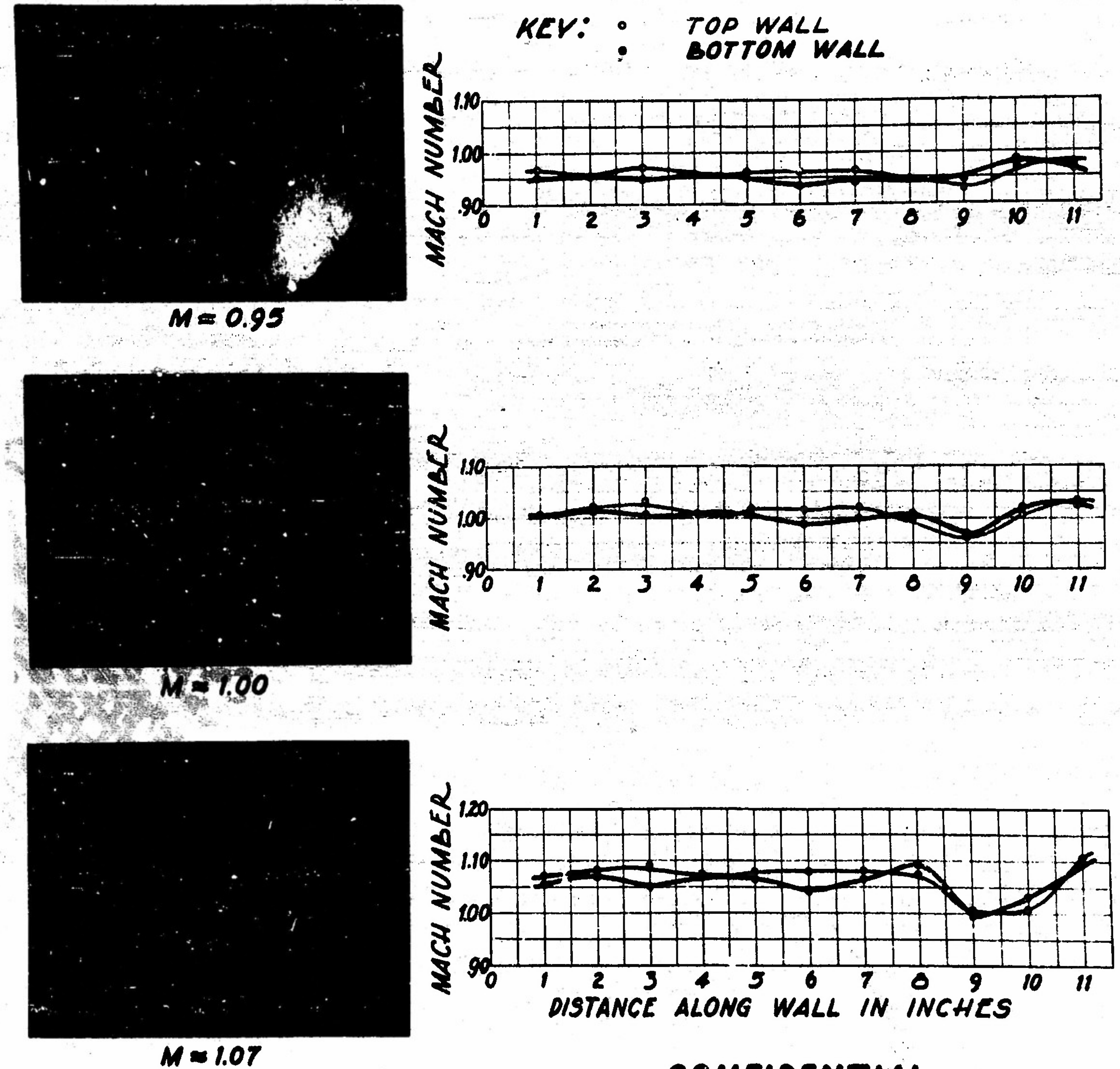


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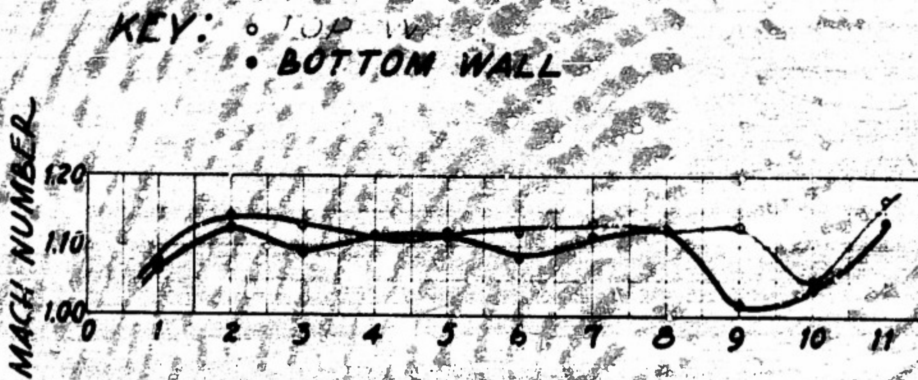
FIG. 23

C.A.L. PERFORATED WALL WIND TUNNEL

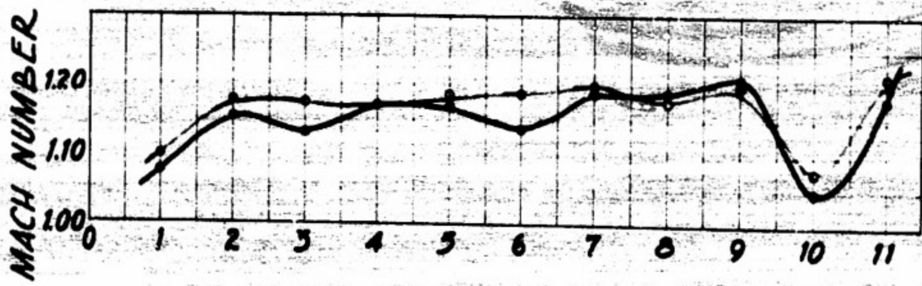
CONFIDENTIAL

FLOW ABOUT 6% BICONVEX AIRFOIL, $\alpha = 0°$
#00 EDDLE SHEET
WALLS PARALLEL

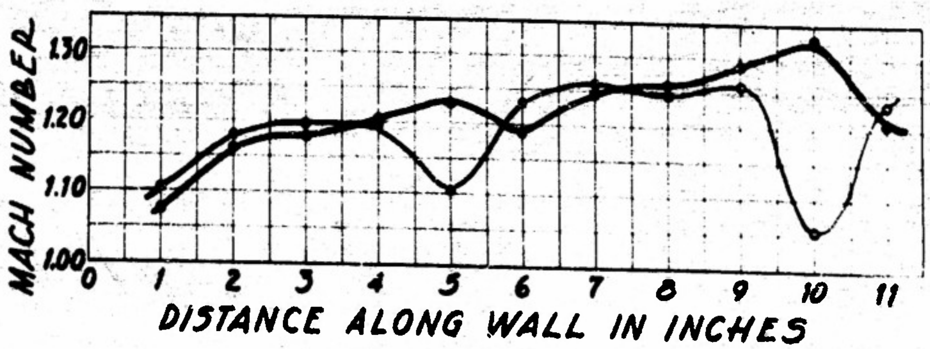
M = 1.12



M = 1.20



M = 1.25



CONFIDENTIAL

FIG. 24

WALL SURVEYS ~ # 00 ERDLE SHEETS
BI-CONVEX AIR FOIL = $\alpha = +2°$
WALLS PARALLEL

O - TOP WALL
Δ - BOTTOM WALL

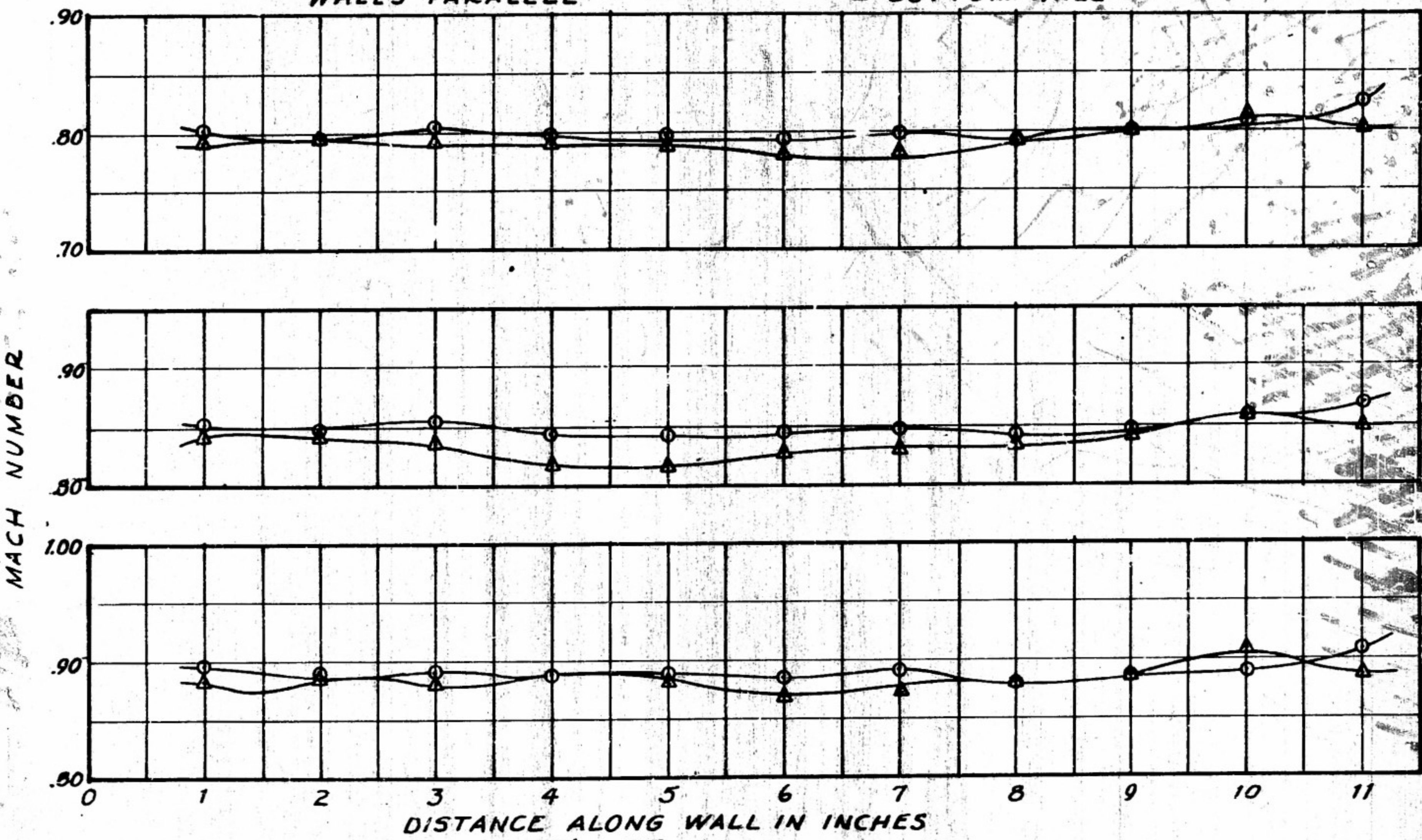


Fig. 25 c.

WALL SURVEYS ~ # 00 ERDLE SHEETS

BI-CONVEX AIR FOIL: α = +2°   O - TOP WALL

WALLS PARALLEL   Δ - BOTTOM WALL

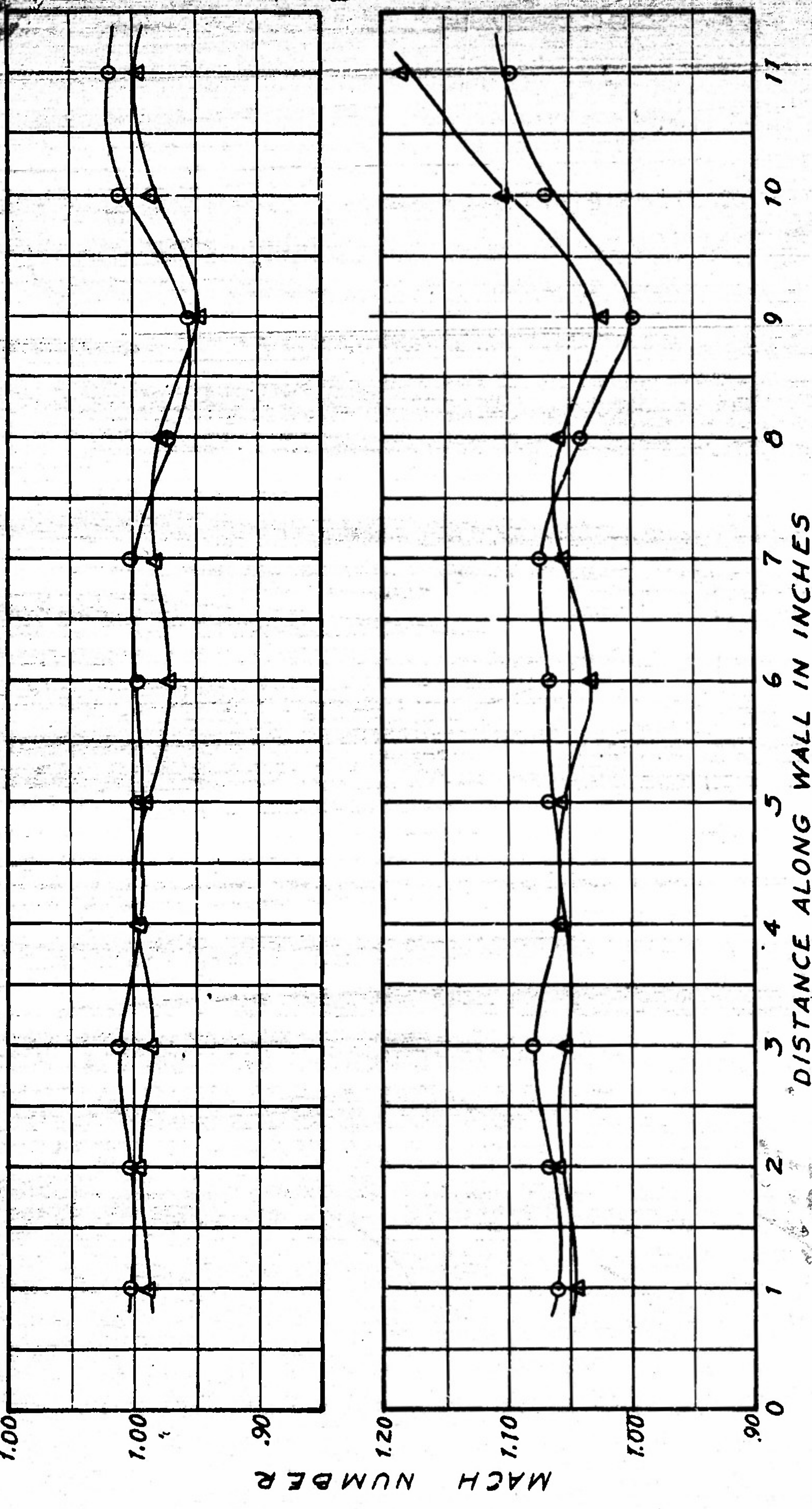


Fig. 25 b

Fig. 26
$M \approx 0.80$

Fig. 27
$M = 0.84$

Fig. 28
$M \approx 0.89$

Fig. 29
$M \approx 1.00$

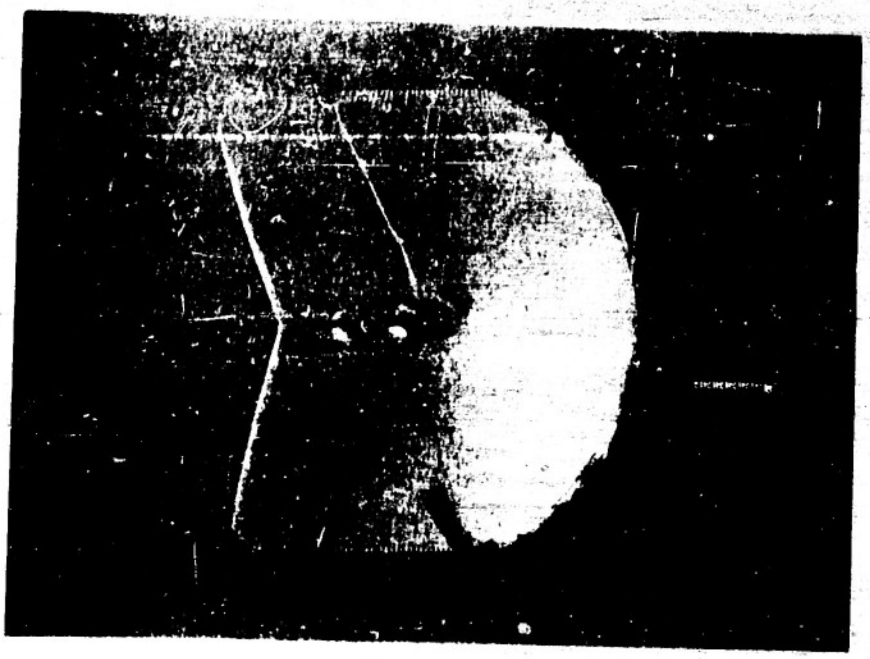


Fig. 30
$M \approx 1.06$

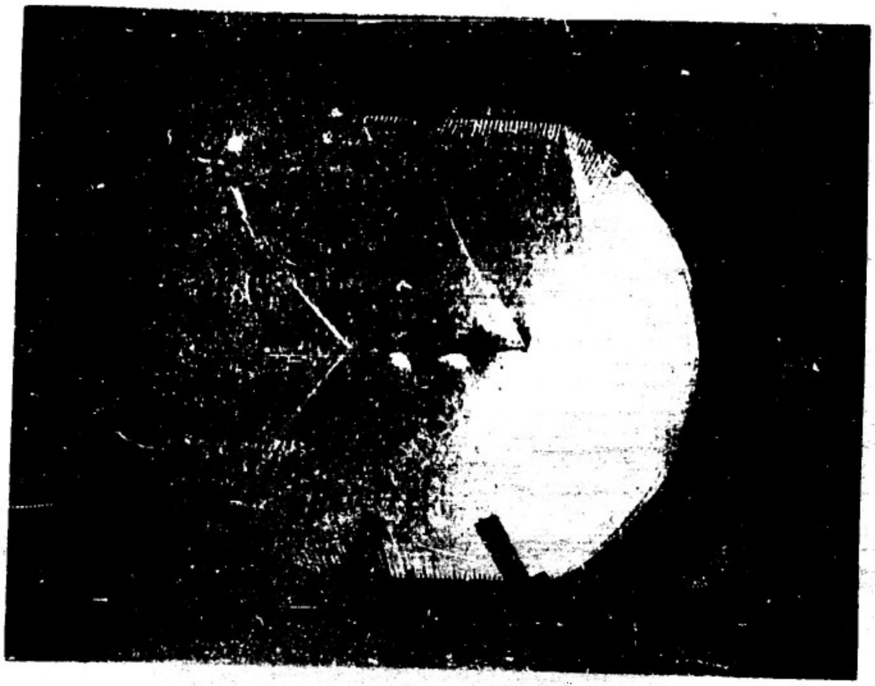


Fig. 31
$M \approx 1.12$

TRUE WEIGHT FLOW VS MACH NUMBER

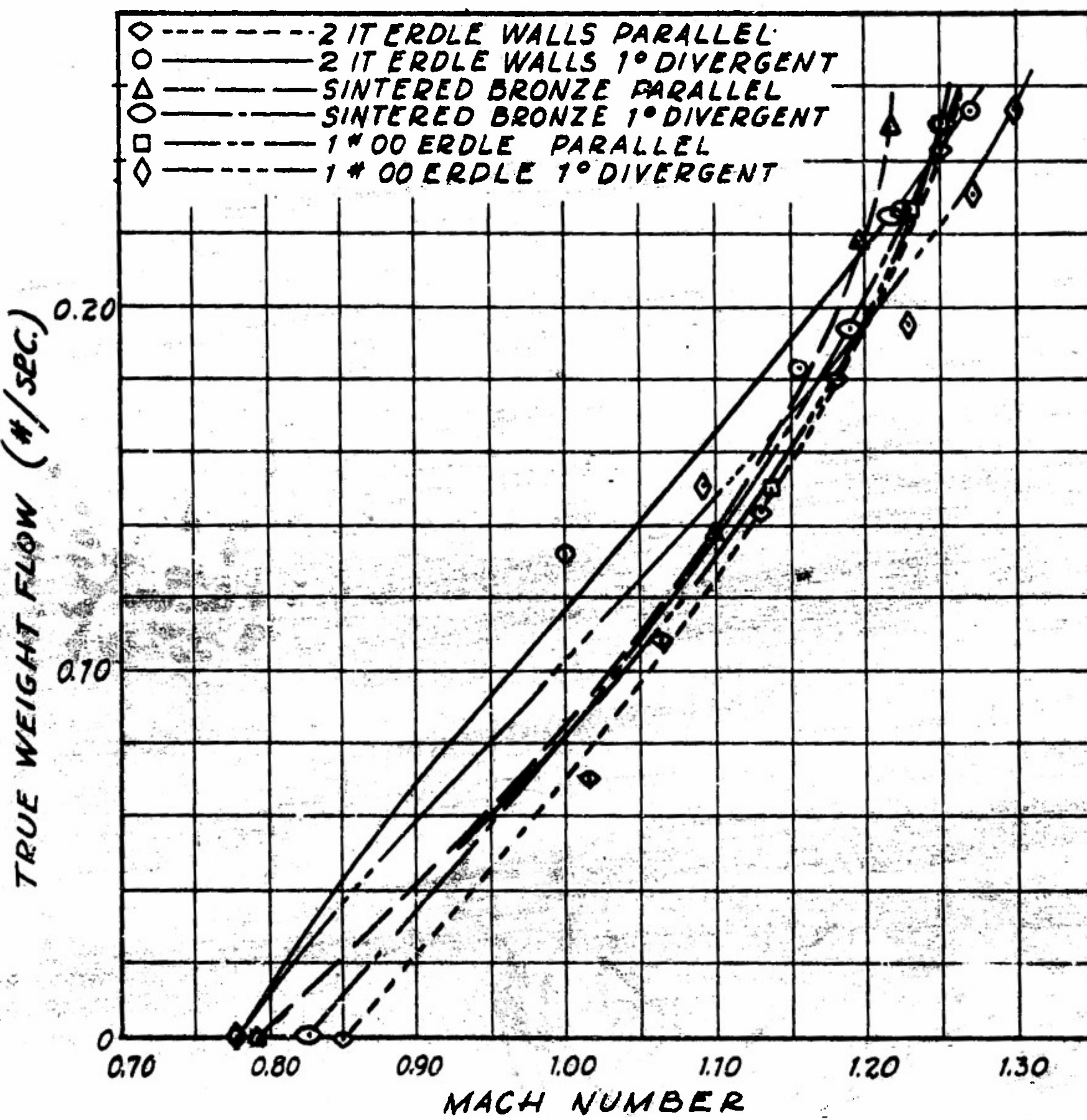


Fig. 32

INCREMENTAL WEIGHT FLOW
VS
MACH NUMBER

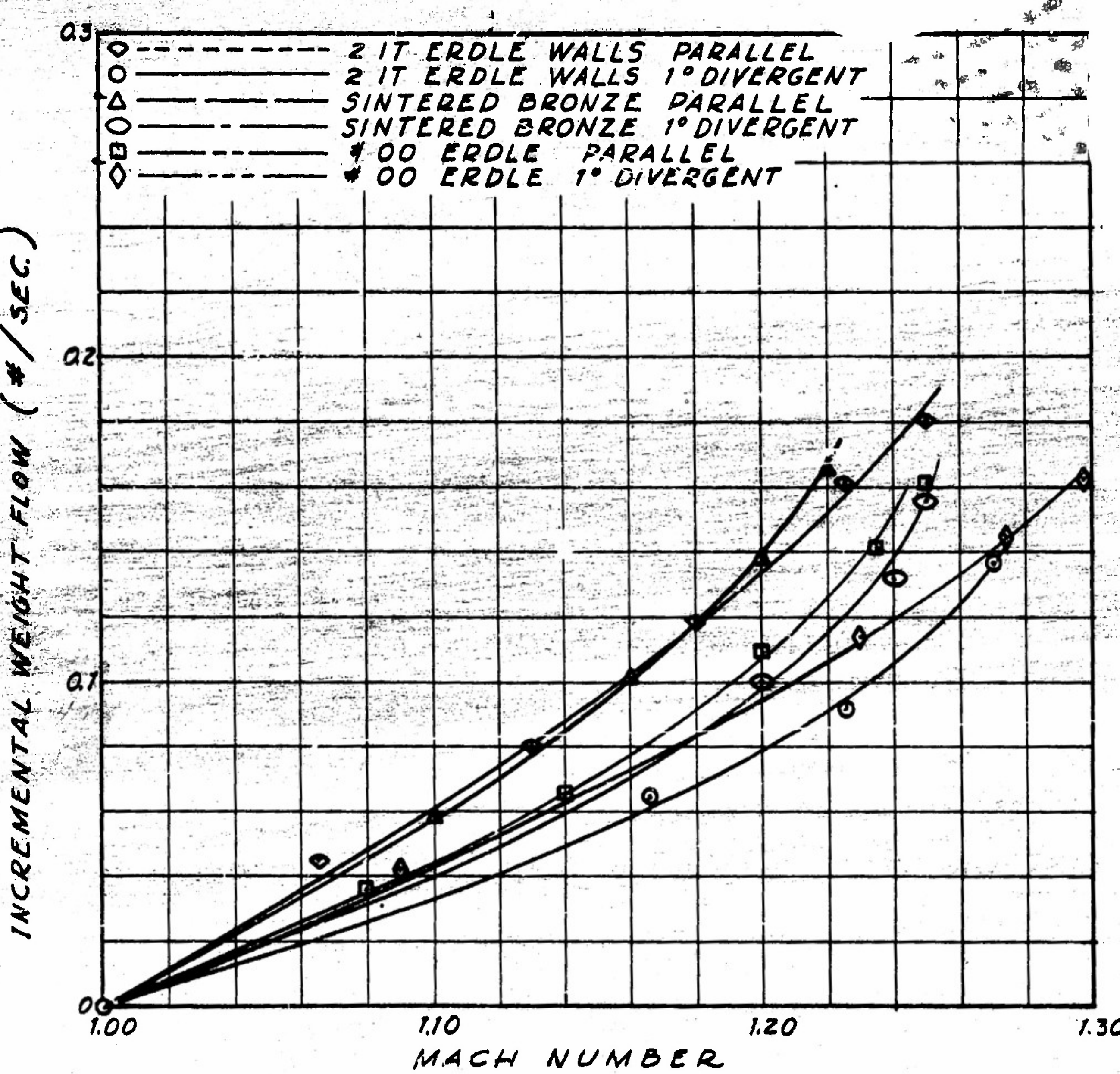


Fig. 33

HP/FT² OF TEST SECTION AREA VS MACH NUMBER

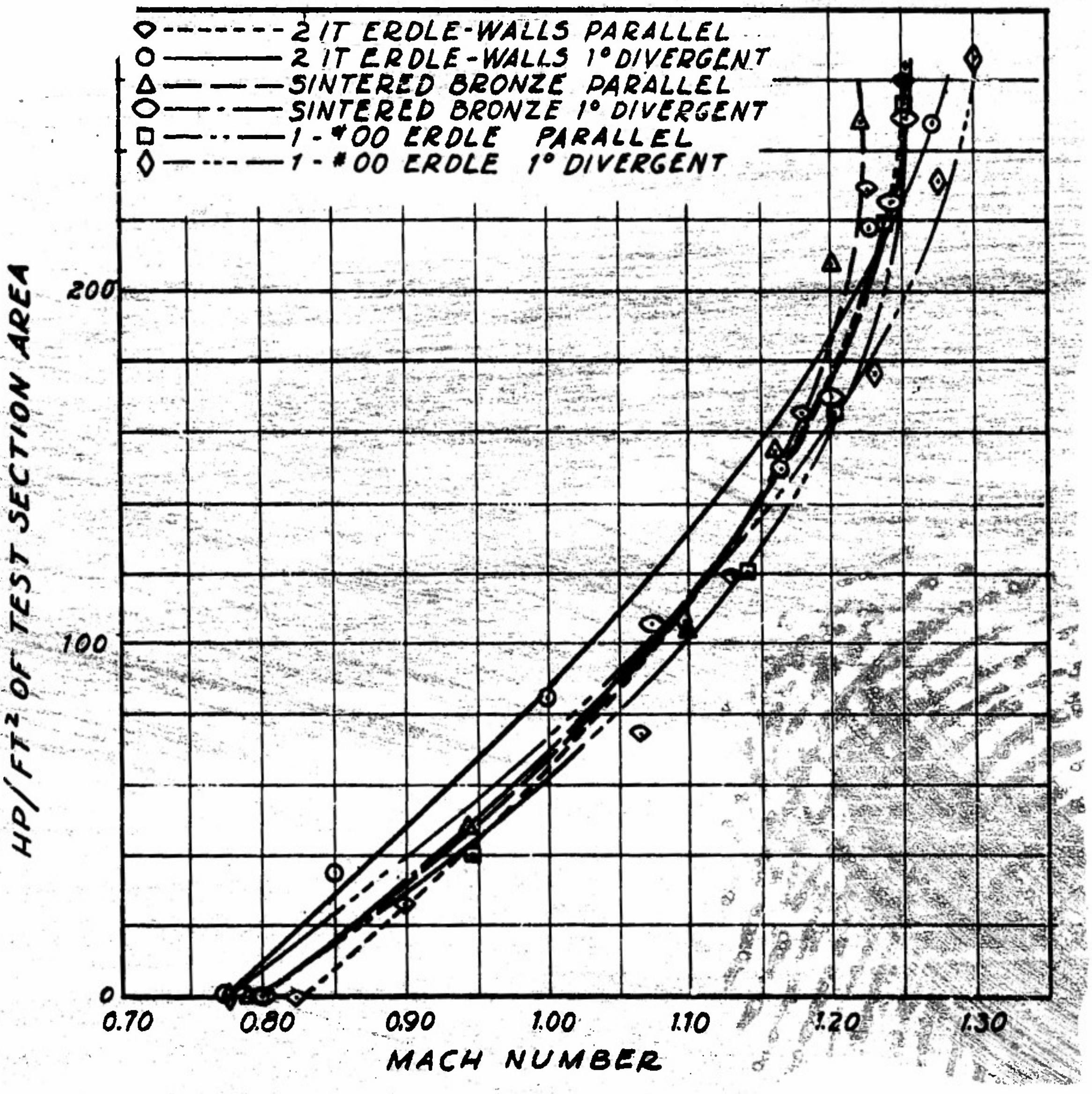


Fig. 34

INCREMENTAL H.P vs MACH NUMBER

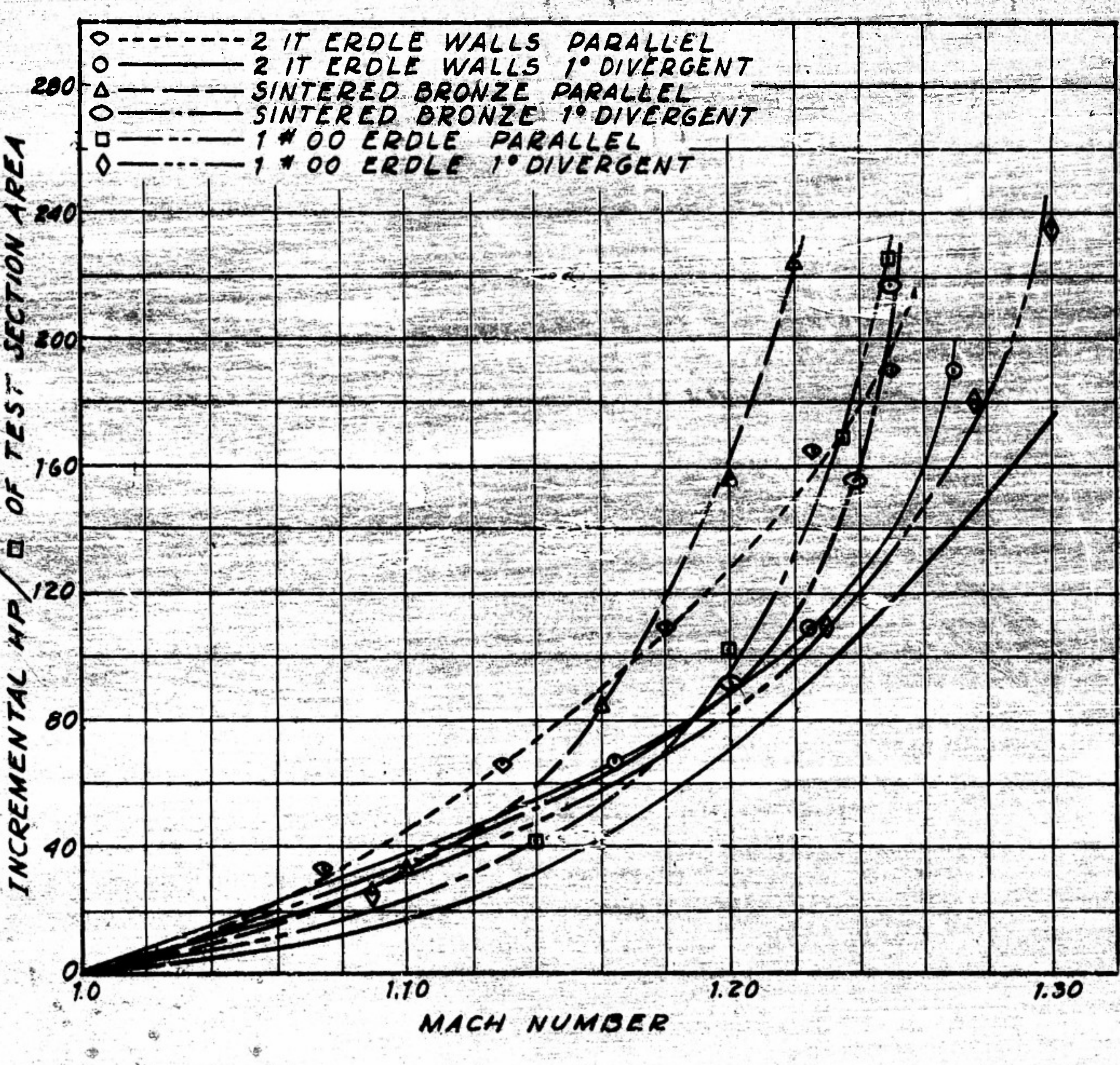


Fig. 35

2 ~ IT ERDLE SHEET

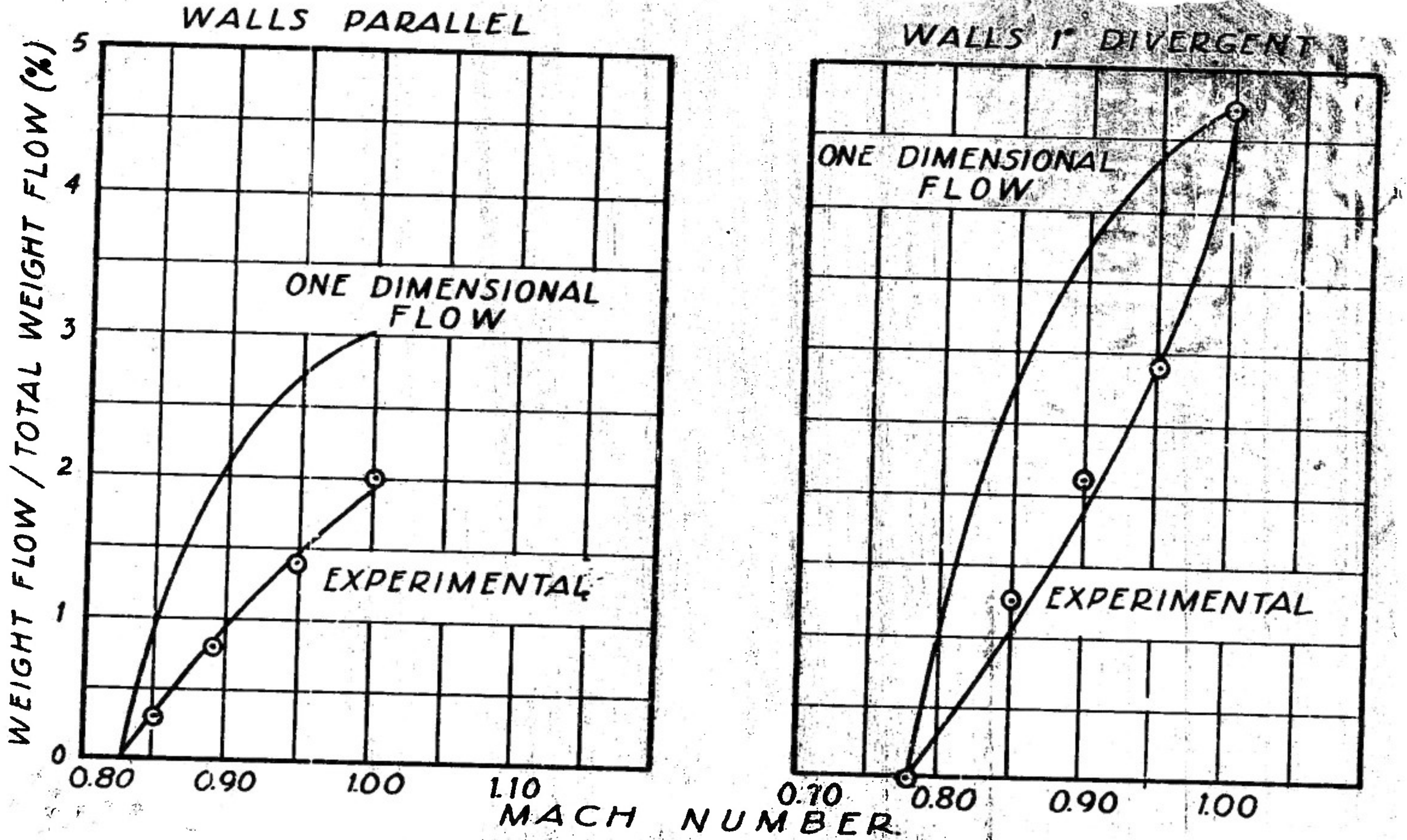
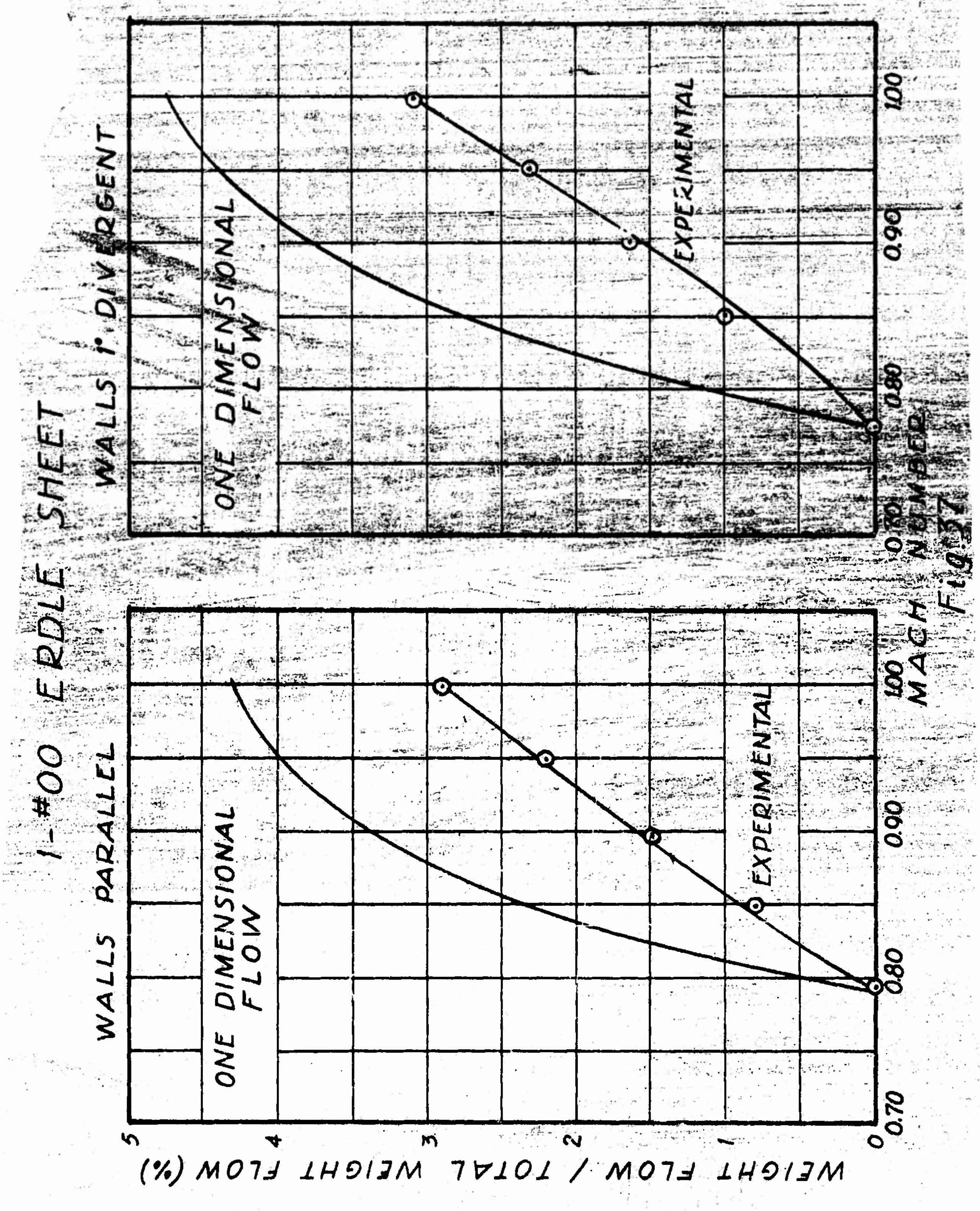
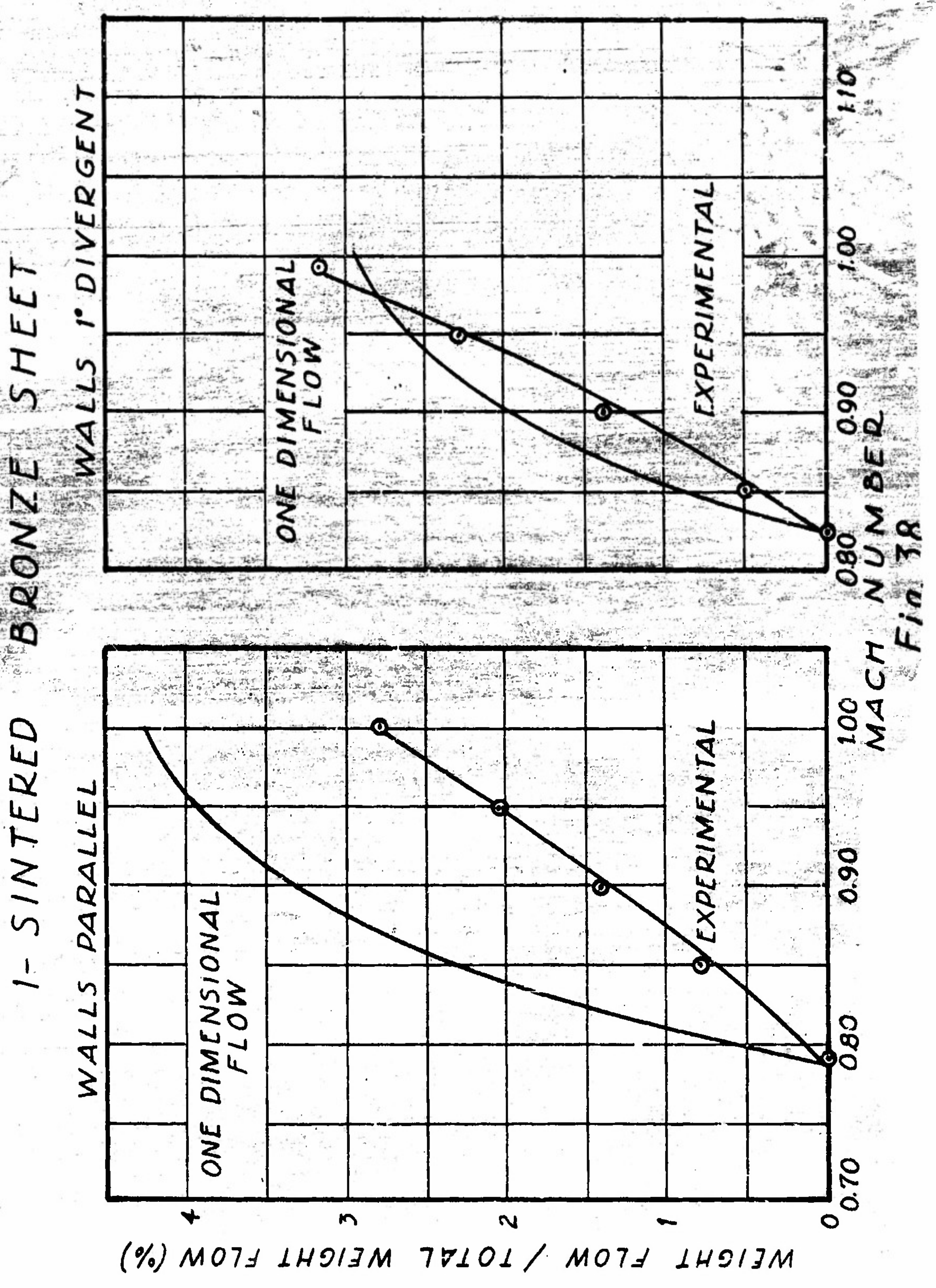


Fig. 36



WALLS PARALLEL
WALLS 1° DIVERGENT
ONE DIMENSIONAL FLOW
ONE DIMENSIONAL FLOW
EXPERIMENTAL
EXPERIMENTAL
0.70
0.80
0.90
1.00
MACH NUMBER
0
1
2
3
4
5
WEIGHT FLOW / TOTAL WEIGHT FLOW (%)

Fig 37



I- SINTERED BRONZE SHEET
WALLS 1° DIVERGENT
ONE DIMENSIONAL FLOW
EXPERIMENTAL
WALLS PARALLEL
ONE DIMENSIONAL FLOW
EXPERIMENTAL
0.80
0.90
1.00
1.10
0.70
0.80
0.90
1.00
MACH NUMBER
0
1
2
3
4
WEIGHT FLOW / TOTAL WEIGHT FLOW (%)

Fig. 38

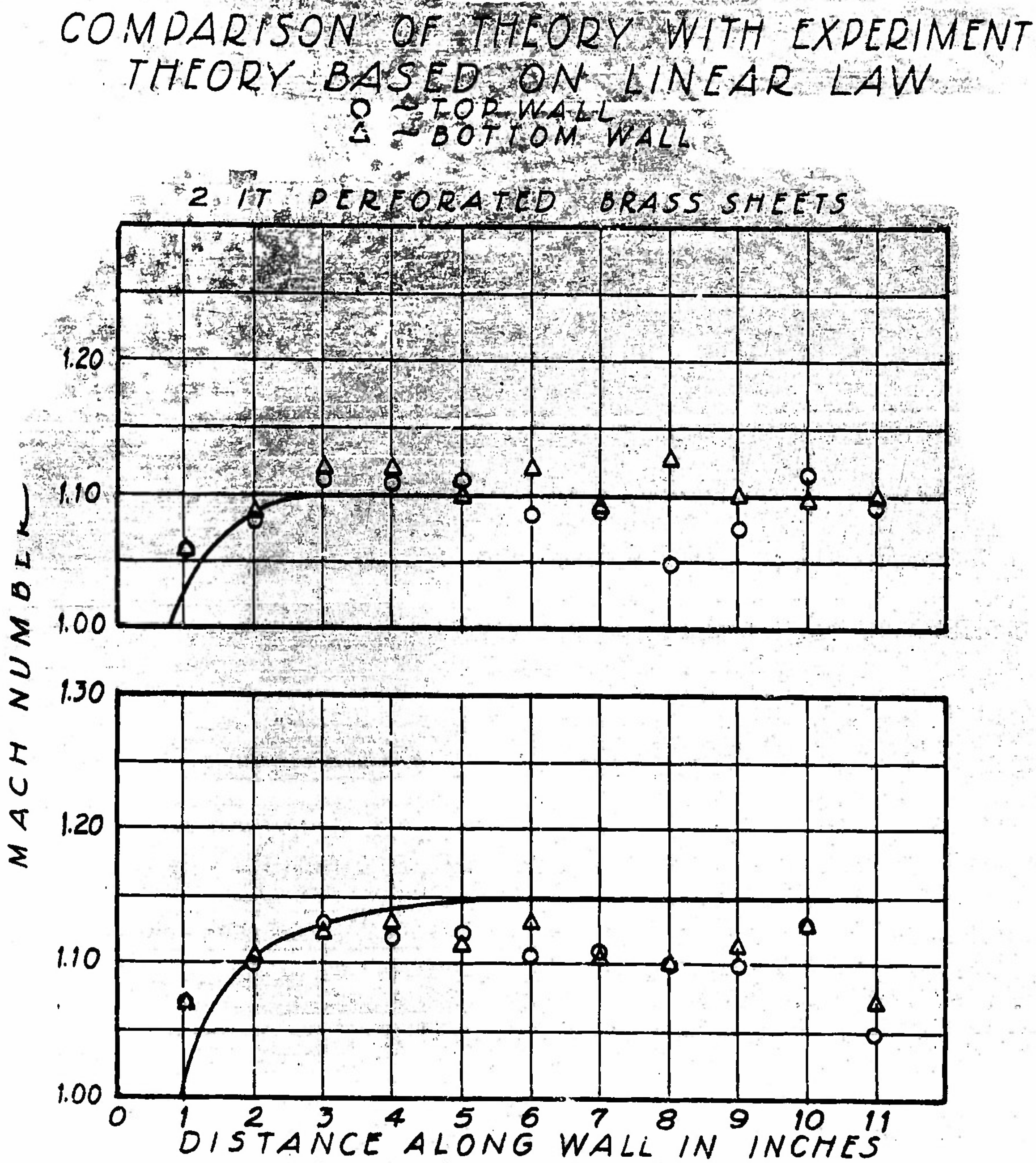

COMPARISON OF THEORY WITH EXPERIMENT
THEORY BASED ON LINEAR LAW
○ ~ TOP WALL
△ ~ BOTTOM WALL
2 IT PERFORATED BRASS SHEETS
MACH NUMBER
1.00
1.10
1.20
1.30
0
1
2
3
4
5
6
7
8
9
10
11
DISTANCE ALONG WALL IN INCHES

Fig. 39

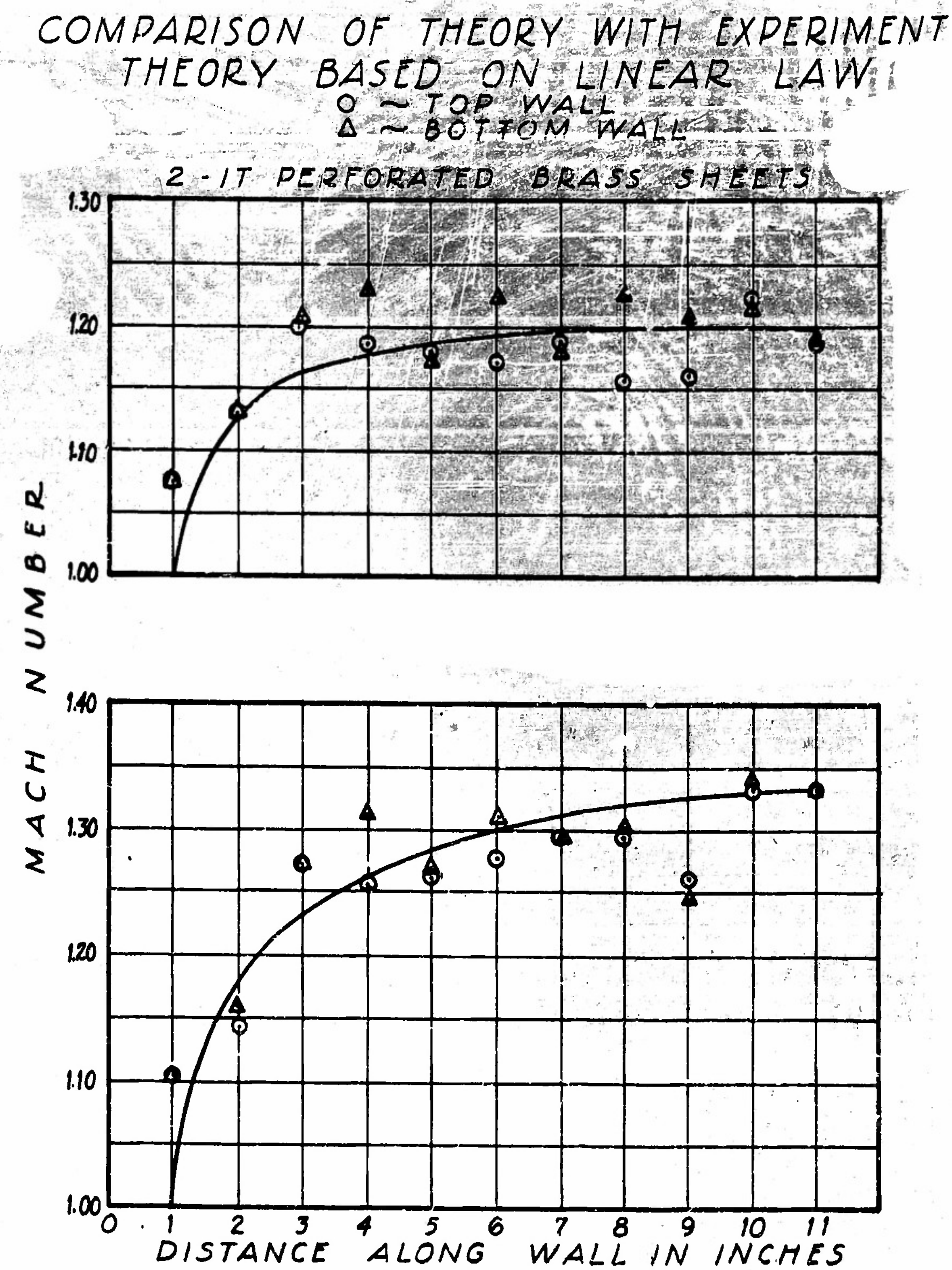

COMPARISON OF THEORY WITH EXPERIMENT
THEORY BASED ON LINEAR LAW
○ ~ TOP WALL
Δ ~ BOTTOM WALL
2 - IT PERFORATED BRASS SHEETS
MACH NUMBER
1.30
1.20
1.10
1.00
1.40
1.30
1.20
1.10
1.00
0
1
2
3
4
5
6
7
8
9
10
11
DISTANCE ALONG WALL IN INCHES

Fig. 40

CONFIDENTIAL

COMPARISON OF THEORY WITH EXPERIMENT
THEORY BASED ON LINEAR LAW
O ~ TOP WALL
Δ ~ BOTTOM WALL

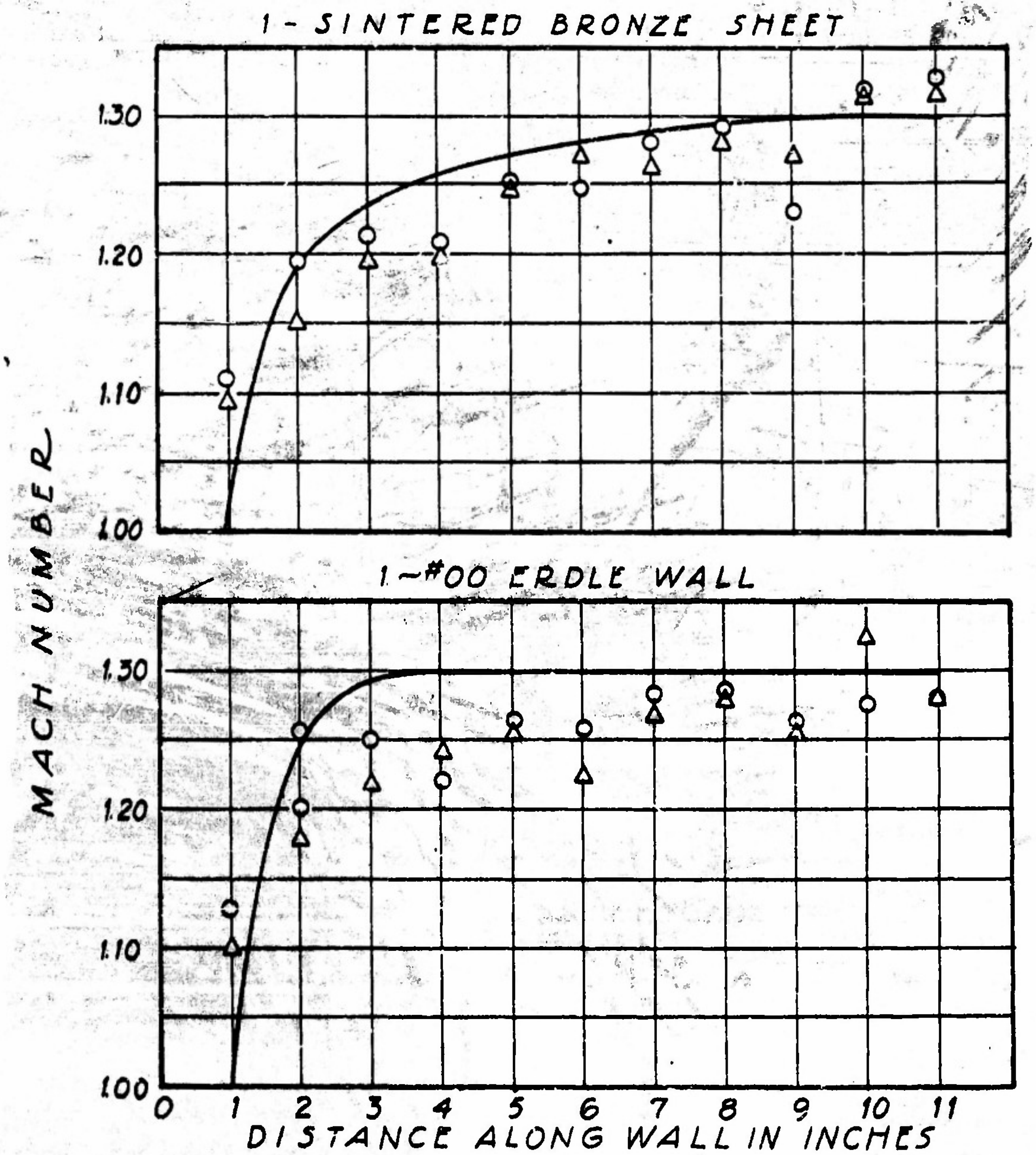


Fig. 41

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