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WADC TECHNICAL REPORT 52-296 SECURITY INFORMATION

DEVELOPMENT OF THE NEW TEST SECTION WITH MOVEABLE SIDE WALLS OF THE WRIGHT FIELD 10-FOOT WIND TUNNEL

(Phase-a Operation With Slots Closed)

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CLASSIFICATION CANCELLED
~~(OR CH[illegible])~~

NOVEMBER 1952 BY AUTHORITY OF Philip P. Antonatos
(INDIVIDUAL OR WRITTEN AUTHORITY)

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(NAME & GRADE OF INDIVIDUAL MAKING CHANGE) (DATE)

20021104071

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Statement A
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56WC-8923

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DEVELOPMENT OF THE NEW TEST SECTION WITH MOVEABLE SIDE WALLS OF THE WRIGHT FIELD 10-FOOT WIND TUNNEL

(Phase-a Operation With Slots Closed)

Bernhard H. Goethert, Dr Ing
Aircraft Laboratory

November 1952

RDO No. 903-1428

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

The investigation covered in this report was conducted by the Aircraft Laboratory of the Wright Air Development Center under Project Number MX-1112 and Research and Development Order Number 903-1428, (UNCL) "High Speed High Altitude Wind Tunnel." The author of this report served as Project Engineer.

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ABSTRACT

The design of the new all-metal test section of the Wright Field 10-Foot Wind Tunnel is discussed with reference to the basic objectives and the actual construction characteristics. The development of this test section during the calibration period for the "slots-closed" configuration is described and the interim as well as the final calibration results on Mach number distribution, flow inclination, power requirements, etc. are presented. As secondary results, some information is presented on the influence of various artificial wall disturbances on the Mach number distribution in the supersonic operation range.

The security classification of the title of this report is CONFIDENTIAL.

PUBLICATION REVIEW

This report has been reviewed and approved.

FOR THE COMMANDER:

H. D. Lippman
for D. D. McKEE
Colonel, USAF
Acting Chief, Aircraft Laboratory
Directorate of Laboratories

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SECTION I

GENERAL CHARACTERISTICS OF THE WRIGHT FIELD 10-FOOT WIND TUNNEL

The Wright Field 10-Foot Wind Tunnel is a closed throat wind tunnel which originally was capable of testing only in the subsonic speed range up to choking. The original test section had a circular cross section with a diameter of 10 feet and a length of approximately 20 feet. The maximum power supply is 40,000 HP at present. Tests showed that the maximum compression ratio of the four- (4) stage compressor system is $\lambda = 1.26$ at a stagnation temperature of 100°F. The temperature of the wind tunnel air is automatically controlled and can be kept constant within ± 1° F at any desired value over a wide range. A special method (see Reference 1) was developed for the automatic temperature control; this new approach became necessary since various difficulties occurred due to the excessive time lag between actuating the control valves and the first indication of a temperature change in the tunnel (approximately 100 seconds). The pressure level in the wind tunnel can be changed between 1/10 atmospheres and 2 atmospheres in the stagnation section. The pressure is also automatically controlled and kept constant by means of an electrical-mechanical balance equipped with bellows. The principle of the automatic pressure control is the same as that for the temperature control referred to previously. Special equipment is available for drying the air for high Mach number testing. The velocity in the test section can be controlled by means of compressor-RPM as well as by stator blade setting. At Mach numbers up to $M = .90$ approximately, the rough speed control is achieved by RPM setting and the fine control by stator blade setting. Above $M = .90$, the compressor operates with maximum RPM and the power input is controlled exclusively by means of stator blade setting. (Reference 2).

The wind tunnel is equipped with an external balance system as well as a sting support for strain gage balances. Pitch and yaw angle of the sting can be simultaneously changed by remote control. Several internal strain gage balances are available with a normal force capacity between 100 lbs and 1400 lbs. The strain gage balance output is transferred by means of Brown potentiometers and digital converters to standard IBM equipment. The Brown potentiometers are standard instruments modified to include a special damping circuit and provisions for range and sensitivity change by personnel of the Wind Tunnel Branch. The digital converters were developed by Wind Tunnel Branch personnel and represent the important link between the analogue output of a potentiometer to digital input to IBM equipment (see Reference 3). A plotter from the Telecomputing Company will be available in the near future. With this equipment, three different curves for any desired combination of forces or moments can be plotted automatically during testing. A schlieren system is available for flow observation.

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SECTION II

DESIGN OF THE NEW TEST SECTION

A. General Design - Criteria

From tests in the Wright Field 10-Foot Wind Tunnel as well as in similar facilities of other Research Centers, it became obvious that an extensive demand for wind tunnel testing in the transonic speed range exists, and will continue to exist in connection with the development program of fast airplanes and missiles. Such a testing demand can be met only in wind tunnels with a maximum velocity which extends not only up to high subsonic speeds but also sufficiently far into the supersonic speed range. Therefore, the goal of the 10-Foot Wind Tunnel modification was to design a test section capable of testing up to a Mach number of 1.15 or 1.20. The upper limit of the Mach number was selected of such a magnitude that it coincides with the lowest Mach number at which standard supersonic wind tunnels start testing. The design should be made flexible enough to permit future simple modifications for incorporating new design features of transonic test sections, like slotted or perforated test section walls. On the other hand, the design should be layed out in such a way that as much as possible of the main structure of the existing wind tunnel could be utilized.

At the time of the freezing of the construction drawings for the new test section, the art of transonic wind tunnel testing was in aprocess of rapid development. The idea of the slotted test section had been taken up anew by the NACA and the first series of systematic model tunnel tests were conducted (see Reference 4). However, no full-scale tests were available yet to prove that power consumptions, tunnel wall interference, and flow characteristics (fluctuations) were favorable enough to warrant full-scale application. The risk involved in slotted test sections appeared serious enough that it was decided to construct the new test section not merely as a slotted test section, but to include provisions for closing the slots by means of cover plates. With such cover plates installed, the wind tunnel would remain operational as a closed test section tunnel even if, during the period of slot development, difficulties should occur which would make the wind tunnel inoperative with the longitudinal slots open.

In the development of a transonic test section, means also need to be developed for cancelling such reflected waves which would meet the model and interfere with the flow around the model. Such means are not thoroughly explored yet. Therefore, no detail provisions have been made for wave cancelling devices. However, the possibility was maintained in the basic design to allow modification of the tunnel wall locally in those regions where the shock waves of the model would meet the wall.

The development of the new test section was planned to take place in the following phases:

Phase-a: Closed test section with a simple device for changing the test Mach number in the supersonic range.

Phase-b: Test section with longitudinal slots for relief of choking due to model installation.

Phase-c: Test section with longitudinal slots and with provisions for cancelling supersonic wave reflections in critical regions of the tunnel wall.

This present report deals with the development and calibration of the supersonic closed test section according to Phase-a.

B. Aerodynamic Design Characteristics

1. Basic Shape - Considering the fact that the test section of Phase-a was supposed to be used as an interim test section, it did not appear feasible to construct a costly flexible nozzle ahead of the test section. Such a flexible nozzle would become extremely complicated in view of the circular cross-sectional shape of the test section. It was decided to use the upstream part of the test section as means for the establishment of the supersonic flow. This decision was made even when the Mach number in the actual testing region of the test section would be not completely constant but would have a certain small gradient in the direction of the flow. It was believed that the influence of such a Mach number gradient of known magnitude could be eliminated through suitable corrections if the need for it should arise.

As a basic shape for supersonic nozzle and test section, a cone with straight elements, starting at the throat region, was selecte As a consequence of this selection, the test section would be designed basically as a supersonic test section with provisions and compromises necessary for adapting it to subsonic testing. This design is in contrast to developing it basically as a subsonic test section with provisions for supersonic testing. The guiding idea herein was that, according to theory and experiment, it is much more difficult to shape a nozzle for establishing good supersonic flow than for subsonic flow since flow disturbances due to wall irregularities have the tendency to die out in subsonic flow, but to remain concentrated in supersonic flow.

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The basic conical shape was intended to make the effective area at the downstream region of the test section approximately 1.8% larger than the throat area which would result in a mean Mach number of approximately 1.13 in the testing region. The Mach number distribution in the flow direction would be basically proportional to the square root of the distance. Thus the Mach number gradient would be largest in the region immediately downstream of the throat while it would become gradually smaller further downstream toward the testing region.

2. Throat Shape - The Mach number distribution according to pure conical source-flow can be realized only when the transition from the straight wall elements towards and through the throat is made according to a precisely determined shape compatible with the laws for wave propagation and cancellation in supersonic flow. This correct throat shape for the conical test section with five (5) minutes effective divergence deviates from a constant curvature throat shape only by such radial differences which are very close to the machining tolerances of the test section. Therefore, it was decided to construct the throat with a constant radius of curvature of 25 times the test section diameter.

In order to check the suitability of such a simplified throat design, a theoretical investigation was initiated within the Theoretical Unit of the Wind Tunnel Branch. The results of this investigation are presented in a special Air Force report (see Reference 5). The Mach number distribution curve obtained at the tunnel centerline is replotted on Figure 3 of this report. Within a testing length of 40 inches, the Mach number deviations from a smooth distribution with a mean value of $M = 1.13$ are not greater than $\Delta M = \pm .002$. For this case, the Mach number gradient is $\Delta M = \pm .007$ for a 40 inch long model. These Mach number differences were considered to be satisfactory for the Phase-a test section.

3. Moveable Side Walls for Mach Number Variations - As described before, the nozzle and test section are shaped such as to establish satisfactorily smooth flow at a particular Mach number, $M = 1.13$. In order to adjust the Mach number to different values, the two (2) plane side walls were made moveable around hinges which were located in the subsonic regions of the throat (see Fig. 1). The movement of the side walls is remotely controlled and can be done during the operation of the wind tunnel. It should be noted that the side walls are not being bent like flexible nozzle walls, but more like rigid elements. The width of each side wall is 33.5 inches, so that a total of 18% of the test section circumference is occupied by the moveable walls. When the downstream end of the side walls is moved inside by

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2.8 inches the effective area throughout the entire length of the test section becomes essentially constant. The side walls are moveable outside from the flush position to a maximum of 3 inches. This feature provides an additional expansion for the supersonic flow of approximately 1% of the effective cross-sectional area.

It is obvious that by moving the side walls, the supersonic Mach number can be continuously controlled at the place of the model. However, for all positions of the side walls different from the flush position, a discontinuity of the inside contour will occur at the location of the wall hinges. It was expected that this discontinuity would have only a small effect on the Mach number distribution in the testing region since, first it is located in the subsonic nozzle region, and secondly, it covers only a part of the tunnel circumference. Both circumstances contribute to weakening and spreading the initial disturbances like in the case of conical disturbances which pass through several irregular wall reflections before reaching the model test region.

Another type of discontinuity occurs along the edges of the side walls when they are located at off-flush positions. The edges of the side walls, however, are orientated in the direction of the local flow so that the resulting flow disturbances may be expected to be of minor importance.

Before the construction of the full-scale test section was begun, the magnitude of the above wall discontinuities was checked in tests on a 1/20-scale model tunnel. Those model tunnel tests did not reveal any excessive flow irregularities for side wall settings either inside or outside from the flush position (see Reference 6, Fig. 6).

Because a considerable portion of the testing time in the Wright Field 10-Foot Wind Tunnel will be devoted to subsonic testing, it appeared important enough to investigate theoretically the flow non-uniformity in the high subsonic Mach number range. This appeared especially advisable since, contrary to supersonic testing, all subsonic testing in the new test section will be conducted with the side walls set inside at nearly the extreme position. The results of this theoretical investigation for $M = .95$ (see Reference 7) show that the Mach number varies in the test section by no more than $\Delta M = \pm .001$ when model wings are considered with a span equal to 1/2 of the test section diameter. Furthermore, the flow direction over similar model wings (span equal to 1/2 tunnel diameter) would vary by no more than ± 1 minute. These results indicate that the flow disturbances due to the unsymmetric test section shape are practically negligible in the subsonic test range.

4. Boundary Layer Influence - As indicated before, the basic shape of the new test section was intended to have a cone angle of such a magnitude that the effective area at the test section end would be larger than the throat area by 1.8%. The effective divergence of the test section corresponds to a slope of 8.4 minutes for the walls (distance between throat and test section end = 221 inches). This effective divergence must be provided in addition to that divergence which is needed for compensation for the boundary layer growth along the walls.

Tests in the old 10-Foot Wind Tunnel test section which was constructed with a geometrical divergence of 5.3 minutes in the test section, showed that at choking, the Mach number at the test section end is $M = 1.035$. Hence, the boundary layer growth in the old test section corresponded to a divergence angle of approximately 5 minutes.

A further check of the expected boundary layer growth was made by means of theory. A completely turbulent boundary layer was assumed in the test section and the boundary layer displacement thickness growth for smooth flat plates was calculated according to theoretical investigations of Karman-Schoenherr (see Reference 8 and 9) and experiments of Wilson, Young, and Thompson (see Reference 10). The results of these calculations are presented in the following table for several cases.

TABLE

CALCULATED SLOPE OF BOUNDARY LAYER DISPLACEMENT THICKNESS
FOR THE WADC 10-FOOT WIND TUNNEL

	L_x = 20 Ft.	L_x = 60 Ft.
p_o = 2 atm T_o = 560° R	ε = 3.8 min; δ^* = .33 inch	ε = 3.6 min; δ^* = .68 inch
p_o = 1/2 atm T_o = 560° R	ε = 4.7 min; δ^* = .41 inch	ε = 4.4 min; δ^* = .85 inch

δ^* = Displacement thickness of boundary layer, inches

L_x = Assumed length of full turbulent boundary layer in the region of the throat, feet

ε = Slope of boundary layer displacement thickness, δ^*

p_o = Stagnation pressure, atmospheres

T_o = Stagnation temperature, R°

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In consideration of both experimental results for the old test section and calculated theoretical data for a perfectly smooth plate, the design of the new test section was based on a boundary layer growth according to 5 minutes. The total geometrical slope of the tunnel wall becomes then

$$\varepsilon_{total} = \varepsilon_{boundary\ layer} = 5.0 + 8.4$$

$$= 13.4 \text{ min.}$$

C. <u>Mechanical Design Characteristics (See Figure 1)</u>

The new nozzle and test section consists of two (2) rigid spools upstream and downstream of the test section proper. The upstream spool begins at 1.4 ft. and ends at 10.0 ft. upstream of the throat. In this way, both circumferencial dividing lines with possible discontinuities of the internal contour will be located in the subsonic region of the nozzle. The downstream spool has a length of 1.73 ft. and forms essentially a part of the diffuser. Both spools which provide the only support for the test section proper are supported on the main structural beams of the test chamber. The downstream spool is rigidly connected to the test chamber beams while the upstream spool has a sliding bearing for length compensation.

1. Test Section Proper - The test section proper consists of eight (8) longitudinal girder sections, each 19.82 ft. long, approximately 3.20 ft. wide. These girders are bolted to the spools. Despite the fact that they are not bolted together along their longitudinal edges, these girders are made strong enough for withstanding the weight and air loads without significant deformation. Between the girders, longitudinal slots exist with a width of approximately 7.81 inches, or a total slot width of approximately 16.8% of the tunnel circumference. For the Phase-a operation of the new test section, the slots were closed by means of heavy wedge-shaped inserts which were bolted and doweled together with the main longitudinal girders.

For the "Phase-b, Slots Open" operation, the closure-inserts were removed and the slot-width reduced to 6.15 inches (total open area = 13.2% of tunnel circumference) by means of wooden inserts. The wooden inserts provided channels of constant width with a slot height of 10.0 inches, or of 16.9% of the test section radius.

For quick conversion from "slots-open" to "slots-closed" configuration during the period of slot-shape development, the slots were covered temporarily by metal plates of .093 inch thickness (see Fig. 1).

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The cover plates for each slot were divided into five (5) longitudinal segments for simpler handling with the dividing line between the plates swept back by 45°. No attempt was made to machine these temporary cover plates to close tolerances but original stock material with surface waves up to .040 inches were used.

The time for changing the test section configuration from "slots-open" to "slots completely closed", amounts to approximately four (4) hours. This short period of time for conversion offered the essential advantage that tests with various slot configurations could be quickly scheduled in between routine tests in the "Phase-a" closed test section. When the final slot shapes have been developed, it is planned to replace the temporary wooden inserts by metal inserts and the temporary sheet-metal cover plates by machined closure plates with close tolerances. In such a way, the possibility for changing over from "slots-open" to "slots-closed" operation will be maintained for the benefit of greater flexibility in testing.

2. Side Walls - The side girders consist of rigid frames in which plane longitudinal plates with a length of 238 inches and a width of 33.5 inches are inserted. These side walls are made plane for the housing of glass windows of optical schlieren quality. Each side wall houses five (5) windows. To machine the side walls, the glass windows were replaced by metal plates so that no steps along the window dividing lines would occur. Testing with both the metal window plates and the actual glass windows served as an indication of what disturbances would be produced by non-perfect window fittings.

The side walls are hinged at their upstream end with the effective hinge axis located at the dividing line between girders and spool. The movement around the hinges is achieved through three (3) spindles along the upper edge and three (3) other spindles along the lower edge of each side wall. All spindles are synchronized through a gear system with one motor for each side wall. The spindles allow a maximum movement of 3 inches inside the tunnel, and 3.5 inches outside with respect to the flush position; these measurements are taken at the extreme downstream end of the side walls.

3. Transition Plates - In order to produce a gradual transition from the circular shape of the subsonic nozzle to the plane shape of the side walls, special transition plates are provided with a length of 58.3 inches at the upstream end in the nozzle and 78.7 inches at the downstream end in the diffuser. The upstream transition plates are rigidly bolted to the tunnel walls with such a contour slope that a smooth transition to the side walls in the flush position is provided. The downstream diffuser plates are made moveable. They follow automatically the movements of the side walls in the range between flush and extreme inward wall position. When the side walls are moved away from the flush position in the direction outside, the transition

plates do not follow them, but stay in the flush position. The downstream transition plates can be operated manually with three-inch maximum movement away from the side walls. By this means, it is possible, for instance, to use the transition plates as a choking device for flow stabilization in tests at high subsonic speed. The available range is such as to produce choking at test section Mach numbers between M = 1.00 and M = .90.

4. Machining of the Test Section - The machining of the new all-metal test section was done with all girders, closure inserts, and the upstream spool assembled by means of bolts and dowel pins. The side walls were replaced by dummy inserts which would allow machining of the test section inside with a complete circular cross-section. A special vertical lathe was constructed and the internal surfaces were first cut and thereafter polished within .005 inch maximum deviation from a smooth internal surface. Due to the nature of the machining process, any inaccuracies resulted mainly in annular grooves. For the benefit of disturbance-free supersonic flow in the test section, it would have been more desirable to use a machine which operates in longitudinal paths instead of in annular paths. However, in view of the serious difficulties in setting up a machine for cutting the internal surfaces of such a large object with the required accuracy, a compromise decision was made in favor of the vertical lathe.

SECTION III

TEST RESULTS

A. Mach Number Distribution After Final Grinding

The Mach number distribution in the direction of the flow was measured by means of a long center tube of 4 inches diameter. The center tube was supported in the subsonic region of the nozzle and in the diffuser by means of cables and a strut leaving the tube entirely undisturbed in the test section itself. Static pressure orifices were provided over a length of 100 inches of the tube with an axial distance of 2 inches between each orifice. The section of the center tube with pressure orifices could be situated either in the upstream or downstream part of the test section.

In the course of the calibration of the new Phase-a test section, some additional grinding of the internal surfaces was carried out as described more in detail in the next paragraphs. The Mach number distribution along the centerline of the test section after final grinding is presented on Figure 2 for various settings of the side walls. In the region between stations 150 and 190, which is most suitable for model testing, the Mach number distribution in the entire subsonic speed range is extremely uniform. In this speed range the deviations from a mean Mach number are negligibly small and the Mach number gradient can be adjusted to positive as well as negative values simply by means of suitable side wall setting.

In the supersonic speed range, the Mach number deviations from a mean straight line are in general not larger than ± .005 within the normal testing region for models. Due to the basic design of the test section, a Mach number gradient in the flow direction becomes apparent with gradually increasing magnitude from a gradient of zero at M = 1.00 to the maximum at the highest supersonic Mach number. At a mean test Mach number of 1.06, the axial gradient results in a difference of $\Delta M = \pm .004$ between the local Mach number at the nose and at the tail of a 40 inch long model. At M = 1.10, the above Mach number difference grows to $\Delta M = \pm .007$, at M = 1.16 to $\Delta M = \pm .010$, and at M = 1.18 to $\Delta M = \pm .014$.

The occurrence of the axial Mach number gradient is a direct consequence of the basic test section design, which can be considered as the design of an utmost simplified adjustable supersonic nozzle. It appears possible to eliminate the influence of the Mach number gradient in the evaluation of model tests by means of suitable corrections, if the need for such a refinement should occur. The Mach number waviness is predominantly caused by surface irregularities, which could have been further reduced by grinding and polishing of the internal surfaces. In view of the small magnitude, however, it was not considered worthwhile to spend more efforts for further reducing the remaining waviness. It shall be noted that the Mach number waviness reached its maximum value at the tunnel centerline due to the focus effects of annular surface irregularities in circular test sections. At stations off the tunnel centerline the waviness will be considerably smaller than presented for the centerline on Figure 2 (see paragraph III, 3).

B. <u>Comparison Between Full-Scale Tests, Model Tests, and Theory</u>

On Figure 3, the results of full-scale and model-tunnel tests are compared with the theoretical values for flush side-wall setting. All three curves have the same general shape. The model tunnel curve, however, is lower than the other curves by approximately $\Delta M = .015$. This difference can be contributed to the fact that differences in the boundary layer growth in full-scale and model tunnel were not considered in the model test section design.

With the exception of the first Mach number wave in the region of station 50, the waviness patterns of the full-scale Mach number curve is not related at all to the waviness pattern of the theoretical curve. Hence, it can be concluded that the Mach number waves of the experimental full-scale distributions are caused by wall irregularities which naturally were not considered in the theoretical calculations.

C. Influence of Small Annular Surface Waviness on the Mach Number Distribution

1. Test Section in Initial Condition - As mentioned in **Sec II, Par** B (3), the test section was machined on a lathe so that machining inaccuracies would result mainly in annular surface waves. In order to obtain quantitative data on such surface irregularities, a thorough profilometer check was conducted on four of the eight main longitudinal girders. By means of double integration, the profilometer readings were converted to radial ordinates. Since the purpose of the profilometer check was to find the magnitude of small surface waves, but not the basic internal contour of the test section, the radial ordinates are presented after arbitrary smooth curves of the second order were subtracted. In general, different second order curves were selected for each girder. In this way, the short waves are maintained in their true form, whereas the over-all shape as well as the over-all curvature of the presented curves have no essential meaning. The accuracy of the 8-inch leg space profilometer results were checked by repeating the survey with a 4 inch profilometer; also, with the same 8 inch profilometer some surveys were repeated. All survey checks resulted in essentially the same curves and proved, therefore, the reliability of the applied method.

The results of the profilometer survey for the new test section before final corrective grinding are presented on Figure 7. It can be clearly recognized that surface waves of a maximum height of approximately .005 inch exist. Furthermore, since the same waves can be recognized on all four girders, they are obviously of the annular type as expected.

Before any corrective action was taken for reducing the surface irregularities for the new test section in its initial state, a survey of the Mach number distribution was conducted by means of the long centerline tube. The results are presented on Figure 4, a through c. The Mach number distributions in the entire subsonic speed range are extremely uniform. In the supersonic speed range, however, a considerable waviness of the Mach number curves can be observed. Along the centerline of the test section, the deviations from a smooth mean line amount to $\Delta M = \pm .012$ in some of the worst cases. The wave length of the centerline disturbances is of the order of 15 to 20 inches and coincides, therefore, roughly with the wave length of the wall irregularities (see Fig. 4a and 7). The wave length does not show any relationship, however, with the wave pattern which would be produced by the imperfect over-all shape of the new test section, as a comparison with the theoretical curve on Figure 3 shows.

The Mach number surveys at stations off the tunnel centerline show considerably less waviness than at the centerline (Fig. 4b & 4c). Along a line 11 inches off the centerline, the Mach number deviations from a smooth mean curve are reduced to $\Delta M = \pm .006$ within the testing region of 40 inches; and they do not exceed in general even $\Delta M = \pm .004$ at 21 inches off the tunnel centerline. This tapering off of the Mach number disturbances from the centerline to off-centerline positions indicates that they are caused by annular wall irregularities which produce a focus-effect on the tunnel centerline.

2. Test Section With Preliminary Wave Corrections by Means of Painting - Before the final grinding and polishing was started for removing the annular waves with their maximum height of .005 inch, it was considered advisable to assure the successfullness of such corrective action in a crude, but much less costly way. For this purpose, the internal test section wall was painted in annular rings at those stations where the profilometer surveys had previously indicated the existence of grooves. The thickness of the painting layers was controlled in steps of .0015 inch, which is the average thickness of one paint coat. The results of the Mach number surveys for the test section with the temporary paint rings are presented on Figure 5. By comparing the corresponding curves for the test section in its initial condition (Fig. 4a) and in the painted condition, it can be clearly recognized that the wave pattern is completely changed and the magnitude of the remaining Mach number waves reduced to approximately one-half (1/2) of the values before the painting.

This test series provided the final proof that most of the Mach number waviness in the test section is caused by small annular surface irregularities and can be reduced, and probably completely eliminated, by means of grinding and polishing the walls.

3. Final Grinding of the Test Section Surfaces - Provided with the information of the preceding paragraph, the test section was gradually reworked inside through controlled local grinding. The high spots were marked by means of a stained straight edge. A hand grinding machine with electric power supply was utilized for lowering the marked high spots. Special efforts were made to have the grinding process

[redacted]

performed in longitudinal instead of annular paths in order to destroy the annular disturbance pattern. This process was repeated as often as necessary until satisfactory results were obtained with both the straight edge check as well as with the normal profilometer check. The profilometer results after the grinding process are presented on Figure 8. By comparing the remaining waviness with the waviness of the original test section (Fig. 7), it will be seen that the surface irregularities are reduced considerably through the grinding. The maximum height of the remaining waves is of the order of .001 to .002 inch. The Mach number survey at the centerline of the reworked test section is discussed previously in Sec. III, Par. A. The comparison of the results for the test section in its initial stage (Fig. 4a) and after the rework (Fig. 2) shows that the Mach number waviness is reduced to approximately one-third (1/3) of the original values. The Mach number deviation from a smooth mean curve are not larger than $\Delta M = \pm .005$ within the testing region of 40 inches length.

D. Test Section With Rough Cover Plates Over the Slots

For the Phase-b calibrations, that is with the longitudinal slots open, simple sheet-metal cover plates were prepared for quick conversion of the test section from "slots-closed" to "slots-open" operation or vice versa (see Sec. II, Par. C). In consideration of the temporary nature of these cover plates their surface was not machined, but they were used with the waviness of the original stock material. This resulted in surface waves up to .040 inch in height (Fig. 9). This value is considerably higher than the irregularities of the test section proper. However, the cover plates extend over only 17% of the tunnel circumference; and, the plate irregularities should be shaped at random instead of following an annular pattern. Therefore, it was reasoned that the installation of the rough temporary cover plates would not disturb the Mach number distribution too seriously.

The results of the Mach number survey at the tunnel centerline indicate that the temporary cover plates increase the waviness of the Mach number distribution as expected (see Fig. 6). However, the deviations from a smooth mean distribution are still not larger than $\Delta M = \pm .007$ in the testing region of 40 inches length.

E. Influence of Artificial Wall Disturbances on the Mach Number Distribution

In order to check the effect of different types of wall irregularities on the Mach number distribution, some tests were conducted with artificial disturbances at the tunnel wall.

First a wire of .030 inch diameter was cemented on the tunnel wall in an annular pattern. The wire did not extend over the side

[redacted]

[redacted]

walls so that, in effect, only 82% of the tunnel circumference was covered by the disturbance. The results of the Mach number survey are presented on Figure 10. The Mach number disturbances at the tunnel centerline are as high as $\Delta M = \pm .07$ in the worst case; that is, the Mach number varies from $M = 1.08$ to $M = 1.23$ for a mean value of $M = 1.16$. The reflected wave is considerably reduced in strength due to diffusion of the originally concentrated disturbance. These results indicate by means of first order interpolation that annular disturbances of no more than 1/14 of the .030 inch wire disturbances are permissible in circular test sections when the Mach number disturbances are to be kept down to $\pm .005$. This result checks those which were obtained with the initial machining grooves in the new test section.

In order to obtain values which are not extremely magnified by the focus effect in circular test sections, two (2) wedge-shaped disturbances of .100 height and a length of 36 inches each were fastened to the upper and lower test section girders, respectively. The longitudinal survey tube was placed at a position 11 inches off the tunnel centerline. For this arrangement, it can be expected that the measured flow disturbances should be essentially the same for both circular and square test sections. The results on Figure 11 indicate disturbances with a maximum magnitude of $\Delta M = \pm .04$. The pattern of the Mach number disturbances is in general such that first a compression occurs, followed by a strong expansion (see sketch on Fig. 12). This expansion even leads to an over-expansion such that a second compression occurs behind the obstacle.

The same wire disturbances as used before were swept back by an angle of 30° with respect to the flow direction. The sweep-back is intended to achieve both reducing the strength of the local disturbances at the wall itself, and distributing the effect of the wall disturbances over a greater axial region. The flow survey shows that the Mach number disturbances of the sweep-back wires are reduced to a fraction of those of the straight wires (Fig. 11). Therefore, all dividing lines in a supersonic test section should be swept back, if possible behind the Mach angle, in order to keep flow disturbances due to improper matching small.

For the last tests on artificial wall disturbance effects, two of the regular circular windows of the new test section were recessed by .035 inch in one test run and by .050 inch in another run. The results on Figure 13 indicate that a recess of approximately .020 inch is tolerable if the Mach number disturbances are not to exceed $\Delta M = \pm .005$.

F. <u>Flow Inclination</u>

The flow inclination, in both the horizontal and the vertical plane was checked by means of a four-tube probe as shown on the Schlieren picture of Figure 14. The pressure difference between the two tubes in each plane were measured through a range of probe inclinations of ± 2° in intervals of one-half degree. The pressure difference per degree had an average value of $\Delta p/q = .04$ in the Mach number range between M = .70 and 1.18. The test runs were conducted for both normal and inverted positioning of the probe in order to eliminate unsymmetry effects of the probe. The tests in the vertical and the horizontal plane were combined by means of moving the probes simultaneously in pitch and yaw by the same angular amount. Check runs proved that this combined method yielded the same results as the normal method with two separate runs for each plane.

The results of the flow inclination tests are shown on Figure 15. For each pressure level the measurements of the flow inclination vary by no more than ± .04 degree from a mean value throughout the entire Mach number range from M = .70 to 1.18. By increasing the stagnation pressure level in the tunnel from 1000 lb/ft^2 to 4000 lb/ft^2, the measured flow inclination shows the tendency to shifting towards greater values with a maximum value of .09 degree. This shift of the indicated flow inclination could be caused either by a true shift of the flow inclination due to elastic deformation of the tunnel structure, or due to different formation of the wall boundary layer. There is also the possibility that part of the shift is caused by deformation of the probe suspension system under air load. Including all test points of the entire test range, however, the measured flow inclinations vary by no more than ± .08 degree with reference to an overall mean value.

G. Power Requirements of the Wind Tunnel

The power input to the main compressor was derived from the power consumption of the electrical drive motors by using a chart for their electric efficiency. The power data were reduced to a standard stagnation pressure of 2000 lb/ft^2 and a standard stagnation temperature of 560°. This power correction amounted to no more than 5% in the extreme cases. The power data are presented for two conditions, "tunnel empty" and "tunnel with center tube and model suspension system installed" (Fig. 1b). In the vicinity of Mach number one, the power curves are not too well defined since it is very difficult to prevent choking in the high subsonic region, or in the low supersonic region to place the main tunnel shock always at the same location in the diffuser. Consequently, the power curves in the region near Mach number one are presented only as dotted lines.

The maximum power for choking the tunnel at p_o = 2000 lb/ft^2 is approximately 260 HP per ft^2 of the test section area. Since 533 HP/ft^2 are available, the wind tunnel is capable of operating with a maximum stagnation pressure of 4100 lb/ft^2 up to choking. At the

[redacted]

Mach number 1.18, the necessary power is increased to 330 HP/ft^2 so that the wind tunnel could operate at M = 1.18 with a maximum stagnation pressure of 3200 lb/ft^2 . These maximum pressure levels are conservative since it has been found previously that the tunnel power requirements are somewhat reduced when the pressure level is increased.

As an indication of the compression ratio required of the compressors, some lines for constant compression ratio based on the equations derived in Reference 11 are presented on Figure 16. The assumption was made that the adiabatic efficiency of the compressor was $\eta = .90$ for all operation conditions. The pressure boost required for M = 1 operation is approximately 1.10, at M = 1.18 it is increased to 1.13. It should be mentioned that the calculations on wind tunnel power requirements as presented in Reference 11, are in satisfactory agreement with the experimentary results of the present calibration (Also see Reference 12, Fig. 25 for a comparison with the power requirements of the NACA 8-Foot Wind Tunnel).

Since a major source of the wind tunnel losses is the diffuser flow, the diffuser efficiency from tests with the old test section is presented on Figure 17a. These values should not be changed essentially by the installation of the new test section. The diffuser efficiency was defined as the ratio of the actual static pressure rise (wall pressure) to the calculated isentropic static pressure rise in one-dimensional flow. The diffuser efficiency of the 10-Foot Wind Tunnel in the subsonic region is approximately 90%. Within the test range of stagnation pressures between .6 atmospheres and 1.2 atmospheres, no influence of the Reynolds number on the diffuser efficiency was observed. A brief check was also conducted with reference to stagnation pressure losses in the nozzle of the old test section. As Figure 17b indicates, the stagnation pressures in both the stagnation section as well as the test section coincide within 1/10% of the dynamic pressure, which is very close to the measuring accuracy of the manometers.

SECTION IV

SUMMARY

The new test section of the Wright Field 10-Foot Wind Tunnel provides the possibility for testing models up to a maximum Mach number of 1.18 in the "Phase-a, closed test section" operation. The adjustable side walls of the new test section allow a close control of the Mach number in the supersonic speed range similar to the operation of a flexible nozzle. The maximum stagnation pressure is p_o = 4000 lb/ft^2 in the subsonic speed range up to choking, it is

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gradually reduced in the supersonic speed range to 3200 lb/ft^2 at $M = 1.18$.

Due to the basic design, the Mach number gradient in the testing region can be closely controlled to obtain desired positive or negative values in the speed range up to choking. Above choking, however, the Mach number gradient is directly related to the test Mach number. For a 40" long model, the Mach number gradient results in a Mach number difference between nose and tail of the model of $\Delta M = \pm .004$ at a mean test Mach number of 1.06; at $M = 1.10$, this difference is grown to $\Delta M = \pm .007$; at $M = 1.16$, to $\Delta M = \pm .010$; and at $M = 1.18$, to $\Delta M = \pm .014$. Since this Mach number gradient follows a well-known smooth curve, it appears possible to eliminate its effect in the test results by means of a suitable correction whenever such a refinement is desired.

Annular surface waves in the test section walls due to machining were reduced to a minimum height of .001 to .002 inch by means of controlled hand grinding. This low magnitude was required in order to keep the Mach number disturbances at the tunnel centerline below $\Delta M = \pm .004$ in the supersonic speed range.

Tests with artificial disturbances at the tunnel wall resulted in information on the maximum disturbance height which can be tolerated without excessive flow disturbances in the testing region. The beneficial effect of sweeping back the lines of wall irregularities, for example, the dividing lines between various structural parts of the tunnel was demonstrated.

Since the first development phase of the test section with the "slots-closed" is completed, the Wright Field 10-Foot Wind Tunnel is now ready for conducting routine tests in the Phase-a closed test section as well as for starting the second phase of development testing with the slots open.

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2. Swan, Walter C. A Note on the Redesign of the 10-Foot Wind Tunnel Fan System Based on Tests of a 1/20-Scale Model of the Fan System. AF Technical Note, WCLS-52-20. November 1952.

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6. Goethert, Bernhard H. Investigation of Transonic Test Sections at the Wind Tunnel Branch, AMC, Wright Field. AF Technical Note WCLS-52-3, September 1950.

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WRIGHT FIELD 10-FOOT WIND TUNNEL

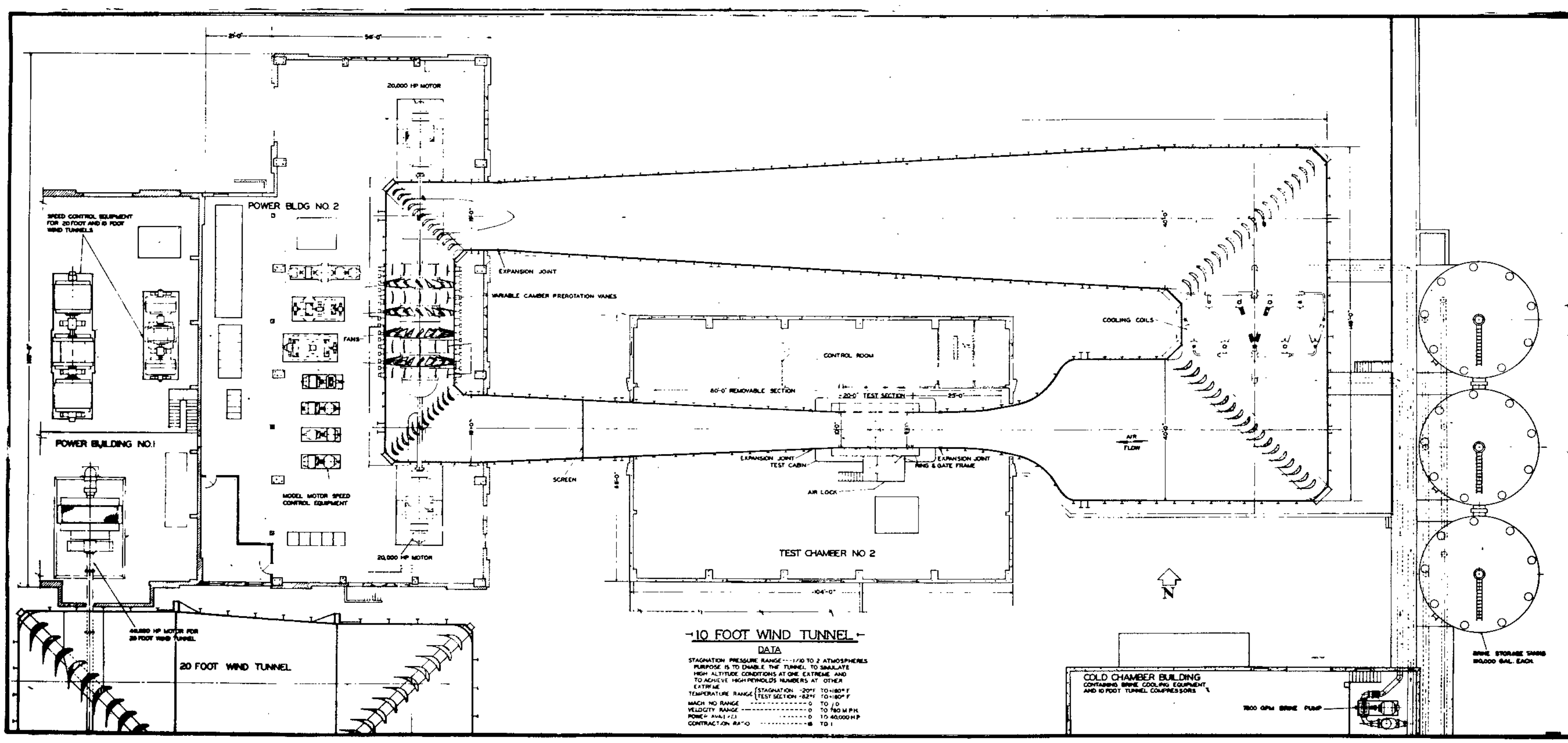

FIGURE 1a : SCHEMATIC DRAWING OF THE WRIGHT FIELD 10-FOOT WIND TUNNEL

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WRIGHT FIELD 10-FOOT WIND TUNNEL

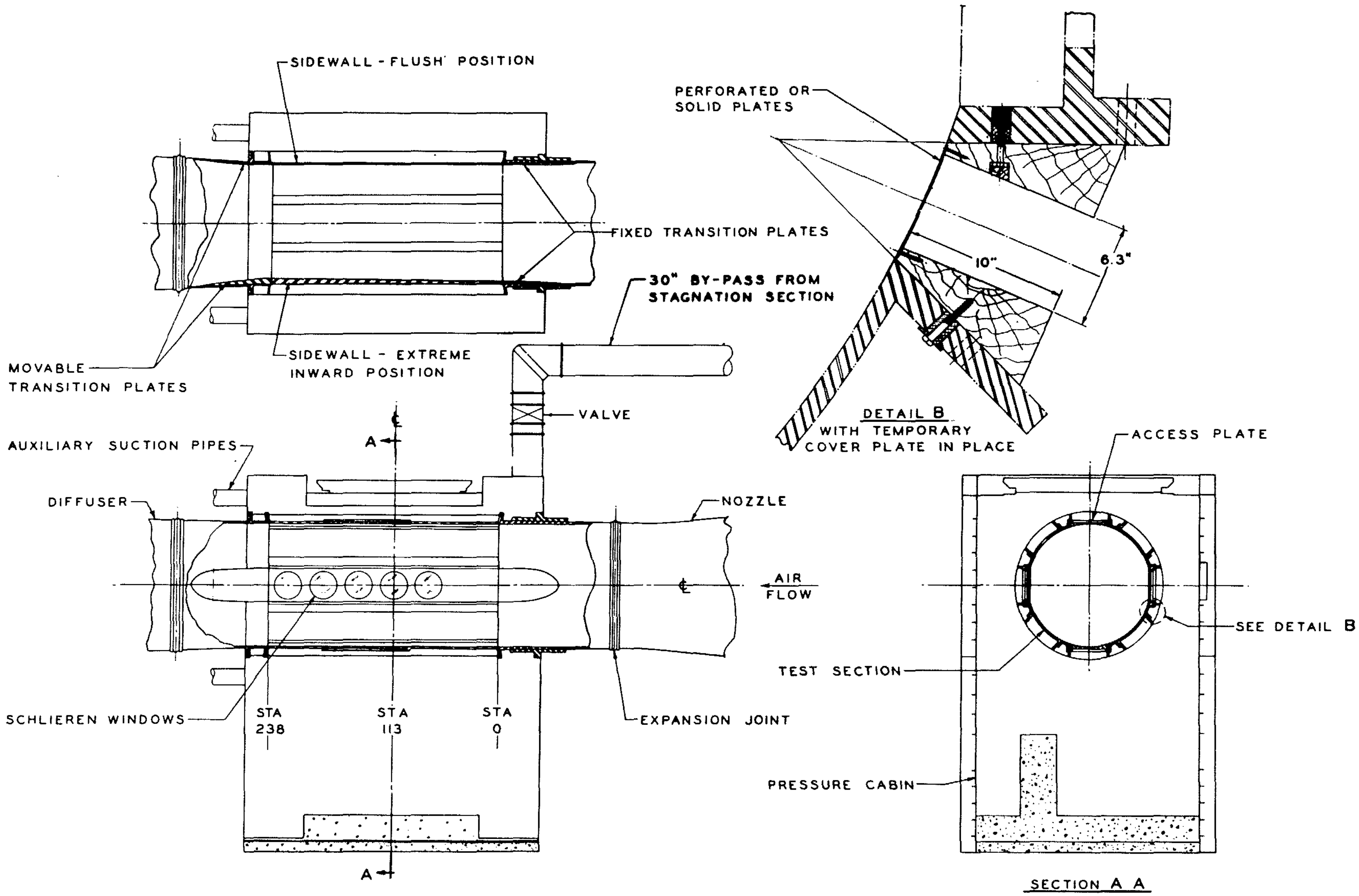

FIGURE 1b: SCHEMATIC DRAWING OF THE TEST SECTION WITH SLOTS CLOSED OR OPEN.

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

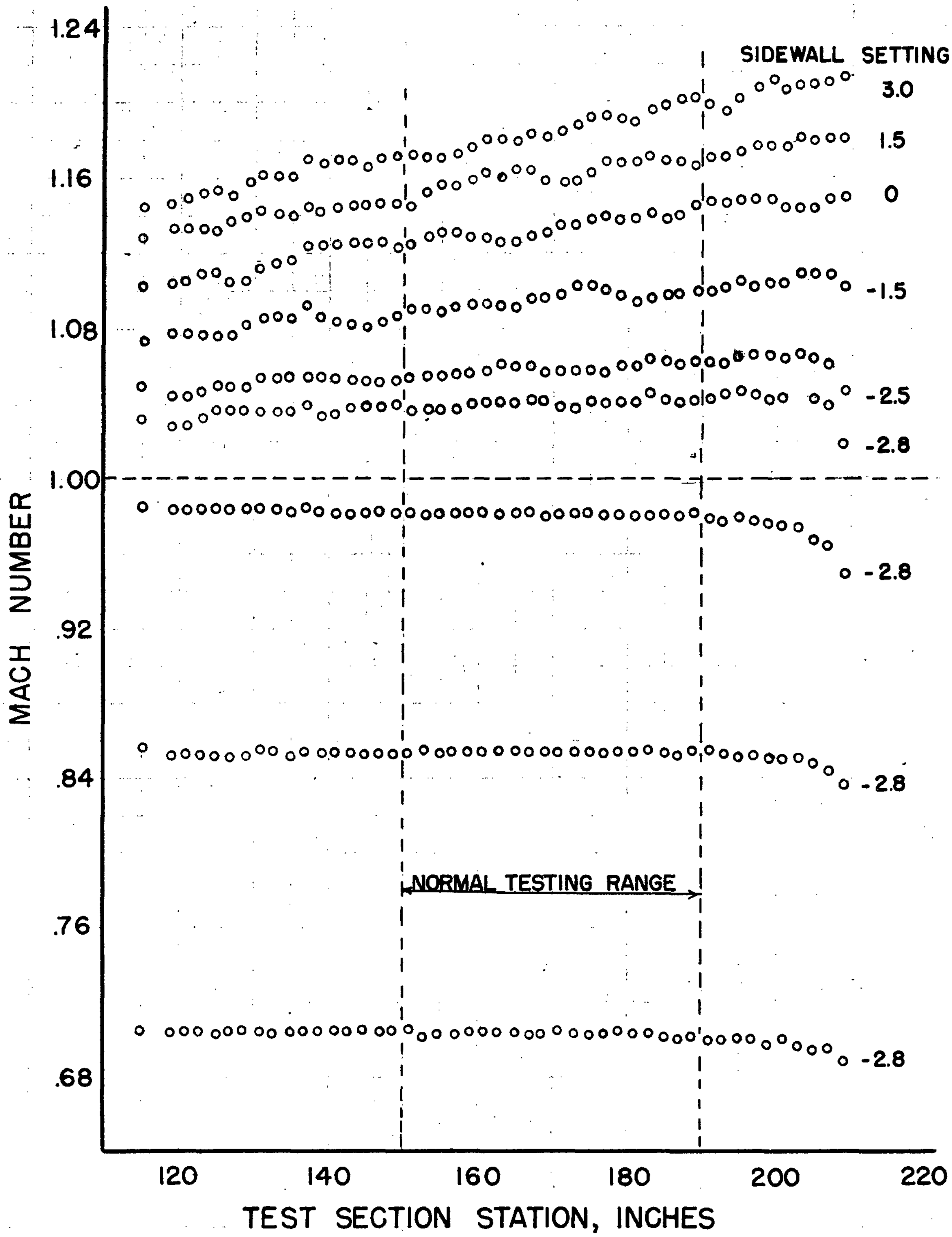

FIGURE 2 : MACH NUMBER DISTRIBUTION ALONG THE CENTERLINE OF THE CLOSED TEST SECTION AFTER GRINDING, $p_o = 2000$ lb/ft^2

(TEST 51, PART 2, TEST DATE: JULY 1952)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

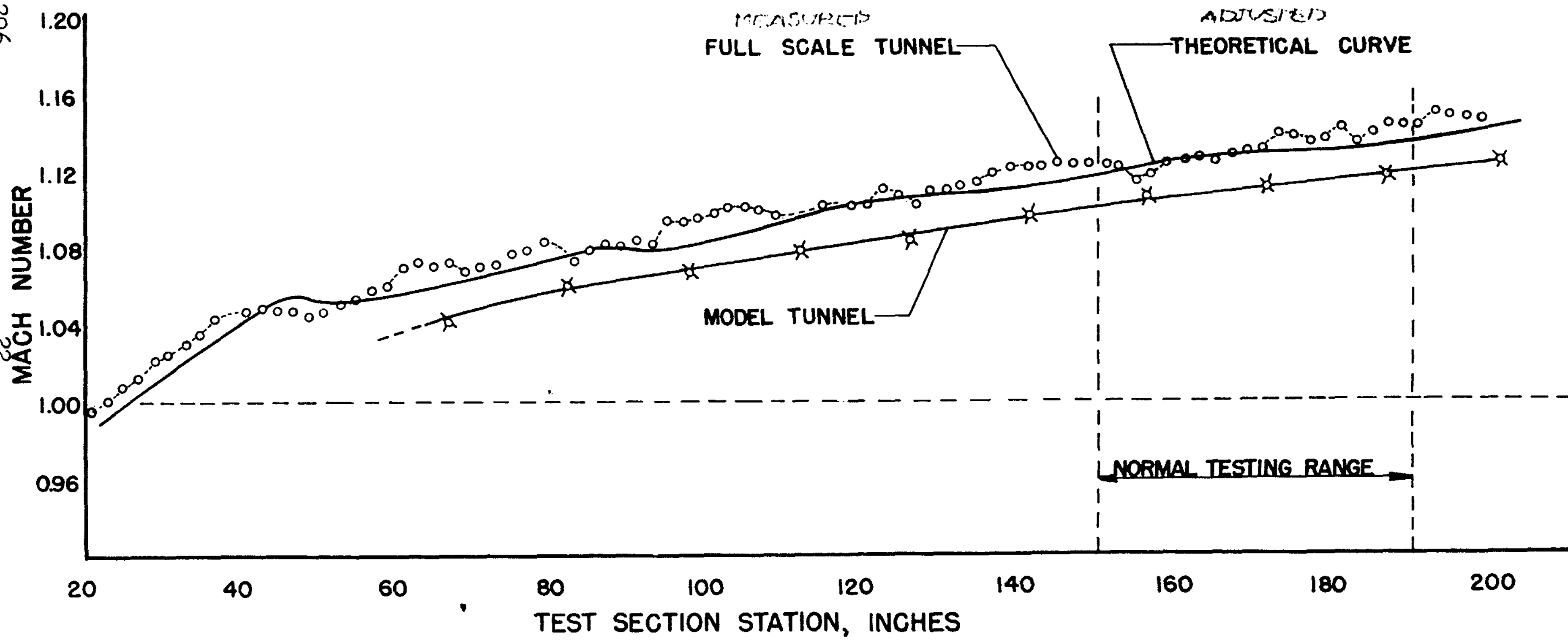

FIGURE 3 : MACH NUMBER DISTRIBUTION AT TEST SECTION CENTERLINE FOR FLUSH SIDE WALL SETTING ACCORDING TO FULL-SCALE TUNNEL TESTS, MODEL TUNNEL TESTS, AND TO THEORY. TEST SECTION WITH PAINTED ANNULAR REGIONS BEFORE FINAL GRINDING.

(EXPERIMENTS: FULL-SCALE TEST 43, PART 10-11; MODEL TESTS 1-16-50. THEORY: AF-TR 5790)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

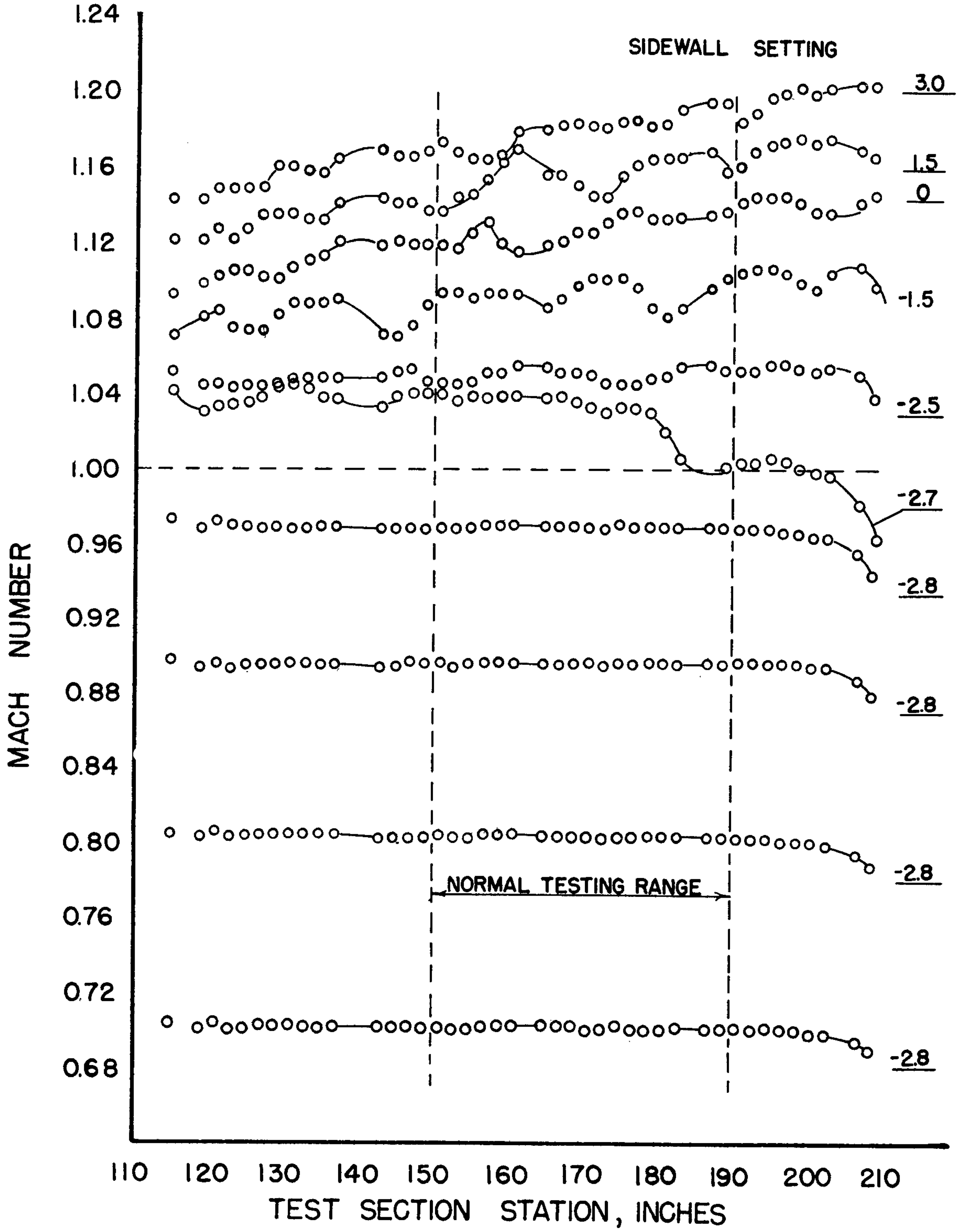

FIGURE 4a : MACH NUMBER DISTRIBUTION ALONG THE CENTERLINE OF THE TEST SECTION FOR VARIOUS SIDE WALL SETTINGS BEFORE GRINDING, p_o=2000 lb/ft^2

(TEST 30, PART 4, TEST DATE: 5 DECEMBER 1951)

[redacted]

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WRIGHT FIELD, 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

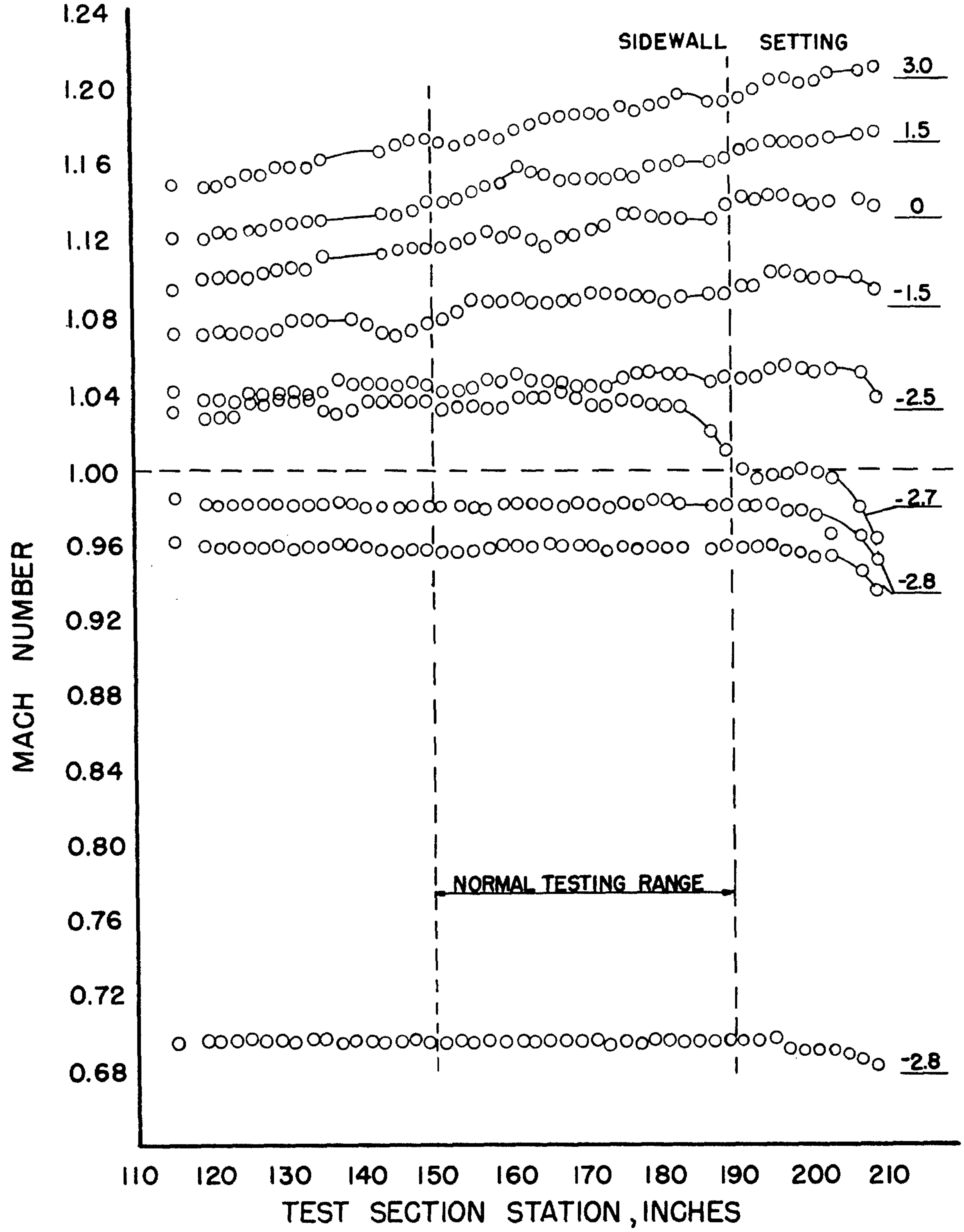

FIGURE 4b : MACH NUMBER DISTRIBUTION ALONG A LINE 11-INCHES OFF THE TUNNEL CENTERLINE FOR VARIOUS SIDE WALL SETTINGS BEFORE GRINDING, p_0=2000 lb/ft^2

(TEST 30, PART 11, TEST DATE: 11 DECEMBER 1951)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

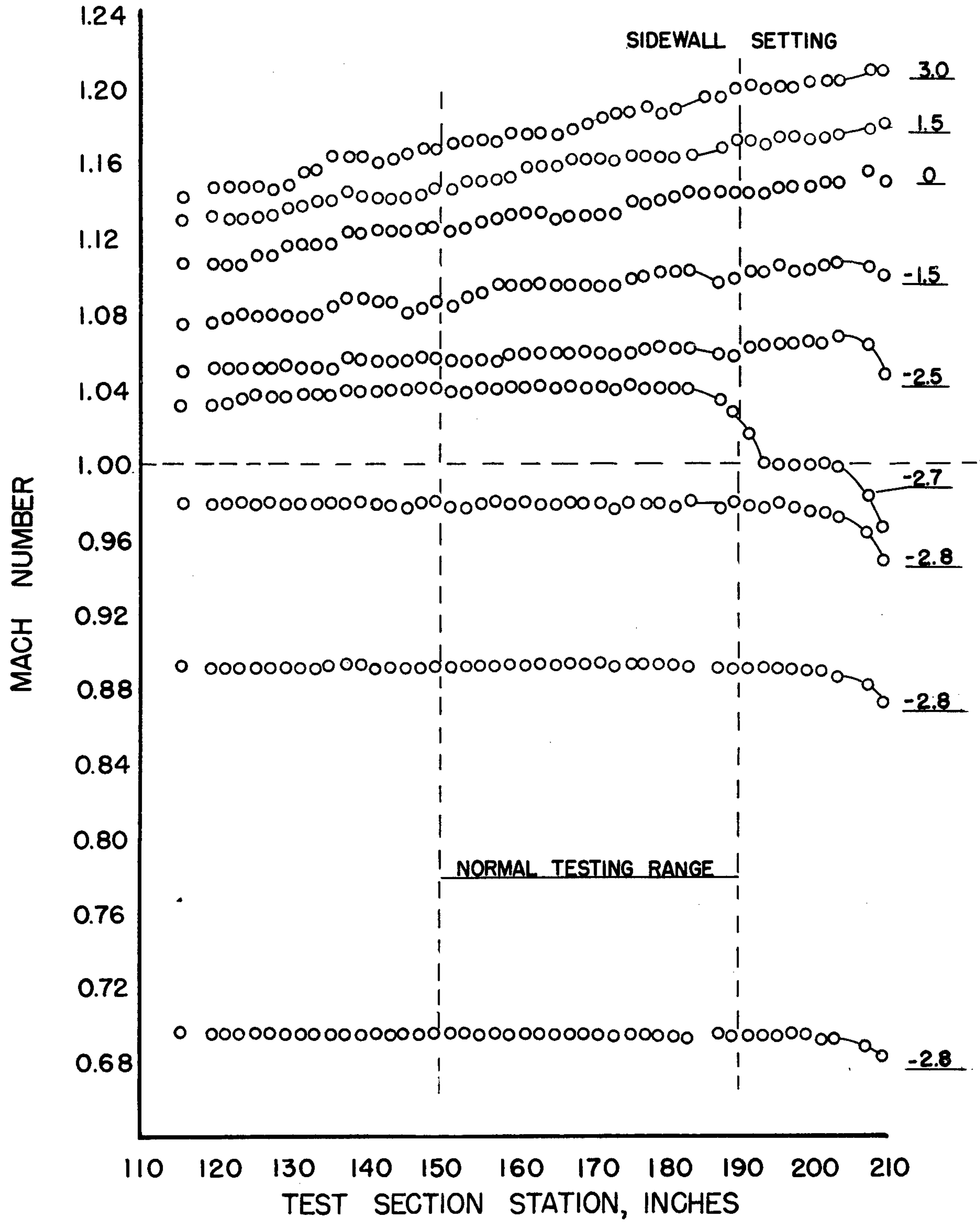

FIGURE 4c : MACH NUMBER DISTRIBUTION ALONG A LINE 21-INCHES OFF THE TUNNEL CENTERLINE FOR VARIOUS SIDE WALL SETTINGS BEFORE GRINDING, p_o=2000 lb/ft^2

(TEST 30, PART 12, TEST DATE: 11 DECEMBER 1951)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

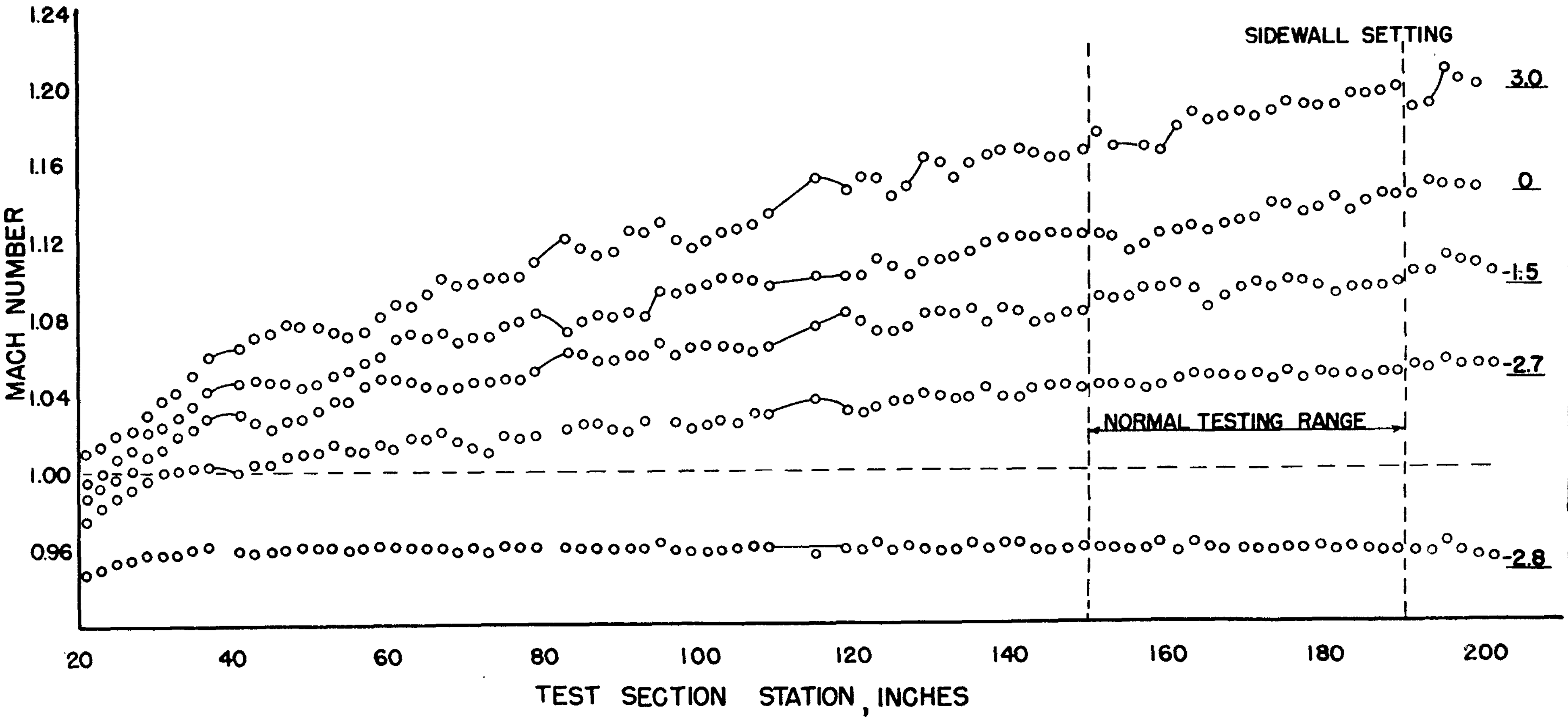

FIGURE 5 : MACH NUMBER DISTRIBUTION ALONG THE CENTERLINE FOR THE CLOSED TEST SECTION WITH PAINTED ANNULAR REGIONS BEFORE FINAL GRINDING, p_o=2000 lb/ft^2

(TEST 43, PARTS 10&11, TEST DATE: MAY 1952)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

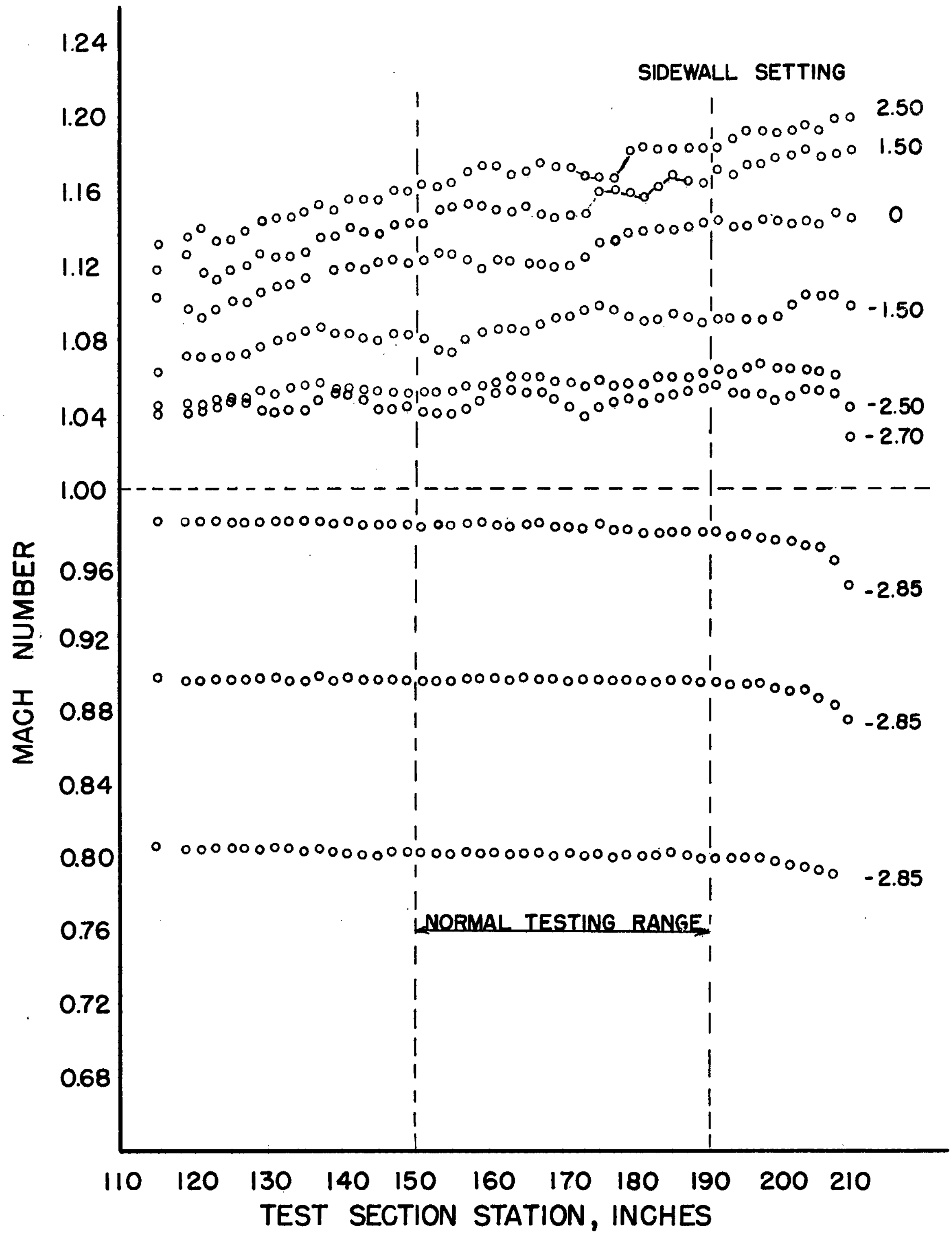

FIGURE 6 : MACH NUMBER DISTRIBUTION ALONG THE CENTERLINE FOR THE CLOSED TEST SECTION AFTER GRINDING WITH ROUGH COVER PLATES OVER THE SLOTS, p_o = 2000 lb/ft^2

(TEST 52, PART 2, TEST DATE: AUGUST 1952)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

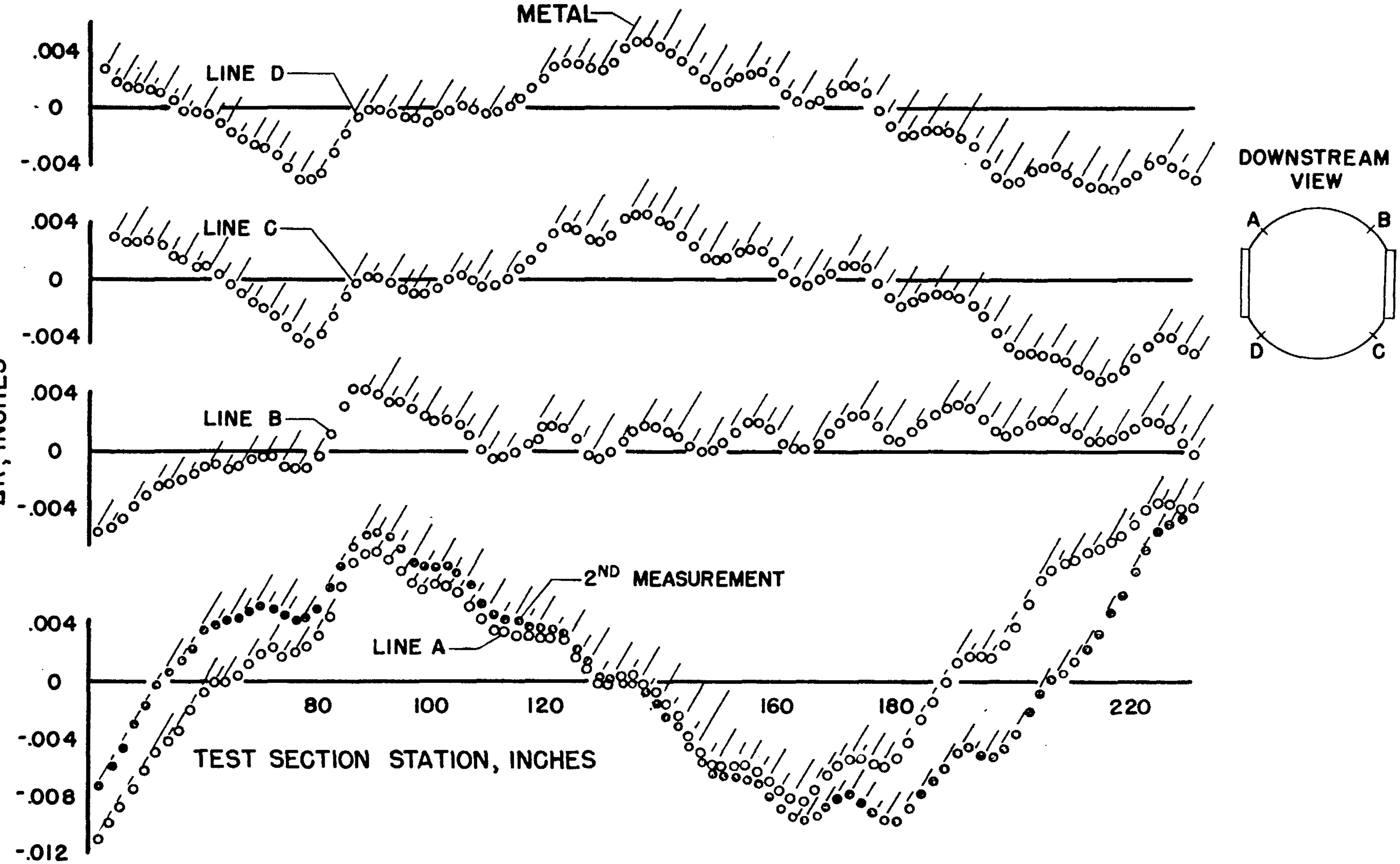

FIGURE 7 : RADIAL DEVIATIONS FROM A SMOOTH INTERNAL SURFACE, Δ R,
BASED ON PROFILOMETER TESTS (8" LEG SPACE) BEFORE FINAL GRINDING

DATE OF MEASUREMENT: FEBRUARY 15 & 19, 1952

[redacted]

[redacted]

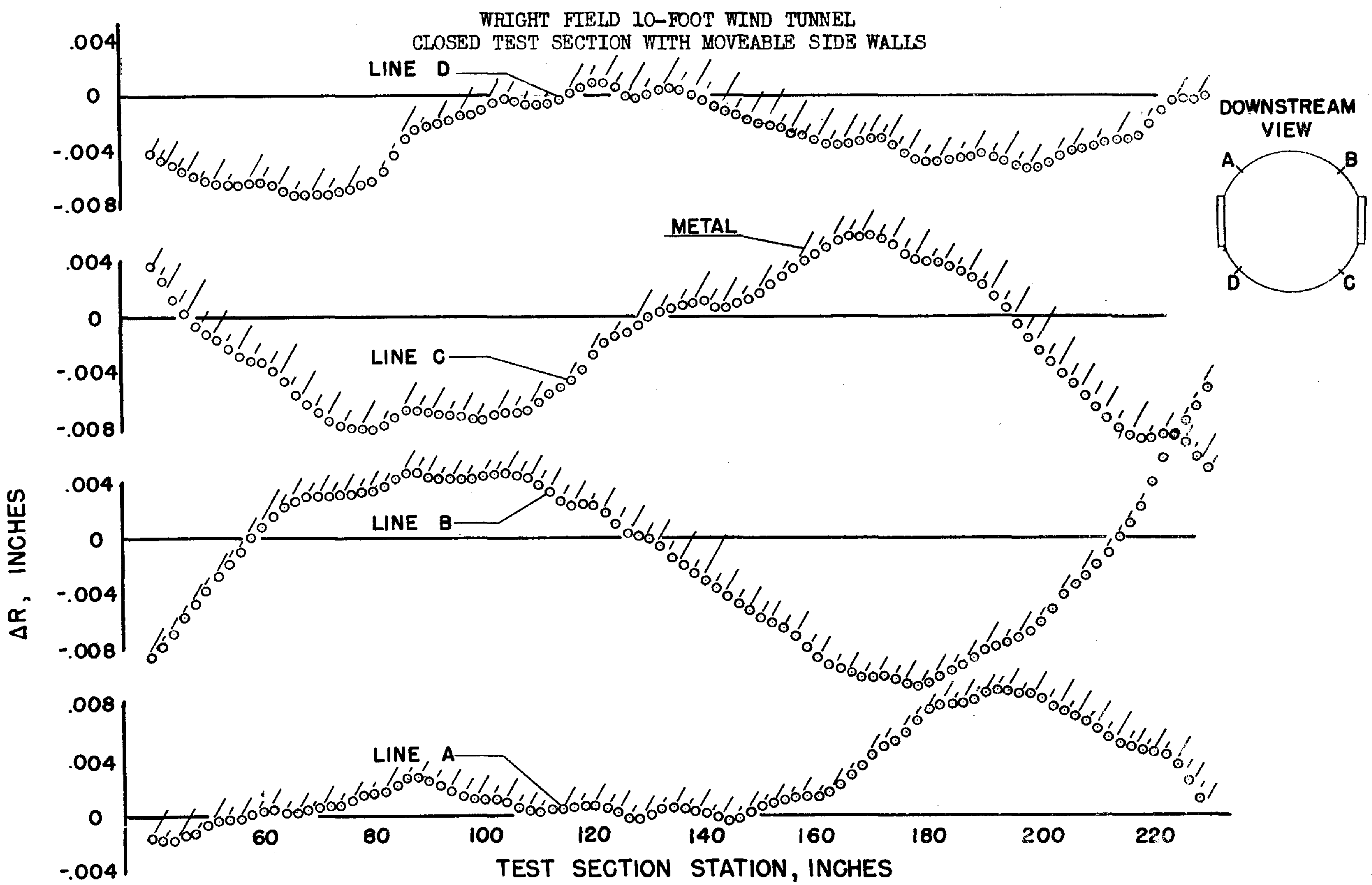

FIGURE 8 : RADIAL DEVIATIONS FROM A SMOOTH INTERNAL SURFACE, Δ R, BASED ON PROFILOMETER TESTS (8" LEG SPACE) AFTER FINAL GRINDING

DATE OF MEASUREMENT: 16 JULY 1952

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

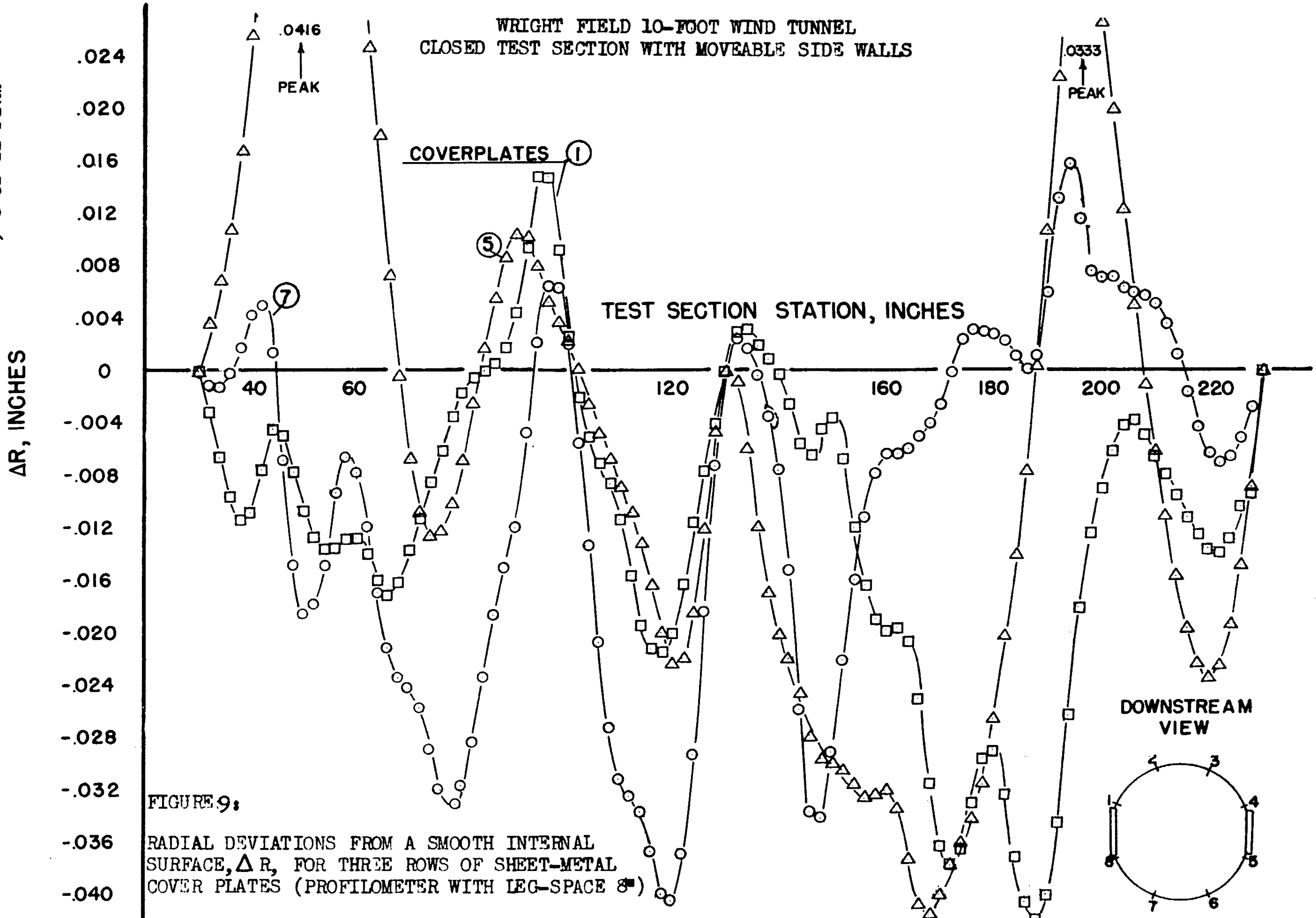

FIGURE 9:

RADIAL DEVIATIONS FROM A SMOOTH INTERNAL SURFACE, Δ R, FOR THREE ROWS OF SHEET-METAL COVER PLATES (PROFILOMETER WITH LEG-SPACE 8")

(DATE OF MEASUREMENT: AUGUST-SEPTEMBER 1952)

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS BEFORE GRINDING

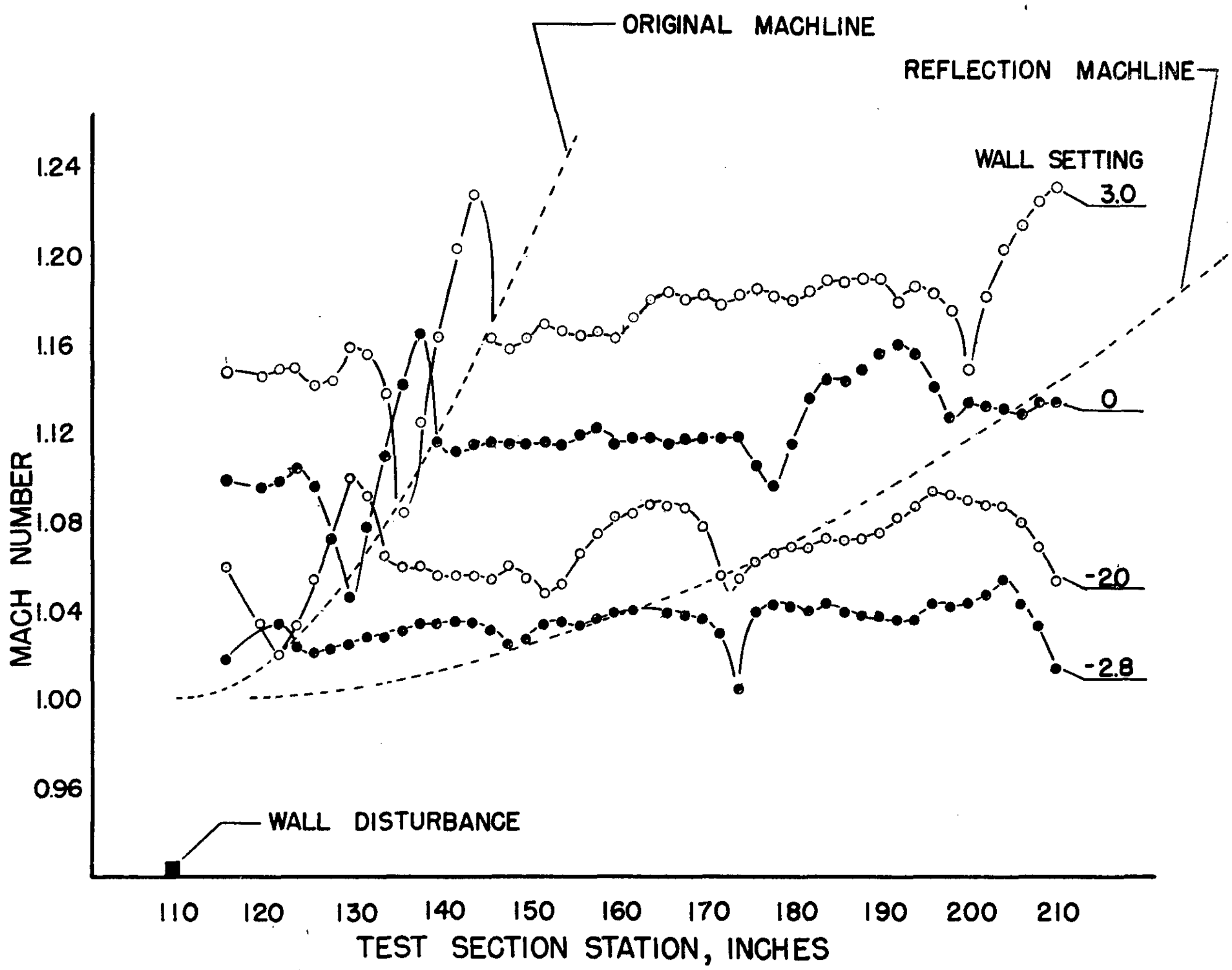

FIGURE 10 : INFLUENCE OF AN ANNULAR WALL DISTURBANCE ON THE MACH NUMBER DISTRIBUTION ALONG THE TEST SECTION CENTERLINE, p_o = 2000 lb/ft^2

WALL DISTURBANCE: CIRCULAR WIRE OF .030" DIAMETER EXTENDING OVER A TOTAL OF 82% OF THE TEST SECTION CIRCUMFERENCE

(TEST 43, PART 9, TEST DATE: 13 MAY 1952)

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WRIGHT [smudged] 10-FOOT WIND TUNNEL
CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

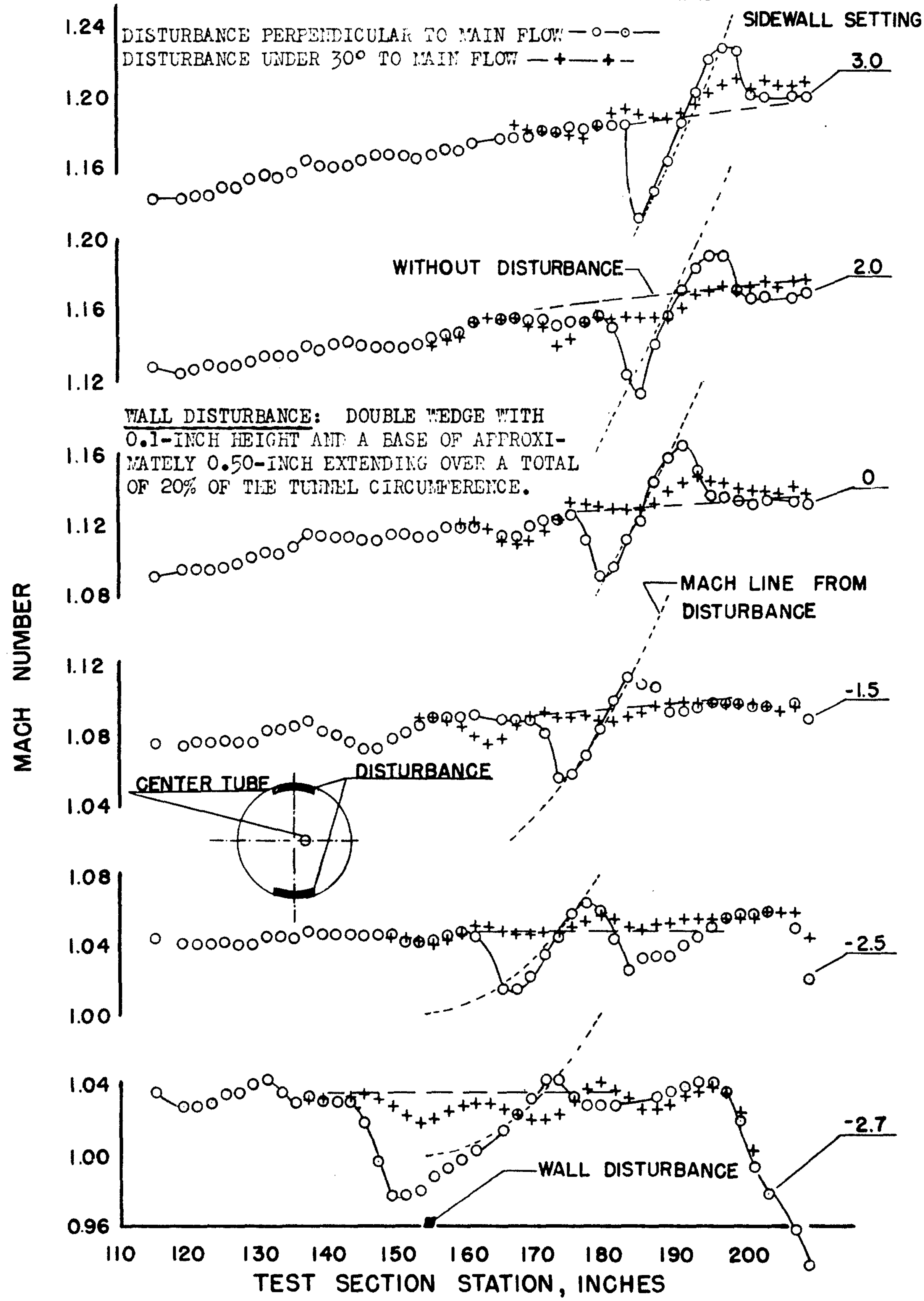

FIGURE 11: INFLUENCE OF AN ANNULAR WALL DISTURBANCE ON THE MACH NUMBER DISTRIBUTION ALONG A LINE 11-INCHES OFF THE TUNNEL CENTER LINE, P_o = 2000 lb/ft². (Test 30, Part 8, Test Date: 12-10-51; Test 36, Part 7, Test Date: 2-12-52)

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WRIGHT FIELD 10-FOOT WIND TUNNEL

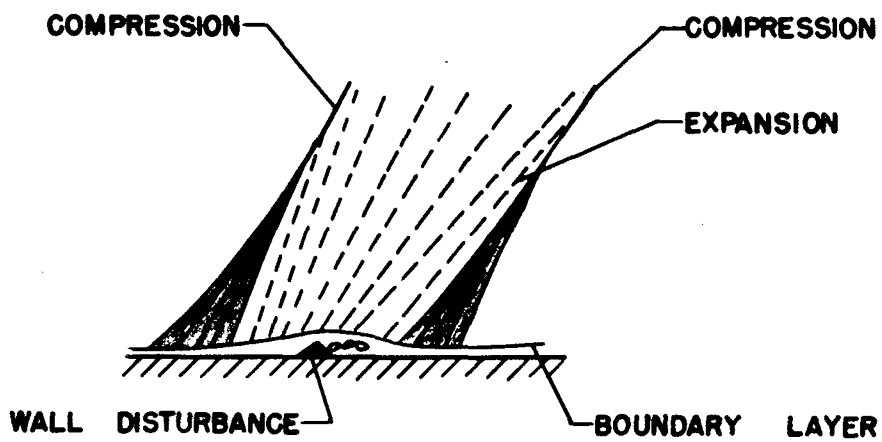

FIGURE 12: SCHEMATIC REPRESENTATION OF THE WAVE PATTERN AROUND A WALL DISTURBANCE IN THE PRESENCE OF THE BOUNDARY LAYER

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS BEFORE GRINDING

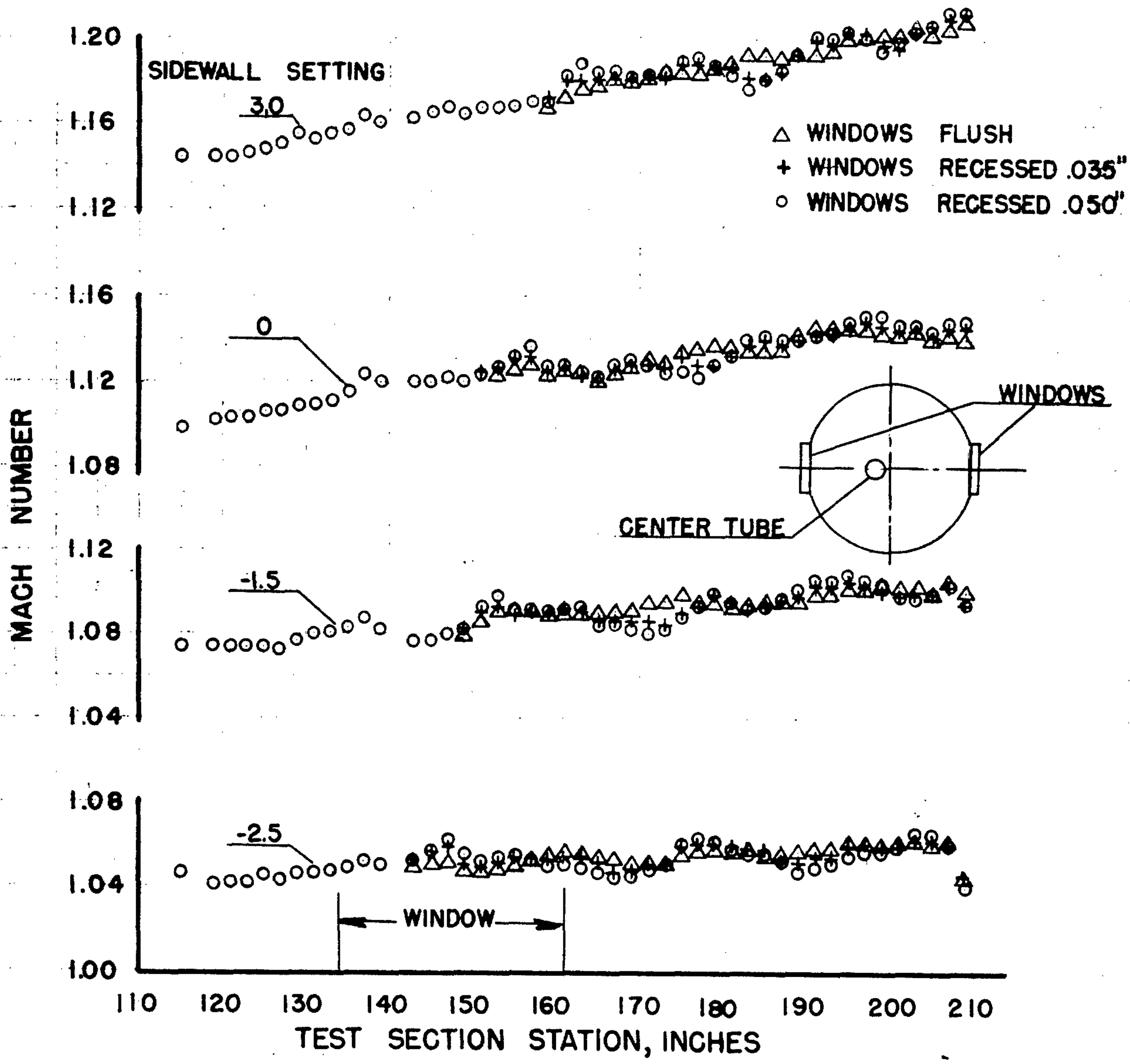

FIGURE 13 : INFLUENCE OF RECESSING TWO CIRCULAR WINDOWS, d=27 INCH, ON THE MACH NUMBER DISTRIBUTION ALONG A LINE 12" OFF THE TUNNEL CENTERLINE AT p_o=2000 lb/ft^2 (BOTH WINDOWS AT OPPOSITE TUNNEL WALLS AT SAME STATION).

(TEST 36, PART 5, 12, 13, TEST DATE: 12 FEBRUARY 1952)

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WRIGHT FIELD 10-FOOT WIND TUNNEL

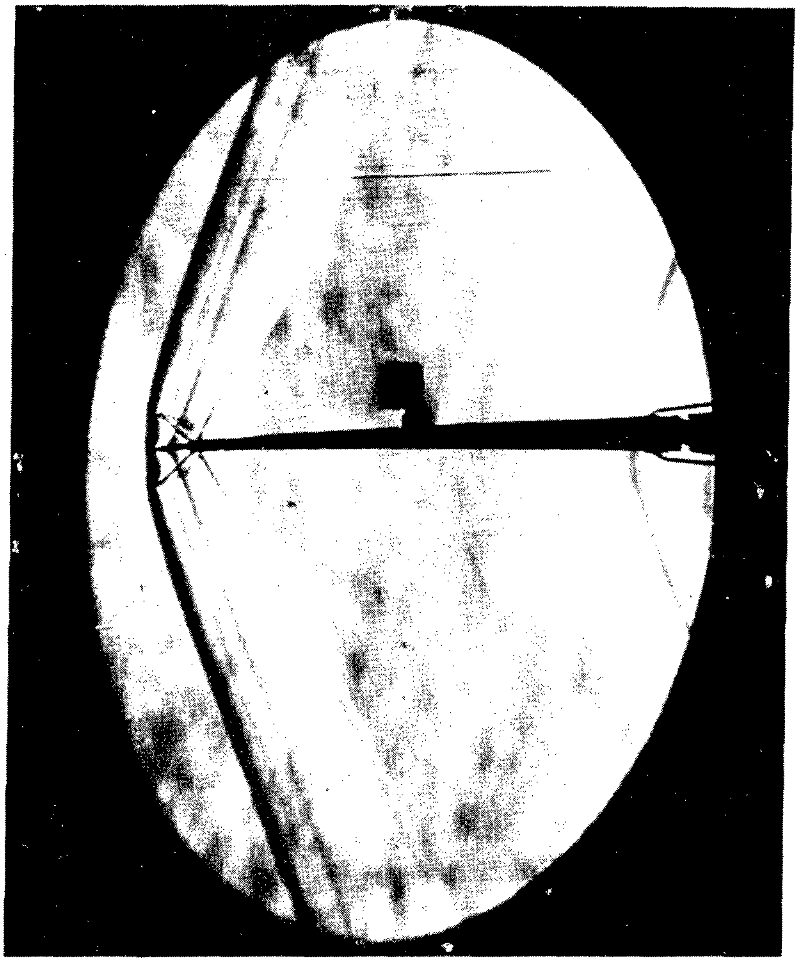

FIGURE 14: PROBE WITH FOUR OBLIQUE TOTAL TUBES FOR MEASURING FLOW INCLINATION IN SUPERSONIC FLOW OF MACH NUMBER M = 1.09.

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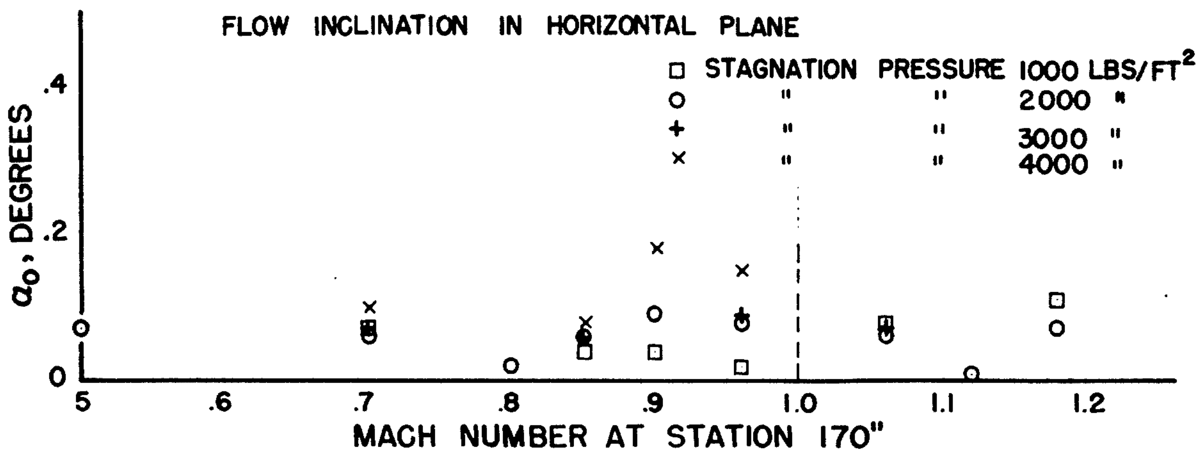

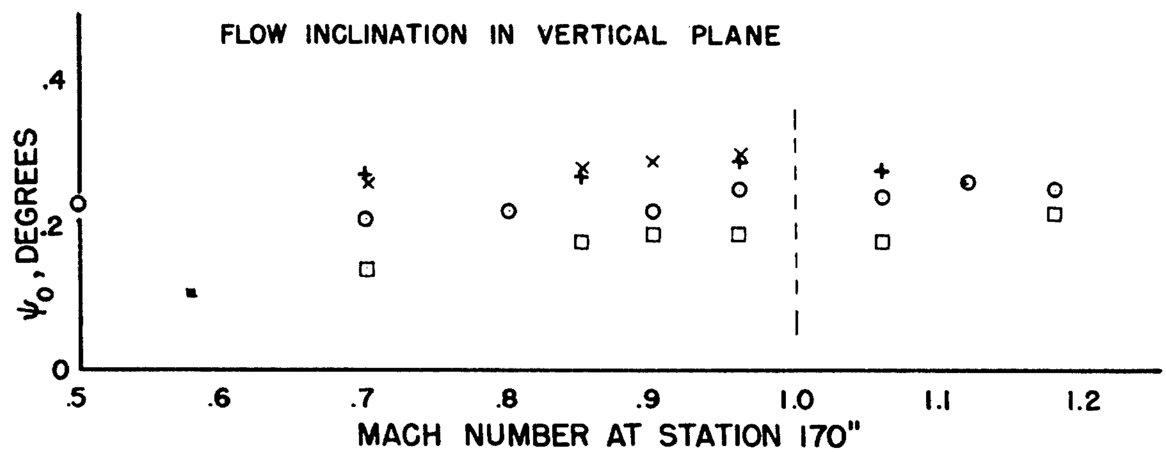

FIGURE 15 : FLOW INCLINATION MEASUREMENTS AT TEST SECTION CENTERLINE, STATION 170"

(TEST 36, PARTS 18-22A, TEST DATE: 20-25 FEBRUARY 1952

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WRIGHT FIELD 10-FOOT WIND TUNNEL
CALIBRATION OF CLOSED TEST SECTION WITH MOVEABLE SIDE WALLS

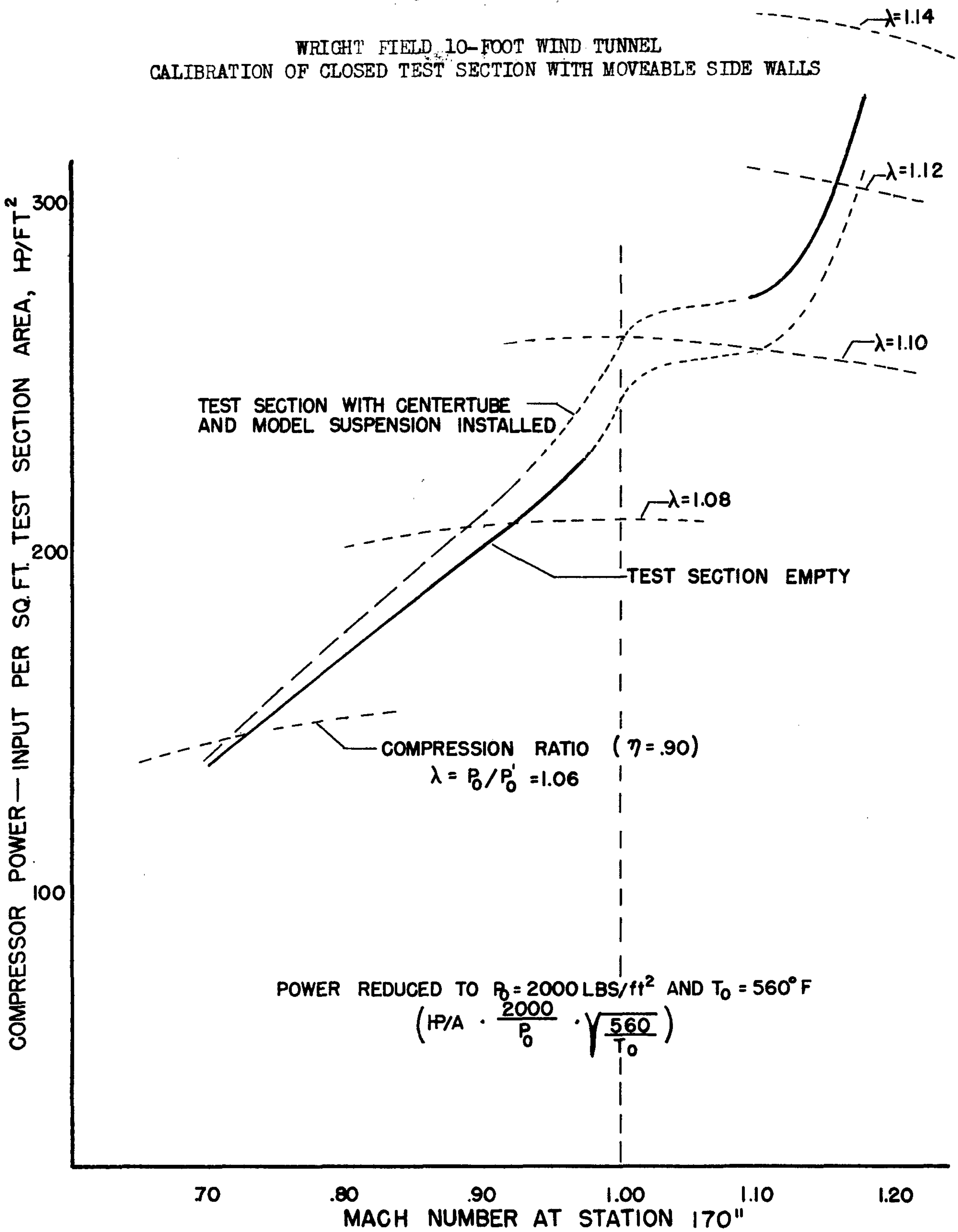


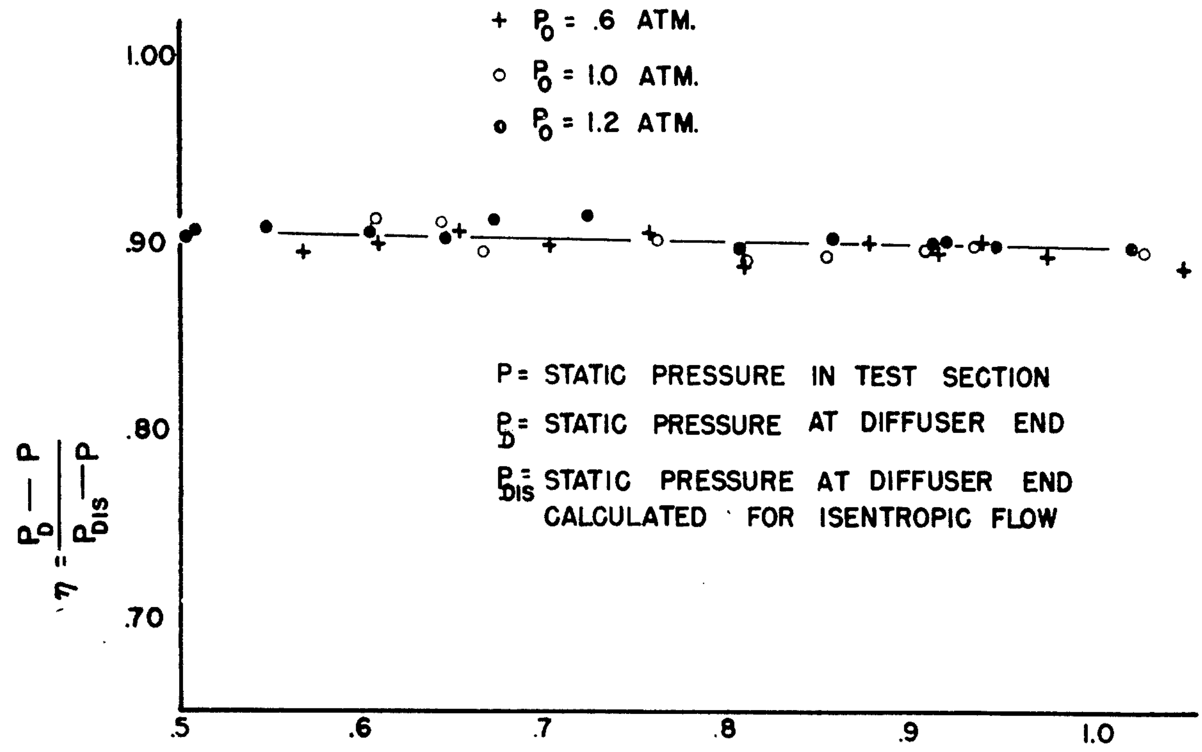
FIGURE 16 : POWER INPUT TO MAIN COMPRESSOR AND COMPRESSION RATIO FROM TESTS AT STAGNATION PRESSURE, p_o = 2000 lb/ft^2

(TEST 43, TEST DATE: 13 MAY 1952)

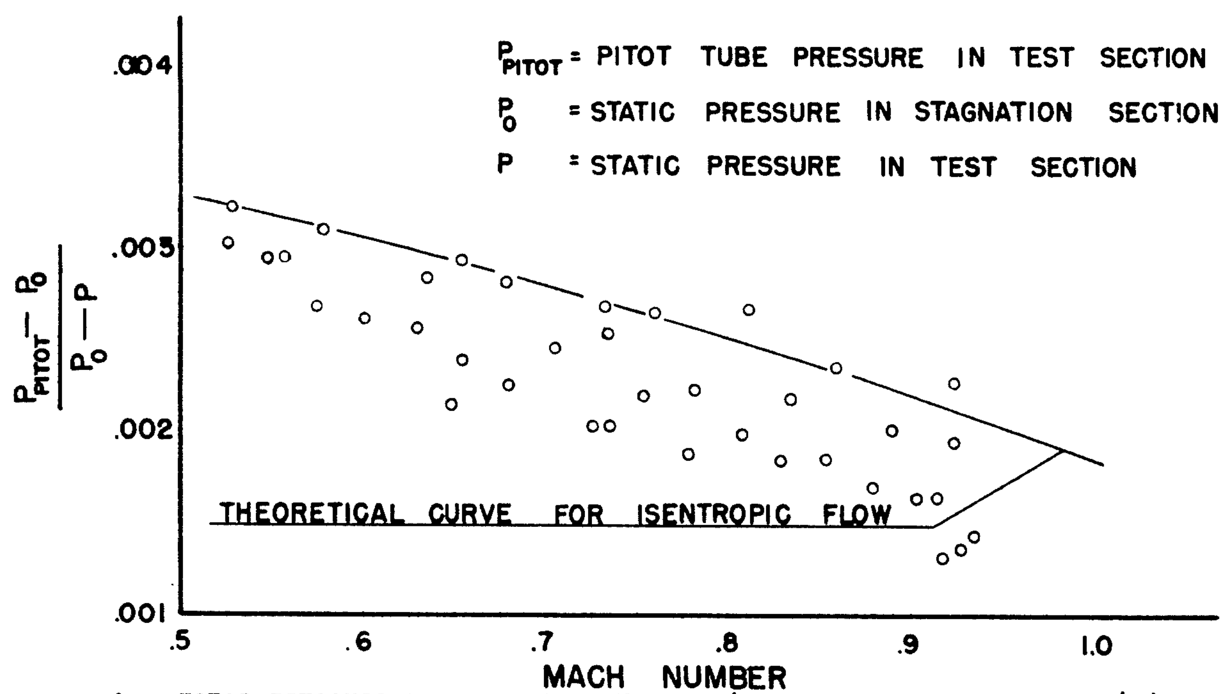
[redacted]

[redacted]

WRIGHT FIELD 10-FOOT WIND TUNNEL
CLOSED TEST SECTION



a. DIFFUSER EFFICIENCY (TEST DATES: MAY 13-16, 1947)



b. TOTAL PRESSURE DROP IN TEST SECTION (TEST DATES: MAY 21-22, 1947)

FIGURE 17 : PRESSURE LOSSES IN NOZZLE AND DIFFUSER

[redacted]