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NOL HYPERSONIC TUNNEL NO. 4 RESULTS II:
DIFFUSER INVESTIGATION

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U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

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NOL HYPERSONIC TUNNEL NO. 4 RESULTS II: DIFFUSER INVESTIGATION

Prepared by:

Peter P. Wegener and R. Kenneth Lobb

ABSTRACT: Results of a diffuser investigation in the continuous 12 x 12 cm Hypersonic Tunnel No. 4 are presented. A brief introduction describes previous supersonic diffuser work. The diffuser investigated and the experimental techniques are then discussed. The results show first that air condensation has little or no effect on diffuser performance. Data on diffuser throat areas and overall pressure ratios needed to start and maintain hypersonic flow are given for a Mach number range from 5.9 to 9.6. The effect of two different throat locations and different diffuser configurations on tunnel performance is investigated. A peaked throat diffuser with 3° wall divergence aft of the throat was selected for a more detailed study. The pressure recovered by this optimum diffuser in the range $5.9 \leq M \leq 9.6$ varies from 1.8 to 2.3 times the value of the pressure recovered by a pitot tube operated at equal Mach number. The best performance with 2.3 times pitot recovery is achieved at $M = 7.2$. Spark schlieren photographs taken throughout the test section and diffuser show the shock waves and boundary layers. Also tunnel starting requirements were measured and are discussed. It is found that if the diffuser throat is opened sufficiently, the tunnel can at all times be started at an overall pressure ratio somewhat lower than the pitot pressure ratio for the same Mach number. Quantitative comparisons of all results are made with data previously given in the literature and one-dimensional theory.

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This is the second NAVORD Report on an investigation carried out in the U. S. Naval Ordnance Laboratory Hypersonic Tunnel No. 4. This wind tunnel was sponsored by the Bureau of Ordnance and was first put into operation in May 1950. The experiments in this report were carried out in the redesigned and improved version of the equipment which was put into operation in Fall 1951. This investigation was partially sponsored by Sverdrup and Parcel, Inc. and the U. S. Air Force. Specifically the diffuser investigated is a scale model of a diffuser considered for the hypersonic working section of the Gas Dynamics Facility of the Arnold Engineering Development Center at Tullahoma, Tennessee. The present report contains an account of the investigation without models and supports in the tunnel. The work with models and supports is presently being carried out and will be reported in a forthcoming NAVORD.

H. Staab and R. Garran participated in the tests. Messrs. E. Stollenwerk (now with Sverdrup and Parcel, Inc.), C. White (N.O.L.), and R. Weiter (S & P) were responsible for the mechanical design of the diffuser.

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NOL HYPERSONIC TUNNEL NO. 4 RESULTS II: DIFFUSER INVESTIGATION

I. INTRODUCTION

1. A major component of a supersonic wind-tunnel working section is the diffuser. The diffuser decelerates the flow from supersonic to low subsonic speeds. This transfer process is not free of losses. Due to shock waves and friction the stagnation pressure decreases and the entropy of the flow increases. A general discussion of the supersonic diffuser problem is given in chapter 9 of reference (a).

2. Diffuser "efficiency," "pressure recovery," and "overall pressure ratio" are quantitative expressions for the potential energy or pressure recovered. It is sufficient to discuss pressure alone because the diffuser end-temperature is approximately equal to the tunnel supply temperature. High-pressure recovery is desirable in order to operate wind-tunnel power plants at a minimum overall pressure ratio for a given Mach number. This operating pressure ratio is widely different for different types of wind-tunnel diffusers or test section configurations. The latter may have open, half open, or closed jets, depending on whether none, two, or four test section walls bound the flow. For a fixed type of test section and diffuser, the pressure recovery is also a function of test section Mach and Reynolds number. Finally one commonly distinguishes between fixed or variable area diffusers. Only the latter type where the diffuser throat area or "second throat" can be closed down after supersonic flow has been established is of interest here.

3. Most supersonic wind tunnels have diffusers whose configurations are largely patterned after subsonic experience. These give overall pressure ratios of the order shown in Figure 5.16, page 85 of reference (b). One may conveniently compare this pressure recovery with that of a pitot tube placed into the test section at the same Mach number. In the pitot case the flow is decelerated through a normal shock and a subsequent isentropic compression. A comparison of the pitot tube as a pressure-recovery device with supersonic wind-tunnel diffusers shows that the latter are ordinarily less efficient. This is due to the fact that for a tunnel diffuser viscosity effects enter the picture in addition to losses corresponding to a normal shock. Since a diffuser employing a system of oblique shocks must be more efficient than a normal shock diffuser, efforts were made to improve supersonic wind-tunnel diffusers. In fact, such a device may theoretically have perfect efficiency. Furthermore, it was long known from ramjet-diffuser studies (reference c) that efficiencies above those of a pitot probe could be obtained in practice. An above pitot-recovery diffuser for a supersonic wind tunnel was demonstrated by Kurzweg (reference d) at $M = 2.9$. This

diffuser had a single, peaked throat, variable area, and straight walls. Detailed investigations in the NOL 18 x 18 cm continuous tunnel were presented by Diggins (reference e). Also Neumann and Lustwerk discussed (references f and s) diffusers of above pitot tube recovery. Diggins (reference g) then extended the Mach number range of the NOL investigations to 4.4. Finally investigations at $M = 6.9$ in the NACA Langley 11" hypersonic tunnel were made by Bertram (reference h). Recoveries up to two times pitot pressure were achieved by him. Furthermore, the Langley 11" hypersonic tunnel diffuser possessed a paralled duct as a second throat. (Similar configurations are also shown at lower Mach numbers in reference f.) Based on considerations by Kantrowitz (reference i) on the stability of channel flows, it became evident that such ducts might be useful to stabilize the final shock transition to subsonic flow. In this arrangement a stable shock will permit the back pressure to reach a maximum before the shock "jumps" upstream through the diffuser throat and the test section.

4. The present investigation covers a Mach number range from 5.9 to 9.6 with a variable area diffuser whose throat could be located at two distances from the nozzle exit. Furthermore, aft of the diffuser throat, the diffuser plates could be adjusted at any angle from zero degree divergence (compare reference h) to large angles and to single peak configurations (compare references e and g). Also the third or last diffuser plates were adjustable.

5. The results show that simple configurations with one peaked throat give diffuser pressure recoveries above pitot tube recovery in the entire range of Mach numbers. The peak recovery is higher than any previously reported data. (2.3 pitot recovery at $M = 7.2$).

6. Aside from efficient operation of a supersonic tunnel after start, the overall pressure ratio needed for this starting is of importance. This pressure ratio determines the maximum performance requirement for the power plant. Very little is known to date on this subject (references e, g, and j). For this reason starting requirements were investigated and the results indicate that hypersonic tunnels may be started at pressure ratios considerably below those previously anticipated. In fact the tunnel may at all times be started at overall pressure ratios which are about equal to the pitot pressure to supply pressure ratio at the corresponding Mach number. This result is of particular importance since it eliminates costly additions to power plants for the momentary attainment of very high-pressure ratios.

7. It is interesting to note that the open jet diffuser type is amenable to theoretical treatment. Hermann (references k and l) has correctly predicted open jet tunnel diffuser-performance. On the other hand the closed jet diffuser of interest here because of its high performance possibilities cannot yet be treated by a

unified theory. This is due to the fact that the losses to be computed are governed by shock waves and friction. Calculation would require the understanding of turbulent boundary-layer characteristics in converging and diverging channels and shock wave-boundary layer interaction (compare Figures 5 and 13). These phenomena are inadequately known at present.

II. DESCRIPTION AND PERFORMANCE OF EQUIPMENT

8. The investigation was conducted in the continuous NOL 12 x 12 cm Hypersonic Tunnel No. 4 described in reference (m) and shown in Figures 1 to 4.

9. Supply temperatures ranging from room temperature to 500°C and supply pressures from 1 to 30 atmospheres can be accurately maintained during the blow in the supply section of the tunnel. A new steel wedge-type nozzle with a built-in cooling system expands the air to a desired Mach number in the range from 5 to 10. Preheating of the air is needed to avoid air condensation in the test section (reference n). The Mach number distribution in the exit plane of the wedge nozzle at $M - 7.2$ is uniform to ± .01 M (outside of the about 2 cm thick boundary layer). The Mach number increases somewhat along the center line throughout the test section.

10. The diffuser has three sets of plates, the first of which is linked directly to the nozzle end. (Due to the high Mach number in the test section, the shock angle caused by the flow deflection at this point is small, and long models can be used without having the conventional paralled wall test section.) Two pairs of motor driven jacks connect to the junction of the first and second, and the second and third plates respectively. Sliding gaskets (silicon rubber stripping) fastened to the diffuser plates seal the diffuser at all positions. A flexible pressure seal between the first plates and the tunnel walls keeps test section pressure behind these plates. The two sets of jacks operate together so that the second plate angle β (see notation) is fixed during the run. This angle can be changed in between runs by offsetting the jacks. Angle φ of the third plates can be changed during the run by a third set of hand operated jacks connected to the diffuser end. The diffuser throat opening is recorded on a mechanical counter by use of a selsyn system, and is known to within ± .005 inch. Steel side walls with pressure taps on the centerline, or walls with 1" thick circular commercial plate glass windows at some points enclose the diffuser. Photographs are taken with a continuous or short duration (0.5×10^{-6} secs) light source. Details can be seen on the Figures 1 to 3 and dimensions are given on Figure 4 (1 caliber refers to the 12 cm nozzle-exit width).

11. The diffuser leads into a 12" and then a 36" pipe connecting the tunnel to vacuum pumps via a 2000 m^3 vacuum sphere. Overall

pressure ratios up to 50,000 are available. Close control of the supply pressure by the pressure regulators and the "sphere pressure" by a vent valve permit the establishment of an arbitrarily chosen accurate overall pressure ratio. This accuracy of p_o/p_{sp} is of the order $1^o/_o$. On this basis a continuous blow down tunnel is ideally suited for diffuser performance studies.

III. EXPERIMENTAL TECHNIQUE

Pressure recovery of operating tunnel.

12. If a tunnel operates supersonically for a given Mach number, supply pressure, and temperature (Reynolds number), there exists a minimum diffuser throat area for a given diffuser configuration below which no supersonic flow can be maintained even for an infinite pressure ratio across the tunnel. This minimum running diffuser area is determined by a test called "area breakdown." During this test the tunnel is started and operated at a very high overall pressure ratio. The diffuser throat area is then slowly reduced until the supersonic flow "breaks down" in the test section as observed with the schlieren system. Minimum running diffuser areas are noted on the counter and indicated as a vertical dashed line in figures depicting pressure recovery.

13. The minimum overall pressure ratio needed to operate the tunnel for a given Mach number, supply pressure, and temperature, and diffuser configuration is determined as a function of diffuser throat area for all values of the latter, larger than the minimum running area. This test is called a "pressure breakdown." After starting the tunnel, the diffuser throat area is set on a given value larger than the minimum running area. Then by increasing the vacuum sphere pressure slowly, while watching the flow in the test section, the pressure ratio at which the supersonic flow "breaks down" can be determined. This pressure ratio is indicated in the figures as p_o/p_e. For actual application, it must be borne in mind that to maintain supersonic flow a slightly higher pressure ratio than p_o/p_e must be provided by the power plant.

Tunnel starting requirements.

14. Minimum starting diffuser areas are determined by operating the tunnel at a very high overall pressure ratio and opening the diffuser. At some critical minimum diffuser throat area, supersonic flow is established in the test section. The identical test can be made by setting the diffuser throat area on different openings and starting the tunnel at very high pressure ratios by use of the fast acting valve (1/500 secs). Some diffuser throat will then be just sufficiently large to permit establishing supersonic flow.

15. Similar to the operating pressure ratio, minimum starting pressure ratios can be found for all diffuser throat areas equal to or larger than the minimum starting diffuser throat area determined above.

IV. EFFECT OF AIR CONDENSATION ON DIFFUSER PERFORMANCE

16. If a wind tunnel is operated from a room temperature reservoir at a nozzle area ratio corresponding to a Mach number higher than about 5, then a fraction of the air will condense at or shortly after reaching saturation in the nozzle. Subsequent to condensation, the further expansion may adequately be described as saturated and isentropic, (references n and o). This condensation of air affects the commonly measured flow parameters differently. In particular, static pressure measurements are very sensitive indicators of air condensation while pitot pressure measurements are nearly insensitive. It can now also be shown experimentally that the overall pressure ratio of a given diffuser configuration is nearly insensitive to air condensation as evidenced by Figures 5 and 6 taken for $M_s = 7.6$. In this comparison Reynolds effects on diffuser performance are minimized by keeping the supply density equal in the two cases of (1) air condensation, and (2) no condensation. In the latter case T_0 is high enough to avoid the coexistence region altogether during the expansion and no condensation is possible. Overall pressure ratios in the case with condensation are slightly lower due to the actually lower Mach number. (Compare reference o). The shock angles are slightly smaller in the case of no condensation as expected and previously demonstrated for shock waves on simple bodies in references (n), (o), and (p). However, this angle change does not significantly alter the shock pattern, In general, the diffuser pressure ratio (similar to that of a pitot tube) is remarkably insensitive to condensation. The following tests (with the exception of the sensitive static pressure measurements and checks on starting) were therefore made without preheating the air and the Mach numbers indicated as $M(p_0'/p_0)$ are to be taken as those derived from pitot measurements with the aid of a flow table (reference q). This procedure of running the tunnel "cold" makes it possible to photograph extensively without the danger of cracking windows and it generally simplifies testing. The "pitot Mach numbers" may, however, be taken as actual Mach numbers for the diffuser study without appreciable error.

V. PRESSURE RECOVERY OF OPERATING TUNNEL FOR VARIOUS DIFFUSER CONFIGURATIONS

17. The pressure recovery (in terms of pitot pressure) over the range of Mach numbers tested is generally of the same order (1.8 to 2.3) with a maximum around Mach number 7. A detailed investigation to determine diffuser performance for various operating conditions, configurations, etc. was therefore carried out at this Mach number only.

18. The pressure recoveries at a Mach number 7.2 for three diffuser configurations, different only downstream from the diffuser throat, are given in Figure 7. (The Reynolds number based on tunnel width for the comparable case free of air condensation is about 3.4×10^6). The arrangement with the second diffuser plates parallel gives a slightly better recovery for the larger diffuser throat openings. No significant improvement is obtained when the angle between the second plates is increased to 1° to allow for boundary-layer growth. Recovery is also practically unaffected if the angle between the third plates is increased from 3° to 12°.

19. It appears that the configuration beyond the diffuser throat has no significant effect on the pressure recovery. This indicates that the important pressure ratio increase is already obtained in the converging section of the diffuser. In the present tests the length of the converging section could be changed by locating the throat at 3.62 or 6.64 calibers from the nozzle exit. These throat locations correspond to the first and second jack positions of Figure 4. The recovery comparison given in Figure 8 shows the optimum recovery is considerably better for the shorter converging section. The schlieren photographs in Figure 9 show that in this case the initial oblique shock is reflected twice before the flow enters the throat. Apparently this design criterion of two shock reflections optimizes pressure recovery while further shock reflections in a longer duct do not improve the recovery due to increasing viscous losses in the Reynolds number range of the tests (compare reference g).

20. During all tests it was found that small mechanical changes, such as different seals, slack in diffuser plate suspension, etc. affect the recovery appreciably. For one series of tests the third diffuser plates were free to move by about ± 1/16" and "rattled" during the run. The pressure recovery for this case was less than that for a "rattle-free" diffuser as seen on Figure 10.

21. Schlieren observations for the "rattle-free" case show a rapidly fluctuating flow in the diverging section of the diffuser. From noise measurements it is found that, as the diffuser throat area decreases towards the optimum, the predominant sound frequency increases from about 1,000 to 5,000 cycles per second.

22. After breakdown of supersonic flow is achieved, e.g. by closing the diffuser throat below the permissible minimum area, the noise frequency changes abruptly to about 10,000 cycles per second. Pressure distributions to be given later reveal that the final transition to subsonic flow occurs through an unsteady shock system as is to be expected from results of other investigators, (references e, f, g, i).

23. For a given Mach number and diffuser configuration, increasing the supply pressure improves the pressure recovery, (compare Figure 11

with Figure 7). Here the higher Reynolds number reduces the boundary layer thickness and relatively decreases the viscous losses. This also results in a smaller minimum running area as shown in Figure 12. These data show that for application of these results to larger tunnels at higher Reynolds numbers, better overall pressure ratios may be expected. Most data presented here were obtained at p_o - 10 atm to shorten the running time of the tests.

24. Spark schlieren photographs of the flow in the converging section of the diffuser for the optimum throat area at various supply pressures, are shown in Figure 13. Photographs of the shock system in the converging section of the diffuser for four throat areas are shown in Figure 14. As the first plate angle decreases the number of shock reflections traversing the flow decreases, thus lowering the pressure recovery.

Pressure distribution.

25. A static pressure survey along the centerline of the tunnel side wall for the optimum diffuser throat area is shown in Figure 15. The overall pressure ratio was set at a value where supersonic flow could be just maintained in the test section. Beyond the nozzle exit the pressure decreases slightly as a result of the diverging flow in the wedge nozzle. The pressure then increases through oblique shock waves (compare Figure 13) up to the diffuser throat where the flow is still supersonic. The transition from supersonic to subsonic flow occurs just beyond the diffuser throat. (Breakdown occurs when this transition moves into the diffuser throat.) A similar survey for a diffuser throat area large enough to start the tunnel is given in Figure 16.

26. In comparison to a diffuser with parallel or nearly parallel throat plates, a single peak diffuser is simpler to construct, is shorter and provides approximately equal pressure recoveries. For hypersonic tunnels operating at high-supply temperatures, it offers an additional advantage. Such tunnels exhibit maximum rates of heat transfer from the flow to the wall at the nozzle (first) throat and also at the diffuser (second) throat. To operate continuously, cooling systems must be installed at these points and a short, single peak diffuser presents smaller overall cooling requirements.

27. The broken 1" thick windows shown in Figure 17 are examples of the effect of this localized heat transfer near the diffuser throat. Prior to the breaking, the tunnel ran roughly 5 minutes at $M = 7.2$, $p_o = 21$ atm and $T_o = 330^\circ C$ with the diffuser throat area at the optimum setting. In both cases the cracks in the glass originated near the diffuser throat.

28. The pressure recoveries for Mach numbers 5.88 and 8.49 are given in Figures 18 and 19. As the Mach number increases the overall pressure ratio required to maintain supersonic flow increases greatly. However, again the recovery in terms of pitot pressure remains nearly constant.

29. A further check at Mach number 9.6 gives a minimum overall running pressure ratio of 142. This corresponds to 1.9 times pitot recovery.

VI. TUNNEL STARTING REQUIREMENTS

30. The overall pressure ratios required for starting supersonic flow, free of air condensation, in the test section for various diffuser throat areas are given in Figure 20 ($M = 7.2$, $T_o = 330C$). The minimum starting area shown as a vertical dashed line is roughly three times the minimum running area. However, for all areas larger than this minimum, there is little difference between the pressure ratio required for starting supersonic flow and the pressure ratio required to maintain supersonic flow. The optimum starting pressure ratio (at an area slightly greater than the minimum) is somewhat lower than the pitot pressure ratio.

31. Figure 21 gives a comparison between "fast" and "slow" starts for $M(p_o'/p_o) = 7.2$. A "fast" start refers to the case where there is sufficient mass and overall pressure ratio available to start the tunnel quickly by opening a valve (within 1/500 sec), while a "slow" start means a start achieved by slowly increasing the overall pressure ratio until steady supersonic flow is established. No difference in the minimum starting area or in the starting pressure ratio could be found in these two tests.

32. During starting of the tunnel, a supersonic jet detaches from the nozzle walls and passes into the diffuser. Spark schlieren photographs, (see Figure 22), show the jet in an unsymmetrical position in the test section (compare with photographs in reference j). When a certain area ratio or pressure ratio is reached, the jet suddenly occupies the whole test section and steady supersonic flow is established.

33. The starting requirements for $M(p_o'/p_o) = 8.49$ are given in Figure 23. As in the previous cases, there is little difference between the starting pressure ratio and the running pressure ratio for the same diffuser throat area.

34. The optimum starting pressure ratios and the pitot pressure ratios for the range of Mach numbers tested are given in Figure 24. In all cases the tunnel can be started at a lower pressure ratio than the pitot pressure ratio. The minimum starting area ratios are compared

to the minimum running area ratios in Figure 25 for this same range of Mach numbers.

35. Tests with other diffuser configurations showed no noticeable difference in the minimum starting area. The change in the starting pressure ratios corresponded to the change in recovery pressure.

VII. COMPARISON WITH OTHER DIFFUSERS

36. In Figure 26 optimum pressure recoveries of four closed jet tunnels are given in terms of pitot pressure. This recovery increases up to M = 7.2. (The drop at the two highest Mach numbers might be due to the relative decrease of Reynolds number or the increasing departure from optimum first diffuser plates length.) However, the pressure recovery in terms of supply pressure decreases greatly as Mach number increases. Figure 27 gives the inverse overall optimum running pressure ratio for the same tunnels. To every Mach number one may also read test section and pitot pressure. Although the diffuser recovers about 100 times the test section pressure at the higher Mach numbers, the final diffuser pressure is only about 1/100 of the supply pressure. Figure 28 finally gives "efficiency" values as defined on the graph. The three previous figures show that at the higher Mach numbers no significant performance difference exists between the diffusers compared.

37. Figures 29 and 30 compare starting data from several tunnels with the simple one-dimensional non-viscous theory. (Compare reference a). The minimum diffuser throat area and minimum overall pressure ratio needed for starting are calculated assuming that a "normal" shock at test section Mach number must be "swallowed" by the diffuser. It can be seen from Figure 30 that the tunnel will start at one-half the predicted swallowing diffuser throat area. If the starting were correctly described by the above theory then an actual diffuser, with viscosity entering the picture, should only start at larger areas than predicted. Since this is not the case, one must assume that a system of oblique shocks is built up during starting. Therefore, as shown on Figure 29, the starting pressure ratios are even slightly smaller than the pitot pressure ratio although viscous effects (compare Figure 22) must play an important role in the actual process.

VIII. SUMMARY

38. A diffuser investigation carried out in the NOL 12 x 12 cm continuous Hypersonic Tunnel No. 4 in the Mach number range from 5.9 to 9.6 is described. It is first shown that air condensation does not affect diffuser performance. A detailed investigation of a number of diffuser configurations and diffuser throat positions resulted in the following observations:

39. A single peak, plane wall, variable area diffuser with converging plates of 3.6 calibers length (one caliber equals nozzle exit width) and a 3° plane wall divergence aft of the throat gives optimum performance at $M = 7.2$. The pressure recovery ranges up to 2.3 times that of a pitot tube measured at equal Mach number. In the range of Mach numbers investigated, pressure recovery is never below 1.8 times that of a pitot tube. It is found that a parallel wall center portion of the diffuser does not significantly improve efficiency, but lengthens the diffuser undesirably. Detailed data on all configurations, pressure distribution measurements, and spark schlieren photographs of the flow in the test section and diffuser are given. The effect of increasing Reynolds number, resulting in decreasing minimum diffuser throat area, is demonstrated. Comparisons with other high efficiency diffusers and the one-dimensional theory are given.

40. An investigation of starting overall pressure requirements was also carried out. It is shown that if the diffuser is closed to an empirically determined minimum starting throat area, the tunnel can at all Mach numbers be started at an overall pressure ratio about equal to that of pitot to supply pressure for the same Mach number. The minimum starting diffuser throat is considerably smaller than that predicted by one-dimensional theory and the comparatively low starting pressure ratios required eliminate costly power plant additions for the momentary attainment of extreme pressure ratios.

41. The effect of a model and support on pressure recovery will be discussed in a forthcoming report.

IX. NOTATION

42. The symbols used represent the following physical quantities (see sketch on page 13)

M_s	Mach number setting from nozzle area ratio
$M(p_o'/p_o)$	Mach number determined from measured pitot pressure, using isentropic flow tables, reference (q) (insensitive to air condensation)
T_o	supply temperature
p	static pressure
p_{∞}	static pressure at nozzle exit
p_o	supply pressure
p_o'	pitot pressure
p_{sp}	diffuser end pressure
p_e	p_{sp} when supersonic flow breaks down in test section
A	test section area
A^*	nozzle throat area
D^*	diffuser throat area
β	total angle between second diffuser plates
φ	total angle between third diffuser plates

Note: Jacks 1 and 2 move together so that angle β remains constant for all D^*. The angle is adjusted by offsetting one set of jacks before the test begins.

X. REFERENCES

(a) Ferri, A., "Elements of Aerodynamics of Supersonic Flows," The MacMillan Company, New York, 1949

(b) Liepmann, H. W. and A. E. Puckett, "Introduction to Aerodynamics of a Compressible Fluid," Galcit Aeronautical Series, John Wiley and Sons, Inc., New York, 1947

(c) Oswatitsch, K., "Zeutrale fuer wissenschaftliches Berichtswesen," Report No. 1005, 1944

(d) Kurzweg, H. H., "A Few Aspects of Future Supersonic Wind-Tunnel Design and Test Techniques," U. S. Naval Ordnance Laboratory NOLR 1133, 29 June 1949

(e) Diggins, J. L., "Diffuser Investigation in a Supersonic Wind Tunnel," U. S. Naval Ordnance Laboratory NAVORD Report 1570, 3 January 1951

(f) Neumann, E. P. and F. Lustwerk, "High Efficiency Supersonic Diffusers," Jour. of the Ae. Sci. 18, No. 6, pp 369, June 1951

(g) Diggins, J. L. and A. H. Lange, "An Improved Diffuser for Supersonic Wind Tunnels," U. S. Naval Ordnance Laboratory NAVORD Report 2421, in preparation

(h) Bertram, M. H., "Investigation of the Pressure-Ratio Requirements of the Langley 11-inch Hypersonic Tunnel with a Variable-Geometry Diffuser," NACA RM L 50 I 13, Oct. 6, 1950, Declassified, NACA Change in Classification Form No. 750, 21 March 1952

(i) Kantrowitz, A., "The Formation and Stability of Normal Shock Waves in Channel Flows," NACA TN No. 1225, March 1947

(j) Bull, G. V., "Starting Processes in an Intermittent Supersonic Wind Tunnel," Institute of Aerophysics, University of Toronto, UTIA Report No. 12, February 1951

(k) Hermann, R., "Diffuser Efficiency and Flow Process of Supersonic Wind Tunnels with Free Jet Test Section," USAF Air Materiel Command, AF Technical Report No. 6334, December 1950

(l) Hermann, R., "Diffuser Efficiency of Free Jet Supersonic Wind Tunnels at Variable Test Chamber Pressure," IAS Preprint No. 349, Presented at IAS Meeting, 28 January, 1 February 1952, New York

(m) Wegener, P., S. Reed, E. Stollenwerk, and G. Lundquist, "NOL Hyperballistic Tunnel No. 4 Results I: Air Liquefaction," U. S. Naval Ordnance Laboratory NAVORD Report 1742, 4 January 1951

(n) Wegener, P., S. Reed, E. Stollenwerk, and G. Lundquist, "Air Condensation in Hypersonic Flow," Jour. of Appl. Phys., Vol. 22, No. 8, pp 1077, August 1951

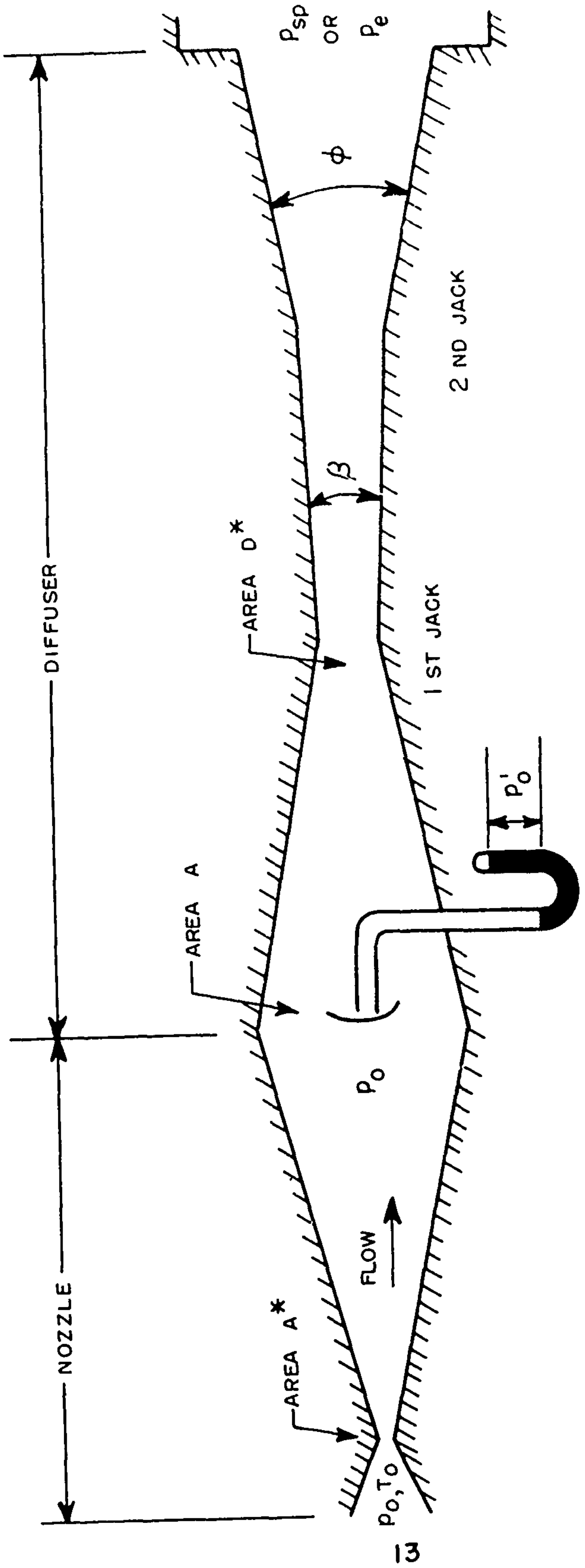
(o) Wegener, P., "Hyperballistic Wind Tunnel Research at NOL," Bureau of Ordnance Symposium on Aeroballistics at the University of Texas, November 1950

(p) Wegener, P., "Summary of Recent Experimental Investigations in the NOL Hyperballistics Wind Tunnel," Jour. of the Ae. Sci., Vol. 18, No. 10, pp 665, October 1951

(q) Burcher, M. A., "Compressible Flow Tables for Air," NACA TN No. 1592, August 1948

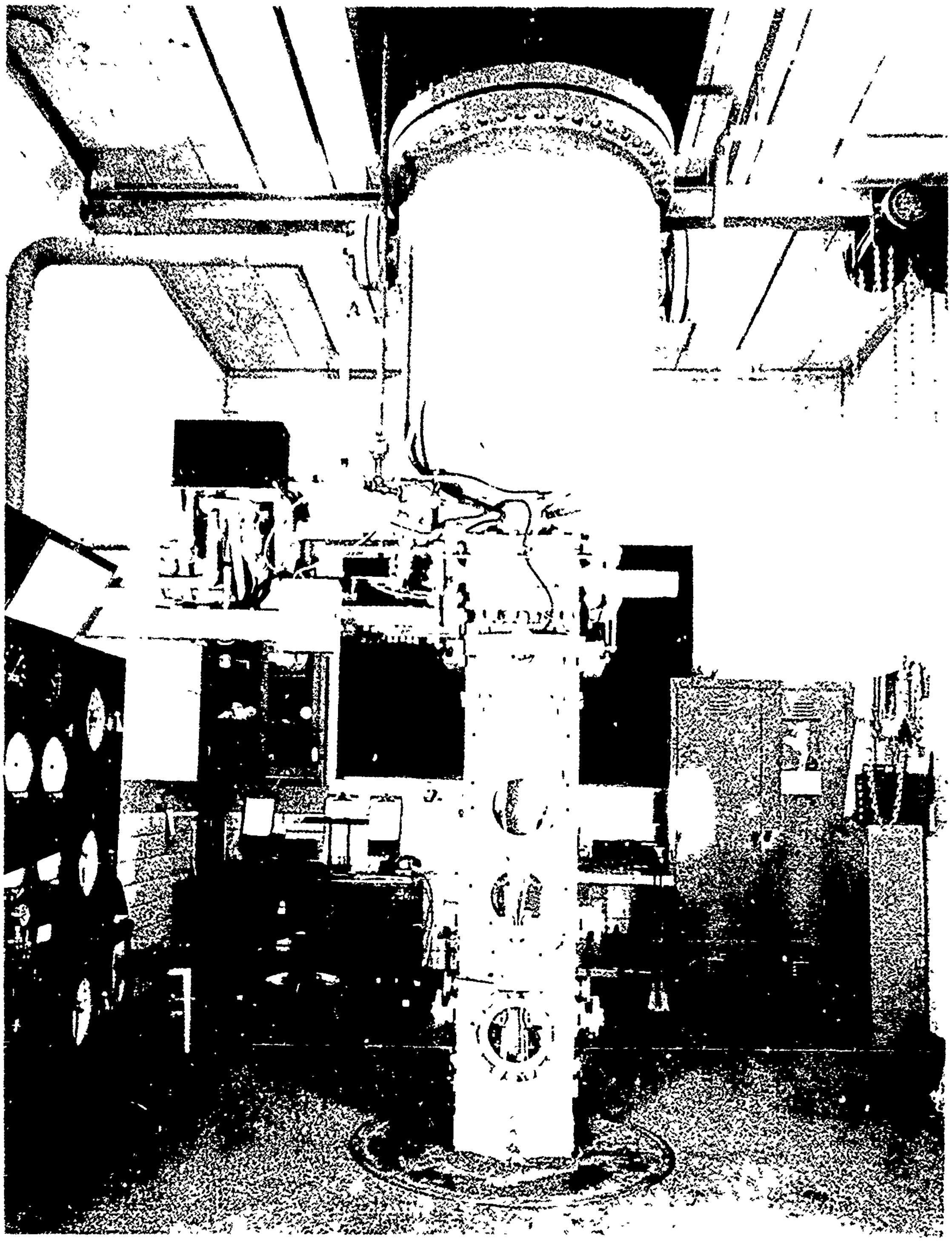
(r) Eggink, H., "Stroemungsaufbau und Druckrueckgewinnung in Ueberschallkanaelen," Forschungsbericht No. 1756, ZWB 1943. English translation by the University of Michigan: Flow Structure and Pressure Recovery in Supersonic Tunnels, ATI 3570, CGD 808

(s) Neumann, E. P., F. Lustwerk, "Supersonic Diffusers for Wind Tunnels," Jour. of Applied Mechanics, Vol. 16, No. 2, pp 195, June 1949



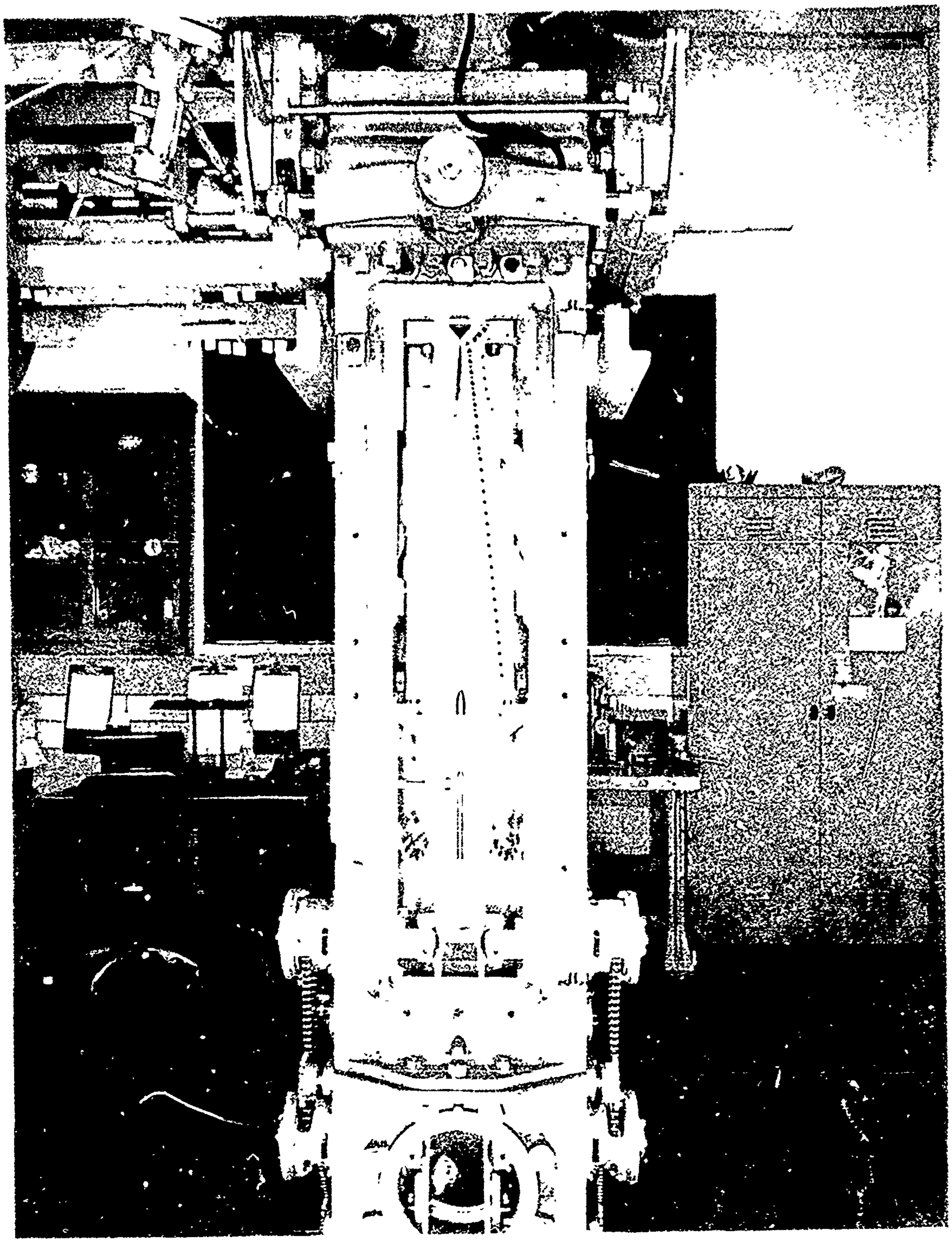
SKETCH SHOWING NOTATION USED

FIG. 1



NOL 12X12 CM HYPERSONIC WIND TUNNEL No. 4

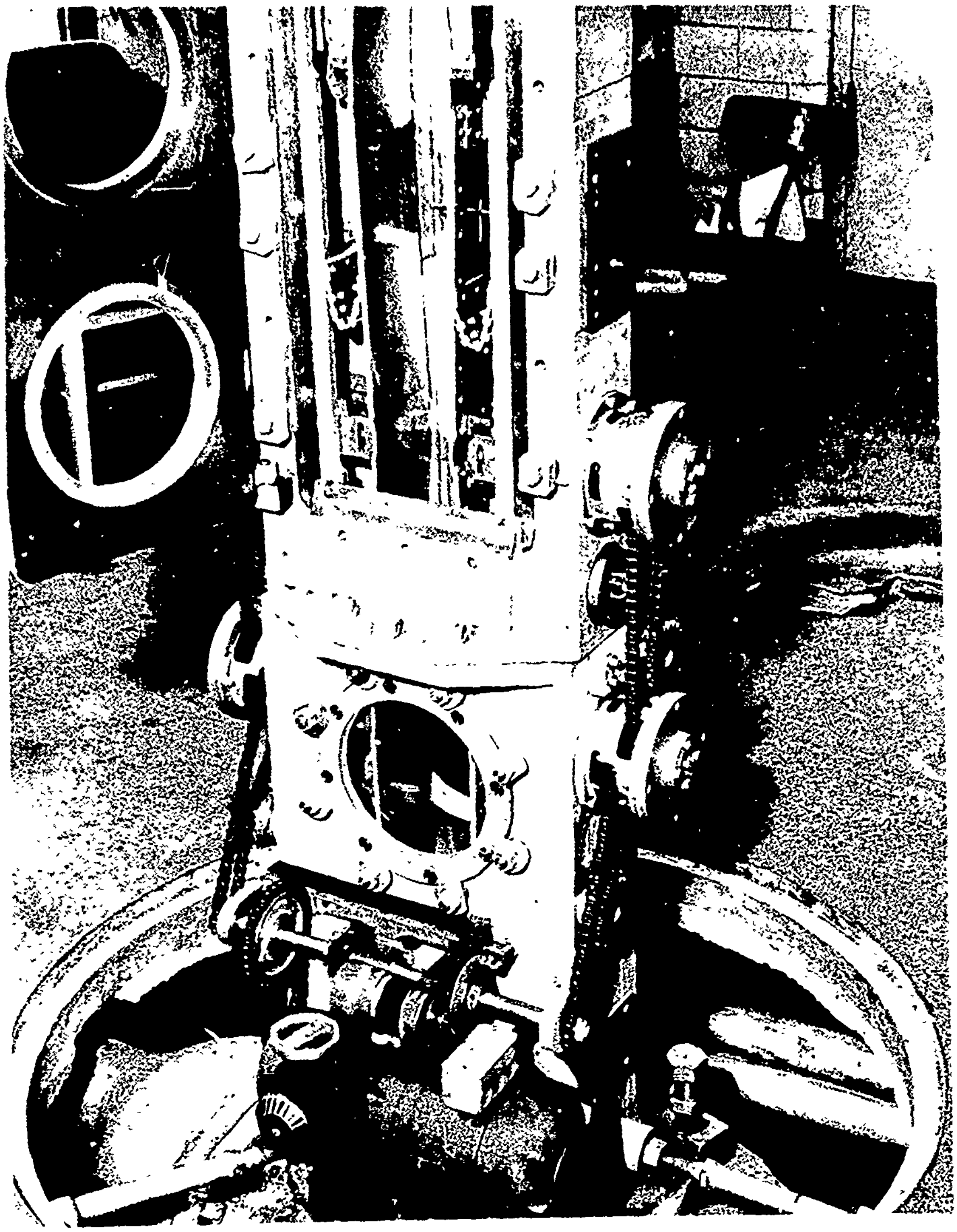
FIG. 2



NOL 12X12 CM HYPERSONIC TUNNEL No. 4
(COOLING SYSTEM EXPOSED ON ONE SIDE)

WEDGE NOZZLE AND ADJUSTABLE DIFFUSER

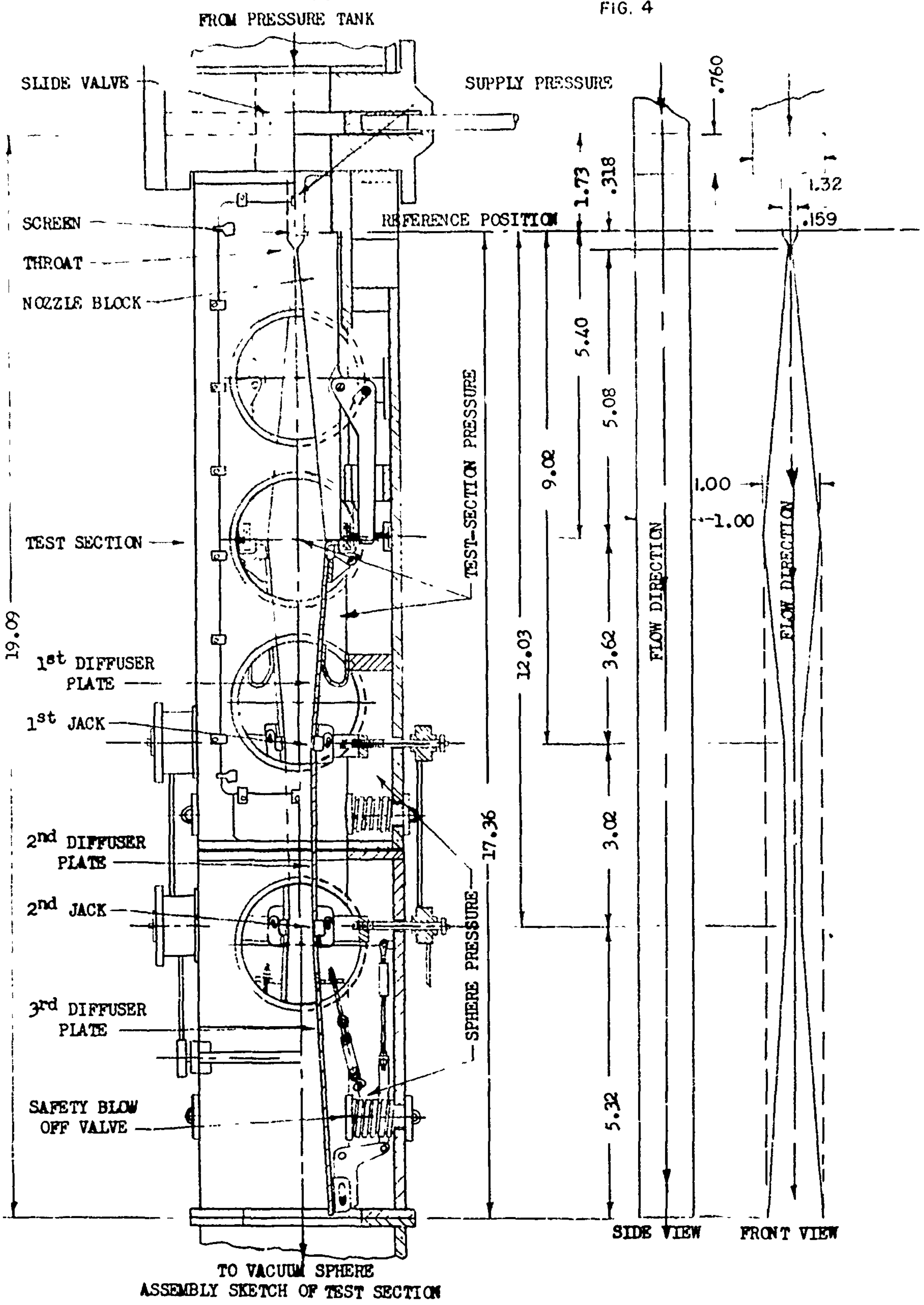
FIG. 3



NOL 12X12 CM HYPERSONIC TUNNEL No. 4

DIFFUSER CONTROL MECHANISM

FIG. 4



SCHEMATIC LAYOUT OF NOL HYPERSONIC TUNNEL NO. 4
(All dimensions in calibers: 1 caliber = 12 cm)

SCHLIEREN PHOTOGRAPHS OF "HOT AND COLD" DIFFUSER FLOW
$M(p_0'/p_0) = 7.2$

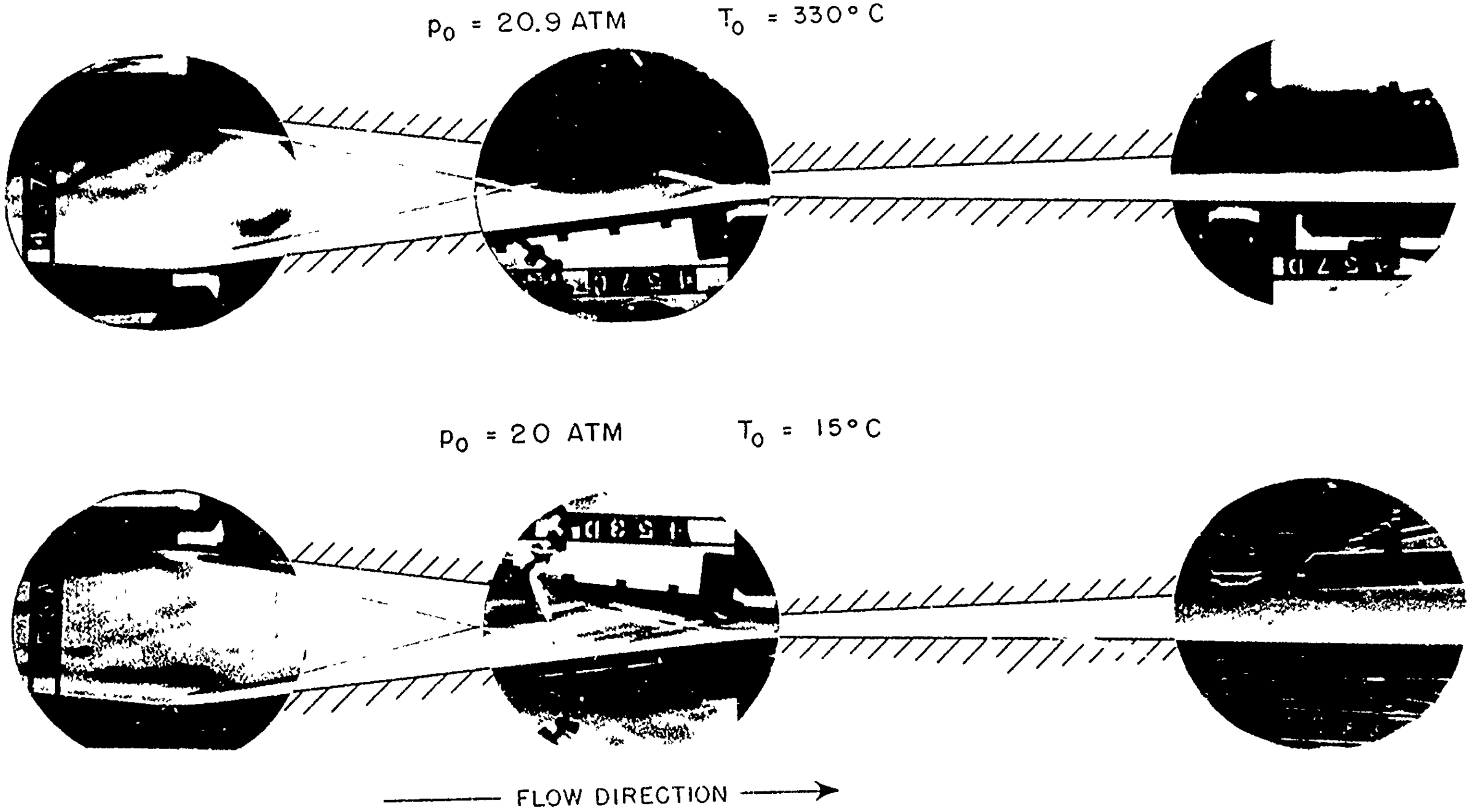


FIG. 6

COMPARISON OF "HOT" AND "COLD" PRESSURE RECOVERIES VS DIFFUSER AREA RATIO

(EMPTY TEST SECTION)

RUNS 440, 442, 452, 458

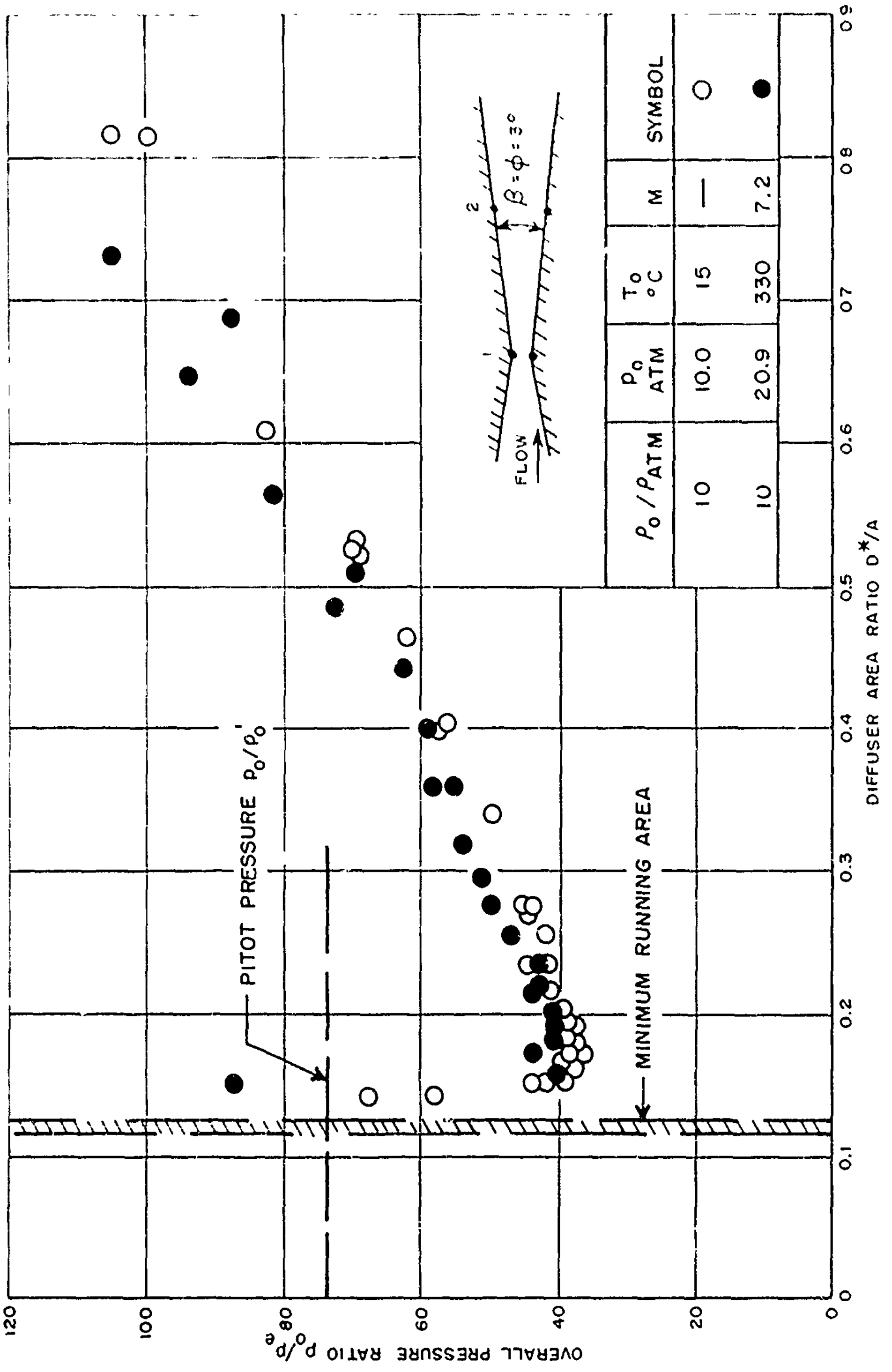


FIG. 7

COMPARISON OF PRESSURE RECOVERIES FOR THREE CONFIGURATIONS BEYOND FIRST DIFFUSER JACK (THROAT)

$M(p_o'/p_o)=7.2$, $p_o = 10$ ATM, $T_o = 15°C$, RUNS 440, 442-446, 452, 465

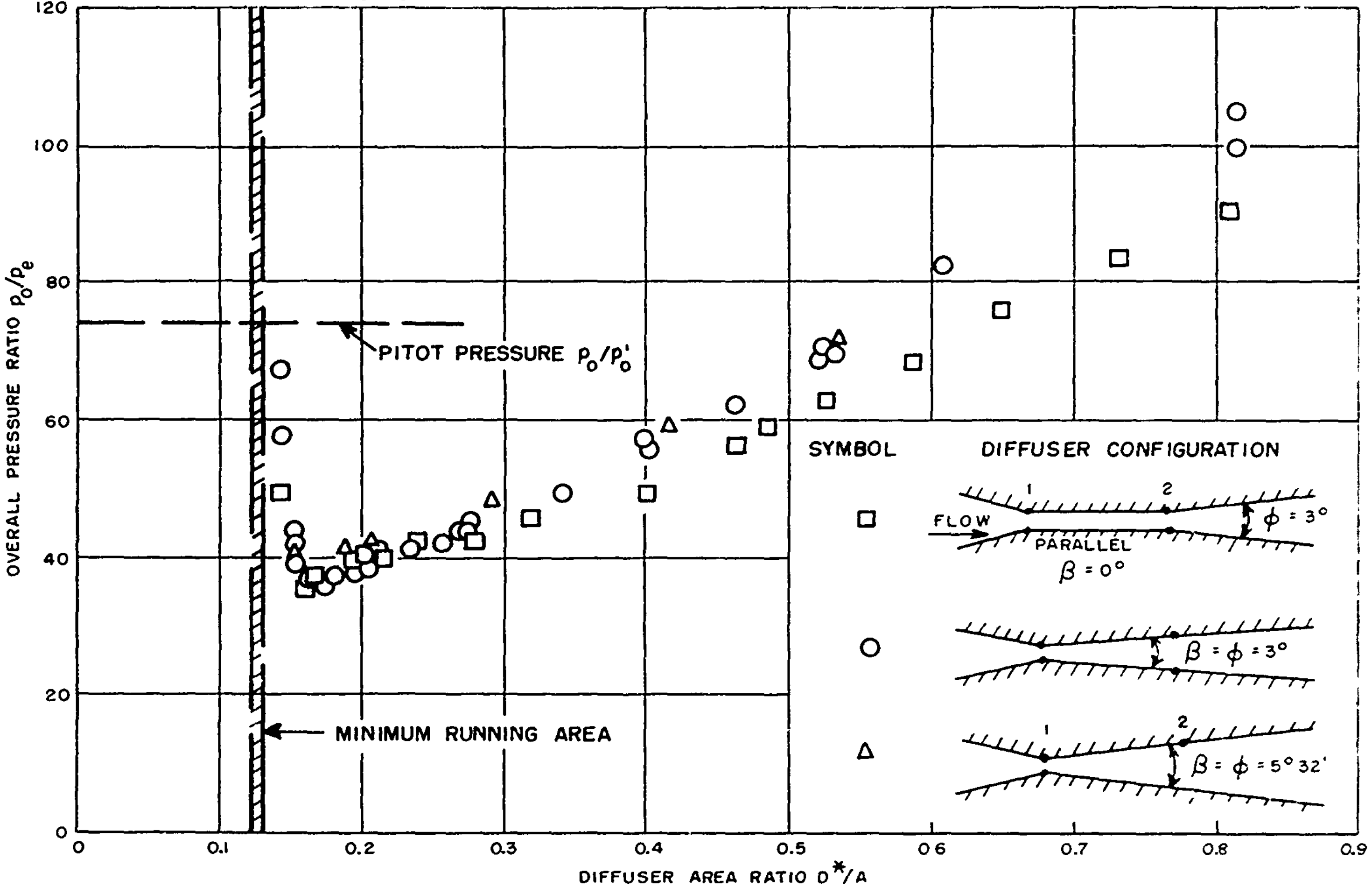


FIG. 8

PRESSURE RECOVERY VS DIFFUSER AREA RATIO
(FOR TWO DIFFUSER THROAT POSITIONS)

$M(p_0'/p_0) = 7.2$

$p_0 = 10$ ATM, $T_0 = 15°C$, RUNS 439, 440, 442, 452

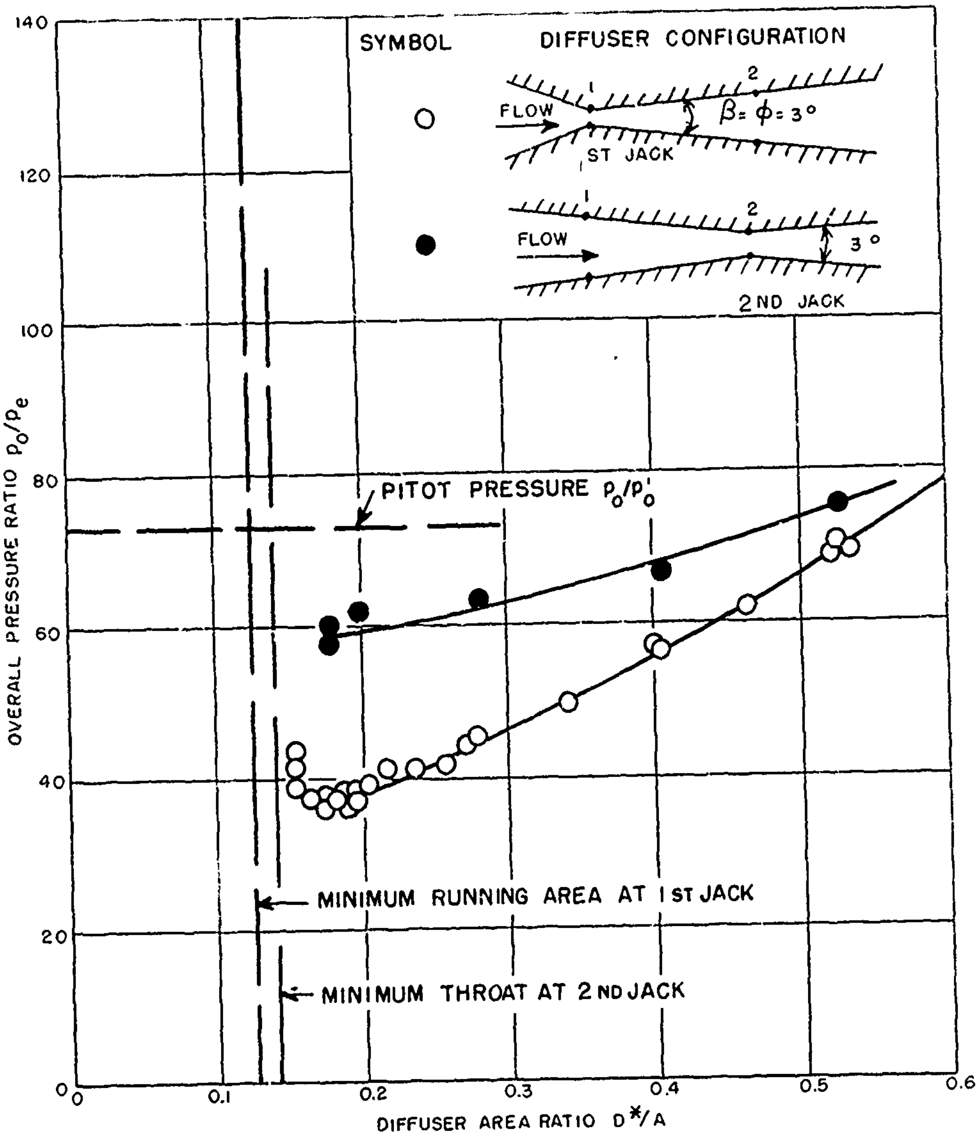
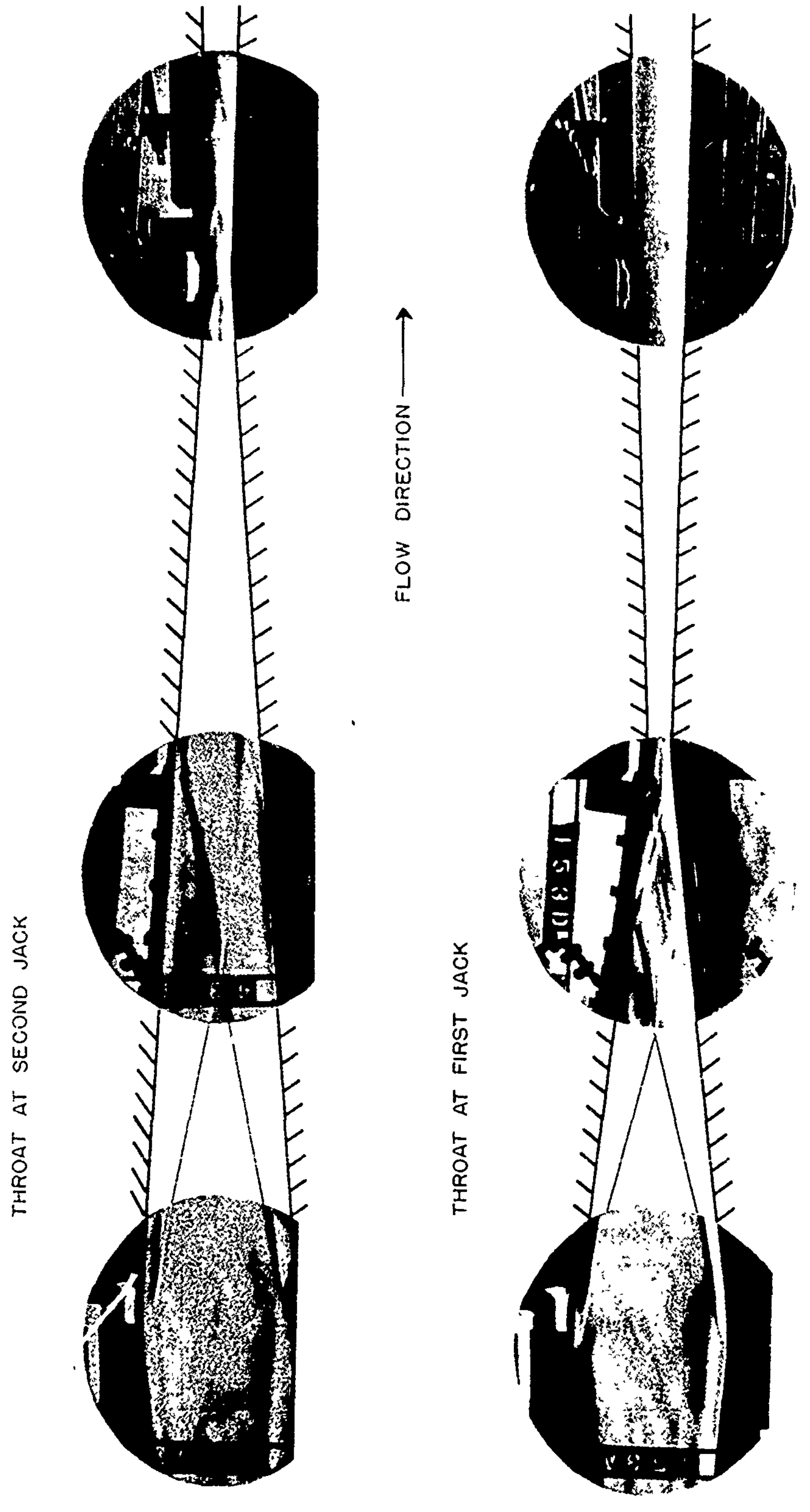


FIG. 9



SCHLIEREN PHOTOGRAPHS OF DIFFUSER FLOW

$M(p_0'/p_0) = 7.2,\ P_0 = 20$ ATM, $T_0 = 15°$ C

FIG. 10

EFFECT OF "RATTLING" DIFFUSER PLATES ON PRESSURE RECOVERY

$M\ (p_0'/p_0) = 7.2$

p_0 10 ATM, $T_0 = 15°C$, RUNS 427-430, 444

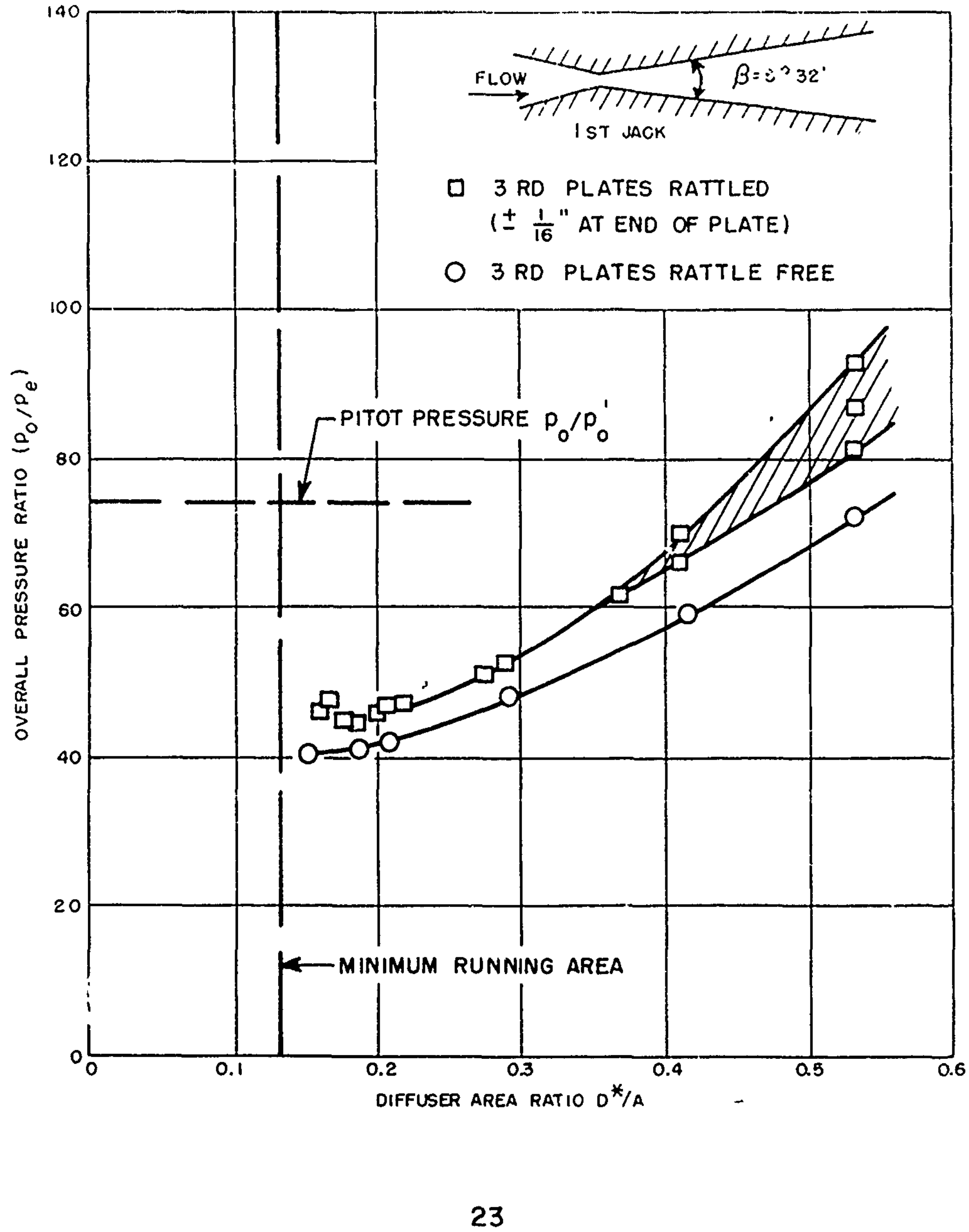


FIG. 11

PRESSURE RECOVERY VS DIFFUSER AREA RATIO

(EMPTY TEST SECTION)

$M(p_0'/p_0) = 7.22$

$P_0 = 20$ ATM, $T_0 = 15°$ C, RUN 453

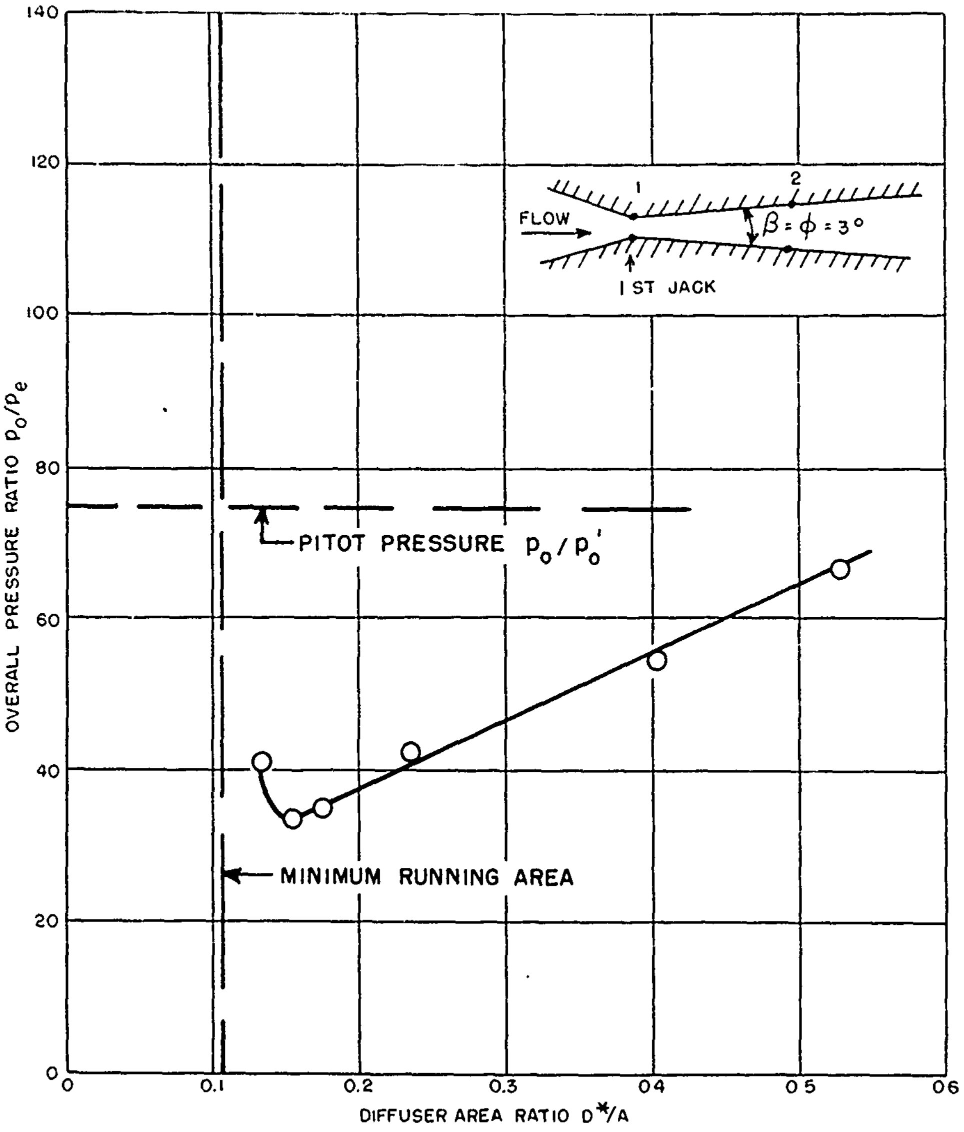
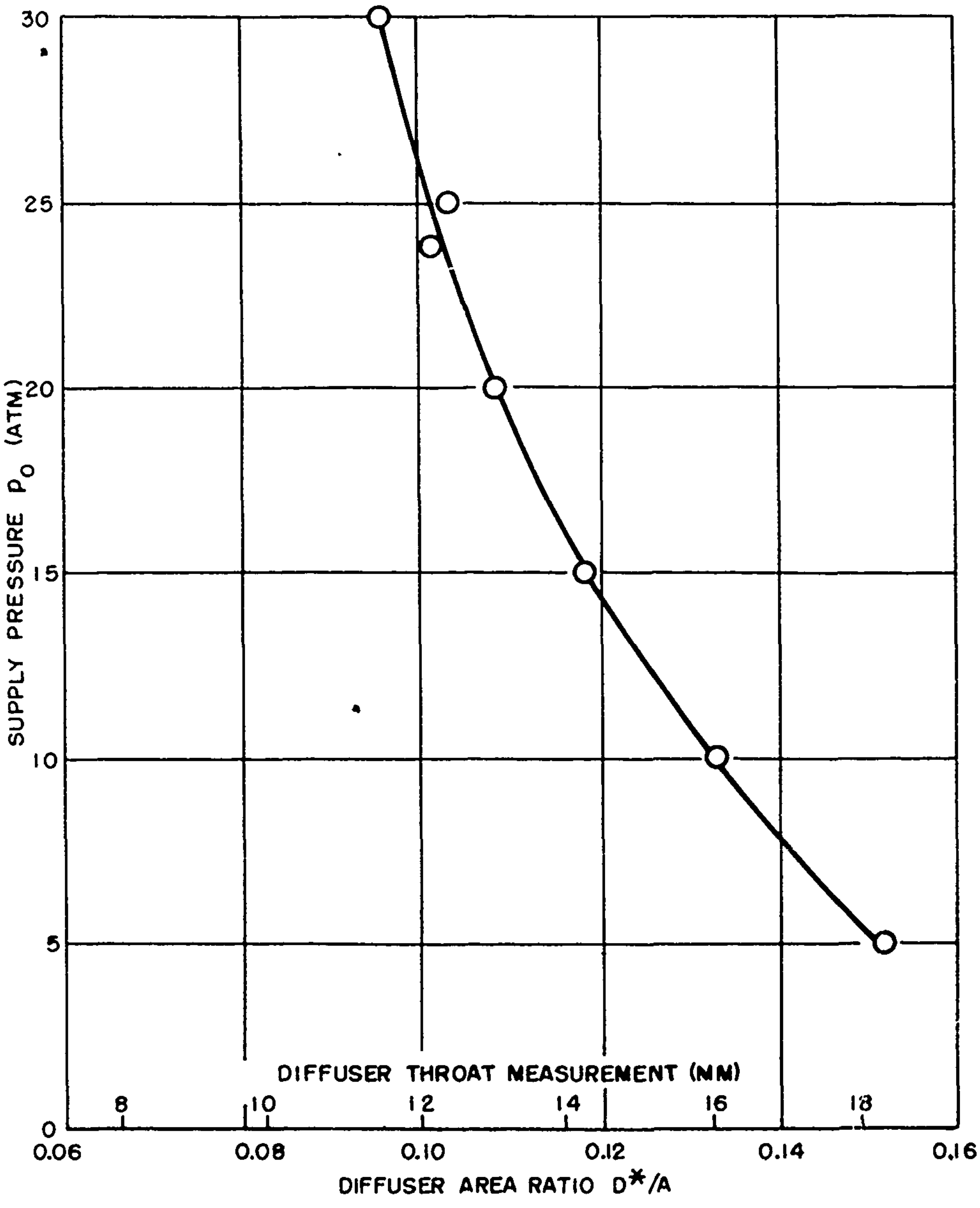


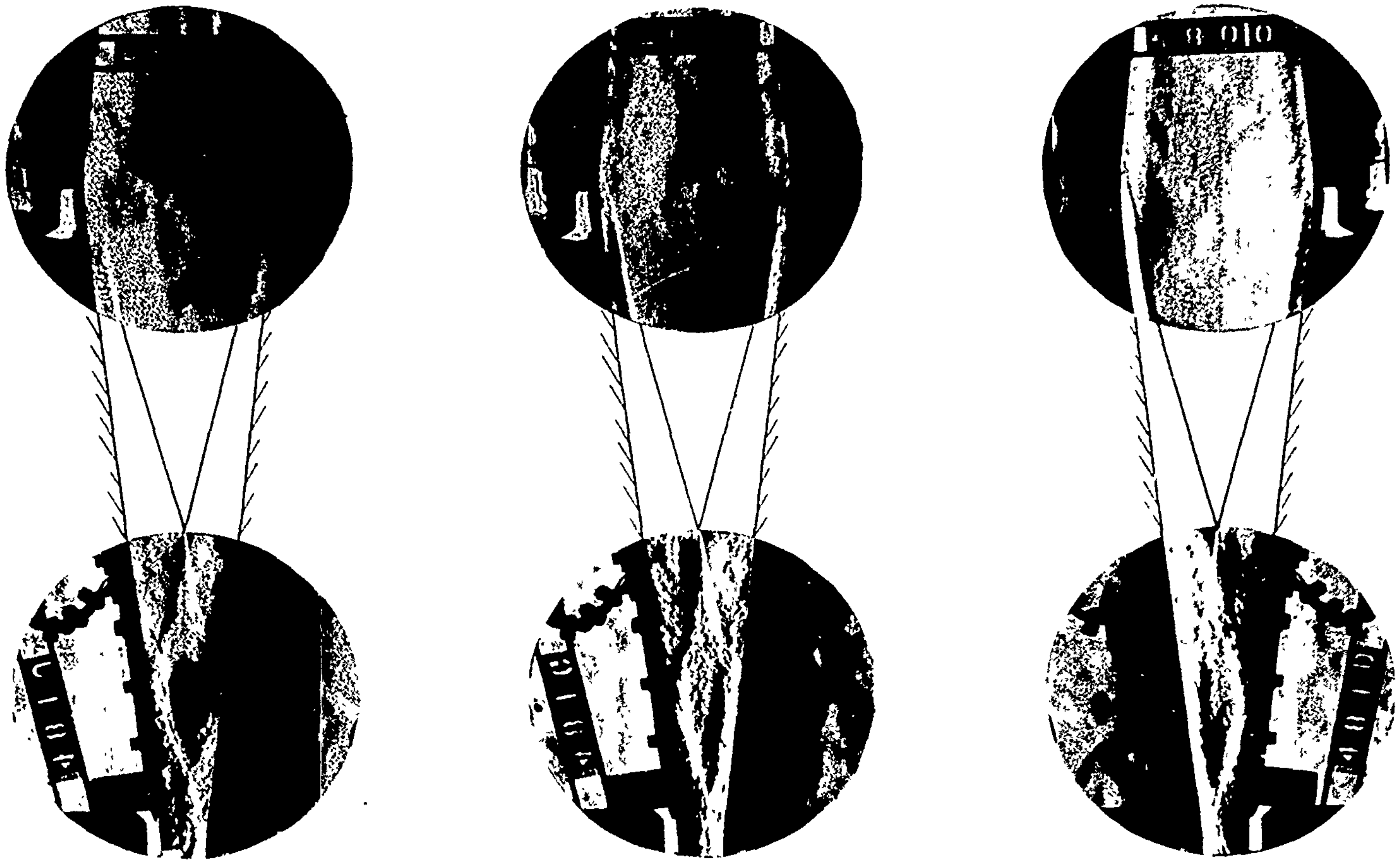
FIG. 12

MINIMUM RUNNING DIFFUSER AREA RATIO VS SUPPLY PRESSURE

$M(p_0'/p_0) = 7.2$

$T_0 = 16°C$, RUN 482





$p_0 = 5$ ATM

$p_0 = 15$ ATM

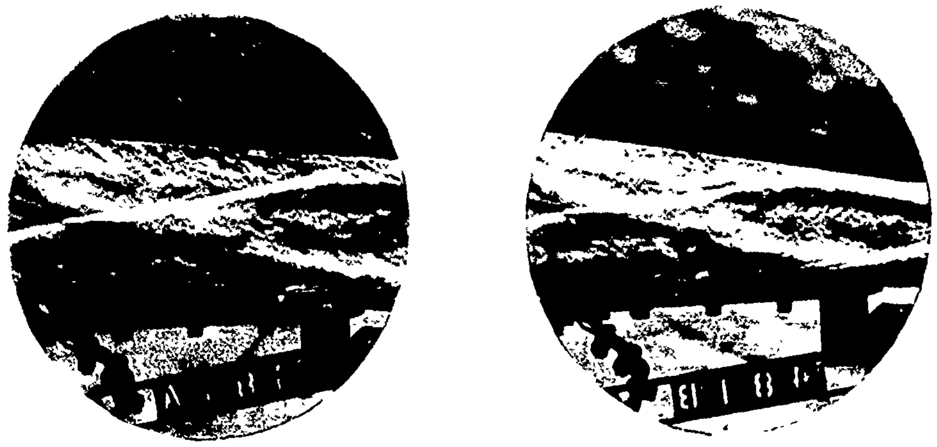
$p_0 = 30$ ATM

SCHLIEREN PHOTOGRAPHS OF FLOW IN CONVERGING SECTION OF DIFFUSER FOR THREE SUPPLY PRESSURES

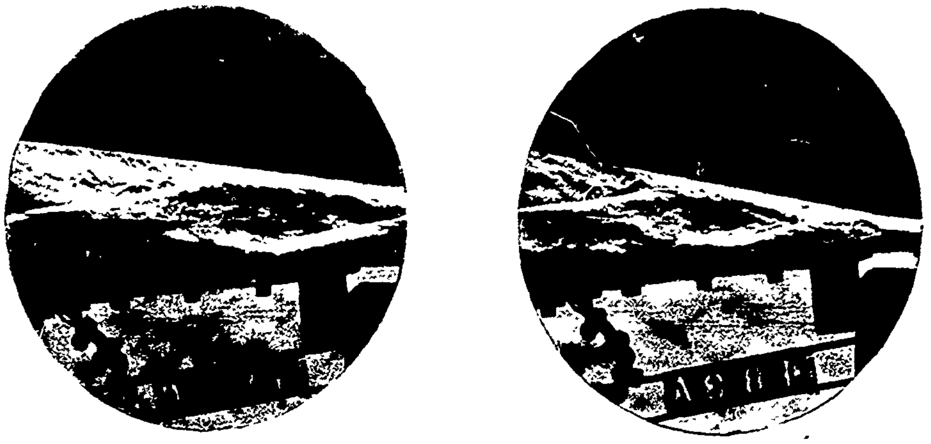
$M(p_0'/p_0) = 7.2$, $T_0 = 15°C$, $D^*/A = 0.20$ (OPT)

FIG. 14

DIRECTION OF FLOW ⟶



D*/A = 0.6 D*/A = 0.4



D*/A = 0.3 D*/A = 0.1 (MIN)

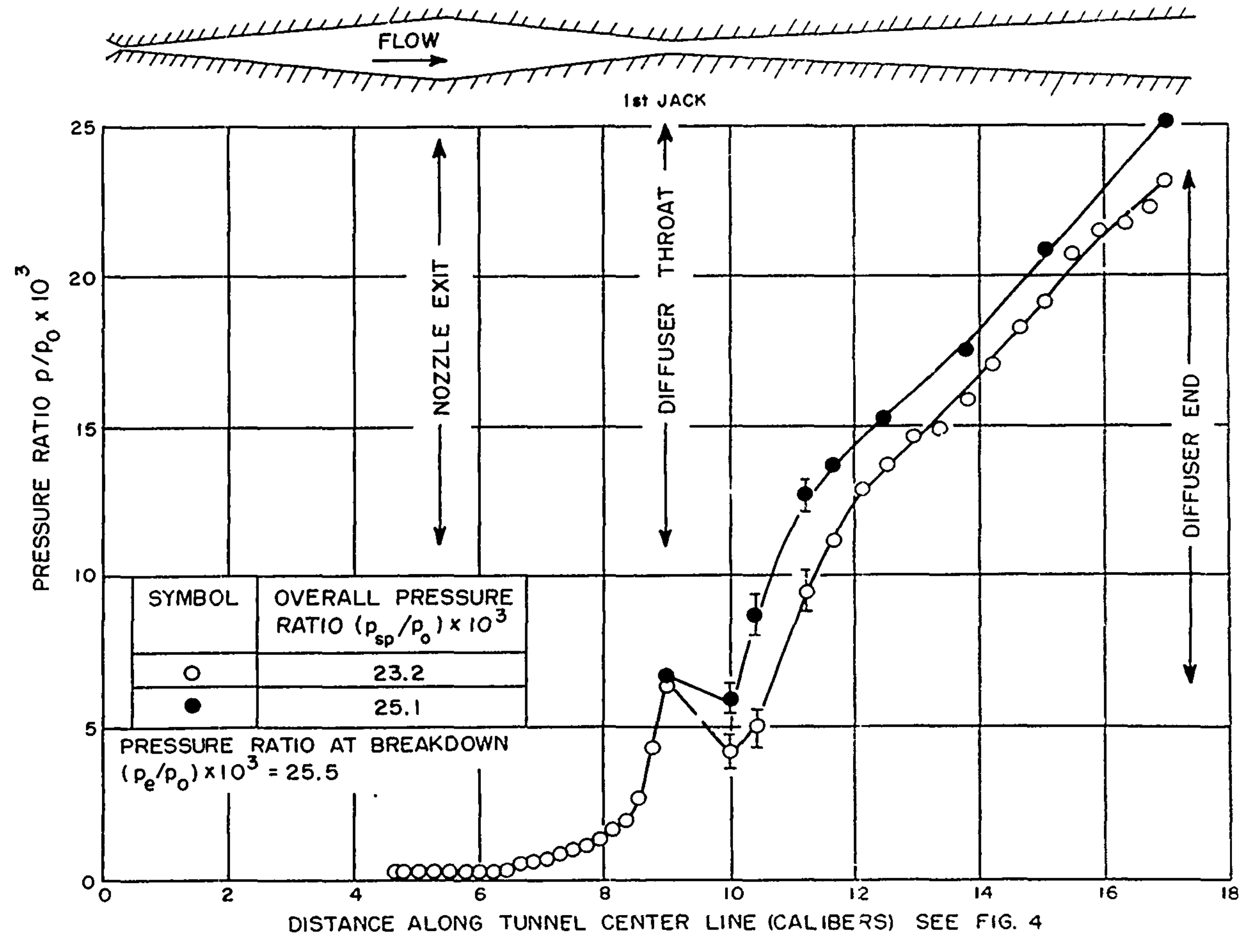
FLOW IN CONVERGING PART OF DIFFUSER
FOR FOUR DIFFUSER THROAT AREA RATIOS

$M(p_0'/p_0) = 7.2$

$p_0 = 30$ ATM, $T_0 = 15°C$

PRESSURE SURVEY ALONG CENTER LINE OF TUNNEL SIDEWALL $M = 7.2$, $D^{*}/A = 0.20$ (OPT)

$T_0 = 320°$ C, RUN 489, $p_0 = 20.9$ ATM



PRESSURE SURVEY ALONG CENTER LINE OF TUNNEL SIDEWALL $M = 7.2$, $D^{*}/A = 0.423$

OVERALL PRESSURE RATIO $(p_{sp}/p_0) \times 10^3 = 13.7$, $T_0 = 320°$ C, RUN 490, $p_0 = 20.9$ ATM

PRESSURE RATIO AT BREAKDOWN $(p_e/p_0) \times 10^3 = 16.3$

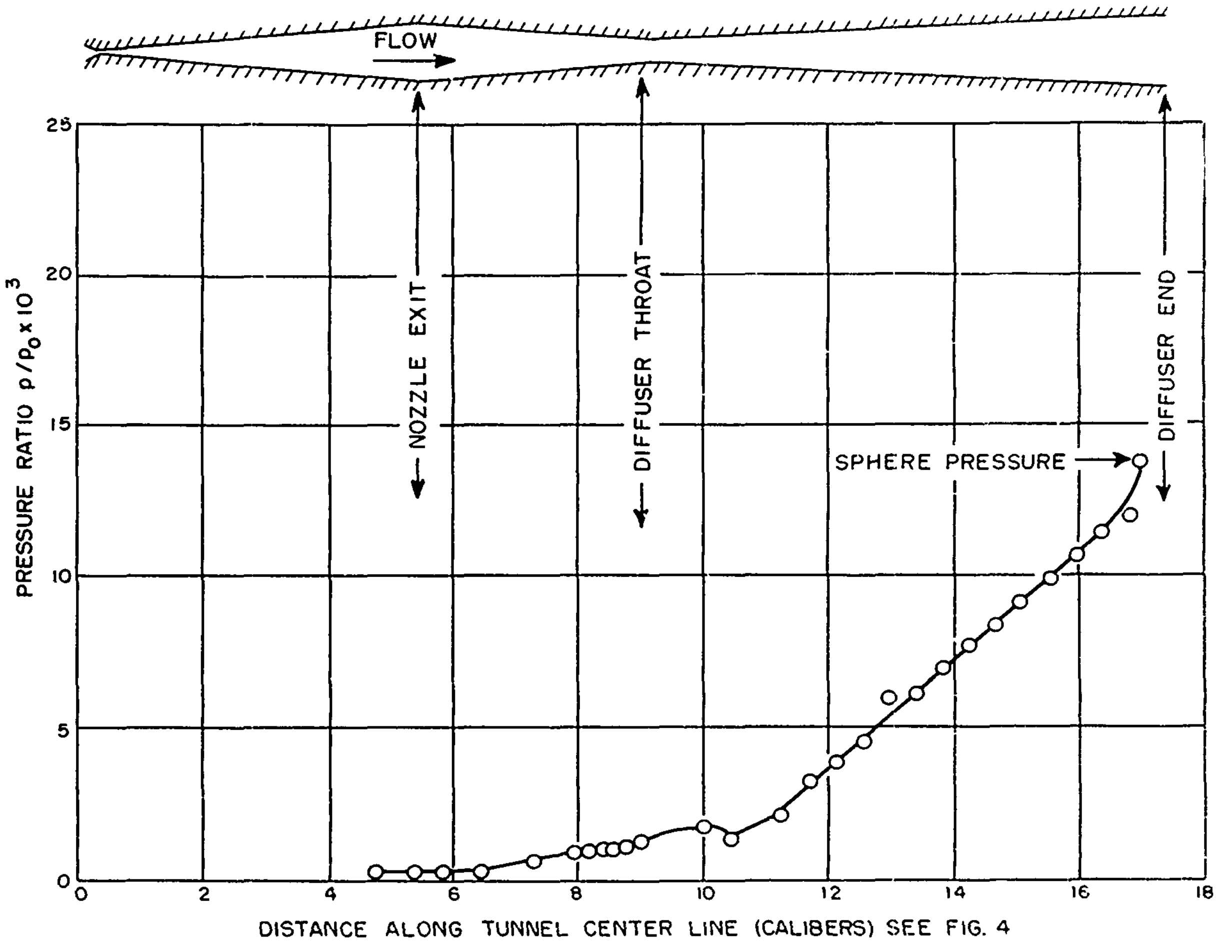
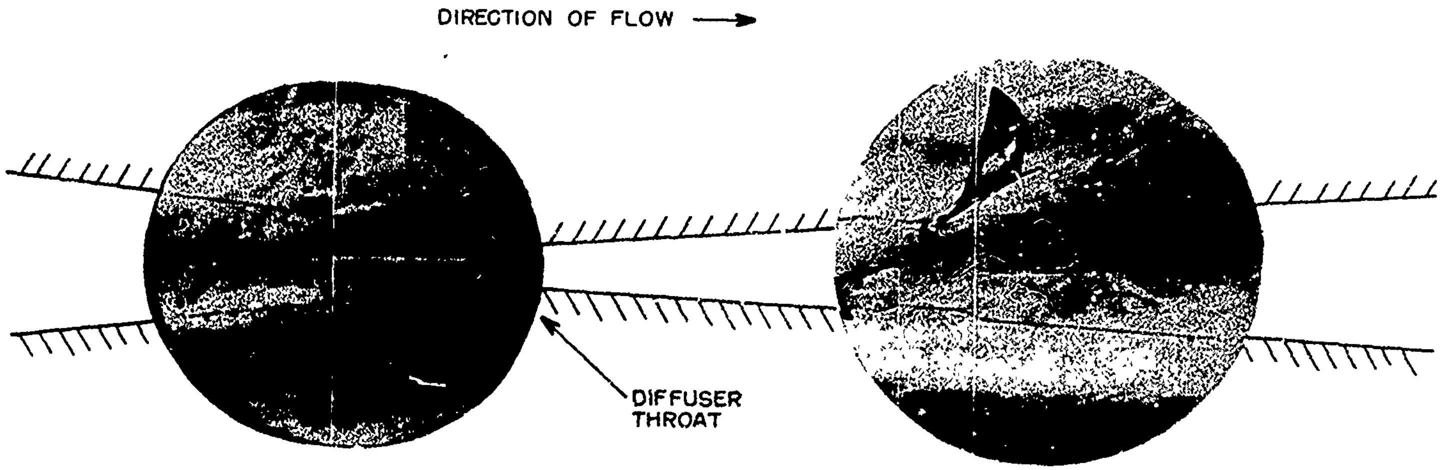


FIG. 17



GLASS WINDOWS BROKEN DURING A "HOT" RUN

$M(p_0'/p_0) = 7.2$, $p_0 = 21$ ATM., $T = 330°$ C, RUN 423

PRESSURE RECOVERY VS DIFFUSER AREA RATIO

FIG. 18

(HYPODERMIC PITOT TUBE IN TEST SECTION)

$M(p_0'/p_0) = 5.80$

$p_0 = 7.3$ ATM, $T_0 = 52°$ C, RUNS 350-355

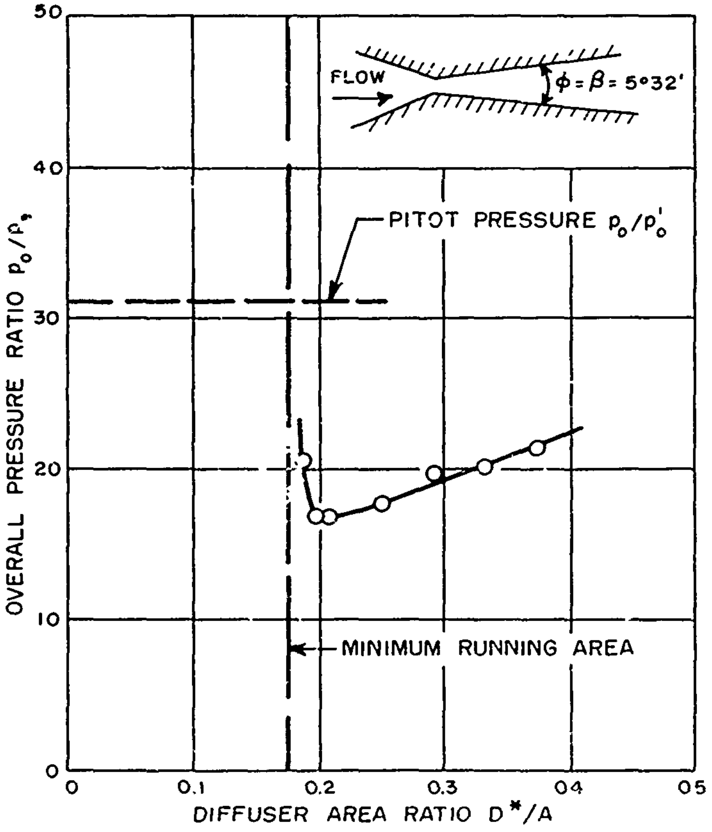


FIG. 19

(EMPTY TEST SECTION)

$M(p_0'/p_0) = 8.49$,

$p_0 = 30$ ATM, $T_0 = 16°$ C, RUNS 433, 434, 438

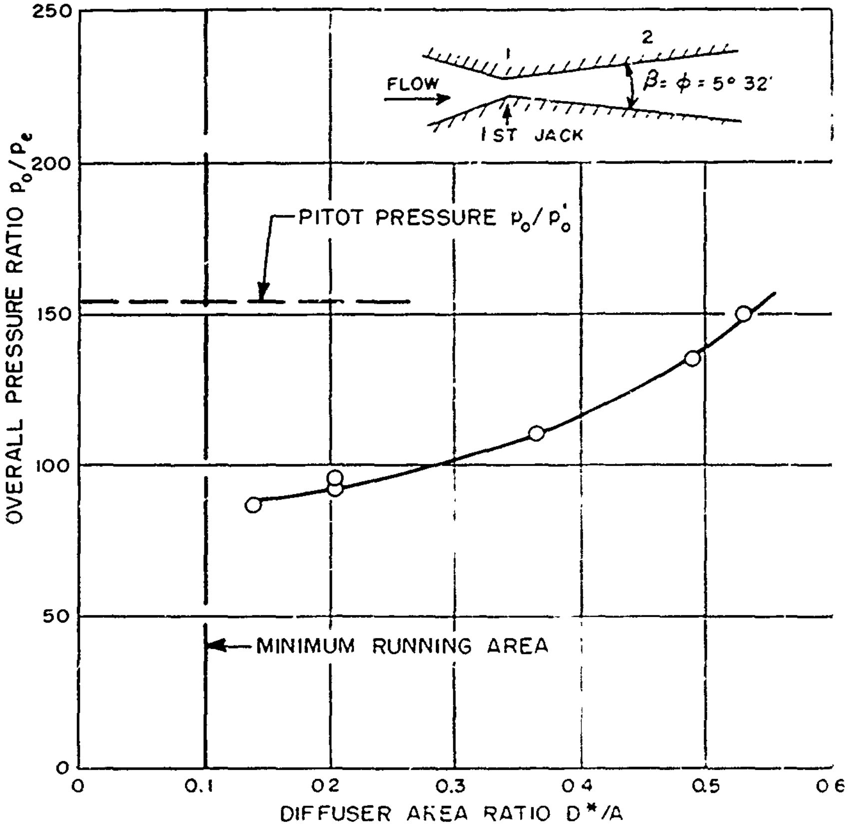
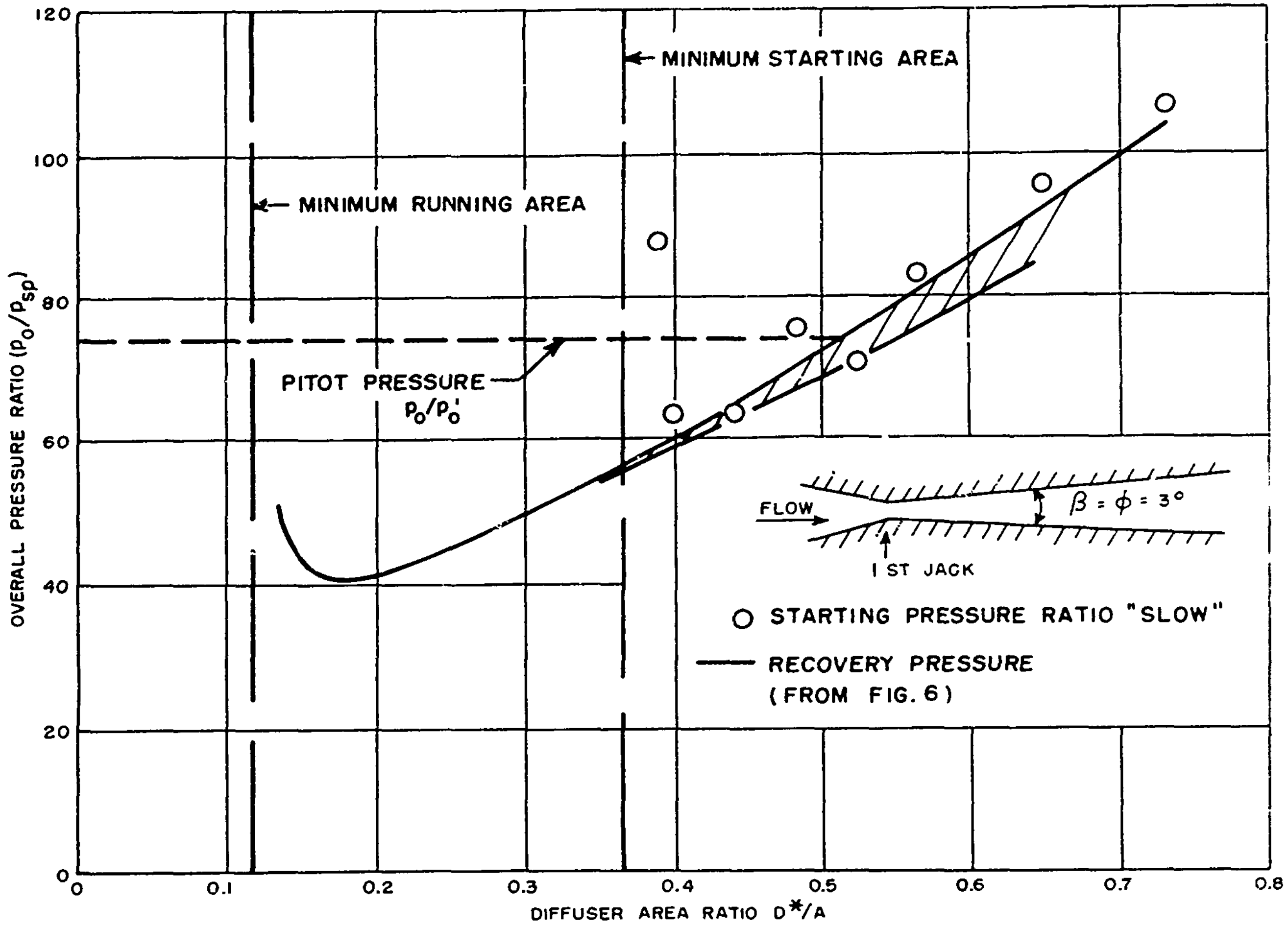


FIG. 20

STARTING PRESSURE RATIO VS DIFFUSER AREA RATIO "HOT"
(EMPTY TEST SECTION)

$M = 7.2$, $T_0 = 330°C$, $p_0 = 20.9$ ATM, $\rho_0/\rho_{ATM} = 10.0$, RUN 458



STARTING PRESSURE RATIO VS DIFFUSER AREA RATIO

(EMPTY TEST SECTION)

$M(p_0'/p_0)=7.2$

$p_0=10$ ATM, $T_0=15°C$, RUNS 440, 442, 452

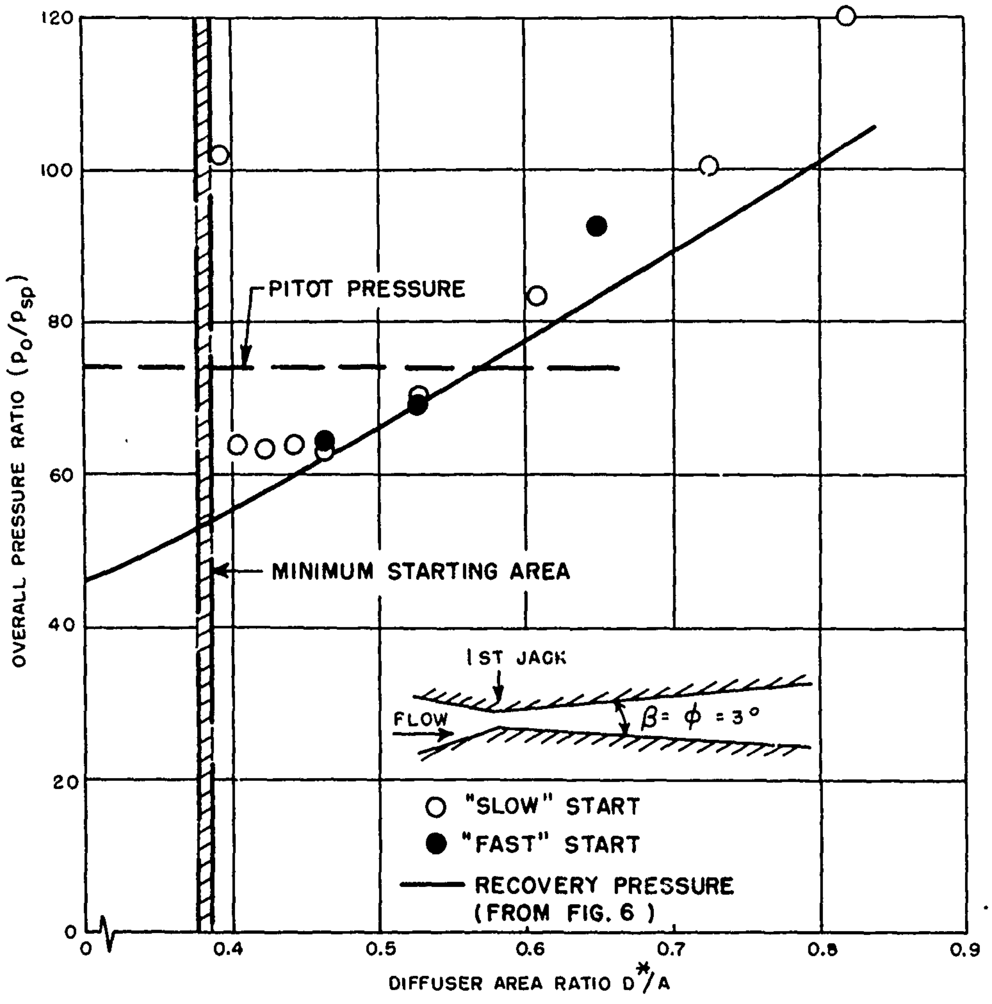
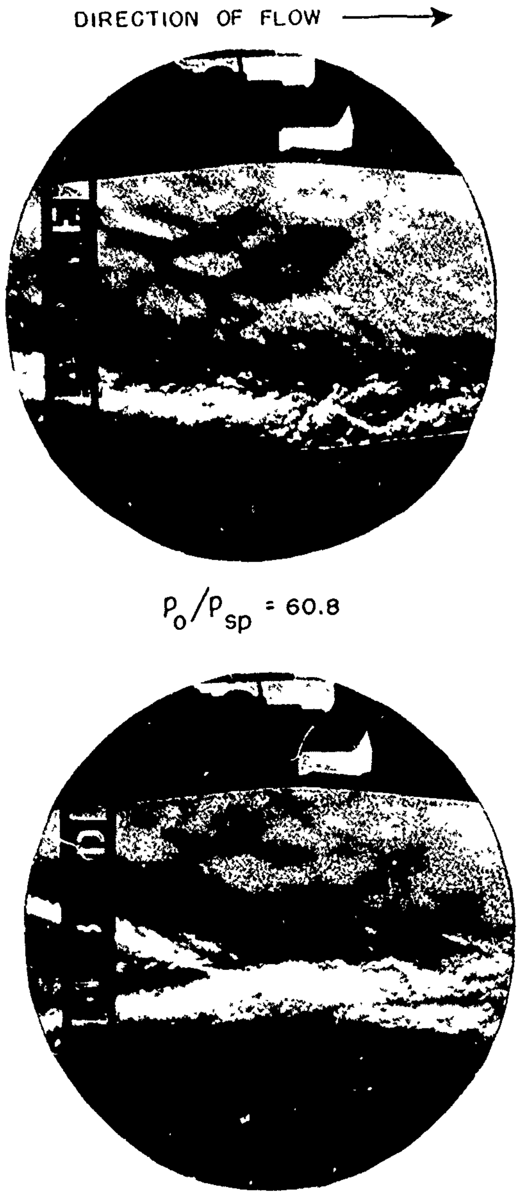


FIG. 22



$p_0/p_{sp} = 60.8$

$p_0/p_{sp} = 62.8$

SPARK SCHLIEREN PHOTOGRAPHS OF JET IN THE TEST SECTION DURING STARTING OF TUNNEL

TUNNEL STARTED AT $p_0/p_{sp} = 64.4$, $M(p_0'/p_0) = 7.2$

$p_0 = 10$ ATM, $T_0 = 25°C$

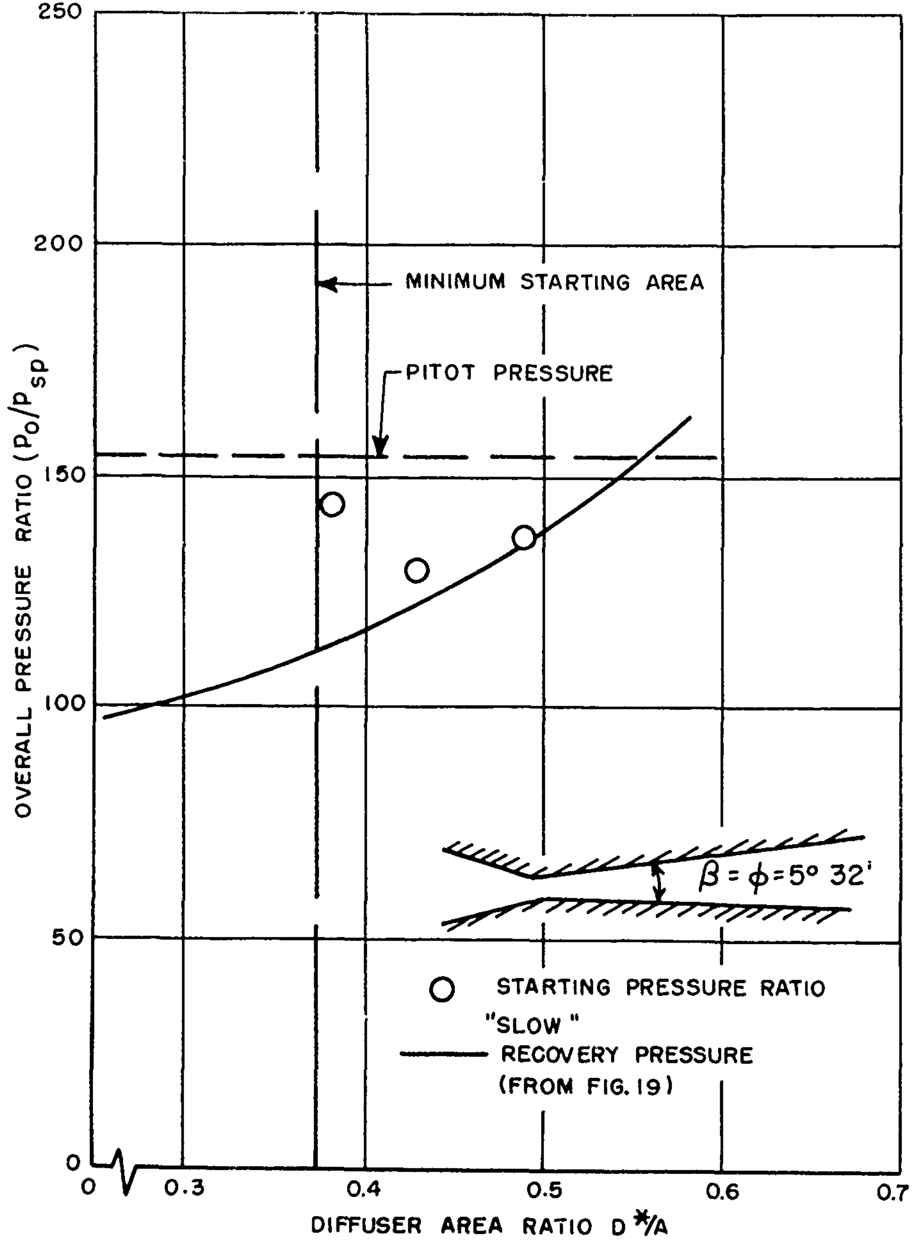
FIG. 23

STARTING PRESSURE RATIO VS DIFFUSER AREA RATIO

(EMPTY TEST SECTION)

$M(P_0'/P_0)=8.49$

$P_0=30$ ATM, $T_0=16°C$, RUNS 433, 434, 438

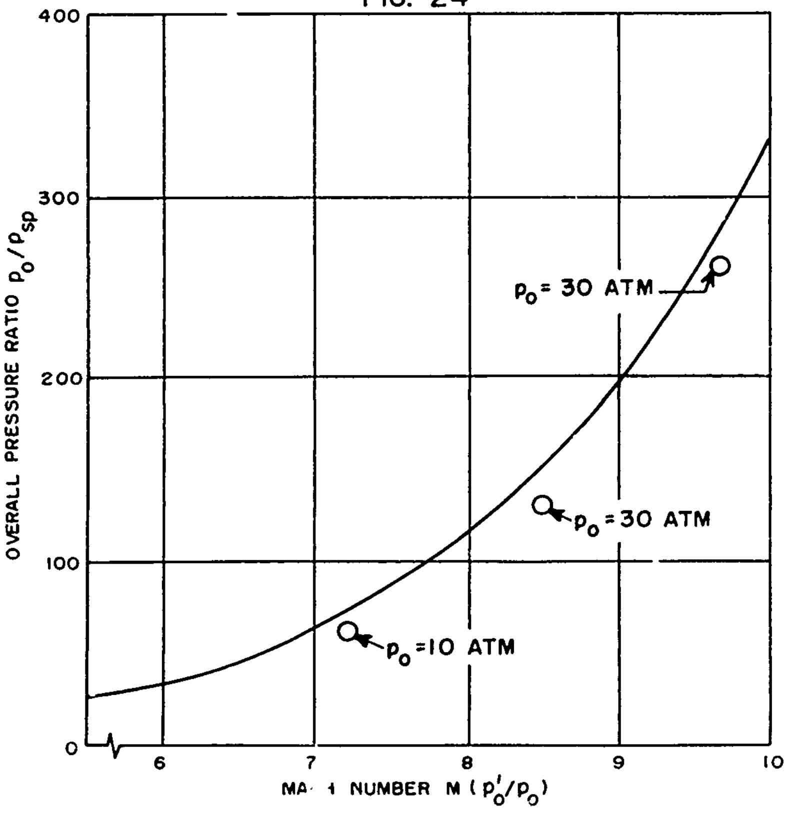


MINIMUM STARTING PRESSURE RATIO VS MACH NUMBER

(EMPTY TEST SECTION)

T_0 = 15° C RUNS 374, 438, 452
○ STARTING PRESSURE RATIO
—— PITOT PRESSURE RATIO

FIG. 24

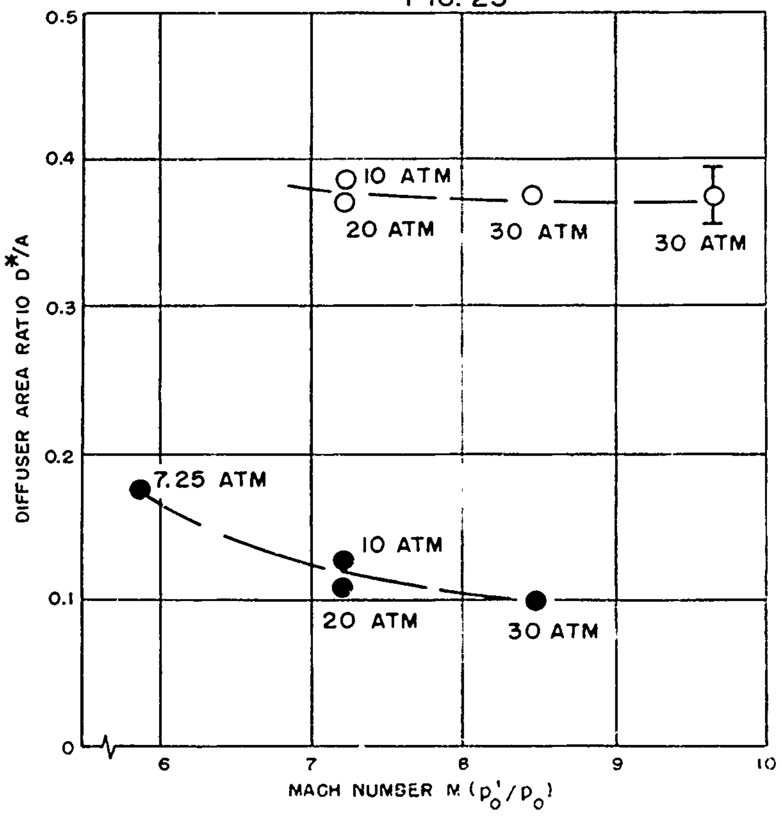


MINIMUM STARTING AREA RATIO AND MINIMUM RUNNING AREA RATIO VS MACH NUMBER

(EMPTY TEST SECTION)

T_0 = 15° C, RUNS 350, 374, 433, 434, 440, 453, 458, 465
○ MINIMUM STARTING AREA RATIO
● MINIMUM RUNNING AREA RATIO

FIG. 25



PRESSURE RECOVERY IN TERMS OF PITOT PRESSURE FOR CLOSED JET TUNNELS

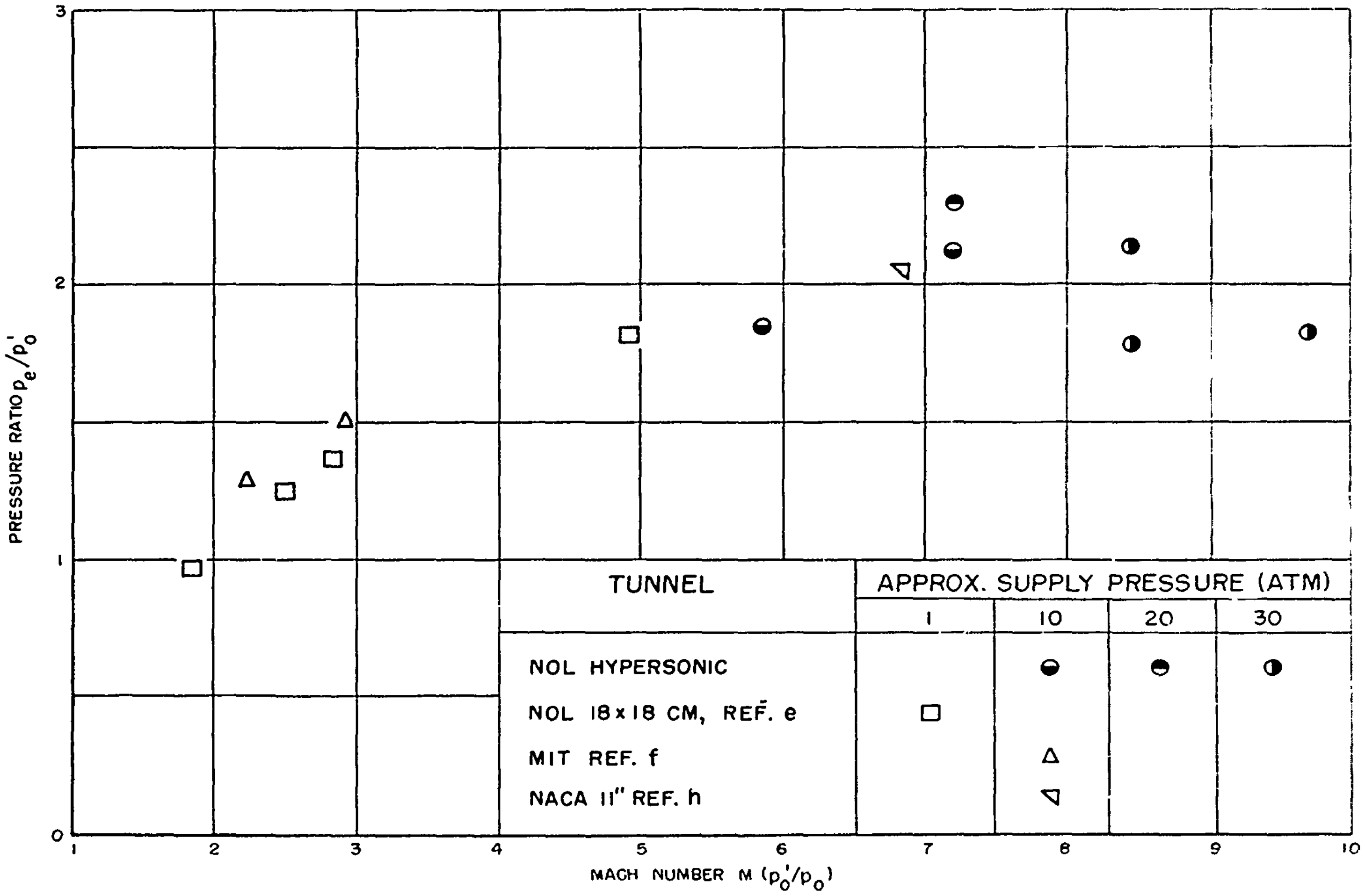


FIG 27

PRESSURE RATIOS FOR OPERATING TUNNEL

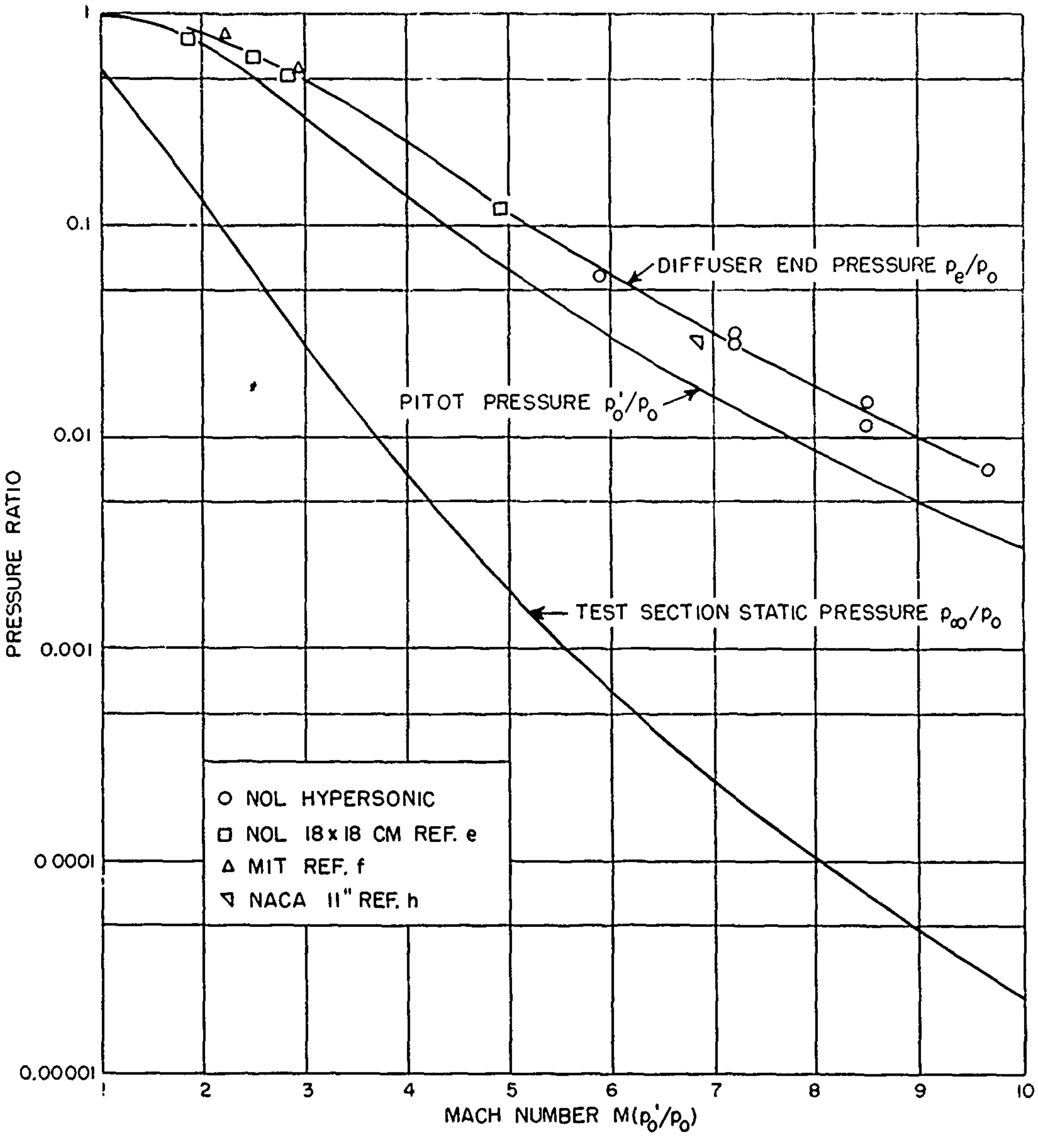


FIG. 28

DIFFUSER EFFICIENCY FOR VARIOUS TUNNELS

DEFINED AS $p_o/p_e = (p_o/p)^{1-n}$

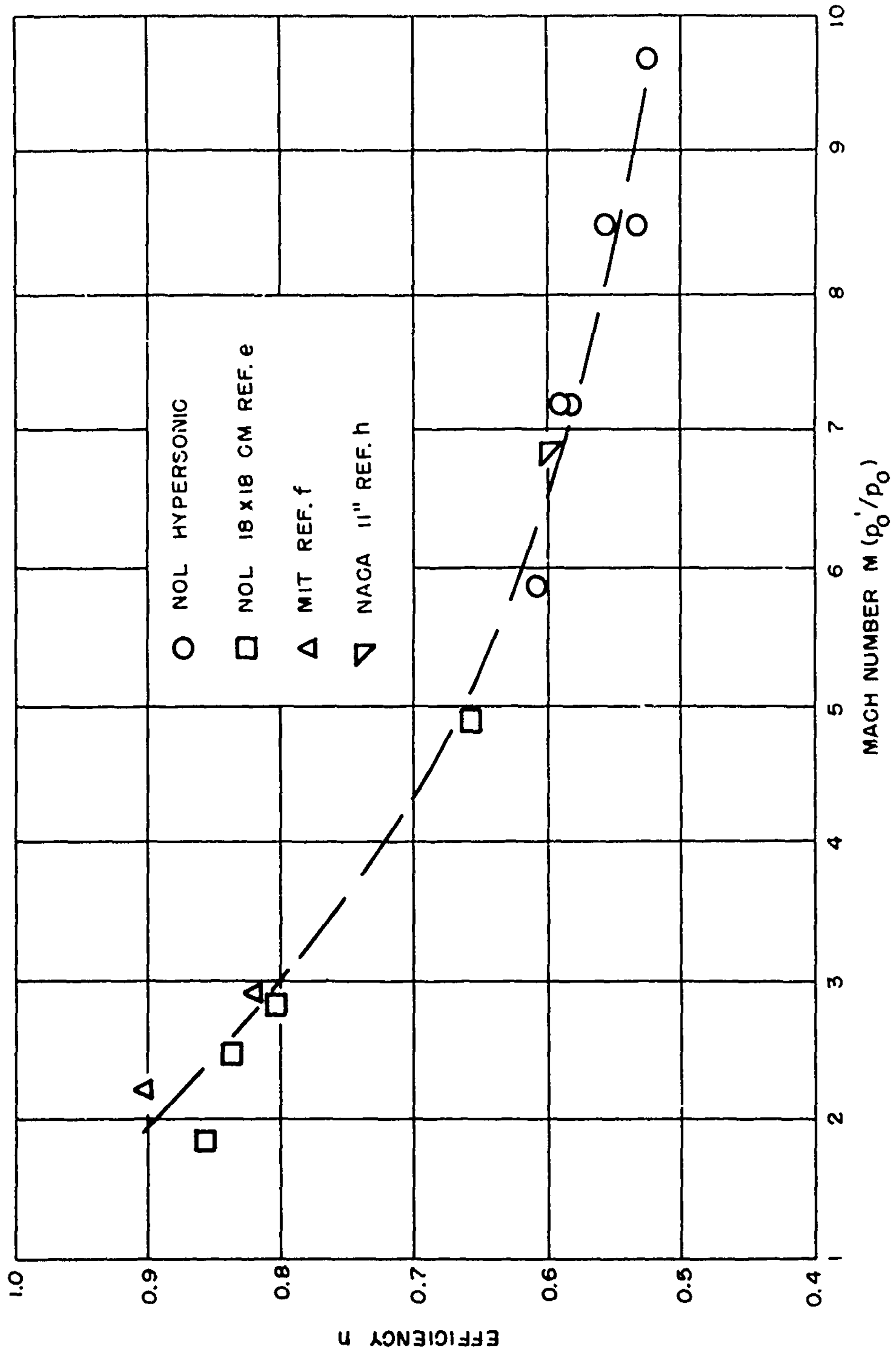


FIG. 29

COMPARISON OF STARTING PRESSURE RATIOS WITH PITOT PRESSURE RATIOS

(ONE DIMENSIONAL THEORY)

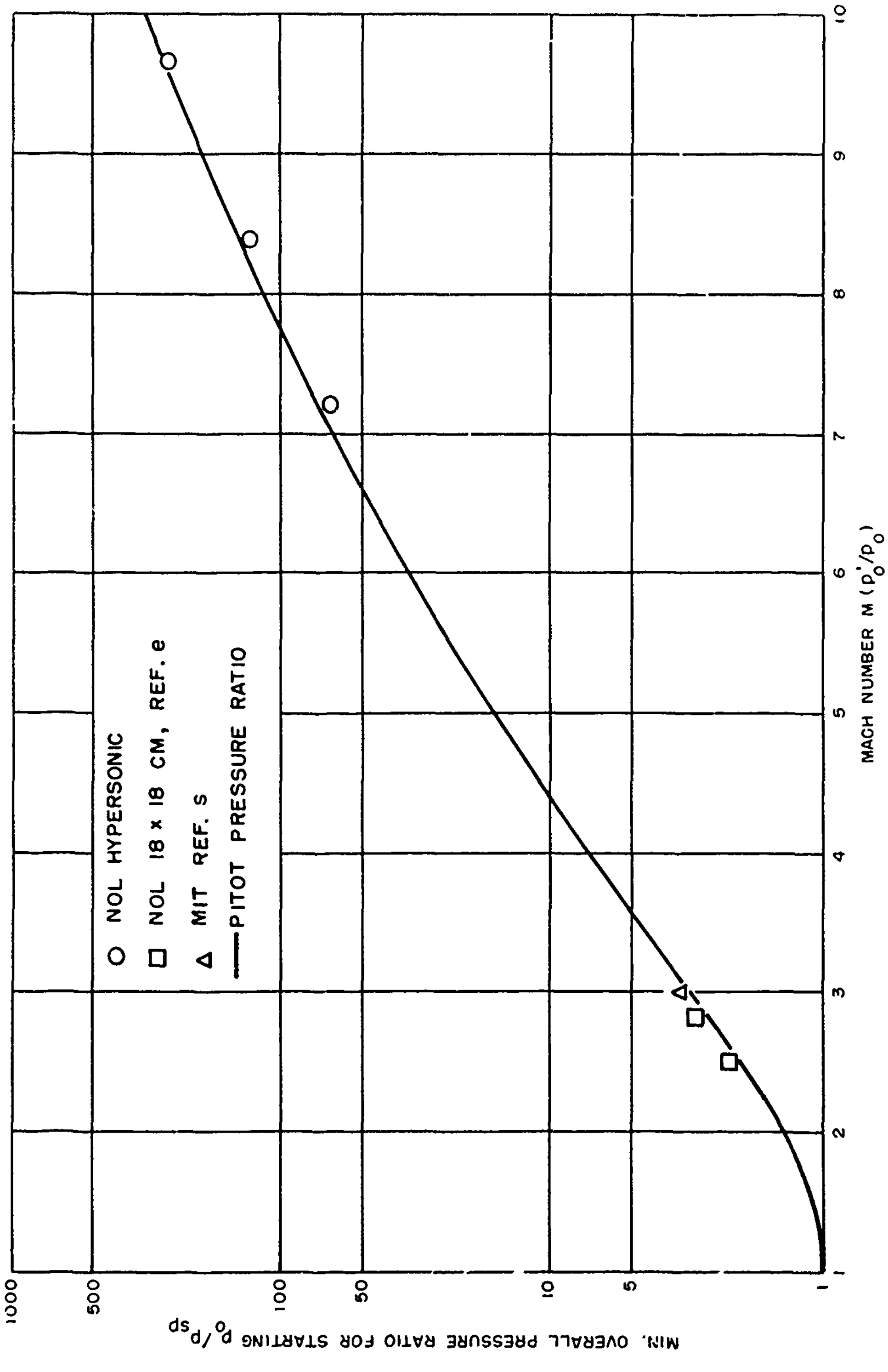


FIG. 30

COMPARISON OF STARTING AREA RATIOS WITH ONE DIMENSIONAL THEORY