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A SYSTEMATIC STUDY OF A VARIABLE AREA
DIFFUSER FOR SUPERSONIC WIND TUNNELS

December 1952



U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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A SYSTEMATIC STUDY OF A VARIABLE AREA
DIFFUSER FOR SUPERSONIC WIND TUNNELS

Prepared by:

J. L. Diggins and A. H. Lange

ABSTRACT: A diffuser of variable geometric shape was tested for pressure recovery at Mach numbers 1.9, 2.5, 2.8, and 4.9 in the continuous NOL 18 x 18 cm Aerophysics Tunnel No. 3. The diffuser consisted of a converging-diverging, two-dimensional, variable-area duct. The opening of the diffuser throat and the location of the throat along the center line of the duct was varied systematically during the tests. Furthermore, the effect of closed or half open test section on diffuser efficiency and that of a model in the air stream were investigated.

Operating and starting pressure ratios of the wind tunnel were determined and performance data of the diffuser are given for both cases. Pressure recoveries of the operating tunnel were obtained for optimum diffuser configurations with diffuser end-pressure ranging up to 1.8 times pitot pressure in the test section at $M = 4.9$. Also lower pressure ratios to start the tunnel than previously known were found. This means that, using this diffuser, a continuous tunnel can now be operated with less power, or an intermittent tunnel can run for a longer time, and that they both can be started with a smaller (closer to one) over-all pressure ratio.

The pressure recoveries obtained in a half open test section and with models in the stream are somewhat lower, but the performance of the diffuser is not seriously offset by those modifications.

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This NAVORD discusses a systematic study of a high efficiency diffuser for a supersonic wind tunnel. It was decided in 1946 to build a new version of the NOL 18 x 18 cm continuous wind tunnel. Dr. H. H. Kurzweg initiated the design of an improved diffuser as a part of this project. The first results on pressure recovery were published in 1949 and the efficiency attained was higher than that of previous diffusers. Mr. J. L. Diggins then carried out a systematic study on optimum diffuser configuration in a range of Mach numbers. Before completion of this work Mr. Diggins transferred from NOL and Mr. A. H. Lange completed the investigation and therefore reports the data.

The authors wish to acknowledge the work of Mr. H. W. Henderson who designed the complex diffuser mechanism.

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LIST OF SYMBOLS

A	Diffuser entrance area equal to nozzle exit area = $18 \times 18 \text{ cm}^2$
A**	Diffuser throat area
A*	Nozzle throat area
D	Diffuser width = 18 cm
l	Length of diffuser = $12.7D = 228.6 \text{ cm}$
l**	Distance from diffuser entrance to diffuser throat
P ₀	Supply pressure
P _p	Pitot pressure corresponding to M
p	Static pressure (free stream) corresponding to M
P _S	Sphere pressure = pressure in the vacuum vessel usually given for starting conditions
P _E	End pressure = sphere pressure at flow breakdown
P _E /P _p	Pitot pressure recovery
P _E /P ₀	Supply pressure recovery
P _S /p	Starting pressure ratio
A**/A	Diffuser area ratio
M	Mach number of flow entering diffuser
Re	$= \frac{M D}{\nu} \sqrt{\rho p_0}$, Reynolds number referred to tunnel width and free stream conditions

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A SYSTEMATIC STUDY OF A VARIABLE AREA
DIFFUSER FOR SUPERSONIC WIND TUNNELS

I. INTRODUCTION

1. Until 1946, diffusers in supersonic wind tunnels were generally shaped following a design given by Prandtl in 1926 for the small 6 x 6 cm Goettingen tunnel (reference 1) or simple diverging ducts were employed as in subsonic tunnels. Prandtl's variable area diffuser, however, was mainly meant to be a device to keep the flow steady and independent of the pressure in the vacuum vessel over the blow-down period of intermittent wind tunnels and irreversibilities in the flow were of little concern at that time. Later, the high power requirement of larger tunnels directed the attention to the more efficient transformation of the kinetic energy contained in the flow into pressure by the use of better diffusers. In 1944, Oswatitsch (reference 2) demonstrated experimentally for a ramjet diffuser that pressure recoveries higher than those attained by a normal shock and subsequent isentropic deceleration (pitot recovery) could be obtained when the fluid was made to pass through a number of oblique shocks. The application of these results to the design of wind-tunnel diffusers was initiated at NOL by Kurzweg (reference 3) in 1946. Under his direction, subsequently, a "wedge" diffuser was designed and incorporated in 1949 (reference 4) as part of the NOL Aerophysics Tunnel No. 3. The first above pitot recovery diffuser end pressure was demonstrated by Kurzweg at $M = 2.48$ (reference 5). In the following, the detailed results obtained from this diffuser are reported. Minimum pressure ratios necessary for starting the tunnel were also determined because the minimum pressure ratio that must be produced by a pump strongly influences its size, cost, and the total cost of a wind-tunnel installation. The final data will be compared with other higher efficiency diffusers such as those given by Neumann and Lustwerk (references 6 and 7) and others (references 8, 9, and 10).

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II. TEST EQUIPMENT

2. A description of the NOL Aerophysics Tunnel No. 3, and particularly the elaborate diffuser mechanism, is given in reference 4. The tunnel (see Figure 1) has an 18 x 18 cm cross-section and parallel sidewalls. The test section Mach number is changed by inserting various nozzle blocks. The dried supply air has atmospheric temperature and pressure. The air is taken from the atmosphere through drier and tunnel into the vacuum vessel called "sphere." This vessel is evacuated by a set of vacuum pumps sufficiently large to permit continuous tunnel operation. (The sphere is needed for larger tunnels operated intermittently by the same plant.) The diffuser is 228.6 cm or 12.7 D long. It consists of two pairs of plane hinged plates which are held between the parallel sidewalls. These plates form a convergent-divergent duct with the diffuser throat, at the hinge. The front plate and the rear plate of a pair of hinges (Figure 2) are connected, with the edge of the rear plate having a 6.4 cm radius. The throat can be set at various locations between 0.7 D and 11.7 D downstream from the diffuser entrance and can be opened or closed during the blow by an electric drive. The axial distance between nozzle exit and diffuser entrance is 25 cm or 1.4 D. With two parallel plates connecting diffuser entrance with nozzle exit, the test section arrangement is called "closed tunnel." With these plates removed the arrangement is called "half-open tunnel." The model used in some tests is a 60° total angle cone of 3 cm base diameter on a circular arc support with a total projected area of 8.7 cm² or 0.027 A. Figure 3 shows the model in the tunnel and the top plate removed.

III. TEST PROCEDURE

3. The test procedure is as follows:
- a. Establish a vacuum in the sphere considerably higher than needed for starting the tunnel.
 - b. Open valve between tunnel and sphere (blow valve, Figure 4) while having diffuser throat

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open until supersonic flow is established in the test section.

c. Close diffuser throat to a predetermined value of throat opening.

d. Let sphere pressure rise slowly (by opening of a bleeding valve or stopping of pumps) and read the sphere pressure at the moment the flow breaks down. (The flow breakdown is determined from schlieren observation in the test section.

4. The following quantities were measured. (See Figure 4)

a. Mach number, M , in the test section, taken from nozzle calibrations.

b. Sphere pressure, p_S , at the start and at flow break down, p_E , to average accuracy of 0.1 mm Hg.

c. Diffuser throat opening A^{**} .

5. Variable parameters for different groups of tests.

a. Location of the diffuser throat, placed at various positions between 1.14 D and 9.53 D downstream of the diffuser entrance.

b. Shape of the duct upstream of the diffuser entrance. The three configurations tested were the closed tunnel with nozzle and diffuser connected flush, the half-open tunnel with top and bottom of the connecting duct removed, and finally the closed tunnel with a model placed into the test section.

IV. RESULTS

6. To present the results, the pressure at the end of the diffuser (p_S or p_E) is divided by:

a. the pitot pressure p_p in the test section at the specified Mach number viz. $\frac{p_E}{p_p}$,

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b. the supply pressure p_0 viz. $\frac{P_E}{P_0}$.

The ratios formed in this manner are called pressure recoveries and one must therefore distinguish between "pitot-recovery" and "supply recovery."

7. The pitot recovery is plotted versus the diffuser area ratio in Figures 5 through 8 for the Mach numbers 1.86, 2.48, 2.83, and 4.92. Three curves are shown on each graph for the three duct configurations investigated. The four graphs represent the relation of p_E/p_P vs. A^{**}/A for the optimum diffuser geometry; i.e., for the location of the throat where the highest recoveries were obtained. This optimum location is different for each Mach number and is noted on the graphs.

8. The break-off of the curves at the right end denotes the minimum diffuser throat area required for starting the tunnel, while the left side break-off marks the minimum area for running the tunnel.

9. It is seen that after supersonic flow is established it can be maintained up to pressures which are larger than pitot pressure with the exception of the lowest Mach number. The gain in terms of pitot recovery becomes more pronounced with increasing Mach number. A pressure ratio of $p_E/p_P = 1.81$ is reached at $M = 4.92$ with the present diffuser. The pressure recovery is adversely affected by a model in the test section or a half open test section. The added model gives the lowest recovery. The detrimental effect of the model is less pronounced at the higher Mach numbers where losses due to friction and wake are partly compensated by the oblique shock system added by the model. The effect of the model may be negligible at Mach numbers above 6 as demonstrated in reference 10.

10. The influence of variations in throat location is shown in Figure 9 and Figure 10. Here, the highest values of pressure recovery referred to pitot pressure and supply pressure obtained for the closed tunnel, (without a model), are plotted vs. throat location l^{**}/D . Determined by the mechanical construction of the diffuser, the throat could not be shifted continuously but had to be set at discrete points, the exact location of which is noted at the top of the figures. However, there is good reason to assume that no extreme values were missed by the densely spaced settings. It must be realized that every vertical line in the graphs represents a diffuser

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of different basic geometry and that the points shown indicate the optimum pressure recovery attainable.

11. It can be seen that in contrast to the pitot recovery the supply recovery decreases with Mach number. This is to be expected from the fact that static pressure ratios drop strongly with increasing Mach number. Furthermore the Reynolds numbers of the flow (noted next to M in Figures 9 and 10), decrease with increasing Mach numbers, (constant supply pressure).

12. It is interesting to note the optimum throat location in Figure 9. The optimum of the recovery as a function of throat location is not pronounced up to $M = 2.83$. However, at $M = 4.92$ a definite optimum is noted at 4 D.

13. Figure 11 shows under the designation "operation closed" a plot of the diffuser area ratios that yield optimum values of pressure recovery vs. Mach number for the operating tunnel. Also given is the theoretical nozzle area ratio for potential flow. This curve represents an ideal limiting case (reference 11) that can never be reached actually. The group of curves of the same figure (Figure 11) shows the other diffuser area ratios required for starting the flow in the tunnel for the case of the closed tunnel and the closed tunnel with the model mounted in the air stream. Additional area is required to start the tunnel with the model but this additional area becomes smaller with increasing Mach number and is insignificant at $M = 4.92$.

14. Another fact of practical importance is borne out by the experimental curves; i.e., that area ratios greater than 1 are required to start and operate the tunnel at $M = 1.56$.

15. The experimental values are compared with:

$$\left(\frac{A^{**}}{A}\right)_{Start} = \frac{A^*}{A} \frac{p_0}{p_p} \quad (1)$$

the theoretical minimum opening (see e.g. reference 11) required for "swallowing" the normal shock. Here it is seen that the qualitative behavior is well represented

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by the theoretical curve in a certain Mach number range ($2 < M < 4$) in which the deviation is approximately constant.

16. The pressure ratio required for starting the flow in the tunnel is shown in Figure 12 as a function of the diffuser area ratio. The vertical tangents of the curves on their left indicate that closing the diffuser throat beyond a definite area ratio prevents the flow from getting established and that even very high vacua are unable to overcome a small defect in throat area.

17. Although starting of the tunnel in the fashion described in section III is not feasible at $M = 1.56$, it was possible to establish and hold flow in the tunnel by first opening the blow-valve while having a plug in the nozzle throat and then quickly removing this plug.

18. Figure 13 shows a comparison of the optimum pressure recoveries obtained at various facilities. The pressure data are compared with those measured at MIT (reference 7) in the NACA Langley Hypersonic Tunnel (reference 8) and in the NOL 12 x 12 cm Hypersonic Tunnel No. 4 (reference 9). The solid line (p_E/p_0) represents the faired recoveries obtained in various tunnels. It is represented by

$$\frac{p_E}{p_0} = 1.081 e^{-0.0865M^2} \quad \text{in the range } 1.75 < M < 6.5 \quad (2)$$

All the tunnels are in the same range of Reynolds numbers and have approximately similar diffusers.

19. The pitot recoveries are faired by the dashed line and show scatter, that is not noticeable in the insensitive supply pressure recovery plot.

20. The optimum starting pressure, i.e., the highest pressures (referred to pitot pressure and static pressure) with which flow can be established are shown in Figure 14. The results of the NOL hypersonic diffuser investigation (reference 9) are also shown and again these data are on one curve with the data of the present investigation. The starting pressure referred to the pitot pressure shows the following deviation over the whole Mach number range:

$$\frac{p_s}{p_a} = 1.0 \pm 12.5 \% ; \quad (1.8 < M < 9.6) \quad (3)$$

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21. A series of schlieren picture frames of the flow in the diffuser throat selected from a moving picture film is shown in Figure 15. The pictures were taken with rising pressure at the diffuser exit (left side) which produced finally the breakdown of supersonic flow. They were taken at a rate of 24 frames per second and with a flow of $M = 1.86$ at the diffuser entrance. The 27 pictures selected are typical and are presented in true sequence, however, they do not represent equal time intervals. The shock system causing final transition to subsonic flow moves upstream approaching the throat, getting unstable, i.e., oscillating with increasing violence, until it finally passes the throat. Picture No. 12 is typical for the shock configuration with which the optimum recoveries are obtained and is similar to those obtained for the other Mach numbers.

V. CONCLUSION

22. A two-dimensional, converging - diverging duct with plane walls is an efficient diffuser for a supersonic wind tunnel. In order to obtain optimum pressure recoveries above those of a pitot tube in the test section the throat opening of the diffuser must be variable. Also the throat must be closed to a point where maximum pressure recovery is obtained after supersonic flow has been established in the test section.

23. The distance of the throat from the diffuser entrance (or nozzle exit) that gives maximum pressure recovery varies slightly with Mach number and Reynolds number. However, it is possible to choose as a compromise for a practical design a fixed throat location such that the pressure recovery is reasonably constant over a wide range of Mach numbers.

24. The pressure ratios needed to start the tunnel were found to be lower (closer to one) than those previously known.

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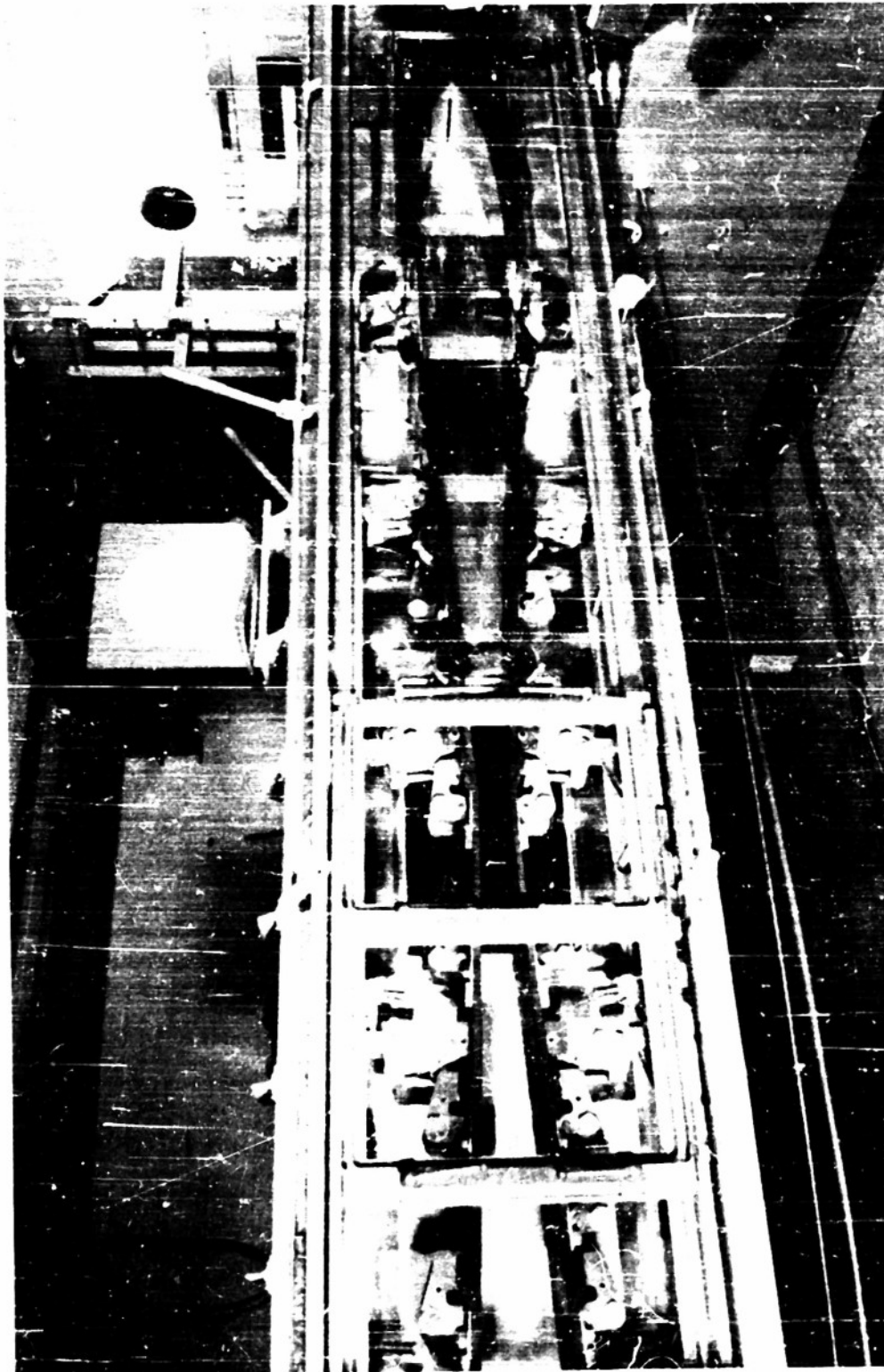


FIG.1 NOL 18X18 CM AEROPHYSICS WINDTUNNEL



FIG. 2 DIFFUSOR HINGE

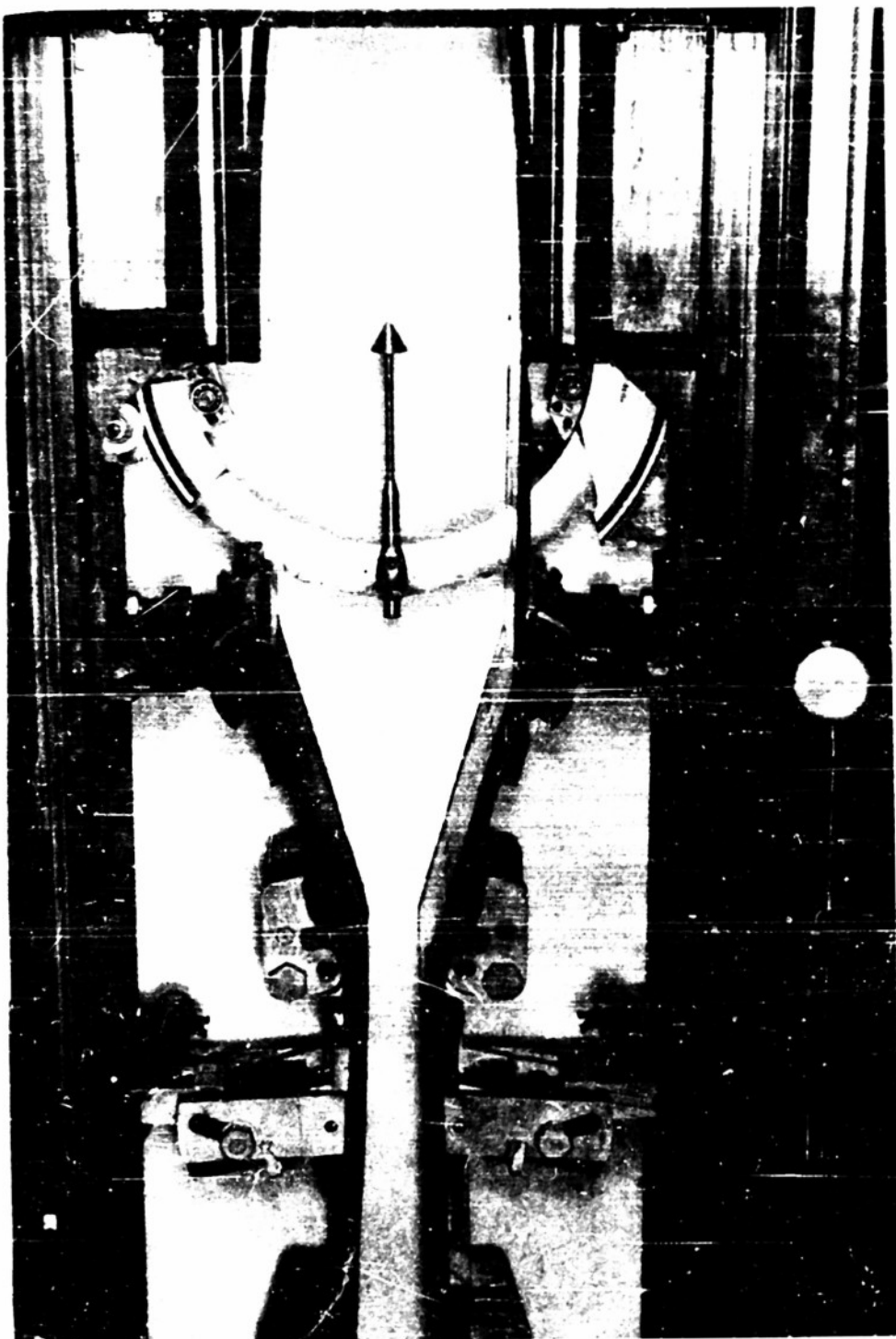


FIG. 3 DIFFUSOR ENTRANCE AND DUCT MODIFICATIONS

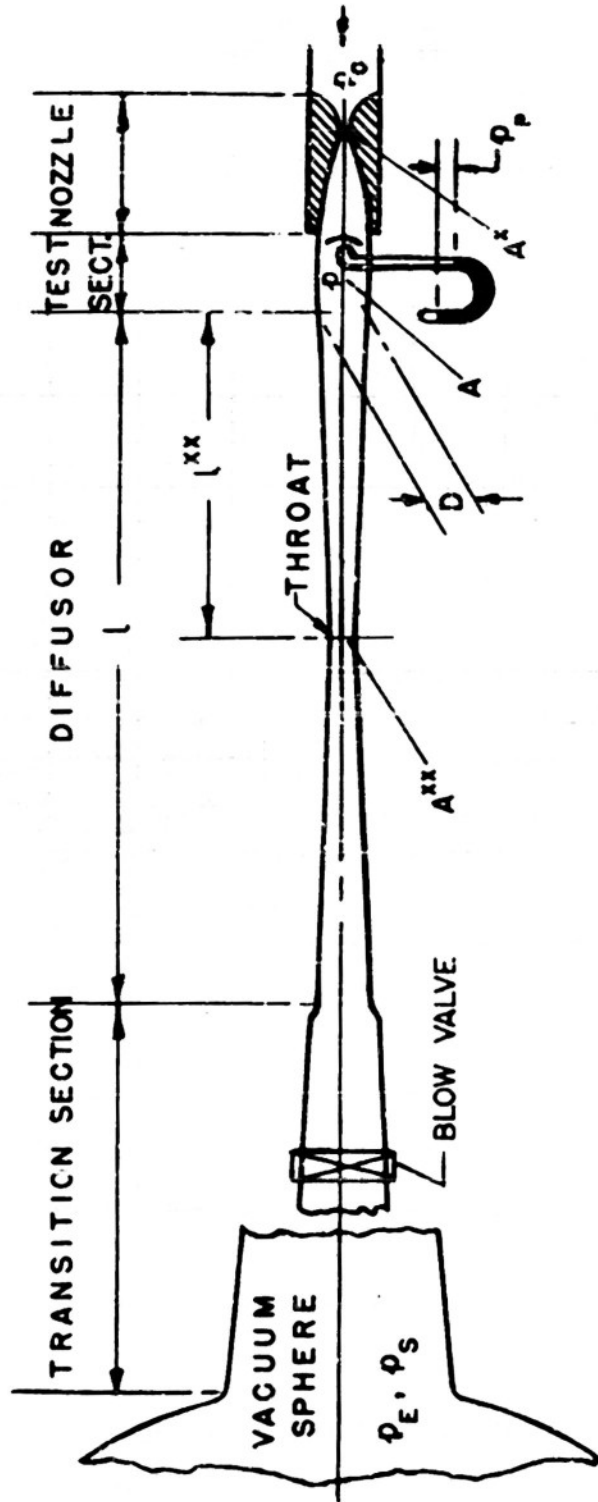


FIG. 4 DUCT CONFIGURATION, SCHEMATIC

M 1.86

THROAT AT $l^{xx}/D = 1.41$

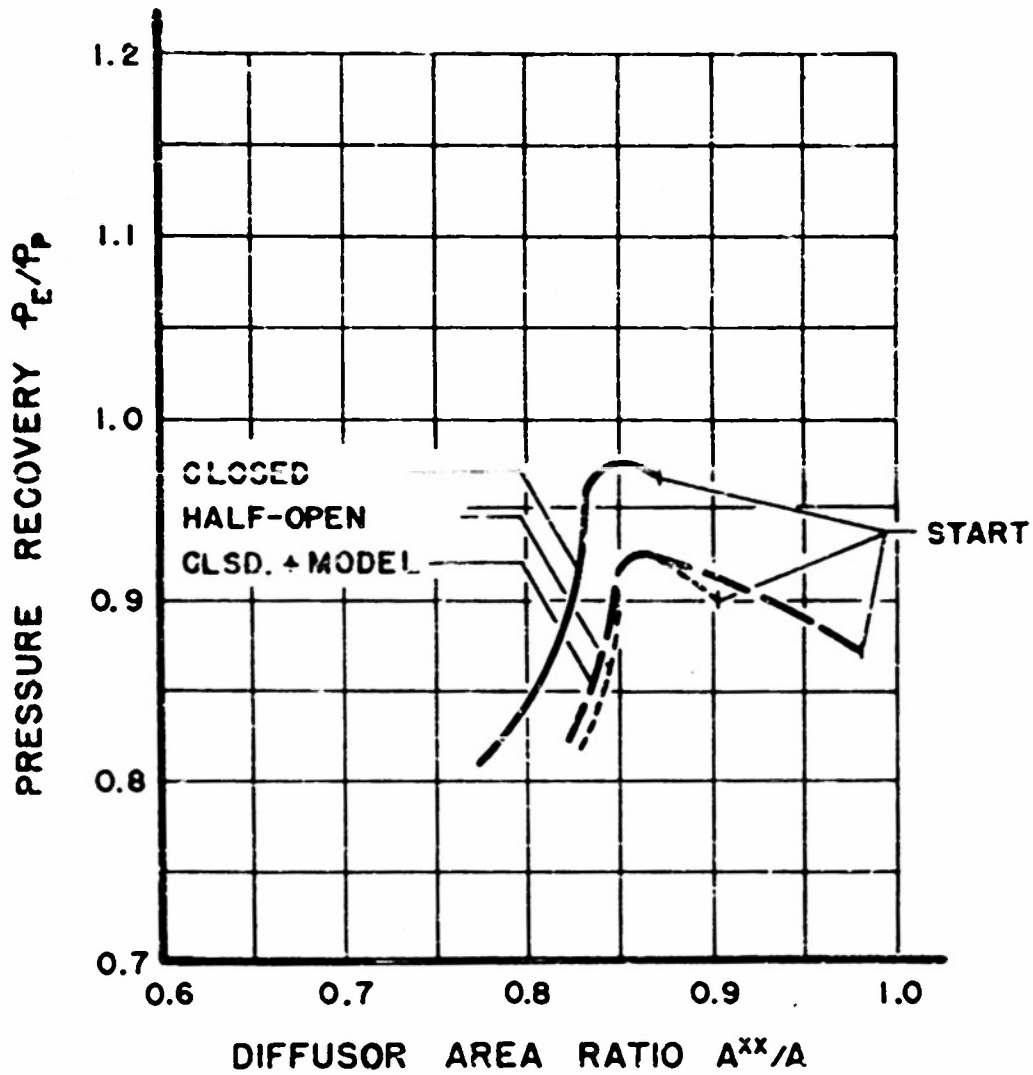


FIG. 5 PRESSURE RECOVERY FOR OPTIMUM DIFFUSOR THROAT LOCATION

M 2.48

THROAT AT $x/D = 5.29$

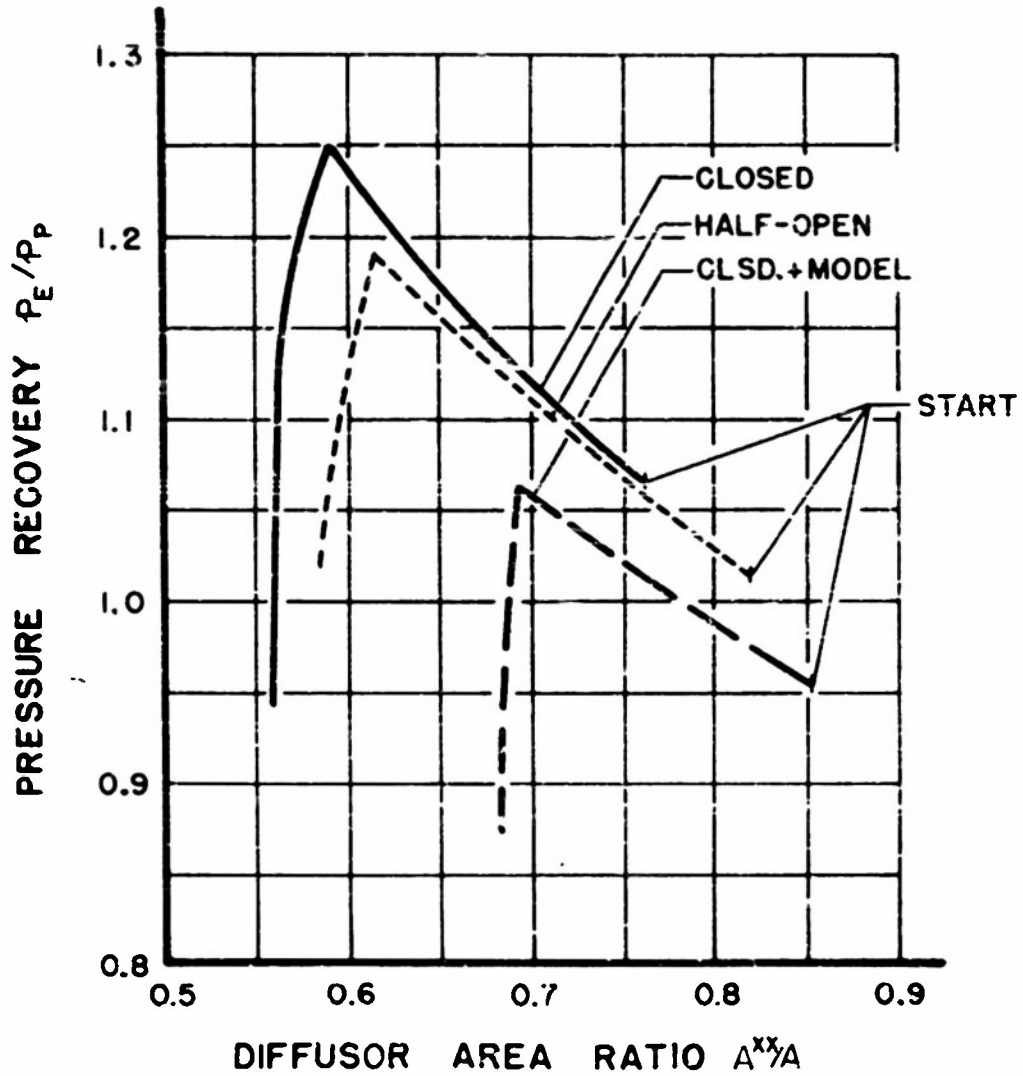


FIG. 6 PRESSURE RECOVERY FOR OPTIMUM DIFFUSOR THROAT LOCATION

M 2.83

THROAT AT $l^{xx}/D = 5.29$

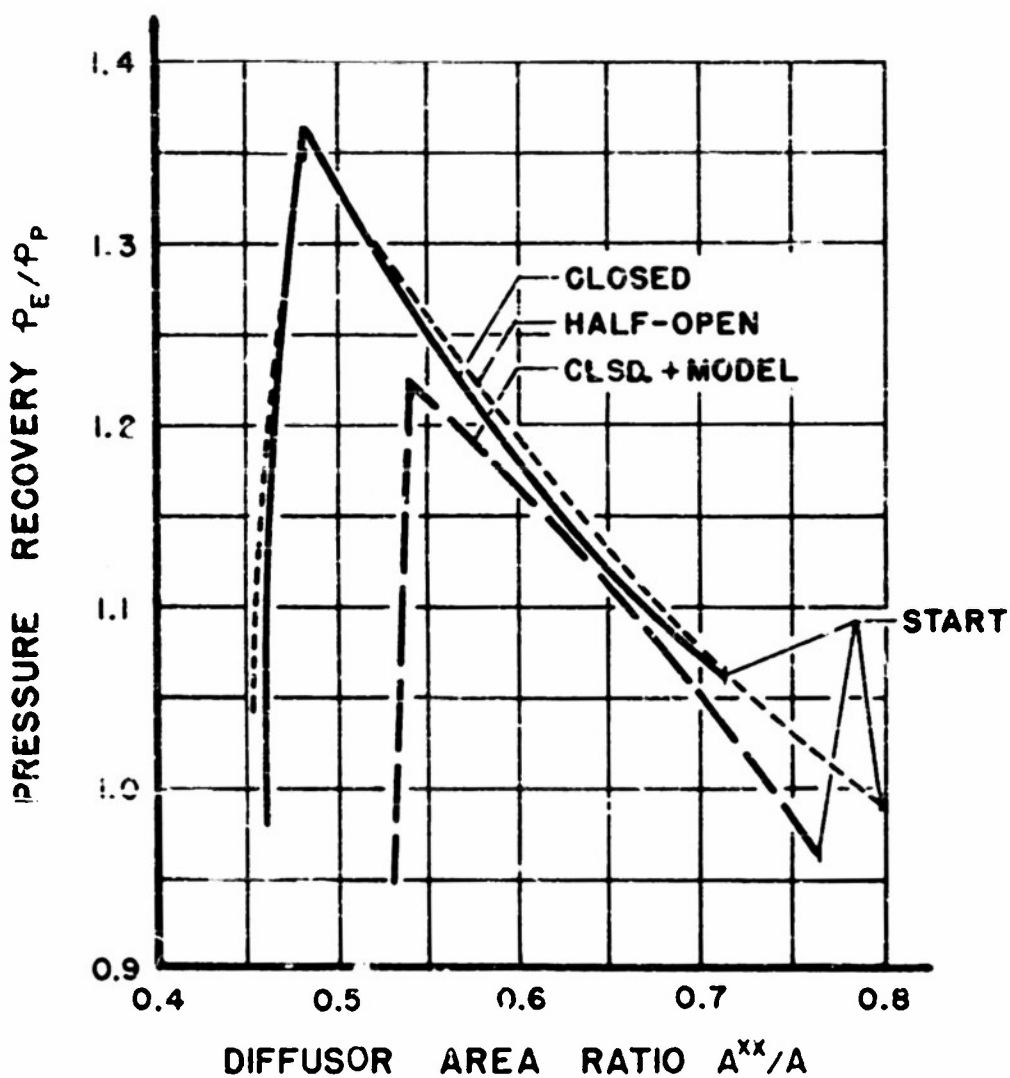


FIG. 7 PRESSURE RECOVERY FOR OPTIMUM DIFFUSOR THROAT LOCATION

M 4.92

THROAT AT $l^{xx}/D = 3.88$

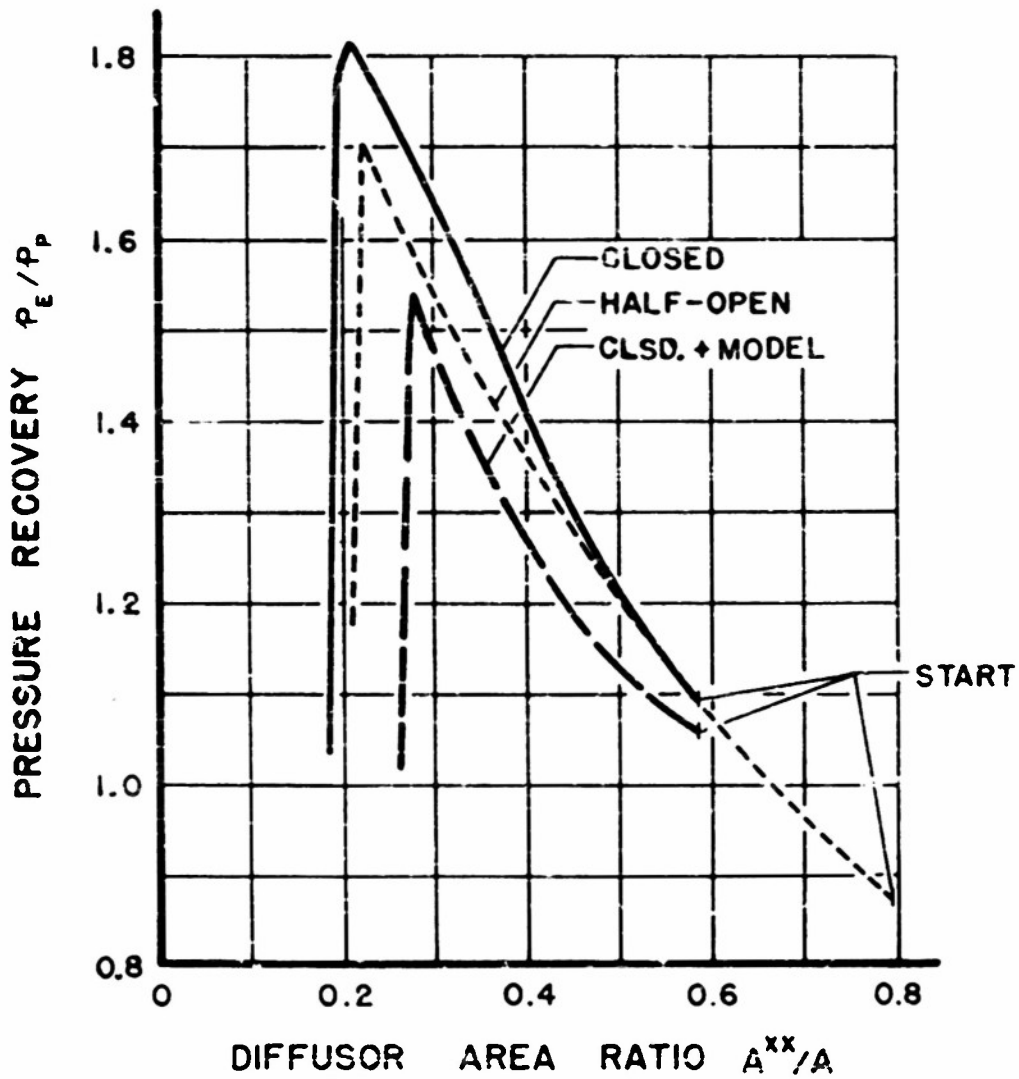


FIG. 8 PRESSURE RECOVERY FOR OPTIMUM DIFFUSOR THROAT LOCATION

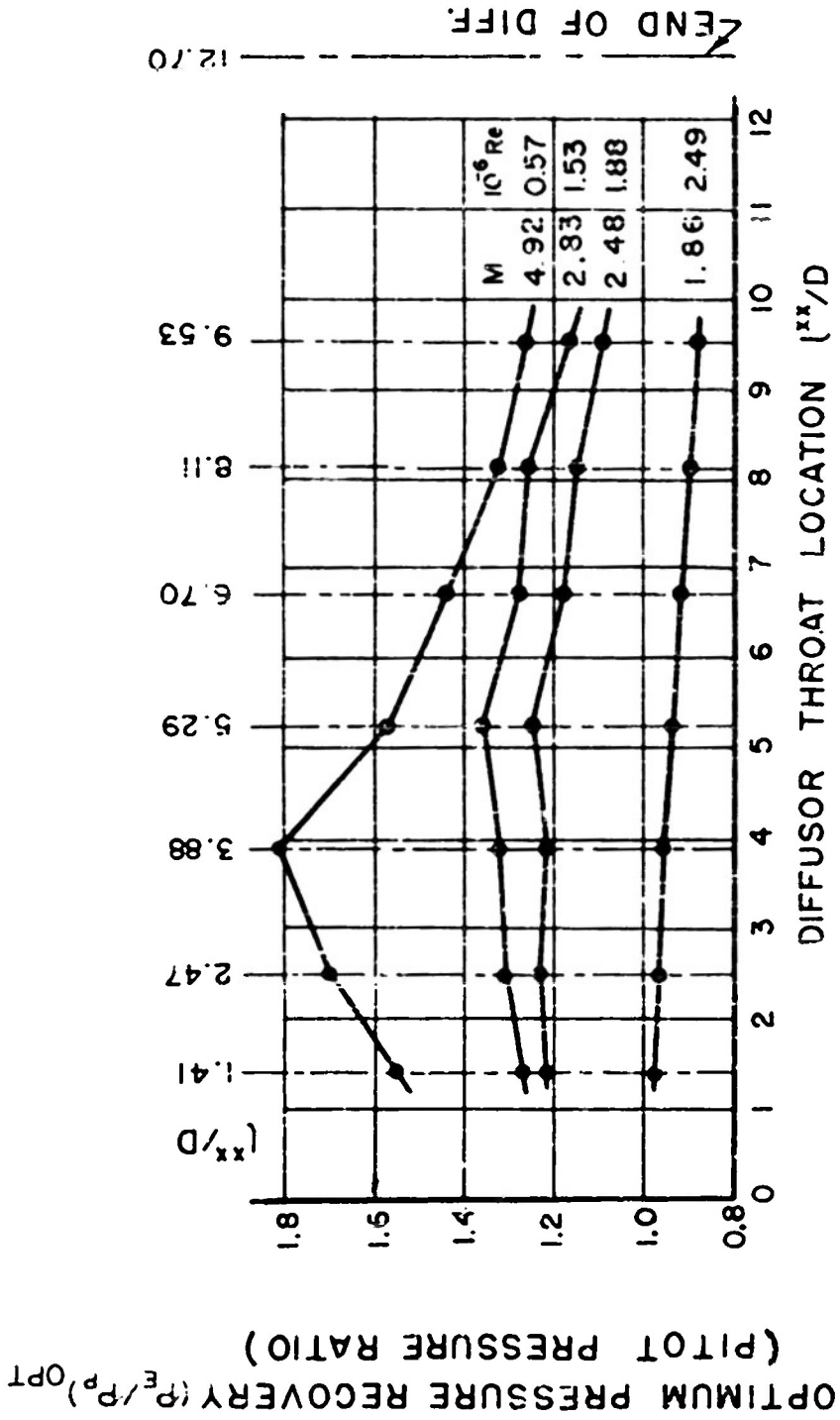


FIG. 9 OPTIMUM PRESSURE RECOVERY (PITOT PRES. RATIO) AS A FUNCTION OF THROAT LOCATION

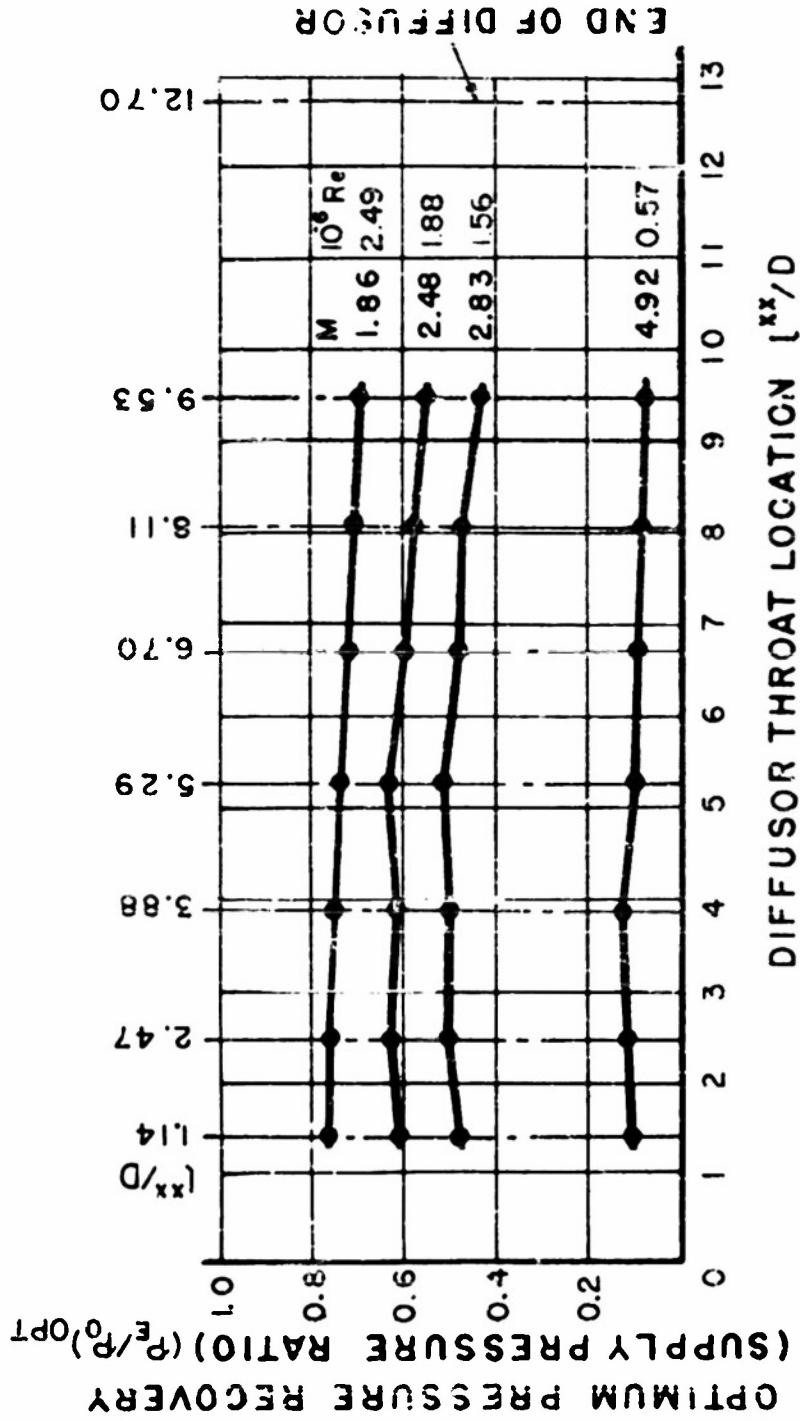


FIG. 10 OPTIMUM PRESSURE RECOVERY (SUPPLY PRESSURE RATIO) AS A FUNCTION OF THROAT LOCATION

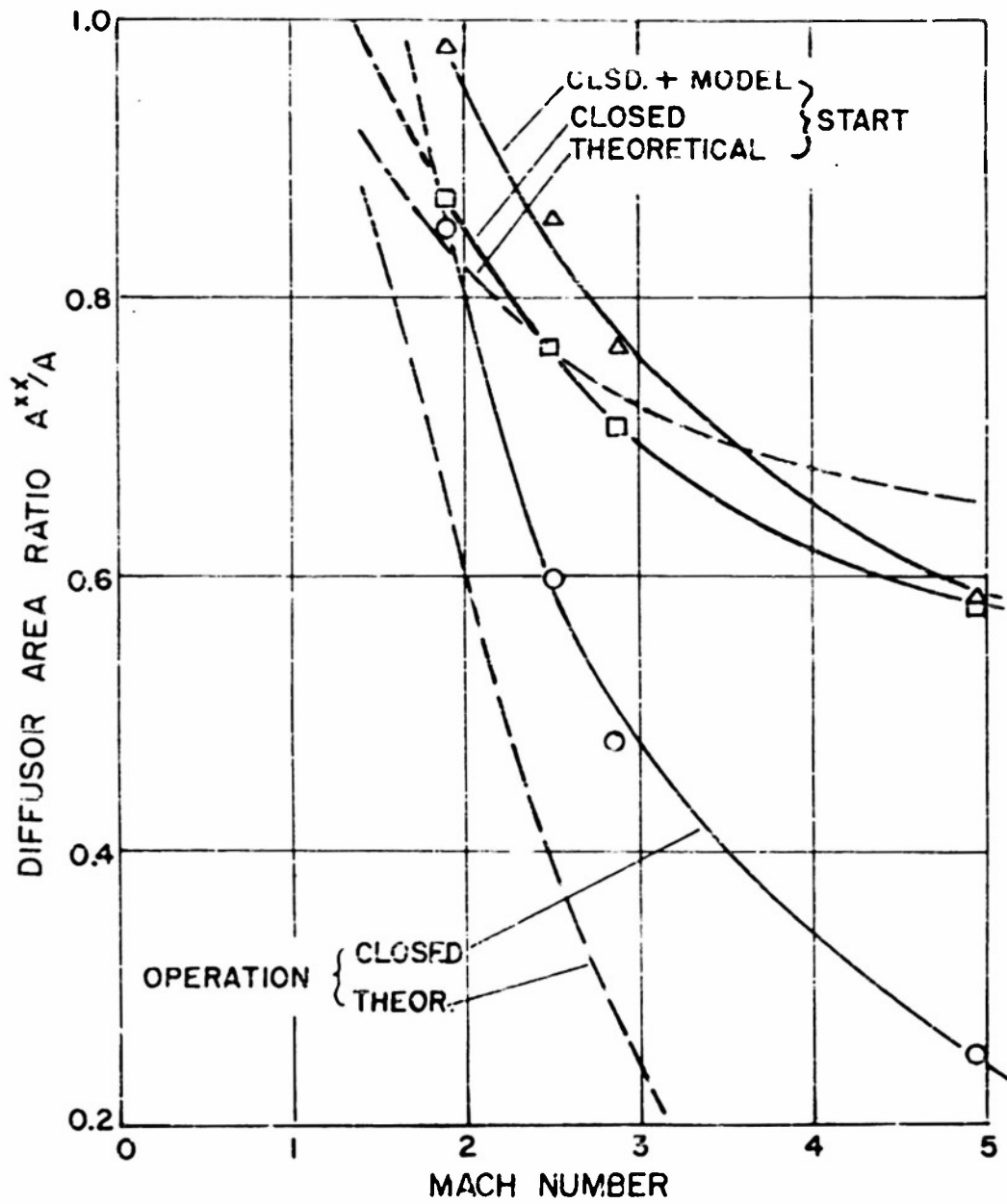


FIG.11 DIFFUSOR THROAT OPENING A^{xx}/A VS. MACH NUMBER FOR START AND OPERATION

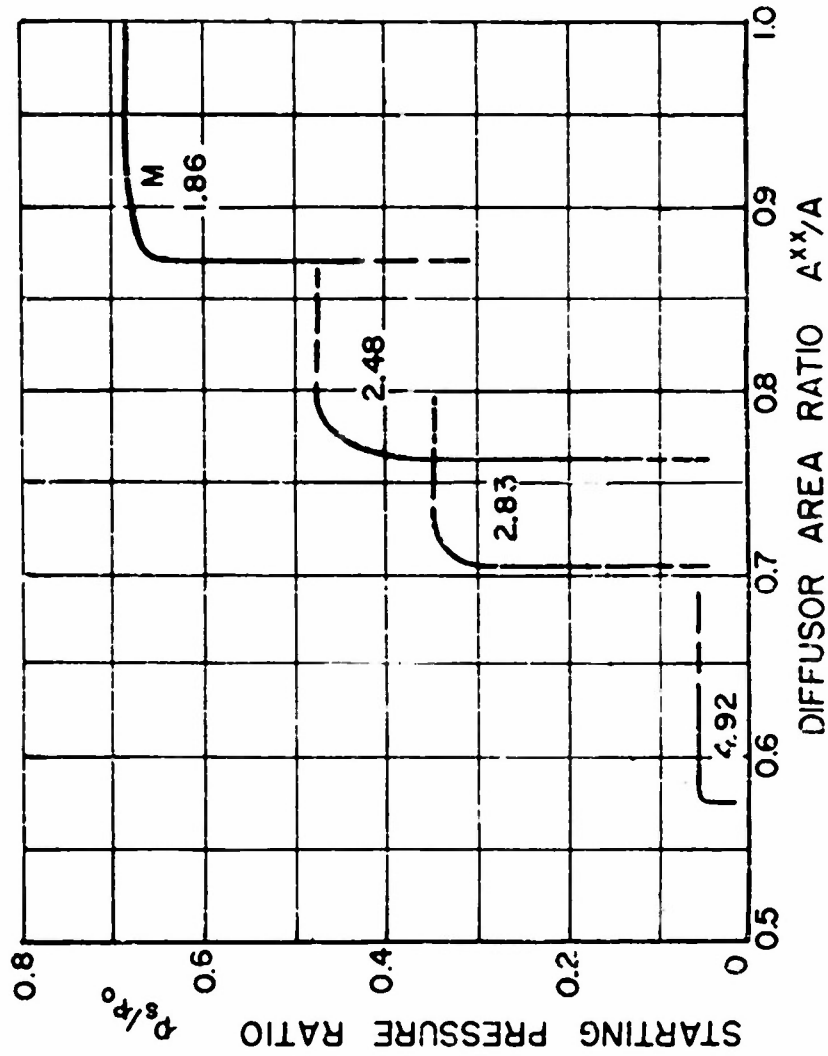


FIG. 12 STARTING PRESSURE RATIO VS. DIFFUSOR AREA RATIO FOR OPTIMUM DIFFUSOR THROAT LOCATIONS

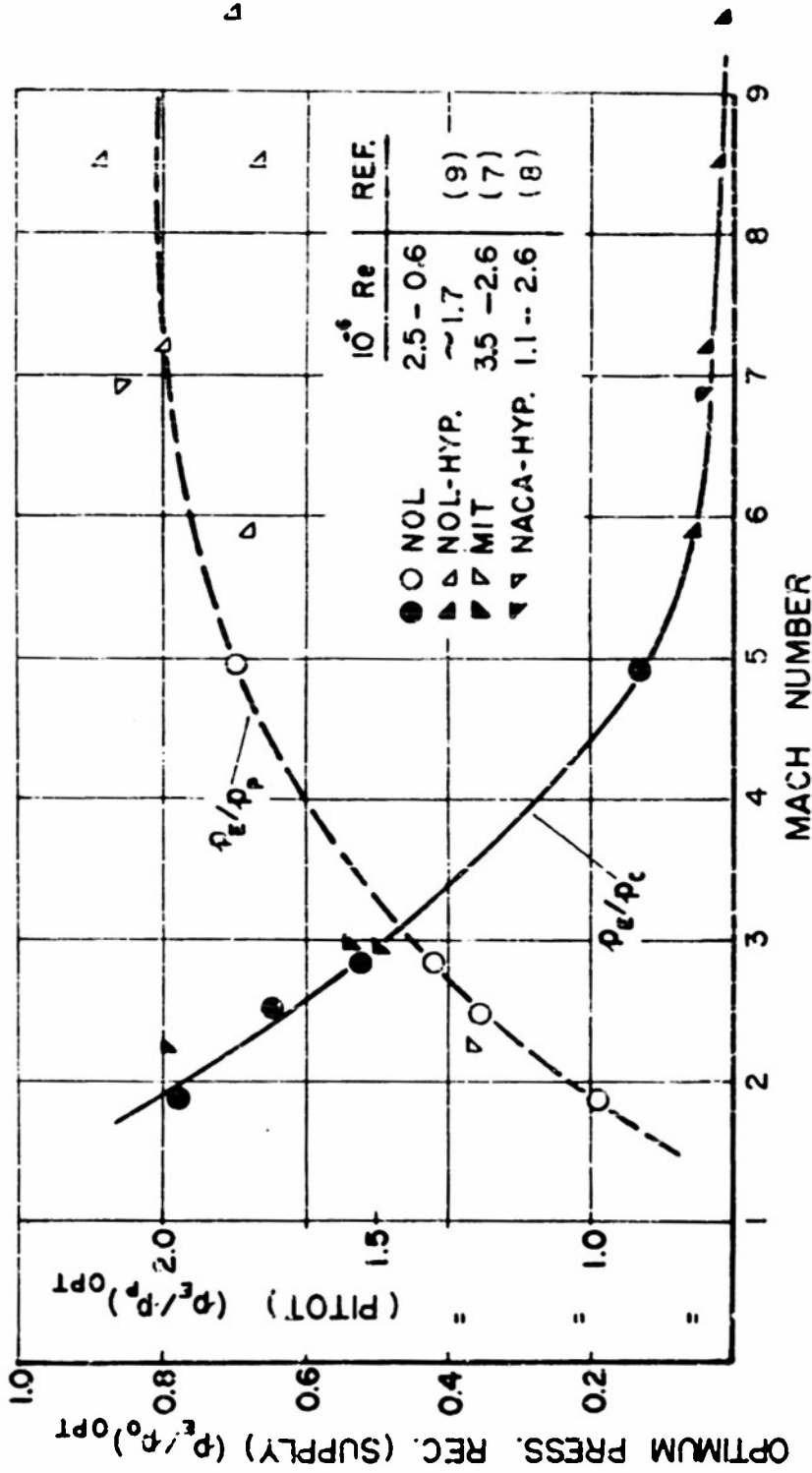


FIG. 13 COMPARISON OF DIFFUSOR RECOVERIES REFERRED TO SUPPLY-(●▲▼▲) AND PITOT-PRESS.(○△▽△)

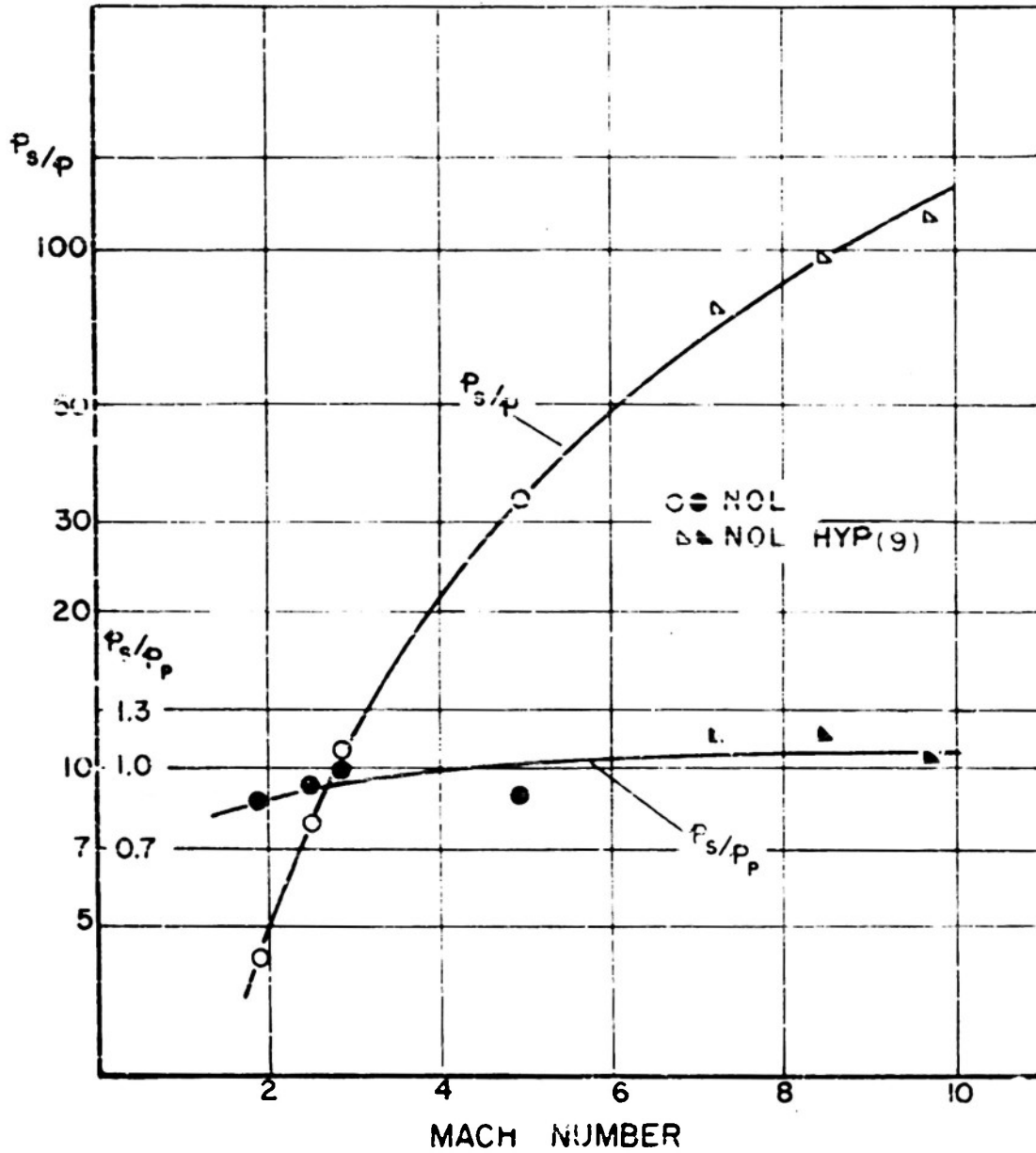


FIG. 14 COMP. OF STARTING PRESSURES
REF. TO STATIC-(○△) AND PITOI PRESS. (●▲)

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← FLOW DIRECTION

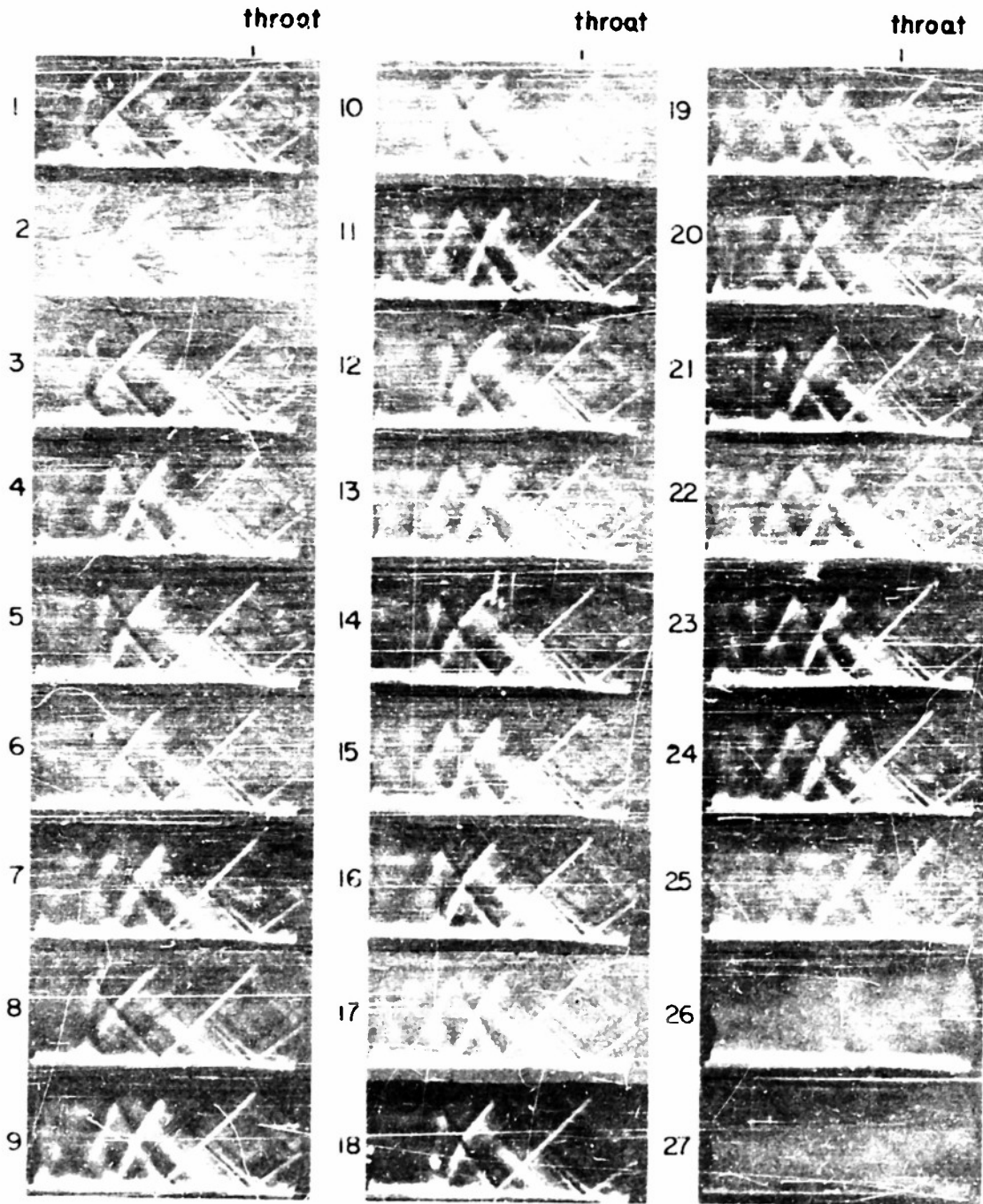


FIG.15 FLOW BREAKDOWN IN THE DIFFUSOR THROAT, $M = 1.86$

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