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SOME RESULTS OF AN INVESTIGATION INTO THE USE OF AIR INJECTION IN A MODEL OF THE DIFFUSER FOR THE A.R.A. SUPERSONIC TUNNEL

By

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Some Results of an Investigation
Into the Use of Air Injection in
a Model of the Diffuser for the
A.R.A. Supersonic Tunnel
- By -
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SUMMARY

The use of air injection in the diffuser of the A.R.A. supersonic
tunnel has been investigated to determine the decrease in running and
starting pressure ratios obtained at a given Mach number. The tests were
made in a 4 in. × 4 in. working section tunnel operating with atmospheric
downstream pressure; the majority being conducted at $M = 3.15$ giving
a Reynolds number of approximately 2.4 millions based on tunnel height
compared with 5.4 millions for the full scale tunnel. Air injection at
tunnel stagnation pressure was made at two slots in opposite walls of the
diffuser at a distance 4 tunnel heights downstream of the working section.
This initial portion of the diffuser could be contracted to determine the
most efficient entry conditions to the injection section. The angle of
injection was 15° to the tunnel axis at a constant Mach number of 1.63.
Control of the direction of the injected stream and size of second throat
was provided by adjustable flaps downstream of injection.

It is shown that the use of 120% by-pass injection at
$M = 3.15$ permits the starting pressure ratio to be reduced to 3.2
from values in excess of 4.0 and the running pressure ratio to be
reduced to under 3.0; both figures being obtained with a representative
model and support in the working section. It is also shown that further
decrease in pressure ratio can be obtained with the use of larger
injection quantities.

In addition to the main tests the effects of model incidence
and a hole in the floor of the working section were investigated. Also
three different subsonic diffuser shapes were tested in the presence of
the disturbed flow from the supersonic diffuser. The results of this
latter test indicated that it is essential to maintain an expansion
rate equivalent to a 6° cone or less even if it means decreasing the
expansion area ratio of the subsonic diffuser.

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Introduction

The matching of compressor characteristics to supersonic tunnel characteristics has been the subject of considerable investigation in recent years. Two solutions have become quite evident as a result of these enquiries. Either it is necessary to select a compressor system which in its various combinations will approximate to the required tunnel characteristic, or a particular compressor characteristic must be accepted and some of the air must by-pass the working section to obtain the higher Mach numbers. The latter has until recently been accepted as a necessary wastage, but investigations into the benefits of injecting high speed air into the diffuser have shown that there are considerable advantages to be gained. American experiments (Refs. 1 and 2) first showed that the pressure ratio requirements could be very appreciably reduced by injecting air at moderate supersonic Mach numbers along the supersonic diffuser. Calculations on one-dimensional theory showed that decreases of pressure ratio would occur as a result of the high energy imparted to the stream at the injector. By analysing the momentum and total energy of the system, good qualitative agreement with experiment was achieved. No account however could be taken of the varying shape of the free stream boundary of the injected jet and its effects on the deceleration of the air from the working section. This American work has also demonstrated not only the benefits of diffuser injection but the effect of some of the very numerous variables of geometry and flow conditions. Some of these factors, particularly the model and support constrictions at the entry to the diffuser vary to a large degree between one application and another. It is, therefore, important that any diffuser system designed on the basic principles of Ref. 1 should be tested on a small scale before finalising the full scale design.

Fig. 1 has been prepared to show how it is thought by-pass injection will improve the potential performance of the A.R.A. $2\frac{1}{2}$-ft × $2\frac{1}{4}$-ft supersonic tunnel now in process of construction. This tunnel has been designed to operate with a Brown Boveri axial flow compressor which has a pressure ratio at surge of 4.2:1 and has a pressure ratio vs. weight flow characteristic at motor synchronous speed as shown in Fig. 1. The estimated characteristics required from a tunnel of this size with and without injection are also shown. These curves have been based on assumed pressure ratio vs. Mach number characteristics for different diffusers as plotted in Fig. 2. Curve A in Fig. 1 labelled 'without injector' is replotted from the curve for the simple divergent diffuser in Fig. 2 while curve B labelled 'with injector' from the assumed values of pressure ratio using injection.

Fig. 1 demonstrates that the benefits of injection are complementary. The more the injection is successful in reducing the required pressure ratio, the greater is the mass flow available for injection. For example on Fig. 1, OZ represents the mass flow available from the compressor at a pressure ratio of 2.75. OY is the amount needed by a tunnel with a simple divergent diffuser and this would, therefore, leave YZ as the mass available for injection into the diffuser. This implies a certain reduction in required pressure ratio, e.g., some point between Y and X - which gives more mass flow available for injection until the process is finally stabilised at some point X. In other words, if the benefits of injection are so great as to reduce the pressure ratio characteristic to the value shown in curve A on Fig. 2, then at a Mach number M, the pressure ratio required by the tunnel is reduced to X and the mass flow available for injection is WX. If curve A is achieved in practice, then the amount of air available for injection is shown in Fig. 3.

In terms of potential Mach number range of the tunnel Fig. 1 suggests a possible increase in the maximum Mach number from near 2.8 to more than 3.5: a very significant and worthwhile gain.

In order to substantiate these predictions, tests have been made with injection on a model with the geometry of the particular diffuser proposed. The variables investigated were:-

(1) The effect of convergence of the diffuser from working section to injector section.

(2) The effect of convergence of the diffuser between the injector section and minimum section downstream of injector.

(3) Injector mass ratio, i.e., $\dfrac{\text{weight flow through by-pass}}{\text{weight flow through working}}$ section

(4) The effects of adding model, model support and balance, and cut out in working section floor.

Tests were also made on three different subsonic diffusers to determine the optimum shape for use with these mixed entry flow conditions.

The tests described were made at the Royal Aircraft Establishment, Bedford from April to October, 1955.

2. Models and Apparatus

2.1 Test Equipment

The tests were made in the High Speed Laboratory at R.A.E., Bedford. This facility was capable of operating a 4 in. × 4 in. test section at pressure ratios up to 3.8:1 and also providing sufficient flow for large injection at the higher Mach numbers. The return line to the compressor was vented to atmospheric pressure giving a tunnel stagnation pressure equal to the pressure ratio in atmospheres. This arrangement had the great advantage that one reading of stagnation pressure immediately provided the pressure ratio at which the tunnel commenced to run at supersonic speeds, or broke down supersonic flow to subsonic.

The dryness level was at all times kept at a dew point of the order of -40°C by feeding dry air into the atmospheric vent chamber, thus any inspired air was completely dry. A by-pass drying system was also in continuous use. The stagnation temperature was approximately 10°C.

2.2 Contraction

A teak contraction piece was fitted between the low speed contraction in the pressure shell and the two-dimensional contraction at the upstream end of the liners. The position of this is shown in Fig. 4.

2.3 Working Section

A light alloy box constructed of 1-in. thick side walls separated by 4-in. wide channels, 22.5-in. long provided the structure into which the working section liners were fitted. The liners, 4-in. wide and 22.5-in. long were made of teak and profiled to give a Mach number of 3.2. Details are shown in Fig. 4.

In order to obtain Mach numbers between 3.2 and 3.5 the M = 3.2 liners were rotated to give a change in area ratio corresponding to the higher Mach numbers, by this method M = 3.42

was/

was achieved with a fair distribution. The resultant step in the contraction produced no noticeable effects on the Mach number distribution. Static pressure tappings were spaced at 1-in. intervals along the centre of the side wall of the tunnel. These were 1/32-in diameter holes drilled from the inside surface to meet 1/8-in. copper tubing which had been screwed in position from the outside, final sealing was achieved with Araldite.

2.4 Supersonic Diffuser

Details of this are shown in Fig. 4. The diffuser was made of steel and was symmetrical about a horizontal centre plane. The top and bottom flat plates between working section and injector slot could be adjusted to give any of 5 different contraction ratios from 0.7 working section heights to 1.1 working section heights. The injector slot could be adjusted whilst running by the external controls as shown, and also the setting of the flaps downstream of the injector slot could be adjusted whilst running. These adjustable plates were sealed at the edges with baize which afforded easy movement with a minimum of leakage to atmosphere. The backs of the hinges were sealed with sheet rubber as was a sliding joint between the supersonic and subsonic diffusers. The side walls of the diffuser were made of $\frac{1}{2}$-in. thick 'perspex' to permit shadowgraph flow visualisation. The diffuser was maintained parallel at the working section width up to the injector slots and from there a slight wall divergence was incorporated to give a resultant expansion ratio between beginning and end of diffuser of 1.4:1. The injector was arranged to give a constant injection Mach number of 1.63 irrespective of injection quantity, the maximum angle of injection being 15° to the diffuser centre line at small injection quantities.

Static pressure tappings similar to those in the working section were spaced at intervals along the centre of the side wall of the diffuser.

2.5 Subsonic Diffuser

For the majority of tests a long 5° total angle diffuser was used; this had an area ratio of 4:1 and provided a smooth transition from the square end of the supersonic diffuser to the circular section of the downstream leg of the tunnel. This diffuser was made of teak. Two other diffusers were tested to determine the effects of different expansion ratios and expansion angles. The first expanded at a 10° included angle for an area ratio of 2.5:1, the second expanded at a 5° included angle for an area ratio of 1.7:1 with a rapid step expansion to give a total ratio of 2.5:1. Details of these are shown in Fig. 20.

Static pressure tappings along the side wall were available.

2.6 Model

The model is a cone-cylinder body with a larger balance body fixed to the quadrant which is 0.22-in. thick. The balance body could be mounted at 0°, 22.5° and 45° to the wind stream. Details of model, quadrant and balance body are shown in Fig. 5.

2.7 Flow Visualisation

Simple shadowgraph observation of the diffuser flow was made using a mercury vapour lamp shining into a 4-in. plane, surface-aluminised mirror and then through the diffuser walls to a translucent paper screen. Flow past the model could not be observed.

3. Procedure of Tests

It should be noted that the object of these tests was to investigate various design features which are particularly appropriate to the A.R.A. supersonic tunnel. The tests did not set out to be a complete investigation into the function and nature of by-pass injection nor was it an investigation into the effects of the many variables associated with supersonic diffusers. As a result of this approach, various ad hoc tests were made to demonstrate the validity of certain design features. The objects of the tests may be enumerated as:

(1) To determine the values of the starting and running pressure ratios with different injection quantities, diffuser settings and Mach numbers.

(2) To determine the effects of mounting a representative quadrant and model in the working section of the tunnel, on the optimum values derived for the empty tunnel.

(3) To determine the optimum subsonic diffuser shape.

Most of the tests were made with the M = 3.2 liners which gave a fair Mach number distribution as shown in Fig. 6, the general level of Mach number being about 3.15. This discrepancy was due to the use of an incorrect boundary layer allowance.

The starting procedure was to raise stagnation pressure rapidly to a value giving a pressure ratio slightly less than that required for full supersonic flow in the working section. The pressure was then increased slowly until the supersonic condition was attained. The value at which the working section ran fully supersonic was noted as giving the minimum starting pressure ratio. At these higher Mach numbers the change-over from subsonic to supersonic flow in the working section was accompanied by a distinct change of noise level from the tunnel. This arises from the tunnel shock moving rapidly from a position upstream of the model to the end of the supersonic diffuser. A similar change of noise level was noted when the flow changed from supersonic to subsonic in the working section. This change of sound was used as an indication of the changeover from one flow condition to another.

4. Discussion of Results

4.1 M = 3.15 Starting and Running Pressure Ratios: Tunnel Empty

4.1.1 With Parallel Diffuser Ahead of Injector Slot

Figs. 7 and 8 show how the pressure ratio varies with percentage by-pass flow and settings of the downstream diffuser flap. It can be seen that

(i) As expected, the pressure ratio decreases appreciably with increase of by-pass mass flow,

(ii) The optimum flap setting increases with increase of by-pass,

(iii) Closing the flap beyond the optimum position has a marked adverse effect on the pressure ratio but opening the flap has a much more gradual effect.

These last two effects of the downstream flap setting can be explained by pointing out that the purpose of these flaps is to control the degree of expansion of the injected stream into the free stream.

Hence/

Hence, up to a point, closing the flaps, i.e., increasing the amount of expansion, decreases the size of the aerodynamic second throat, giving progressively more efficient diffusion. Ultimately, however, i.e., beyond the optimum setting, further closing of the flaps creates a choked tunnel: a large increase in pressure ratio results and there is a breakdown of the supersonic flow in the working section. With increasing by-pass flow, this choked condition is produced with less closing of the flaps.

The optimum values of pressure ratio for the starting and running conditions from Figs. 7 and 8 are given in Fig. 9. This figure illustrates the rather unexpected feature that the starting and running pressure ratios are very similar and do not exhibit the large difference that is demonstrated in theory. This feature is also found from results of by-pass injection in Ref. 1. It was also found that the setting of the downstream flaps did not have to be changed much to achieve the optimum running and starting values (Fig. 10). This can probably be attributed to the particular configuration of diffuser used in these tests as the long diffuser entry from working section to injector provides very little recompression. As a result of this, in the running condition, the Mach number of the main stream at the injector is very similar to the working section Mach number and the injected air has a tendency to expand freely into the free stream creating a constant pressure boundary. The boundary of the injected air creates an aerodynamic second throat which recompresses the air of the free stream until the whole flow breaks down through a normal shock near the throat of the downstream flaps. In the starting condition, on the other hand, the static pressure in the injected stream $(M = 1.6)$ is less than the local static pressure in the main stream which is subsonic and near to the total head pressure behind a normal shock for $M = 3.15$ at the end of the nozzle. The injected stream actually contracts during the starting process and hence helps the tunnel to start. Evidently only a small geometric opening of the flap is then required to give an aerodynamic second throat size large enough to permit starting. It is shown in Fig. 10 that for by-pass ratios greater than 90%, for optimum performances the flaps actually have to be closed more during starting than for running. This is not so at low by-pass ratios - then the flaps need to be opened more during starting.

It follows, therefore, that the near-coincidence of flap settings for starting and running would not necessarily apply for other stream Mach numbers or if the Mach number of the injected stream were different or if an attempt was made to recompress the main stream significantly prior to injection for the running condition.

4.1.2 With Convergent Diffuser Ahead of Injector Slot

Figs. 11 and 12 illustrate the effects of contracting the flow from the working section before the injector slots, the amount of contraction being quoted as a percentage of the working section size. The running pressure ratios show a very marked improvement with increase of contraction to 90% but very little gain is to be achieved by increasing to 80%. Results of tests with 70% contraction showed a very marked increase in the required pressure ratio. Results for the starting condition show an improvement in starting pressure ratio with increase of contraction for the lower values of by-pass, but for by-passes greater than 80% the optimum contraction appears to be 90%. The cause of this must be associated with the mixing process downstream of the injector. The starting mechanism is also largely affected by the state of the boundary layer in the convergent entry and this will be controlled to a varying degree by the injected stream.

Shadowgraph observations helped to confirm these results and to indicate the boundaries of the mixed flows. The presence of the expansion of the injected stream during running was indicated by a

fairly strong oblique shock from the upstream lip of the injector which coalesced with the tunnel breakdown shock to form an X shock: the normal portion of which was in the main tunnel stream, the two oblique portions being in the injected stream. Further shadowgraph observations showed the presence of weak oblique shock waves in the initial straight portion of the diffuser increasing in strength as the contraction of the entry to the diffuser increased. These, however, did have a reasonable effect in decreasing the Mach number, as pressure readings for the maximum contraction setting of 70% indicated that the Mach number had dropped to about 2.0 before entering the injector section.

Theoretical results from Ref. 1 also indicate the benefit to be derived from a contracting passage before the injector but in that case the contraction was shorter and showed improved efficiency right down to the maximum contraction of 0.72 x working section height, for a working section Mach number of 3.0 and an injection Mach number of 1.5. This theoretical case, however, assumed injection parallel to the axis of the diffuser and the maximum contraction was defined by recompression to M = 1.0 at the entry section to the injector. Both conditions would be difficult to attain in practice.

These results show, therefore, that with the arrangement tested, in which the diffuser entry converges at a constant angle to the point of injection, a limited increase in overall efficiency can be gained from recompression in the diffuser entry.

Although it was not expected that convergence would improve the starting pressure ratio to any large extent, it was considered possible that a different geometrical arrangement with a fair amount of convergence might improve the running pressure ratio, particularly if the angle of convergence is made steeper with a following parallel portion to establish steady flow at a lower Mach number. A modification of this form will probably result in a poorer starting pressure ratio but this is of little consequence when the diffuser is used in combination with a flexible nozzle. These remarks are at present purely speculative but it will be possible to investigate these geometry effects in the full scale tunnel whose mechanical design has been arranged with this in mind. The remarks are included here merely as a suggestion that with a different geometry, a convergence ratio less that 90% might be beneficial whereas with the geometry as tested, 90% certainly is about the best value.

In Figs. 13 and 14 the optimum flap settings are given, the change of flap setting with by-pass agrees very closely for the parallel and 90% diffuser entry but for 80% contraction the variation of flap setting shows a marked divergence. At the higher by-pass the flap setting has to be considerably larger to compensate for the effective increase of injector angle, at the lower by-pass the flaps can be set in further to maintain near continuity of slope with the angle of the first diffuser.

4.2 Effect of Support Sector on Diffuser Efficiency

The representative model support sector is shown in Fig. 5. For these tests the model and balance body were not present. The results are shown in Fig. 15 for the three diffuser contraction ratios (100%, 90% and 80%).

The presence of the sector tended to create an instability of the shock system in the diffuser which gave rise to different values for pressure ratio being observed. Sometimes the tunnel breakdown was the same as that described for the empty tunnel but at other times a strong pair of oblique shocks could be observed from a separation a little upstream of the injection point. When this condition occurred the pair of oblique shocks were unstable and oscillated between the position just

upstream/

upstream of the injection point and a position just downstream of the support sector. When the shocks were observed in the latter position the tunnel breakdown occurred in the normal manner downstream of the injector. There is evidence as shown in Fig. 15 that these two types of diffuser flow give rise to different diffuser efficiencies and hence different overall pressure ratios. The changeover from one type of flow to another is dependent upon by-pass quantity, the higher the by-pass the better the diffuser efficiency. During the test it was possible to obtain exact repeatability from day to day to demonstrate that the different types of flow are quite consistent. The curves of Fig. 15 give the impression that it was possible to obtain two values of starting pressure ratio for one value of percentage by-pass in the region of 90% to 100% by-pass. The tests did in fact give consistent values of pressure ratio for 90% by-pass which were lower than those obtained for 100% by-pass. On the other hand, it was found that for the 90% diffuser setting at 70% by-pass two different values of running pressure ratio could be obtained in repeated tests.

Instead of there being little difference between the pressure ratios for 80% and 90% convergence, the 90% value is seen to be definitely the optimum in the presence of the sector. Converging the diffuser further made it impossible to start the tunnel at by-pass values greater than 70%.

In general, as might be expected, the presence of the sector at the entry to the diffuser improves the efficiency for the running condition but decreases the efficiency for starting. At the higher by-pass rates, however,· both run and start conditions are improved.

4.3 Effect of Model, Balance and Sector on Diffuser Efficiency

To determine the effects of model disturbance on the efficiency of the diffusor a representative balance body was mounted on the sector as shown in Fig. 5. The results of tests on the configuration at zero incidence are shown in Fig. 16. Also included in this figure are the results for the sector-only condition to act as a comparison. Fig. 16 gives results for the 90% diffuser entry condition.

The presence of the model and its associated wake has the effect of eliminating the special flow conditions which were found to prevail in the 'sector alone' configuration, and the resulting pressure ratio curves conform more to those of Fig. 11 for the empty tunnel case. Comparison of Figs. 11 and 16 demonstrates however that there is still an advantage to be gained from a disturbance in the working section in triggering off a shock recompression system in the running case, but the starting conditions require a pressure ratio 5% higher than that needed for the empty tunnel.

4.4 Effect of a Hole in the Floor of the Working Section

The requirements of large incidence in the full scale tunnel have made it necessary to have a hole in the floor at the rear of the working section to accomodate the balance body. In order to determine the effects of this hole on diffuser efficiency, measurements were made of overall pressure ratio for the 'sector alone' condition with a hole in the liner floor (0.2 tunnel height wide × 0.75 tunnel height long). The results of this test are compared with the 'sector alone' case with no cut out in Fig. 17. The most interesting feature of these results is the way in which the disturbance created by the hole in the floor modifies the flow in the starting condition, and does in fact considerably improve the efficiency at the lower values of by-pass flow. The flow instability due to separations which were discussed in Section 4.2 have been steadied by the changes of flow condition in the working section and have resulted in an improved flow in the diffuser and at the entry to the injection section.

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The pressure ratio for running conditions shows a small increase at the higher values of by-pass but in general corresponds very closely to the conditions for the plain working section.

4.5 Effect of Balance Angle in Working Section

To obtain a realistic picture of the performance of the full scale supersonic tunnel it was necessary to determine the effects of changes of model attitude on the required pressure ratio. The model for these tests however was only a representative cylindrical body Fig. 5 as it was not safe to test a lifting model under starting and shut-down conditions in the model tunnel. It is considered that this model would create a representative flow condition.

Fig. 18 shows the result of these tests with balance angles of 0°, 22° and 45° for the minimum running pressure ratio. Contrary to expectation the 22° setting provides the most efficient conditions being very slightly better than the 0° setting. The results show that 5% extra pressure ratio is required to run the tunnel with a model at 45° incidence. Results for starting pressure ratio, which are not included in Fig. 18 show that the starting pressure ratio for the 0° and 45° settings are almost identical but the 22° setting requires about 4% less pressure ratio.

Later tests on a model with a large delta wing at $M = 2.0$ have indicated that an increase of pressure ratio of about 5% is required from 0° to 22° incidence. At $M = 3.15$ with the same model it was found that an increase of 4% was needed for the minimum running pressure ratio from 0° to 22°.

4.6 Effect of Increased Mach Number

In order to check the effect of diffuser configuration at higher Mach numbers the liners which were used for the previous tests were adjusted to give Mach numbers of 3.22 and 3.42. In both cases the Mach-number distribution was satisfactory. The most significant features that resulted from these tests was the need to expand the entry of the initial part of the diffuser to 110% of working section size at $M = 3.42$. Diffuser settings which did not include this expansion would not permit starting. This effect must be associated with the increased expansion of the injected stream creating too much blockage for starting. This effect might be expected because the pressure of the main stream drops with increase of working section Mach number and so causes the injected stream to expand more into the mainstream, at the same time the size of the permissible second throat for starting changes only very slowly according to

$$\frac{\text{Area of second throat}}{\text{Area of working section}} = \sqrt{\frac{M^2 + 5}{7M^2 - 1}} \left\{ \frac{7M^2 - 1}{6M^2} \right\}^3$$

It should be possible to improve the running pressure ratio for $M = 3.42$ by closing the diffuser when it has started in the normal manner of convergent-divergent diffusers but this could not be demonstrated in these tests.

Fig. 19 shows that the advantages of injection continue for the higher Mach numbers but at these values a higher injection Mach number could probably be used to advantage as its choking effects would be reduced.

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5. Relationship of Injection Results to Compressor Characteristic

It is of interest to examine how these results relating by-pass flow, pressure ratio and Mach number match with the compressor flow characteristic. The operation of a tunnel from a fixed speed compressor having one characteristic is very different from an experimental test plant where all quantities may be varied independently.

In Fig. 20 the results of these tests have been used to show how variation of quantity of by-pass flow varies the operating characteristic for any Mach number. The curves of constant Mach number are derived from the experimental results of variation of pressure ratio with by-pass flow. The intersection of a Mach number curve and the compressor characteristic gives the optimum tunnel setting for that Mach number, i.e., it gives the minimum pressure ratio. Operation at any other point on the constant Mach number curve requires less mass flow than the compressor provides at that pressure ratio and so the tunnel will in fact operate at a higher pressure ratio corresponding to a point on the compressor characteristic which provides the required mass flow. For example the constant Mach number curve M on Fig. 20 has an optimum setting at A, any other tunnel setting giving less by-pass flow will move the operating point to B and the compressor will actually run at a point on its characteristic corresponding to C. Thus from the operating point of view the injector flow may be set to any value on a constant Mach number line between the compressor characteristic and a line representing the mass flow at surge.

From the results in Fig. 20 it appears that the final limitation on Mach number will probably be the mass flow available for injection rather than pressure ratio.

6. Subsonic Diffuser

As a final detail in the design of the full scale tunnel it was desirable to test the effect of different subsonic diffuser shapes. As a standard for these tests a long slow diffuser was used with a 4:1 expansion ratio and a 5° included angle. This gave a completely smooth transition from square to circular, and was designated diffuser A. Two other diffusers were tested and compared with this on the basis of overall pressure ratio. Diffuser B also expanded at a 5° included angle to a ratio 1.7:1 where it expanded at a step to a ratio of 2.5:1 and remained parallel for 3 tunnel heights before finally expanding at a step to a ratio 4:1. Diffuser C initially expanded at 10° included angle to a ratio 2.5:1 and remained parallel for three tunnel heights before expanding at a step to a ratio 4:1.

The results are given in Fig. 21 and show that there is quite a considerable difference between diffusers B and C the former being considerably more efficient despite the losses at the extra step. It is shown that diffuser B is quite as efficient as the more ideal diffuser A for the running conditions and does in fact show an improvement in the starting case. This latter effect must be associated with the balance of losses between the friction of a long uniformly expanding duct and pressure recovery of an expansion at a step. It is of interest to note when comparing diffusers B and C that despite the presence of the poor entry conditions that must prevail in both diffusers there is still considerable pressure to be recovered by keeping within the accepted expansion rate of 6° for diffuser.

7./

7. Conclusions

(1) Using by-pass injection in the supersonic diffuser of a tunnel running at M = 3.15 has the effect of decreasing the required pressure ratio from an estimated value of at least 4.0 with an adjustable diffuser down to 3.0 with a by-pass flow quantity of 1.2 × working section flow. This pressure ratio could be further decreased by the use of larger injection quantities.

(2) An improved efficiency could probably be obtained with a shortened entry portion at the front of the diffuser but the possible amount of contraction would probably be limited by the choking effect induced by the extra expansion of the injected stream.

(3) At the higher working section Mach numbers an increase of injection Mach numbers would decrease the amount of expansion of the injected stream and would permit additional contraction of the diffuser entry giving improved pressure recovery,

(4) The presence of a model support sector at the entry to the diffuser gives improved diffuser efficiency in both the running and starting conditions for high values of by-pass. Apart from the expected increase in efficiency due to the creation of oblique shock waves by the sector in the running condition, there also appears to be a modified shock system in the diffuser which gives pressure recoveries better than those achieved for the empty tunnel.

(5) The presence of a model and balance mounted on the sector in the working section has the effect of decreasing the running pressure ratio below that required for the empty tunnel, but 5% greater starting pressure ratio is required.

(6) The effect of model incidence is shown to be quite small but the model did not carry lifting surfaces which would create a true wake.

(7) Tests on three subsonic diffusers following the supersonic diffuser indicate that it is essential to maintain an expansion rate equivalent to a 6° cone or less. It would appear from these tests that in this case, there is also nothing to be achieved by making the subsonic diffuser abnormally long as a small step at the end of a shorter diffuser has smaller losses than the friction of the larger surface area of a long diffuser.

References/

References

No.	Author(s)	Title. etc.
1	Spiegel, Hofstetter and Kuehn	Applications of Auxiliary Air Injectors to Supersonic Wind Tunnels. N.A.C.A. RM. A53I01.
2	Huoczak and Pousso	Starting and Operating Limited of Two Supersonic Wind Tunnels Utilising Auxiliary Air Injection Downstream of the Test Section. N.A.C.A. TN. 3262.
3	Fejer and Clark	Compressors for High Speed Wind Tunnels. AGARDOGRAPH 14.

FIG. I.
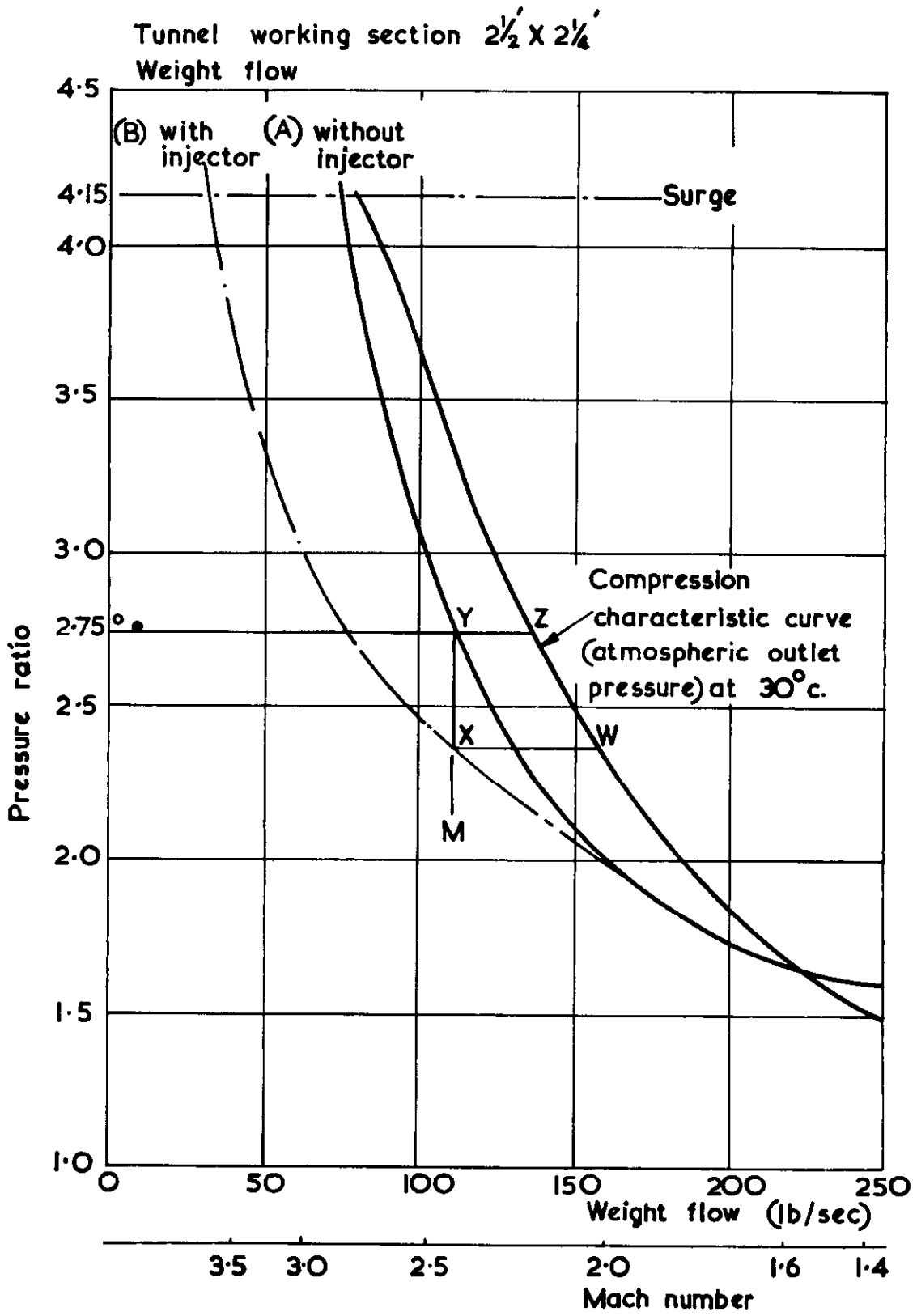
FLOW REQUIREMENTS

FIG. 2.
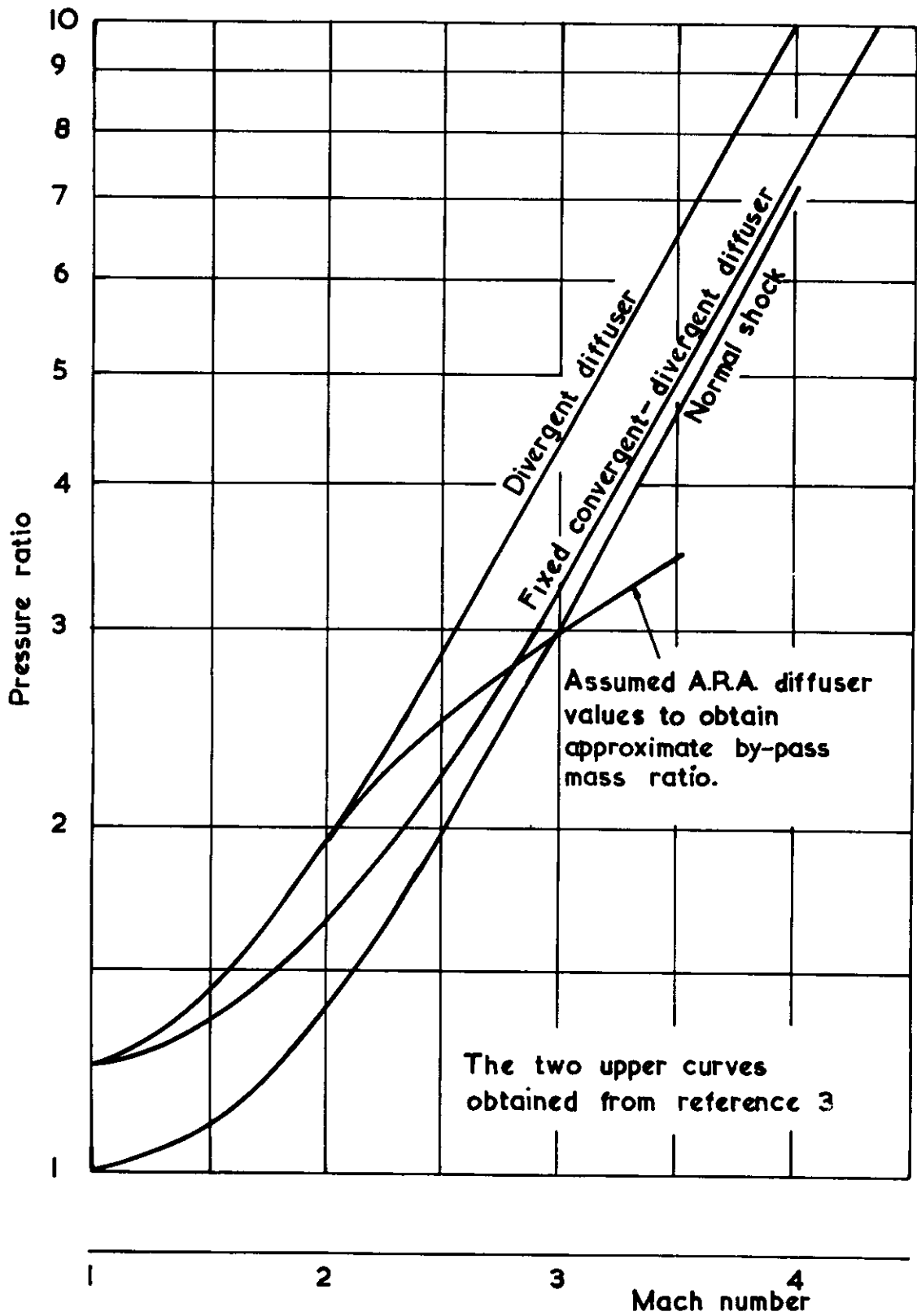
PRESSURE RATIO VERSUS MACH NUMBER

FIG. 3.

Percentage by pass = $\dfrac{\text{wt. flow through by pass}}{\text{wt. flow through working section}}$

(based on one-dimensional sonic flow areas).

Wt. flow percentage by-pass available.

Mach No.
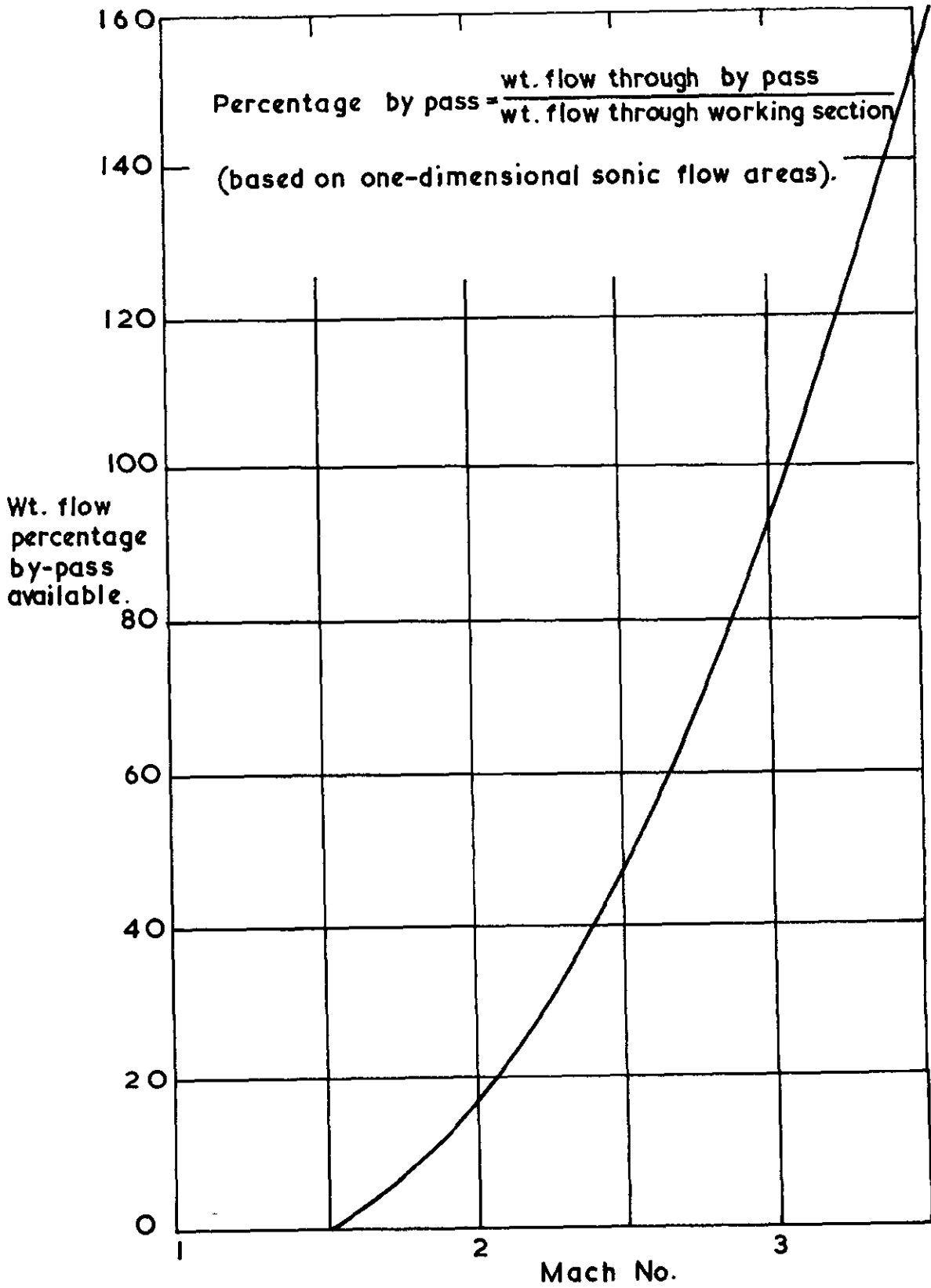
ESTIMATED PERCENTAGE BY PASS FLOW.

Adjustable flaps

Perspex side panel

Pressure shell

Nozzle block $M=3.5$

Supersonic diffuser

Subsonic diffuser

$M=3.15$ Working section

Injector slot

Contraction

Plenum chamber

Position control
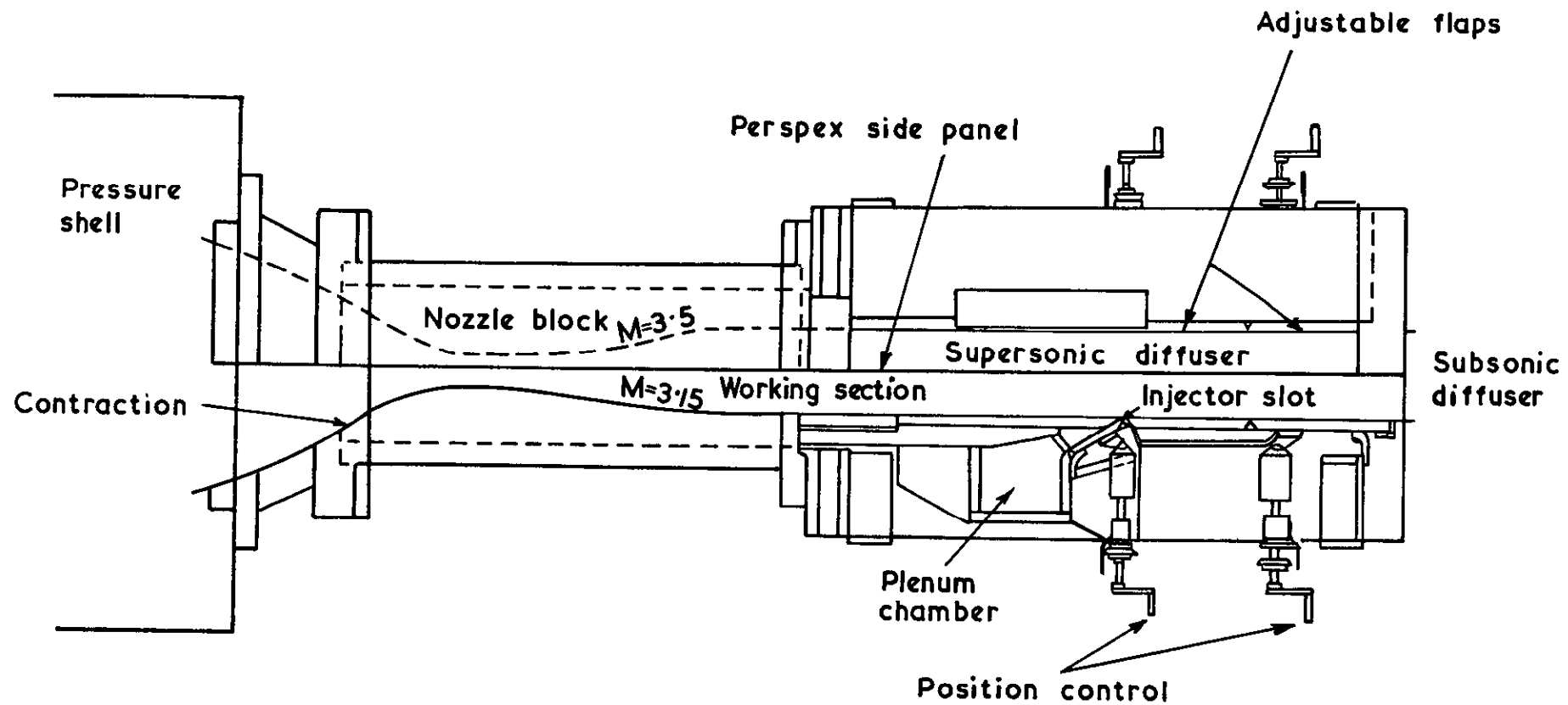
FIG. 4.

GENERAL ARRANGEMENT OF WORKING SECTION AND DIFFUSER.

0·2"

Nozzle block

1·1"

26°

1·6"

2·4" R.

4"

0·7" dia.

0·2"dia.

3·2"

0·8"

45°

22½°

FIG. 5.
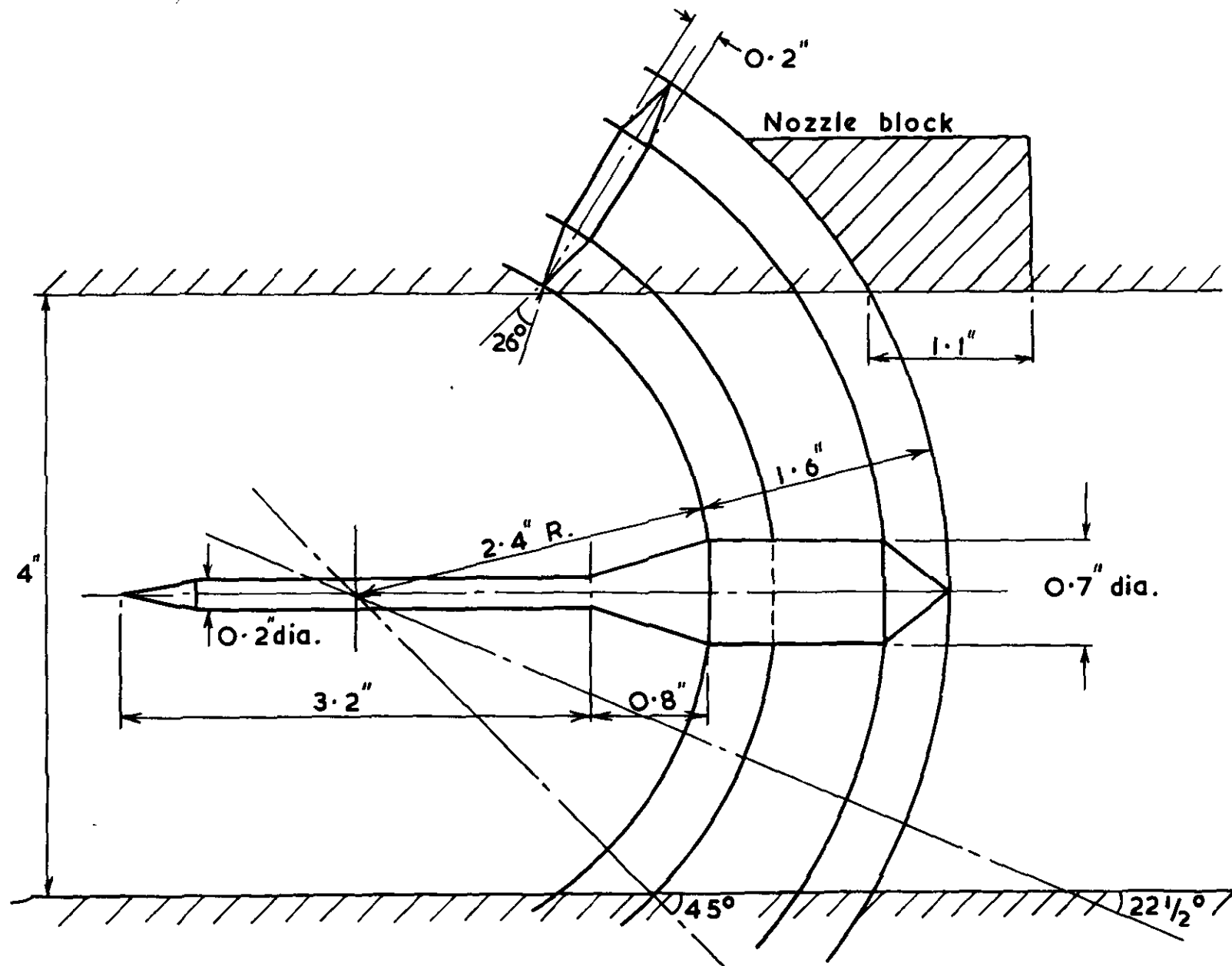
REPRESENTATIVE MODEL, BALANCE, AND SECTOR FOR DIFFUSER TEST.

Working section

Height   1·0   0·7

Mach number

3·5

3·0

2·5

2·0
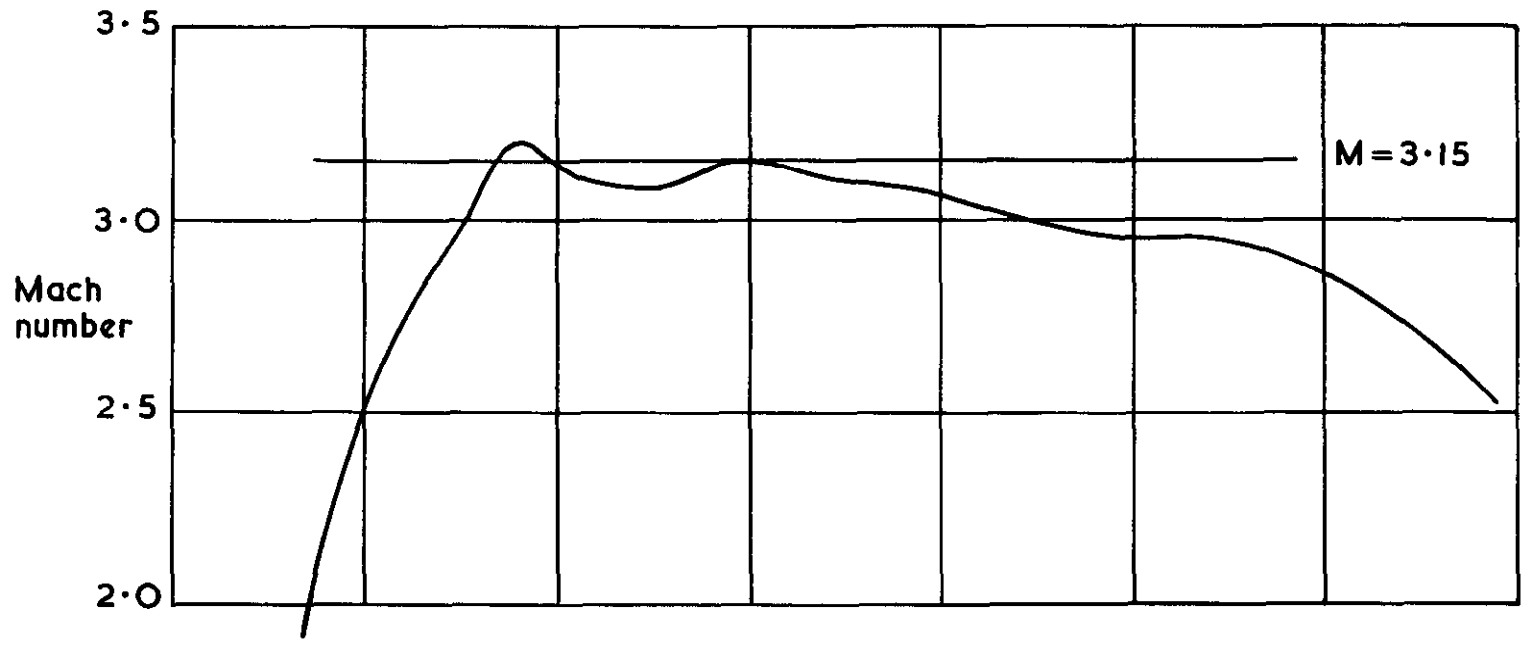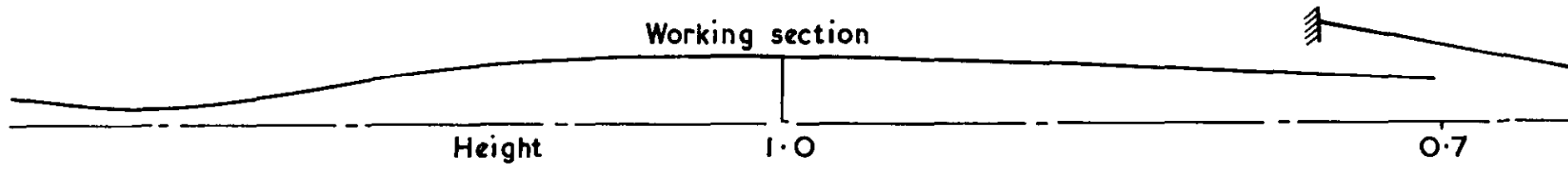
M = 3·15

SUPERSONIC LINER. NOMINAL M = 3·2

FIG. 6.

FIG. 7.
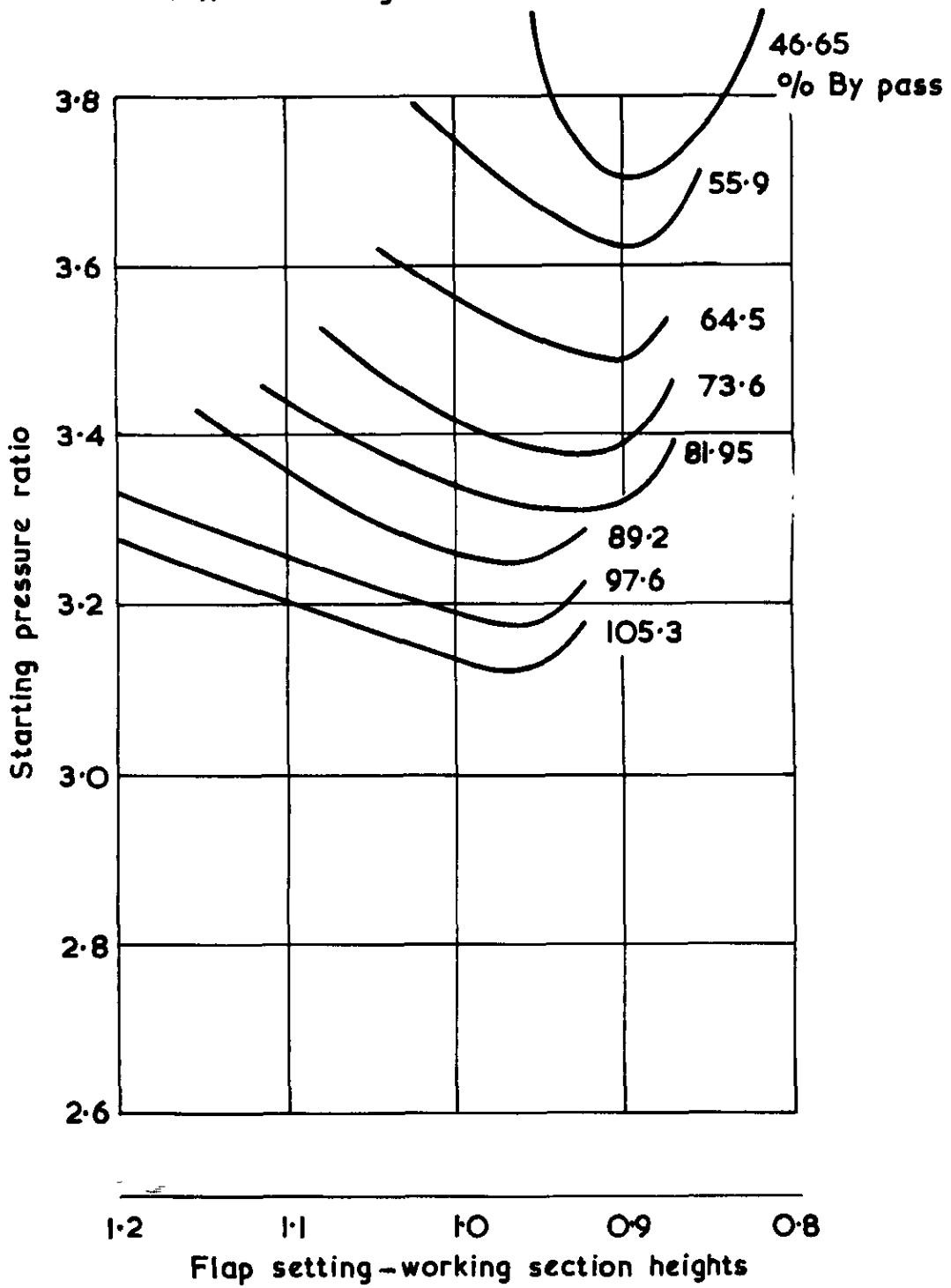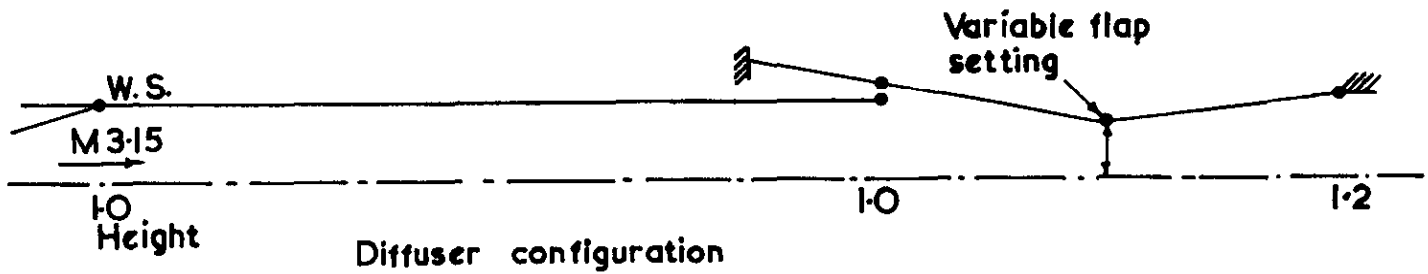
M 3·15 STARTING PRESSURE RATIO-PARALLEL DIFFUSER

FIG. 8.
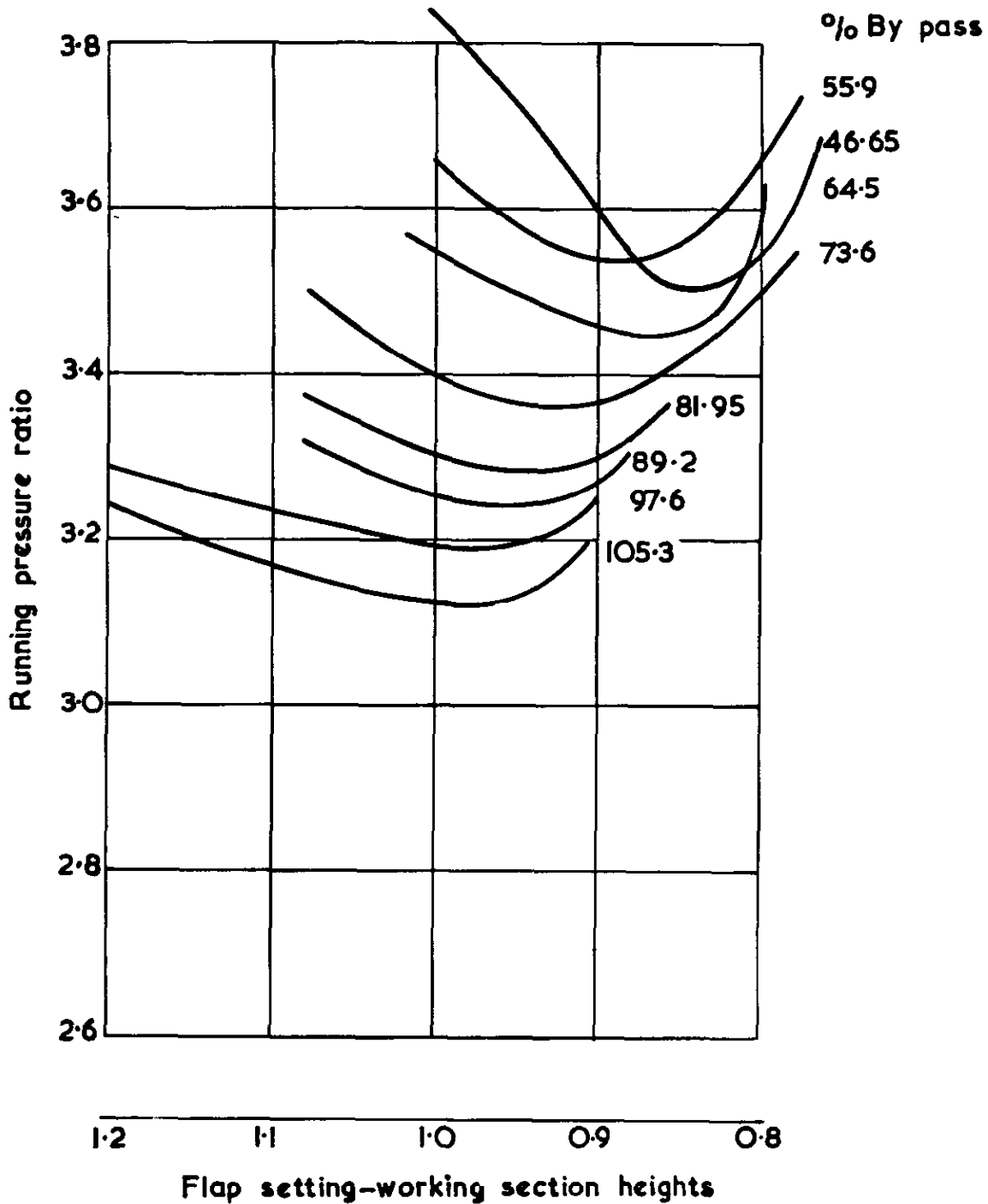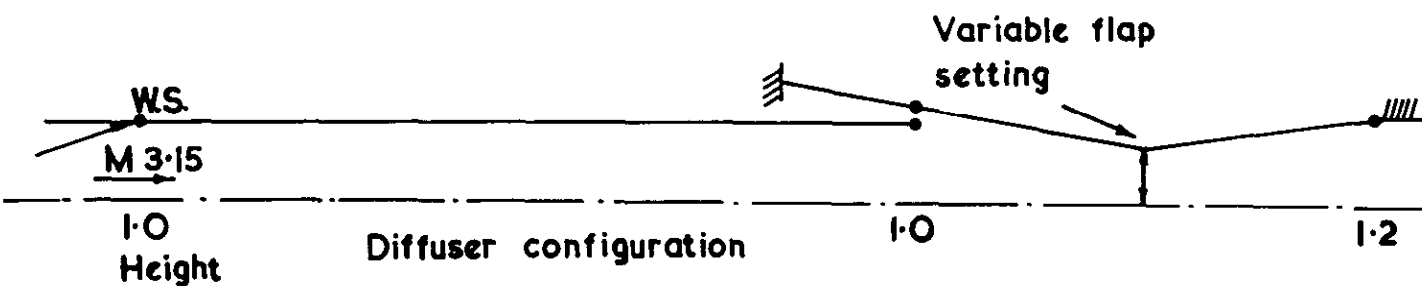
M 3·15 MINIMUM RUNNING PRESSURE RATIO—PARALLEL DIFFUSER

FIG. 9 .
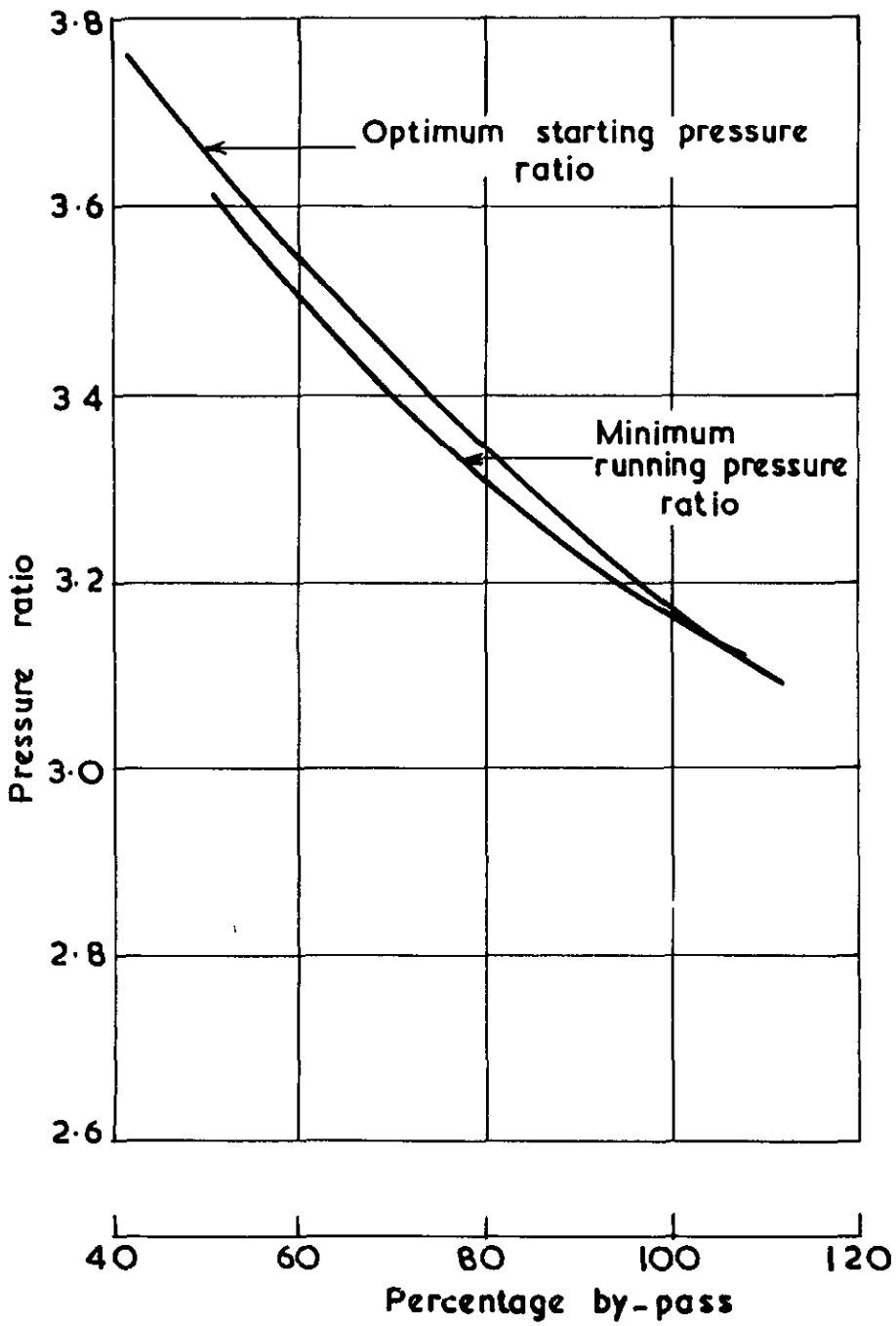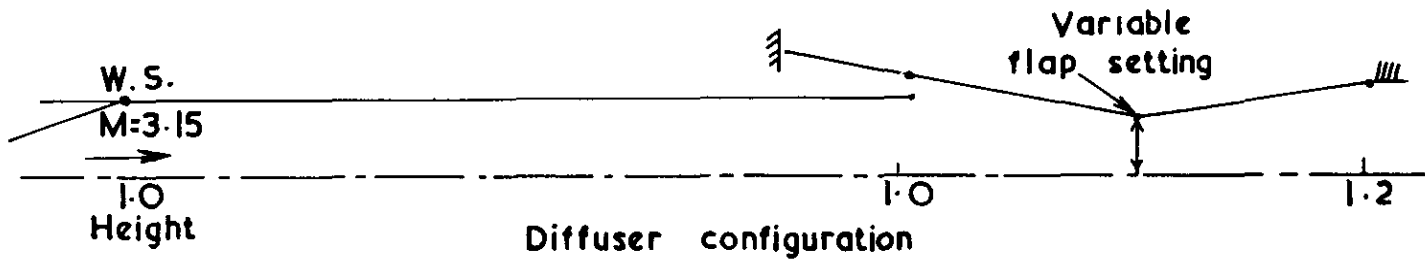
M= 3·15 OPTIMUM STARTING AND RUNNING PRESSURE RATIO PARALLEL DIFFUSER.

FIG.10

Variable flap
setting

W.S.

M=3.15

1.0
Height

1.0

1.2

Diffuser configuration
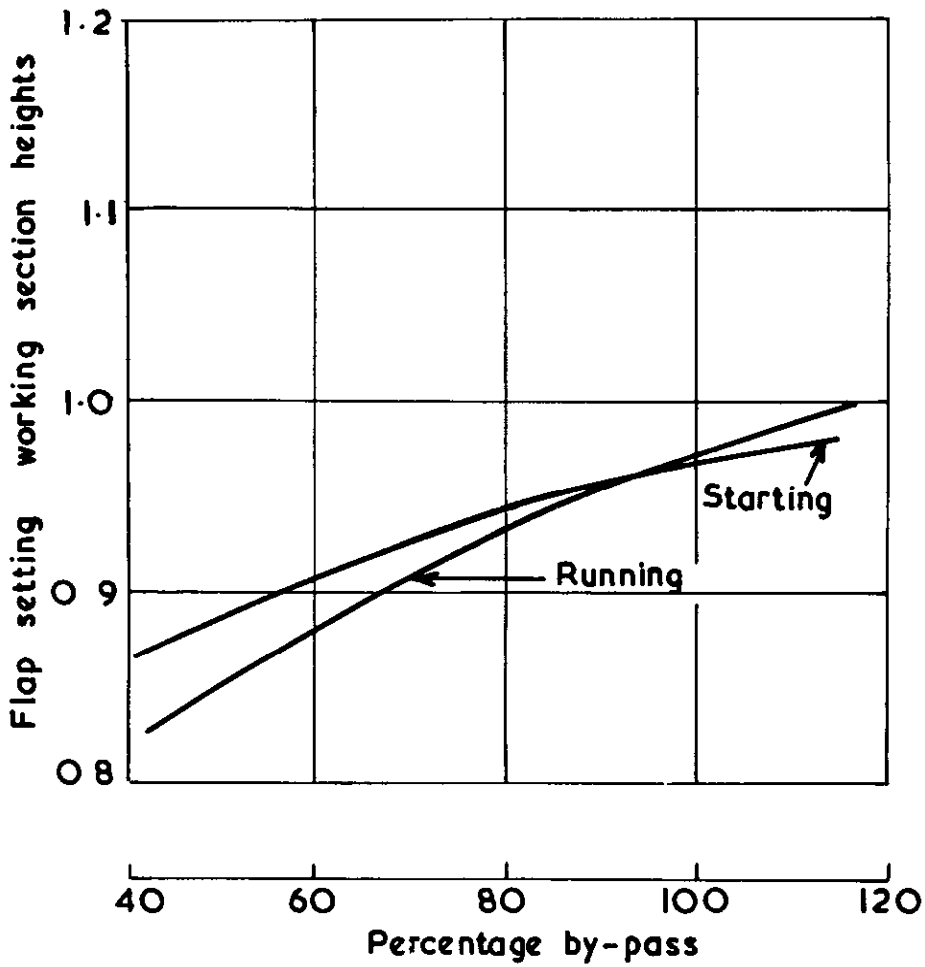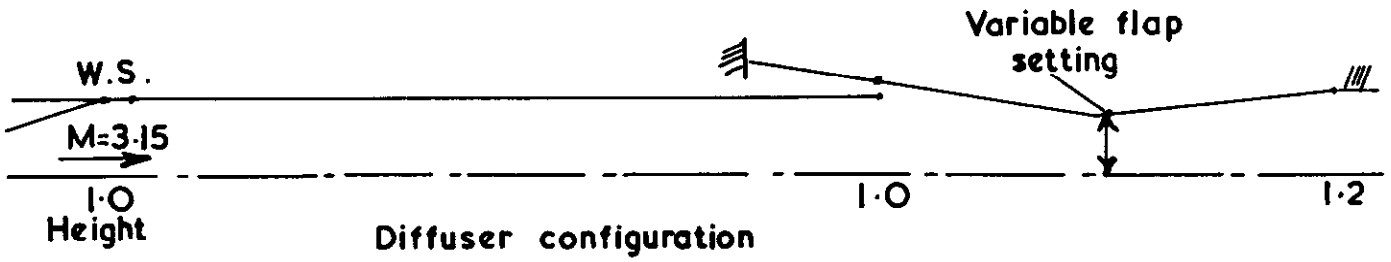
Starting

Running

M = 3.15 OPTIMUM FLAP SETTING RATIO PARALLEL
DIFFUSER.

FIG. II

Diffuser configuration
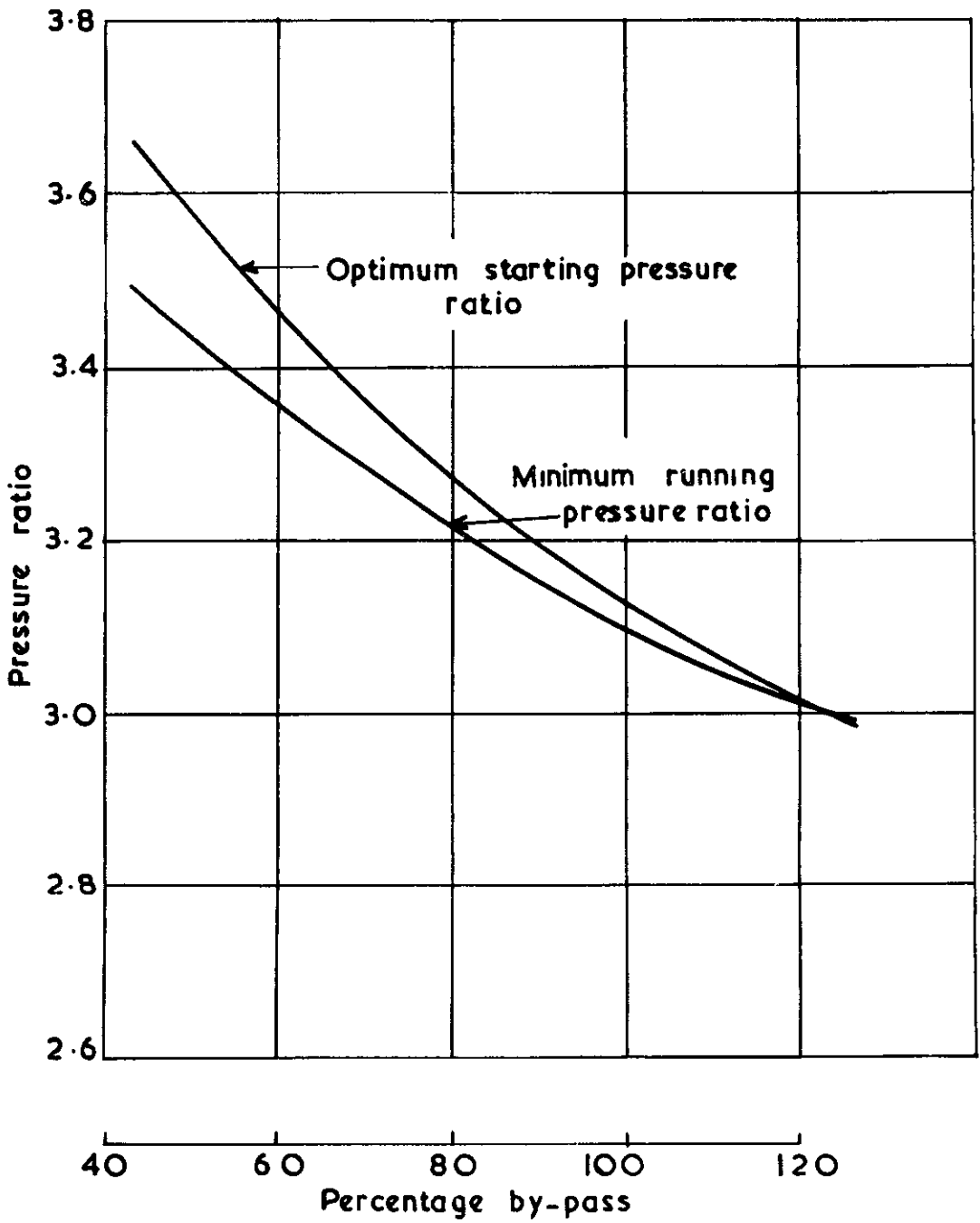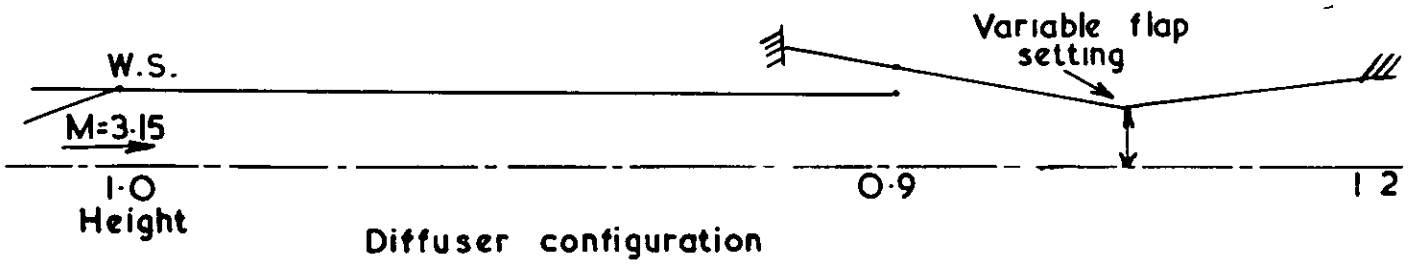
M=3.15 OPTIMUM STARTING AND RUNNING RATIO 90% DIFFUSER.

FIG.12
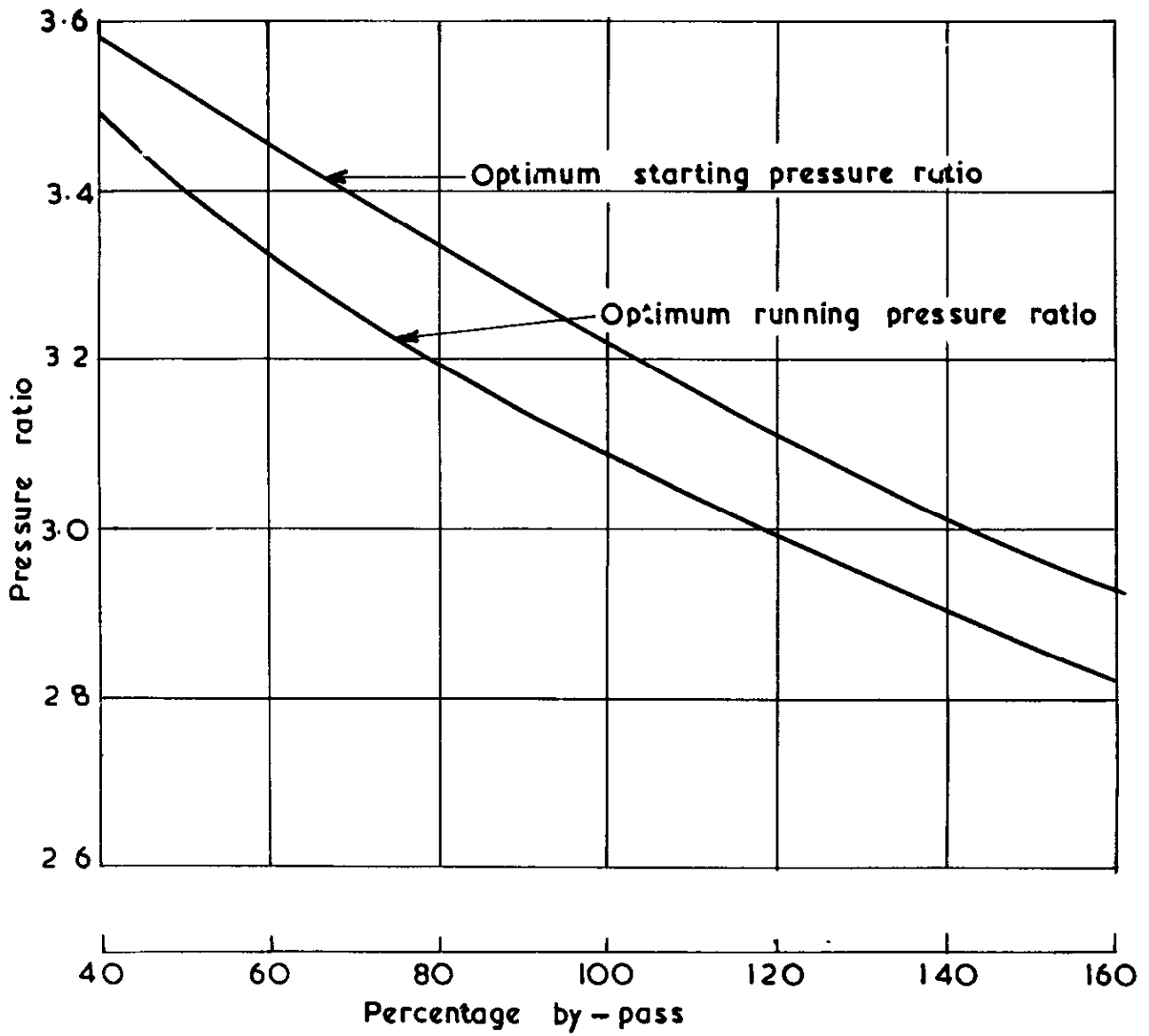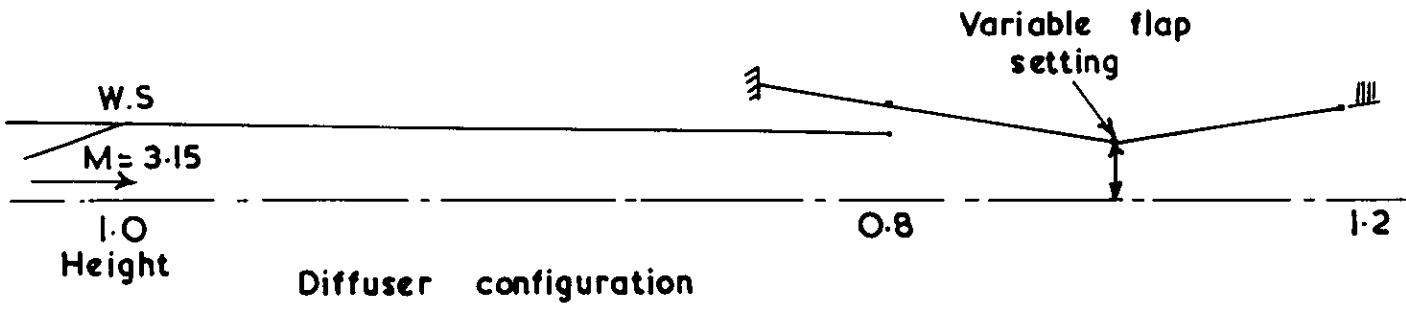
M = 3 15 OPTIMUM STARTING AND RUNNING RATIOS. 80% DIFFUSER.

FIG.13.
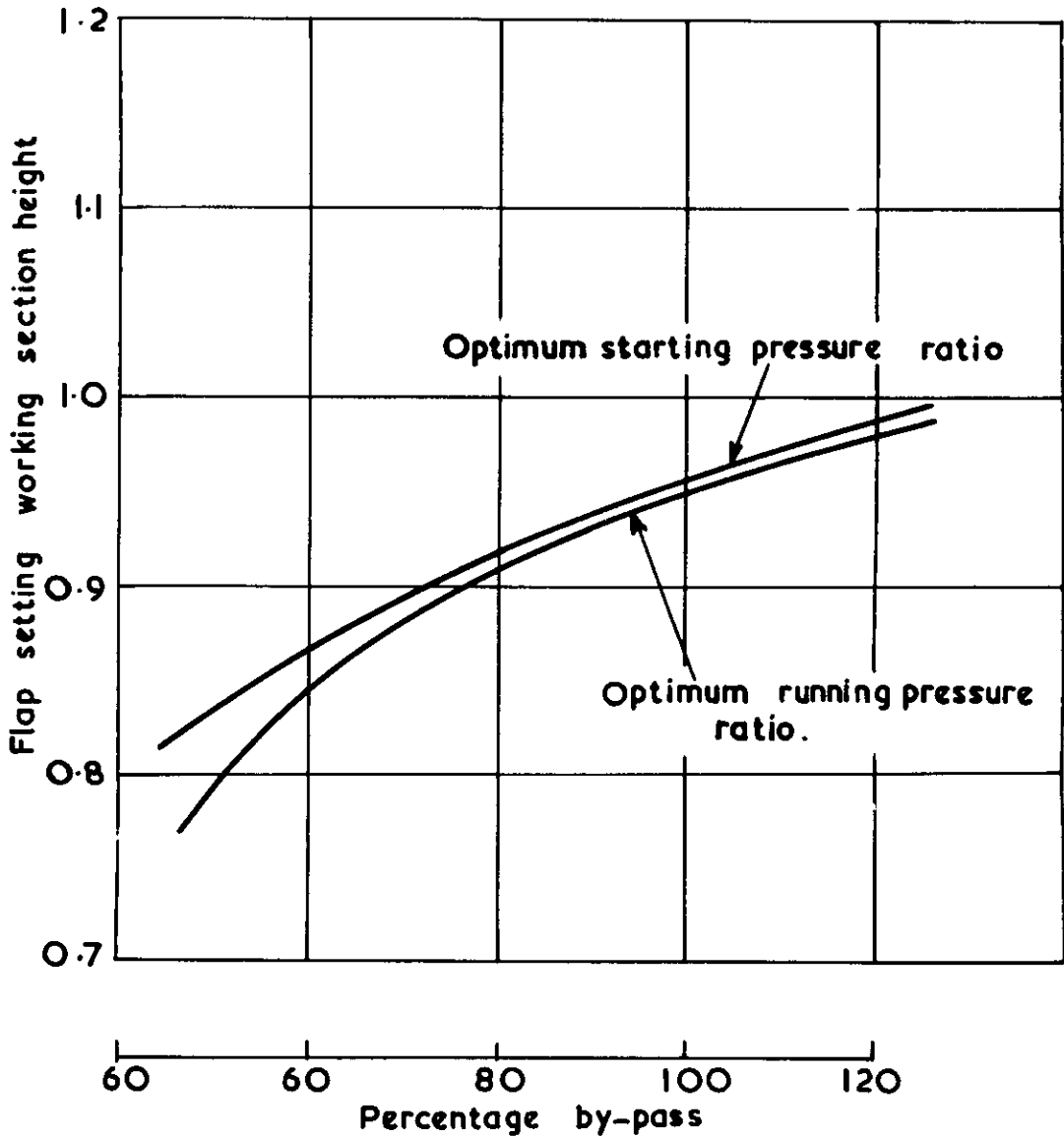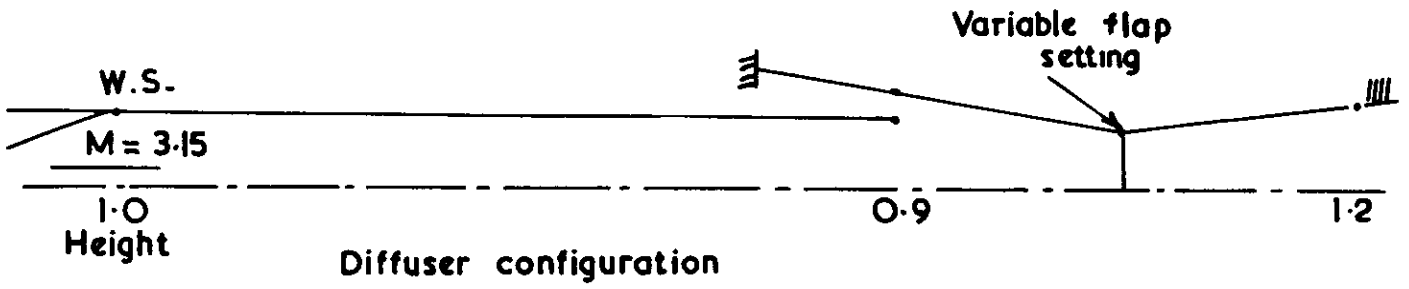
M = 3·15   OPTIMUM   FLAP   SETTING   RATIOS.   90 %   DIFFUSER

FIG.14.
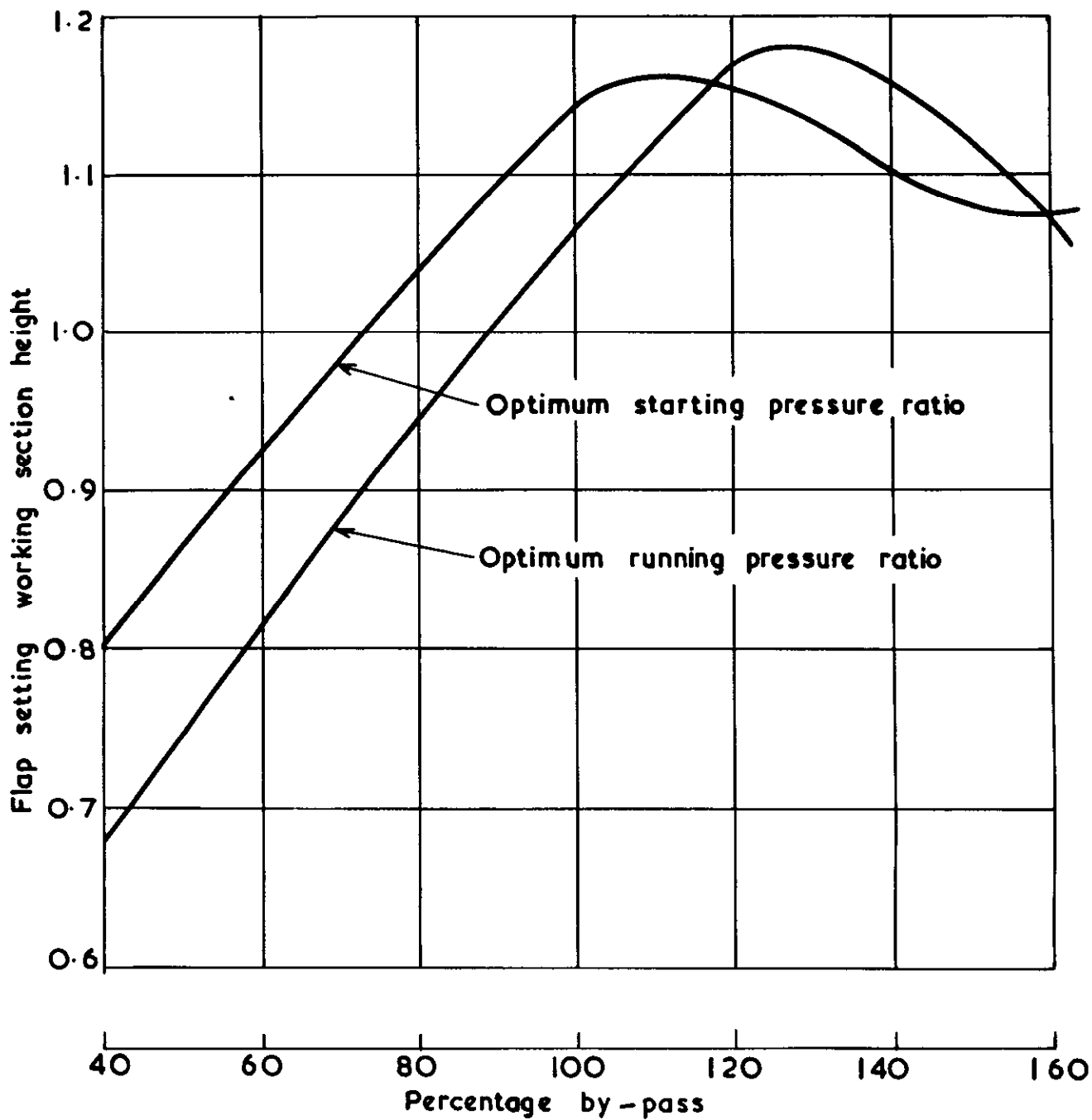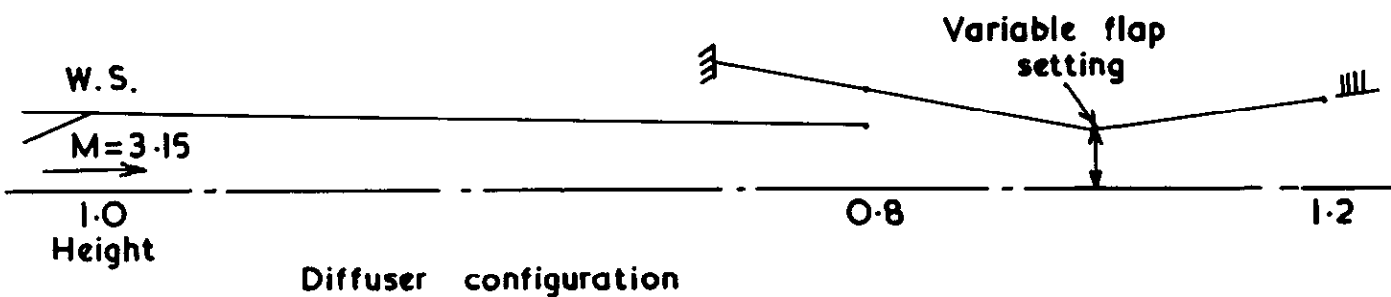
M= 3·15 OPTIMUM FLAP SETTING RATIO. 80% DIFFUSER.

FIG.15.

W S

M = 3·15

Height
1·0

Diffuser configuration

Variable flap
setting

1·0
0·9
0·8

1 2

— 100 % Diffuser
— 90 % Diffuser
--- 80 % Diffuser

These local dotted
regions illustrate the
points where the
curves are not
applicable:
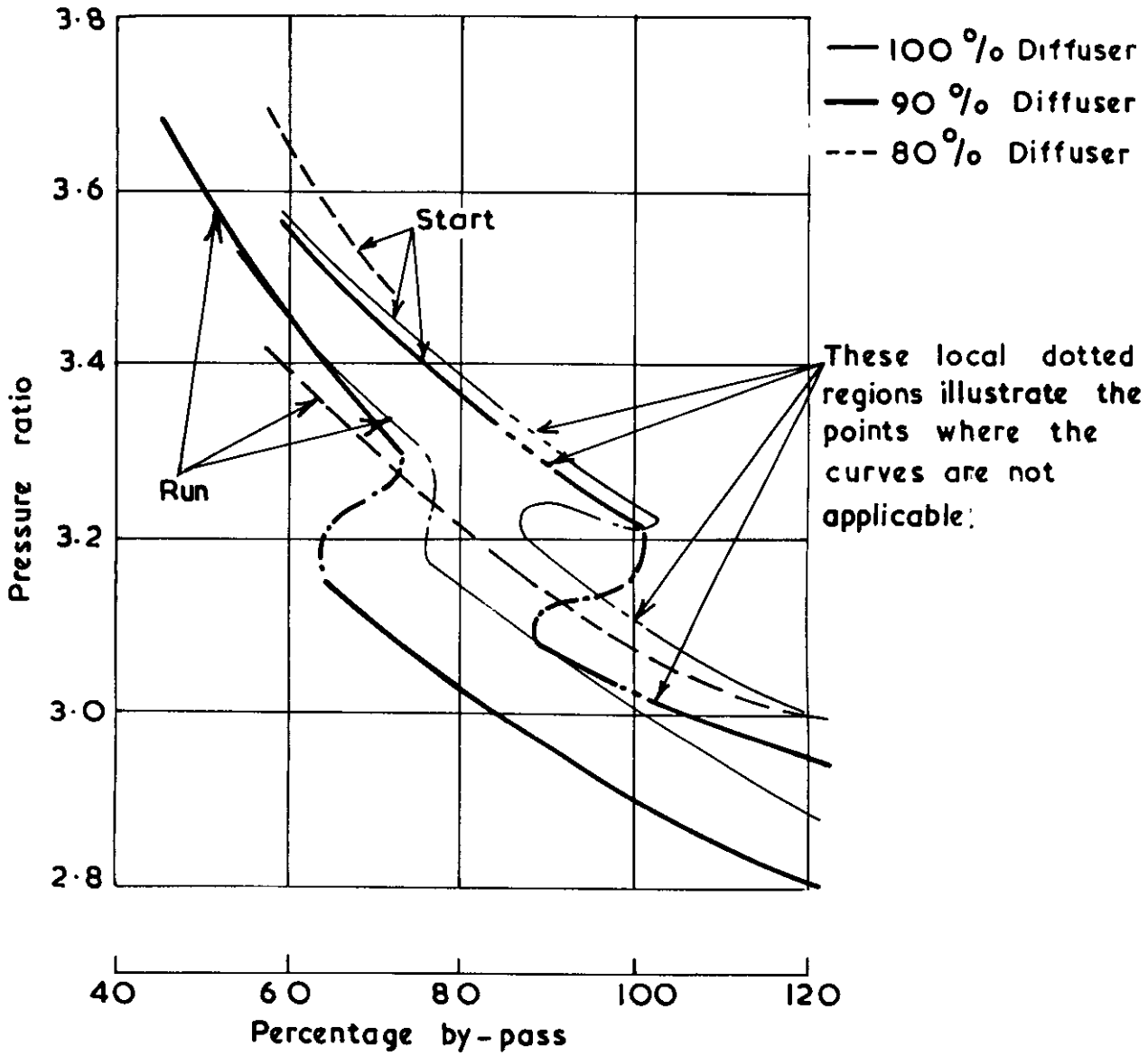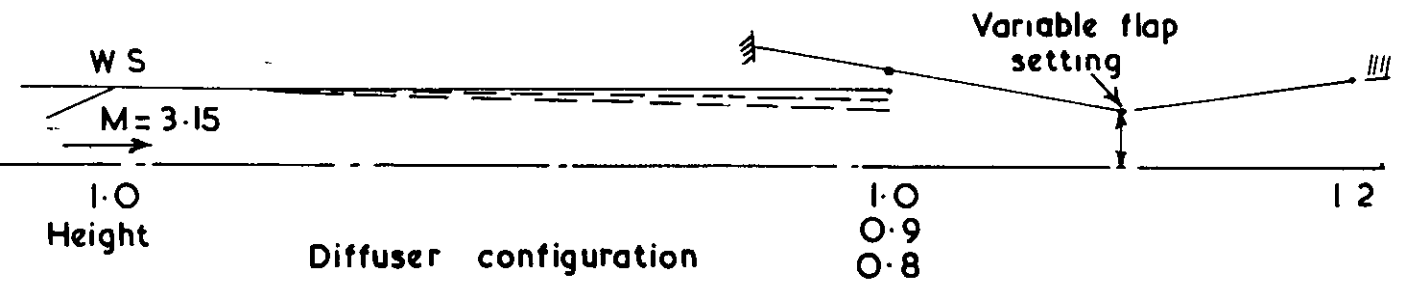
OPTIMUM STARTING AND RUNNING RATIOS. WITH SECTOR, $\left(100\,\%,\right.$
$\left.90\,\%, 80\,\% \text{ DIFFUSER}\right)$ M 3·15.
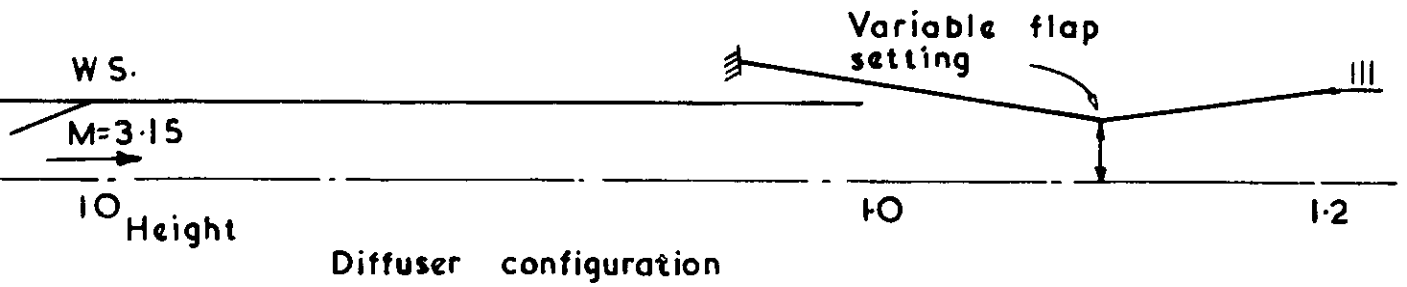
FIG.16.

Diffuser configuration
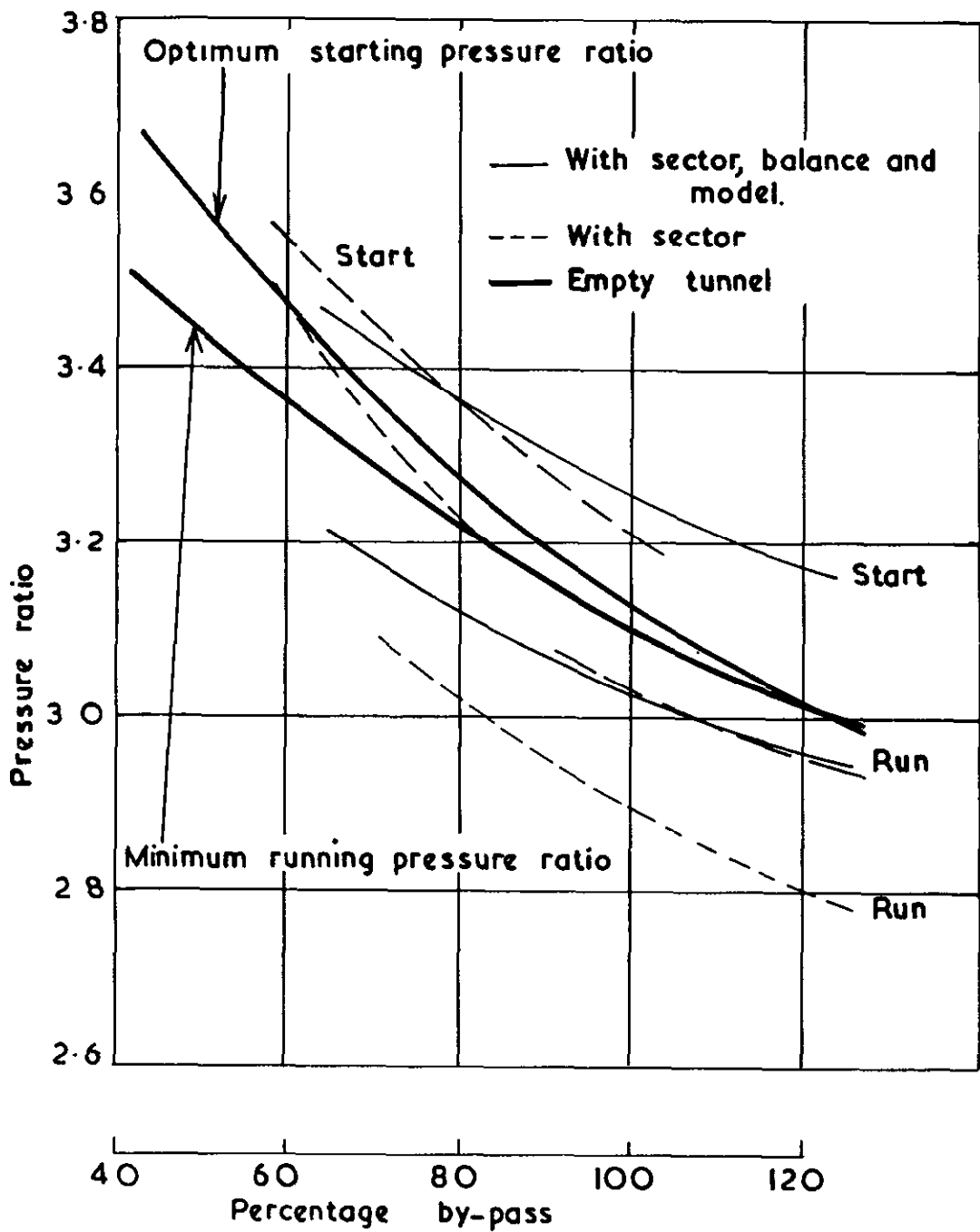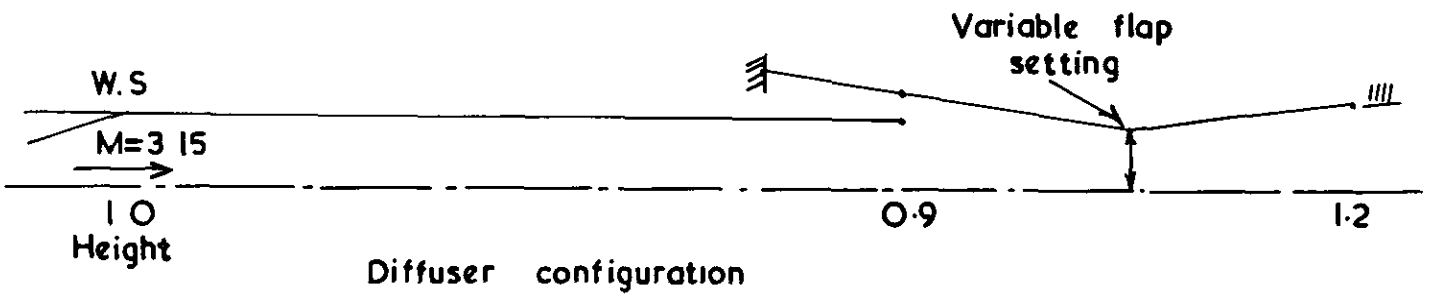
M 3·15 OPTIMUM STARTING AND RUNNING RATIOS . WITH SECTOR
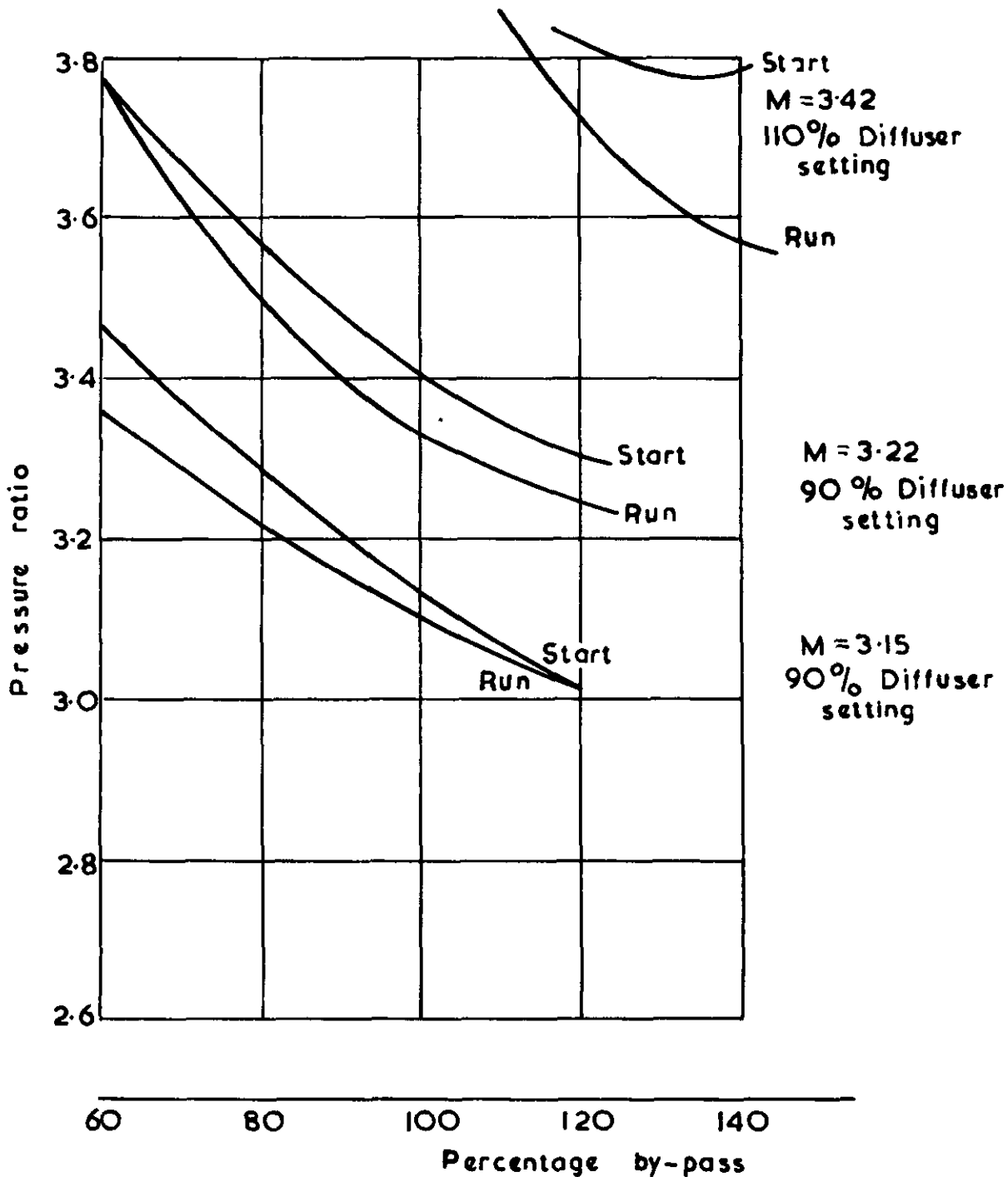AND BALANCE (90 % DIFFUSER) AND MODEL.

FIG. 17.
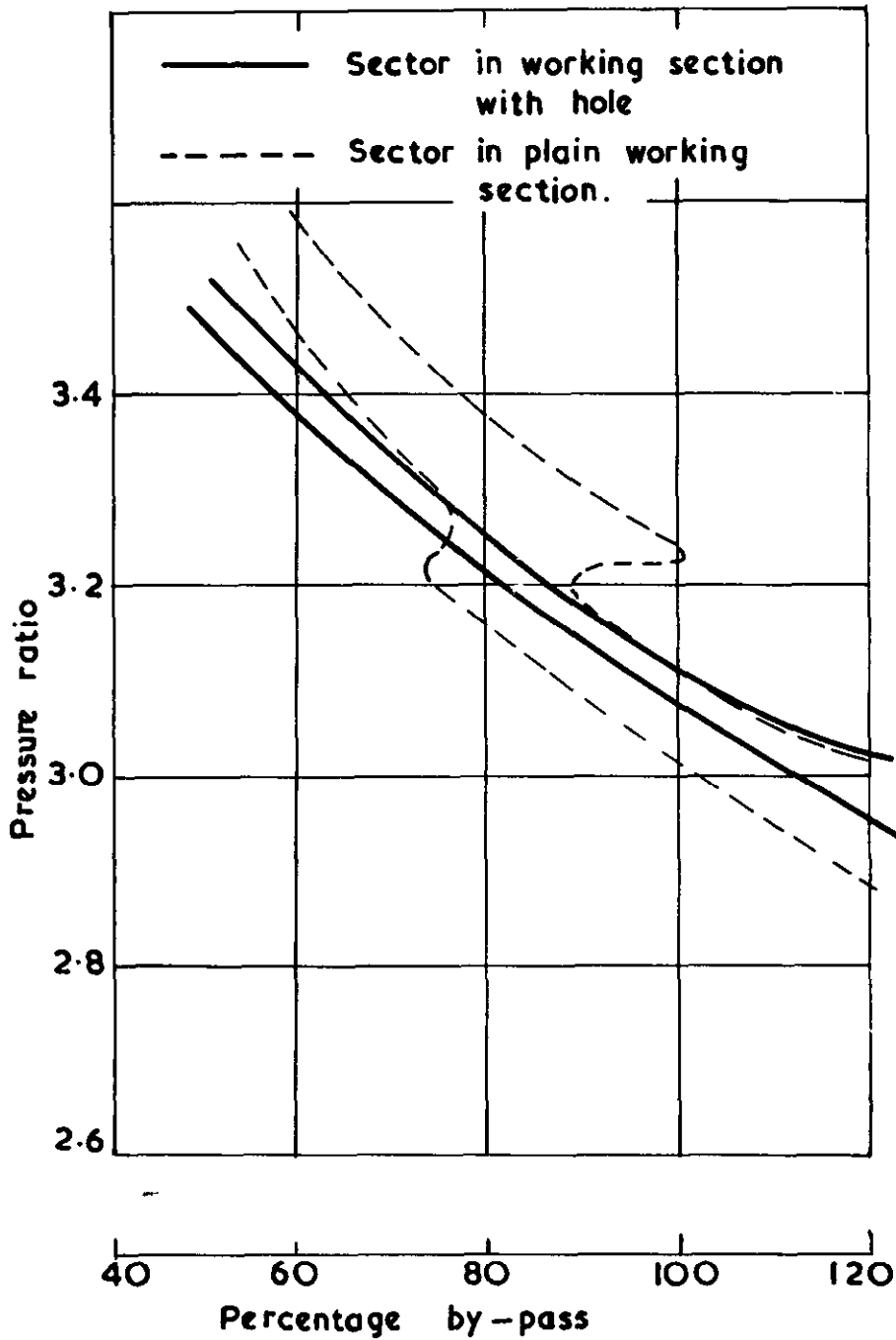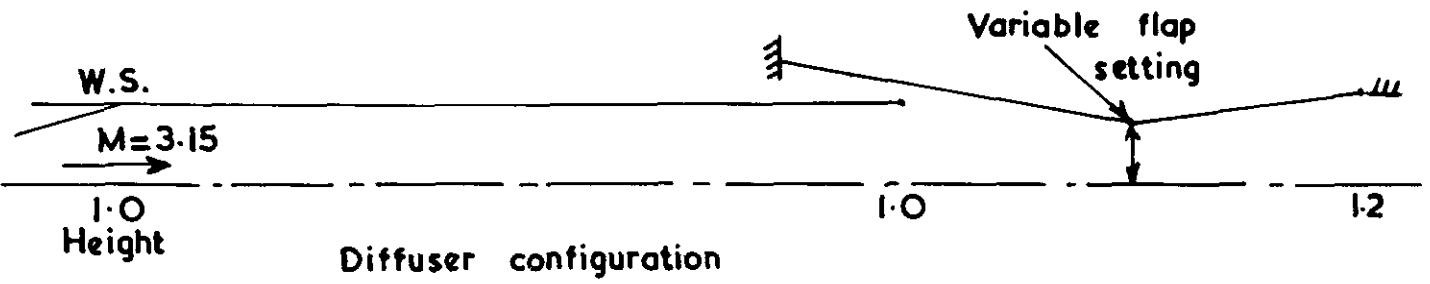
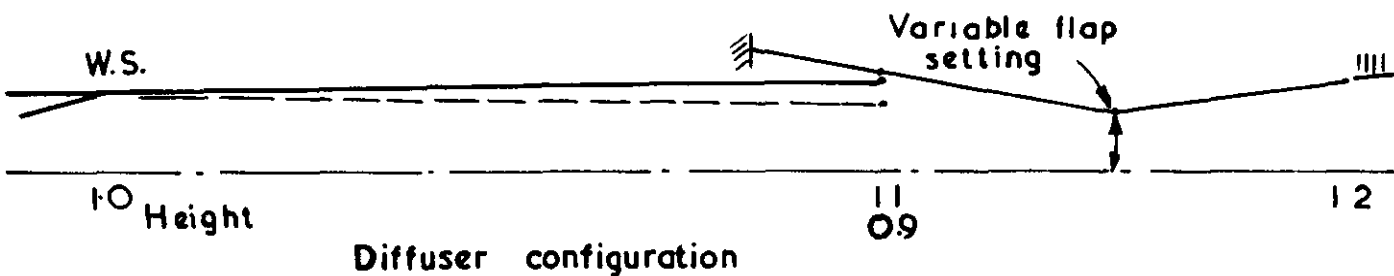EFFECT ON PRESSURE RATIO OF THE PRESENCE OF HOLE IN THE WORKING SECTION TO ACCEPT BALANCE BODY (PARALLEL DIFFUSER) M = 3·15.
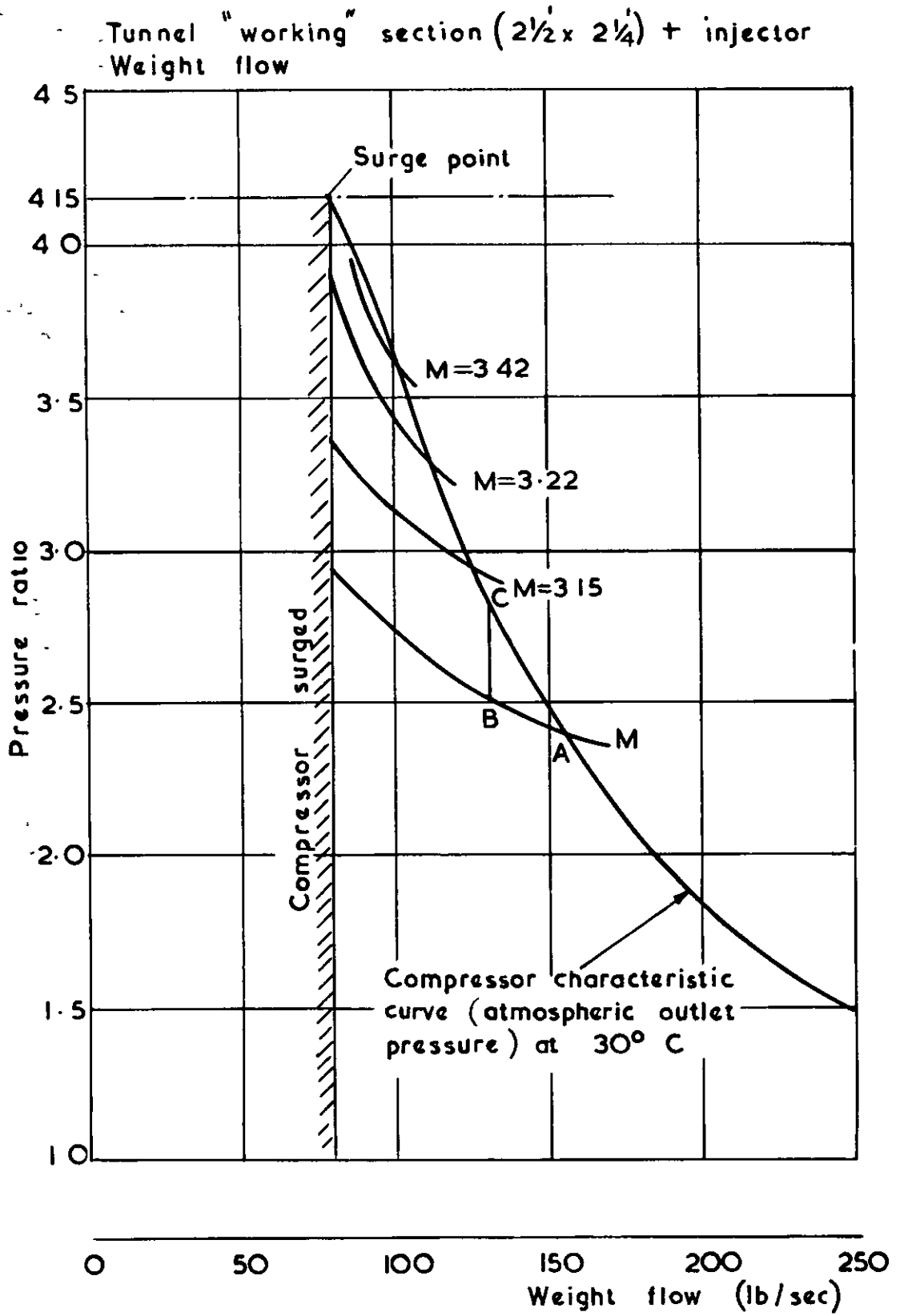
FIG. 18.

W S.

$M=3.15$

Variable flap
setting

III

1.0 Height

Diffuser configuration

1.0

1.2

3·8

3·6

3·4

3·2

3·0

2·8

Pressure ratio

—45°

—O°

—22°

40   60   80   100   120

Percentage by-pass
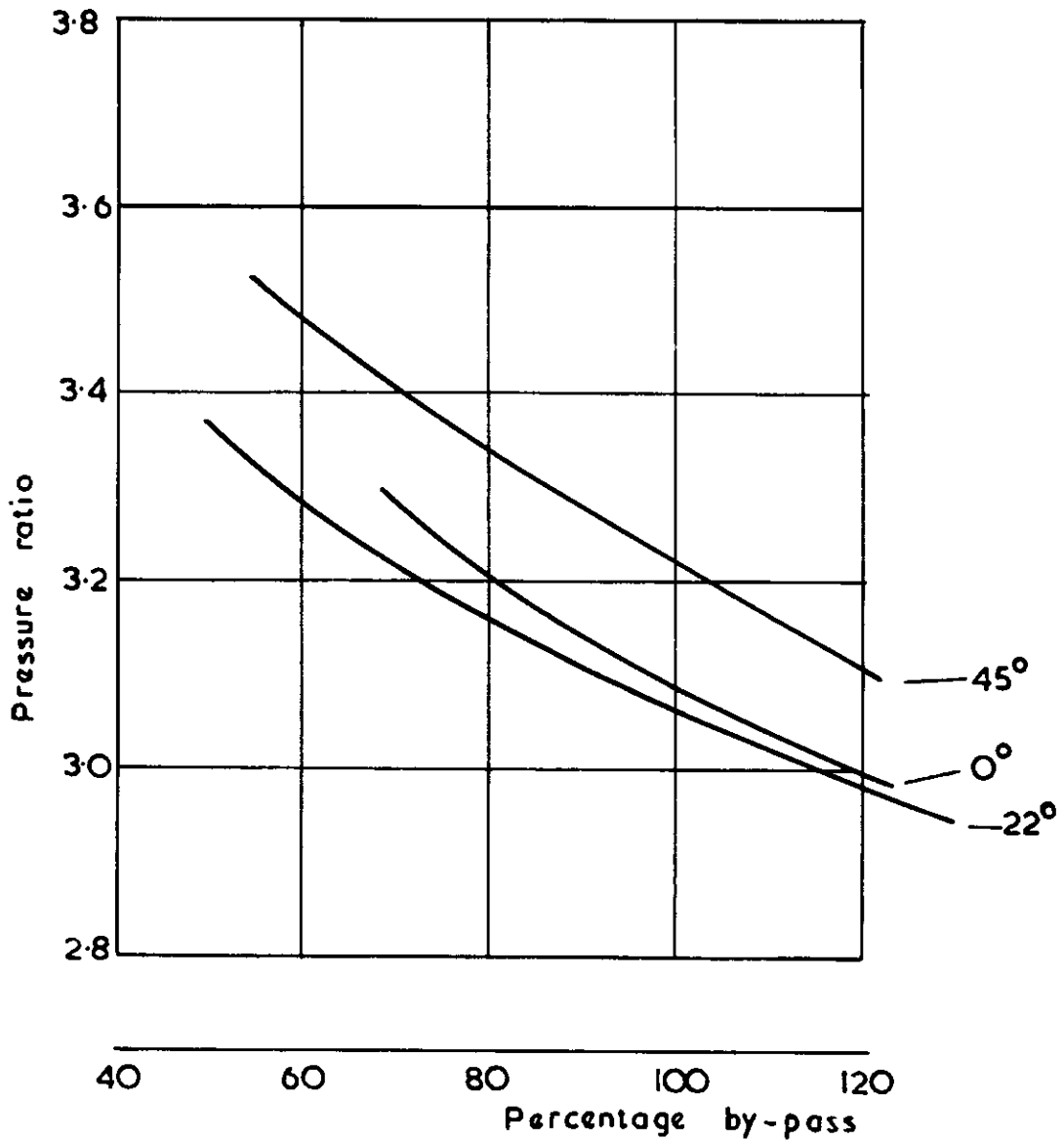
$M=3.15$ EFFECT OF BALANCE POSITION ON
MINIMUM RUNNING PRESSURE RATIO (PARALLEL DIFFUSER)

FIG. 19.

Variable flap setting

W.S.

Height

Diffuser configuration

Pressure ratio

Percentage by-pass

Start
M = 3.42
110% Diffuser setting

Run

Start
Run

M = 3.22
90% Diffuser setting

Start
Run

M = 3.15
90% Diffuser setting

HIGHER MACH NUMBER. OPTIMUM STARTING AND RUNNING RATIOS. (EMPTY TUNNEL)

FIG. 20.

Tunnel "working" section $\left(2\frac{1}{2} \times 2\frac{1}{4}\right)$ + injector
Weight flow

Surge point

M=3 42

M=3·22

C M=3 15

B

A M

Compressor surged

Compressor

Pressure ratio

Compressor characteristic curve (atmospheric outlet pressure) at 30° C

Weight flow (lb/sec)

MATCHING OF TUNNEL FLOW TO COMPRESSOR CHARACTERISTIC

FIG. 21.

10° ARA diffuser

5° ARA diffuser

Step in diffuser

5° Incl. angle long diffuser
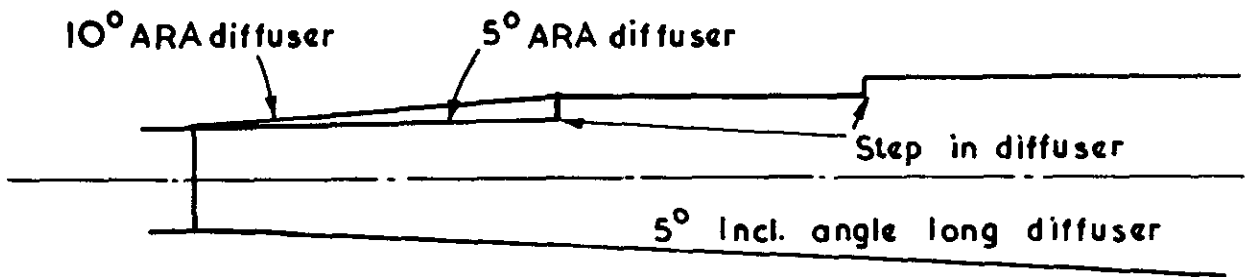
3 Diffusers
- A. 5° Included angle long diffuser — No steps
- B. 5° Included angle short diffuser — 2 steps
- C. 10° Included angle — 1 step

- - - - Min. start
——— Min. run
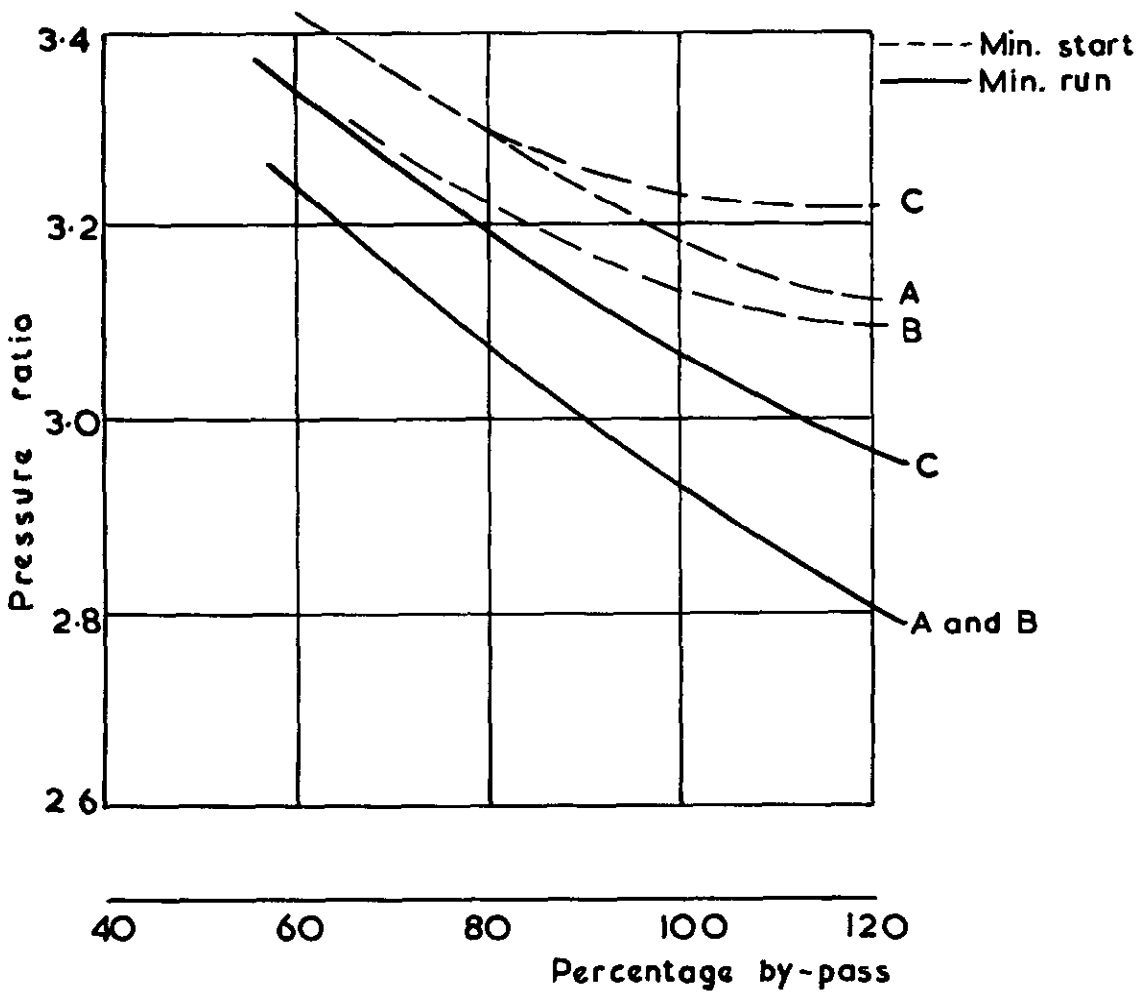
EFFECT OF SUBSONIC DIFFUSER SHAPE
ON PRESSURE RATIO (90° DIFFUSER)