C.P. No. 894

C.P. No. 894

LIBRARY
ROYAL AIRCRAFT ESTABLISHMENT
BEDFORD.

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Performance of a Centre Body Propelling Nozzle with a Parallel Shroud in External Flow

Part II

By

M. V. Herbert, G. T. Golesworthy and R. J. Herd

LONDON: HER MAJESTY'S STATIONERY OFFICE

1966

Price £1 1s. 6d net

U.D.C. No. 621-225.1:533.691.18

C.P. No.894

April, 1964

The performance of a centrebody propelling nozzle with a parallel shroud in external flow

Part II

- by -

M. V. Herbert, G. T. Golesworthy and R. J. Herd

SUMMARY

In continuation of the work on axisymmetric centrebody nozzles with translating parallel outer shrouds and fixed throat areas described in Part I, further tests have been carried out with external flow in the range of Mach number 0.7 to 1.5. For combinations of exhaust pressure ratio and external Mach number representative of flight requirements, the results show that this type of nozzle can offer quite a high level of gross thrust efficiency throughout its operating range. The off-design performance is much superior to that of a plain convergent-divergent nozzle of the same design pressure ratio.

Conical centrebodies only were used, and the effect of varying the half-angle from 15 to $7\frac{1}{2}^{\circ}$ has been investigated. Some improvement is gained by going to 10°, but further reduction is unlikely to be worthwhile in practice.

- -

Replaces N.G.T.E. M.384 - A.R.C.25 992

CONTENTS

TABLE

APPENDICES

ILLUSTRATIONS

ILLUSTRATIONS (cont'd)

ILLUSTRATIONS (cont'd)

1.0 Introduction

The principle of partial external expansion was discussed in Part I (Reference 1), in special relation to the propelling nozzle requirements of such an aircraft as a supersonic transport. It was noted that a nozzle designed in this way could better accommodate the widely different exhaust pressure ratios encountered at the two ends of its required operating range.

Tests on some axisymmetric nozzles with conical centrebodies and parallel outer shrouds were described in Part I. This form of nozzle geometry is illustrated in Figure 1; relative axial movement between the centrebody and shroud is required, throat area remaining constant. Quiescent air performance was found to be very good, a high gross thrust efficiency being obtained throughout the range of exhaust pressure ratio. Part I covered external flow only in the band of Mach number 1.3 to 2.4, and here the off-design efficiency fell off. It was found possible to predict optimum performance to a fair accuracy under these conditions by means of a computer programme. No prediction could, however, be made for the case of subsonic external flow, which is of greater practical interest at low exhaust pressure ratio, and the present work is mainly concerned with rig tests to provide data in the range of Mach number 0.7 to 1.5.

Some fresh variants within the same basic geometry have also been tested at off-design conditions, following suggestions put forward in Part I. These include narrower centrebody angles, and "ventilation" of the centrebody surface by secondary air close to ambient pressure.

2.0 The test rig

A description of the rig equipment used for these tests appears in Reference 2. It contained two alternative working sections, the arrangement of which is illustrated in Figure 2. The lower of these provided supersonic external flow in the range of Mach number 1.3 to 2.4, being equipped with a two-dimensional flexible wall nozzle of 12 in. × 12 in. outlet. This same working section had been used for the external flow tests reported in Part I. The upper line in Figure 2 embodied a slotted nozzle of circular cross-section, 11.3 in. diameter, enabling external Mach numbers to be produced in the range 0.7 to 1.5.

Test models were mounted on the end of a $3\frac{1}{2}$ in. diameter sting, which was interchangeable between the two working sections and passed centrally through the throat of either external flow nozzle. This sting consisted of two co-axial tubes, the inner supplying air to the model, while instrumentation lines passed through the annular gap between them. Arrangement of the sting in the two working sections is illustrated in Figures 3 and 4.

2.1 Thrust measurement

Means for direct measurement of model thrust were not available, and recourse was had to pressure plotting the centrebody. Gross thrust of the model was then determined by summation of the stream thrust in the throat plane (obtained by calculation) and the thrust upon the divergent surfaces (given by the pressure tappings). An expression for gross thrust efficiency† was developed in Appendix III of Reference 1, viz:-

$$\eta_F = \frac{1.26789\, C_D \cdot \mu + \int_0^{(A_e/A_g-1)} \frac{P_w}{P_t}\, d\left(\frac{A}{A_g}\right) - \frac{1}{E.P.R.}\left(\frac{A_e}{A_g}\right) - \phi}{0.0123156\, C_D \left[\frac{v}{\sqrt{T_t}}\right]_{EPR}}$$

taking $\gamma = 1.4$.

This depends upon knowledge of the following quantities:-

(i) Discharge coefficient (C_D), taken to be 0.9945 for these models when choked, as in Reference 1.

(ii) Throat stream thrust efficiency (μ), taken to be 1.001 when choked, as in Reference 1.

(iii) Exhaust pressure ratio $\left(E.P.R. = \frac{P_t}{P_\infty}\right)$, obtained from pitot rake at model entry and static pressure measurement at the wall of the working section.

(iv) Computed allowance for internal friction downstream of the model throat (ϕ). The method of estimating this for a centrebody nozzle is given in Appendix III of Reference 1, use being made of the curves for "momentum loss" and "displacement loss" presented in Reference 3.

It should be noted that in the above relation no account is taken of the drag force acting on the thin annular base of the parallel shroud (Figure 1).

In accordance with the argument given in Part I for the conditions of these tests, no correction for "real air" effects has been applied.

2.2 Air supplies

Both model and external flow lines were fed with dry air at stagnation temperatures around 35°C. Air dryness was measured by an R.A.E.-Bedford pattern frost-point hygrometer, and held at better than -20°C throughout.

Supply pressure was at an initial level of 5 atm, throttled independently as required for the two lines. Model throat Reynolds numbers encountered in these tests were in the range 1.3 to 4.8 million, the characteristic dimension being taken as the diameter of a circle enclosing an area equal to the model throat area.

† For definition see Appendix II

3.0 Model geometry

The general layout was in all cases similar to Figure 1, and a typical set of parts is shown in Figure 5. Details of the various builds will be found in Table I, from which it can be seen that the tests covered basically two values of design pressure ratio (D.P.R. = 20 and 15) and three angles of plain conical centrebody (15, 10 and $7\frac{1}{2}^{\circ}$ half-angle). In the ensuing discussion, identification of the various builds will be according to the D.P.R. and centrebody angle; thus $20/15^{\circ}$ means the first design listed in Table I.

It should be appreciated that in practice the shroud and centrebody of each design are intended to be capable of continuous translation relative to one another, so as to provide the optimum amount of external expansion to match particular operating conditions throughout a flight path. As was explained in Part I, this entails keeping the internal expansion pressure ratio (I.E.P.R.) approximately equal to the E.P.R. up to the condition at which a Mach line from the end of the shroud just meets the tip of the centrebody; at any higher E.P.R. the shroud length remains fixed. This limiting I.E.P.R. varies with both nozzle D.P.R. and centrebody angle; a rough relationship is:-

70 per cent of nozzle D.P.R. at	15° half-angle
80	10°
90	$7\frac{1}{2}^{\circ}$

For the purposes of model testing, however, a set of fixed position shrouds was made. This set comprised eight shroud lengths, of which only six were employed in the present tests, as listed in Table I; numbers 2, 3, 4 and 5 had previously been used in the tests of Part I, where they gave the approximate values of 6, 9, 12 and 14 for I.E.P.R.

3.1 Plain centrebody models

Figure 6 shows the arrangement of one such model with plain centrebody. This consisted of:

(i) a common mounting assembly, incorporating a three-limb hollow spider support for the centrebody, an entry pitot rake of equal-area spacing, and a row of bulkhead connections for the instrumentation lines;

(ii) one of the interchangeable centrebodies, each of which carried between 10 and 15 pressure tappings 0.020 in. diameter positioned spirally along the downstream-facing surface;

(iii) one of the interchangeable shrouds;

(iv) a cover sleeve for the pressure connection recess.

3.2 Cut-off centrebody model

This model, of which a sketch appears in Figure 7, differed only from the plain $20/7\frac{1}{2}^{\circ}$ design in that the conical centrebody was cut off to form a plane circular base, of area ratio $\left(\frac{A}{A_g}\right) = 0.287$. Two pressure tappings were fitted in this base. In length the cut-off nozzle was equivalent to one with a continuous conical centrebody of approximately $12\frac{1}{2}^{\circ}$ half-angle.

3.3 Ventilated centrebody model

The arrangement in this case is shown in Figure 8. Apart from the ventilation slot, the design was otherwise a $20/15^{\circ}$ nozzle. Details of slot geometry are also given in Figure 8, from which it will be noted that the secondary or ventilation air was discharged in an almost axial direction. The internal area ratio up to the beginning of the slot corresponded to an expansion pressure ratio of 3.75.

With the longer shroud tested (marked A in Figure 8) the ventilation slot was thus within the internal-expansion region; with the shorter (marked B) it was just outside. In case A the shroud was the longest of those used in the tests of Part I. That the I.E.P.R. was now higher - 14.5 instead of 13.9 - resulted from the discontinuity in centrebody area introduced by the ventilation slot.

Secondary air was induced from the external stream through a row of holes in the cover sleeve, passing via the pressure connection recess and the hollow spider limbs to a plenum chamber in the centrebody. The two portions of the centrebody were held in position by means of a spacer assembly and central drawbar. No attempt was made to measure the quantity of ventilation air admitted, but an additional pressure tapping was fitted on the downstream facing lip of the ventilation slot, which measured the effective pressure of the system.

The necessity for ducting secondary air through the spider limbs caused some significant constriction of the supply passage, and the minimum passage area was in fact slightly less than the flow area in the ventilation slot.

4.0 Object of tests

From the work of References 1 and 2, a number of points emerge.

(i) In quiescent air, Figure 9 demonstrates that a centrebody nozzle of the same D.P.R. is much superior to a simple convergent-divergent nozzle at low pressure ratio.

(ii) With supersonic external flow, the same nozzles are compared in Figure 10. The optimum amount of external expansion confers higher performance at low E.P.R.

(iii) In general the running-full line for a simple convergent-divergent nozzle with wholly-internal expansion is unique, peak efficiency† occurring at a pressure ratio equal to the

† So long as this is based only on nozzle internal thrust, with no base or afterbody drag included

nozzle D.P.R. and having a value which is independent of external Mach number. This may be reasoned analytically, and experimental confirmation appears in Reference 2*. Now Figures 9 and 10 show that a centrebody nozzle of the same D.P.R. follows the shape of this running-full line in the vicinity of the design-point†, and has a peak efficiency again independent of M_{∞}. It thus follows that the performance of either type of nozzle over this range can be adequately investigated without external flow.

(iv) In the case of a centrebody nozzle with near-optimum external expansion, its performance in supersonic external flow or quiescent air can be predicted theoretically. Such calculations fall into two parts: the first employs the method of characteristics to obtain nozzle surface pressures in the absence of friction, for which a computer programme[5] can be used; in the second the effects of friction are obtained from boundary layer considerations, as given in Reference 3. Where tested, theoretical values derived in this way agree quite closely with experiment.

(v) According to computer results, the performance of a centrebody nozzle at low E.P.R. in supersonic external flow can be further improved if the centrebody angle be reduced, thereby lessening the turn imposed on the flow just downstream of the throat. This predicted effect is illustrated in Figure 11, reproduced from Reference 1.

(vi) It is not readily possible to predict theoretically the performance of a centrebody nozzle with subsonic external flow. Test data are already available from Reference 2 for the convergent-divergent nozzle at this condition and low E.P.R.

Hence the first two objects of the present series of tests may be stated thus:-

To confirm the effect of centrebody angle at low E.P.R. in supersonic external flow which was predicted theoretically, and thereby to enhance faith in the theoretical method.

* See also Reference 4.

† The same values of peak efficiency are shown for the two nozzles in Figures 9 and 10, for the sake of simplicity. In the tests of References 1 and 2, using only pressure plotting methods, the levels of design-point performance for this D.P.R. differed in fact by much less than the accuracy attributable to either result. If theoretical estimates be compared[1,3], it is found that the centrebody nozzle is superior to a convergent-divergent with 10° semi-cone angle ($\eta_F = 0.991$, as against 0.988, taking a turbulent boundary layer at the same Reynolds number in both cases). This advantage derives from the reduced loss due to outlet divergence in the centrebody nozzle, which outweighs the extra friction on its increased divergent surfaces.

To compare the performance of a centrebody nozzle at low E.P.R. in subsonic external flow with that of a simple convergent-divergent nozzle of the same D.P.R. at the same conditions.

In order to carry out this second object, it was necessary to change from the supersonic working section used for the tests of Part I to the transonic working section. Some overlap occurred in their operating ranges, as mentioned in Section 2.0, and a check could be made that the two test arrangements gave compatible results with an external-expansion model.

So far the comparison between all-internal and partly-external expansion nozzles at low E.P.R. has been restricted to D.P.R. 20, and it would be of interest to extend this to other values. Simple convergent-divergent nozzles of D.P.R. 15 and 12 have also been tested in external flow[4], and the third present object was therefore

To extend to D.P.R. 15 the comparison between a centrebody nozzle and a simple convergent-divergent nozzle at low E.P.R., including the case of subsonic external flow.

In any particular flight application, the nozzle D.P.R. must be chosen to give a satisfactory compromise between operating requirements at both high and low E.P.R. It is therefore necessary to know both the design-point and the off-design performance of each nozzle arrangement. In the light of previous discussion, item (iii) above, no external flow tests are required for the former case. The effect of changing design pressure ratio of a centrebody nozzle on its performance at a particular E.P.R. near the design-point can readily be predicted by the computer programme already mentioned, and the results of such an exercise appear in Figure 12.

Good though its performance should be (Figure 11), a $7\frac{1}{2}^{\circ}$ centrebody would be very long and perhaps mechanically unattractive. It was thought possible that some advantage at off-design conditions might be retained by a centrebody of $7\frac{1}{2}^{\circ}$ with its tip cut off so as to reduce length and weight. Thus the fourth object was

To investigate the effect on performance of cutting the tip off a narrow angle centrebody, both at low E.P.R. in subsonic external flow and at the design-point.

In this case tests were necessary to establish the design-point performance, as theoretical methods could not satisfactorily evaluate the pressure on the plane base of the centrebody. The design-point configuration was accordingly tested in the supersonic working section; all other tests in the present series were conducted in the transonic working section (see Table I). In the event of there proving to be a serious design-point loss, the technique of "base bleed" might be worth invoking at that condition.

4.1 Centrebody ventilation

Finally, it was intended to examine the question of centrebody "ventilation". This name has been given to the transmission of ambient pressure to the internal surfaces of an overexpanded nozzle by means of comparatively small quantities of air induced from the outside atmosphere. A necessary feature of successful operation is that the main jet is caused to detach from the nozzle walls at low pressure ratio. Such a means for improvement of off-design performance was employed by Crosse[6] in short conical convergent-divergent nozzles, and later tests on nozzles of larger area ratio were carried out at N.G.T.E.[7] using more than one stage of air admission. This secondary air was allowed to enter through circumferential slots in the divergent surface of the nozzle when operating at low pressure ratio, the supply being shut off as pressure ratio increased. All this work was done in quiescent air, and although the design-point loss arising from the discontinuities in wall surface was far from negligible, the benefits accruing at low pressure ratio were large, since the usual overexpansion of flow within the nozzle at these conditions could be to a great extent prevented.

However, subsequent tests[8] in external flow (M_∞ up to 1.5) gave a very different picture. The performance of an internal-expansion nozzle at low E.P.R. is naturally worse under conditions where a base pressure exists substantially below ambient (e.g. References 2 and 4). To improve the situation the base pressure must be raised. It had been hoped that admission of air at nearly ambient pressure within the nozzle would produce a region of separated mainstream flow in which the pressure was considerably higher than the original base pressure. This conspicuously and consistently failed to happen; instead, the base pressure remained at much the same low level, and continued to control the nozzle wall pressure downstream of separation. With two stages of air admission, the pressure in the second ventilation slot was also lowered to near base level, and even that in the first slot was at times appreciably below ambient.

Later tests of a different nature[9] have shown that direct injection of secondary air into the base region of a nozzle (base bleed), whilst effective in raising base pressure in supersonic external flow ($M_\infty \simeq 2$), has almost no influence in subsonic. It is difficult to find any comprehensive evidence of the effect of base bleed at transonic conditions, but limited data from the same work[9] tend to support other sources in suggesting that the technique has some success around $M_\infty = 1.1$. One may conclude that, in subsonic external flow, secondary air will serve no useful purpose if discharged into a region to which base pressure can communicate.

Now let us consider a nozzle which is, as it were, turned inside out so that the divergent surfaces are transferred to a centrebody. "Ventilation" might be applied to the centrebody in this arrangement, and two possible cases of interest may be distinguished.

Take first that which is analogous to the conventional use of the technique in a convergent-divergent nozzle, the intention being to prevent internal overexpansion at low pressure ratio. This would only occur, of course, if the shroud length were not reduced to give optimum external expansion. Thus the appropriate geometry is a long shroud with centrebody ventilation slot well upstream of the shroud end (as A in Figure 8). In such a system, the base pressure on the shroud end will govern flow separation on the inside surface of the shroud, just as in a convergent-divergent nozzle, but the ventilation region of the centrebody is not in direct communication with this base pressure. There seemed therefore some chance that admission of secondary air close to ambient pressure could improve performance at low E.P.R. in this case even in a subsonic external stream. Hence the fifth object of these tests may be stated as follows

> To discover whether ventilation of a fixed geometry centrebody nozzle is effective at low E.P.R. in subsonic external flow.

If satisfactory, this arrangement could perhaps offer an alternative to translation of the outer shroud of a centrebody nozzle, with some mechanical simplification, although with some design-point loss also. The secondary air inlet drag at low E.P.R. would then require evaluation. In this design, the fixed shroud length would be that for the maximum I.E.P.R. of a similar conventional centrebody nozzle without ventilation. This, as observed in Section 3.0, is around 70 per cent of the nozzle D.P.R. for a centrebody half-angle of 15°.

The second possible application has already been mentioned briefly in Part I. A 15° half-angle centrebody nozzle with optimum shroud length gives performance at low E.P.R. in supersonic external flow (Figure 10) which, although better than that of an all-internal-expansion system, is still rather low. It was thought that some further improvement might be achieved by the use of ventilation within the external-expansion region, where the centrebody surface pressure is otherwise below ambient. The appropriate geometry in this case is a short shroud with centrebody ventilation slot just downstream of the shroud end (as B in Figure 8). Such a nozzle is in a rather different category to other ventilated systems, since the design prevents separation occurring within the internal-expansion region, and the centrebody is therefore shielded by wholly supersonic flow from the base pressure on the shroud end. Accordingly, a sixth object of testing was

> To find whether ventilation in the external-expansion region can improve performance of a centrebody nozzle at low E.P.R. in supersonic external flow.

5.0 Test results

Data obtained from the various model builds listed in Table I are presented in Figures 13 to 26. Two general points arise in relation to these results.

The first concerns friction. In the expression given in Section 2.1 for gross thrust efficiency there is a quantity denoted by ϕ, which comprises the total deduction to be made for friction in the case of thrust obtained from a plot of divergent wall pressure. It comes from the sum of what are termed in Reference 3 the "momentum loss" and "displacement loss", values of which are given there for conical convergent-divergent nozzles. In Appendix III of Part I, it is suggested that the case of a centrebody nozzle can conveniently be dealt with by considering an equivalent conical convergent-divergent nozzle. This has the same throat area, outlet Mach number, throat Reynolds number, and wetted surface area; the friction properties may then be assumed to be also the same. Because of the difficulty involved in making separate estimates of ϕ for every test condition, the data have first been evaluated without this correction, and appear in that way in Figures 13 to 26. From the values of efficiency shown therein must be deducted the following average amounts:-

Nozzle design	Efficiency correction (%)	
	To test results	To computer results
20/15°	1.0	0.6
20/10°	1.3	0.8
20/7½°	1.5	0.9
15/15°	0.9	0.5

An average correction is taken for each basic nozzle design, despite differences in shroud length, on the grounds that two effects oppose each other. On the one hand, supersonic surface area and hence friction obviously decrease with shortening of the shroud. However, the appropriate range of E.P.R. is also lower, implying lower entry total pressure in these tests and hence lower Reynolds number, which for a turbulent boundary layer throughout means in turn higher friction. The figures given above are in fact estimated for design-point operation.

The second point is related to what appears to be wide scatter in certain test results. Examples of this will be found in Figures 13, 15, 18, 19, 21 and 23, in the case of short shrouds at low external Mach number. Reference to the centrebody pressure distributions, of which examples are shown in Figures 27 and 28, reveals that much more irregular patterns develop on external-expansion surfaces at these conditions. The number of pressure tappings then becomes inadequate to give an accurate and complete picture, and sizeable errors in estimation of thrust from pressure distribution in this part of the nozzle may ensue. Nevertheless, it can be seen from the examples given (Figure 27) that large changes in the pattern of distribution do occur with quite small shift of E.P.R., and some of the variation in efficiency which has been smoothed out when drawing the curves in Figure 13 etc. may perhaps be genuine.

6.0 Discussion

This is divided into sections according to the test objects stated in Section 4.0.

6.1 Working section agreement

Test results for the same model (20/15° design, with I.E.P.R. = 5.9) are available from both supersonic and transonic working sections at a similar external Mach number, and these are compared in Figure 29. Fair general agreement is evident.

6.2 Effect of centrebody angle in supersonic external flow

The computer results from Figure 11 have been adjusted in Figure 30 to allow for friction, and the design-point performance for all three centrebody angles is now the same within 0.1 per cent. Shown also on Figure 30 for comparison are points relating to experimental results both from Part I and from the present work (Figures 13, 14, 16, 17, 19 and 20). These points were obtained by reading off the mean experimental curves at optimum shroud length, i.e. at the condition where E.P.R. = I.E.P.R. Exact quantitative agreement is not always found, but a trend in the direction predicted theoretically can certainly be discerned.

It should be noted that, in the calculations leading to Figures 11 and 12, a particular relationship between external Mach number and E.P.R. was assumed, viz:-

E.P.R.	M_∞
3.75	1.1
5	1.25
10	1.75
15	2.0
20	2.2

Little effect on thrust at any given E.P.R. was found by altering Mach number, except in the neighbourhood of 1.1. The experimental points on Figure 30 relate only to $M_\infty \geqslant 1.25$.

6.3 Nozzle comparison in subsonic external flow

Data from Figures 13 to 16, 18 and 19 have been used in Figure 31. This completes the comparison between centrebody and plain convergent-divergent nozzles for the case of D.P.R. 20, and forms a family together with Figures 9, 10 and 30. Appropriate friction allowances are included throughout, and optimum shroud length is assumed for the centrebody nozzles as defined above.

It can be seen from Figure 31 that the performance of $7\frac{1}{2}$ and 10° centrebody nozzles is similar in subsonic external flow. At 0.7 Mach number this is not a lot better than with a 15° centrebody, but the advantage of a narrower angle at 0.9 Mach number and low E.P.R. is quite substantial.

In general, this comparison shows that it is in subsonic external flow where a centrebody nozzle with optimum external expansion has the greatest benefit to offer. For combinations of exhaust pressure ratio and external Mach number representative of probable flight requirements, quite a high level of gross thrust efficiency can be maintained throughout the nozzle operating range: this should exceed 94 per cent even with a centrebody half-angle of 15°.

6.4 Change of nozzle design pressure ratio

An exactly comparable picture to Figure 31 appears in Figure 32 for the case of D.P.R. 15 with subsonic external flow. The centrebody nozzle data (15° half-angle only) come from Figure 23, and results for the convergent-divergent nozzle are taken from Reference 4. Both were obtained in the same working section. Where evidence is available (E.P.R. = 3.8), the change of D.P.R. has produced a similar increment in efficiency for both types of nozzle; at that condition a convergent-divergent is consistently about 11 per cent worse than a centrebody with optimum shroud length.

Adequate information as to the effect on performance near the design-point can be obtained from Figure 12, making suitable allowance for friction (as given in Section 5.0).

6.5 Cutting off the centrebody tip

At the design-point the penalty of this device can be seen approximately from Figure 30, on which is shown a level derived from Figure 22, but it should be borne in mind that experimental thrust efficiencies based on pressure plotting are generally not reliable to better than $\frac{1}{2}$ per cent. However, an alternative approach is to consider only the base pressure measured on the plane end of the cut-off centrebody. Corresponding to the results in Figure 22 is a pressure distribution in terms of $\frac{P_w}{P_t}$ which, inclusive of the pressure on the base (which was uniform), is independent of E.P.R. This is to be expected, since the whole base region is upstream of the Mach line from the end of the shroud, and the nozzle behaves simply as an all-internal-expansion system, for which the pressure distribution is unique until separation occurs. Just ahead of the station where the centrebody is cut off, this pressure distribution agrees closely with that computed theoretically. If one then takes the theoretical distribution for the remainder of a continued centrebody, and converts the difference between this and the actual base pressure on the same projected area into a loss of efficiency, a figure is reached around 0.15 per cent at the design-point. This does in fact tally quite well with the values in Figure 30.

So far as the off-design performance is concerned, Figure 33 compares the data from Figures 18 and 21, showing an average loss of around 1 per cent. Unfortunately, the comparison is fogged by the rather wide scatter in efficiency which is obtained from pressure distributions such as those in Figure 27.

It is interesting once again to look at the base pressure on the plane end of the centrebody, this time corresponding to Figure 21. The ratio of this pressure to free-stream static $\left(\frac{P_b}{P_\infty}\right)$ lay between 0.9 and 1.0 over the range of E.P.R. 2 to 4, so that the loss at off-design conditions arising from use of this cut-off centrebody should indeed be small.

What is equally important to observe, however, is the comparison between 10 and $7\frac{1}{2}^{\circ}$ plain centrebodies at these conditions. According to Figure 31, there is no effective difference between the two angles in subsonic external flow, and this can be verified by reference to the original data in Figures 15 and 18. Moreover, even in supersonic external flow, the advantage of $7\frac{1}{2}^{\circ}$ at low E.P.R. is shown by Figure 30 to be quite small. Thus the case for a $7\frac{1}{2}^{\circ}$ centrebody, cut-off or otherwise, is not strong. Even a 10° plain centrebody is long, and in view of the above results there seems every reason to expect that a limited amount could be cut off in that case also without serious penalty; shortening at any rate to the length of a $12\frac{1}{2}^{\circ}$ centrebody should be permissible.

Before leaving the cut-off $7\frac{1}{2}^{\circ}$ centrebody nozzle, it is worth having another look at Figure 22 for maximum shroud length in supersonic external flow, and noting the severe fall in efficiency at low E.P.R. This is in fact slightly worse than occurs in the case of a 15° centrebody nozzle of the same D.P.R. and also with maximum shroud length in supersonic external flow (see Figure 14 of Part I). Such behaviour may at first sight appear to be inconsistent with the beneficial effects of low centrebody angle generally observed in Figure 30. The explanation lies in the change of maximum I.E.P.R. with centrebody angle (see Section 3.0). For D.P.R. 20, this involves an increase from 13.9 (for the 15° centrebody of Part I) to 17.8 (for the $7\frac{1}{2}^{\circ}$ centrebody of Figure 22), and if the shroud is not translated relative to the centrebody, this extra amount of internal expansion will introduce greater loss at low E.P.R.

6.6 Centrebody ventilation upstream of shroud end

This section relates to the fifth test object as stated in Section 4.1. It will be recalled that the case of interest is a nozzle with fixed geometry, a shroud length corresponding to maximum I.E.P.R., and ventilation within the internal-expansion region at low E.P.R. The conditions tested were subsonic external flow, with the secondary air passage open throughout. No attempt was made to assess the design-point loss arising from the ventilation slot, nor were any alternative positions or geometries of slot investigated in these tests.

In Figure 34 the values of thrust efficiency taken from Figure 26 are replotted with adjustment for friction. This performance is poor in comparison with results[7] from quiescent air tests of a convergent-divergent nozzle of the same design pressure ratio and also having one stage of ventilation with the same slot geometry. It is evident that this centrebody system has achieved only very limited success.

Also shown on Figure 34 are subsonic external flow test results for a plain convergent-divergent nozzle with the same D.P.R. Both sets of data come from the same working section, with the same range of model throat Reynolds number. Although secondary air quantities and the associated drag penalties have not been evaluated, it seems that, if fixed geometry of divergent surfaces is essential, some improvement can be achieved at low E.P.R. by the use of a centrebody nozzle with ventilation slot. But it is small in comparison with the gain which is afforded by translation of the shroud (vide Figure 31)[†]. Moreover, some of the

---

[†] For no accompanying loss at the design-point.

advantage displayed in Figure 34 results not from ventilation at all, but simply from re-arranging nozzle shape so that the divergent surfaces form a centrebody. The parallel outer shroud can then be terminated upstream of the centrebody tip as already described for design-point operation, thereby reducing the amount of internal expansion for the same D.P.R. A fixed geometry nozzle designed in such a way will naturally have better off-design performance than an all-internal-expansion system, at least so long as both are running full. Figure 40 gives a further example of this for nozzles without ventilation. In the ventilated build the value of I.E.P.R. was 14.5, and it can be seen from Figure 26 that the behaviour above E.P.R. 5 conforms quite closely to that of a plain convergent-divergent nozzle of D.P.R. 14.5 running full.

To discover why the performance of this arrangement is at such a low level, it is necessary to look at the pressure distributions along the centrebody, of which examples are given in Figure 35. For the technique of ventilation to operate successfully, the pressure in the ventilation slot must be close to ambient, as was the case with convergent-divergent nozzles in quiescent air. But Figure 35 shows that in the present tests it was substantially below ambient throughout†. Levels of base pressure on the shroud end are also marked, and it may be observed that there is some approximate correspondence between pressures there and in the ventilation slot at values of E.P.R. below 4. These relationships are shown more clearly in Figure 37.

In an attempt to reach a better understanding of this behaviour, a test of the same build was carried out in quiescent air. The centrebody pressure distributions obtained appear in Figure 36. In this case ambient and shroud base pressures were approximately equal, but the ventilation slot pressure was still appreciably below ambient.

An interesting feature of Figure 36 is the almost perfectly horizontal portion of the curves at low E.P.R. (≤ 3) between the ventilation slot and the end of the shroud, that is, within the internal-expansion region of the nozzle. Such a pattern is usually found[7,8] in a ventilated convergent-divergent nozzle in quiescent air, but in the present case the level seems to imply that the centrebody separation system is being controlled by some pressure well below ambient. We will refer to this as the intermediate pressure. Only beyond the confines of the shroud is the centrebody found to rise above this intermediate pressure.

At higher E.P.R. ($> 3\frac{1}{2}$) in quiescent air, where separation no longer takes place at the ventilation slot, it appears that the centrebody reaches ambient pressure well upstream of the shroud end.

The centrebody pressure distributions of Figure 36 may be compared with those appearing in Figure 39, for the corresponding nozzle build without ventilation ($20/15^{\circ}$, I.E.P.R. = 13.9) also in quiescent air. In the latter case, there is no regular pattern of sub-ambient intermediate pressure at low E.P.R., and the pressure opposite the shroud end is in most instances quite close to ambient.

---

† The effective pressure on the projected area of the slot is drawn as uniform and equal to the downstream-facing lip pressure for lack of better information.

Two possible origins of the low level of intermediate pressure may be envisaged. In the first place, it could be thought to result from the constricted passage afforded to the secondary air, which in this installation had to negotiate the centrebody mounting spider (Section 3.3). However, were a high pressure loss in the supply circuit the direct and sole cause of low pressure in the ventilation slot, one might expect to see in quiescent air a centrebody pressure distribution rising gradually from that value in the slot to ambient at the end of the internal-expansion region. Alternatively, a low intermediate pressure could be imposed on the centrebody by conditions existing near outlet of the internal-expansion region.

Unfortunately no pressure measurements on the shroud surface are available. But it may be estimated[10] that separation would take place on the inside of the shroud below E.P.R. about $6\frac{1}{2}$ in quiescent air. Thus, within the internal-expansion region of the nozzle at E.P.R. around 3, an annular system of intersecting shocks must exist, originating at the separation points on shroud and centrebody. From the intersection a branch will return to meet the centrebody, and it could be supposed that the intermediate pressure is that corresponding to the region between origin of the first shock and arrival of the second. The fact noted above, that the corresponding nozzle without a ventilation slot does not exhibit this pattern (Figure 39), could be attributed to the differences in position of the separation shock on the centrebody at E.P.R. $< 3\frac{1}{2}$.

Whichever the reason, sub-ambient pressure in the ventilation slot is evidently a feature inherent in this design of centrebody nozzle, and not the result of external flow. It must therefore be concluded that, when secondary air is induced in this manner, centrebody ventilation within the internal-expansion region is not very successful.

In this design of ventilated nozzle, sudden movement of the separation shock from the lip of the slot to the downstream surface takes place at a value of E.P.R. ($\simeq 3.5$) which is the same in external flow as in quiescent air. At higher E.P.R., the ventilation slot pressure correlates closely with ambient (Figure 38a), but not at all with base pressure (Figure 38b).

An abrupt fall in thrust efficiency is produced as the shock leaves the slot lip (Figure 26). It has been found elsewhere that some hysteresis can be associated with this change, the critical pressure ratio for shock movement being lower when pressure ratio is decreased than when it is increased. In the present tests only increasing E.P.R. was applied.

6.7 Centrebody ventilation downstream of shroud end

In this section we are concerned with the sixth and final test object, namely, the attempted use of ventilation to raise sub-atmospheric pressures on external-expansion surfaces, as suggested in Part I. The conditions of interest are low E.P.R. in supersonic external flow, with nozzle I.E.P.R. already reduced below the maximum. A practical version of this nozzle arrangement would therefore have capability for both shroud translation and centrebody ventilation. Once again, the secondary air passage was open throughout these tests, flow quantities were not investigated, and neither was design-point loss.

A comparison is given in Figure 41 between the performance of otherwise similar geometries of nozzle with and without ventilation, using data from Figures 13 and 25. It is clearly to be seen that no improvement whatsoever has been achieved. The reason for this is, once again, a level of pressure in the ventilation slot considerably below ambient, as shown in Figure 42; in fact, slot pressure generally did not differ greatly from the pressure existing over that region of the centrebody in the absence of a slot. For all the purpose it served, the secondary air might as well have been shut off. Such disappointing behaviour cannot in this application be associated with either

(i) communication with a low base pressure, or

(ii) the presence of an intersecting shock system, as the internal-expansion region must be running full.

We have already seen that only supersonic external flow induces serious depression in the external-expansion region of a centrebody nozzle with optimum shroud length, and it appears that in these circumstances ventilation offers no advantage.

7.0 Conclusions

A series of axisymmetric centrebody nozzles with parallel outer shrouds has been tested in external flow over the range of Mach number 0.7 to 1.5. Test models covered nozzle design pressure ratios of 20 and 15, and centrebody half-angles of 15, 10 and $7\frac{1}{2}^{\circ}$. Various shroud lengths were tested for each design, in order to simulate the relative translation of centrebody and shroud needed for maintaining the optimum amount of external expansion. From this and previous work, the following observations can be made on the performance of this type of centrebody nozzle in general, and in comparison with plain conical convergent-divergent nozzles.

(i) The design-point value of gross thrust efficiency is effectively independent of centrebody half-angle over the range 15 to $7\frac{1}{2}^{\circ}$.

(ii) At low exhaust pressure ratio in supersonic external flow, the narrowest centrebody angle gives the highest performance.

(iii) At low exhaust pressure ratio in subsonic external flow, a nozzle with 10° centrebody half-angle has better performance than one with 15°, but further reduction of angle is not advantageous.

(iv) For combinations of exhaust pressure ratio and external Mach number representative of probable flight requirements, it seems likely that centrebody half-angles below 10° need not be considered.

(v) For the same general range of operating conditions, this type of centrebody nozzle offers quite a high level of performance throughout, when optimum shroud length is preserved. In the case of a nozzle with design pressure ratio 20 and centrebody half-angle 15°, it should be possible to maintain values of gross thrust efficiency above 94 per cent; with reduction of either design pressure ratio or centrebody angle, this minimum level can be improved.

(vi) If the tip of a $7\frac{1}{2}^{\circ}$ half-angle centrebody be cut off so as to reduce length to that of a $12\frac{1}{2}^{\circ}$ centrebody, there is some small loss in design-point efficiency (around 0.15 per cent). The performance at low exhaust pressure ratio in subsonic external flow falls by about 1 per cent.

(vii) It is thought that, for practical purposes, the optimum arrangement is probably one with 10° half-angle centrebody, cut off to give length equal to a $12\frac{1}{2}^{\circ}$ centrebody.

(viii) At the design-point there is little to choose between centrebody and convergent-divergent forms of nozzle design. The performance of a centrebody nozzle with optimum shroud length and without its tip cut off should be slightly higher than that of a plain conical convergent-divergent nozzle with 10° semi-angle and the same design pressure ratio, taking similar boundary layer conditions for both.

(ix) For off-design operation, in both subsonic and supersonic external flow, a centrebody nozzle with optimum shroud length is consistently better than a plain convergent-divergent. This advantage is most marked at low exhaust pressure ratio in subsonic external flow, where differences in gross thrust efficiency can exceed 10 per cent.

(x) In a fixed geometry centrebody nozzle (i.e. one no longer with mutual translation of shroud and centrebody to give the optimum amount of external expansion at all conditions), "ventilation" of internal-expansion divergent surfaces at low exhaust pressure ratio, by admission of air taken from ambient pressure, is not very successful, either in quiescent air or in external flow. When separation occurs at the ventilation slot, pressures considerably below ambient exist on the centrebody over the subsequent internal-expansion region.

(xi) The depression induced on external-expansion surfaces of a centrebody nozzle with optimum shroud length, when operating at low exhaust pressure ratio in supersonic external flow, cannot be overcome by "ventilation" with air from ambient pressure.

ACKNOWLEDGEMENT

The authors wish to thank Mr. C. Overy, Miss M. Faiers and Miss V. Searle for their assistance in this work.

REFERENCES

No.	Author(s)	Title, etc.
1	R. J. Herd G. T. Golesworthy	The performance of a centrebody propelling nozzle with a parallel shroud in external flow. Part I. A.R.C. C.P.841, November, 1963.
2	G. T. Golesworthy M. V. Herbert	The performance of a conical convergent-divergent nozzle with area ratio 2·9 in external flow. A.R.C. C.P.891, November, 1963.
3	D. L. Martlew M. V. Herbert	The design-point performance of model internal-expansion propelling nozzles with area ratios up to 4. A.R.C. R. & M.3477, December, 1963.
4	G. T. Golesworthy J. B. Roberts C. Overy	The performance of conical convergent-divergent nozzles of area ratio 2·44 and 2·14 in external flow. A.R.C. C.P.893, February, 1964.
5	Sqn.Ldr. H. J. Willcocks, R.A.F. R. J. Herd	A computer programme for the analysis of nozzle performance, with or without external flow. Unpublished M.O.A. Report, 1964.
6	G. W. Crosse	The development of an aerodynamically variable convergent-divergent propelling nozzle. A.R.C.21 915 February, 1960.
7	M. V. Herbert Flt.Lt. C. Sutcliffe, R.A.F. C. Overy	Unpublished M.O.A. Work, 1961.
8	M. V. Herbert C. Overy R. A. Pinker G. T. Golesworthy	The effect of external flow on an internal-expansion propelling nozzle incorporating ventilation by ambient air. A.R.C. C.P.897, November, 1964.
9	J. B. Roberts G. T. Golesworthy	An experimental investigation of the influence of base bleed on the base drag of various propelling nozzle configurations. A.R.C. C.P.892, February, 1964.
10	M. V. Herbert R. J. Herd	Boundary-layer separation in supersonic propelling nozzles. A.R.C. R. & M.3421, August, 1964.

TABLE I

Nozzle builds tested

D.P.R.	Centrebody half-angle (degrees)	Shroud number	I.E.P.R.	Range of M_∞
20	15	1	3.5	0.7, 0.9, 1.1, 1.25
		2	5.9†	0.9, 1.1, 1.25
20	10	1	3.4	0.7, 0.9
		2	4.9	0.9, 1.1, 1.25
		3	7.0	1.25, 1.5
20	$7\frac{1}{2}$	1	3.2	0.7, 0.9
		2	4.3	0.9, 1.1, 1.25
		4	7.4	1.25, 1.5
20	$7\frac{1}{2}$ (Cut-off)	1	3.2	0.7, 0.9
		8	17.8	2.2
15	15	1	3.8	0.7, 0.9
		2	5.9	1.1, 1.25, 1.5
20	15 (Ventilated)	1	3.5	1.1, 1.25
		5	14.5	0.7, 0.9

† This build was tested in supersonic external flow in Reference 1

APPENDIX I

Notation

A	cross-sectional area
A^*	isentropic nozzle throat area
A_g	geometric nozzle throat area
A_e	nozzle exit area
C_D	discharge coefficient (see Appendix II)
M_∞	external Mach number
P_t	model entry total pressure
P_w	wall static pressure
P_∞	ambient or free-stream static pressure
T_t	model entry total temperature
v	velocity
η_F	nozzle gross thrust efficiency (see Appendix II)
μ	throat vacuum thrust efficiency (see Appendix II)
ϕ	friction factor on supersonic expansion surfaces

APPENDIX II

Definitions

E.P.R. = exhaust pressure ratio $= \dfrac{\text{nozzle entry total pressure}}{\text{ambient static pressure}} = \dfrac{P_t}{P_\infty}$

D.P.R. = design pressure ratio = that pressure ratio corresponding to the area ratio A_e/A_g (see Figure 1) in one-dimensional theory

I.E.P.R. = internal expansion pressure ratio = that pressure ratio corresponding to the area ratio A_i/A_g (see Figure 1) in one-dimensional theory

C_D = discharge coefficient $= \dfrac{\text{measured air mass flow}}{\text{isentropic air mass flow for the same physical throat area}} = \dfrac{A^*}{A_g}$

μ = throat vacuum thrust efficiency $= \dfrac{\text{measured throat vacuum thrust with the nozzle choked}}{\text{isentropic throat vacuum thrust, passing the same mass flow}}$

η_F = nozzle gross thrust efficiency $= \dfrac{\text{measured thrust at given E.P.R.}}{\text{gauge thrust of an isentropic nozzle, passing the same mass flow, at the same E.P.R., when fully expanded}}$

DIAGRAM OF NOZZLE ARRANGEMENT.

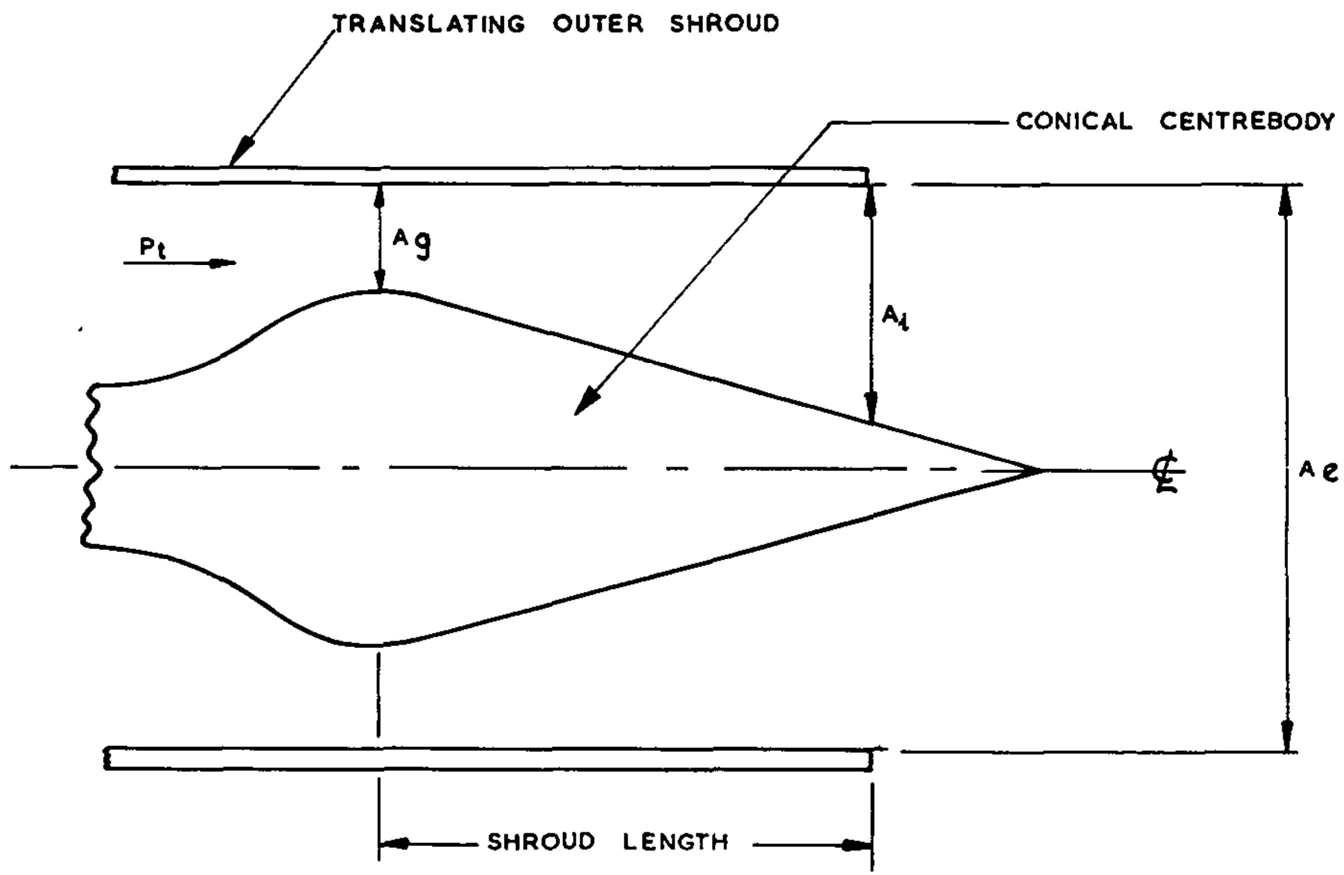
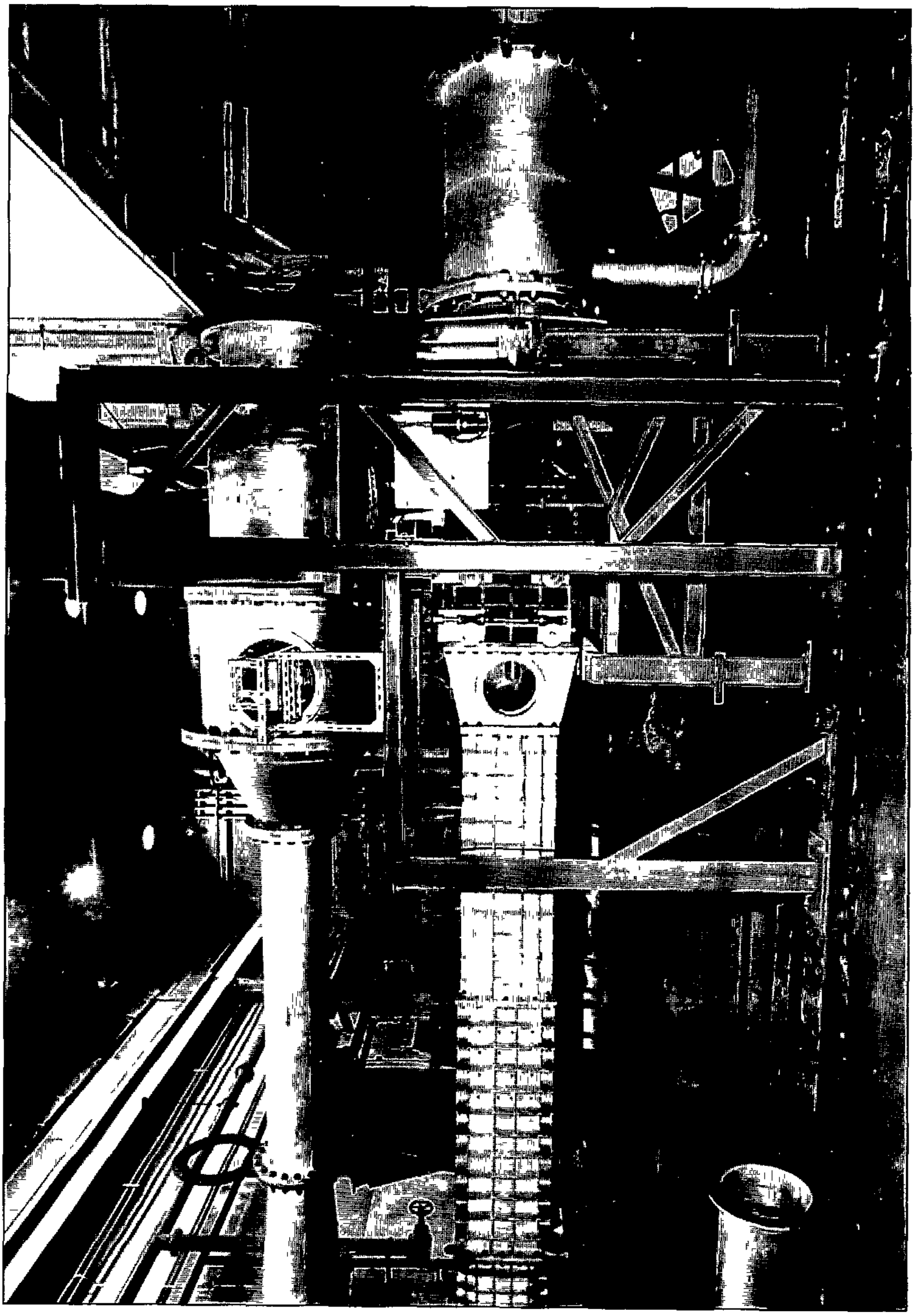


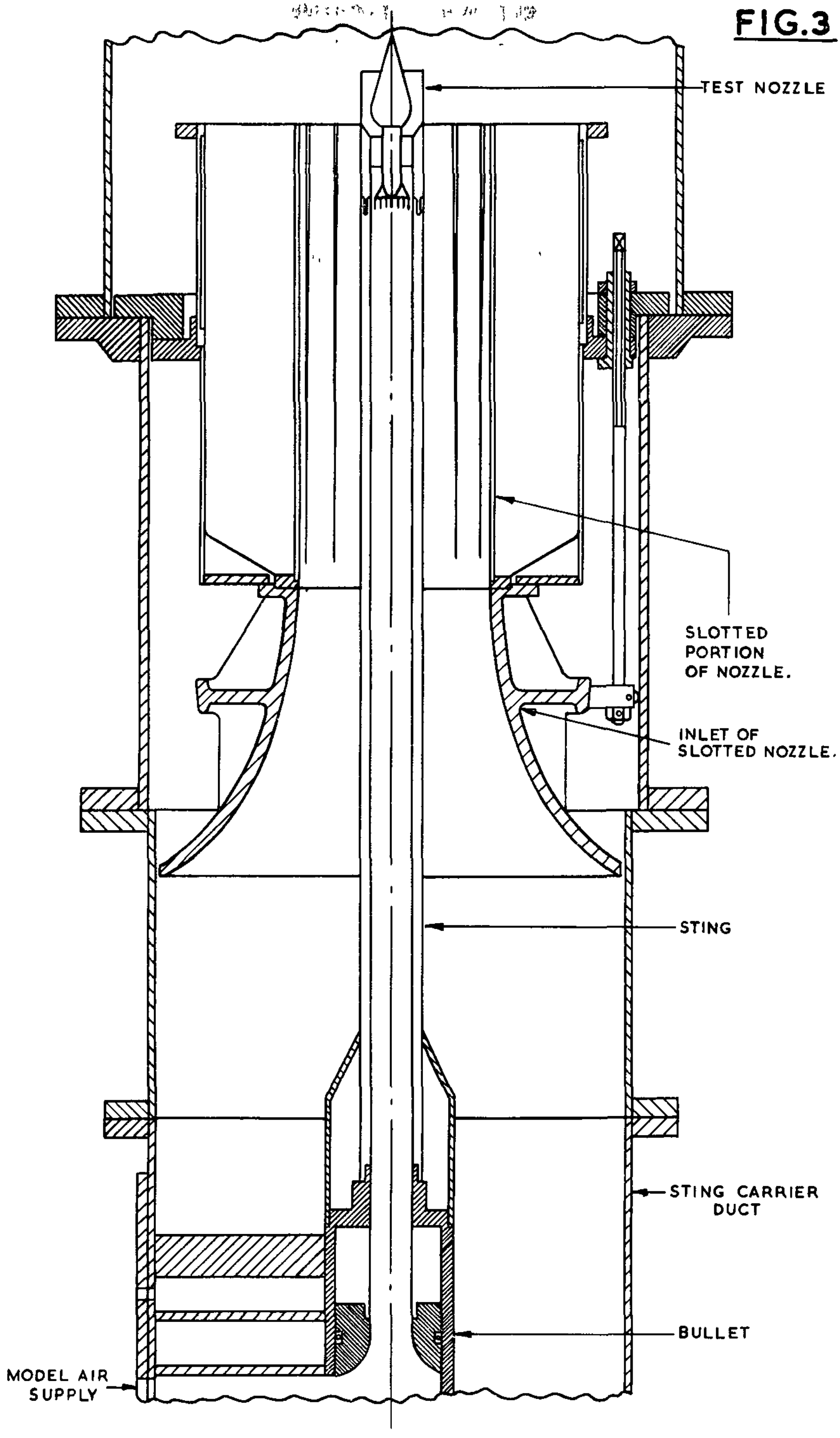
FIG. 1

FIG. 2



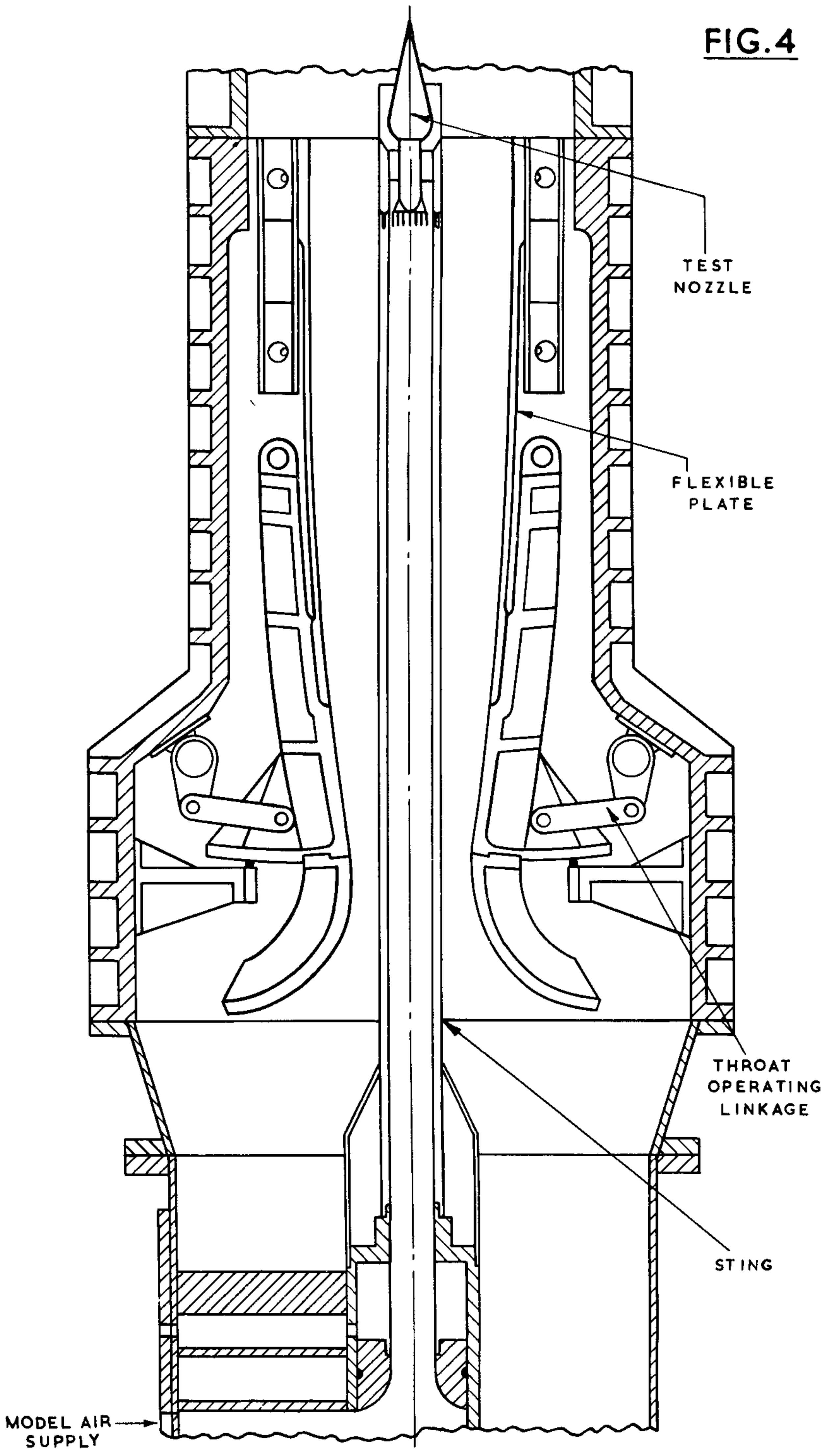
MODEL PROPELLING NOZZLE TEST RIG.

FIG.3



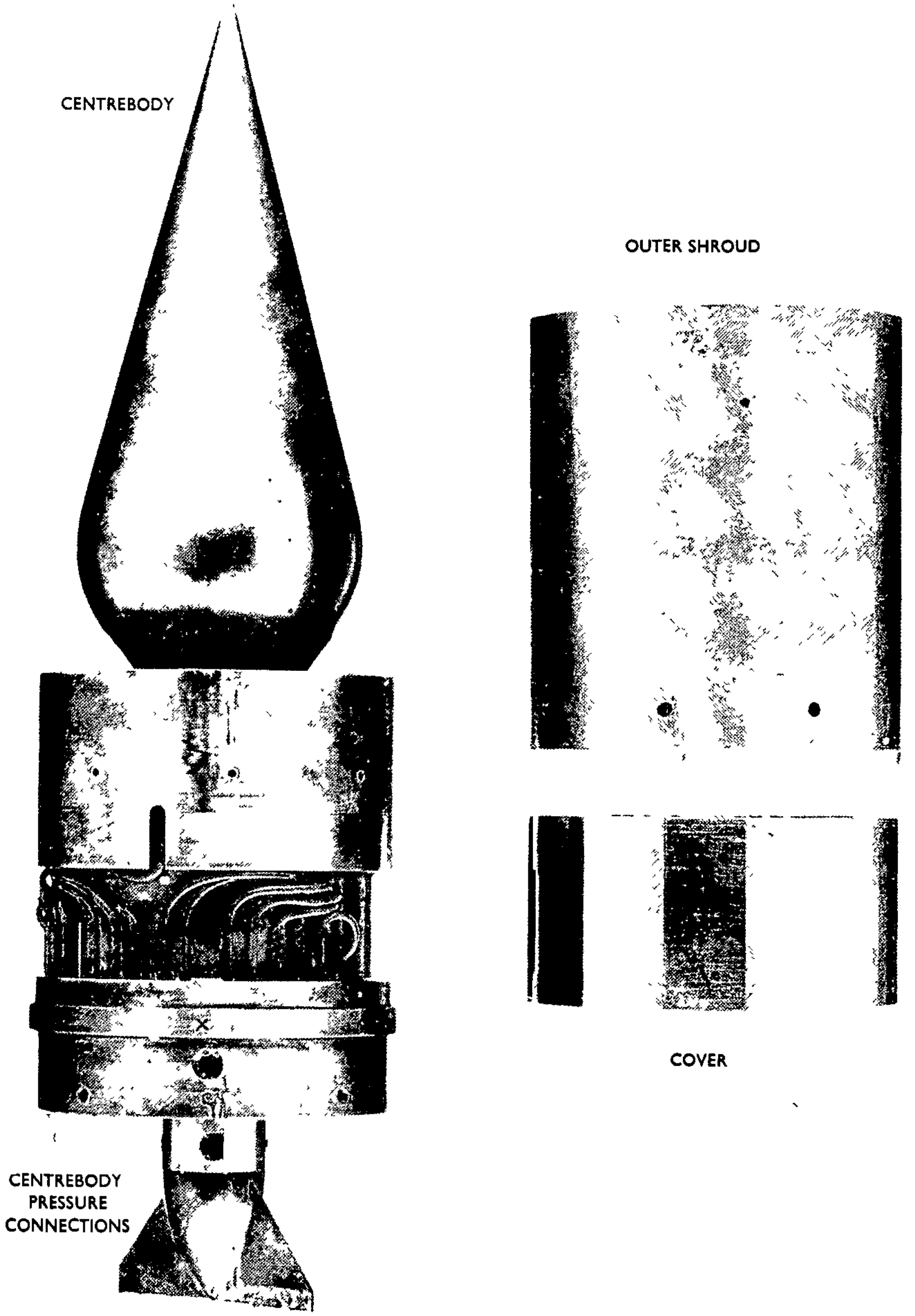
CROSS SECTION OF TEST RIG – TRANSONIC EXTERNAL FLOW.

FIG. 4

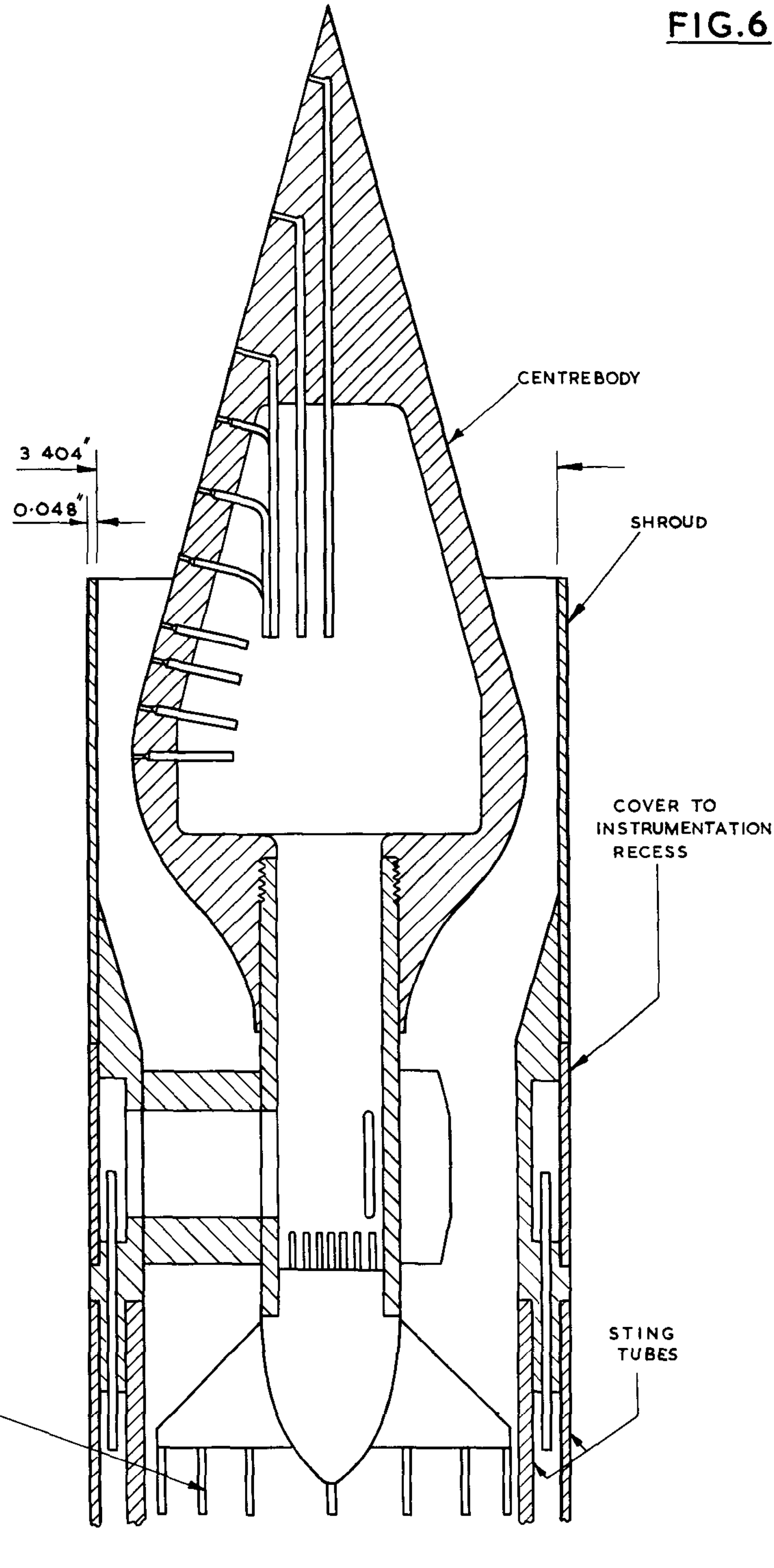


CROSS SECTION OF TEST RIG SUPERSONIC EXTERNAL FLOW.

FIG. 5

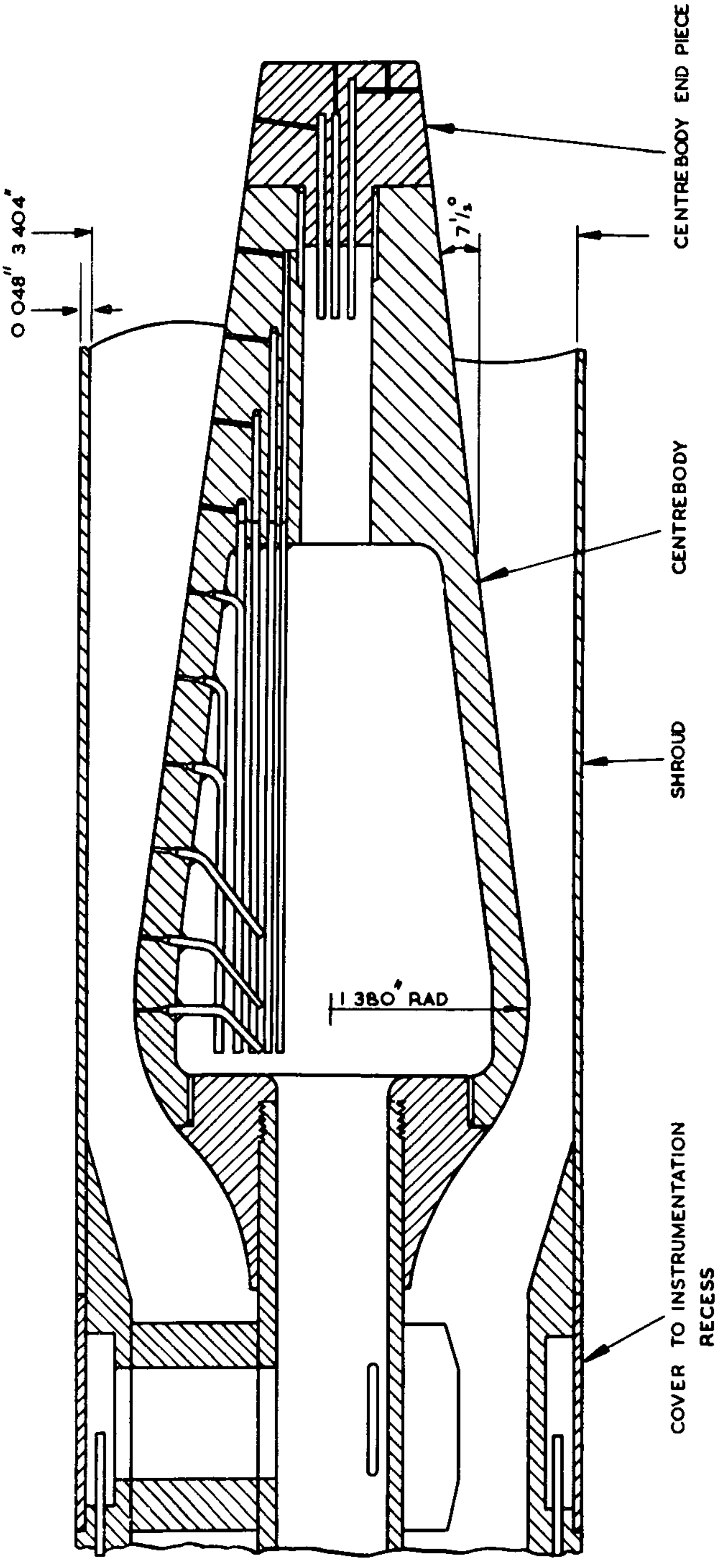


TEST NOZZLE



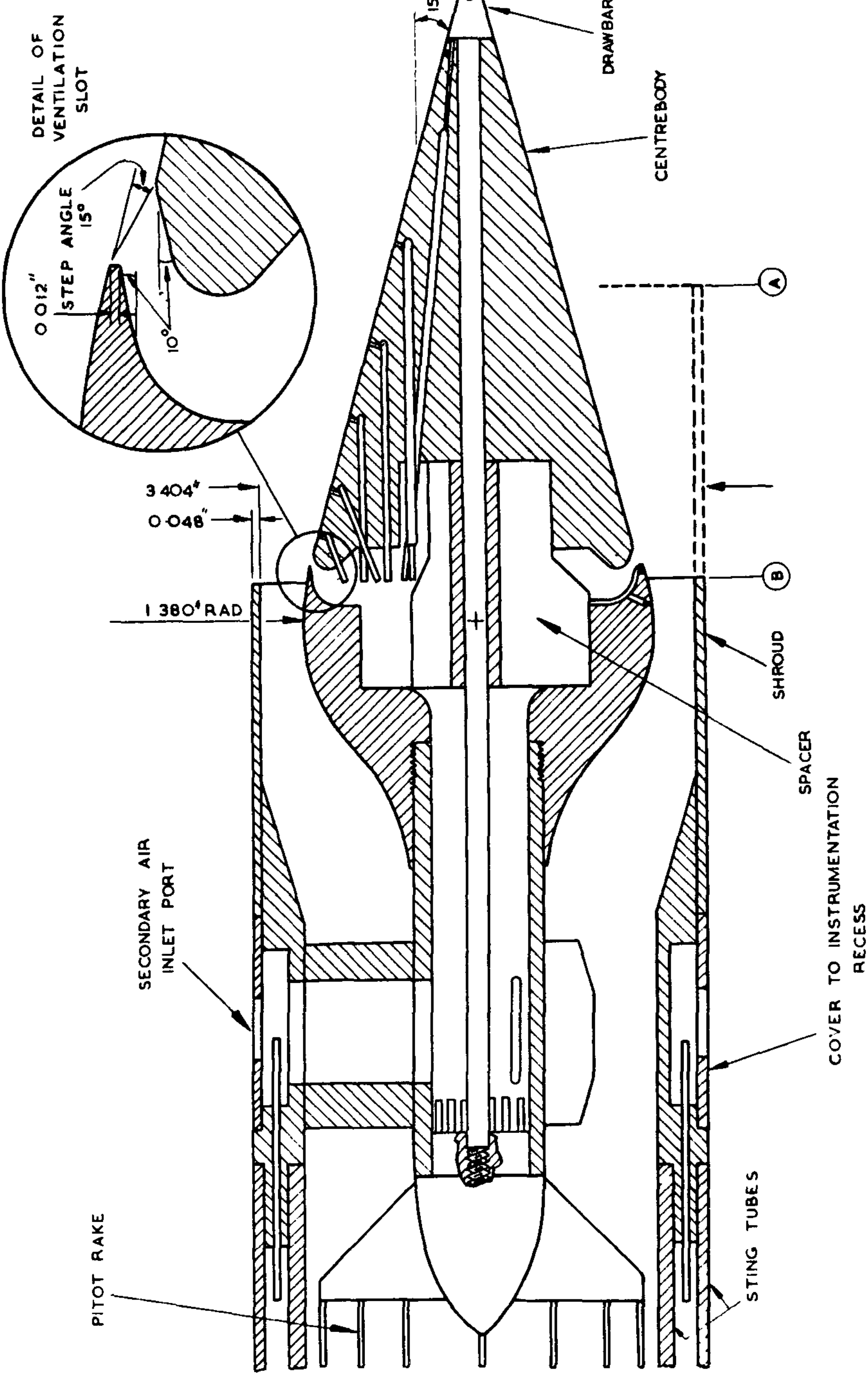
ARRANGEMENT OF TEST MODELS.

FIG. 7



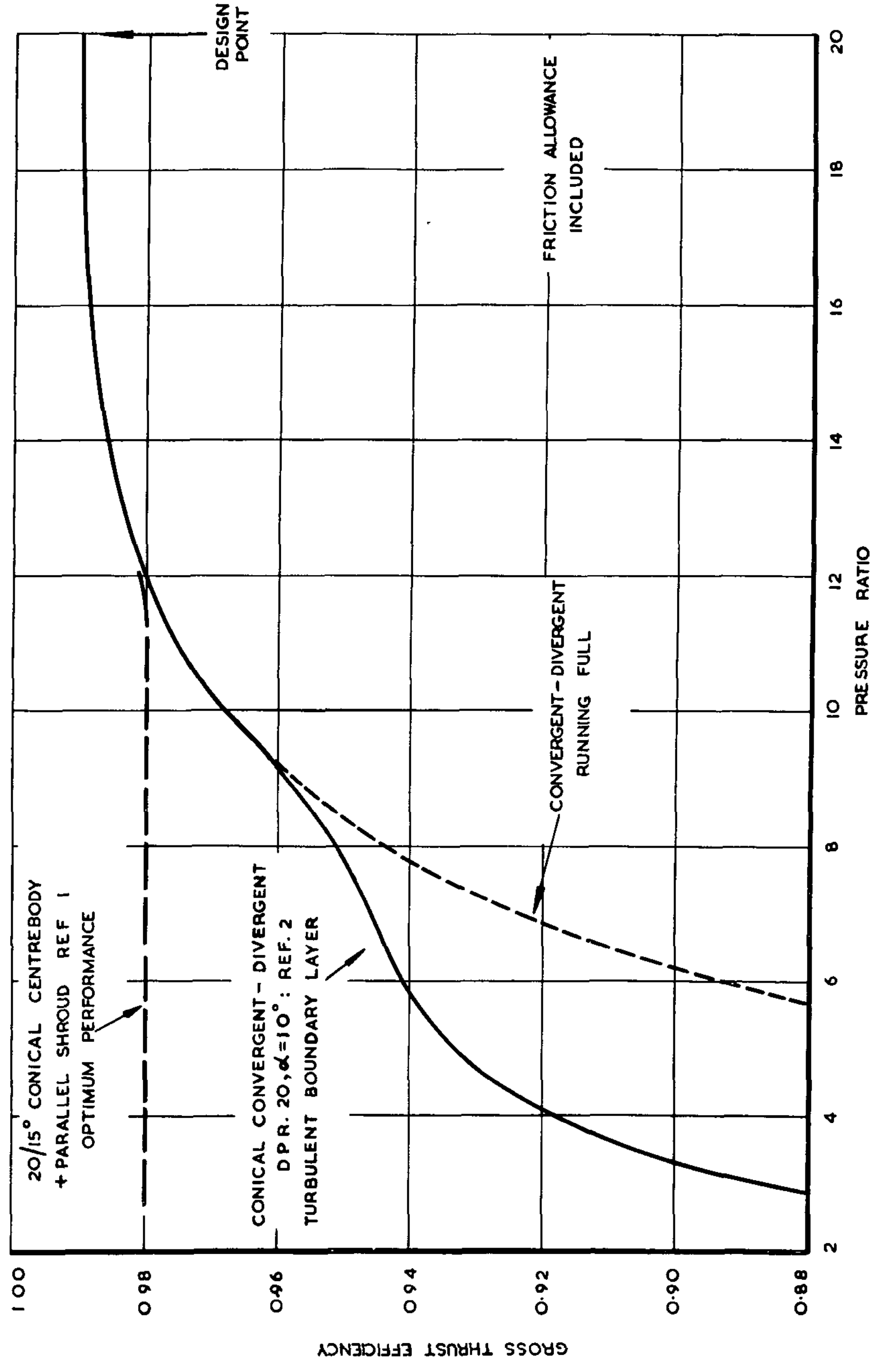
ARRANGEMENT OF CUT-OFF CENTREBODY MODEL

FIG. 8



ARRANGEMENT OF VENTILATED CENTREBODY MODEL

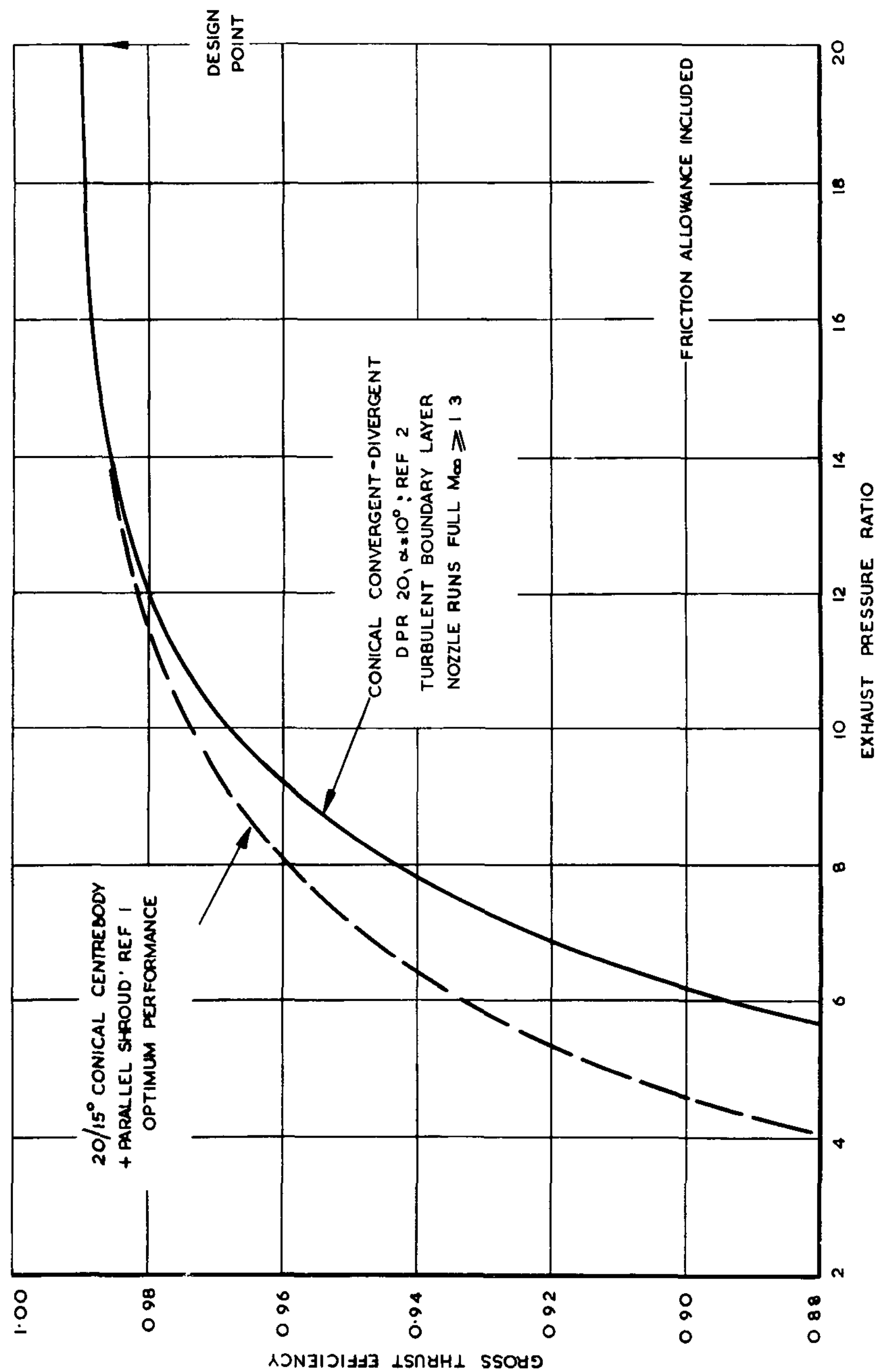
FIG. 9



COMPARISON OF CENTREBODY AND CONVERGENT-DIVERGENT NOZZLES

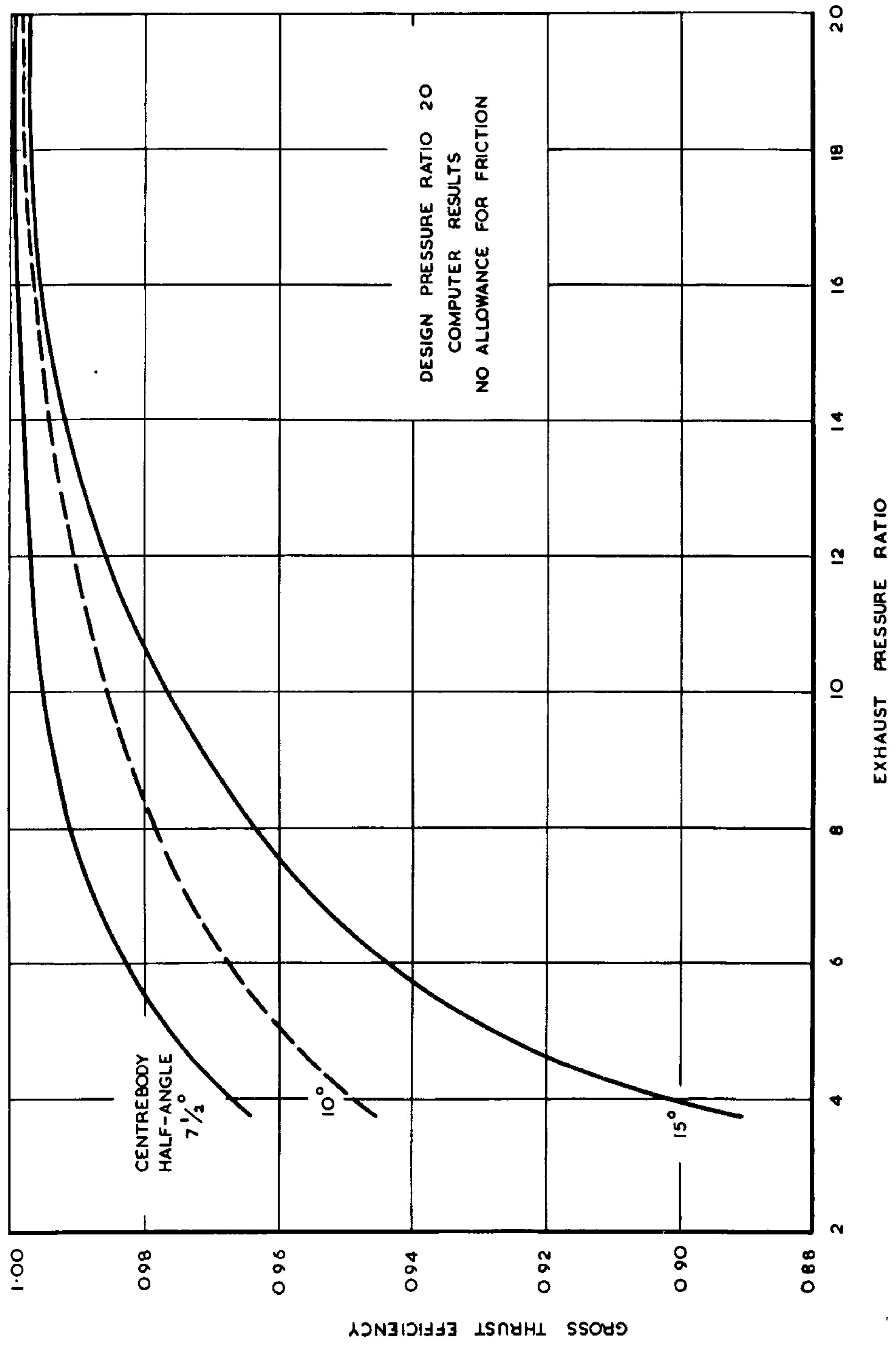
I-QUIESCENT AIR

FIG. 10



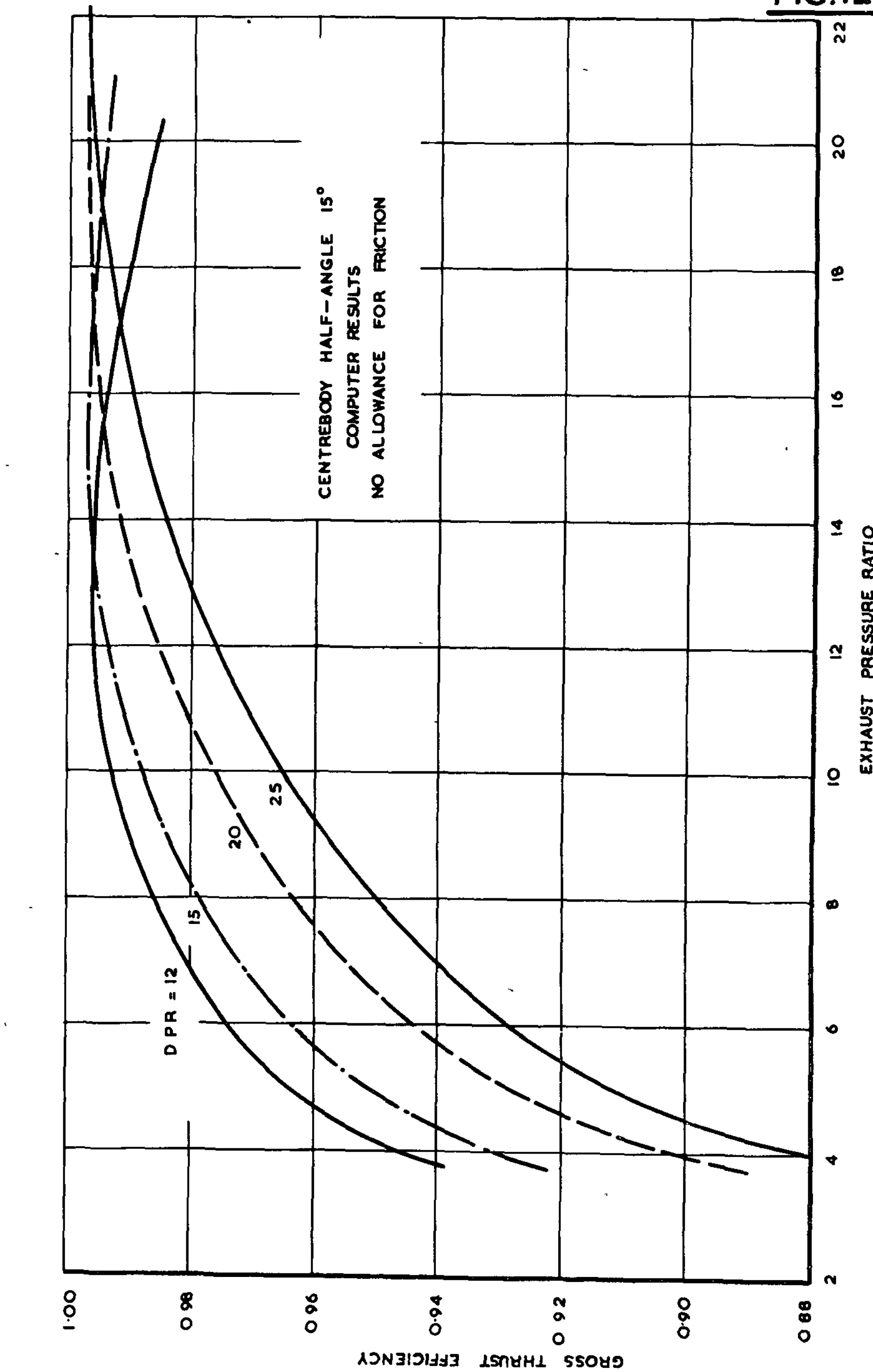
COMPARISON OF CENTREBODY AND CONVERGENT-DIVERGENT NOZZLES II ~ SUPERSONIC EXTERNAL FLOW

FIG. 11



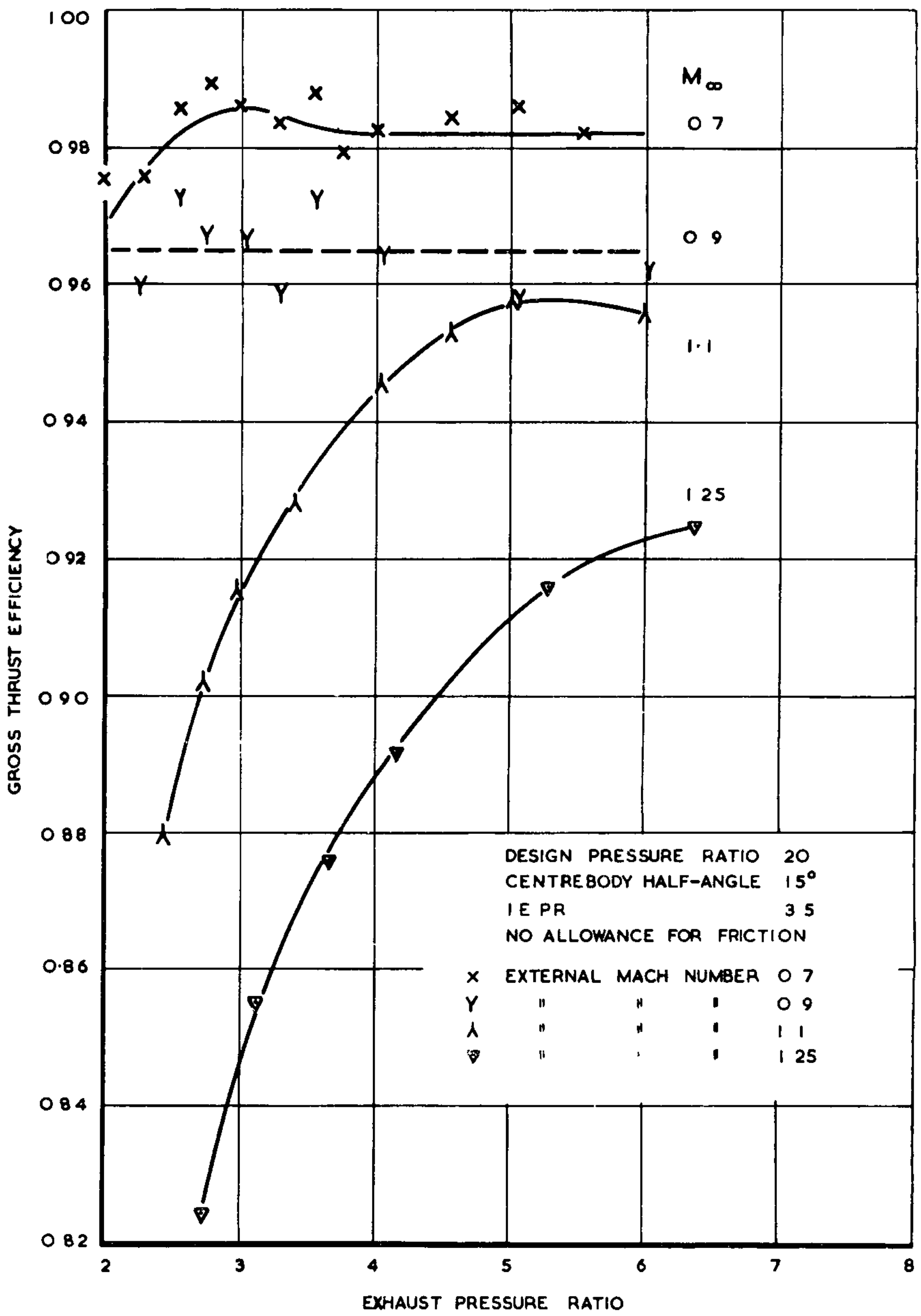
EFFECT OF CENTREBODY ANGLE ON THE PERFORMANCE OF PARALLEL SHROUD NOZZLES IN SUPERSONIC EXTERNAL FLOW

FIG.12



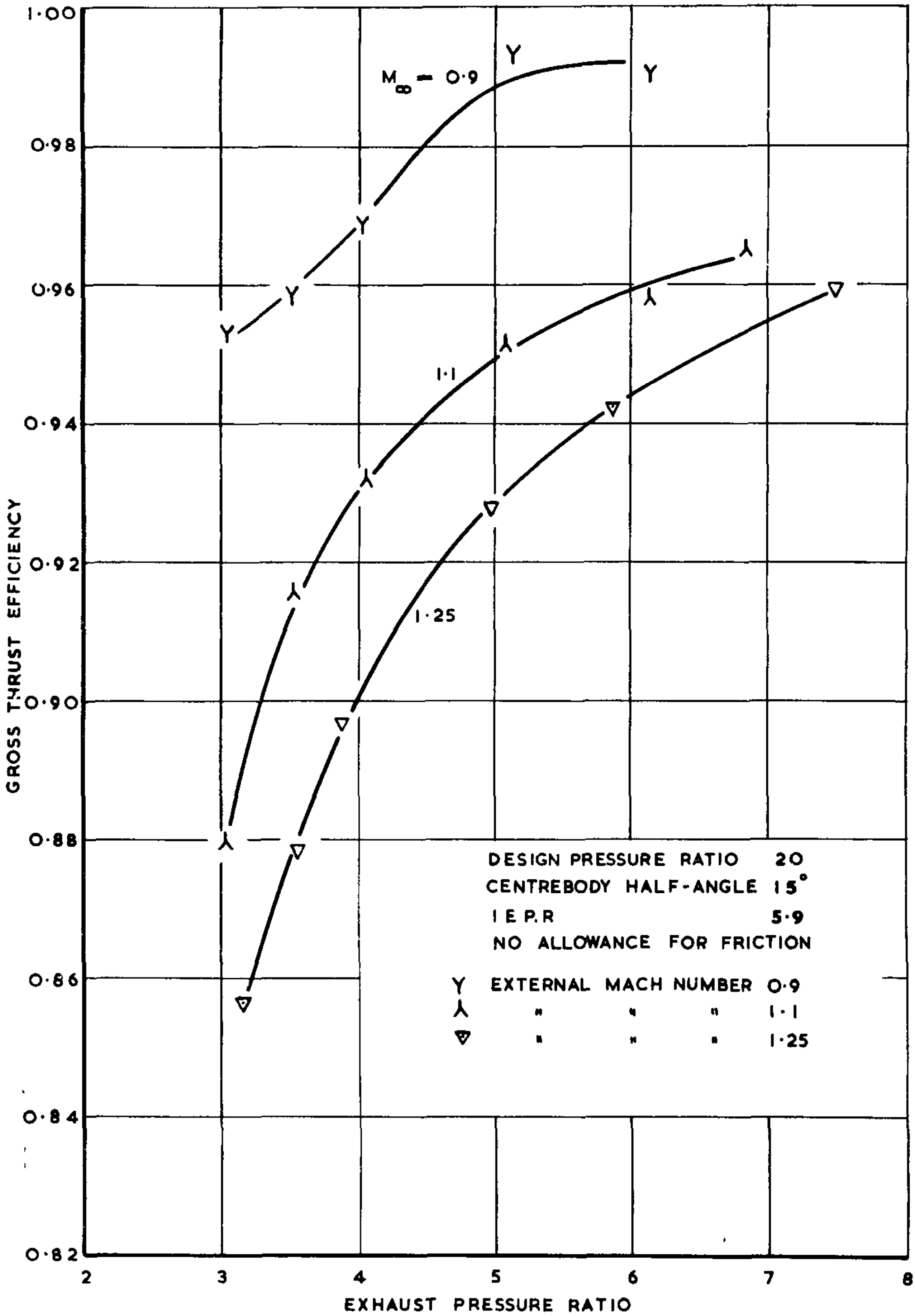
EFFECT OF DESIGN PRESSURE RATIO ON THE PERFORMANCE OF PARALLEL SHROUD CENTREBODY NOZZLES IN SUPERSONIC EXTERNAL FLOW

FIG. 13



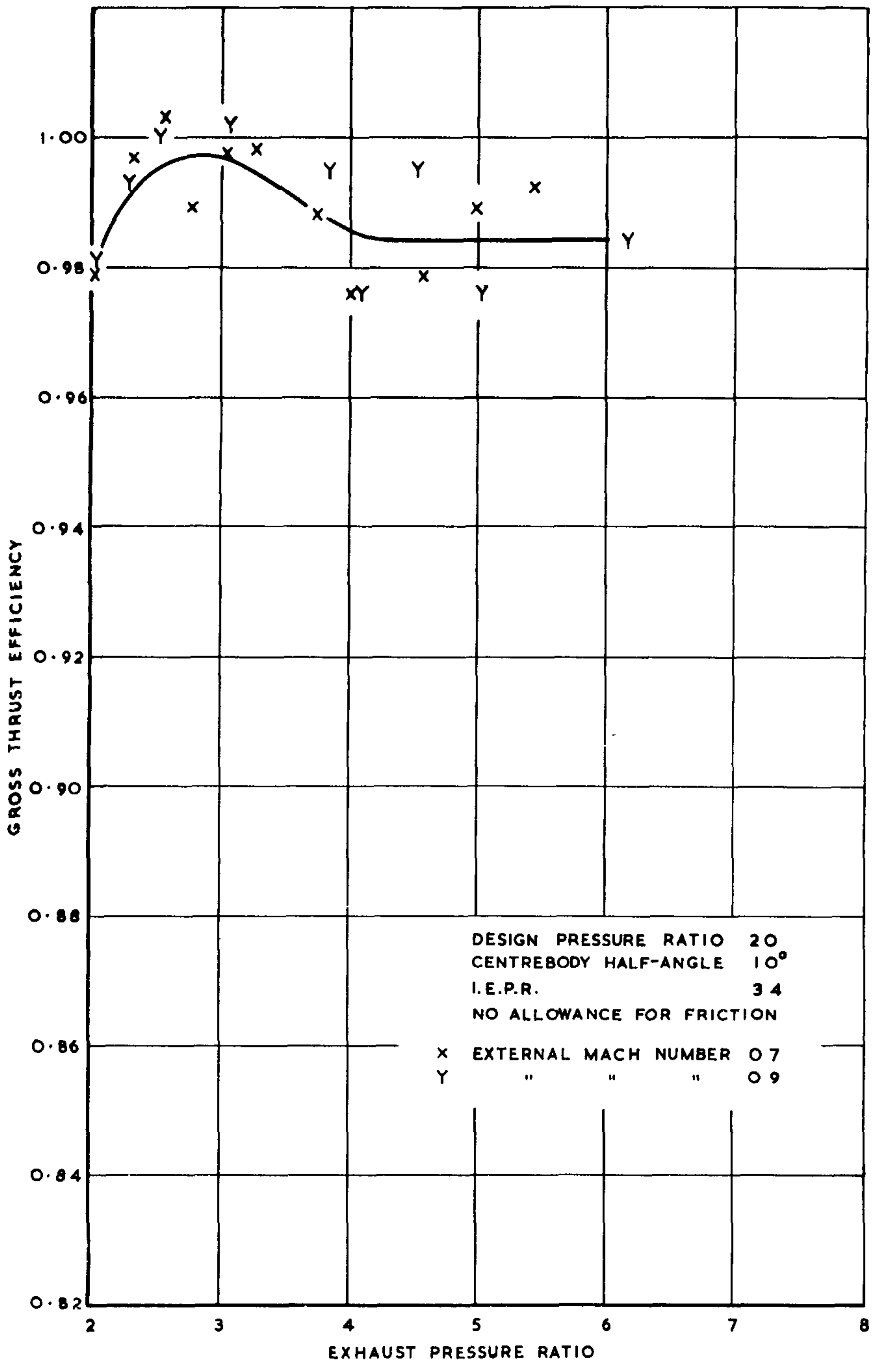
20/15° NOZZLE PERFORMANCE (I.E.P.R.=3·5)

FIG.14



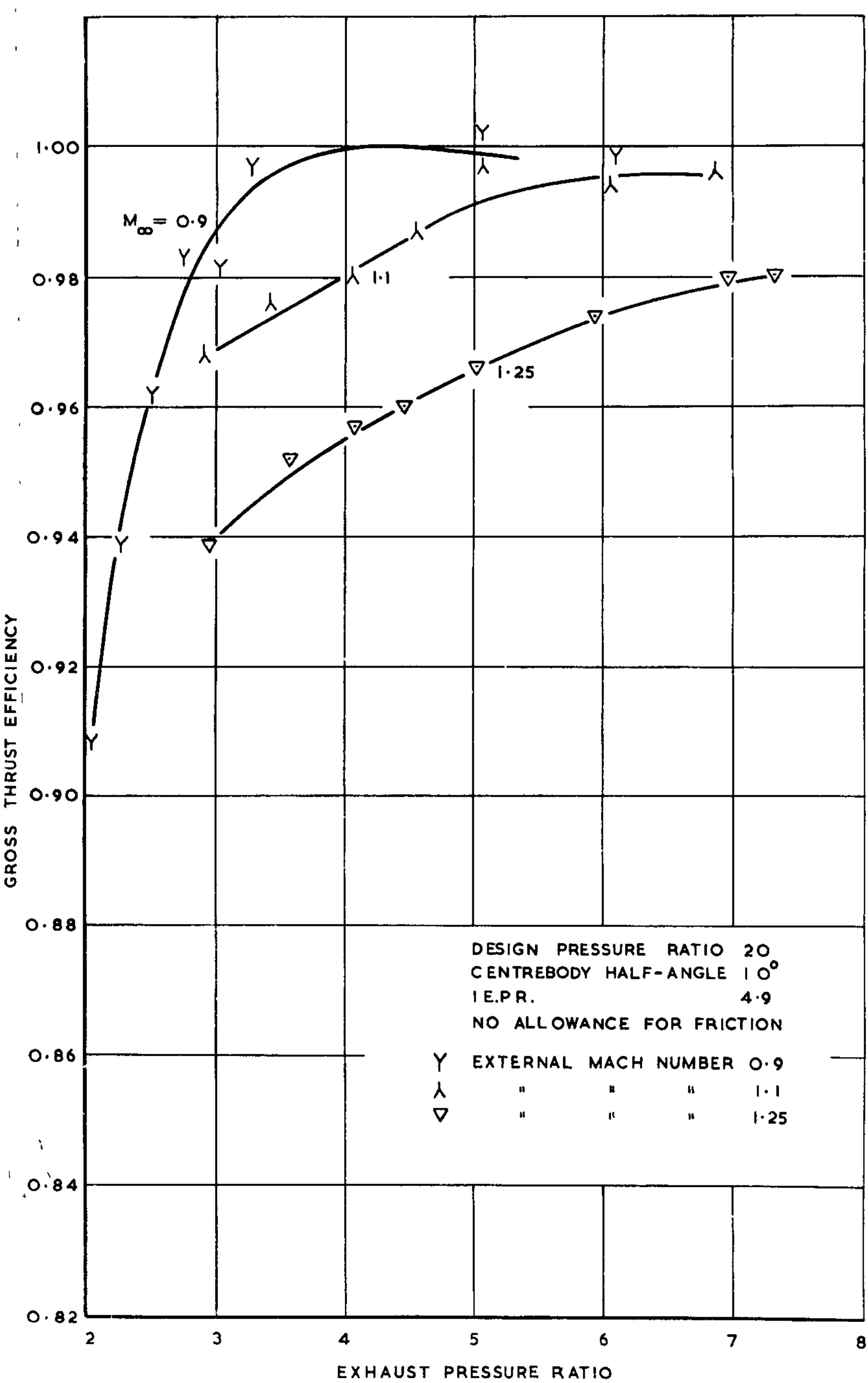
20/15° NOZZLE PERFORMANCE (I.E.P.R.=5·9)

FIG. 15



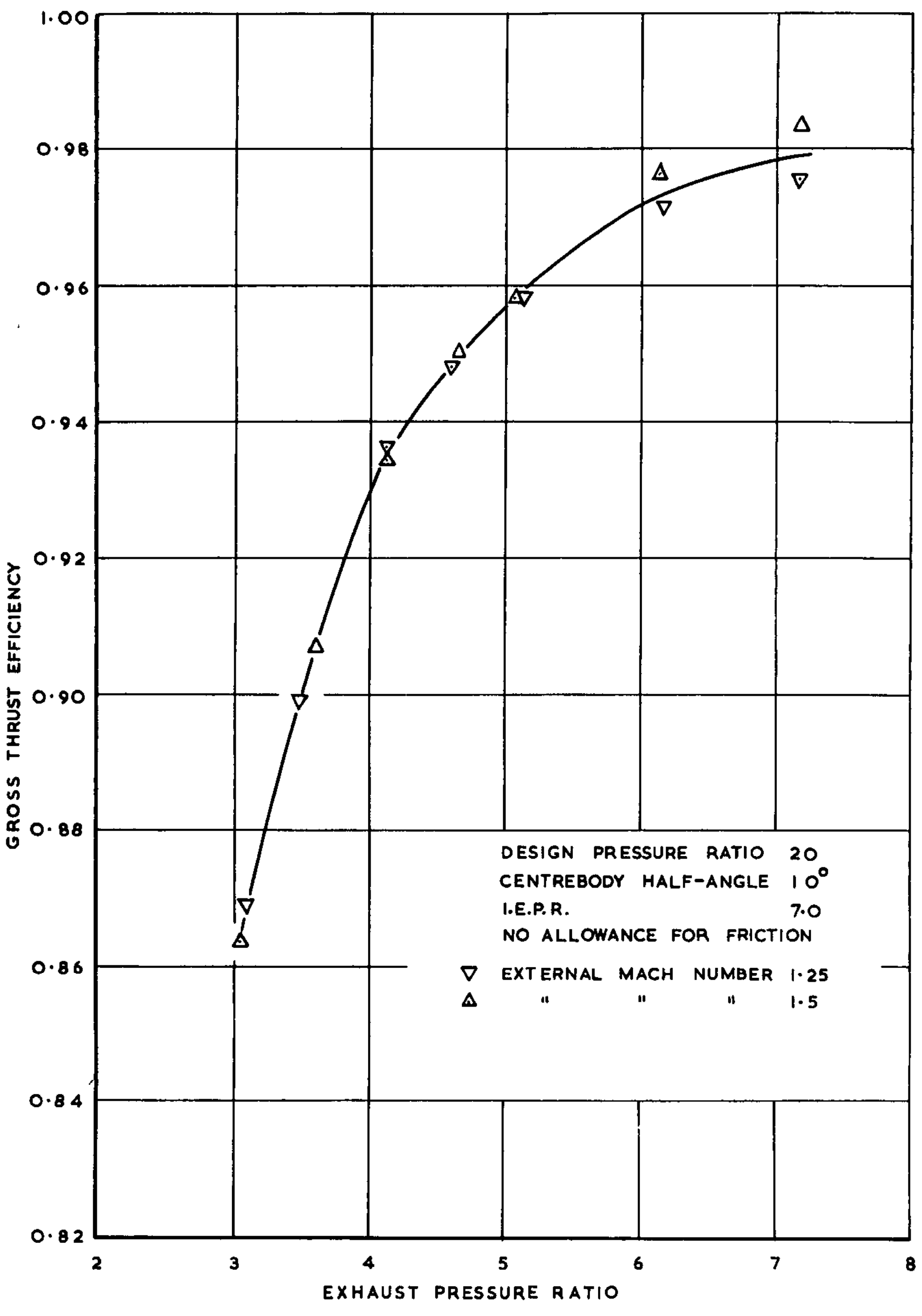
20/10° NOZZLE PERFORMANCE (I.E.P.R. = 3·4)

FIG.16



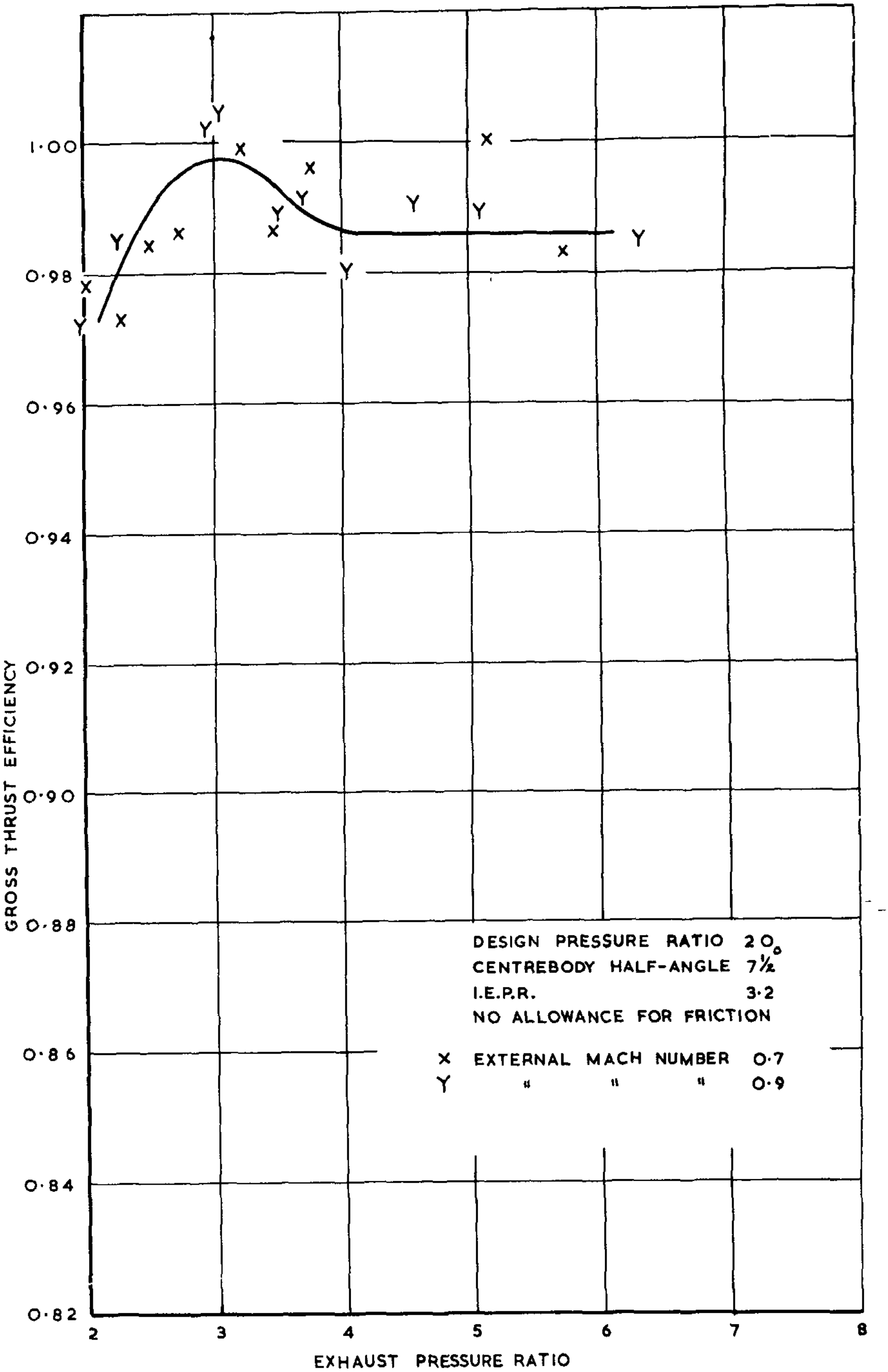
20/10° NOZZLE PERFORMANCE (I.E.P.R. = 4·9)

FIG.17



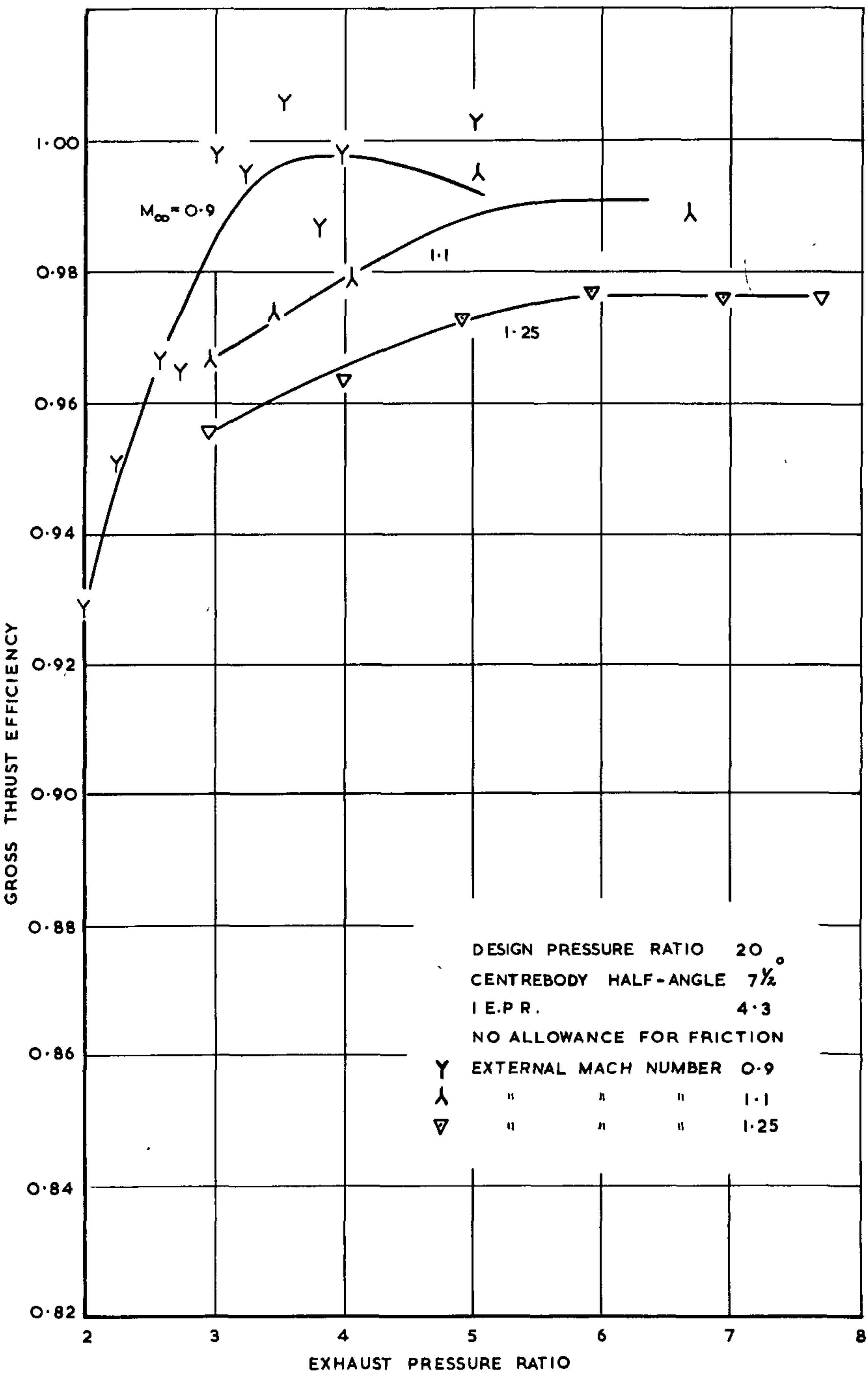
20/10° NOZZLE PERFORMANCE (I.E.P.R.=7·0)

FIG. 18



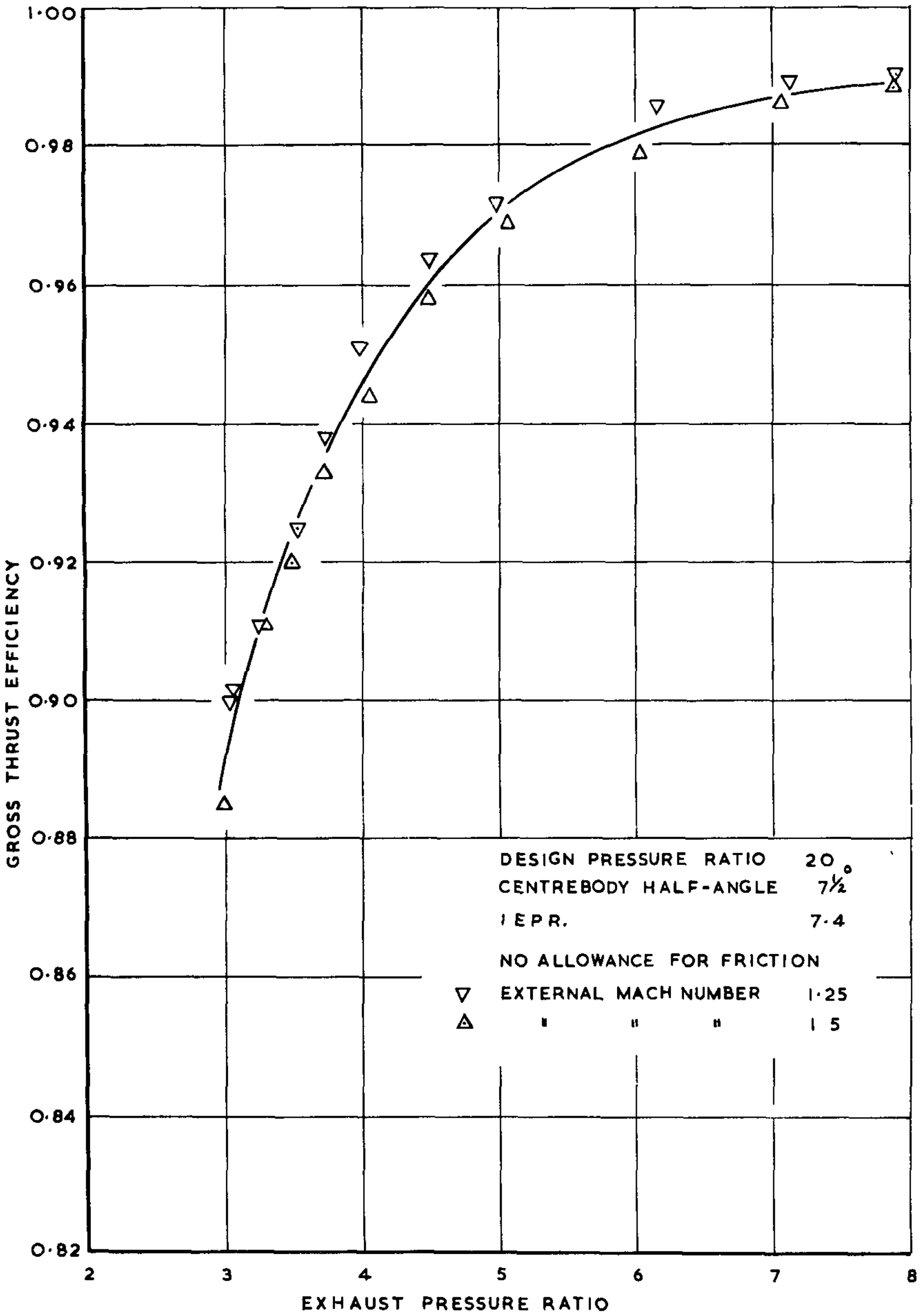
20/7½° NOZZLE PERFORMANCE (I.E.P.R.=3·2)

FIG.19



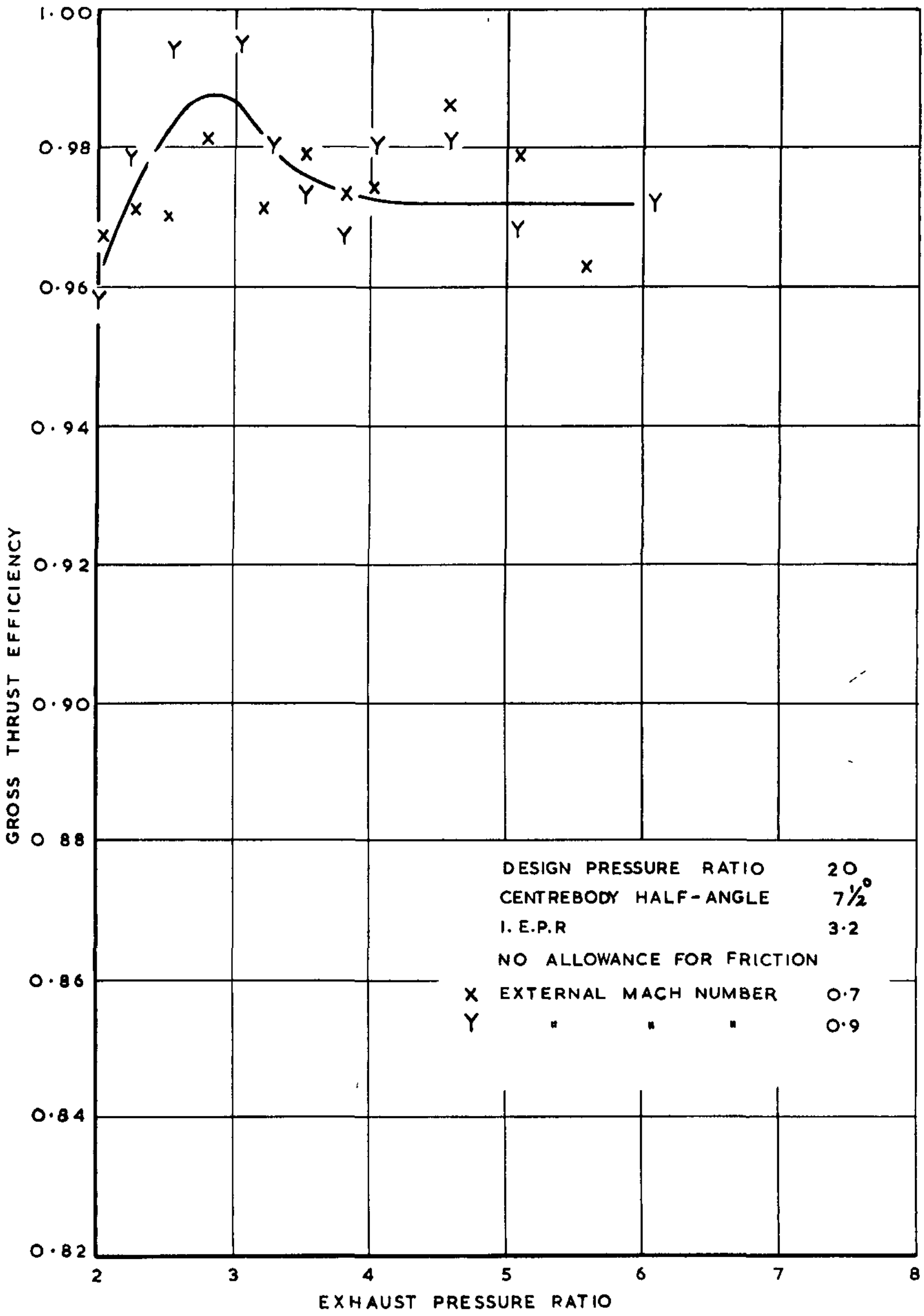
20/7½° NOZZLE PERFORMANCE (I.E.P.R. = 4·3)

FIG. 20



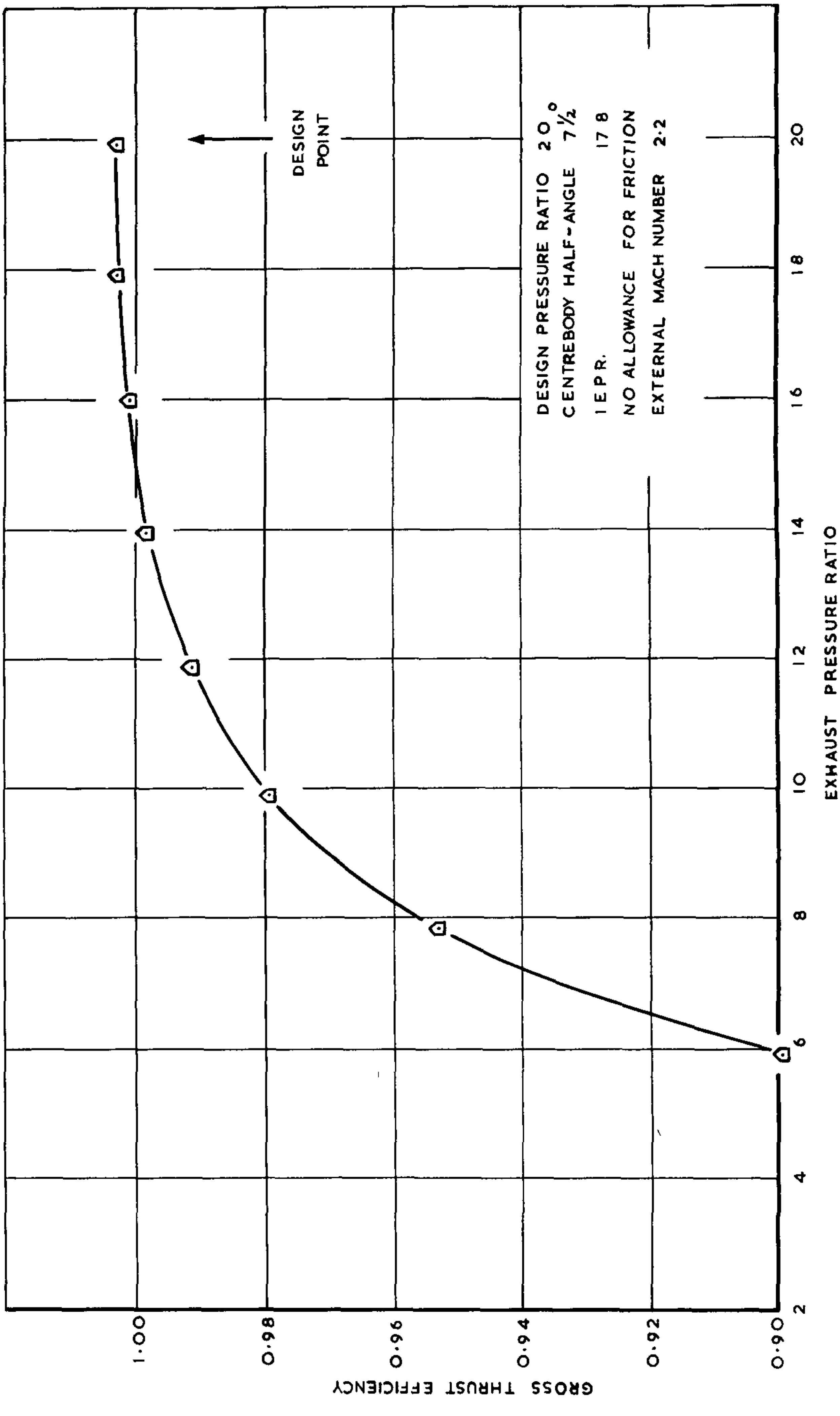
20/7½° NOZZLE PERFORMANCE (I.E.P.R.=7·4)

FIG. 21



20/7½° (CUT-OFF) NOZZLE PERFORMANCE (I.E.P.R=3·2)

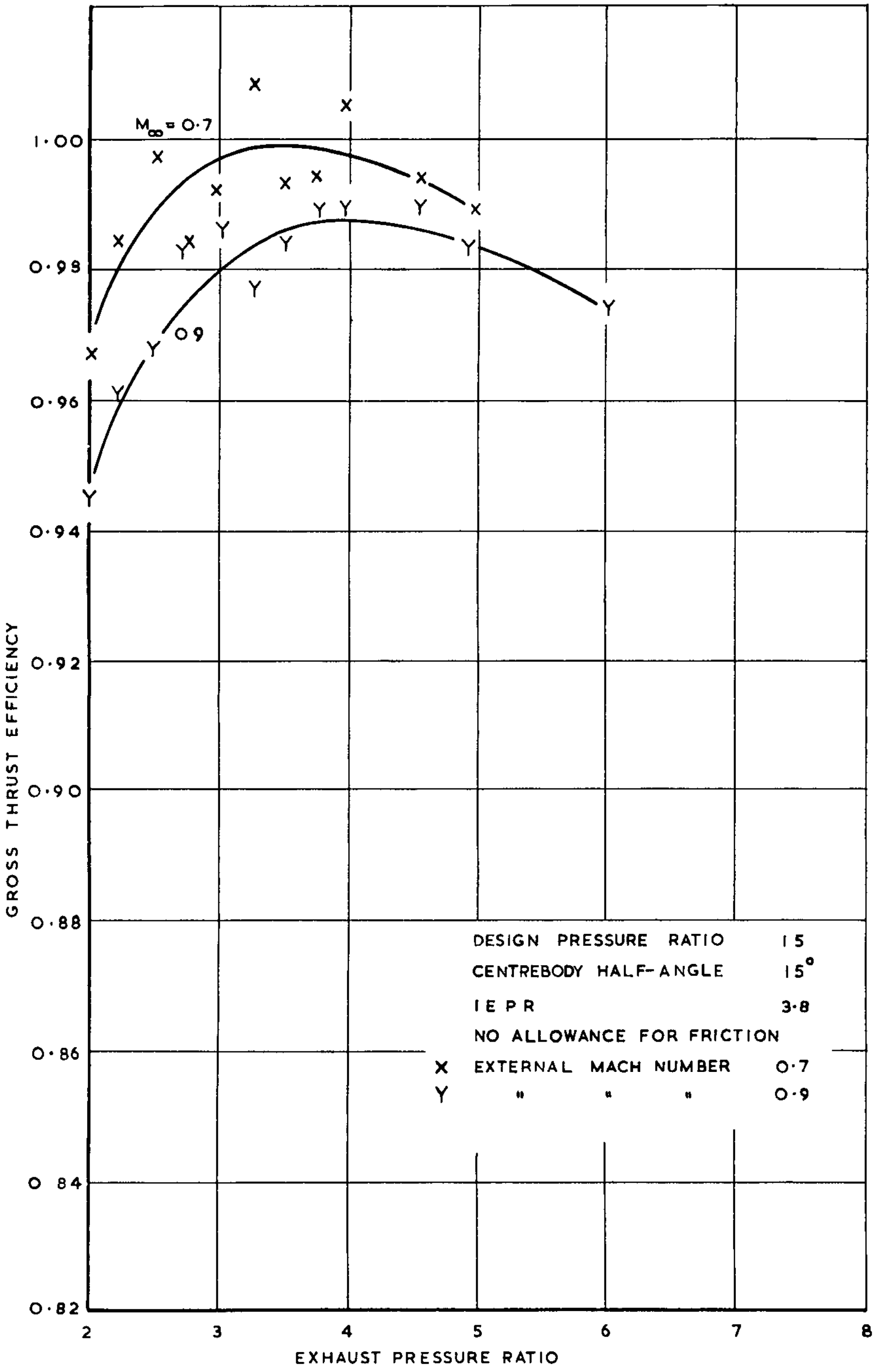
FIG.22



20/7½° (CUT–OFF) NOZZLE PERFORMANCE

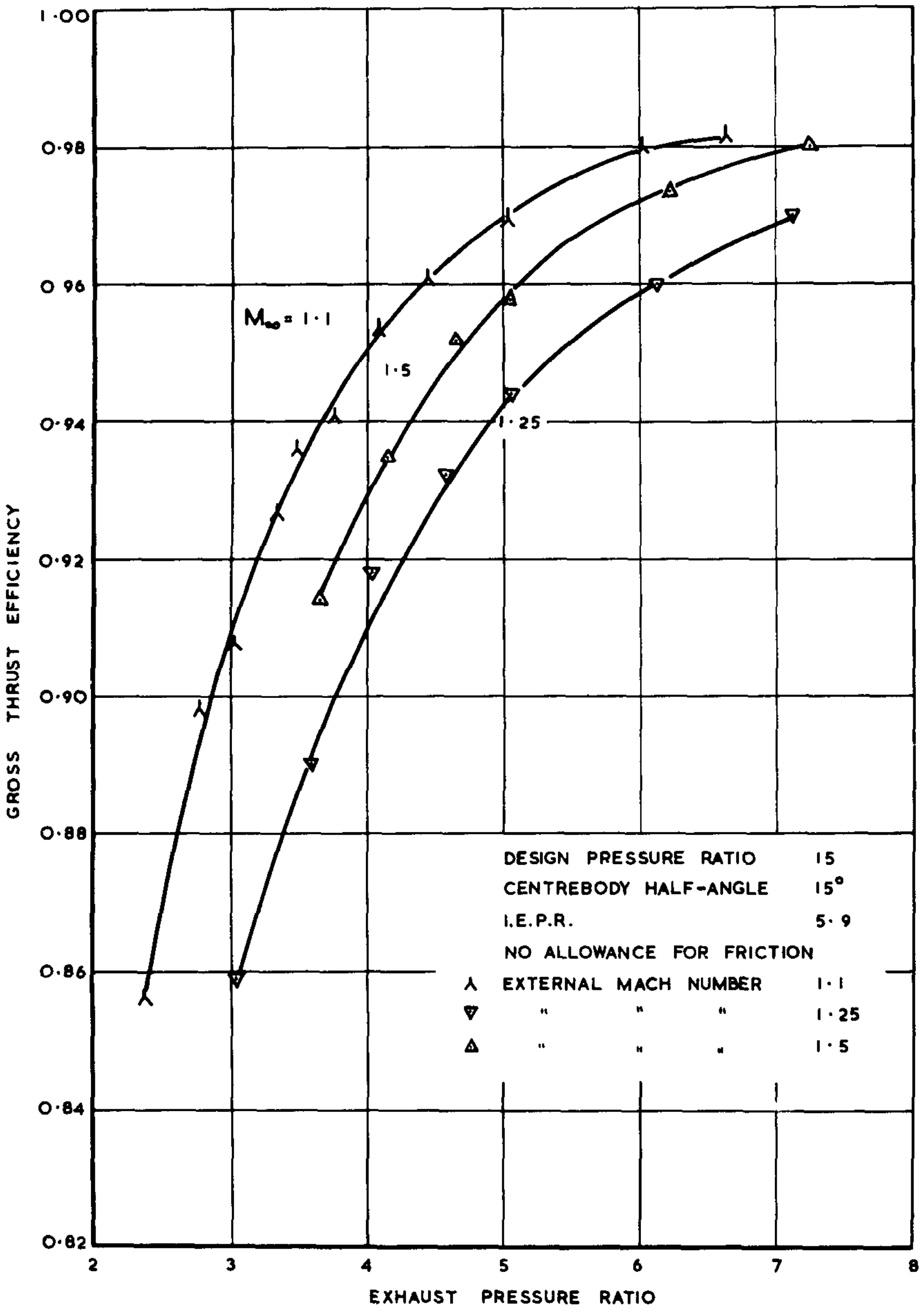
(I.E.P.R. = 17·8)

FIG. 23



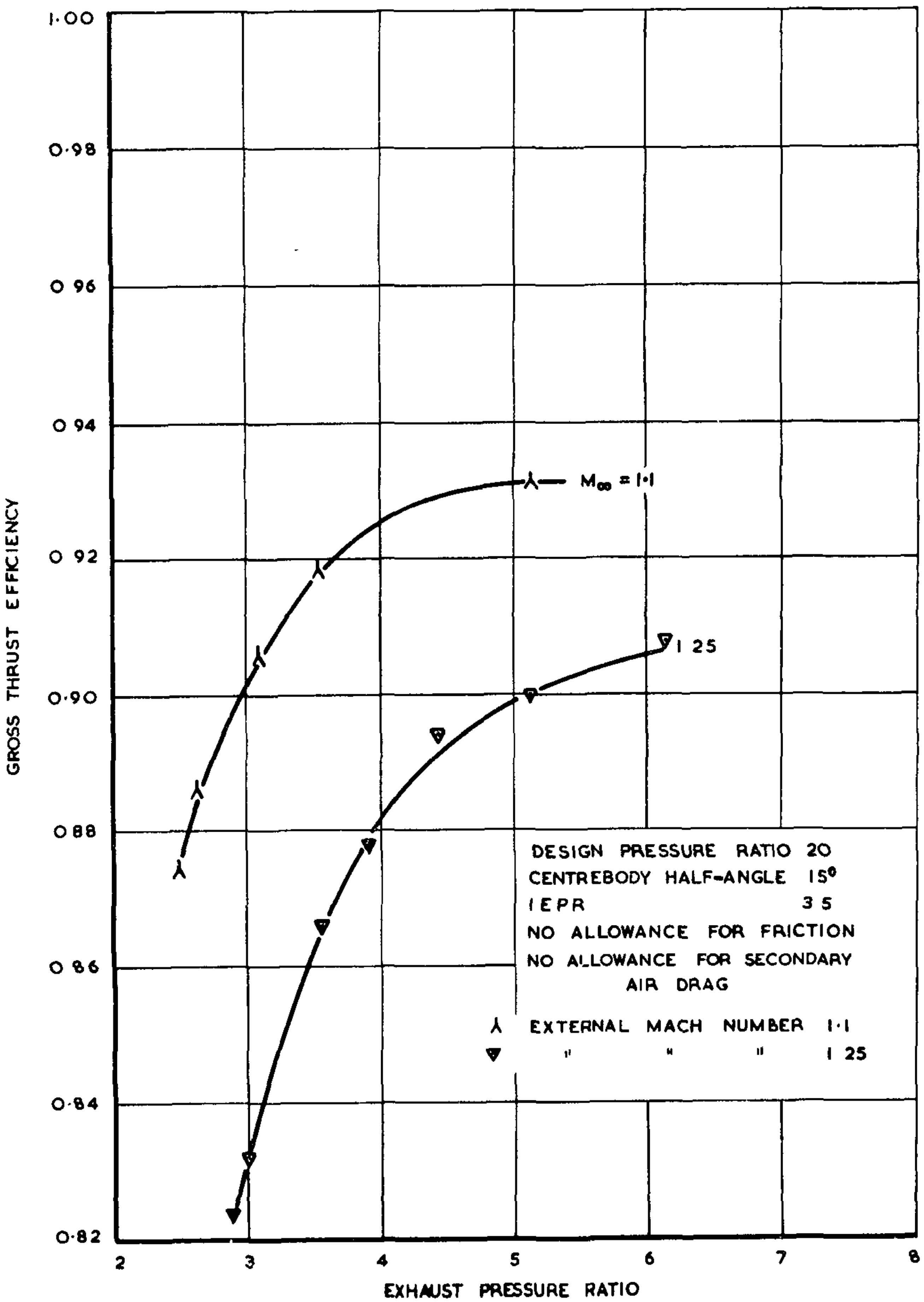
15/15° NOZZLE PERFORMANCE (I.E.P.R. = 3·8)

FIG. 24



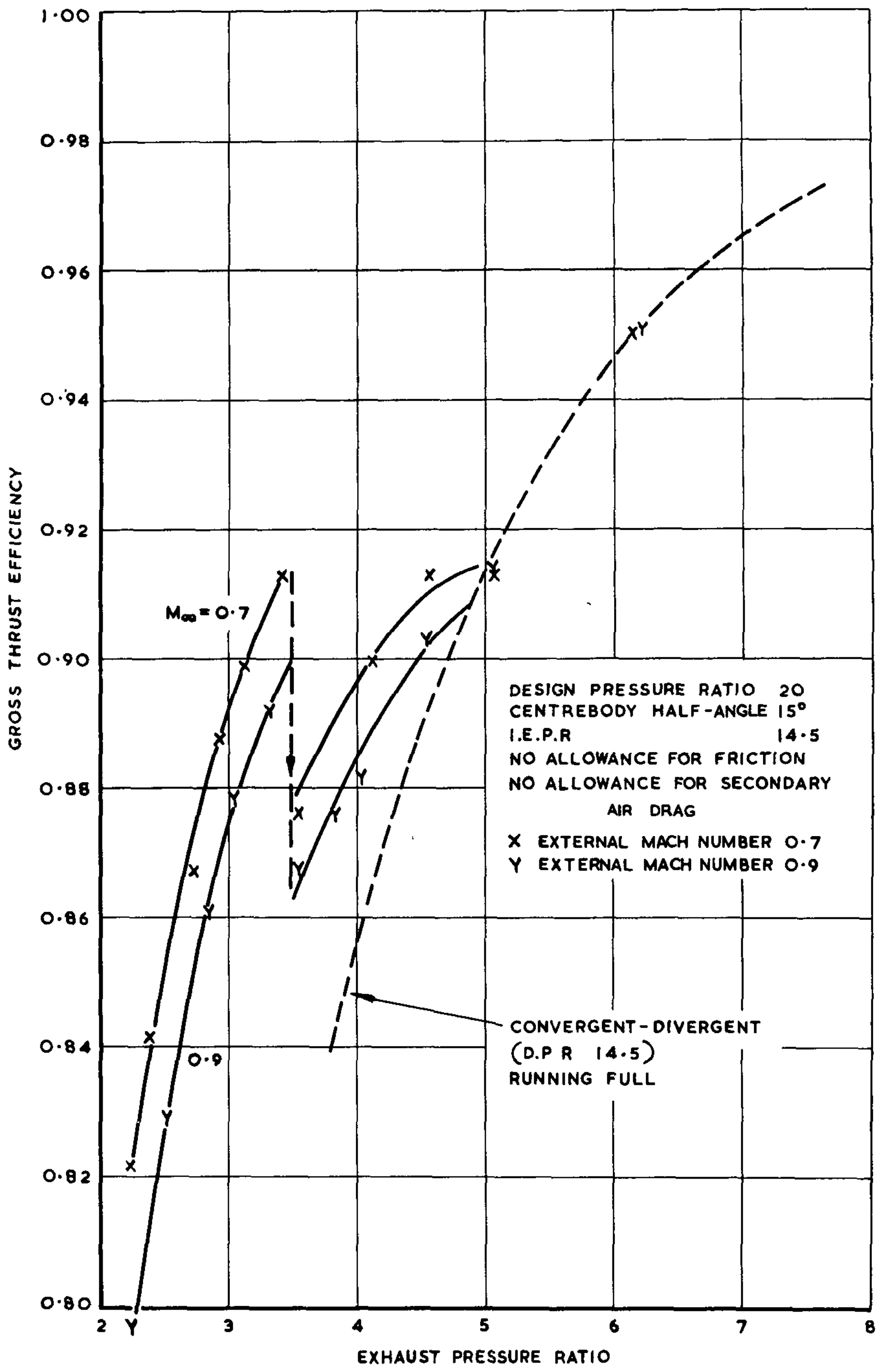
15/15° NOZZLE PERFORMANCE (I.E.P.R. = 5·9)

FIG. 25



20/15° (VENTILATED) NOZZLE PERFORMANCE (I.E.P.R.=3·5)

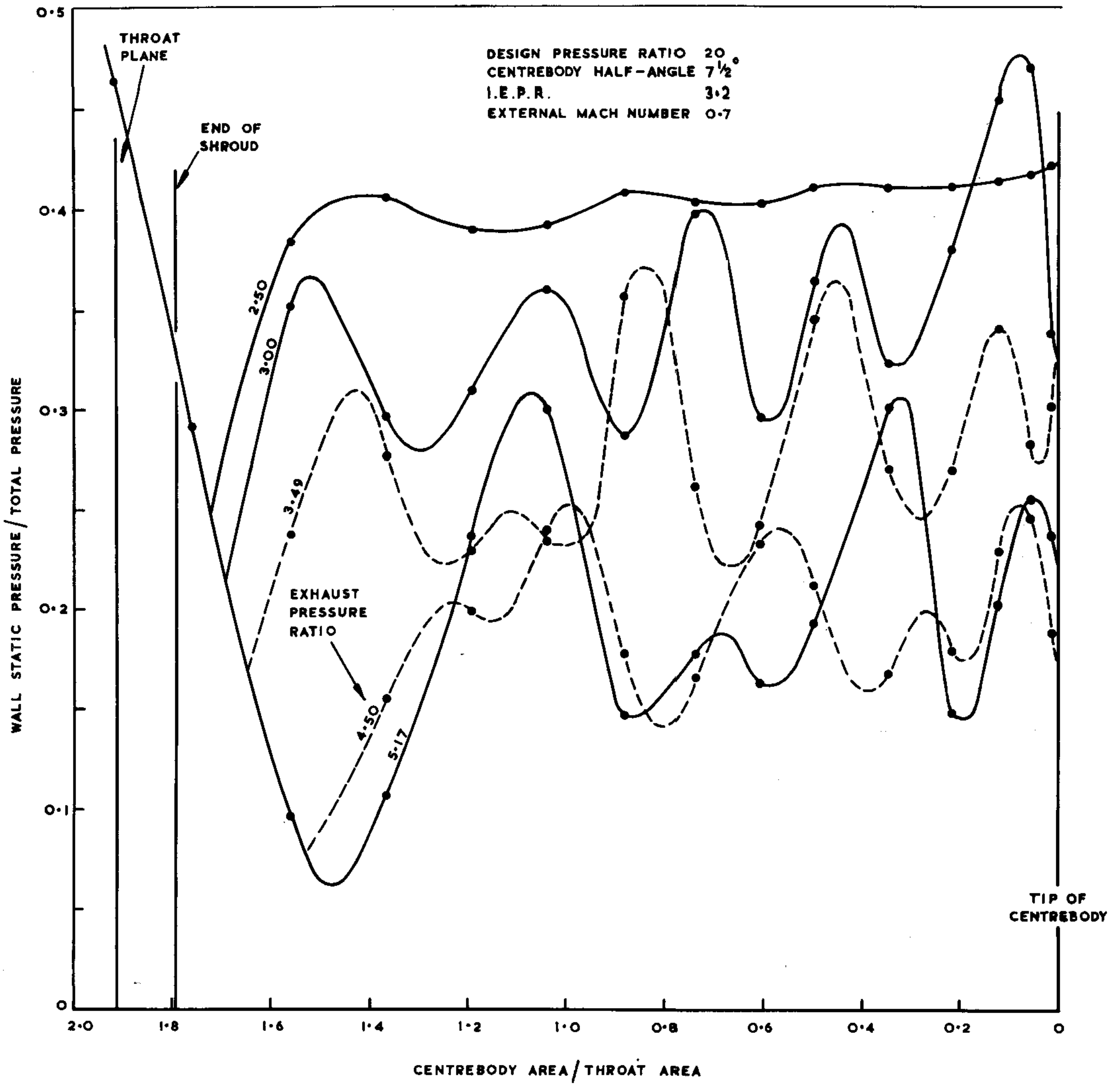
FIG. 26



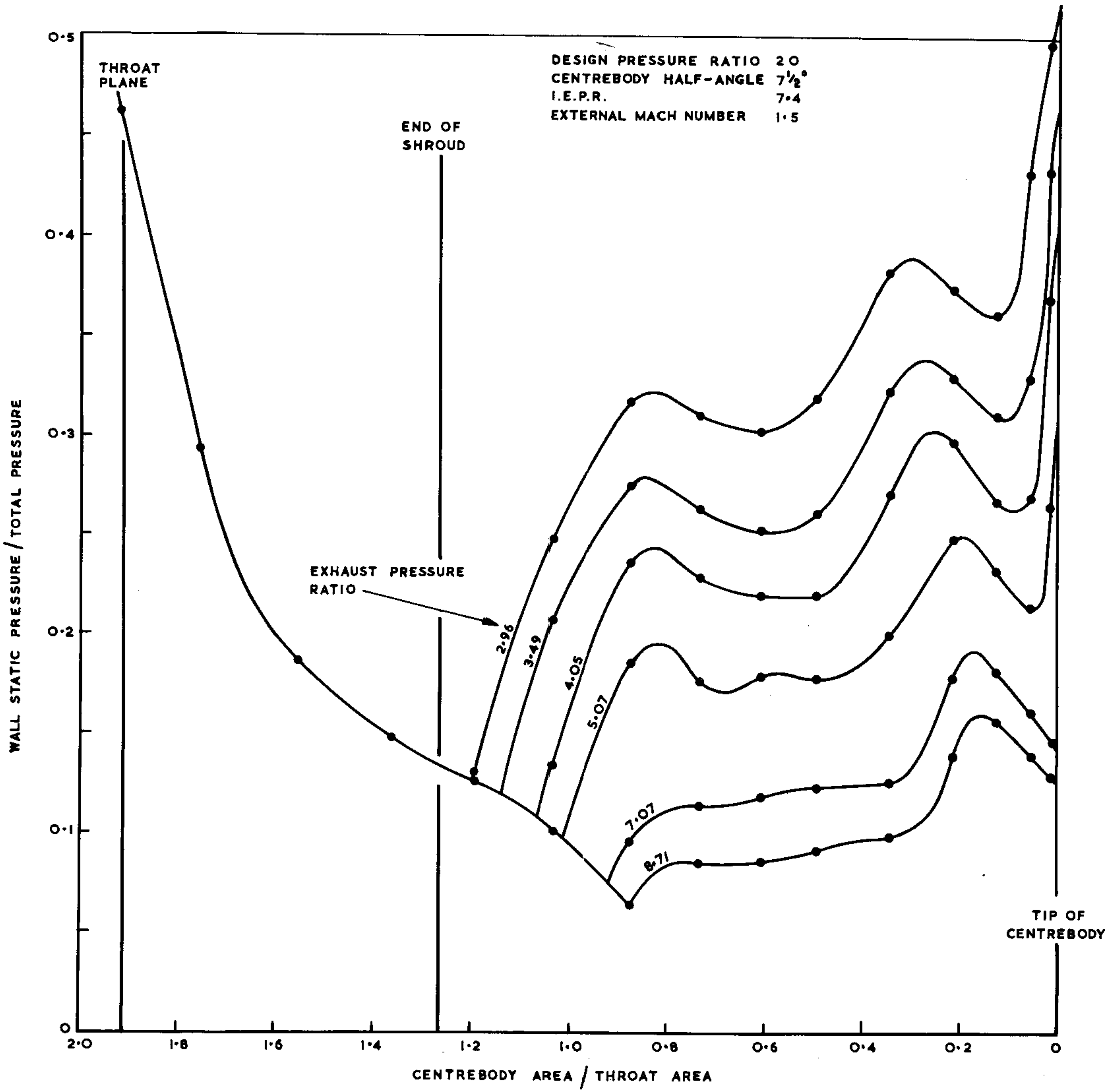
20/15° (VENTILATED) NOZZLE PERFORMANCE

(I.E.P.R. = 14·5)

FIG. 27

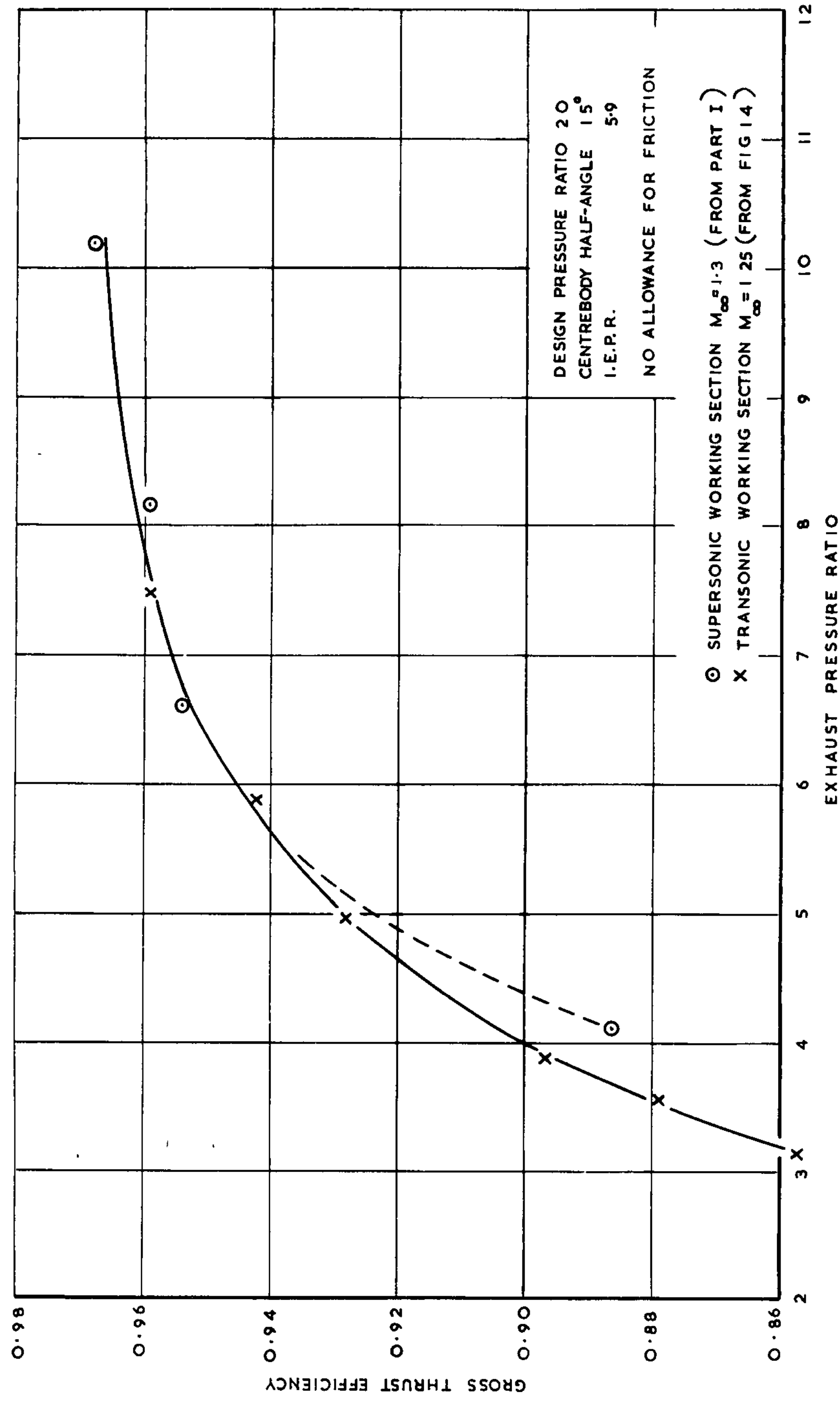


CENTREBODY PRESSURE DISTRIBUTION - I.



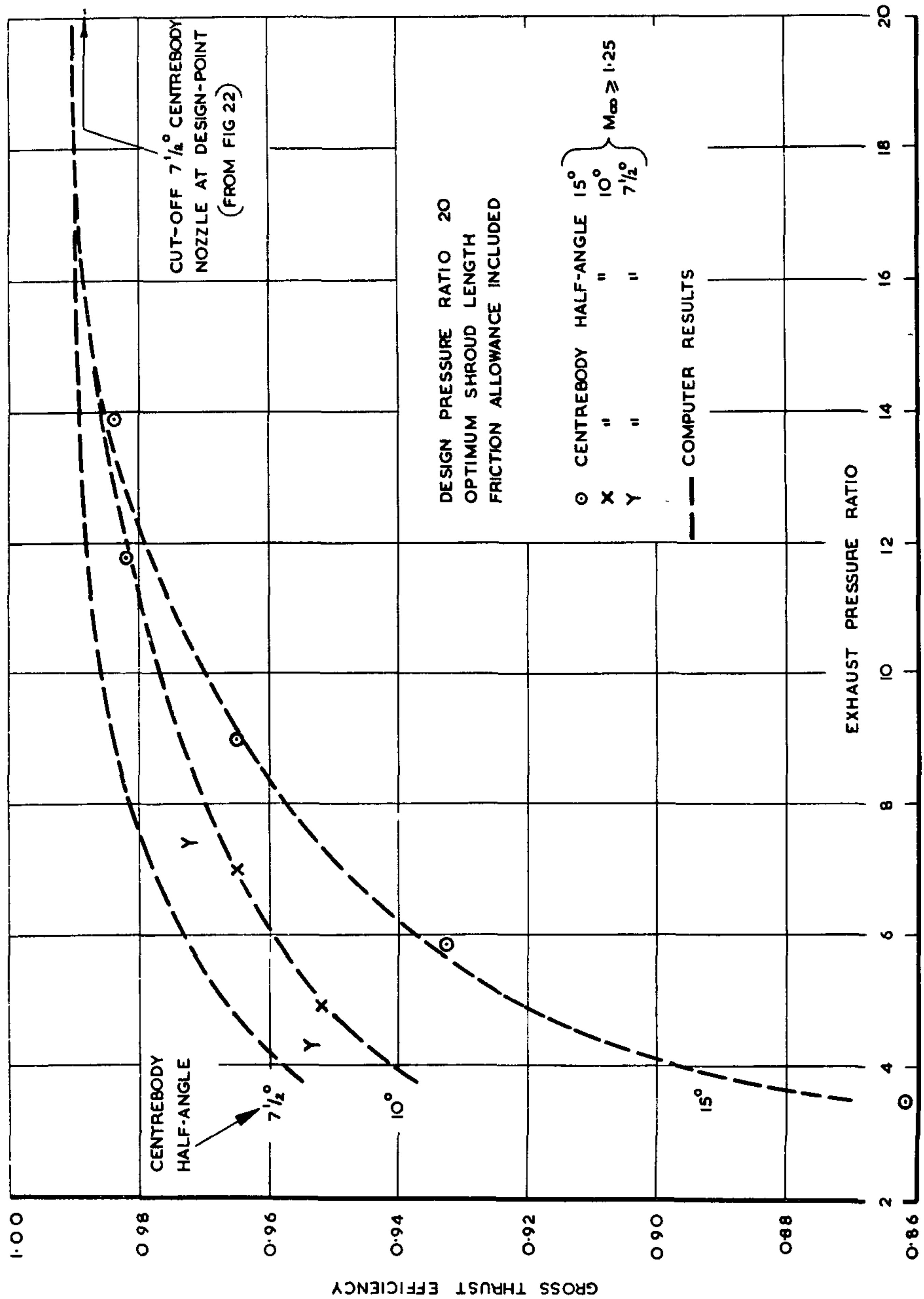
CENTREBODY PRESSURE DISTRIBUTION – II.

FIG. 29



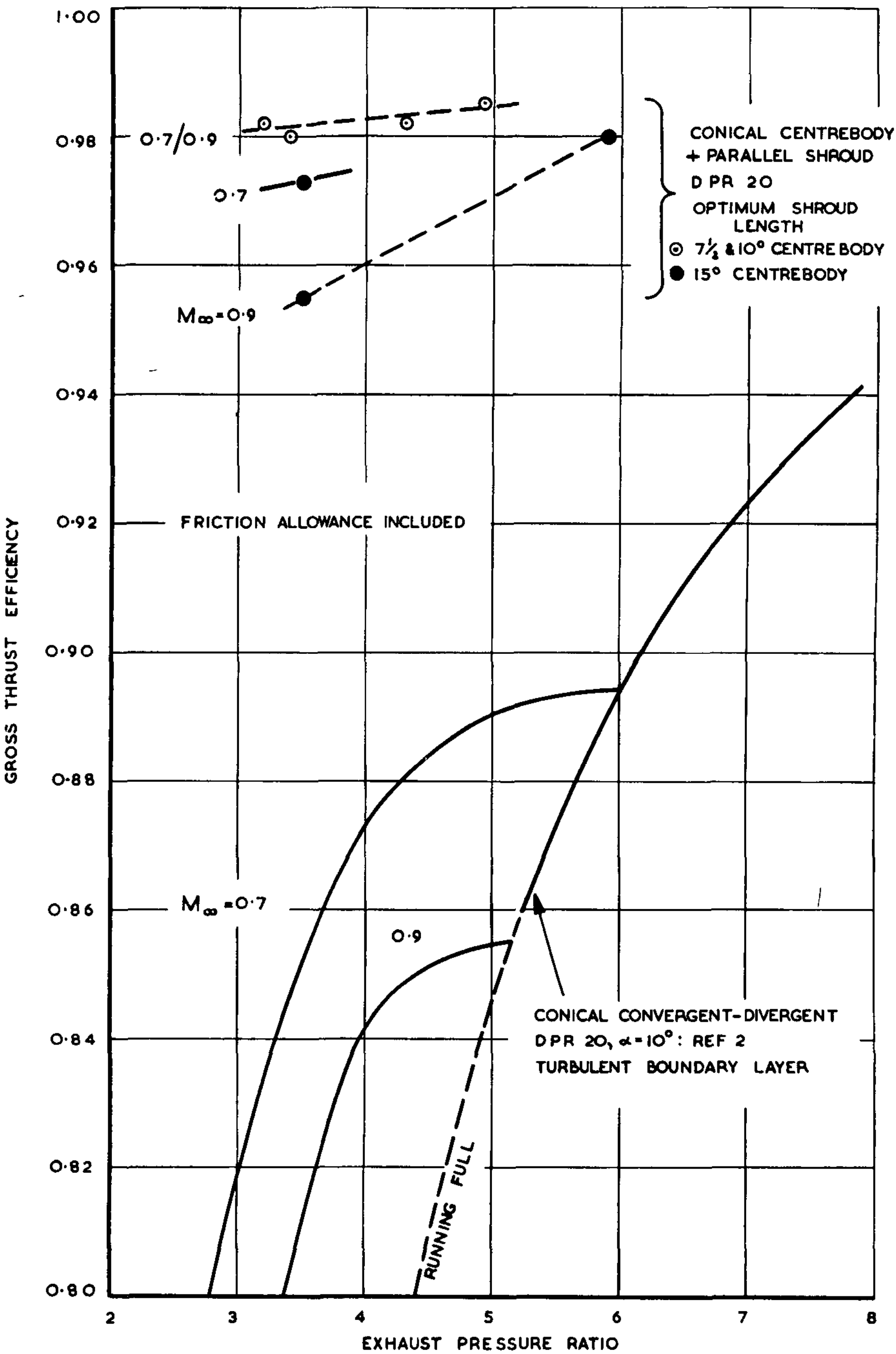
COMPARISON OF TEST RESULTS IN TWO WORKING SECTIONS.

FIG. 30



COMPARISON OF COMPUTER AND TEST RESULTS FOR VARIOUS CENTREBODY ANGLES IN SUPERSONIC EXTERNAL FLOW

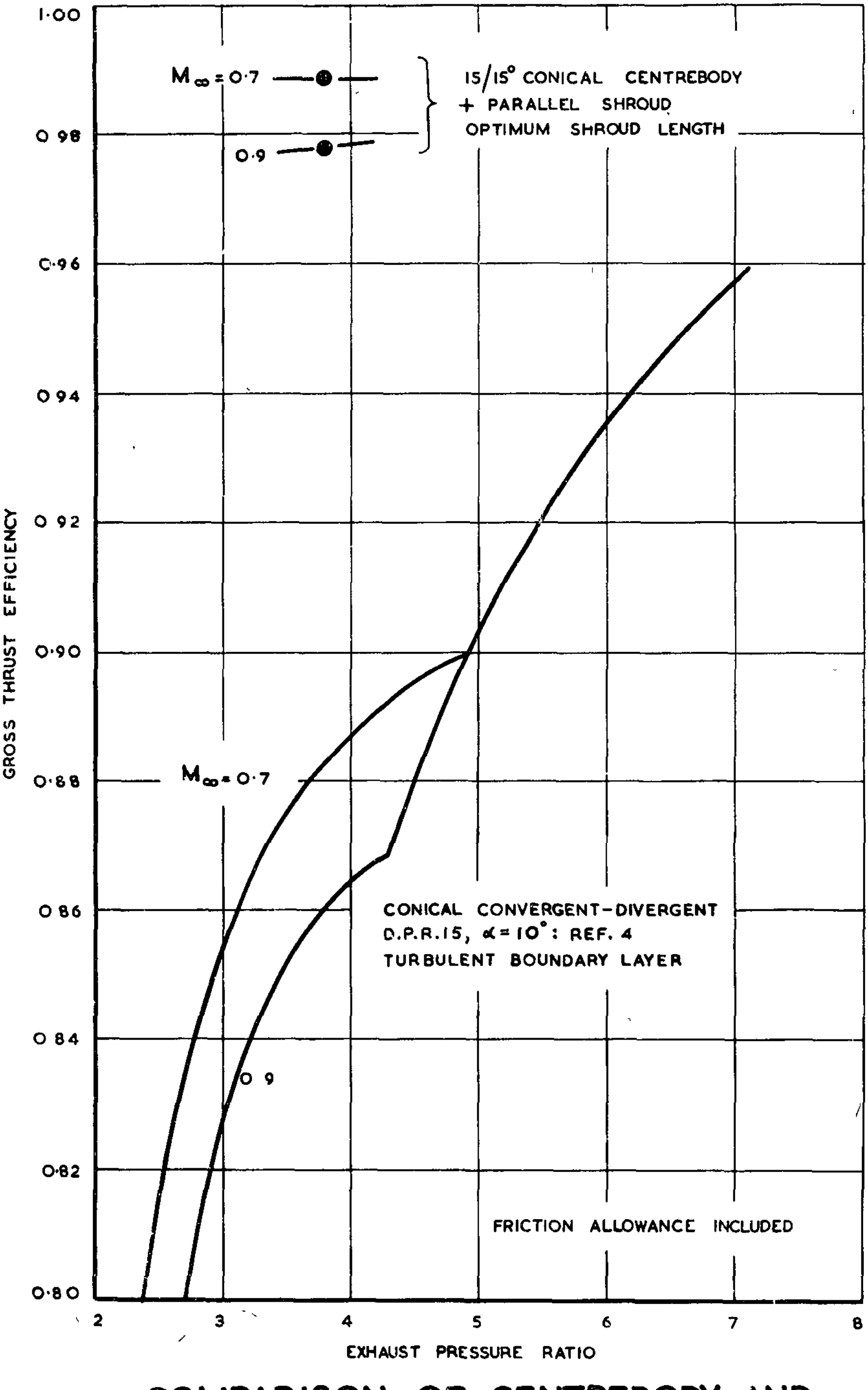
FIG. 31



COMPARISON OF CENTREBODY AND CONVERGENT-DIVERGENT NOZZLES

III ~ SUBSONIC EXTERNAL FLOW: D.P.R.=20

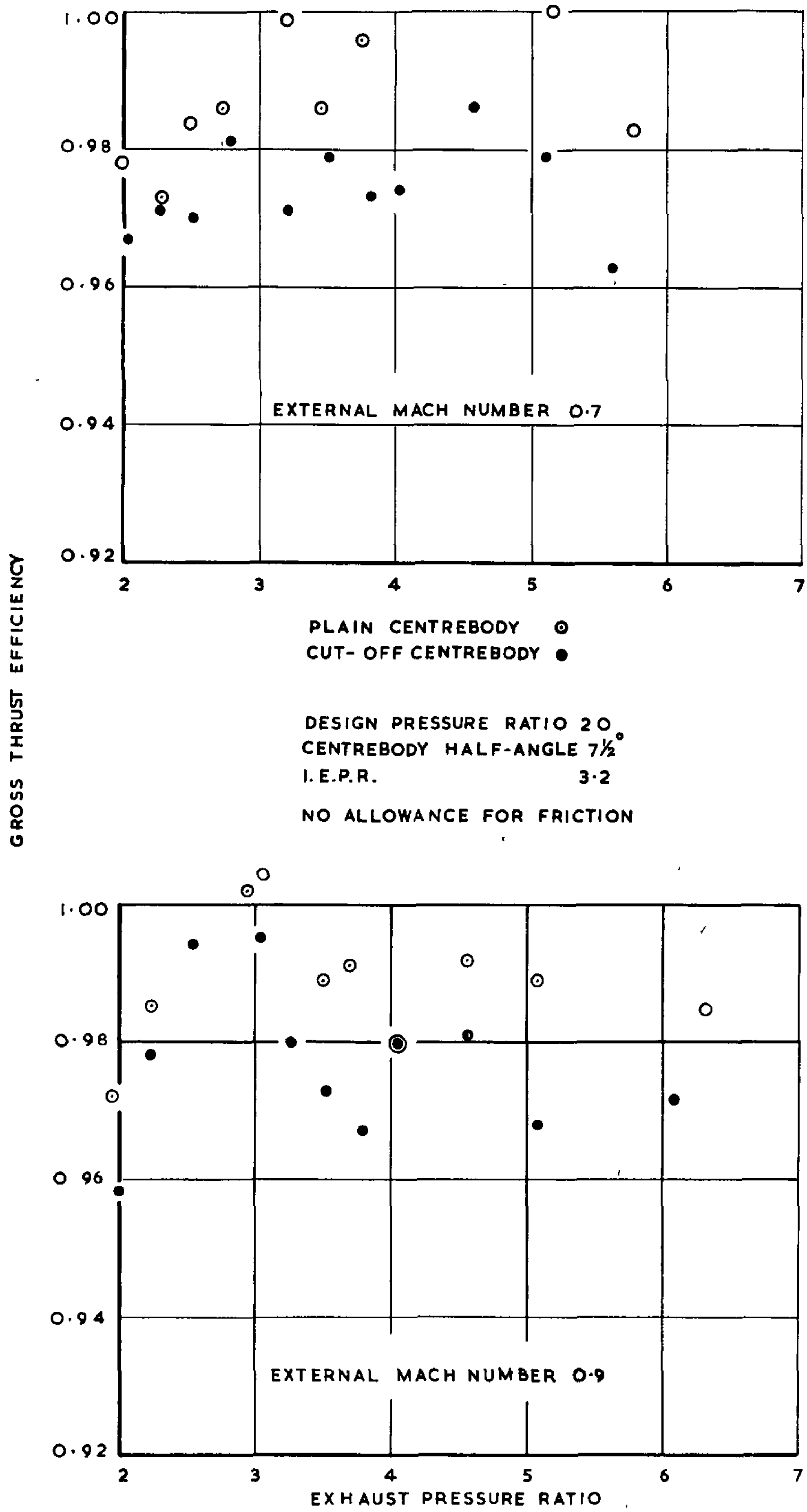
FIG. 32



COMPARISON OF CENTREBODY AND CONVERGENT-DIVERGENT NOZZLES

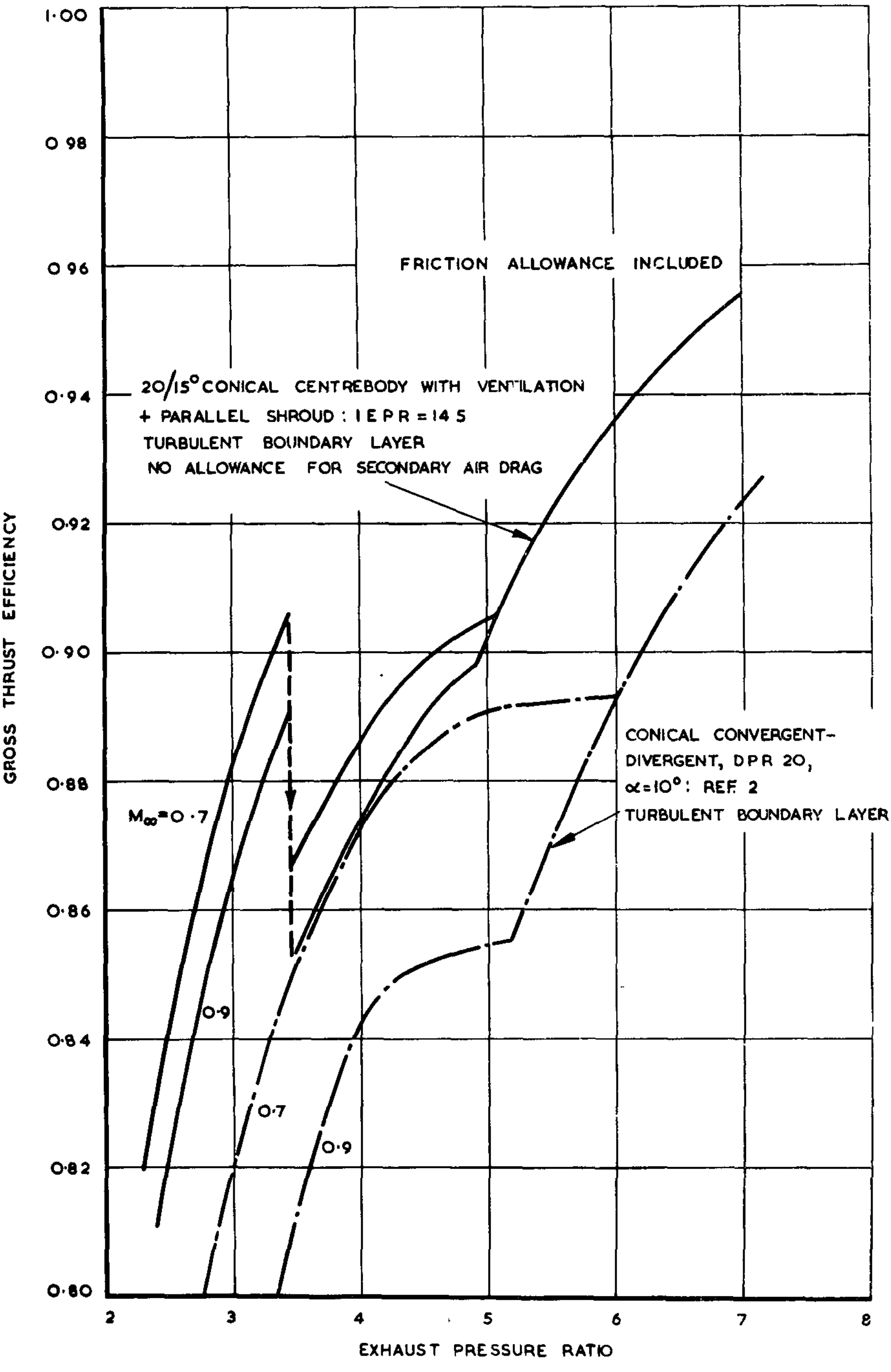
IV ~ SUBSONIC EXTERNAL FLOW: D.P.R. = 15

FIG.33



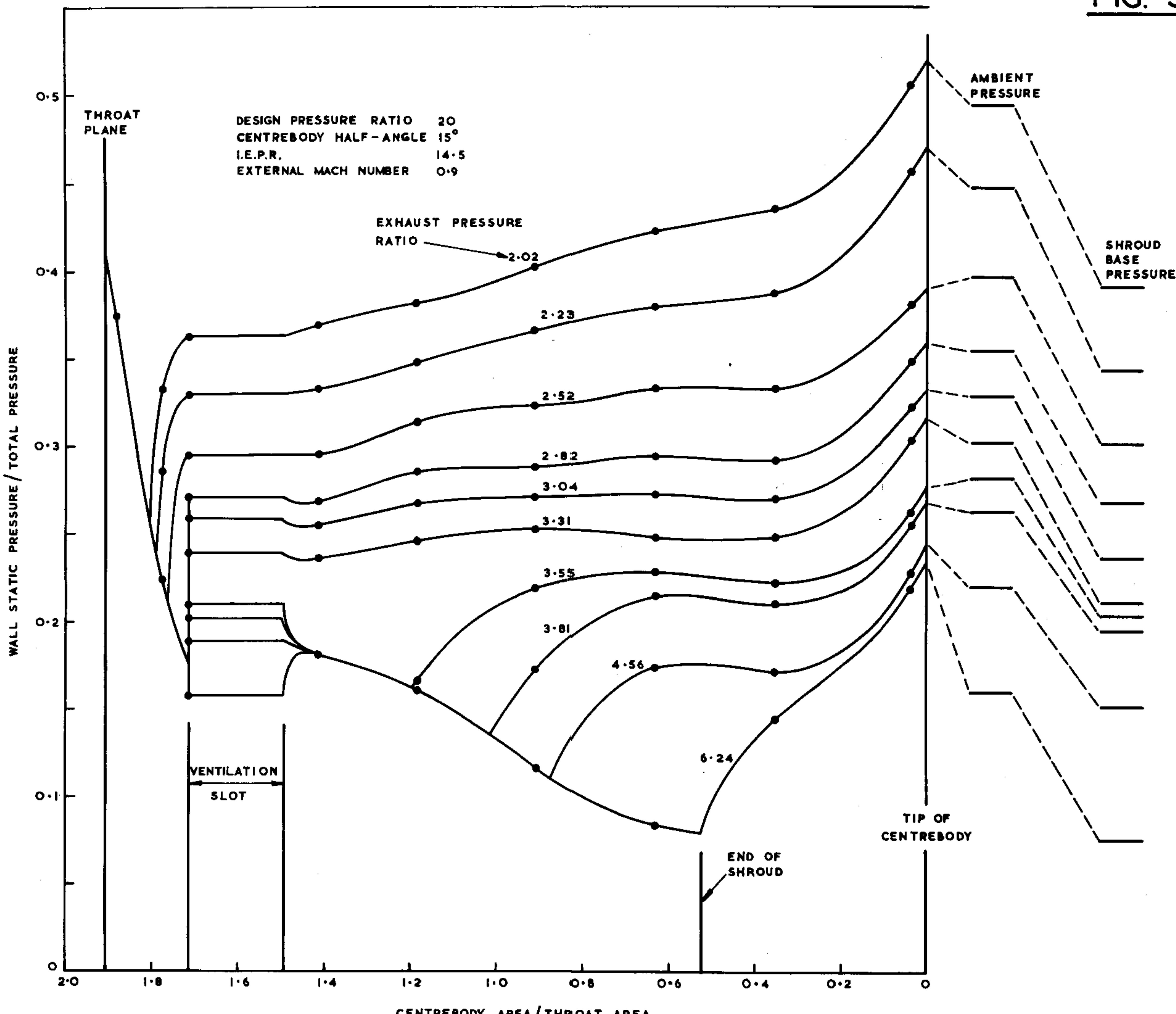
EFFECT ON OFF-DESIGN PERFORMANCE OF CUTTING OFF CENTREBODY TIP.

FIG. 34



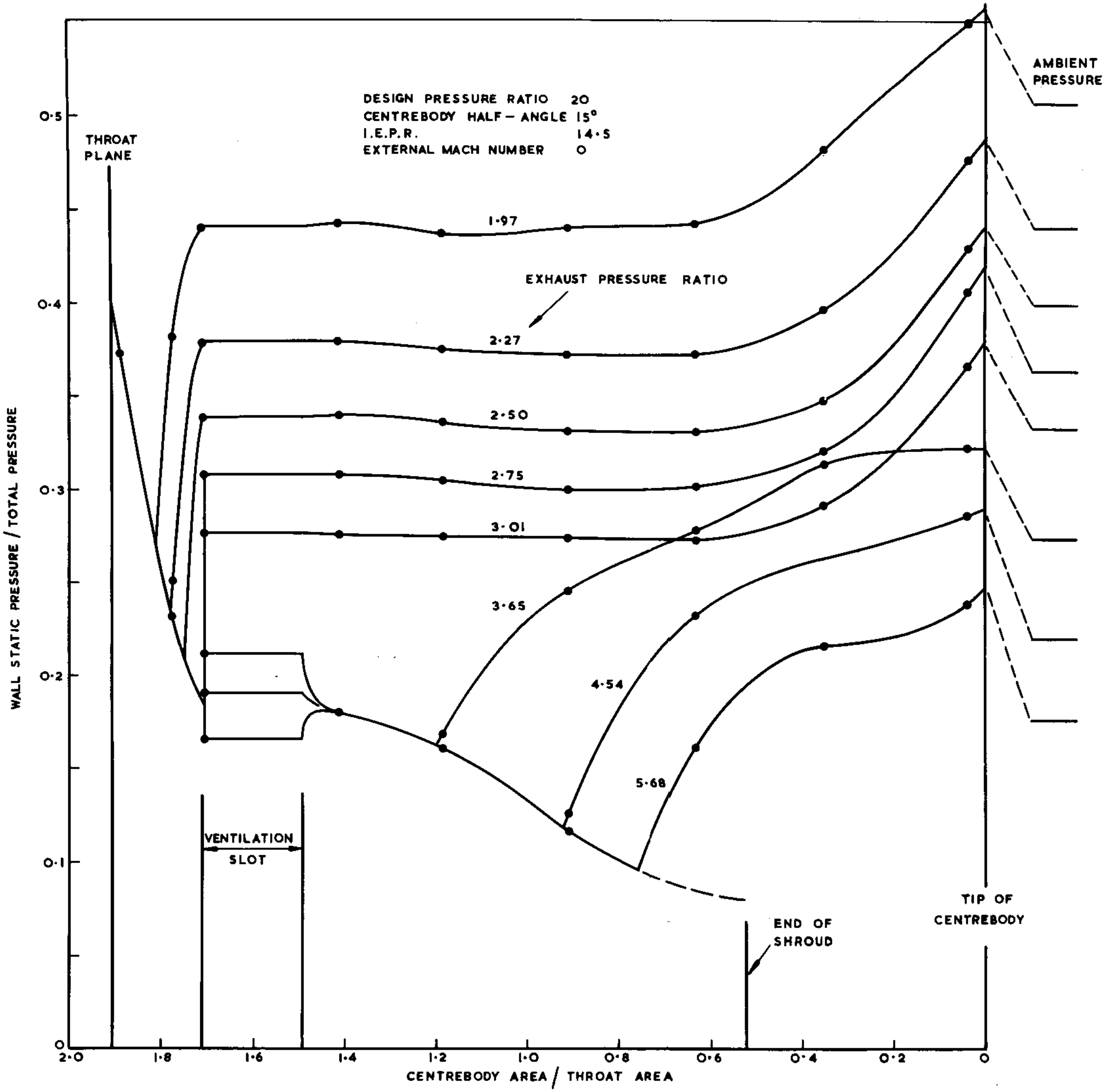
CENTREBODY VENTILATION UPSTREAM OF SHROUD END

FIG. 35



VENTILATED CENTREBODY PRESSURE DISTRIBUTION
I — SUBSONIC EXTERNAL FLOW.

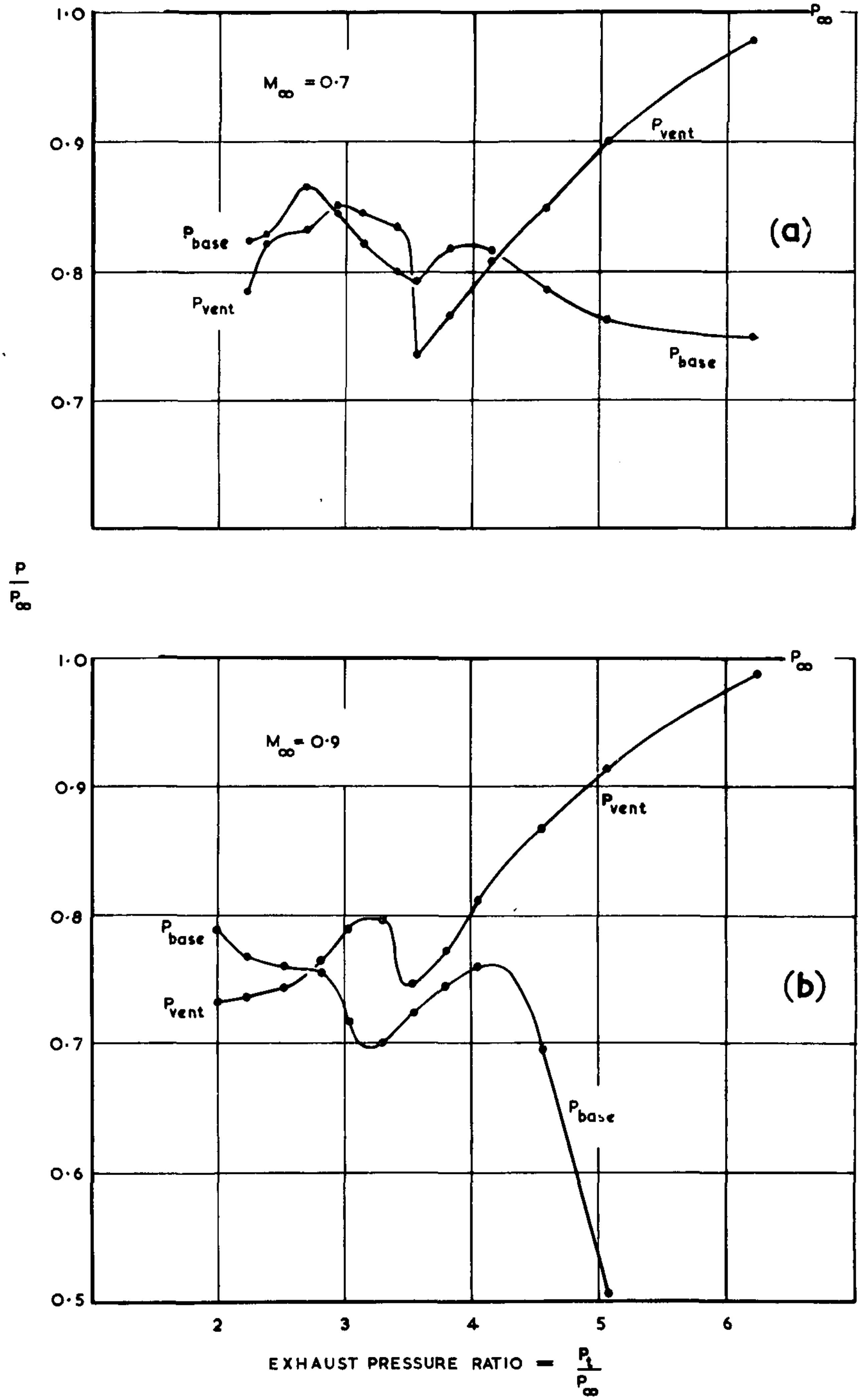
FIG. 36



VENTILATED CENTREBODY PRESSURE DISTRIBUTION

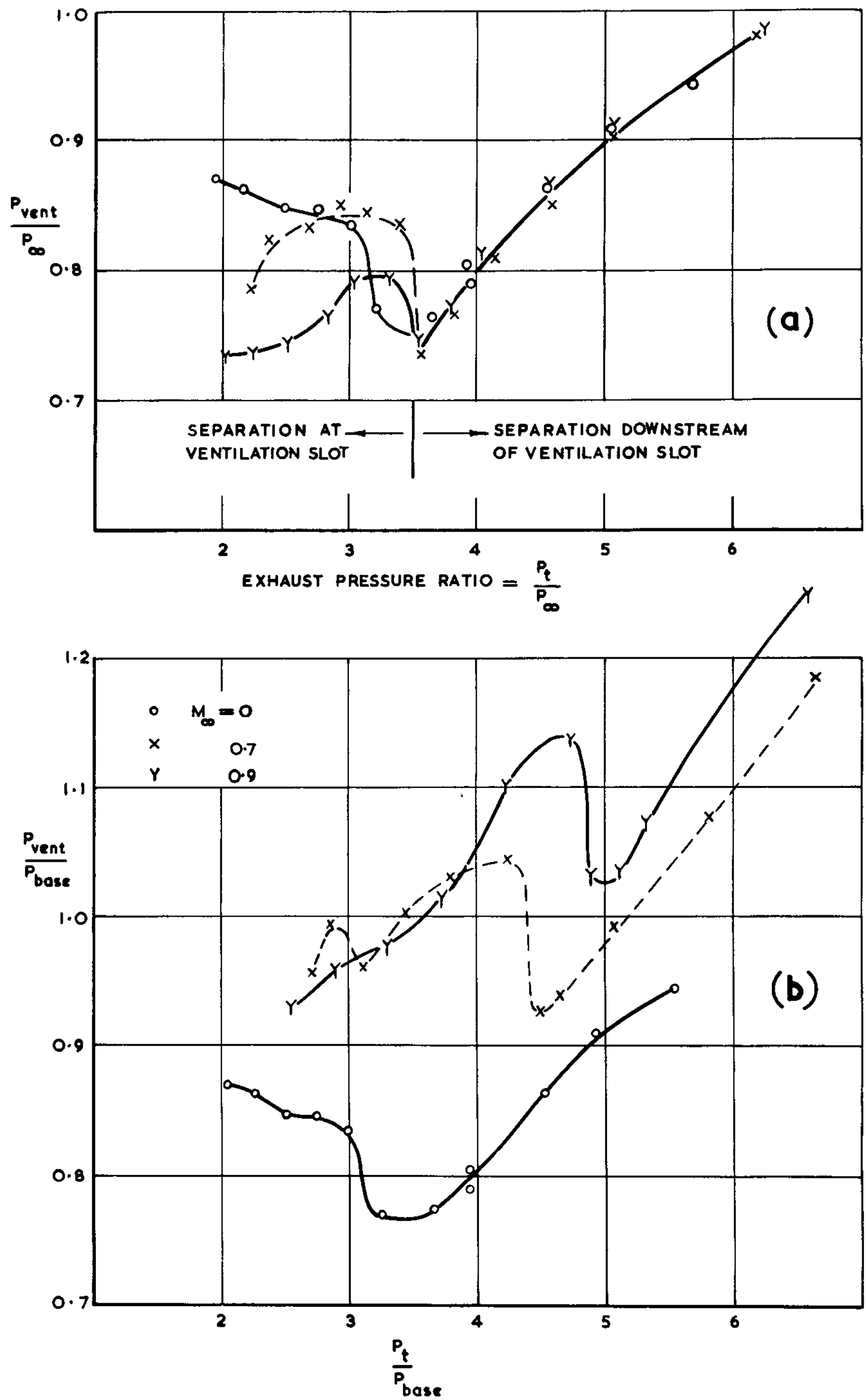
II — QUIESCENT AIR.

FIG. 37



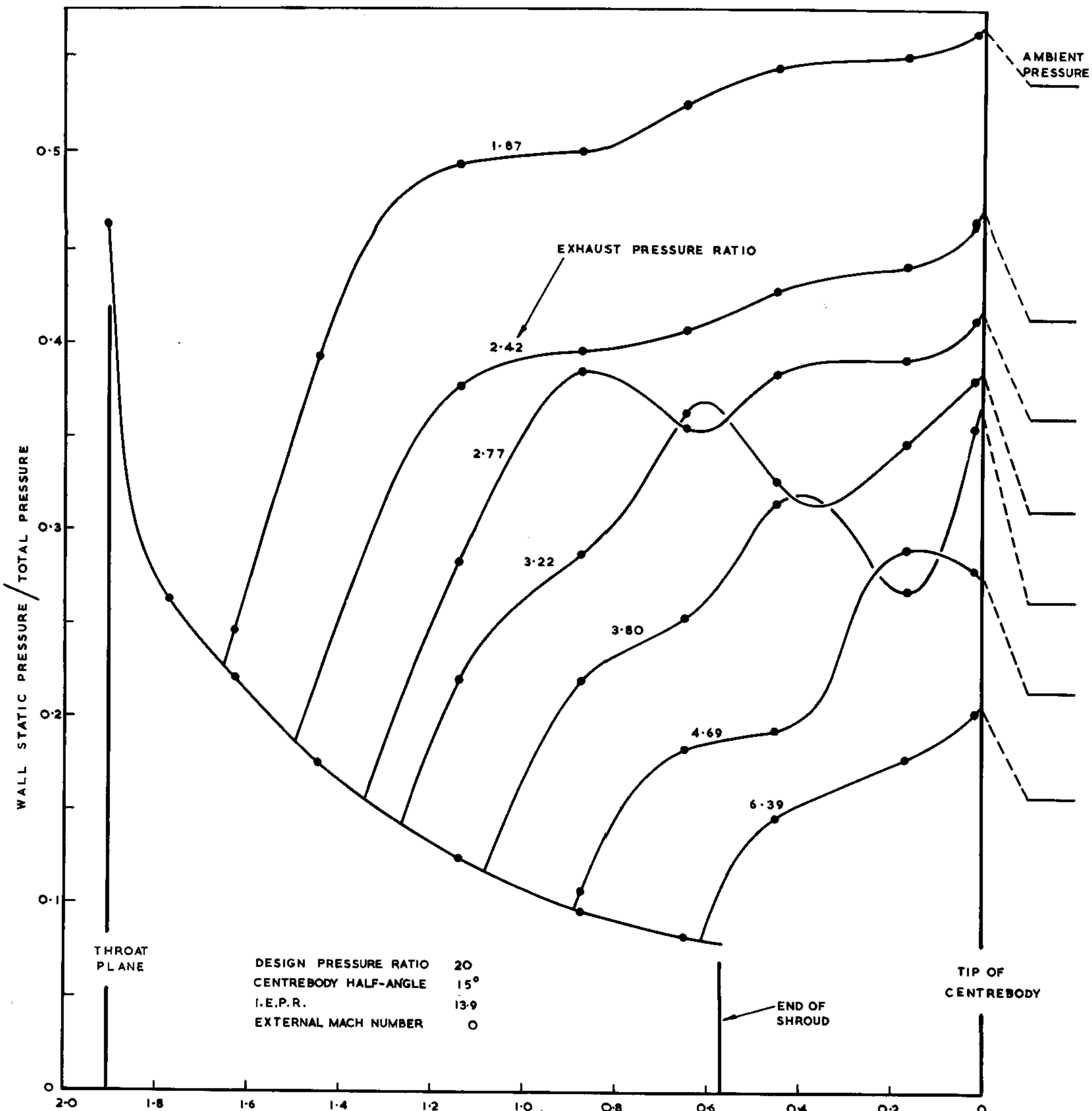
PRESSURES IN VENTILATION SLOT UPSTREAM OF SHROUD END ~ I

FIG. 38

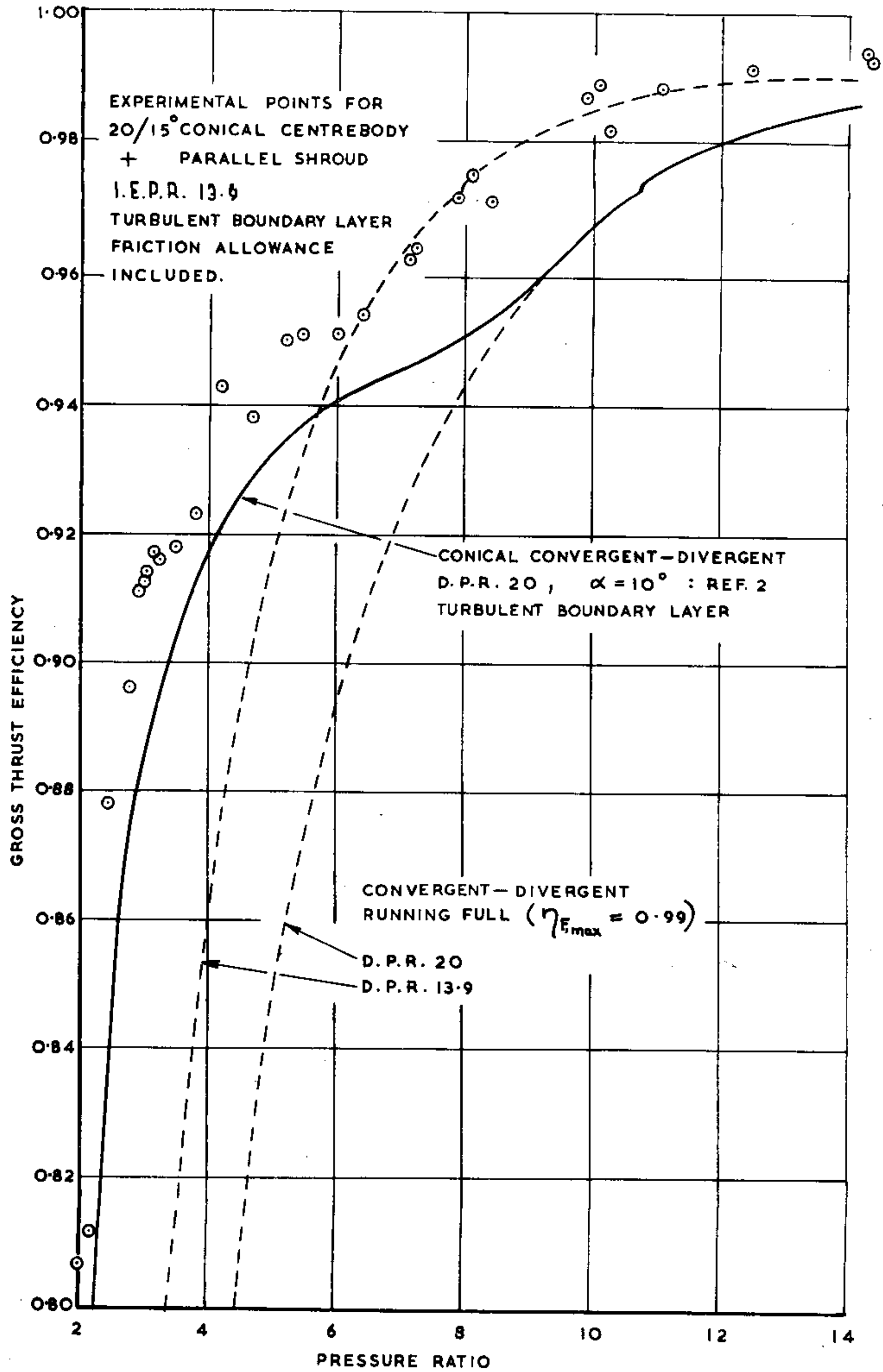


PRESSURES IN VENTILATION SLOT UPSTREAM OF SHROUD END ~ II

FIG.39

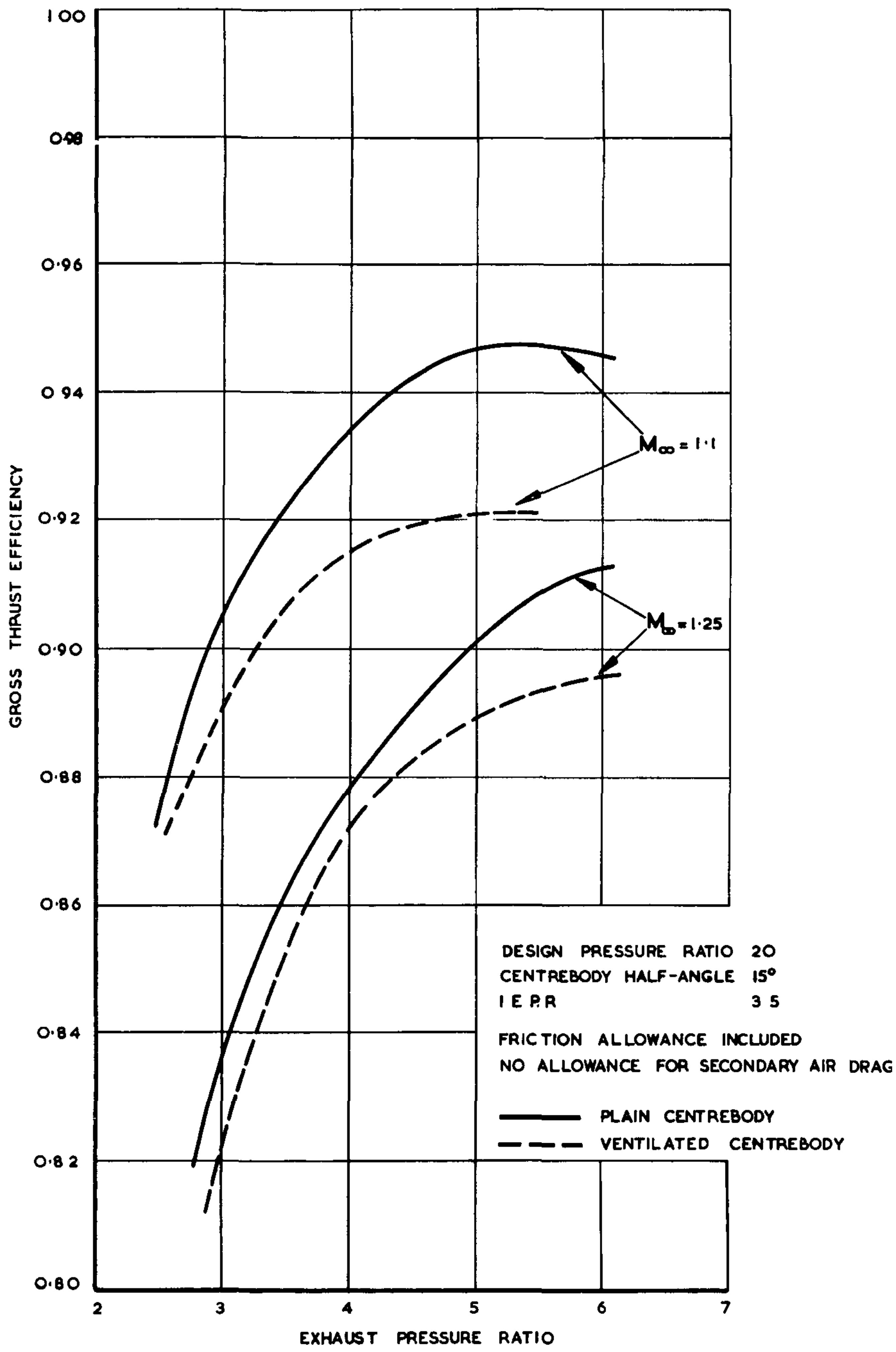


CENTREBODY PRESSURE DISTRIBUTION IN QUIESCENT AIR.

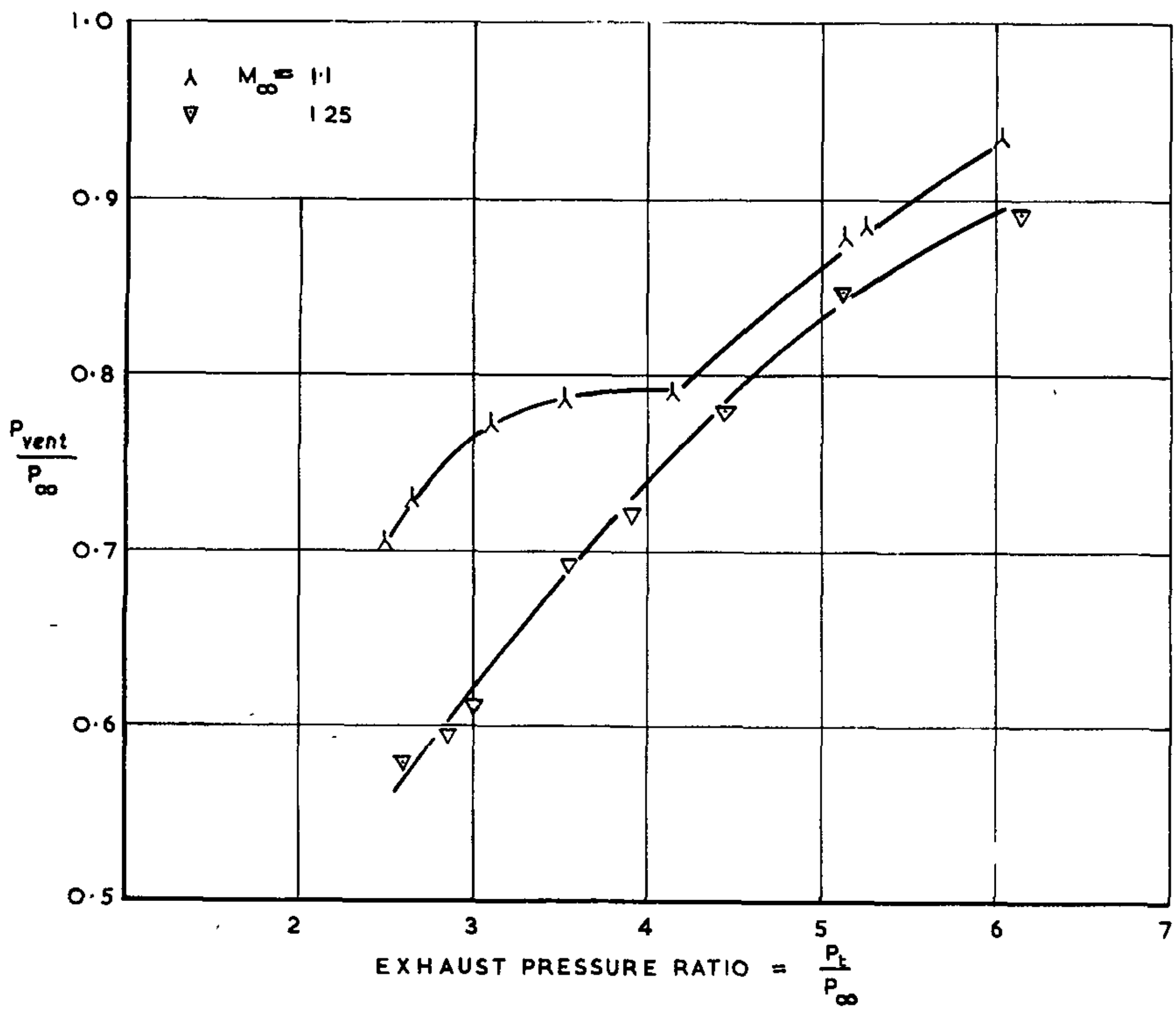


FIXED GEOMETRY NOZZLE PERFORMANCE IN QUIESCENT AIR.

FIG. 41



CENTREBODY VENTILATION
DOWNSTREAM OF SHROUD END



PRESSURES IN VENTILATION SLOT DOWNSTREAM OF SHROUD END.

ABSTRACT CARDS

A.R.C. C.P. No.894
April, 1964
Herbert, M. V., Golesworthy, G. T. and Herd, R. J.

THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE WITH A PARALLEL SHROUD IN EXTERNAL FLOW
PART II

In continuation of the work on axisymmetric centrebody nozzles with translating parallel outer shrouds and fixed throat areas described in Part I, further tests have been carried out with external flow in the range of Mach number 0·7 to 1·5. For combinations of exhaust pressure ratio and external Mach number representative of flight requirements, the results show that this type of nozzle can offer quite a high level of gross thrust efficiency throughout its operating range. The off-design performance is much superior to that of a plain convergent-divergent nozzle of the same design pressure ratio.

Conical centrebodies only were used, and the effect of varying the half-angle from 15 to 7½° has been investigated. Some improvement is gained by going to 10°, but further reduction is unlikely to be worthwhile in practice.

A.R.C. C.P. No.894
April, 1964
Herbert, M. V., Golesworthy, G. T. and Herd, R. J.

THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE WITH A PARALLEL SHROUD IN EXTERNAL FLOW
PART II

In continuation of the work on axisymmetric centrebody nozzles with translating parallel outer shrouds and fixed throat areas described in Part I, further tests have been carried out with external flow in the range of Mach number 0·7 to 1·5. For combinations of exhaust pressure ratio and external Mach number representative of flight requirements, the results show that this type of nozzle can offer quite a high level of gross thrust efficiency throughout its operating range. The off-design performance is much superior to that of a plain convergent-divergent nozzle of the same design pressure ratio.

Conical centrebodies only were used, and the effect of varying the half-angle from 15 to 7½° has been investigated. Some improvement is gained by going to 10°, but further reduction is unlikely to be worthwhile in practice.

A.R.C. C.P. No.894
April, 1964
Herbert, M. V., Golesworthy, G. T. and Herd, R. J.

THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE WITH A PARALLEL SHROUD IN EXTERNAL FLOW
PART II

In continuation of the work on axisymmetric centrebody nozzles with translating parallel outer shrouds and fixed throat areas described in Part I, further tests have been carried out with external flow in the range of Mach number 0·7 to 1·5. For combinations of exhaust pressure ratio and external Mach number representative of flight requirements, the results show that this type of nozzle can offer quite a high level of gross thrust efficiency throughout its operating range. The off-design performance is much superior to that of a plain convergent-divergent nozzle of the same design pressure ratio.

Conical centrebodies only were used, and the effect of varying the half-angle from 15 to 7½° has been investigated. Some improvement is gained by going to 10°, but further reduction is unlikely to be worthwhile in practice.

C.P. No. 894

© Crown copyright 1966

Printed and published by
HER MAJESTY'S STATIONERY OFFICE
To be purchased from
49 High Holborn, London W C 1
423 Oxford Street, London W 1
13A Castle Street, Edinburgh 2
109 St Mary Street, Cardiff
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

C.P. No. 894

S O. Code No 23-9016