C.P. No. 841

C.P. No. 841

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

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

Part I

By

R. J. Herd and G. T. Golesworthy,

With Appendix III by M. V. Herbert

LONDON: HER MAJESTY'S STATIONERY OFFICE

1966

Price 6s. 6d. net

U.D.C. No. 621-225.1:621.018

C.P. No.841
November 1963

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

PART I

- by -

R. J. Herd and G. T. Golesworthy

With Appendix III by M.V. Herbert

SUMMARY

The performance of two axially-symmetric centrebody propelling nozzles, with translating parallel outer shrouds and fixed throat areas, has been investigated both in quiescent air and in an external stream having a Mach number range of 1.3 to 2.4.

The results confirm that, in quiescent air, translation of the outer shroud gives a high nozzle gross thrust efficiency over a wide range of exhaust pressure ratio. In supersonic external flow, however, the results indicate a noticeable drop in efficiency as the exhaust pressure ratio decreases.

A computer programme has been written to analyse supersonic shock-free flow through a nozzle, taking into account the effect of any external stream. In general, results for both centrebody nozzles obtained from the computer agree satisfactorily with those obtained from the rig. Computer results have indicated a means whereby the drop in efficiency at low exhaust pressure ratio might be lessened.

Replaces N.G.T.E. Report M.369 - A.R.C.25 993.

CONTENTS

APPENDICES

ILLUSTRATIONS

1.0 Introduction

For applications where the pressure ratio available across an engine exhaust system is sufficient to generate supersonic velocity, it is usual to consider propelling nozzles in which this is achieved by suitable convergent-divergent shaping of the passage inside the nozzle. Such nozzles are said to have wholly internal expansion, meaning that under design conditions the supersonic expansion field is contained within the walls of the nozzle.

When a given geometry of internal expansion nozzle is operated at a pressure ratio substantially below its design, the flow is forced to over-expand by the divergent walls. This results in pressures below ambient acting on much of the nozzle walls, and constitutes a serious drag penalty. An external stream surrounding the nozzle exhaust jet aggravates the situation, in that a low base pressure is created by the interaction of the two streams, and the nozzle flow is still further over-expanded.

It thus comes about that the exhaust system of, for example, a supersonic transport aircraft has to meet requirements at the extremes of its operating range which are, in the case of an internal expansion nozzle, quite incompatible. On the one hand, a very high efficiency is demanded for the phase of sustained supersonic cruise, so that pressure ratios in the bracket 15 to 30 must be handled with the minimum possible loss, whilst, at the other extreme, the need must be met for an acceptable performance during subsonic operation, where the exhaust pressure ratio may only be around 2 to 3.

The limitations of conventional nozzle design in the context of this duty are such as to stimulate interest in alternative arrangements, and particularly in the principle of partial external expansion. In this, the supersonic expansion field is not wholly contained within the nozzle walls, and the flow can in large measure accommodate itself to the prevailing conditions.

Such a concept is not new. Much work has been done in the U.S.A. and elsewhere on nozzles with a centrebody and sharply convergent outer shroud, in which the supersonic expansion field is mainly or entirely external. There are, however, certain disadvantages associated with this shape of shroud when considered in an installation immersed in external flow. The shroud itself gives rise to boat-tail drag, and may cause the overall cross-section of the engine nacelle to be enlarged above the minimum area, with attendant penalties in wave and friction drag as well as size and weight. In favour of this arrangement of nozzle is the fact that, for a given throat area, it offers fairly good performance over the flight range without the necessity for variable geometry. But this merit is illusory, since any engine for supersonic transport duty is likely to require appreciable variation of nozzle throat area, and some mechanical variability seems to be obligatory.

These circumstances have led to the consideration of a design employing a mixture of internal and external expansion, and composed of a centrebody and parallel outer shroud (Figure 1). By means of relative translation between these two components, the degree of internal expansion can be regulated to suit the operating conditions. Sutcliffe[1] investigated the performance of a nozzle of this type in quiescent air, and concluded that a high efficiency is maintained over a wide range of exhaust pressure ratio. Further tests, described herein, were undertaken to examine the behaviour in external flow.

2.0 Scope of tests

Since much effort is at present being directed towards a proposed supersonic transport aircraft with a Mach number of 2.2 at cruise, the tests were arranged to embrace conditions likely to be met by such an aircraft. Exhaust pressure ratios from 4 to 25, and external Mach numbers from 1.3 to 2.4 were available, thereby leaving unresolved the effects of subsonic external flow. Subsequent tests of centrebody nozzles covering the latter region will be reported in Part II.

The main tests were of a nozzle having a design pressure ratio of 20 - considered appropriate to the cruise requirements at Mach 2.2 - and a conical centrebody of 15° half-angle. A similar nozzle, but with a design pressure ratio of 25, was also tested.

As Sutcliffe's[1] work was carried out using undried air, it was decided to check his results on a dry air rig, and consequently the nozzles were also tested in quiescent air.

3.0 Test equipment

3.1 Test rig

The test rig consisted of a variable Mach number tunnel, having a 12 in. × 12 in. outlet, and its associated supply and recovery ducting. In these tests, the Mach number range of the tunnel was from 1.3 to 2.4. Through the centre of the tunnel protruded a $3\frac{1}{2}$ in. diameter sting (Figure 2), the test nozzles being fitted to the downstream end in the plane of the tunnel outlet. The upstream end of the sting was mounted on a single support limb, through which the air for the nozzle was supplied. Instrumentation lines from the nozzle were run between the walls of the two co-axial tubes which made up the sting, air to the nozzle being passed through the inner tube. This arrangement, of a $3\frac{1}{2}$ in. diameter sting passing through the throat of the 12 in. × 12 in. tunnel, had been calibrated previously[2].

For tests involving no external flow, a different rig arrangement was used, based upon the quiescent rig described in Reference 3. The nozzle and the end of the sting were inserted into a recovery system tuned to the dimensions of the nozzle (Figure 3), and this smaller system was sealed, at its upstream end, around the sting. A baffle plate was inserted, close to the shroud lip, in order to prevent a recirculation of flow being set up around the shroud.

Means for direct measurement of nozzle thrust were not available, and recourse was had to pressure plotting the model surfaces.

3.2 Nozzle geometry

Consider a nozzle incorporating some external expansion, as illustrated in Figure 1, and take the design condition, say pressure ratio 20. It is clearly undesirable to extend the outer shroud beyond the point from which a Mach line just meets the tip of the centrebody (Figure 4a), as further shroud length merely adds weight and friction without at all affecting the centrebody expansion field (Figure 4b). With the above value of design pressure ratio and with centrebody half-angle 15°, this corresponds to a one-dimensional internal expansion pressure ratio (I.E.P.R., Appendix II) of 13.9. At this condition the flow leaving the shroud is under-expanded, and the remainder of the expansion is accomplished through the fan illustrated.

Now, as exhaust pressure ratio (E.P.R.) is reduced below 20, so is the under-expansion at the shroud lip reduced, until eventually - when E.P.R. = I.E.P.R. (= 13.9) - the internal and external static pressures there are approximately balanced (Figure 4c). Still further reduction of E.P.R. requires a shortening of the shroud in order to preserve this pressure balance. If the shroud is not so shortened, the flow within the nozzle will become over-expanded, with consequent loss in performance.

3.3 Test nozzles

The several arrangements of parallel-shrouded centrebody nozzle (Figures 5 and 6) were made up of a common mounting assembly, two centrebodies of 15° half-angle, and four shrouds. Thus two nozzles, having design pressure ratios of 20 and 25, and each with a choice of four shroud lengths, could be assembled. The internal expansion pressure ratios, corresponding to the four shroud lengths of the design pressure ratio 20 nozzle, were approximately 6, 9, 12 and 14, and its throat area was π sq. in. There were ten static tappings from the centrebody surface, two from the annular base formed at the lip of each shroud, one from the outside of the model, and seven total pressure tappings from a rake of pitot tubes, at equal-area spacing, located ahead of the model throat. Supporting the centrebody was a three-limb spider, through which the instrumentation lines passed to a connection recess in the wall thickness of the model.

The improved recovery in the tunnel, by comparison with that in the quiescent air rig, necessitated that supply pressures to the model should be lower for a given E.P.R. when installed in the tunnel, resulting in some difference of Reynolds number level between the two cases. For the design pressure ratio 20 nozzle, the overall range of nozzle throat Reynolds number covered was 0.7 to 3.4 million. These values are based upon the flow conditions at the throat and the diameter of that circle enclosing an area equal to the nozzle throat area.

3.4 Thrust measurement

In all cases, the thrust of the nozzle was determined by summation of the stream thrust at the throat (obtained by calculation) and the thrust upon the diverging surfaces (given by the pressure tappings), according to the method derived in Appendix III.

Certain quantities associated with the flow in the throat plane are required, namely the discharge coefficient (C_D) and the vacuum thrust efficiency (μ). A value of $C_D = 0.9945$ was taken for both centrebody nozzles, following mass flow measurements on a dry air static rig, independent of exhaust pressure ratio when the nozzle is choked. This value is very high by comparison with plain circular-section nozzles tested on the same rig[3]. Typical values of C_D for both convergent and convergent-divergent nozzles, with radius of throat curvature equal to half throat diameter, were there found to be around 0.990. It is necessary to attribute roughly the same flow defect (0.003) to friction in every case, leaving a much smaller flow defect from throat curvature in the centrebody nozzles (only 0.0025). This is presumably because a parallel shroud results in much of the flow being axial in the throat plane. Now a value of $\mu = 1.003$ was derived[3] for a convergent nozzle with $C_D = 0.990$ (curvature defect 0.007), and it is estimated that an appropriate value for the centrebody nozzles of the present tests would be $\mu = 1.001$ when choked.

4.0 Theoretical computer analysis

A programme[4] was written for the Ferranti Mercury computer in order to analyse supersonic flow through a nozzle, taking into account the effect of any supersonic external stream. It is necessary to describe to the computer the conditions at the nozzle throat, the nozzle geometry, the exhaust pressure ratio and the Mach number of the external stream. Having received these values, the pressure distributions down the nozzle surfaces are calculated. These are integrated to form the thrust due to the supersonic expansion, whence the gross thrust efficiency of the nozzle is determined.

The programme employs the method of characteristics to establish the flow field. Thus it cannot analyse subsonic external flow, treats shock waves only approximately, and ignores boundary layer effects such as separation and friction. However, despite these limitations, it has produced useful comparative results. Where required, allowance can subsequently be made for friction in the design point thrust performance as described in Appendix III.

5.0 Discussion of results

Unless indicated to the contrary, it may be taken that all results refer to the nozzle with design pressure ratio (D.P.R.) equal to 20.

Sutcliffe[1] found that the shroud length* which gives highest efficiency in quiescent air is generally such that the nozzle I.E.P.R. is close to the E.P.R. He also noted that this ceases to be true above a certain E.P.R., which is about 70 per cent of the nozzle D.P.R.

The computer programme was used to investigate nozzles of this type, both in an external stream and in quiescent air. Figure 7 is a plot of loss of gross thrust efficiency as a result of shroud length variation, for an E.P.R. of 9, and external Mach numbers of 0 and 1.5. In both cases efficiency is highest with the datum length, which condition is approximately that of equality between the E.P.R. and the one-dimensional I.E.P.R., confirming Sutcliffe's experimental finding. For these conditions the effect of changing the shroud length 20 per cent either way is negligible, corresponding to a variation of ±17 per cent in I.E.P.R.

As was observed in Section 3.2, it is pointless to extend the shroud lip beyond that position corresponding to an I.E.P.R. of 13.9, which is approximately 70 per cent of the D.P.R. Consequently, at an E.P.R. above

---

*Shroud length is defined as the distance along the shroud between the throat and the lip (Figure 1). Datum shroud length is such that the static pressure on the shroud inner surface, just upstream of the lip, is equal to the ambient static pressure (see Section 3.2).

13.9, one may expect the efficiency to be highest at an I.E.P.R. less than the E.P.R., as Sutcliffe indeed observed.

Turning now to rig results, Figure 8 shows a typical set of curves of static pressure down the centrebody, for a given external Mach number and shroud position, and various values of E.P.R. Corresponding curves obtained from the computer are also shown.

Figure 9 is similar, except for the nozzle being in quiescent air. In both cases, the general pattern of agreement between rig results and computer is good, except towards the tip of the centrebody, where the presence of shock waves makes the analytical treatment inaccurate.

Figure 10 relates nozzle gross thrust efficiency to E.P.R., for various shroud positions, in quiescent air. The envelope of these curves gives the efficiency which may be achieved by translating the shroud as E.P.R. varies. This curve confirms that, in quiescent air, the nozzle has a high efficiency over a wide range of exhaust pressure ratio.

Figures 11 to 14 relate efficiency to E.P.R. for a given shroud position and range of external Mach number. These rig results exhibit a high efficiency at high E.P.R., but all show a substantial drop as E.P.R. decreases. Except for Figure 11, efficiency values are independent of the magnitude of the external Mach number, which is in agreement with computer results. A rather curious circumstance in this figure is that the higher efficiency curve corresponds to the higher external Mach number.

The envelope of the curves in Figures 11 to 14 is shown in Figure 15, indicating the efficiency which may be achieved by translating the shroud as E.P.R. and external Mach number vary. Those efficiencies taken from Figure 11 are for the external Mach number of 1.3. The corresponding envelope obtained from computer results is also shown, and there is quite close agreement between the two.

Also shown in Figure 15 are similar envelope curves for both rig and computer quiescent air results. In the lower range of E.P.R. the rig curve is the mean of rather wide scatter, which may account for some of its deviation from the computer curve. Above an E.P.R. of 12 the efficiency is the same in quiescent air as in an external stream.

Results quoted in Reference 5 for a comparable centrebody nozzle with convergent outer shroud suggest the internal performance of the present arrangement to be superior.

In general, the nozzle with design pressure ratio 25 behaved in a way similar to that with 20.

6.0 Methods of increasing nozzle efficiency

There are two ways in which the efficiency drop at low values of E.P.R. in external flow might be lessened. In both cases the basic aim is to increase the level of static pressure down the centrebody.

The first method is to reduce the centrebody angle, and so lessen the turn imposed on the nozzle flow downstream of the throat. This was examined theoretically using the computer programme, and the results are shown in Figure 16. From these curves it appears that a useful increment in efficiency may be available, but rig tests are needed to determine whether sufficient may be achieved in practice to justify increased weight.

A second possibility is to try and provoke separation at some position on the centrebody downstream of the shroud lip, so raising the pressure in the over-expanding region to a value nearer ambient. This might be accomplished by the injection of a small quantity of secondary flow at substantially ambient pressure, through slots in the centrebody surface. Such a "ventilation" technique has been used[6] in wholly internal expansion nozzles, where separation was successfully produced and over-expansion largely prevented when the nozzle was surrounded by quiescent air. Subsequent tests with external flow showed this ventilation to be comparatively unsuccessful in preventing the creation under these conditions of a low base pressure at outlet from the nozzle, or in raising the pressure in the region of separated internal flow above the level of this base pressure. In the present application, the centrebody is shielded by the expanding internal flow from direct communication with an external stream, and any separated flow region on the centrebody would not be in contact with a low base pressure. It may therefore be hoped that admission of ambient pressure to the centrebody could offer some advantage.

7.0 Conclusions

The performance has been investigated of two parallel-shrouded conical-centrebody nozzles, having design pressure ratios of 20 and 25 and centrebody half-angle 15°. Within the range of test conditions applied, the following features were noted:-

(i) When in quiescent air, the nozzle gross thrust efficiency is high over a wide range of exhaust pressure ratio, confirming the finding of Reference 1.

(ii) When in an external stream at Mach number 1.3 or above, the nozzle efficiency decreases as the exhaust pressure ratio falls.

(iii) In general, the position of the shroud giving the highest efficiency is such that the internal expansion pressure ratio is close to the exhaust pressure ratio. However, it is unnecessary to extend the shroud beyond the position where a Mach line just meets the centrebody tip. For the present angle of centrebody, this corresponds approximately to an internal expansion pressure ratio 70 per cent of the design pressure ratio.

(iv) Despite its limitations, the computer programme produces results which agree quite closely with rig results.

Computer studies suggest that the drop in nozzle efficiency in an external stream may be lessened by decreasing the centrebody half-angle.

ACKNOWLEDGEMENTS

The authors wish to thank Squadron Leader H. J. Willcocks, R.A.F., for his part in the preparation of the computer programme, Mr. C. Overy for his assistance with the test work, and Miss M. Faiers for her help in the computation of the results.

REFERENCES

No.	Author(s)	Title, etc.
1	Flt. Lt. C. Sutcliffe, R.A.F.	Performance of a centrebody propelling nozzle with a parallel shroud Unpublished M.O.A. Report
2	G. T. Golesworthy	The performance of a 12 in. × 12 in. variable Mach number nozzle with a co-axial sting Unpublished M.O.A. Report 1963
3	M. V. Herbert D. L. Martlew	The design-point performance of model internal-expansion propelling nozzles with area ratios up to 4 N.G.T.E. Report No. R.258 December, 1963 A.R.C. No. 26,495
4	Sq. Ldr. H. J. Willcocks, R.A.F. R. J. Herd	A computer programme for the analysis of nozzle performance with or without supersonic external flow Unpublished M.O.A. Report
5	A. S. Valerino R. F. Zappa K. L. Abdalla	Effects of external stream on the performance of isentropic plug-type nozzles at Mach numbers of 2.0, 1.8 and 1.5. NASA Memo. 2-17-59E March, 1959
6	G. W. Crosse	The development of an aerodynamically variable convergent-divergent propelling nozzle N.G.T.E. Report No. R.240 February, 1960 A.R.C. No. 21,915
7	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 N.G.T.E. Memo No. M.393 November, 1964 A.R.C. No. 26,719

APPENDIX I

Notation

A	Cross-sectional area
A_s	Area of supersonic expansion surfaces
C_D	Discharge coefficient (see Appendix II)
F	Gauge thrust
M	Mach number
P_t	Total pressure
P	Static pressure
Q	Mass flow
T_t	Total temperature
v	Velocity
β	"Displacement loss" due to friction
$1-\eta_f$	"Momentum loss" due to friction
η_F	Nozzle gross thrust efficiency (see Appendix II)
μ	Throat vacuum thrust efficiency (see Appendix II)
ϕ	Friction factor on supersonic expansion surfaces (see Appendix III)

Suffices, etc.

e	nozzle exit
g	geometric nozzle throat
$*$	isentropic nozzle throat
w	nozzle wall
$'$	the equivalent term with isentropic flow
is	isentropic fully expanded flow
∞	ambient

APPENDIX II

Definitions

E.P.R. = exhaust pressure ratio = $\dfrac{\text{nozzle upstream total pressure}}{\text{ambient static pressure}}$

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 = $\dfrac{\text{measured air mass flow}}{\text{isentropic air mass flow for the same physical throat area}}$

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 = $\dfrac{\text{measured thrust at a given exhaust pressure ratio}}{\text{gauge thrust of an isentropic nozzle, passing the same mass flow, at the same exhaust pressure ratio, when fully expanded}}$

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

A derivation of this relationship is given in Appendix III.

APPENDIX III

Derivation of nozzle gross thrust efficiency from wall pressure measurement

by M. V. Herbert

With reference to Figure 17:-

$$F_e = F_g + \int_0^{(A_e - A_g)} (P_W - P_\infty) dA - \int \tau dA_s$$

where $\int \tau dA_s$ is the total shear force in the axial direction on all supersonic expansion surfaces. It is treated as a function of nozzle D.P.R.

$$F^* = \frac{Qv^*}{g} + A^*(P^* - P_\infty)$$

and according to the definition of μ

$$F_g = \mu\left[\frac{Qv^*}{g} + A^* P^*\right] - A_g P_\infty$$

$$\text{Thus} \qquad F_e = \mu \cdot \frac{Qv^*}{g} + \mu A^* P^* - A_g P_\infty + \int_0^{(A_e - A_g)} (P_W - P_\infty) dA - \int \tau dA_s$$

$$\text{Now} \qquad \text{E.P.R.} = \frac{P_t}{P_\infty} \quad \text{and} \quad C_D = \frac{A^*}{A_g}$$

$$\text{and putting} \quad \phi = \frac{\int \tau dA_s}{A_g P_t}$$

$$\text{we get} \qquad \frac{F_e}{A_g P_t} = \mu C_D \cdot \frac{Q\sqrt{T_t}}{A^* P_t} \cdot \frac{v^*}{\sqrt{T_t}} \cdot \frac{1}{g} + \mu C_D \cdot \frac{P^*}{P_t} + \int_0^{\left(\frac{A_e}{A_g} - 1\right)} \frac{P_W}{P_t} d\left(\frac{A}{A_g}\right) - \frac{1}{\text{E.P.R.}}\left(\frac{A_e}{A_g}\right) - \phi$$

For $\gamma = 1.4$, this becomes:-

$$\frac{F_e}{A_g P_t} = 1.26789\,\mu C_D + \int_0^{\left(\frac{A_e}{A_g}-1\right)} \frac{P_w}{P_t}\, d\left(\frac{A}{A_g}\right) - \frac{1}{\text{E.P.R.}}\left(\frac{A_e}{A_g}\right) - \phi$$

Now $F_{is} = \frac{Qv_{is}}{g}$

$$\therefore \quad \frac{F_{is}}{A_g P_t} = C_D \cdot \frac{Q\sqrt{T_t}}{A^* P_t} \cdot \left(\frac{v}{\sqrt{T_t}}\right)_{EPR} \cdot \frac{1}{g}$$

where $\left(\frac{v}{\sqrt{T_t}}\right)_{EPR}$ is the value of $\left(\frac{v}{\sqrt{T_t}}\right)$ corresponding to the exhaust pressure ratio in isentropic flow

Thus, for $\gamma = 1.4$

$$\frac{F_{is}}{A_g P_t} = 0.0123156\, C_D \left(\frac{v}{\sqrt{T_t}}\right)_{EPR}$$

Now $\eta_F = \frac{F_e}{F_{is}}$

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

It should be noted that in the above relation both the isentropic fully expanded thrust in the denominator and the isentropic sonic stream thrust in the numerator have been treated as for "ideal air" with constant $\gamma = 1.4$. Allowance should strictly be made in both cases for the fact that "real air" velocities are slightly lower. However, for given conditions of total pressure and temperature, it can be shown (e.g. Appendix VI of Reference 3) that the amount of the correction to velocity is almost independent of the pressure ratio through which air is expanded. This means that a proportion of the total numerator (amounting to between 50 and 150 per cent depending on nozzle type and operating pressure ratio) and the whole denominator are factored by approximately the same amount. For the range of these test conditions, this factor never falls below 0.9975. Hence the effect on η_F as a whole can scarcely exceed 0.1 per cent, and may be neglected.

This only leaves a requirement for the evaluation of the friction term ϕ. Consider the supersonic expansion surfaces of any nozzle running full and with no outlet divergence. As above, the measured axial force on the walls is:-

$$F_e - F_g = \int_0^{(A_e-A_g)} (P_w - P_\infty)dA - \int \tau dA_s$$

where $$F_e = \frac{Qv_e}{g} + A_e(P_e - P_\infty)$$

Now the corresponding isentropic force (assuming that the throat conditions are the same) would be:-

$$F_e' - F_g = \int_0^{(A_e'-A_g)} (P_w' - P_\infty)dA$$

where $$F_e' = \frac{Qv_e'}{g} + A_e'(P_e - P_\infty)$$

it being noted that both the actual nozzle, with exit area A_e, and its isentropic counterpart, with area A_e', both have the same exit pressure P_e when running full.

Define η_f such that

$$\frac{Qv_e}{g} = \eta_f \cdot \frac{Qv_e'}{g}$$

Then, by eliminating $\frac{Qv_e}{g}$ and F_g between the above relations, it can be shown that

$$\left\{(1 - \eta_f) + \beta\right\} \frac{Qv_e'}{g} = \int \tau dA_s$$

where $$\beta = \frac{\int_0^{(A_e-A_g)} P_w dA - \int_0^{(A_e'-A_g)} P_w' dA - P_e(A_e - A_e')}{\frac{Qv_e'}{g}}$$

The term $(1 - \eta_f)$ is the "momentum loss" due to friction downstream of the throat. It may be determined from the results of a thrust rig, or calculated from boundary layer momentum considerations. By using a boundary layer treatment, the "displacement loss" β may also be found. Thus $\int \tau dA_s$ may be evaluated.

In Reference 3, these quantities are calculated for conical convergent-divergent nozzles, with various divergence angles, design pressure ratios, and throat Reynolds numbers. Results for both laminar and turbulent boundary layers are given. The friction quantities for the present centrebody nozzles were obtained by considering an equivalent conical convergent-divergent nozzle, having the same throat area, outlet Mach number, throat Reynolds number, and wetted surface area. The centrebody nozzle was assumed to have the same friction quantities as its equivalent conical convergent-divergent nozzle.

When relying on wall pressure measurement, as in the present series of tests, the friction term in the expression for η_F is $\int \tau dA_s$. For the D.P.R. 20 nozzle with the throat Reynolds number of these tests this is 1.0 per cent at its design point.

In comparing the computer thrust efficiencies and the experimental values, allowance must be made for the assumption of inviscid flow in the computation. The appropriate quantity is the term $(1 - \eta_f)$. For the D.P.R. 20 nozzle with the throat Reynolds number of these tests, this is 0.6 per cent at its design point.

FIG. 1

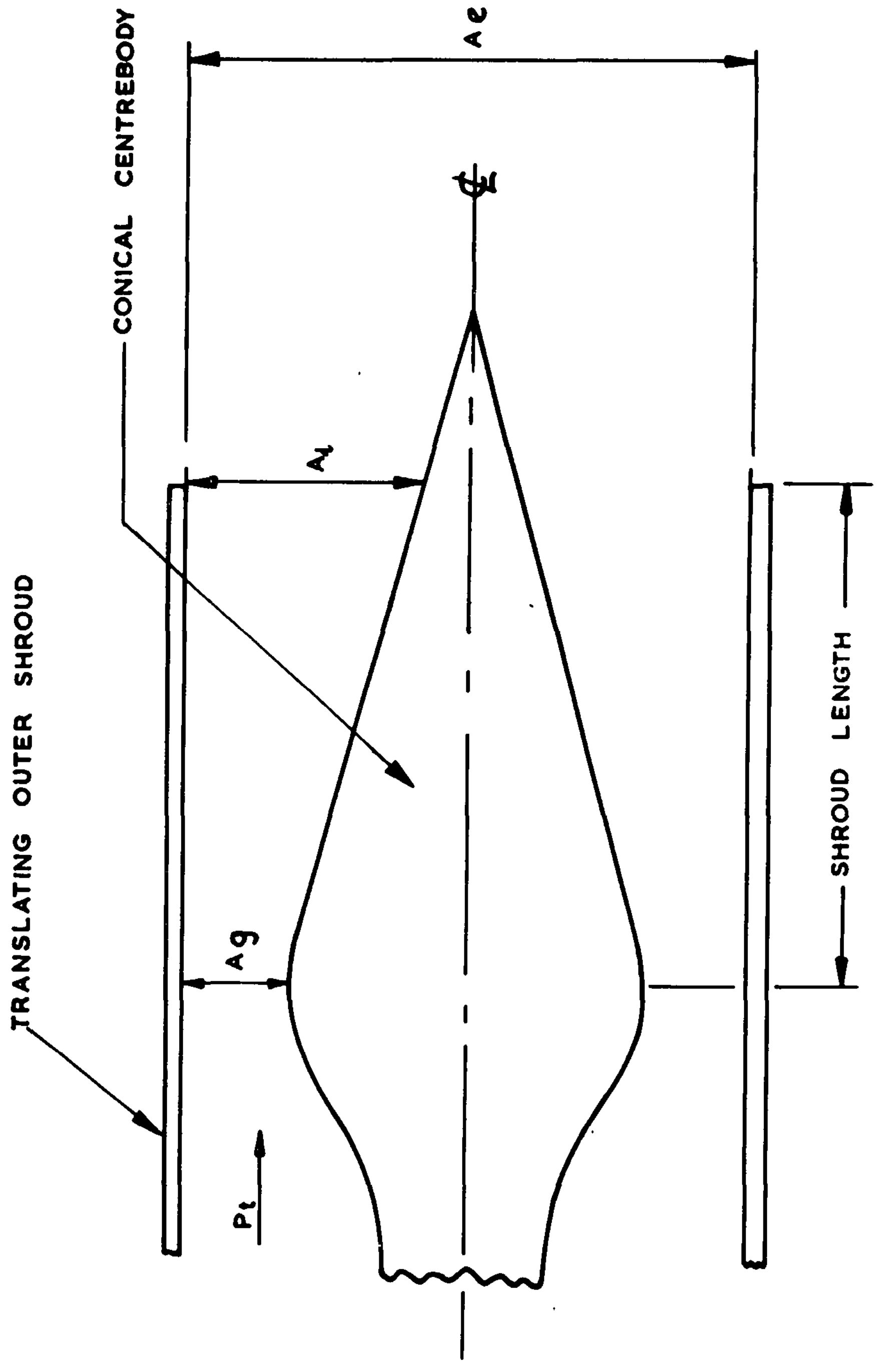
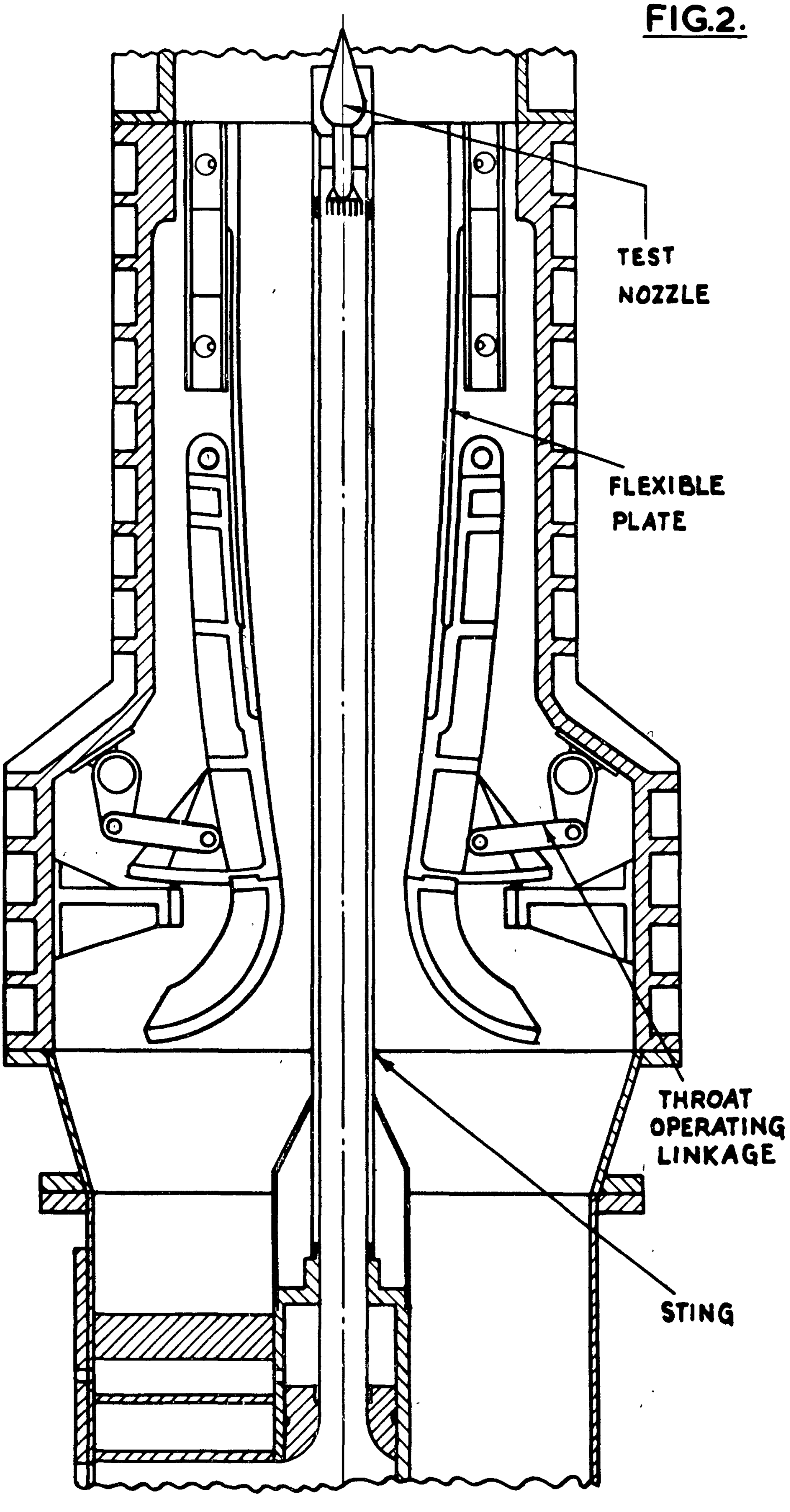


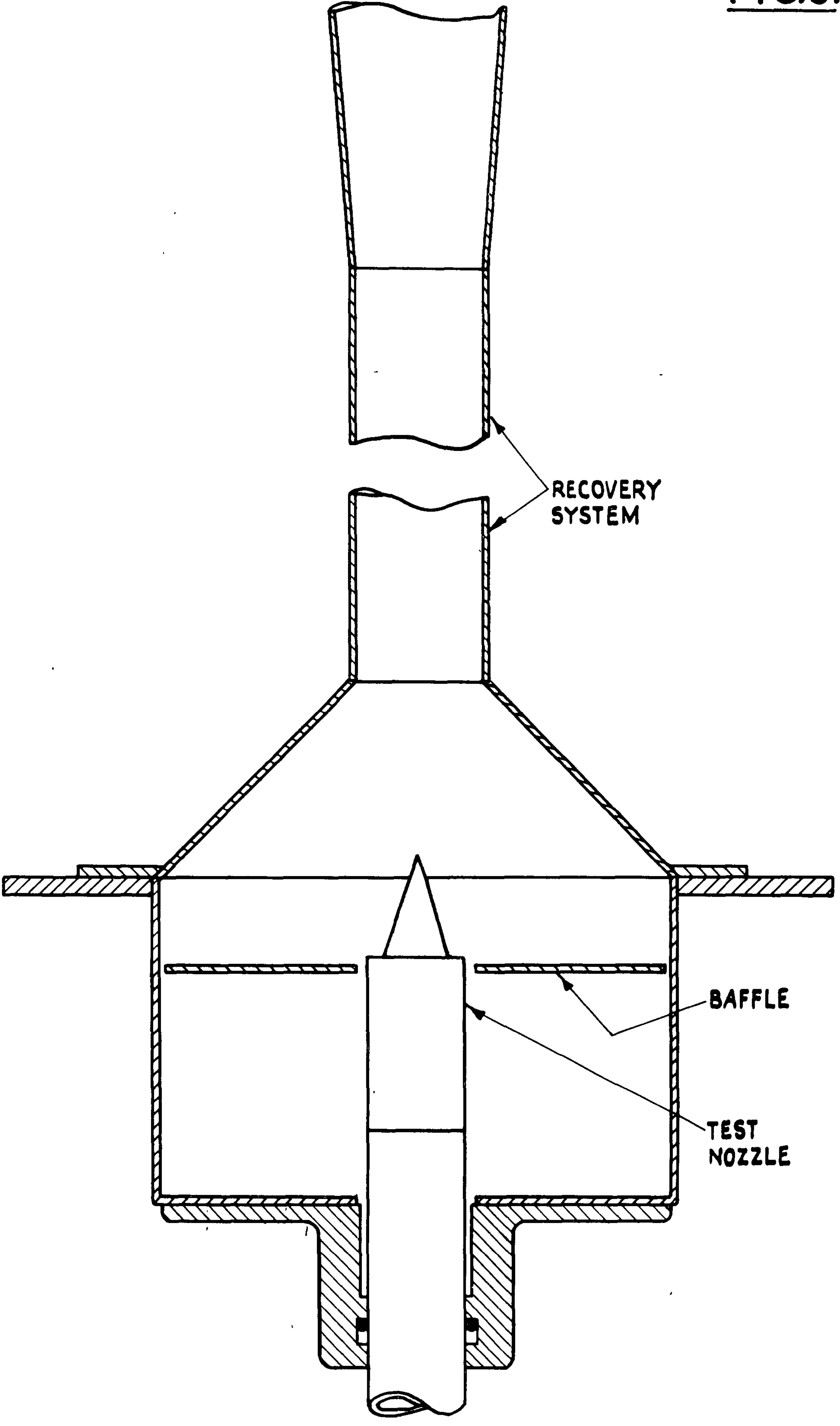
DIAGRAM OF NOZZLE ARRANGEMENT.

FIG.2.



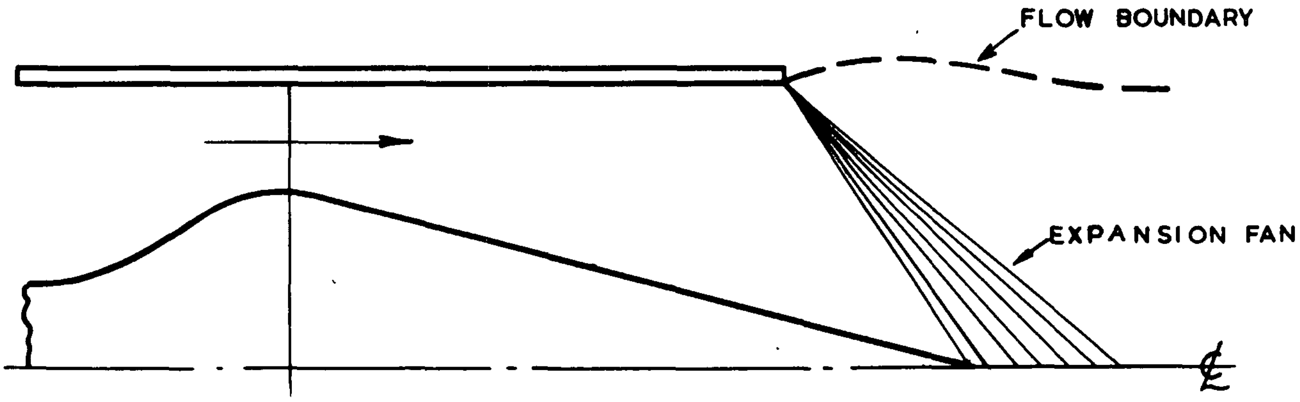
CROSS SECTION OF TEST RIG — EXTERNAL FLOW.

FIG.3.

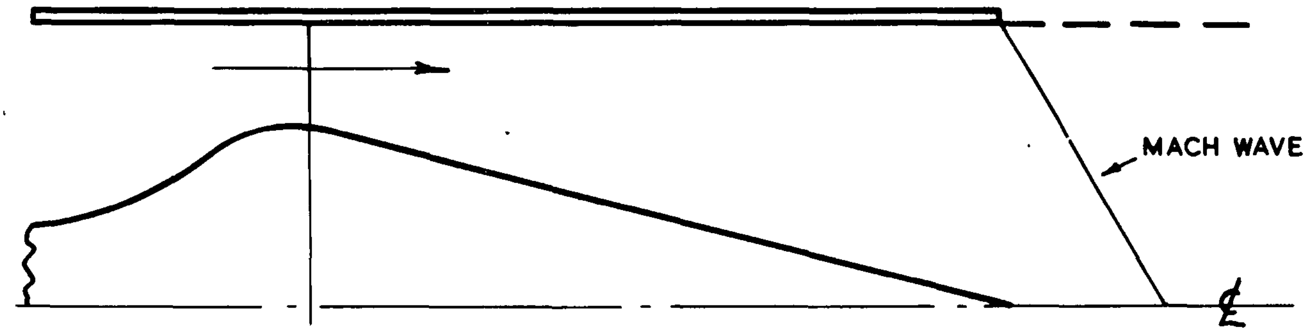


CROSS SECTION OF TEST RIG—
QUIESCENT AIR.

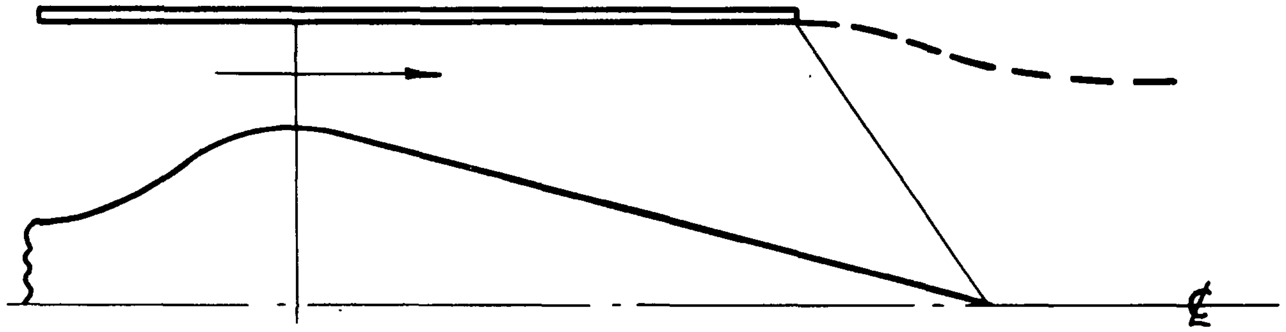
FIG.4
(A, B & C)



(A) DESIGN PRESSURE RATIO — MINIMUM SHROUD LENGTH



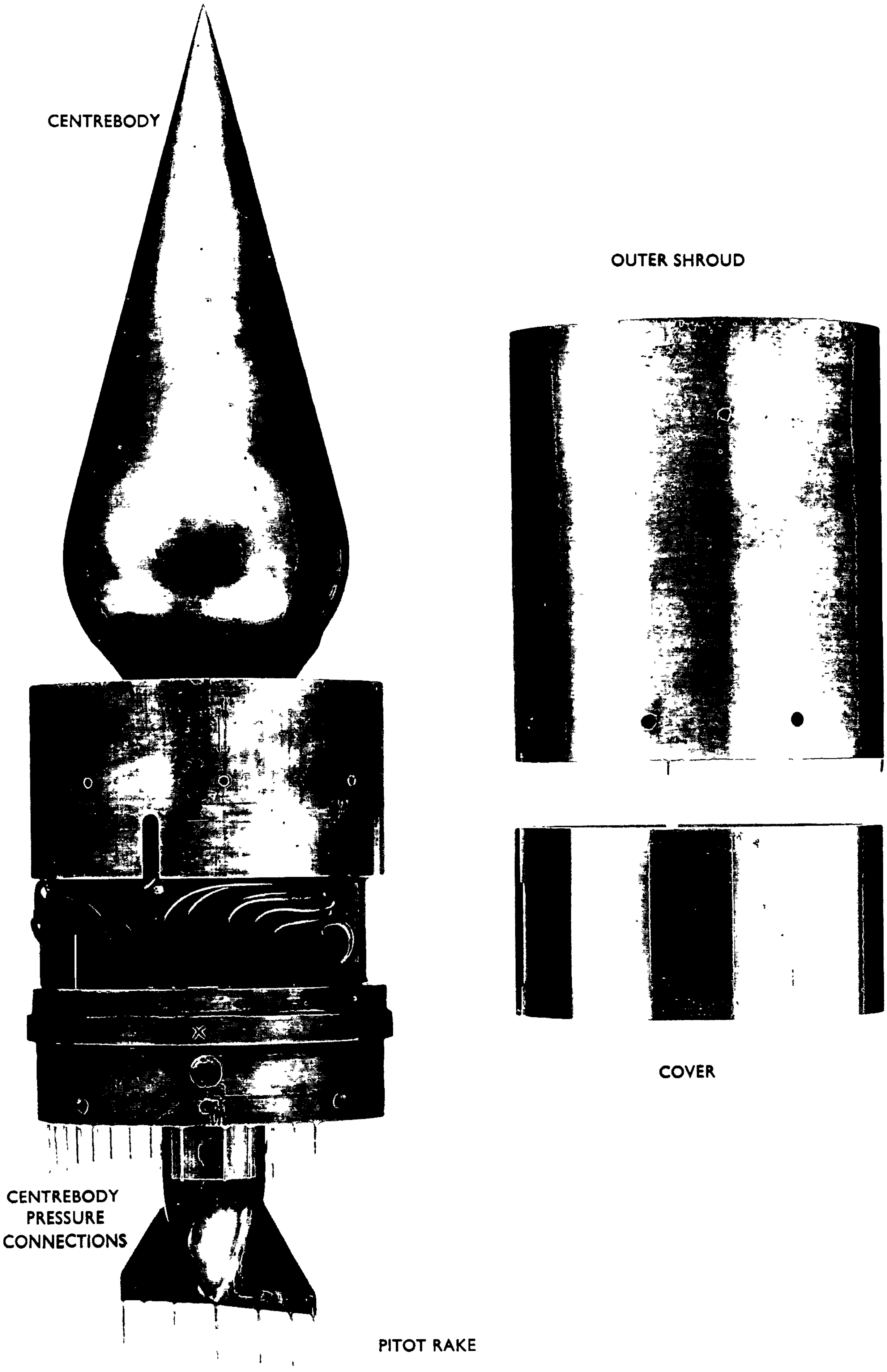
(B) DESIGN PRESSURE RATIO — EXTENDED SHROUD



(C) MINIMUM E.P.R. FOR SHROUD LENGTH AS IN (A)

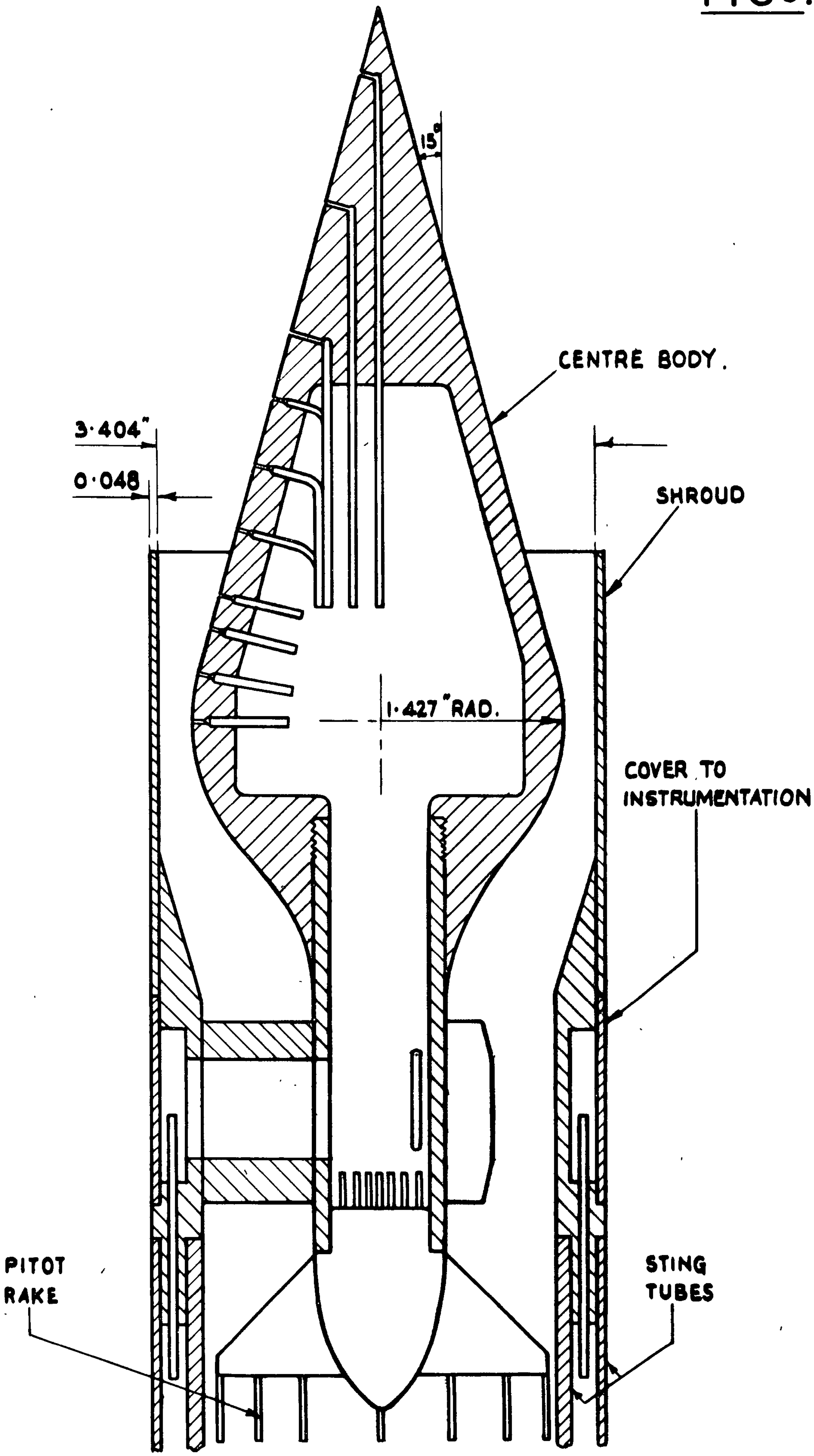
SHROUD LENGTH CHOICE, THEORY DIAGRAMS

FIG. 5



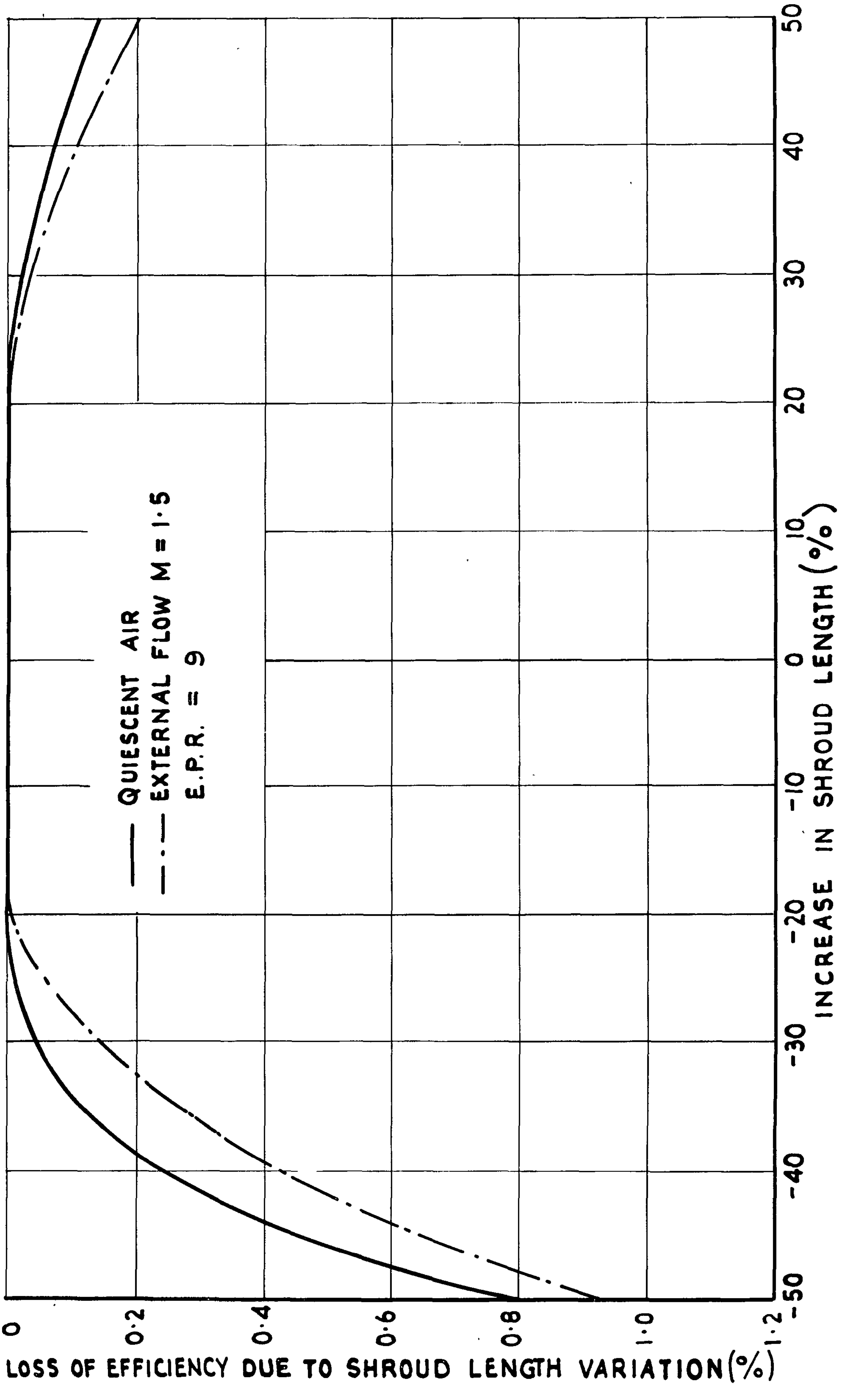
TEST NOZZLE

FIG 6.

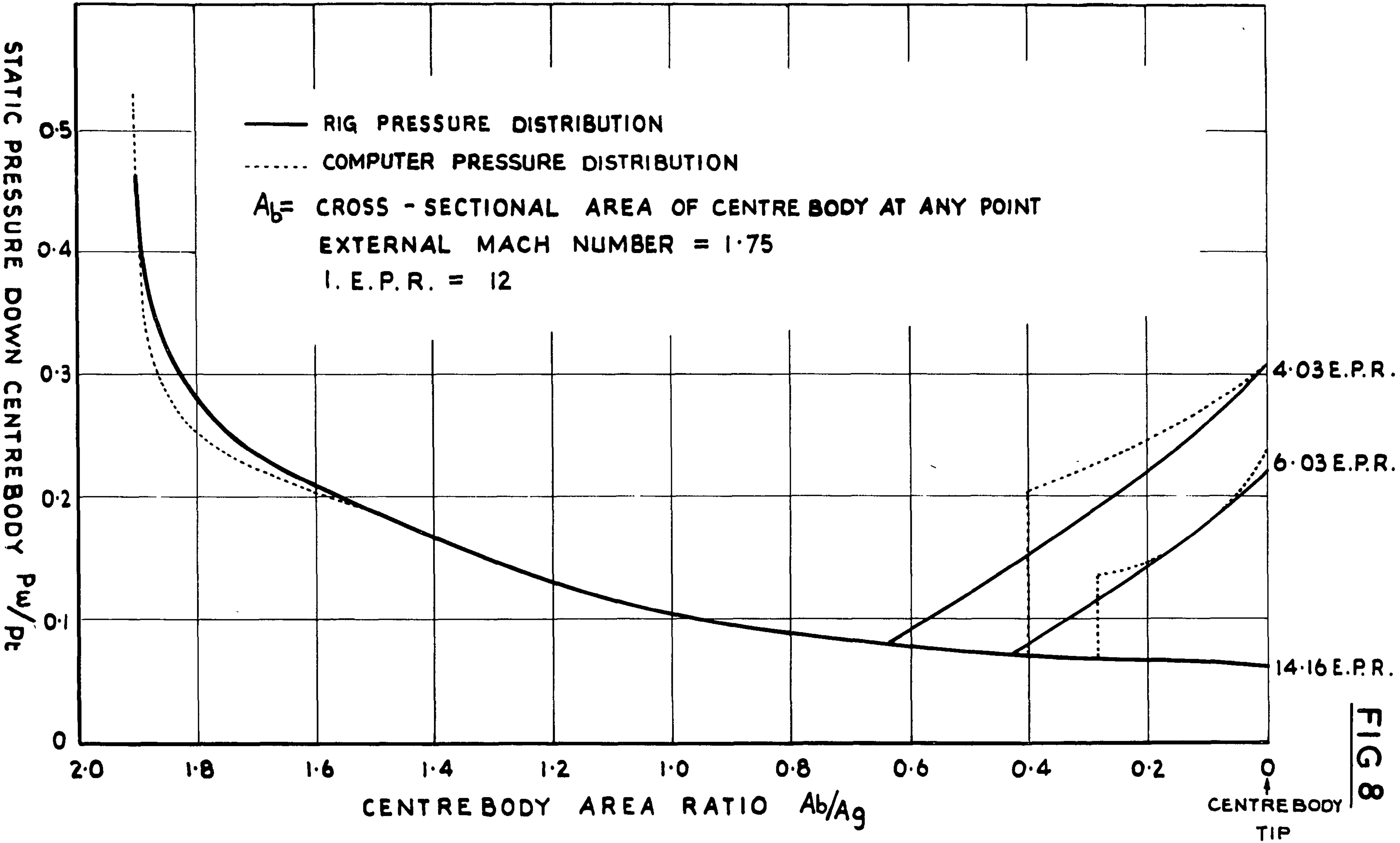


CROSS SECTION OF TEST NOZZLE.

FIG.7.



NOZZLE PERFORMANCE - SHROUD LENGTH VARIATION.



STATIC PRESSURE DOWN THE CENTREBODY-
EXTERNAL FLOW

FIG 8

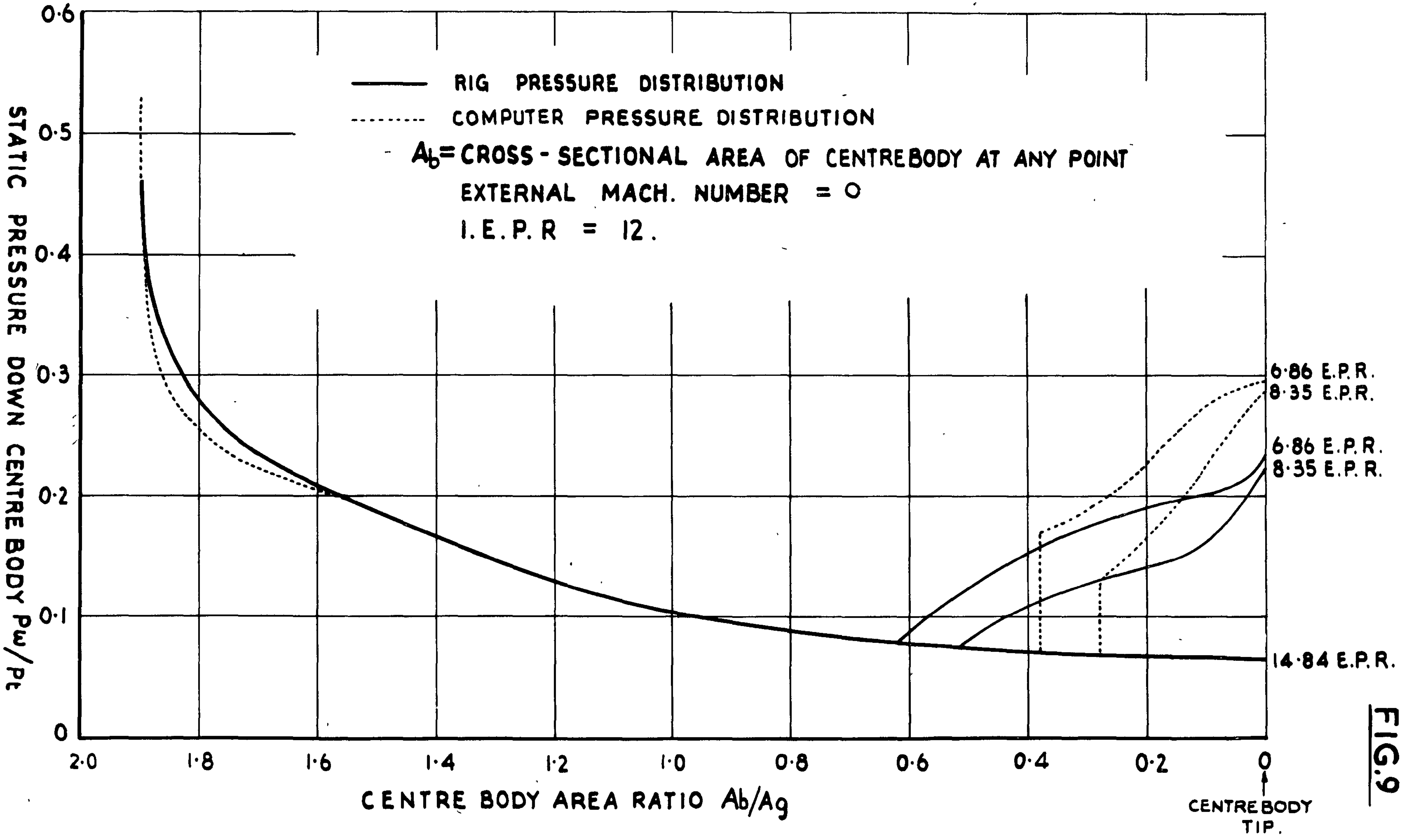
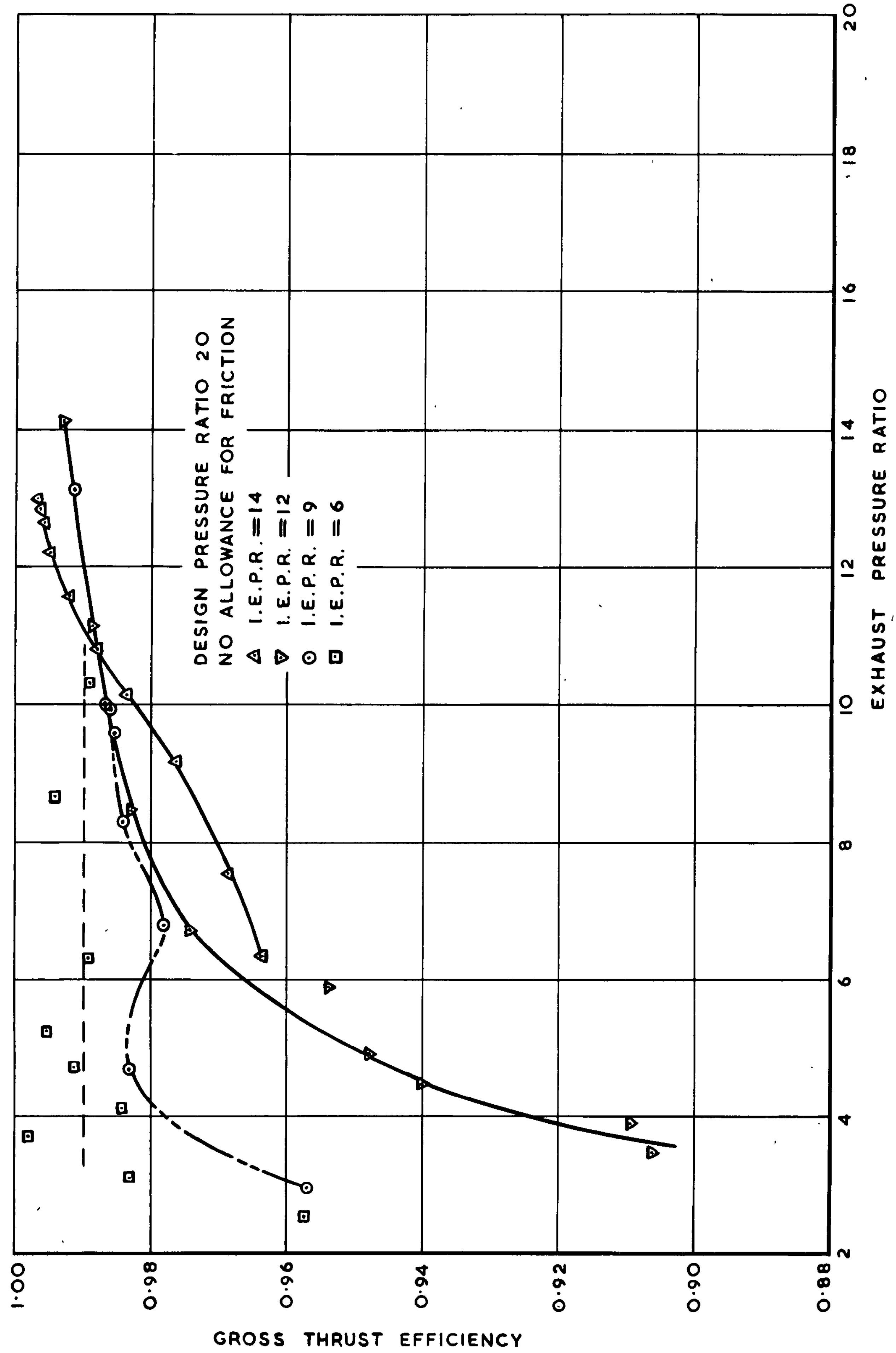


FIG.9

STATIC PRESSURE DOWN THE CENTREBODY—
QUIESCENT AIR.

FIG. 10



NOZZLE PERFORMANCE – QUIESCENT AIR.

NOZZLE PERFORMANCE — EXTERNAL FLOW — I.E.P.R.=6

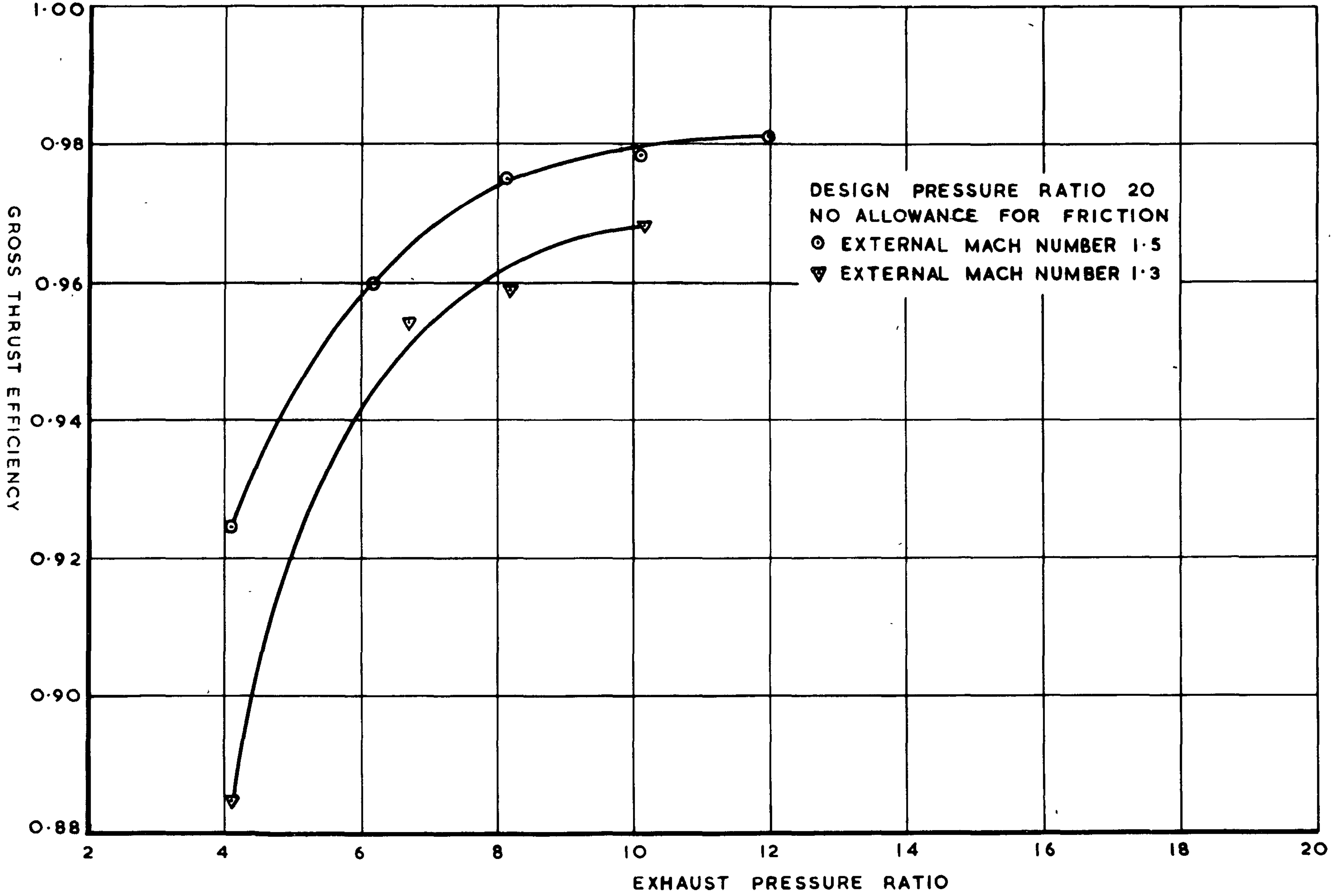


FIG.11.

NOZZLE PERFORMANCE — EXTERNAL FLOW — I.E.P.R. = 9

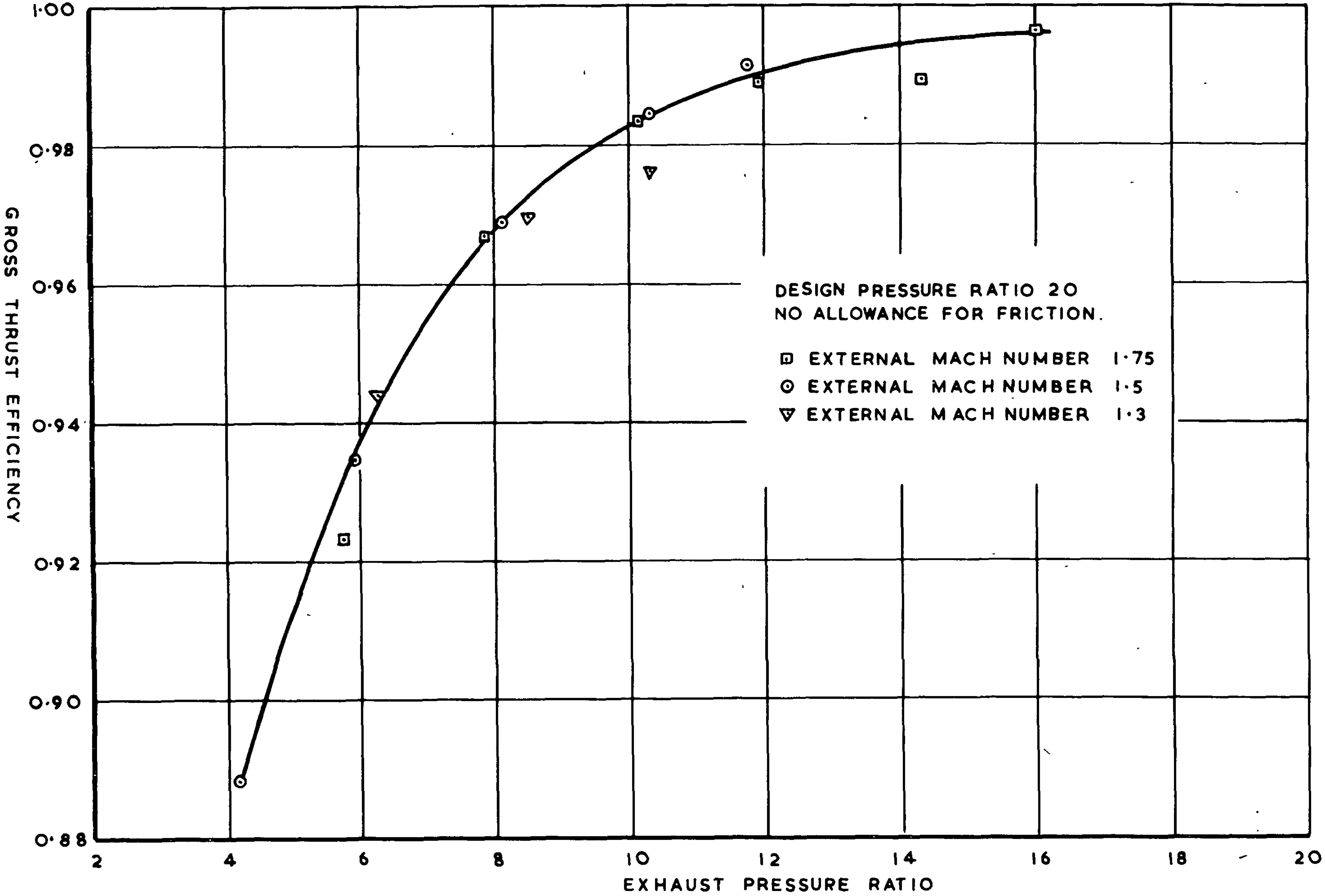


FIG.12

NOZZLE PERFORMANCE — EXTERNAL FLOW —

I.E.P.R.=12

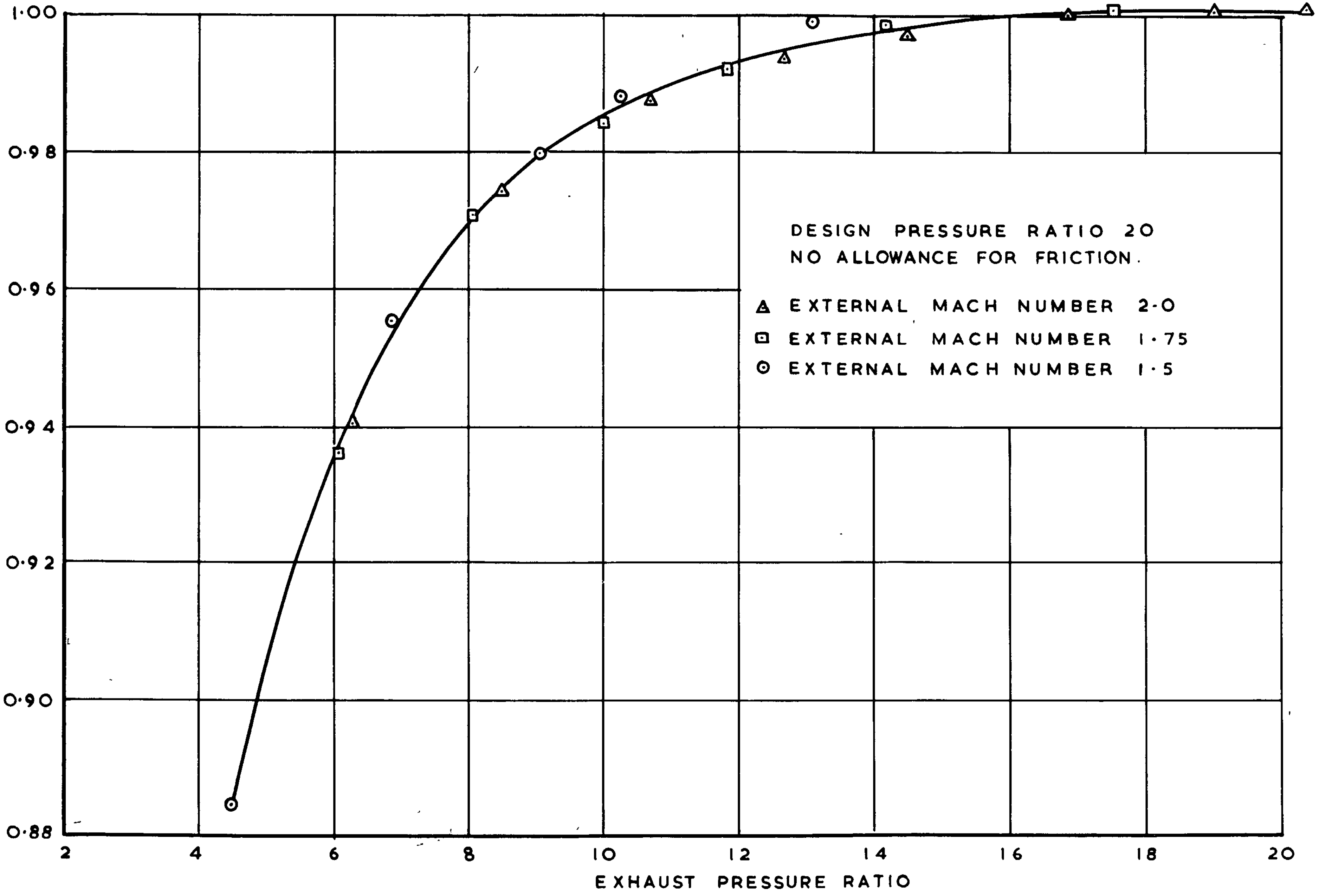
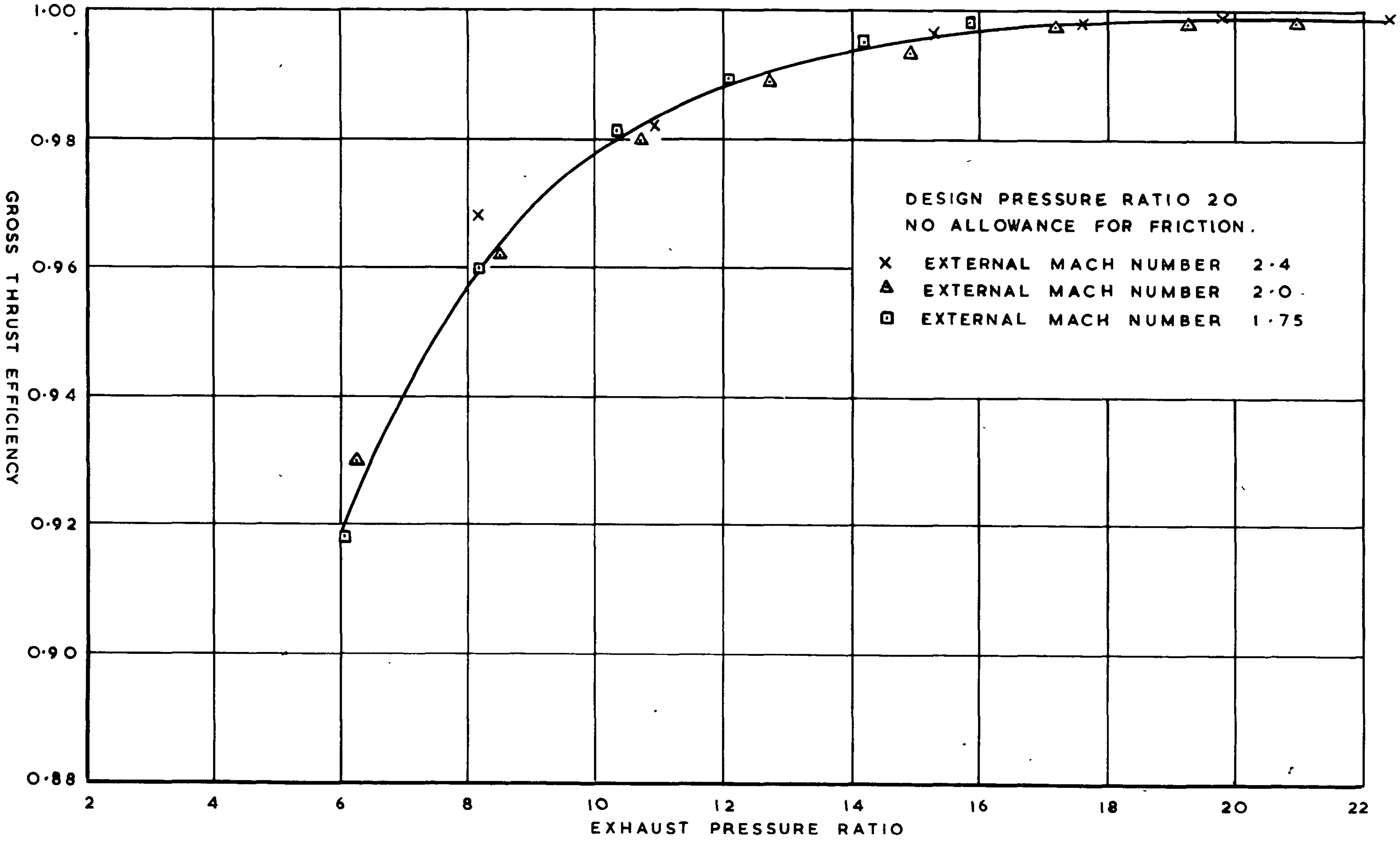


FIG.13

FIG.14



NOZZLE PERFORMANCE — EXTERNAL FLOW —
I.E.P.R. = 14

NOZZLE PERFORMANCE—EXTERNAL FLOW & QUIESCENT AIR

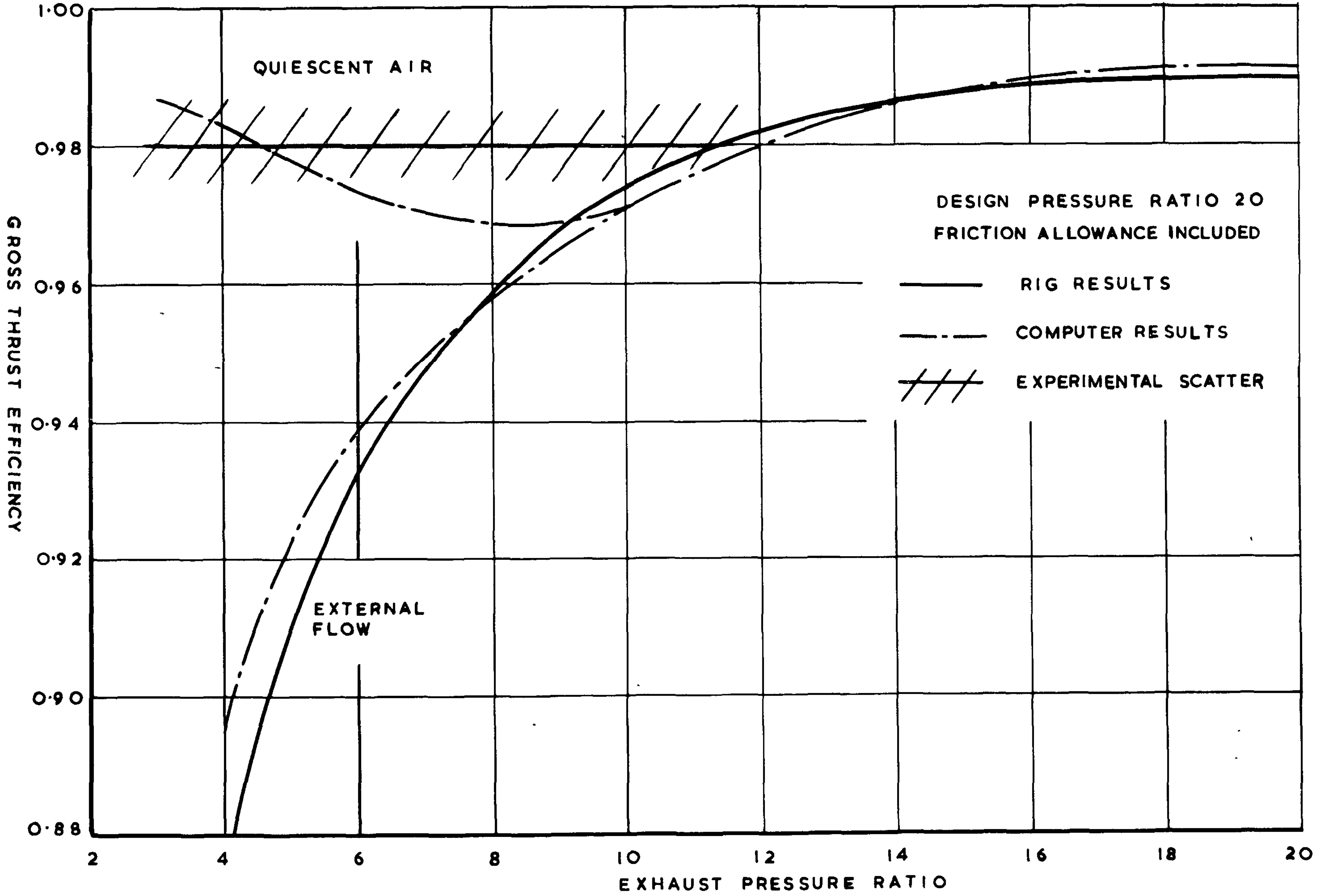


FIG.15

NOZZLE PERFORMANCE — EXTERNAL FLOW
7½°, 10° & 15° HALF-ANGLES.

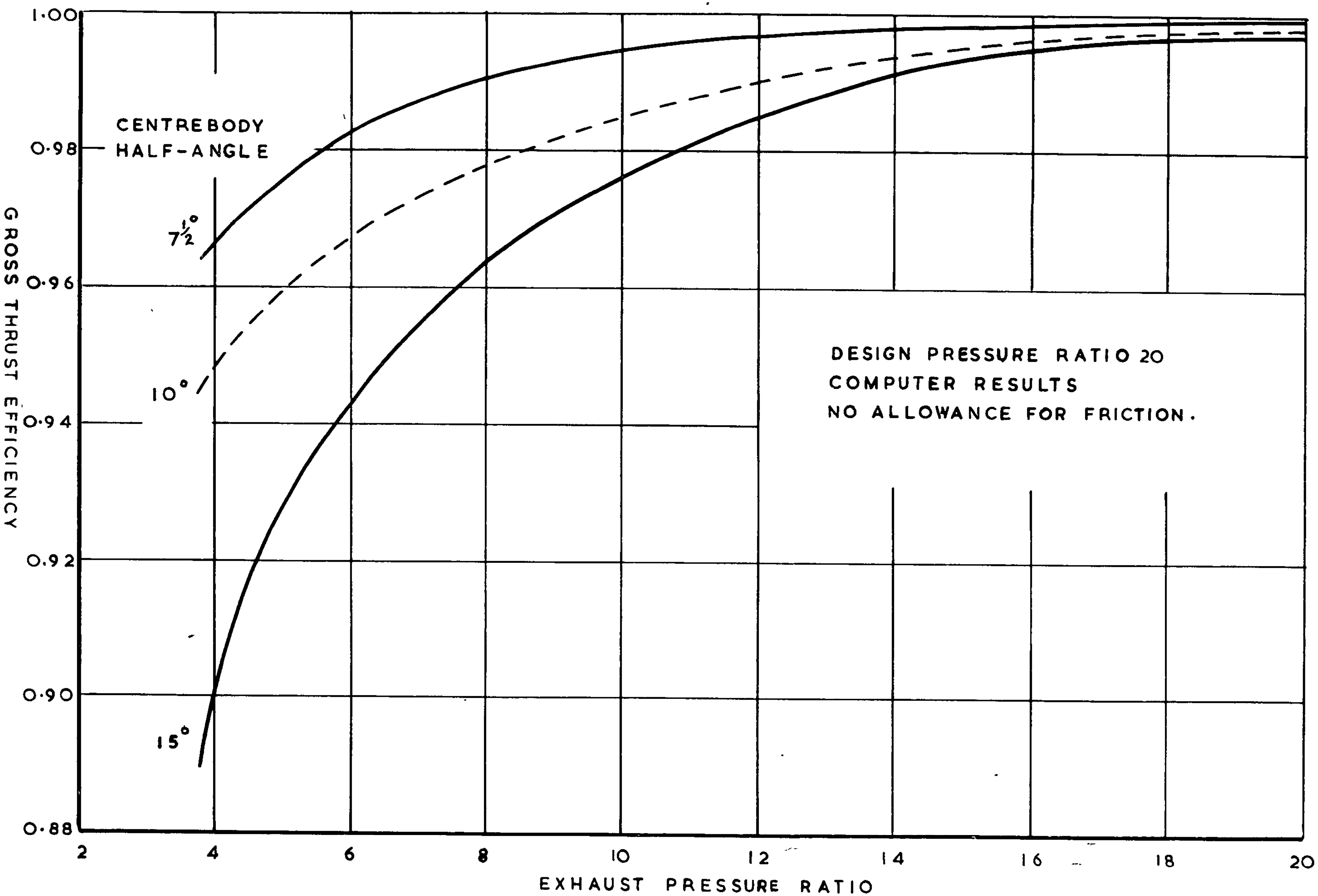
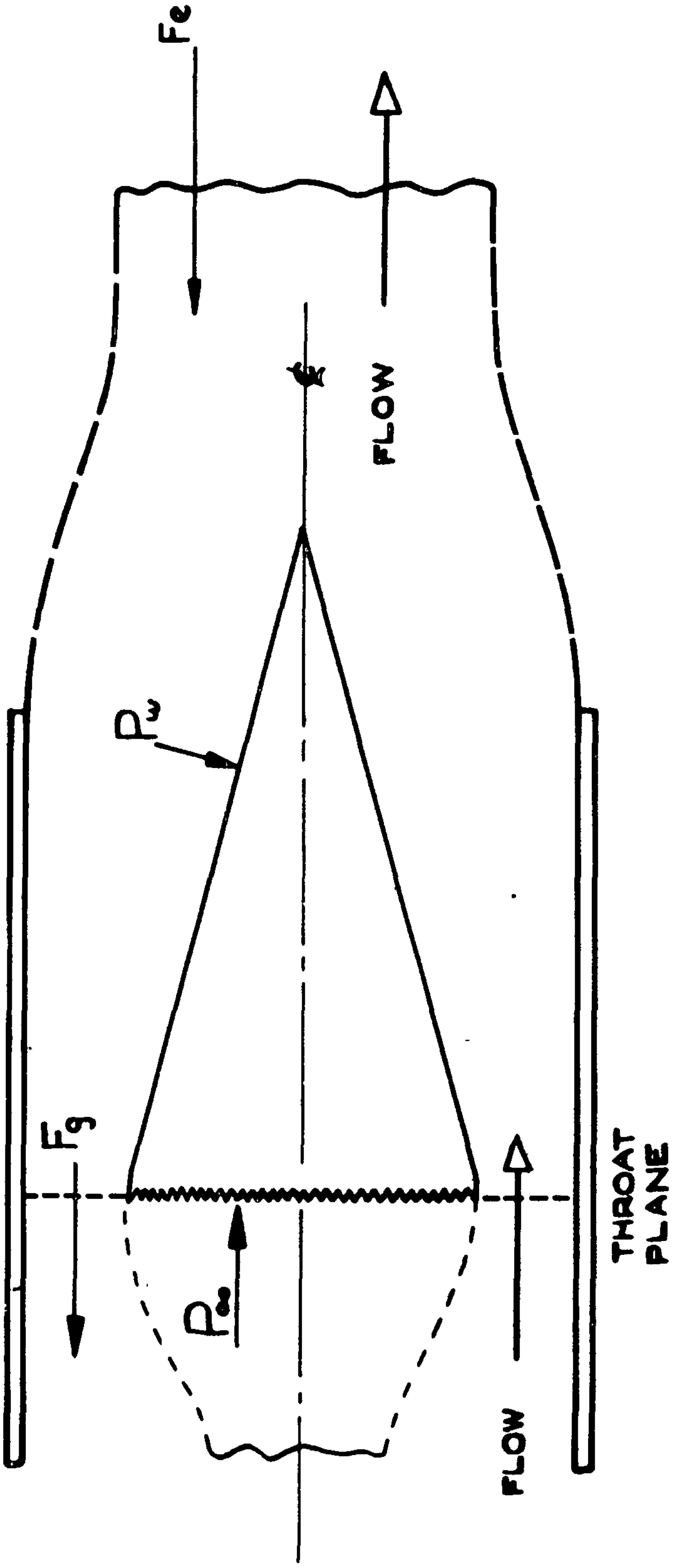


FIG.16

FIG.17



THRUST QUANTITIES.

A.R.C. C.P. No. 841 621-225.1:621.018
THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE
WITH A PARALLEL SHROUD IN EXTERNAL FLOW
Herd, R. J., Golesworthy, G. T. November 1963

The performance of two axially-symmetric centrebody propelling nozzles, with translating parallel outer shrouds and fixed throat areas, has been investigated both in quiescent air and in an external stream having a Mach number range of 1.3 to 2.4.

The results confirm that, in quiescent air, translation of the outer shroud gives a high nozzle gross thrust efficiency over a wide range of exhaust pressure ratio. In supersonic external flow, however, the results indicate a noticeable drop in efficiency as the exhaust pressure ratio decreases.

P.T.O.

A.R.C. C.P. No. 841 621-225.1:621.018
THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE
WITH A PARALLEL SHROUD IN EXTERNAL FLOW
Herd, R. J., Golesworthy, G. T. November 1963

The performance of two axially-symmetric centrebody propelling nozzles, with translating parallel outer shrouds and fixed throat areas, has been investigated both in quiescent air and in an external stream having a Mach number range of 1.3 to 2.4.

The results confirm that, in quiescent air, translation of the outer shroud gives a high nozzle gross thrust efficiency over a wide range of exhaust pressure ratio. In supersonic external flow, however, the results indicate a noticeable drop in efficiency as the exhaust pressure ratio decreases.

P.T.O.

A.R.C. C.P. No. 841 621-225.1:621.018
THE PERFORMANCE OF A CENTREBODY PROPELLING NOZZLE
WITH A PARALLEL SHROUD IN EXTERNAL FLOW
Herd, R. J., Golesworthy, G. T. November 1963

The performance of two axially-symmetric centrebody propelling nozzles, with translating parallel outer shrouds and fixed throat areas, has been investigated both in quiescent air and in an external stream having a Mach number range of 1.3 to 2.4.

The results confirm that, in quiescent air, translation of the outer shroud gives a high nozzle gross thrust efficiency over a wide range of exhaust pressure ratio. In supersonic external flow, however, the results indicate a noticeable drop in efficiency as the exhaust pressure ratio decreases.

P.T.O.

DETACHABLE ABSTRACT CARDS

A computer programme has been written to analyse supersonic shock-free flow through a nozzle, taking into account the effect of any external stream. In general, results for both centrebody nozzles obtained from the computer agree satisfactorily with those obtained from the rig. Computer results have indicated a means whereby the drop in efficiency at low exhaust pressure ratio might be lessened.

A computer programme has been written to analyse supersonic shock-free flow through a nozzle, taking into account the effect of any external stream. In general, results for both centrebody nozzles obtained from the computer agree satisfactorily with those obtained from the rig. Computer results have indicated a means whereby the drop in efficiency at low exhaust pressure ratio might be lessened.

A computer programme has been written to analyse supersonic shock-free flow through a nozzle, taking into account the effect of any external stream. In general, results for both centrebody nozzles obtained from the computer agree satisfactorily with those obtained from the rig. Computer results have indicated a means whereby the drop in efficiency at low exhaust pressure ratio might be lessened.

C.P. No. 841

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. 841

S.O. Code No. 23-9016-41