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Experimental Verification of Predicted Static Hole Size Effects on a Model with large Streamwise Pressure Gradients

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Experimental Verification of Predicted Static Hole Size Effects on a Model with large Streamwise Pressure Gradients

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SUMMARY

Data obtained during the measurement of surface pressures on a spherically-blunted cone are used to demonstrate the value of a simple method by which allowance is made for the effects of finite static hole size on the measured distribution of pressure over the spherical portion of the model.

List of Contents/

* Replaces N.P.L. Aero Report 1313 - A.R.C.31 900

List of Contents

Nomenclature

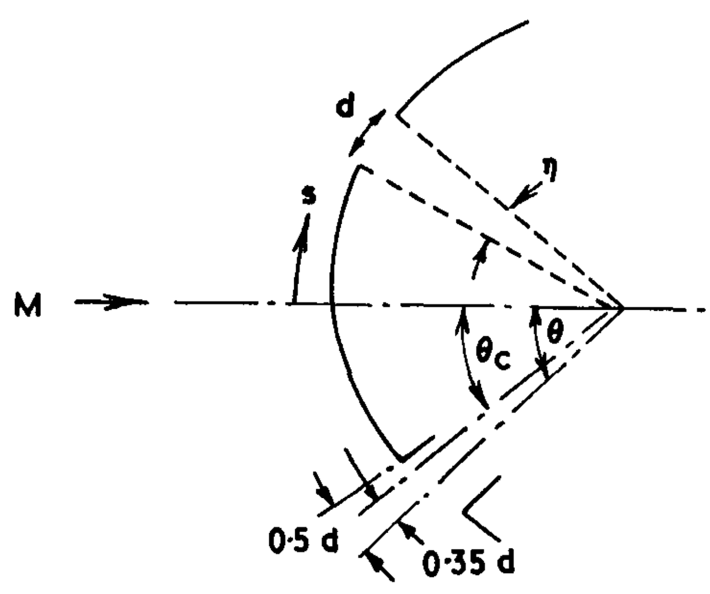
C_p	pressure coefficient formed from surface pressure and free-stream conditions $(C_p = 2\,(p/p_\infty - 1)/\gamma M^2)$
$\hat{C}_p$	value of C_p at stagnation point
C_{p_s}	pressure coefficient based on change in pressure due to the pressure of a static hole (in the absence of a streamwise pressure gradient) and local flow conditions
d	diameter of static hole
M	free-stream Mach number
M_L	local Mach number (just outside boundary layer)
p_o	free-stream stagnation pressure
p	surface pressure
p_∞	free-stream static pressure
Δp	effect of the presence of the static hole on the measured pressure

r_n/

Nomenclature (contd)

r_n	radius of curvature of the spherical portion of the model
s	streamwise distance from the stagnation point
δ^*	displacement thickness of boundary layer
η	angle subtended by distance d along the surface of the model at the centre of curvature of the surface of the model
θ	angle between the free-stream direction and the normal to the surface of the model at the centre of the static hole
θ_c	angle between the free-stream direction and the normal to the surface of the model at a point 0·35d upstream of the centre of the hole
x,ε	parameters used in Ref. 2 (see Section 5) (x is a streamwise distance and ε a surface slope).

Sketch to Illustrate Nomenclature



1. Introduction

Although the conventional static hole has remained virtually unchallenged as a means of measuring surface pressure since the beginnings of the systematic study of fluid dynamics, recent advances in the accuracy of other components of the complete pressure measuring system [1] have caused increasing study to be paid to errors inherent in the use of static holes.

Attention has been mainly concentrated upon the case of zero or small streamwise pressure gradients external to the boundary layer, [2,3,4] principally because this eases problems of establishing the true pressure (i.e. that which would occur in the absence of the hole). However, studies have also been made of the effects of the presence of static holes when the streamwise pressure gradient external to the boundary layer is large [4,5]. This problem is of practical importance, for example, in the interpretation of data obtained using hemispherical-headed incidence-meters. Various ways of correcting the measured pressure to allow for the size of static holes have been advanced [3,5]. The purpose of this paper is to demonstrate the usefulness and validity of the simplest of these correction methods.

2. Wind-tunnel, models and other experimental details

The measurements analysed in this report are a small fraction of the data obtained during a series of tests on blunted bodies performed during 1969 in the NPL 15 in × 10 in (381 mm × 254 mm) blowdown wind-tunnel. They are all measurements of surface pressure on the spherical portions of two pairs of spherically-blunted cones of 7·5° semi-apex angle (Fig. 1). Two nose radii were used, being 3·30 mm (0·13 in) and 6·60 mm (0·26 in). These comparatively small nose radii were chosen because of a desire to have a long conical portion downstream of the blunting, the main purpose of the tests being to study the pressure distribution over that part of the model. However, the diameter of the static-hole was fixed at 0·51 mm (0·020 in) in order to maintain a reasonable pneumatic response time of the pressure measuring system. Thus, the angles (η) subtended by those holes which are on the spherical portion of the model at the centre of the sphere were fairly large. Indeed, they were comparable to those found on incidence meters rather than those used on wind-tunnel models. However, the circumstances which dictated the choices of static hole size and nose radius are by no means unique and corrections of the type discussed in this report are often required for wind-tunnel tests.

The static holes were drilled normal to the surface of the model and had a depth (as defined in Ref. 2) of approximately 10 hole diameters. As is usual, care was taken to ensure that the holes were round and flush with the surface.

The tests were run at ambient stagnation temperature, a stagnation pressure of 0·565 MN/m^2 and a mean free-stream Mach number of 3·05.

The pressure holes were distributed over the surface of the model both circumferentially and longitudinally. A complete coverage of the surface of the model was obtained by performing tests with the model at each of seven different roll angles. During each test, measurements were made at angles of incidence of 0°, 2·5°, 5·0°, 7·5°, 10·0°, 12·5°, 15·0° and 17·5°. In this way 280 separate measurements were made of the surface pressure on the spherical portions of the models.

3. Instrumentation

Pressures were measured using the normal data-acquisition system of the 15 in x 10 in (0·381 m x 0·254 m) tunnel. This is similar in all essential details to that of the 7 in x $4\frac{1}{2}$ in (0·178 m x 0·114 m) tunnel whose data-acquisition system has been described before [1,2]. On the basis of earlier analyses [1], and allowing for the difference in tunnel size etc., the root mean square error of the measured surface pressures was estimated to be everywhere better than approximately 4·3 per cent of the free-stream static pressure or 0·0011 in p/p_0 at $M = 3{\cdot}05$. This figure includes instrumentation errors, and the effects of flow non-uniformity, as well as the influence of manufacturing errors[2].

4. Presentation of data

If there is no streamwise pressure gradient in the flow external to the boundary layer then, in principle, there is no problem of defining the pressure that the static hole is required to measure. If there is a pressure gradient then an additional problem of interpretation arises. Since the pressure that would occur in the absence of the static-hole varies across the area of the surface of the model that is occupied by the hole, it is not obvious what pressure will be sensed by the hole even if its presence were to cause no change in the flow pattern. Alternative ways of stating the problem are to ask:-

(a) by how much does the pressure sensed by the hole differ from the "true" surface pressure at the centre of the hole?

or, (b) for what point on the surface of the body does the hole sense the pressure and how far removed is this point from the centre of the hole?

The two questions are identical in effect because the presence of a pressure gradient means that streamwise location may be interchanged with pressure. They are merely alternative ways of formulating the same basic questions and do not differ in any fundamental way. Of the two, the second is probably to be preferred on the grounds that it is conceptually easier to relate the effect of hole size to model design criteria. This note, therefore, follows the work of Rainbird [3] and seeks the location of a point at which the measured pressure is equal to the true surface pressure (i.e., that which would apply in the absence of the hole). Morrison, Sheppard and Williams [5] showed that the difference between the measured pressure and the true surface pressure at the centre of the area occupied by the hole was proportional to the angle subtended by the hole at the centre of curvature of the body. In fact, for local Mach numbers less than 1·0 and $-\frac{1}{p}\frac{\partial p}{\partial \theta} < 2$, Morrison et al state that:-

$$\frac{1}{p}\frac{\partial p}{\partial \eta} + \frac{0{\cdot}37}{p}\frac{\partial p}{\partial \theta} = 0$$

and since

η/

$$\eta = \frac{d}{r_n}, \quad \text{then} \quad r_n = \frac{\partial d}{\partial \eta}$$

and $\theta = s/r_n$, so, $r_n = \dfrac{\partial s}{\partial \theta}$

Hence,

$$\frac{1}{r_n}\frac{\partial p}{\partial d} + \frac{0 \cdot 37}{r_n}\frac{\partial p}{\partial s} = 0$$

so,

$$\frac{\partial p}{\partial d} = -0 \cdot 37 \frac{\partial p}{\partial s}$$

and since the error in pressure (Δp) is zero for $d = 0$, then

$$\Delta p = -0 \cdot 37 \, d \left(\frac{\partial p}{\partial s} \right)$$

Thus, an upstream displacement of the measuring station by 0·37 d would produce a change in pressure equal and opposite to the error predicted by Morrison et al.

There is, thus, only a slight discrepancy between the suggested corrections due to Morrison et al. and that obtained by Rainbird's analysis of low-speed data. The former correction is equivalent to stating that the measured pressure is equal to the true surface pressure at a point 0·37d upstream of the centre of the hole for $M_L < 1 \cdot 1$. Rainbird found that at low speeds the upstream displacement is 0·3 d . However, this difference is not large and is not normally significant. An intermediate value 0·35 d has been used in this report. Of possibly more significance is that Morrison et al. suggest an additional Mach-number dependent correction for $M_L > 1 \cdot 1$, but in the present text the straightforward 0·35 d displacement correction has been used primarily for the sake of simplicity. This choice will be justified later in this report.

Presentation of the experimental data is greatly eased by the fact that the shape of the spherical portion of the body is invariant under rotation. Further, the limiting characteristic springs from a point on the spherical portion of the body even at the maximum angle of incidence. Thus, the stagnation point is always located at the point where the normal to the surface lies in the free-stream direction. The pressure distribution, when presented in the form of pressure as a function of angle between the free-stream direction and the normal to the surface is thus invariant with incidence. Changes in

incidence/

incidence simply traverse each static hole through a part of the fixed pressure distribution. Hence, only a few holes are needed to map out the complete pressure distribution over the spherical portion of the model.

5. Data from different models: causes of systematic discrepancies other than those peculiar to the presence of static holes on a body with streamwise gradients of surface pressure

In cases, such as that considered in this report, where no completely irreproachable theoretical solutions for the surface-pressure distribution are available, the success of a method for the correction of experimental data must be judged by the extent to which data obtained for different relative sizes of model and static holes can be collapsed on to a single curve. The data analysed were, in this case, obtained with a constant hole diameter and two different nose radii. The tests were run at a fixed stagnation pressure and, hence, at different Reynolds numbers based on nose radius. Thus, before proceeding to the main analysis it is necessary to consider whether causes other than the effect of the size of the static holes could have been responsible for significant systematic discrepancies between data from the different models.

The most probable cause of such discrepancies would be viscous-interaction effects, since the Reynolds numbers based on nose radius and free-stream conditions are fairly small (approximately $1 \cdot 5 \times 10^5$ and 3×10^5). Estimates of the development of the boundary layer, assumed to be laminar* over the spherical portions of the models, were made using an extension of the method of Ref. 7. These suggested that the rate of growth of displacement thickness $\left(\frac{\partial \delta^*}{\partial s}\right)$ was $4 \cdot 4 \times 10^{-3}$ in the vicinity of the sonic point of the larger models and $6 \cdot 2 \times 10^{-3}$ at the corresponding point on the smaller models. The quantity $\left(\frac{\partial \delta^*}{\partial s}\right)$ increases downstream of the sonic point and has maximum values (at the downstream end of the spherical portion of the bodies) of approximately 2×10^{-2} and $2 \cdot 8 \times 10^{-2}$ for the larger and the smaller models respectively.

Baer[6] has shown that the predictions of modified Newtonian theory are in reasonable accord with experimental pressure distributions over hemispheres at $M = 3$. This being so we may write:-

$$C_p = \hat{C}_p \cos^2 \theta$$

or,

$$\left(\frac{\partial C_p}{\partial \theta}\right)_b = -2\hat{C}_p \cos\theta \sin\theta = -\hat{C}_p \sin 2\theta .$$

(the suffix b denotes that the body shape is constant)

but/

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*Transition Reynolds number measured in the same facility on $7 \cdot 5^\circ$ semi-apex angle sharp cones at $M = 3 \cdot 05$ are approximately $1 \cdot 5 \times 10^6$ (start of transition). The favourable pressure gradient would be expected to increase this value.

but, for $\dfrac{\partial\delta^*}{\partial s} \ll 1$, we may estimate the change in pressure coefficient due to viscous interaction as:-

$$\Delta C_p = -\left(\frac{\partial\delta^*}{\partial s}\right) \cdot \left(\frac{\partial C_p}{\partial\theta}\right)_s$$

(the suffix s denotes that s is constant and the change in θ is a result of a change in the effective shape of the body)

Adopting a tangent-sphere approach we write:-

$$\left(\frac{\partial C_p}{\partial\theta}\right)_b = \left(\frac{\partial C_p}{\partial\theta}\right)_s = -\hat{C}_p \sin 2\theta$$

i.e.

$$\Delta C_p = \left(\frac{\partial\delta^*}{\partial s}\right) \cdot \hat{C}_p \sin 2\theta$$

The maximum changes in pressure coefficient due to viscous interaction effects were thus estimated as $7{\cdot}5 \times 10^{-3}$ and $10{\cdot}5 \times 10^{-3}$ (i.e. changes in p/p_o of $1{\cdot}23 \times 10^{-3}$ and $1{\cdot}73 \times 10^{-3}$) for the larger and smaller models respectively. Thus, the maximum difference due to viscous-interaction between pressures at corresponding points on the models tested, amounts to approximately 5×10^{-4} in p/p_o.

Again, systematic discrepancies between data obtained from the two different model sizes could arise from those effects of static hole size which are present even when there is no streamwise pressure gradient. It would not be unreasonable to predict these using the formula proposed by Peto and Pugh [2] with the substitution of the streamwise distance along the surface from the stagnation point (s) for the slant length (x) of Ref. 2 and of the surface inclination for the cone semi-apex angle (ε). However, this is not possible because:-

(1) the values of (d/δ^*) encountered under the conditions considered in this report $(40 \leqslant d/\delta^* \leqslant 1{,}000)$ far exceed those investigated in Ref. 2;

(2) the correlating parameter $Cp_s \sqrt{M_L^2 - 1}$ used in Ref. 2 is clearly related to supersonic similarity considerations and is inapplicable to subsonic flows external to the boundary layer.

Fortunately, it is almost certain that the change in pressure due to the presence of the static hole will have reached an asymptotic value (akin to that found experimentally by Rainbird [3]) at the high values of (d/δ^*) pertinent to the data analysed in this report. It is unlikely that, in the presence of a laminar boundary layer, this asymptotic value will exceed the corresponding value found by Rainbird [3] for turbulent boundary layers, namely:-

C_{p_s} /

$$C_{p_s} \sqrt{M_L^2 - 1} = 0{\cdot}05$$

Over much of the spherical portion of the model (approximately $\theta > 12°$) the values of $\frac{d}{s}$ and $\frac{d.\cot\theta}{s}$ (equivalent to $\frac{d}{x}$ and $\frac{d}{x \tan \varepsilon}$ of Ref. 2) are within the ranges for which predictions may reasonably be made using the methods proposed in Ref. 2. However, the effect of these parameters turns out to be at most about 30 per cent of the above asymptotic value. Thus, and in view of the uncertainty of this estimate, the static hole size effect may be taken as being given simply by:-

$$C_{p_s} \sqrt{M_L^2 - 1} = 0{\cdot}05 .$$

The second difficulty (which arises when $M_L < 1$) may be circumvented by noting that, under the conditions for which the parameter $C_{p_s} \sqrt{M_L^2 - 1}$ was devised $(M_L > 1{\cdot}0)$, the result of Ackeret's linear theory suggests that $C_{p_s} \sqrt{M_L^2 - 1}$ may be interpreted as being twice a change in surface slope. Thus, the statement that $C_{p_s} \sqrt{M_L^2 - 1}$ is independent of M_L is equivalent to saying that the disturbance due to the presence of the static hole is equivalent to a change in surface slope. The asymptotic value of this change in slope is $0{\cdot}05/2 = 0{\cdot}025$. Thus, using the modified Newtonian formula for the pressure distribution around the spherical part of the body, and proceeding in a manner analogous to the estimation of viscous-interaction effects, it is estimated that the maximum likely change in C_p due to this cause is 5×10^{-2}, i.e. a change of $8{\cdot}3 \times 10^{-3}$ in p/p_0.

Two points should be noted about this value. Firstly, that it is the maximum likely magnitude of this effect; indeed its actual value will probably be about 3×10^{-3} in p/p_0[5]. Secondly, (d/δ^*) is so large that C_{p_s} is close to its asymptotic value and, hence, C_{p_s} is virtually independent of (d/δ^*). Further, terms involving $\frac{d}{s}$ and $\frac{d \cot \theta}{s}$ make only a relatively small contribution to the total effect. Thus, the difference between this effect at corresponding points on the different sized models would be expected to be only a small fraction of the change in p/p_0 due to the presence of the holes in the absence of a streamwise pressure gradient. In fact, one might reasonably anticipate that this difference would be of the order of the difference in the contributions to the effect made by terms in

$\left(\frac{d}{s}\right)$ and $\left(\frac{d \cot \theta}{s}\right)$ i.e. of the order of 1×10^{-3} in p/p_0.

The/

The above estimates of maximum likely systematic discrepancies between data obtained using the two sizes of model (5×10^{-4} and 1×10^{-3} in p/p_0) are to be compared with the estimated standard deviation of measurements of nominally identical pressures ($1 \cdot 1 \times 10^{-3}$ in p/p_0) (Section 3).

Such a comparison shows that these systematic discrepancies are of the same size as, or smaller than, the scatter to be expected in the experimental results. Thus, any systematic discrepancy between data, obtained using the two sizes of model, which is larger than the data scatter must be attributed to the effect of the streamwise pressure gradient on the pressure measured by a static hole of finite size.

6. The effects of streamwise pressure gradient on the measured pressure

The measured pressures are shown in Fig. 2, as a function of the angle θ. As is conventional these Figures have been prepared on the assumption that the measured pressure is the pressure which, in the absence of the static hole, would have acted on the surface of the model at the centre of the static hole. In the interests of clarity only data for $2 \cdot 5° \leq \theta \leq 65°$ have been plotted on this Fig. The data for $\theta \geq 65°$ are analysed separately. It will be seen that data obtained from each size of model tend to lie on a single curve. The scatter about a smooth curve through the data is of the order of $\pm 4 \times 10^{-3}$ in p/p_0. This is somewhat larger than the estimated accuracy quoted in Section 4, since three times the estimated standard deviation equals $3 \cdot 3 \times 10^{-3}$ in p/p_0. However, the discrepancy between actual and estimated scatter is not large and the experimental result broadly confirms the estimate and suggests that no significant unexpected sources of error are present in the data.

When data from the two different sizes of model are compared, however, it is clear that a systematic discrepancy exists between the two sets of data. This is particularly evident in the region $25° \leq \theta \leq 45°$ where the streamwise pressure gradients are largest. In Fig. 3 the data are replotted, this time assuming that the measured pressure corresponds to the pressure acting at a point $0 \cdot 35 d$ upstream of the centre of the hole, i.e. applying the displacement type of correction suggested by Rainbird [3]. It is evident that, by plotting the pressure measurements against this "corrected" angle (θ_c) the discrepancy between the two sets of data is considerably reduced. A complete reconciliation is not, however, effected and a greater correction to θ might be beneficial. Nevertheless, the two sets of data overlap and it is doubtful whether any real improvement in the correction method could be developed in view of the fact that the residual discrepancy (typically 2×10^{-3} in p/p_0) is small compared with the data scatter, and is approaching the magnitude of the other sources of systematic differences between the two sets of data (see Section 5).

The value of the displacement type of correction is even better demonstrated in Fig. 4. Here the data obtained from pressure holes at the sphere/cone junction are plotted in the same form as in Figs. 2 and 3. The discrete data points and the chain dotted lines refer to the "raw" data, i.e. that plotted against θ. The hatched area shows the mean curves through the "raw" data (the chain dotted lines) replotted at the corrected angle θ_c.

In fact, the lower boundary of the hatched area corresponds to data from the larger models and the upper boundary to data from the smaller models.

An/

An excellent reconciliation of the two sets of data is achieved. These corrected data almost form a continuation of the data presented in Fig. 3. In fact, the difference between the two curves at $\theta \simeq 62°$ is less than the scatter of the data for $\theta \leqslant 60°$. These data for $\theta \simeq 90°$ are of particular interest in that the local Mach number is of the order of 3·0. Application of the additional correction proposed by Morrison et al. for local Mach numbers above 1·1 would increase the measured pressures by approximately 12 per cent in the case of the large nose radius and by approximately 24 per cent in the case of the small nose radius. The difference between the corrections for the two nose sizes is about 12 per cent. The application of such a correction would considerably worsen the agreement between the corrected sets of data for the two hole sizes shown in Fig. 4. This proposed additional correction does not, therefore, appear to be required in the case considered here. It is only fair to recall that Morrison et al. expressed their reservations about this possible correction term. Some additional confidence in the validity of the correction method used in this report can be gained from Fig. 5, which shows good agreement between the corrected NPL data and a pressure distribution due to Baer[6], who tested a 147·3 mm (5·80 in) diameter hemisphere cylinder at $M = 3·0$ for which hole size corrections are too small to be discerned on the scale of Fig. 5.

7. Conclusions

Analysis of data obtained during an experiment in which it was necessary to use static pressure holes whose diameter was large compared to the local radius of curvature of the surface of the model demonstrates the value of the displacement type of correction method. The additional correction term proposed by Morrison et al. for local Mach numbers in excess of 1·1 does not seem to be required in the case considered in this report. It would appear that, with some additional refinement of the method, it should be possible to use considerably larger static holes than has been normal practice hitherto.

References/

References

No.	Author(s)	Title, etc.
1	P. G. Pugh and J. W. Peto	An analysis of the sources of error in typical pressure measurements in a blowdown supersonic wind tunnel. Third IEEE International Congress on Instrumentation in Aerospace Simulation Facilities - Farmingdale, New York, May 1969.
2	J. W. Peto and P. G. Pugh	The effects of the presence of static holes on the measurement of static pressures on models at supersonic speeds. NPL Aero Report 1292. A.R.C.31 023. March 1969.
3	W. J. Rainbird	Errors in measurement of mean static pressure of a moving fluid due to pressure holes. Quart. Bull., Division of Mechanical Engineering and the National Aeronautical Establishment (Canada). Report No. DME/NAE, 1967(3). September 1967.
4	M. J. Williams	Static pressure hole errors on four simple shapes in hypersonic flow. Australian Defence Scientific Services Aero Res. Labs, Note ARL/A299. May 1968.
5	D. F. Morrison, L. M. Sheppard and M. J. Williams	Hole size effect on hemisphere pressure distributions. J. Royal Aero. Soc. Vol. 71, No. 676. April 1967.
6	A. L. Baer	Pressure distributions on a hemisphere cylinder at supersonic and hypersonic Mach numbers. AEDC-TN-61-96. August 1961.
7	J. F. Nash, J. Osborne and A. G. J. Macdonald	A note on the prediction of aerofoil profile drag at subsonic speeds. NPL Aero Report 1196. A.R.C.28 075. June 1966.

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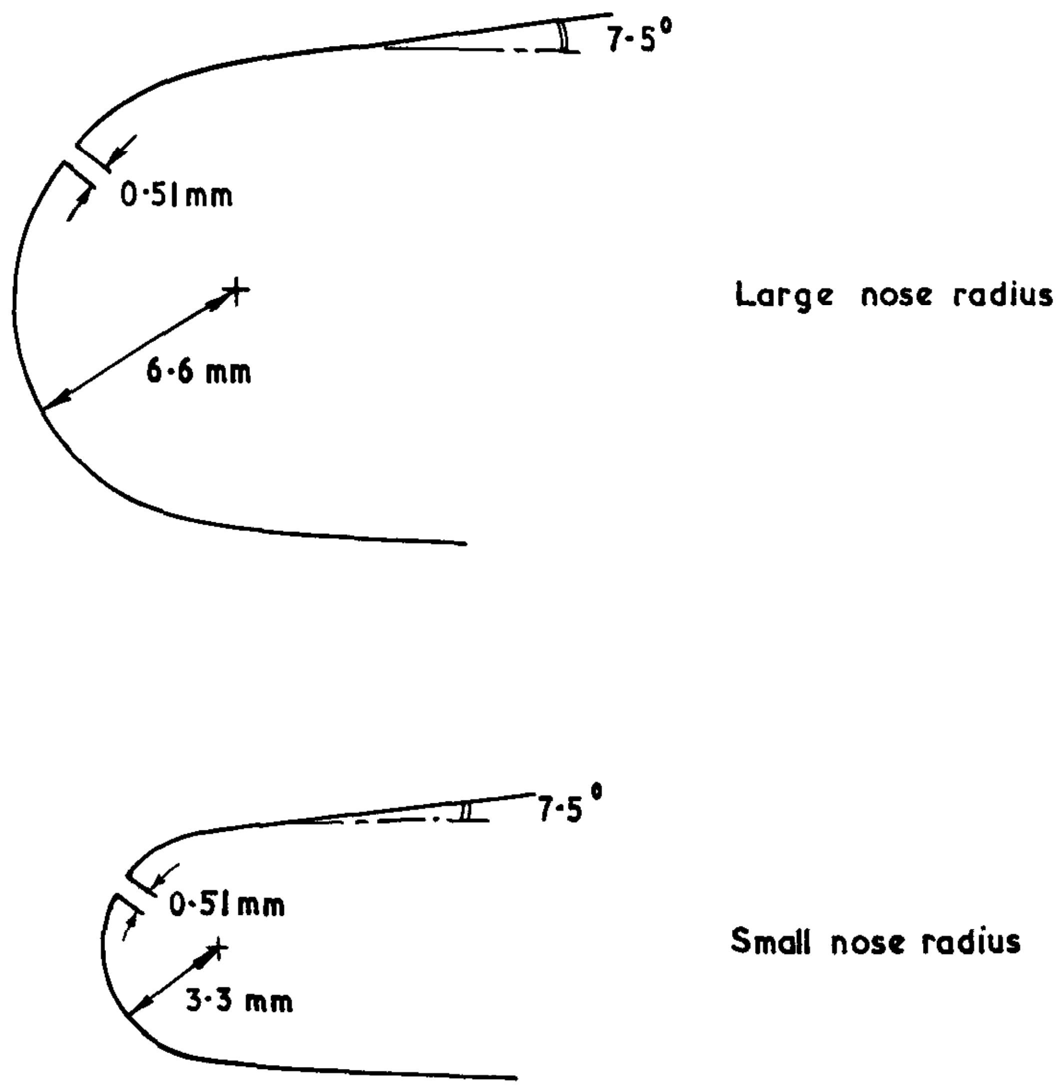
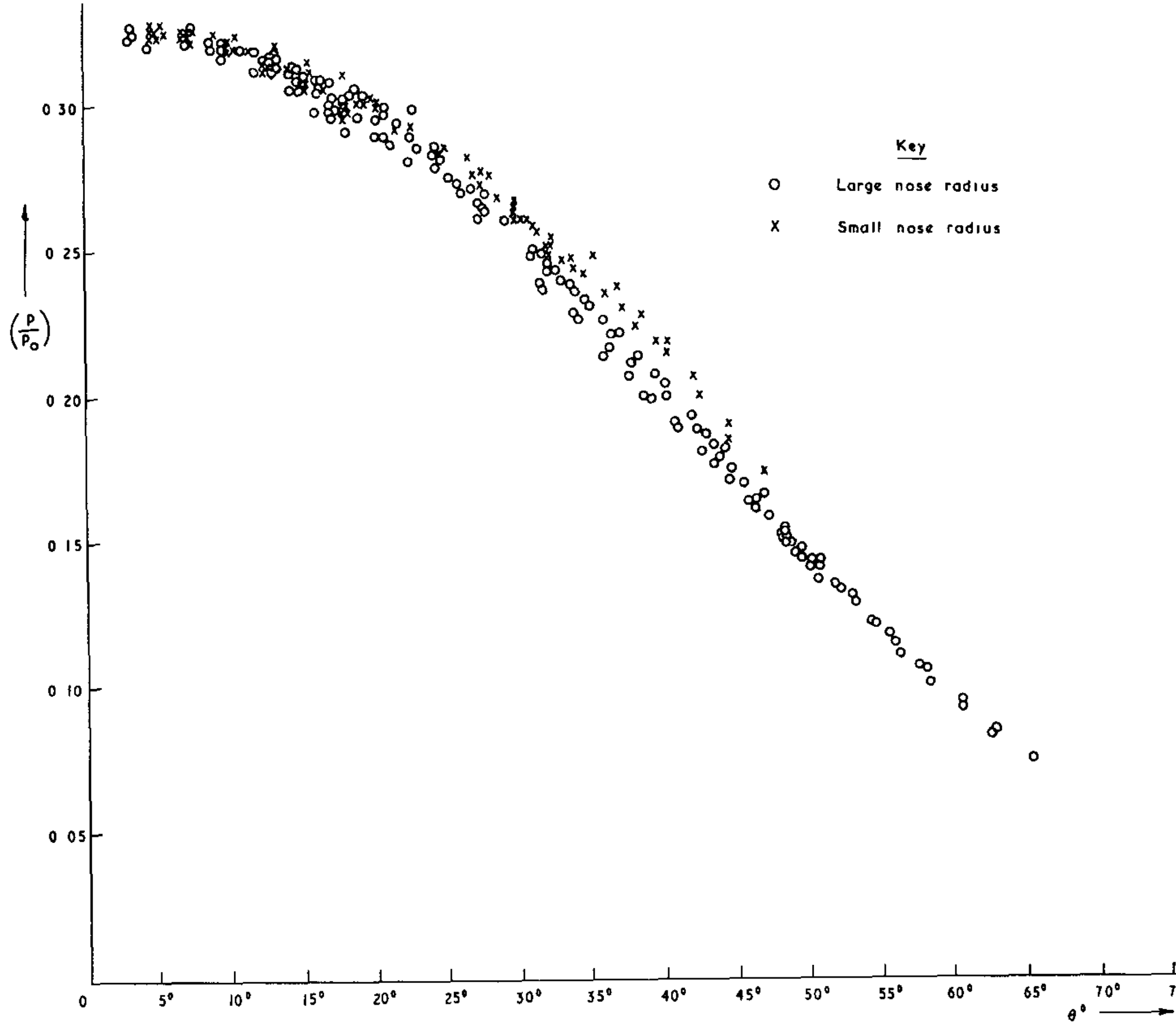
FIG. 1

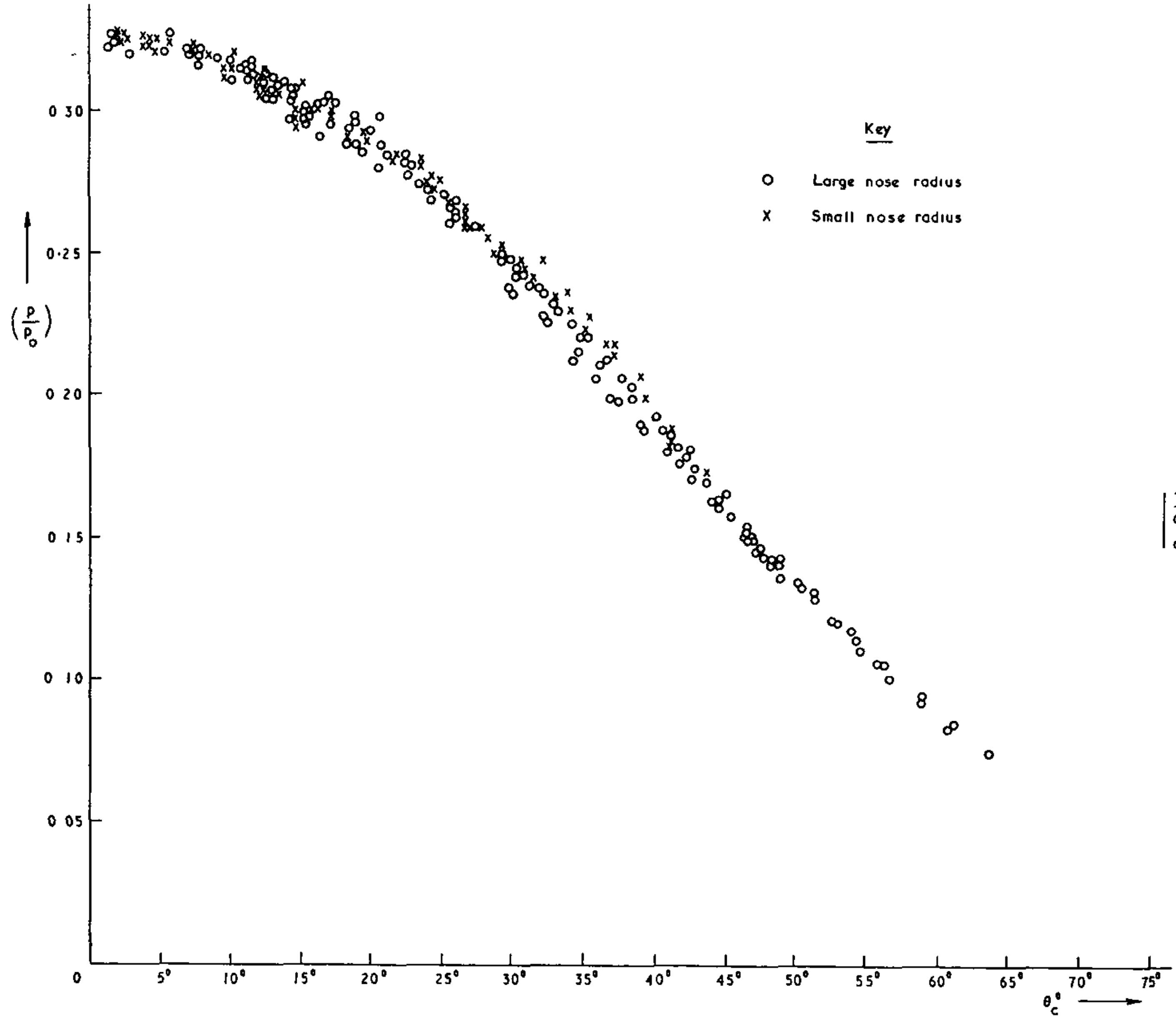


Model and hole dimensions



Raw data for $\theta < 65°$

FIG 2



Corrected data for $\theta < 65°$

FIG 3

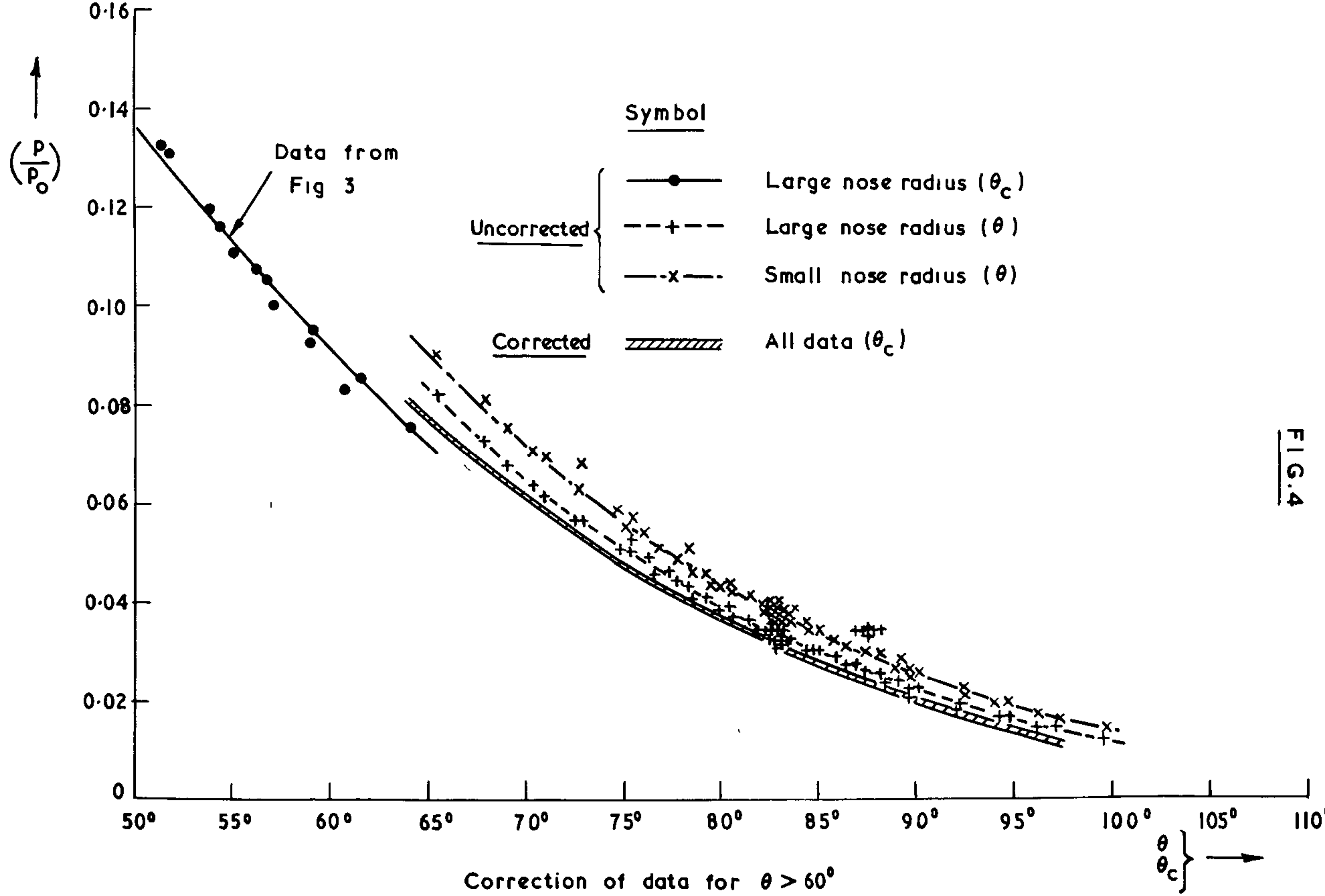
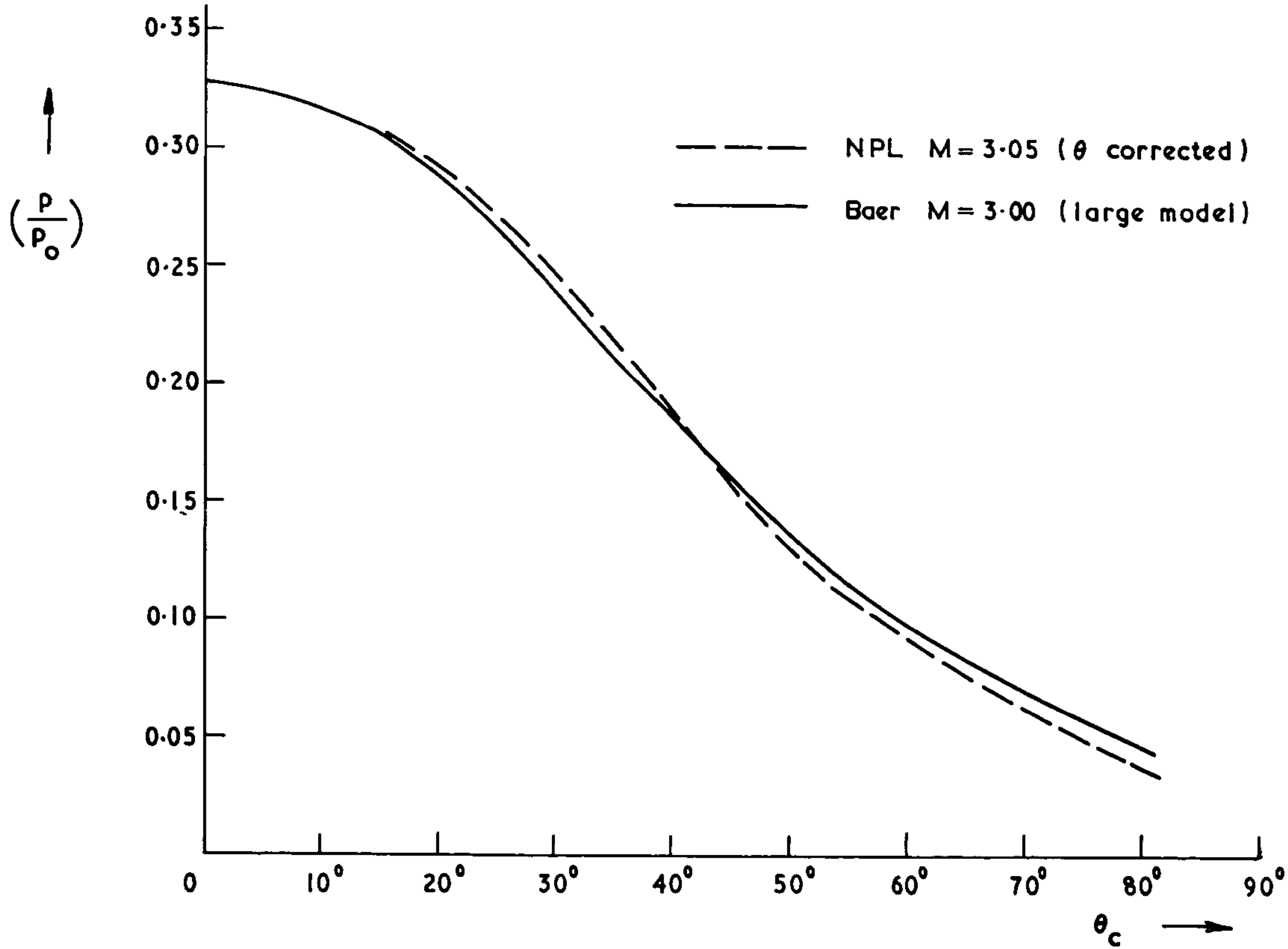


FIG.4

Correction of data for $\theta > 60°$



Comparison between corrected NPL data and measurements due to Baer

FIG. 5

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