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By

A. Stanbrook

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A CORRELATION OF THE FOREBODY DRAG OF CYLINDERS WITH PLANE AND HEMISPHERICAL NOSES AT MACH NUMBERS FROM ZERO TO 2.5

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SUMMARY

Drag-at-zero-lift obtained on some simple shapes during experimental studies of the aerodynamic characteristics of various airborne stores are compared with results from other sources.

Reasonable agreement is found between the measured drag, corrected for the effects of skin friction on the cylindrical surface, and integrated pressure distributions.

The measured variation of forebody drag is found to agree well with modified forms of the prediction of Maccoll and Codd in the case of plane-nosed cylinders and an expression derived by Hoerner in the case of hemispherically-nosed cylinders.

Replaces R.A.E. Tech. Note No. Aero. 2875 - A.R.C. 24,854.

LIST OF CONTENTS

LIST OF FIGURES

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1 INTRODUCTION

In the course of studies of the aerodynamic characteristics of various airborne stores a considerable amount of information has been obtained on the drag at zero incidence of cylindrical bodies with plane or spherical noses. It was thought to be of some general interest to collect these data together and to compare them with results from other sources.

In all cases the effective base pressure has been made equal to free stream static pressure.

2 PLANE NOSED CYLINDERS

The variation of drag with Mach number for cylinders with plane noses is shown in Figs.1 to 3. Experimental results quoted were obtained both by pressure plotting[1-3] and by force measurement[4-8]. Two available theoretical results[9,10] are also shown.

In the analysis of force measurements it will be useful to understand the different types of flow which occur at subsonic and supersonic speeds. Fig.4 shows flow pictures and pressure distributions along the cylindrical surface, obtained from a number of sources for $M = 0.9$ and 1.6. Although these data were obtained at various Reynolds numbers they are typical of the two basic types of flow.

At subsonic speeds the flow separating from the edge of the flat front face forms a large bubble round the cylindrical surface. At Mach numbers up to about 0.81 the velocity at the edge is subsonic[1] so that separation occurs tangentially (i.e. the separated boundary layer is initially tangential to the front face) with no change in velocity. At somewhat higher Mach numbers there is, theoretically, **sonic** velocity at the edge[18] with a Prandtl-Meyer expansion around the sharp corner, followed immediately by separation at some angle to the front face. In either case pressure recovery occurs gradually in a region of high turbulence resulting from breaking up of the separated boundary layer into eddies. As far as pressure recovery and mean streamlines[8] are concerned, the bubble may be said to close after a distance which increases[1] from about 2.6 body diameters at $M = 0.7$ to about 3.5 body diameters at $M = 0.95$. Nevertheless the velocity fluctuations are still very large, as may be expected from the appearance of the shadowgraph picture.

Further increase in Mach number leads eventually to a sudden change in flow pattern to one typical of supersonic speeds. The separated flow reattaches close to the nose, at a clearly defined line, forming a short bubble followed by a thin boundary layer. Pressure recovery occurs through a shock wave emanating from the reattachment line.

It is now possible to analyse the force measurements, which are plotted in collective form in Fig.1. At subsonic speeds the differences between results for cylinders of length 2.5 diameters[4], 4.8 diameters[5] and 10.94 diameters[6] (Fig.1) are attributable to differences in skin friction drag on the cylindrical surface. These differences have been used, along with an estimate of the length of the bubble from Ref.1, to determine the total contributions from skin friction. Fig.2 shows the drag corrected for skin friction. The resulting collapse of the data is striking.

In Fig.3 the curve through the corrected force data (from Fig.2) is compared with results from pressure plotting tests and from theory. The agreement between force and pressure plotting results is seen to be very good, apart from slight differences in the range of Mach numbers from 0.9 to 1.2, which may have arisen from transonic tunnel interference.

The theoretical result due to Maccoll and Codd[9] is in fair agreement with the experimental results. The later theoretical result by Evans and Harlow[10], is too high. It is considered that the discrepancy can be attributed to the coarseness of mesh used in calculations of ref.10.

The variation of drag coefficient with Mach number is very like that of the stagnation pressure coefficient (which is also plotted in Fig.3). It has been shown[1,18] that the flow first attains sonic velocity at the sharp edge of the front face at all free stream Mach numbers above about 0.81 . Hence the pressure at the edge is constant at 0.5283 of the stagnation pressure (which obviously occurs at the centre of the front face); and provided that the pressure distribution between these two points remains constant the drag coefficient will be determined. On this basis Maccoll and Codd[9] estimated the variation of drag with Mach number. The result may be expressed in the form

$$C_D = (0.9054\, H_2 - p_1) / q_1$$

where H_2 is stagnation pressure on face of cylinder

p_1 is free stream static pressure

q_1 is free stream kinetic pressure,

and the factor 0.9054 was determined from their theoretical result at $M = 1.5$. This curve is seen in Fig.3 to follow the trend of the experimental results at Mach numbers above about 1.2 (a coefficient of approximately 0.915 would have represented the data more exactly).

At low subsonic Mach numbers the velocities over the whole face including the edge vary with Mach number. Assuming local velocities to be proportional to the free stream velocity, the drag coefficient is expressible as a function of M^2. In fact the expression

$$C_D = 0.758 + 0.296\, M^2$$

gives a very good representation of the drag at Mach numbers up to 0.9, being indistinguishable from the mean experimental curve through the force data (Figs.2 & 3).

3 HEMISPHERICAL NOSED CYLINDERS

The variation of drag with Mach number for cylinders with hemispherical noses is shown in Fig.3. Experimental results quoted were obtained by pressure plotting[2,3,11-15], interferometry[16] and force measurement[4,6]. No theoretical data are available.

Agreement between results from the various sources is again good, the small differences being attributed to differences in skin friction. The full line represents an estimate of drag of the hemispherical head, obtained from the experimental data after correction for the effects of skin friction.

At the upper end of the Mach number range considered here the experimental data are in reasonable agreement with Hoerner's empirical formula[17] for hypersonic speeds,

$$C_D = \left(\frac{H_2 - p_1}{q_1}\right)\left(0.51 - \frac{0.12}{M^2}\right)$$

However, at lower supersonic Mach numbers this formula gives values which are a little high and a further term is necessary. The empirical formula

$$C_D = \left(\frac{H_2 - p_1}{q_1}\right)\left(0.51 - \frac{0.12}{M^2} - \frac{0.0824}{M^4}\right)$$

is found to be in good agreement with the corrected experimental data at all Mach numbers greater than 1.3.

4 CONCLUSIONS

The variations with Mach number of forebody drag at zero incidence for cylinders with plane and hemispherical noses have been analysed.

Measured drag corrected for the effects of skin friction on the cylindrical surface, agrees in general with the drag obtained by integrating pressure distributions.

The variations of forebody drag are found to agree well with modified forms of the prediction of Maccoll and Codd[9] for plane noses and of the expression due to Hoerner[17] for hemispherical noses. Thus for plane-nosed cylinders

$$C_D = 0.758 + 0.296\,M^2 \qquad \text{for } 0 \leq M \leq 0.9$$

$$C_D = (0.915\,H_2 - p_1)\,/\,q_1 \qquad \text{for } M > 1.2$$

and for hemispherical nosed cylinders

$$C_D = \left(\frac{H_2 - p_1}{q_1}\right)\left(0.51 - \frac{0.12}{M^2} - \frac{0.0824}{M^4}\right) \qquad \text{for } M > 1.3$$

LIST OF SYMBOLS

C_D	Drag coefficient, based on frontal area
H_2	Stagnation pressure on front face of cylinder
M	Mach number
p_1	Free stream static pressure
q_1	Free stream kinetic pressure
R_d	Reynolds number, based on diameter

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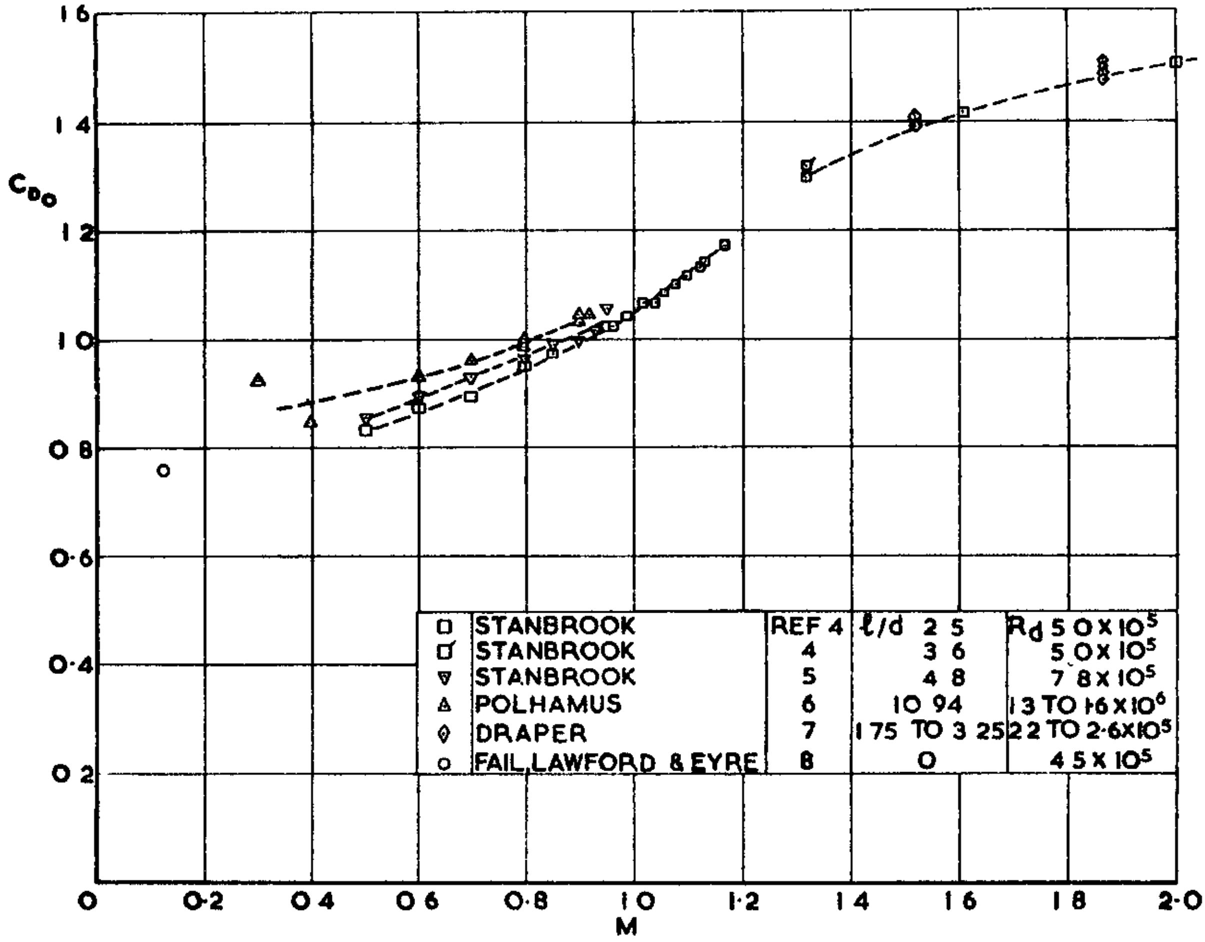

FIG. 1. DRAG OF PLANE NOSED CYLINDERS (OBTAINED FROM FORCE MEASUREMENTS).

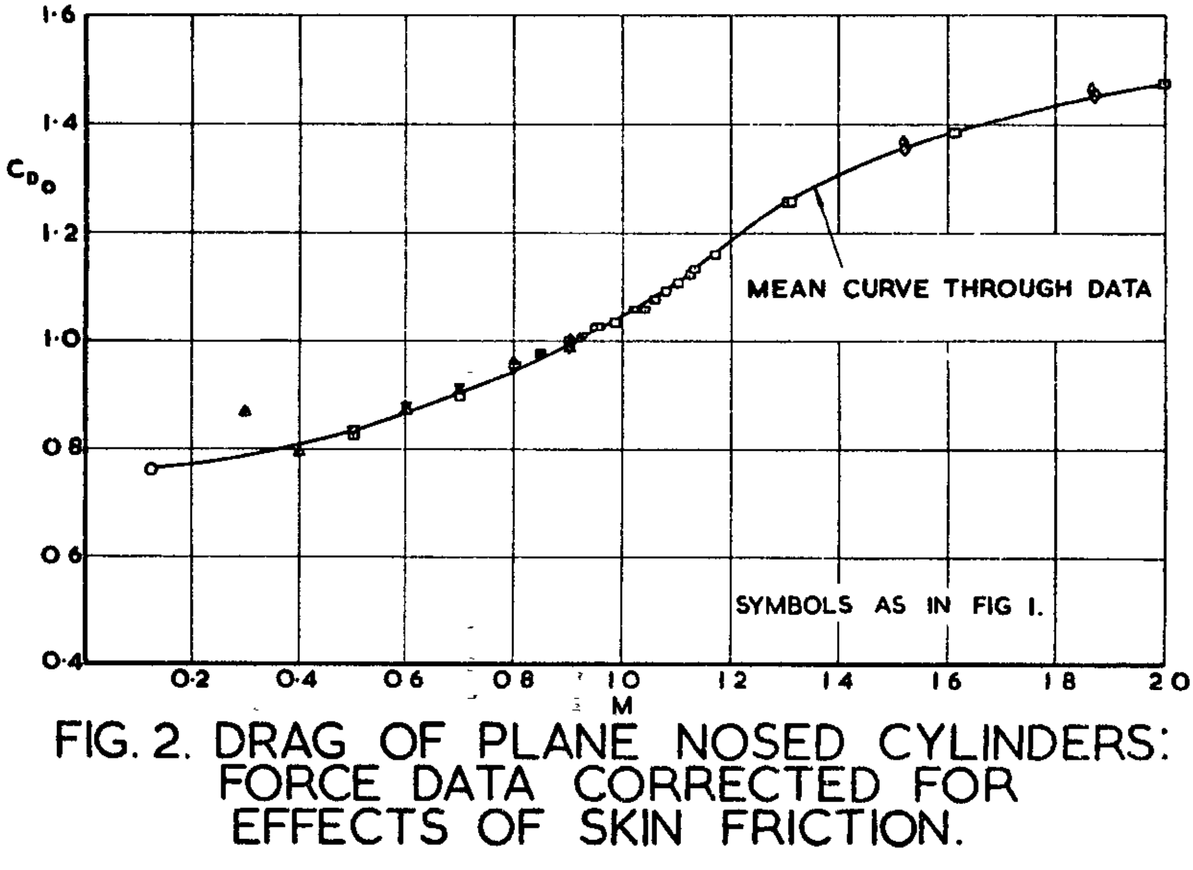

FIG. 2. DRAG OF PLANE NOSED CYLINDERS: FORCE DATA CORRECTED FOR EFFECTS OF SKIN FRICTION.

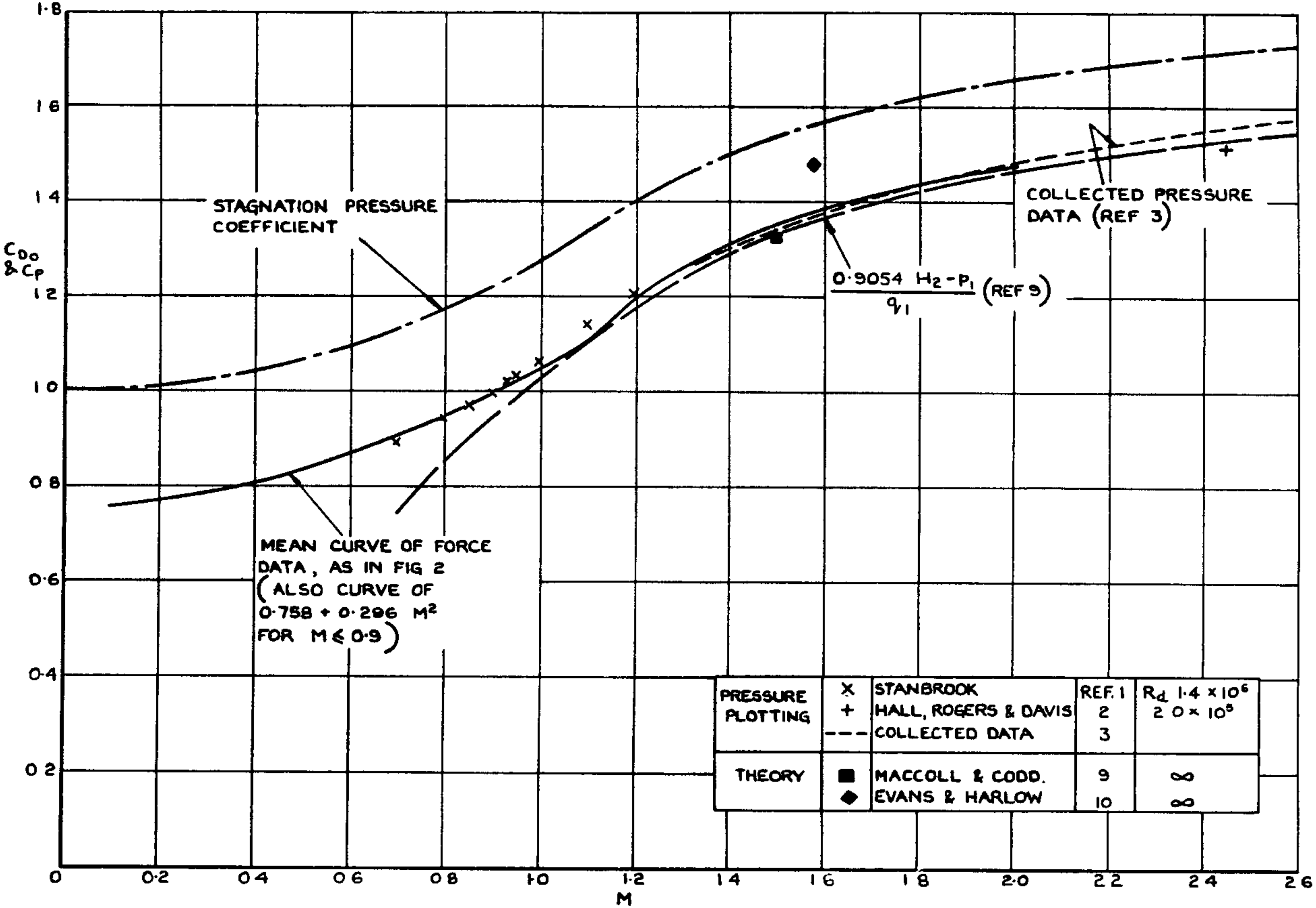

FIG. 3. DRAG OF PLANE NOSED CYLINDERS – COMPARISON OF FORCE DATA (FIG. 2) WITH PRESSURE-PLOTTING DATA FROM VARIOUS SOURCES.

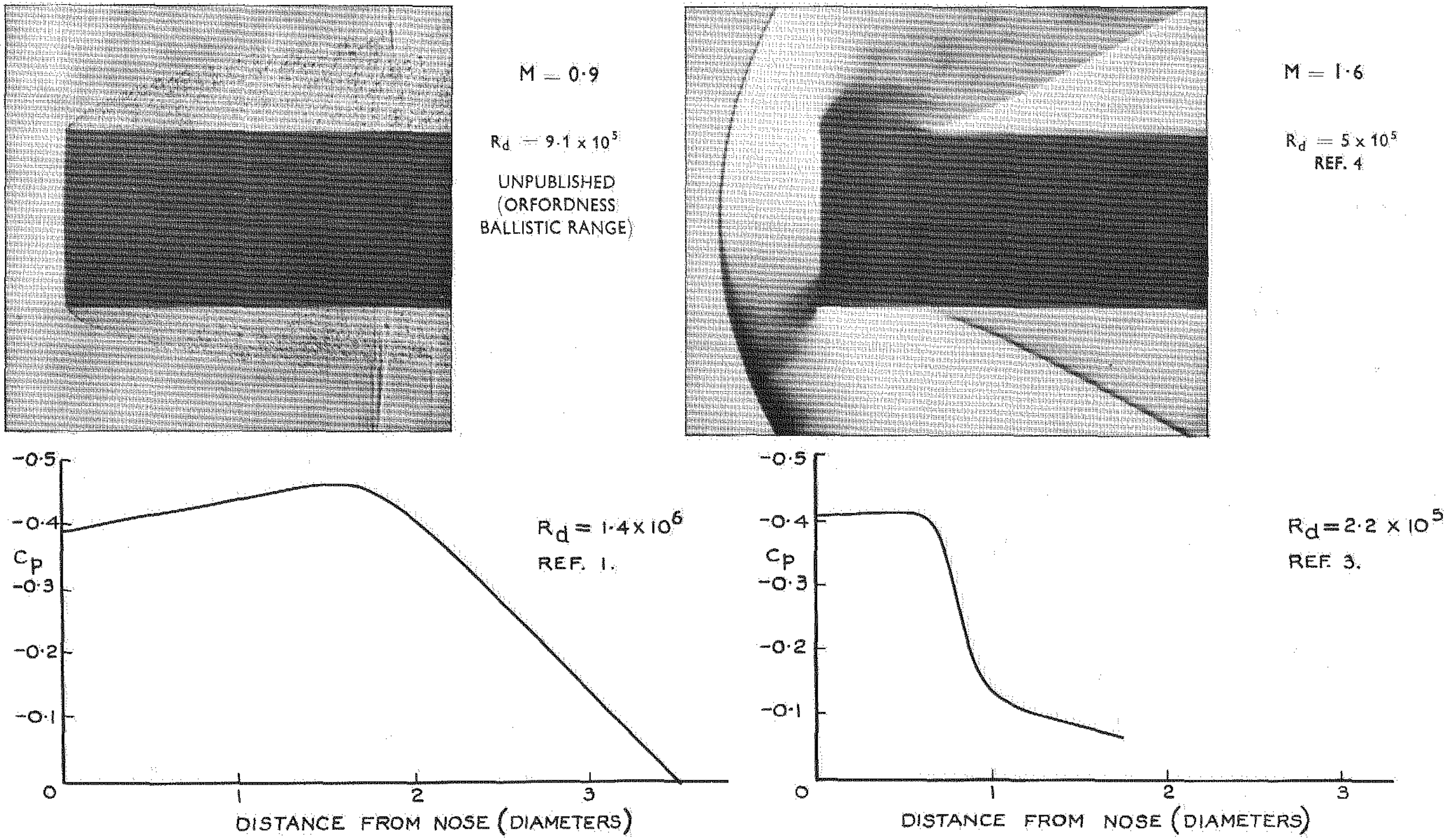

FIG.4. TYPICAL FLOW PATTERNS AND PRESSURE DISTRIBUTIONS ON PLANE NOSED CYLINDERS

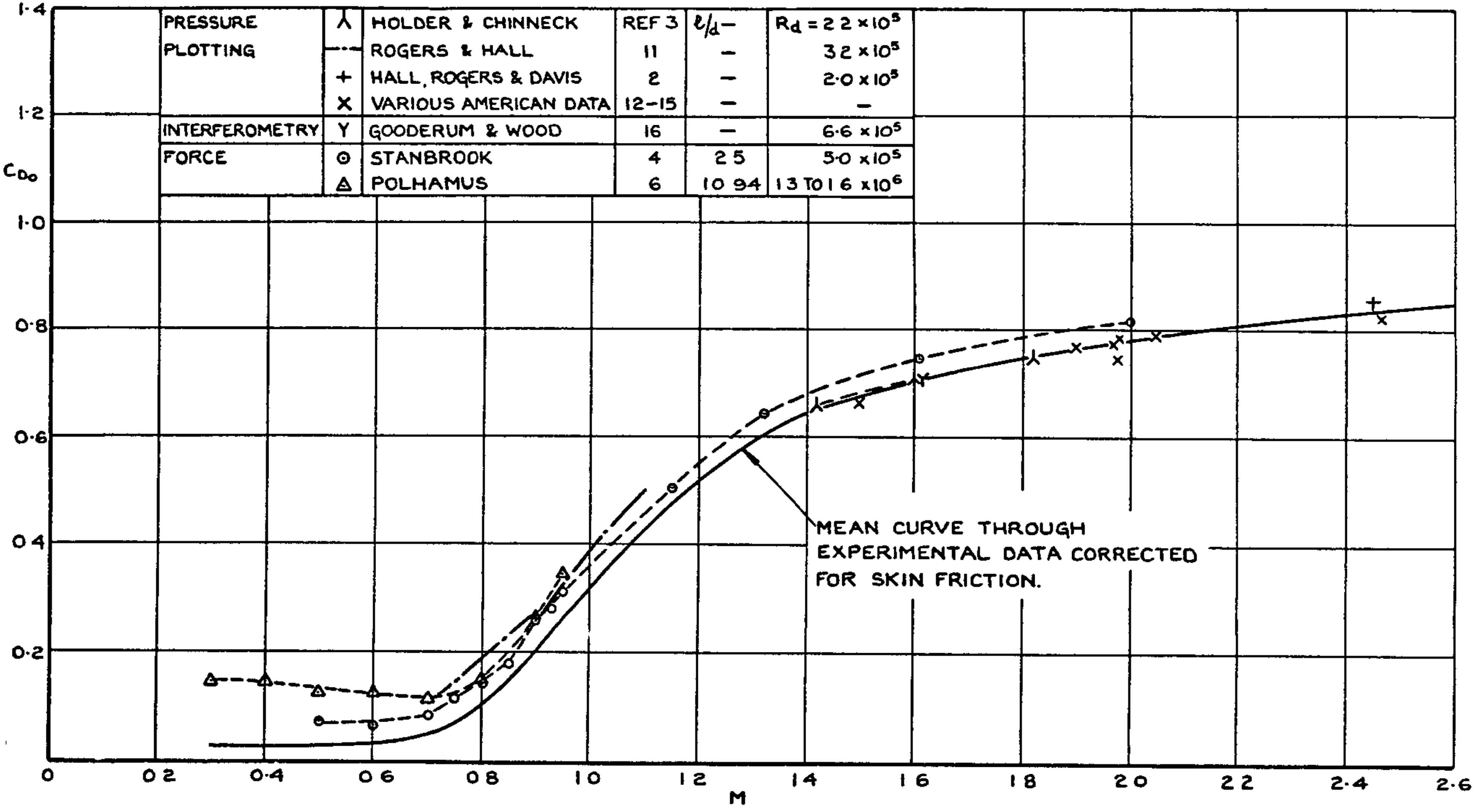

FIG. 5. VARIATION OF DRAG WITH MACH NUMBER FOR HEMISPHERICAL NOSED CYLINDERS.

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