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Council for National Academic Awards

"The Effect of High Speed Rotation on The Performance of Hydrostatic Thrust Bearings"

A thesis submitted for the degree of

MASTER OF PHILOSOPHY

BY

F.B. KLEMZ, C.Eng., M.I.Mech.E.

Department of Mechanical and Production Engineering
Sheffield Polytechnic

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SYNOPSIS

Hydrostatic bearings have been the subject of many theoretical and experimental investigations. Some investigations have confirmed that increasing the speed of rotation of a hydrostatic thrust bearing reduces the load carrying capacity. Previous theoretical predictions of the pressure distribution, during rotation, have not taken into account the radial inertia effects, with the result that the predicted values of pressure near the vicinity of the air inlet, have been much higher than those measured under test.

In this investigation radial and rotational inertia effects have been considered theoretically and experimentally for both 'parallel' and 'stepped' bearings using air as the lubricant. The relevance of compressibility has also been assessed.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr G R Symmons, Director of Studies, for suggesting this research project and for his very helpful supervision.

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The assistance given by Mr R Teasdale and Mr D McKay in the manufacture and construction of the experimental test rig was a valued contribution.

Thanks are also due to Miss J I Senior for typing this thesis so ably.

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FIG

SYMBOLS

Symbols which only arise once, are defined in the text, and are not listed.

D	disc diameter $(D = 2r_2)$
F	total load capacity
Q	volume flow rate
R	dimensionless radius $(\frac{r}{h})$
T	lubricant temperature
U X W	representative velocities
RD1	r_1/r_2
RD3	r_3/r_2
K_1	inertia parameter $\frac{27\rho Q^2}{560\pi^2 h^2 \bar{p} r_2{}^2}$
K_2	inertia parameter $\frac{3\rho\Omega^2 r_2{}^2}{20\bar{p}}$
R_e	Reynolds number $\frac{\rho Q}{\pi\mu h}$
R_n	Reynolds number $\left[\frac{\rho}{\mu}\left(\frac{4h}{D}\right) 2hU\right]$ see page (46)
V_r V_z V_θ	velocity components in the r, z, θ directions
V_r' V_z' V_θ'	velocity ratios $(\frac{V_r}{U}, \frac{V_\theta}{X}, \frac{V_z}{W})$
$\bar{R}$	gas constant
p	pressure
$2h$	gap between parallel discs
r, θ, z	cylindrical co-ordinates
r_1	reference radii
r_2	outside radius of bearing
r_3	radius of step
r'	radius ratio $(\frac{2r}{D})$
$\bar{p}$	mean pressure across the air gap between discs

$\bar{p}_1$	mean pressure at reference radius r_1
$\bar{p}_2$	mean pressure at radius r_2
$\dot{m}$	mass flow rate
α	film thickness ratio $\left(\frac{\text{film thickness in recess}}{\text{minimum film thickness}}\right)$
Ω	rotational speed
μ	co-efficient of dynamic viscosity
ρ	density

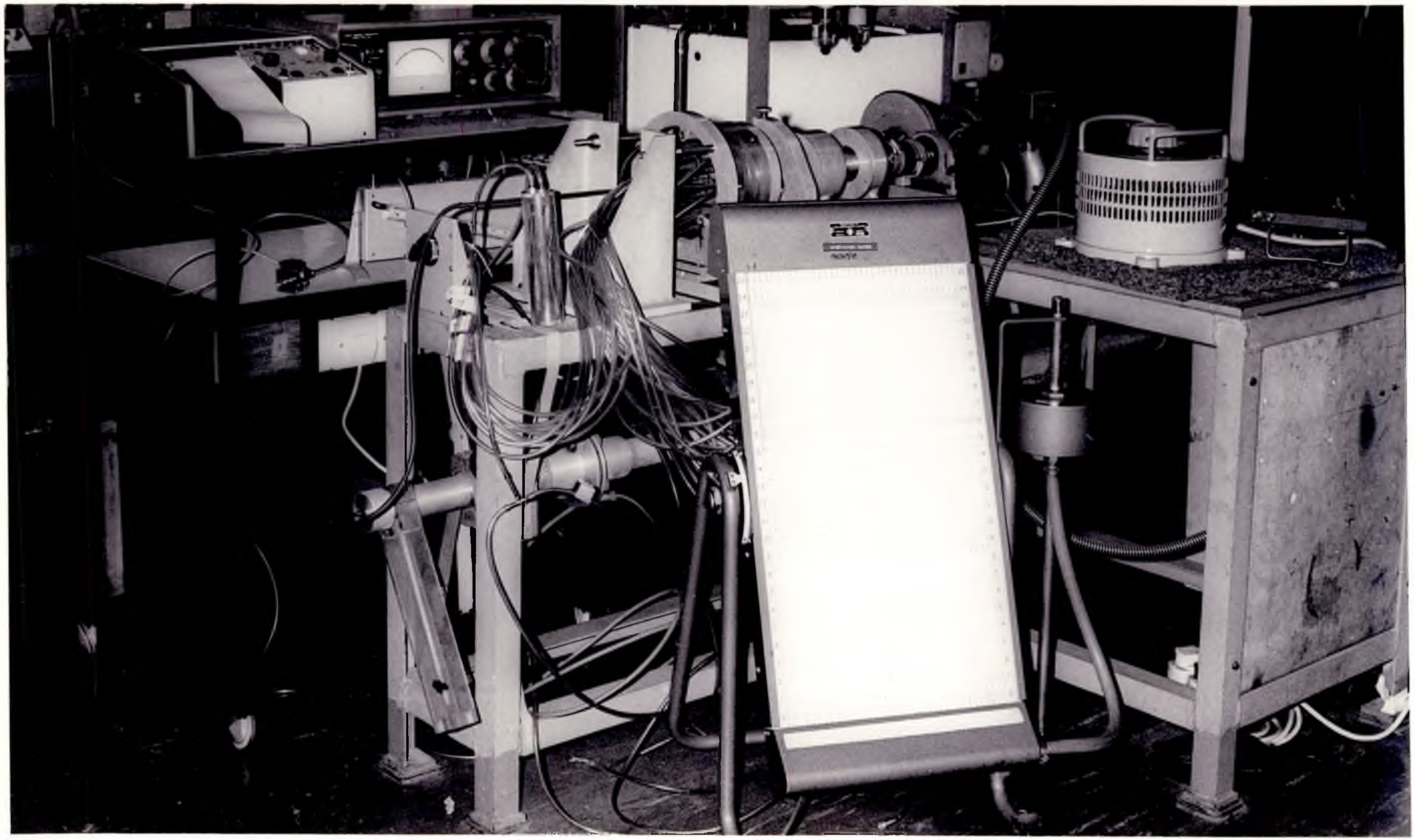


FIG.1. ARRANGEMENT OF TEST APPARATUS.

CHAPTER 1

GENERAL NOTES ON GAS BEARINGS

1.01 Gas bearings have been in existence for many years and their use is increasing due to the many advantages they have to offer. They can be operated at very high and very low temperatures. At the upper end of the scale the expectation is that some devices may be called upon to function at 1100-1700^{o}C, while at the lower end of the scale this could mean -260^{o}C. Gas is the only known lubricant that could possibly be used for such extremes of temperature, and even with this form of lubrication care should be taken over possible condensation at low temperatures.

Extremely high rotational speeds are possible because there is no serious problem in keeping the bearing cool. Ultrafuges using hydrostatic step bearings have been operated at speeds in excess of 1700 rev/sec. In 1962 there evolved the air turbine dentral drill operating at 8500 rev/sec. Drilling spindles operating at 1700 rev/sec are used in the precision drilling of electronic printed circuit boards. A small high-speed expansion turbine for liquefying helium, developed by the British Oxygen Co. Ltd. (19), operates at 6000 rev/sec. The bearings in this unit are lubricated by helium gas at a temperature between -260^{o}C and -223^{o}C.

Gas has an inherent low viscosity, resulting in small frictional forces giving a low power loss. Large structures have been floated successfully on hydrostatic-type bearings. The Hale

200 inch telescope on Mount Palomer has a mass of 453Gg, yet the coefficient of friction for the entire supporting system is claimed to be less than 0.000004. Hydrostatic bearings are currently being applied to large radio telescopes and radar antennae.

There are two fundamental types of air bearing, the hydrodynamic bearing and the hydrostatic bearing. The hydrodynamic bearing relies on the lubricant being continuously forced through a converging gap, or in the case of thrust bearings, a series of converging gaps, in order to generate a force of sufficient magnitude to overcome the applied load. With this type of bearing the viscosity of the lubricant is of paramount importance in determining the load capacity. The viscosity of air is about 4000 times less than an S.A.E. 10 oil, therefore there are few applications for air bearings of this type.

Hydrostatic air bearings rely on an external supply of high pressure air for their operation. The continuous air flow prevents metal to metal contact within the bearing, when the bearing is at rest, and when it is rotating at low speed; thus eliminating wear which is a troublesome feature of all hydrodynamic bearings. This thesis is concerned only with hydrostatic thrust bearings.

In practice, a loaded thrust bearing takes up a position such that the thrust due to the distributed pressure across the active faces of the bearing just balances the applied load. The gap between the two bearing surfaces changes to accommodate changes in the applied load, with an increase in load producing a decrease in the bearing gap. If, for a given mass flow rate of air, the applied load is too great, the two halves of the bearing will touch and failure due to seizure could result. If the flow rate is excessive the bearing will operate satisfactorily but power will be wasted in pumping more air through the bearing than is actually required. It is also known that increasing the speed of rotation of a loaded thrust bearing causes the bearing 'gap' to reduce.

A designer will need to know how the following parameters are related in determining the load carrying capacity of a hydrostatic thrust bearing; mass flow rate, air viscosity, air density, gap size, speed of rotation, bearing size and pressure distribution. The object of this project was to establish how the above parameters are related, confirming the derived theory by means of a thrust bearing of fixed overall dimensions. Theoretically the following sections have been considered:

(i) The formation of an expression for pressure distribution, which embraces radial and rotational terms, for both 'parallel' and 'stepped' bearings, for incompressible flow.

(ii) Expressions for the radial flow velocity, and the axial flow velocity, were derived and used to show graphically the influence of rotation on the axial and radial velocity profiles.

(iii) Compressibility was taken into account and its influence on the theoretical pressure distribution for a thrust bearing was considered.

Theoretical and experimental results have been compared graphically, and computer programs have been used to convert the results to non-dimensional form.

REVIEW OF PREVIOUS LITERATURE

1.02 Radial inertia effects only, in stationary boundaries. Brand (1) investigated theoretically the relative importance of the viscous term compared with the radial inertia term in the Navier-Stokes equation and demonstrated by order of magnitude arguments that inertia forces are not negligible, when a suitably defined Reynolds number was sufficiently large.

The problem of radial flow between two parallel stationary surfaces has been dealt with by Livesey (2). He suggested that inertia effects may be significant at low fluid velocities and that this could bring about a change in the sign of the radial pressure gradient. (This type of condition being most likely to occur in the vicinity of the air inlet, when there was a large bearing gap width.) Livesey derived an expression that predicted the pressure distribution in terms of the volume flow rate, fluid density, gap width and reference radii. The expression contained a term due to the inertia effects, in addition to the well established viscous term.

Morgan and Saunders (3), using compressed air, confirmed experimentally that the viscous term alone could not predict the pressure change between two radial points in the path of the air flow. The inclusion of Livesey's inertia term only partly corrected the error existing when the viscous term alone was used.

Jackson and Symmons (4) extended the power series analysis of Hunt and Torbe (5) to include an inertia term. The solution derived by Jackson and Symmons showed the inertia effect to be 23 per cent greater than the inertia effect predicted by Livesey.

Moller (6) considered the analysis of radial flow without swirl, between parallel discs using air at incompressible speeds. Approximate solutions were obtained for turbulent and laminar pressure distributions, using an integral momentum method. He was able to confirm these results experimentally. Moller showed that it was possible for the flow to be turbulent throughout the channel, provided that the channel exit Reynolds number was large enough. In order to achieve turbulence, high flow rates were necessary, and this was facilitated by using a large inlet jet diameter.

Jackson and Symmons (7), in 1964, investigated experimentally the principal theories predicting the pressure distribution for laminar flow between parallel plates. The apparatus they used was designed with an air inlet jet diameter much smaller than that used by Moller; this resulted in a relatively low flow rate, which ensured that the flow was non-turbulent at all radii, except, possibly, a small area immediately adjacent to the air inlet. They found that the various theoretical analyses gave widely differing results. All the theoretical results predicted higher values than those shown by experimental results, for all radii, except for a small area in the vicinity of the air inlet. Jackson and Symmons proposed that further investigation was needed before a closer correlation between theoretical and experimental results could be expected, particularly for bearings where the central inlet jet was small in diameter.

The relative importance of the basic terms in the Navier Stokes equation, including the compressibility term, has been considered by Hobson and Lawrie (8). As well as a theoretical analysis, their work included an experimental investigation of the radial flow of air between stationary parallel circular plates. First they considered the problem of incompressible flow. Starting with the Navier Stokes equation, and using a transverse velocity profile in parabolic form, they obtained an expression which included pressure, inertia and viscous terms. Their expression was the same as that obtained by Livesey. By considering the inertia and viscous terms only, they were able to obtain an estimate of their significance by determining a parameter K_i, inertia term/viscous term.

Next, using the Characteristic equation for a perfect gas, the transverse velocity profile, V_r, was written in a form applicable to compressible flow. The first and second partial derivatives $(\frac{\partial V_r}{\partial r})$ and $(\frac{\partial^2 V_r}{\partial r^2})$ were evaluated and substituted in the Navier Stokes equation, which included the compressibility term. The partial derivatives $(\frac{\partial p}{\partial r})$ and $(\frac{\partial^2 p}{\partial r^2})$ were determined graphically from the experimental pressure distribution. Parameters, K_c, inertia term/viscous term and β, compressibility term/viscous term, were evaluated and the results for various flow rates, and flow gap thicknesses analysed. Hobson and Lawrie found that for their particular series of tests, ~~that~~ the significance of the viscous and radial inertia terms, based on compressible and incompressible theory, given by K_c and K_i respectively, differed by less than one per cent. Their investigation did not allow for bearing rotation.

1.03 ROTATIONAL INERTIA EFFECTS IN ROTATING BOUNDARIES

Osterle and Hughes (9) considered theoretically the effect of lubricant inertia in hydrostatic thrust bearings, with a single central recess, at normal operating speeds, using both compressible and incompressible lubricants. In the case of incompressible lubricants, the inclusion of a rotational inertia term reduced the error in load capacity that would be experienced if the viscous term alone was used. They calculated that the same effect would occur with compressible lubricants where the recess pressure was low, but that this effect would decrease as the recess pressure increased.

Dowson (10) produced an analysis which included an inertia term associated with the effect of rotation on the pressure distribution in a hydrostatic thrust bearing with a single central inlet. This theory included a solution for a similar bearing with a central recess. (Dowson's rotational inertia term was the same as that derived by Osterle and Hughes.) From the formation of the continuity term he concluded that for a 'static' parallel surface bearing the flow is entirely radial, but with rotation there is an axial component present which causes the 'fluid' to move towards the moving surface as it spirals between the bearing surfaces. Theoretically, it was found that rotation reduces the load carrying capacity of a hydrostatic thrust bearing. Dowson's analysis did not include an inertia term due to radial effects.

Experimental work by Coombs and Dowson (11), using oil as the lubricating ~~media~~ medium, confirmed the general theory of Dowson's earlier work. The best correlation between experimental and theoretical results were obtained when thermal effects were small.

H.N. Shirman (12), using the basic theory proposed by Dowson, obtained an expression for the dimensionless pressure distribution for a hydrostatic thrust bearing with a single central inlet. Using air as the lubricating medium, he showed experimentally the detrimental effect of rotation on the load carrying capacity of a hydrostatic bearing. He did not obtain a good correlation between experimental and theoretical results, which must have been due partly to the absence of a radial inertia term in the basic theory, which would have modified considerably the predicted dimensionless pressure in the vicinity of the central inlet.

Ting and Mayer (13) considered the effects of the lubricant rotational inertia and the temperature on the performance of parallel stepped hydrostatic thrust bearings. They obtained expressions for pressure and temperature distributions and load carrying capacities appertaining to adiabatic flow conditions. They obtained satisfactory correlation between the experimental results obtained by Coombs and Dowson and their own theoretical results, especially when the speed of rotation was high. In common with Dowson's work, their theoretical analysis did not include a radial inertia term, therefore for isothermal conditions they obtained the same differential equation for the pressure distribution. By introducing an exponential viscosity-temperature relation, and assuming that the bearing surfaces were perfect insulators, adiabatic solutions were obtained. Ting and Mayer made the important observation that the adiabatic analysis should not be applied to bearings with extremely small film thicknesses because, under these conditions, the assumption that the lubricant will carry away most of the heat generated is not true.

CHAPTER 2 APPARATUS

2.01 DESIGN REQUIREMENTS OF TEST EQUIPMENT

There were no parts previously manufactured that could be used for the test rig, so the design was not limited, or assisted, by existing components.

It was decided to base the design on the following:

(a) No attempt would be made to measure directly the axial thrust created by the air flow through the thrust bearing; instead the gap width would be adjusted to a predetermined size, and the resulting pressure distribution, measured by a multi-tube manometer, used as a measure of the axial thrust.

(b) The air flow, suitably filtered, would be supplied from the compressed air mains. The amount of air used would compare with that used in an actual air bearing, i.e. the air consumption would be as small as possible so that the power required to supply the air was the minimum. With air consumption in mind, it was decided to use a small inlet jet diameter, similar to that used by Jackson and Symmons (7).

(c) Particular attention was to be paid to the method of supporting and adjusting the relative positions of the discs. The following were considered crucial:

i. rigid construction

ii. easy access to discs

iii. disc alignment to be simple but positive

iv. vibration transfer to be avoided

v. axial float, deflection and wobble to be reduced to a minimum.

vi. no axial thrust to be transmitted to the dynamic disc by the drive shaft.

vii. moving parts to be covered by guards which can easily be removed, to facilitate adjustment of discs.

2.02 DESCRIPTION OF THE TEST EQUIPMENT

Plates of the air bearing are shown in FIGS 1, 2 & 3. The static disc was designed to move axially so that the air gap size could be changed. In addition to axial movement the static disc could be tilted for a few degrees, at any angular position, so that it could be accurately aligned with the dynamic disc. The dynamic disc had the same degree of movement as the static disc, but it was intended that once the dynamic disc was correctly positioned (see 2.04), any adjustment to the air gap size would be made by moving the static disc only.

The drive shaft was supported by a roller bearing and angular contact bearings. Axial movement of the bearing drive shaft was prevented by pre-loading it axially by means of a compression spring acting against a single row ball thrust bearing. The weight of the drive shaft and the dynamic disc was supported by means of a lathe-type steady. The drive shaft was driven by means of a d.c. motor, 2 h.p. A bearing speed of 4000 rev/min was obtained via a vee belt drive. A flexible coupling, designed to transmit axial torque only, was used to connect the drive from the motor to the bearing drive shaft. The speed of the bearing drive shaft was measured using a tachogenerator (SERVOTECH PRODUCTS TYPE SA 740A/7) connected to a digital voltmeter. To adjust the speed of rotation a Variac was used. The motor drive and the hydrostatic bearing assembly were each mounted on a separate stand, constructed from 2in x 2in x ¼in angle iron.

To measure the mass flow rate of the air passing through the bearing, an orifice plate was used. The orifice plate was designed to B.S.1042 Part 1, using D and $\frac{D}{2}$ pressure tappings. Static pressure readings were taken on a multitube water-filled manometer. The pressure upstream of the orifice place was measured with a mercury filled manometer. Clean, moisture free, air was obtained by a PURAIRE FILTER, NORGREN F41-321-AOTB. The mass flow rate of air was controlled by a pressure regulator NORGREN 11-918-100.

A NORGREN 10-way selection switch was used in conjunction with a pressure transducer (S.E. LABS (Eng.) Ltd. Series No.911 25in W.G.) to enable pressure measurements to be made on a U.V. recorder. The arrangement of instrumentation is shown in Fig.14.

2.03 MANUFACTURE OF THE TEST EQUIPMENT

Two discs each 190mm diameter, 30mm thick, made from free cutting stainless steel, were used to form the hydrostatic thrust bearing. A central jet 4.0 mm diameter was machined in the static disc and an array of static pressure tappings, each 0.64 mm diameter, were drilled at 1cm, 2cm, 3cm, 4cm, 5cm, 6cm, 7cm and 8cm radius, so that four tappings were available for each radius as shown in FIG.5. The discs were ground and lapped to a surface finish of less than four micro-inches, and were each tested for flatness using a grade one straight edge. A WADKIN, numerically controlled point-to-point drilling machine, incorporating an AIRMEC autoset controller, using a punch tape, was used when machining the static pressure holes in the static disc.

Modifications to the test rig

Before 'repeatable' results could be obtained from the test rig two modifications were necessary to the original design. A stiffening plate was placed under the bearing housing, and additional supports were provided to strengthen the bracket which supports the static disc. These two modifications provided a more rigid structure, enabling a more accurate air gap width to be maintained.

2.04 TEST PROCEDURE

Before each series of tests it was necessary to adjust the dynamic disc to ensure that it would rotate without wobble i.e. rotate so that the active face of the disc was, for all angular positions, perpendicular to the axis of rotation. Adjustment of the dynamic disc was effected as follows:

(a) The air gap was adjusted to approximately 0.001m, using a feeler guage, and air was allowed to flow, at a low flow rate, through the hydrostatic bearing via the central inlet.

(b) One of the outer static pressure tapping points was connected to a 'sensitive' manometer (FIG.11) and the air flow rate adjusted, so that a mid-scale reading was obtained on the manometer.

(c) The dynamic disc was then slowly rotated, by hand, and any error in the initial setting of the disc was shown by a change in the manometer reading.

(d) An adjustment to the dynamic disc (FIG.12) was followed by reducing the size of the air gap to 0.0005m and testing as before.

The thickness of the air gap was adjusted by the aid of three studs set in the static disc (FIG.6). These studs were adjusted until the required parallel gap was obtained. It was originally intended to use slip-blocks, measuring the distance between anvils set in the static and dynamic discs, to determine the size of the air gap, but later it was found that the use of a feeler guage applied direct to the air gap enabled a more 'parallel' gap to be obtained. The thickness of each feeler guage was tested using a Taylor Hobson Talymin Gauge as a comparator. The size of each gauge was compared with an Inspection grade slip block pile, and the error found to lie within the range ±1%.

Initially a stroboflash was used to calibrate the voltage output from the tachogenerator, but later greater accuracy was obtained by checking the voltage output of the tachogenerator with the aid of a synchronous motor. The voltage output was found to be 2.6v per 1000 rev/min - as stated in the manufacturers specification. This value was used when drawing the calibration curve shown in FIG.15.

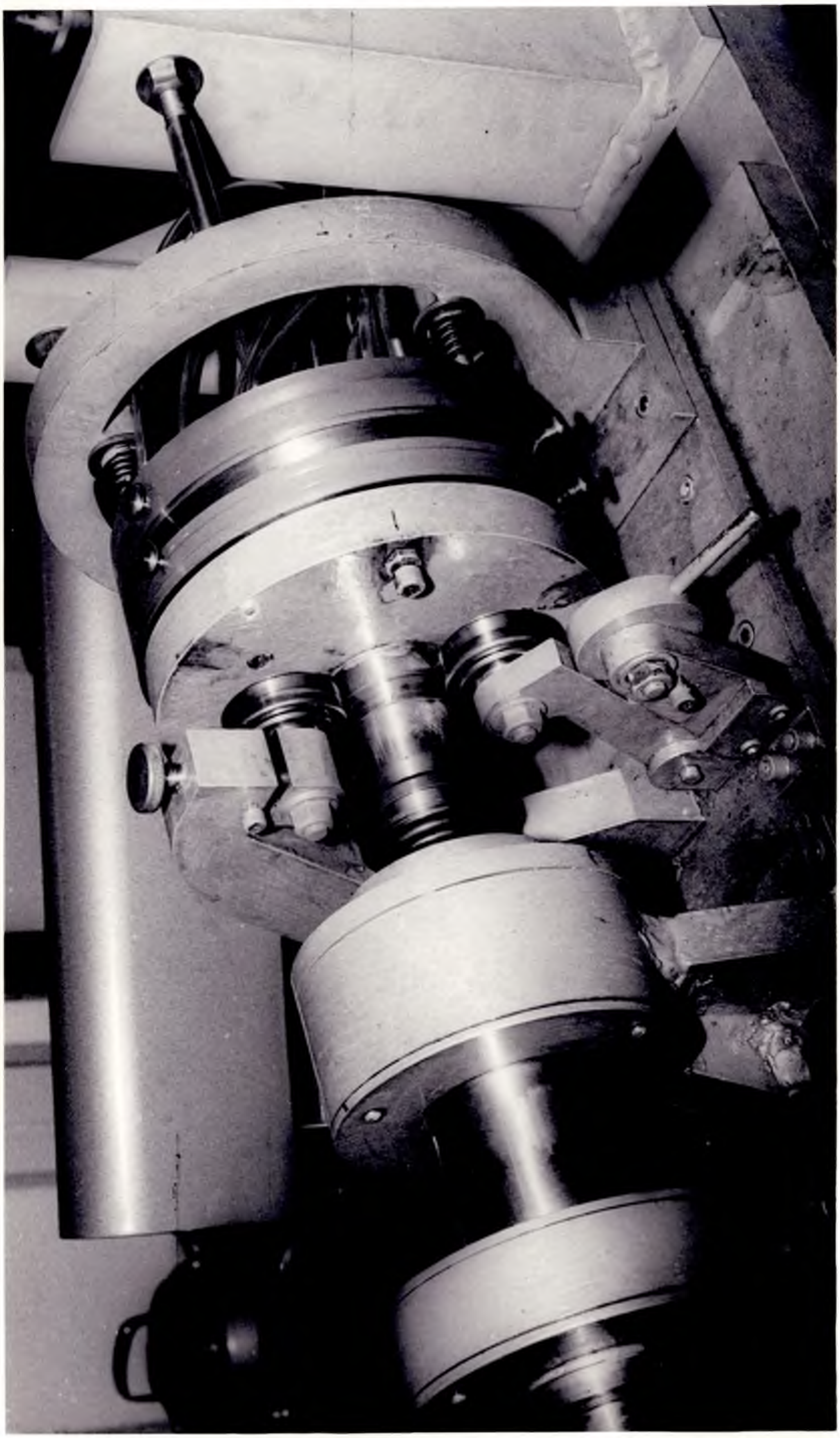


FIG.2. STATIC AND DYNAMIC DISC ASSEMBLY.

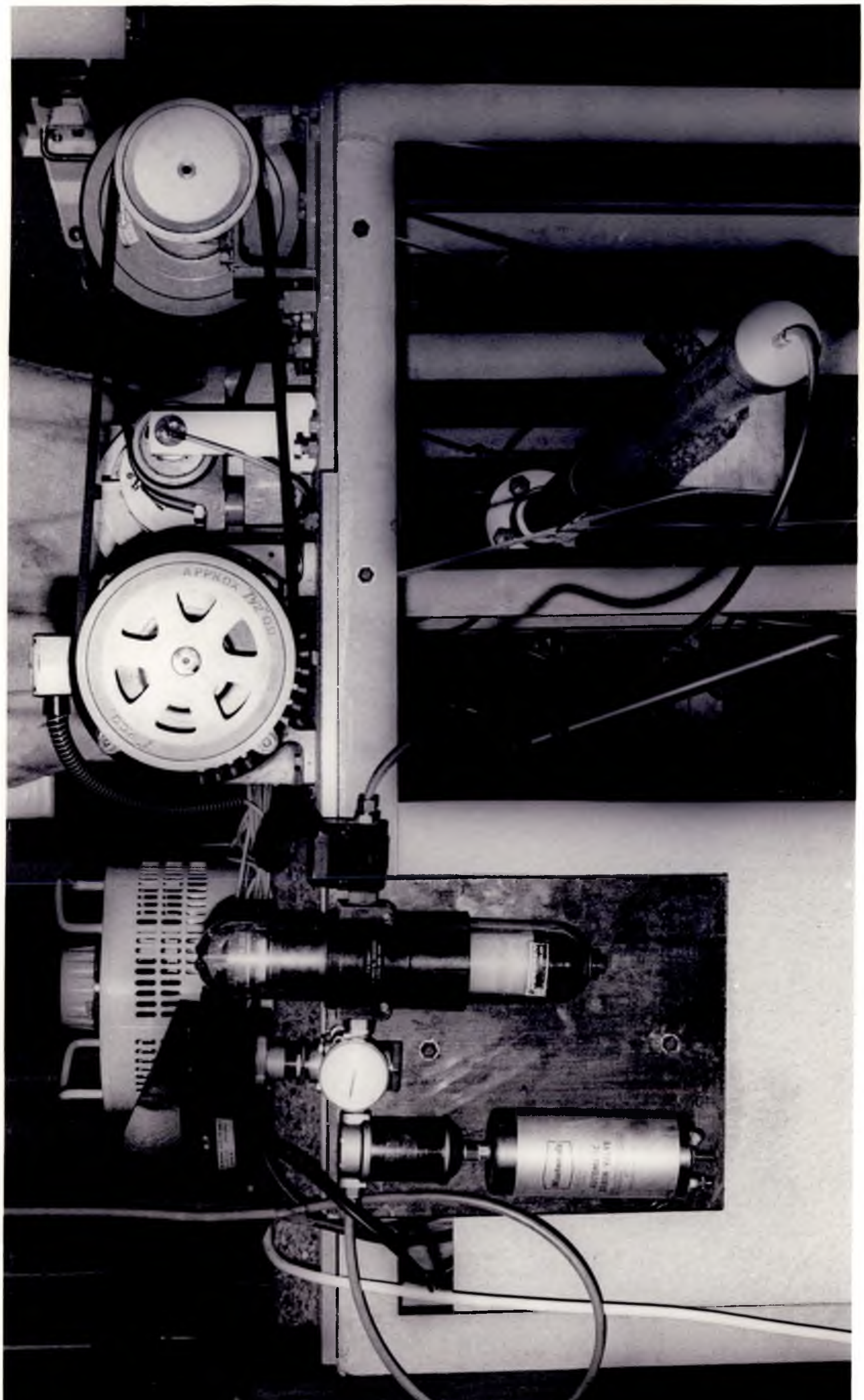
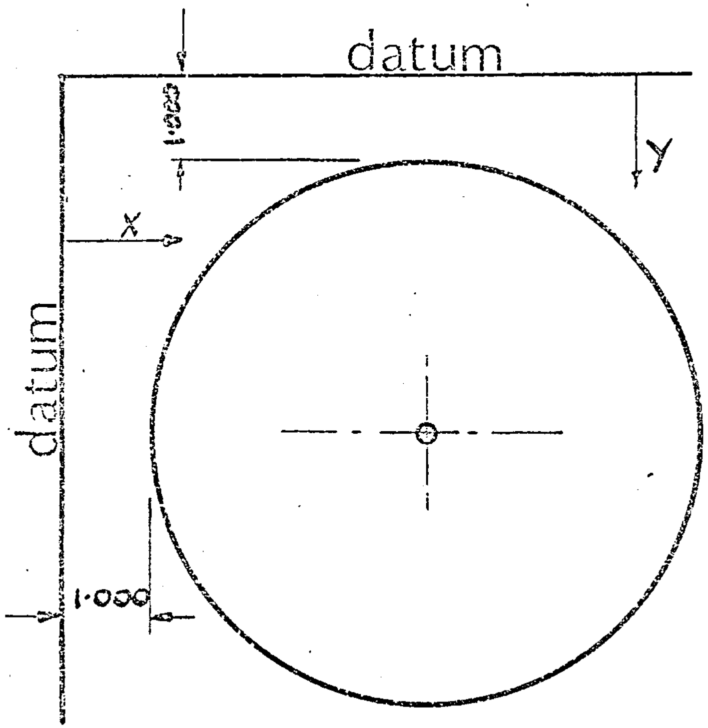


FIG. 3. VIEW OF TEST RIG FROM DRIVE SIDE.

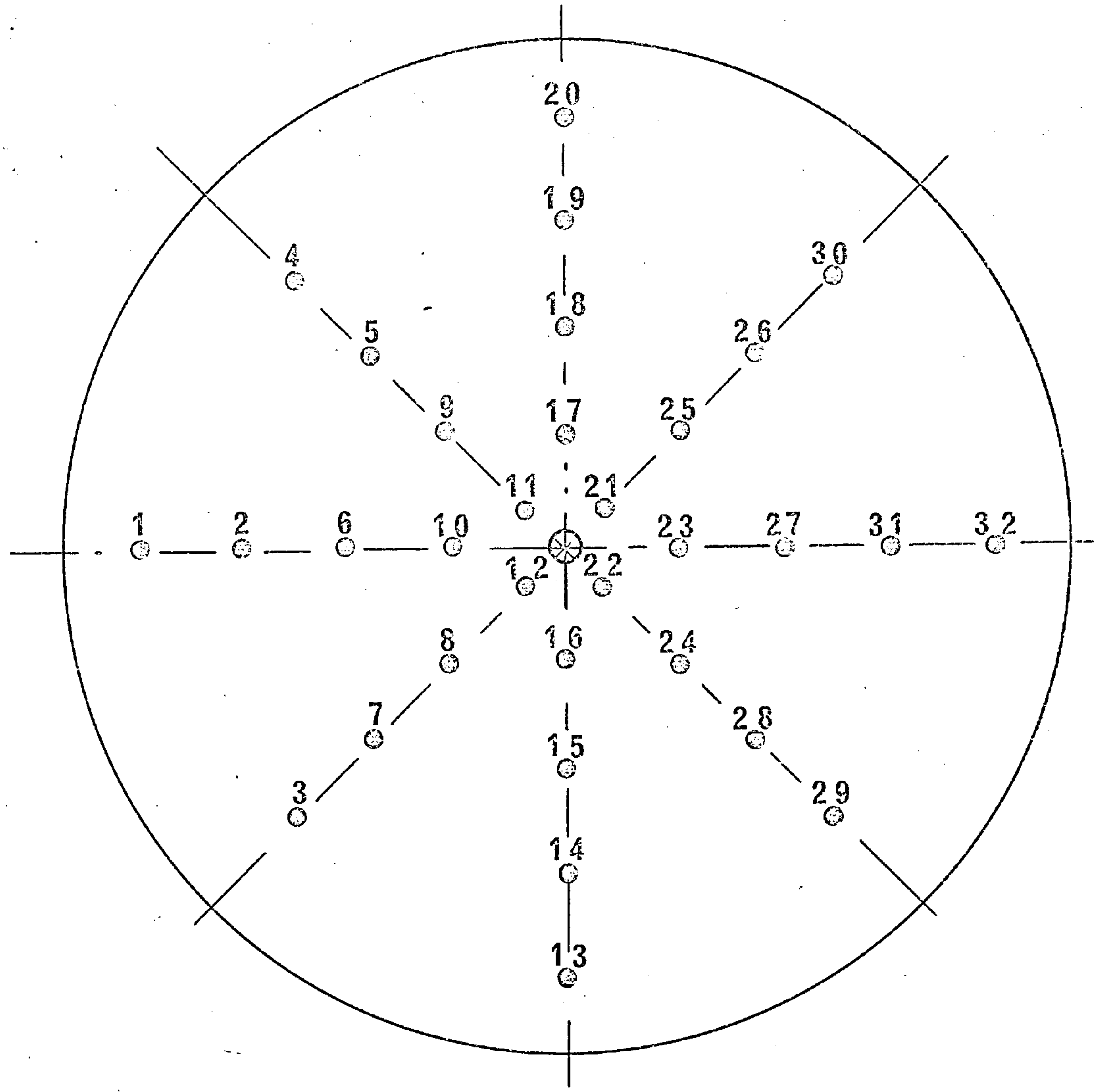


ALL DIMENSIONS IN INCHES.

STATIC DISC HOLE CO-ORDINATES
(FOR N.C. DRILLING MACHINE)

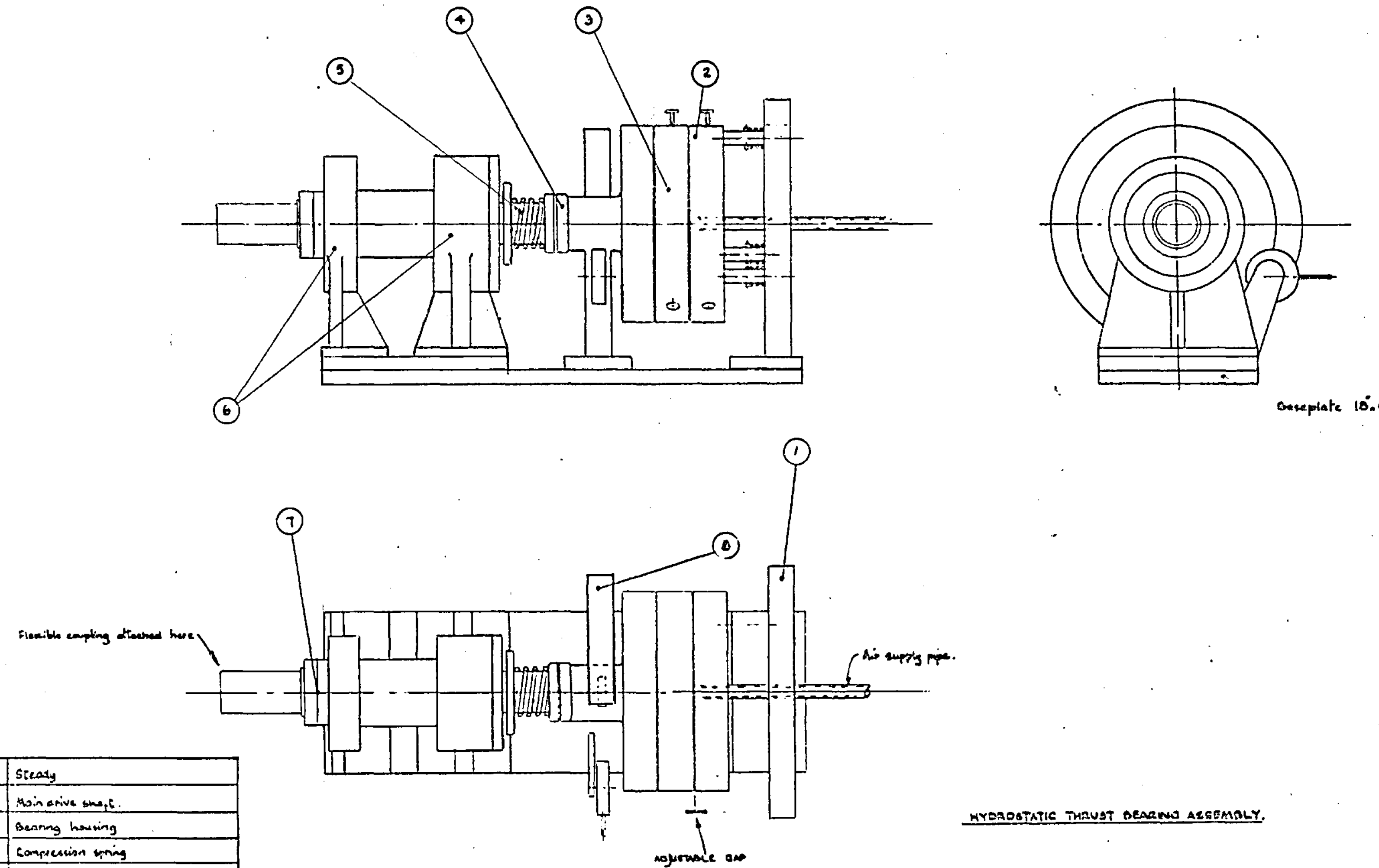
FIG. No 4.

No	x	y	No	x	y
1	1·591	4·740	17	4·740	3·953
2	2·378	4·740	18	4·740	3·165
3	2·791	6·689	19	4·740	2·378
4	2·791	2·791	20	4·740	1·591
5	3·348	3·348	21	5·018	4·462
6	3·165	4·740	22	5·018	5·018
7	3·348	6·132	23	5·527	4·740
8	3·905	5·576	24	5·576	5·576
9	3·905	3·905	25	5·576	3·905
10	3·953	4·740	26	6·132	3·348
11	4·462	4·462	27	6·315	4·740
12	4·462	5·018	28	6·132	6·132
13	4·740	7·889	29	6·689	6·689
14	4·740	7·102	30	6·689	2·791
15	4·740	6·315	31	7·102	4·740
16	4·740	5·527	32	7·889	4·740



ARRANGEMENT OF STATIC PRESSURE HOLES

FIG. Nº 5.



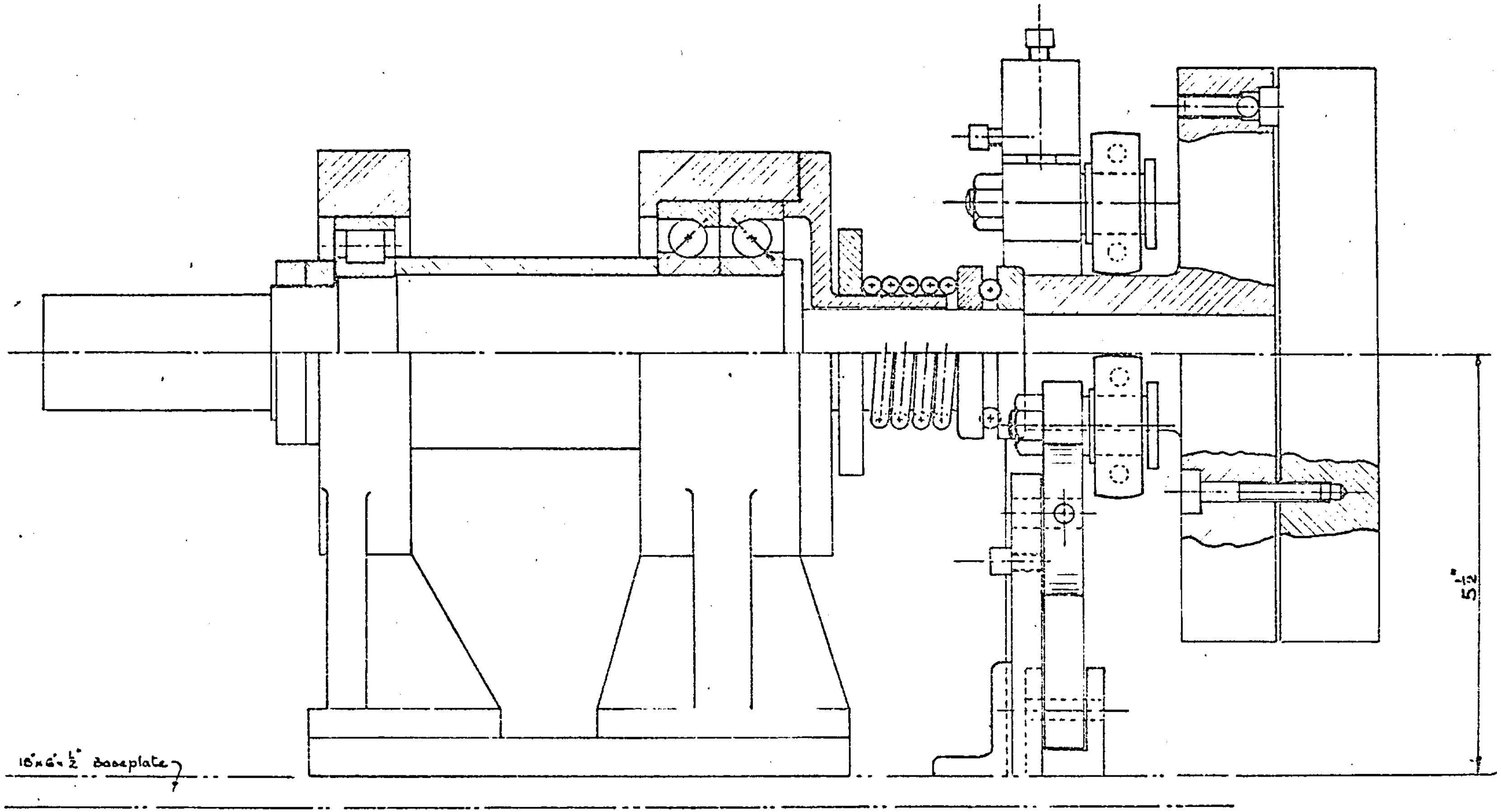
8	Steady
7	Main drive shaft.
6	Bearing housing
5	Compression spring
4	Thrust bearing
3	Hydrostatic bearing rotating plate ← Detail drawing being prepared.
2	Hydrostatic bearing fixed plate ← " " " "
1	Support bracket.

HYDROSTATIC THRUST BEARING ASSEMBLY.

Scale ½ Full Size.

FIG. 6.

Research Project F.B.K. Feb 1970.

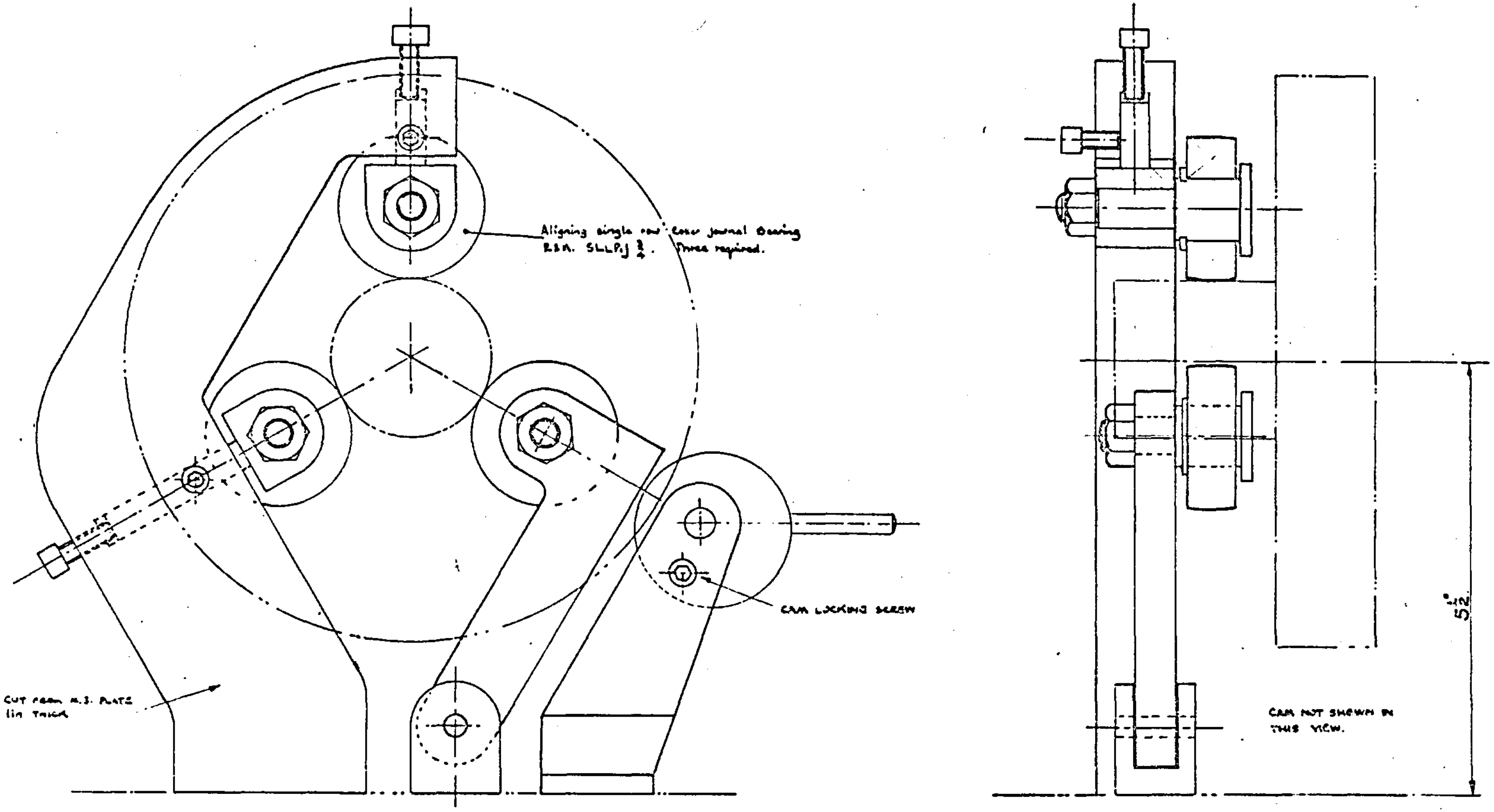


DRIVE SHAFT ASSEMBLY

Scale: Full Size

FIG. 7

Research Project P.S.K. Feb. 1970

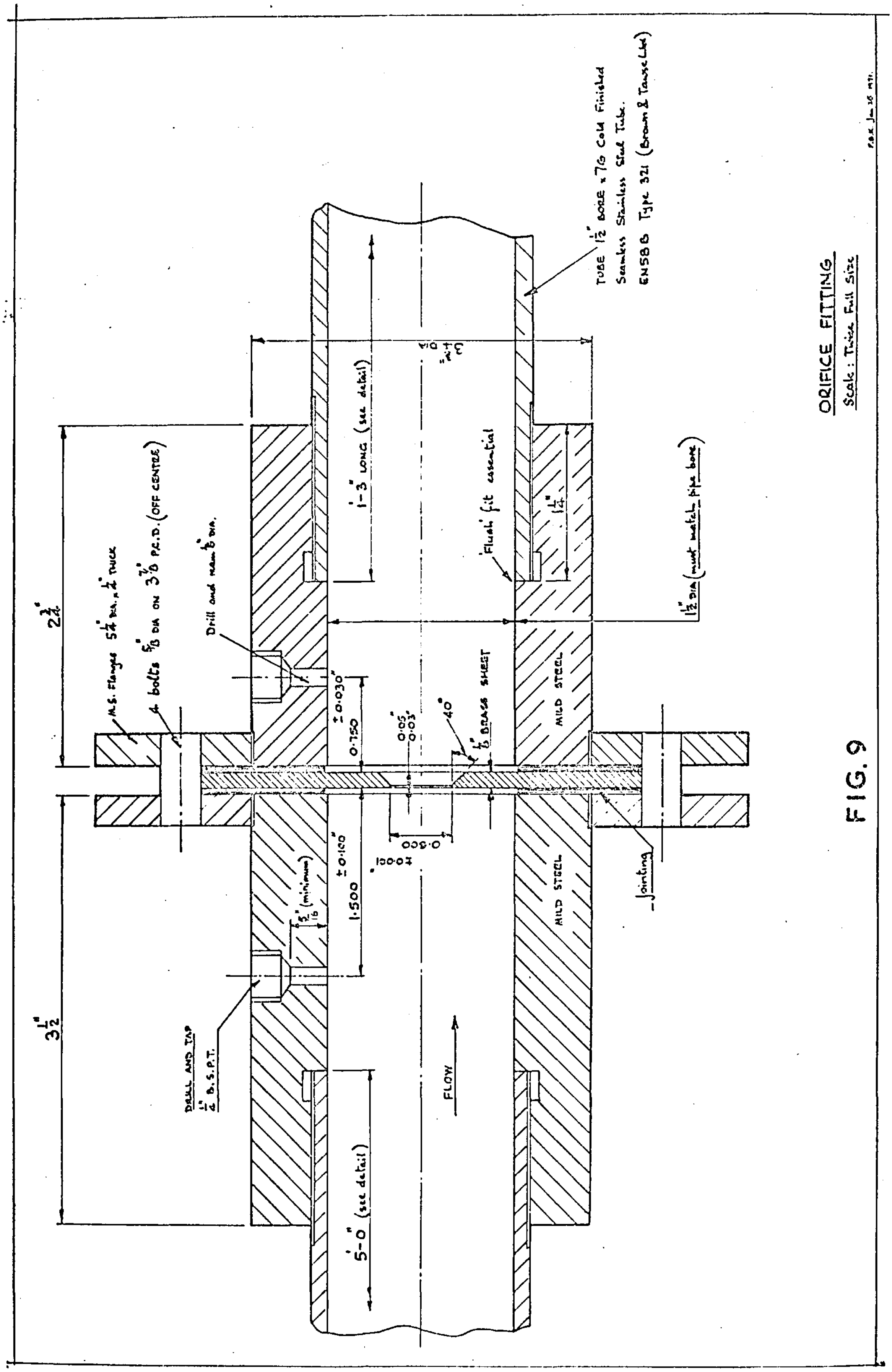


STEADY FOR HYDROSTATIC THRUST BEARING.

SCALE FULL SIZE.

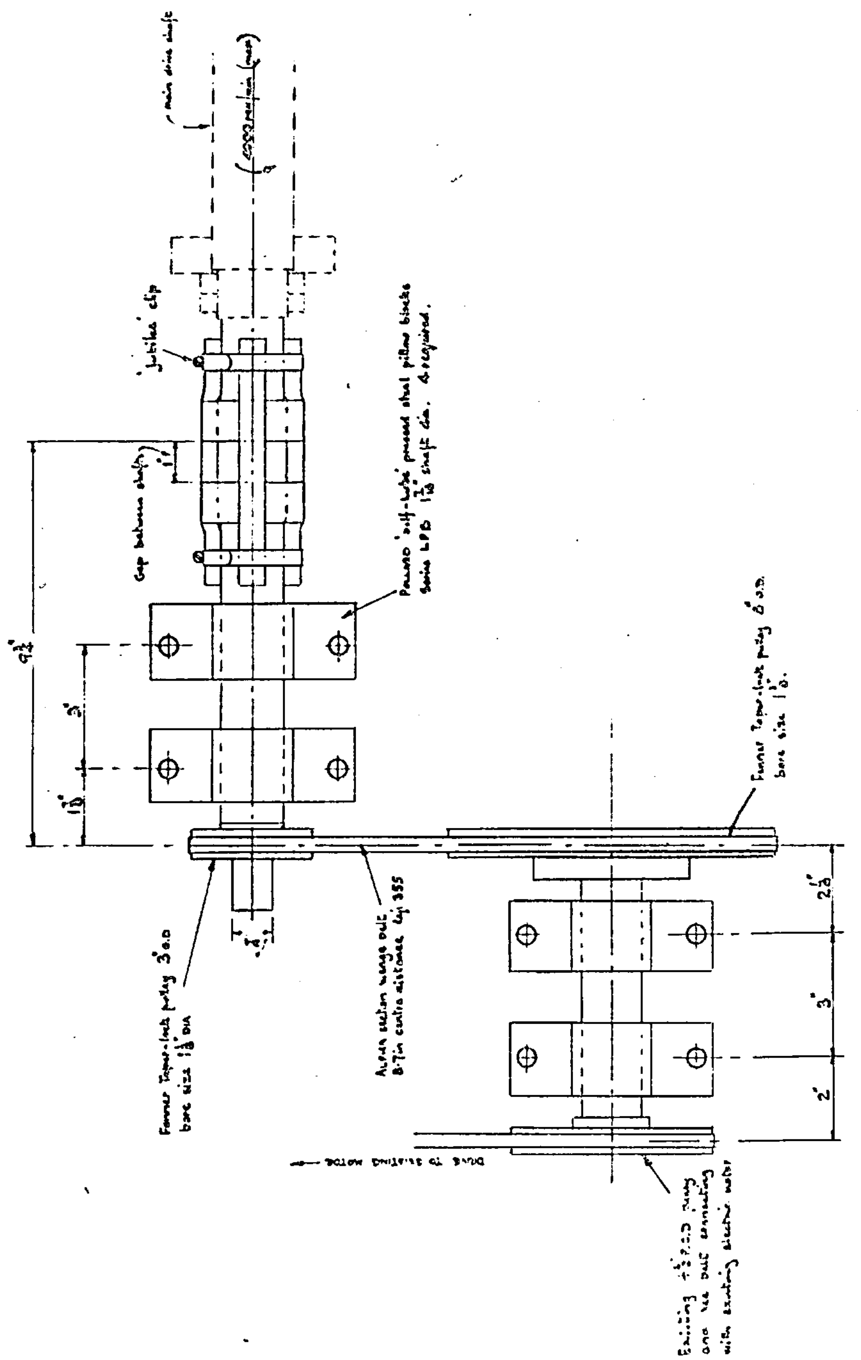
FIG. 8

Research Project F.B.H. Feb. 1970



ORIFICE FITTING
Scale : Twice Full Size

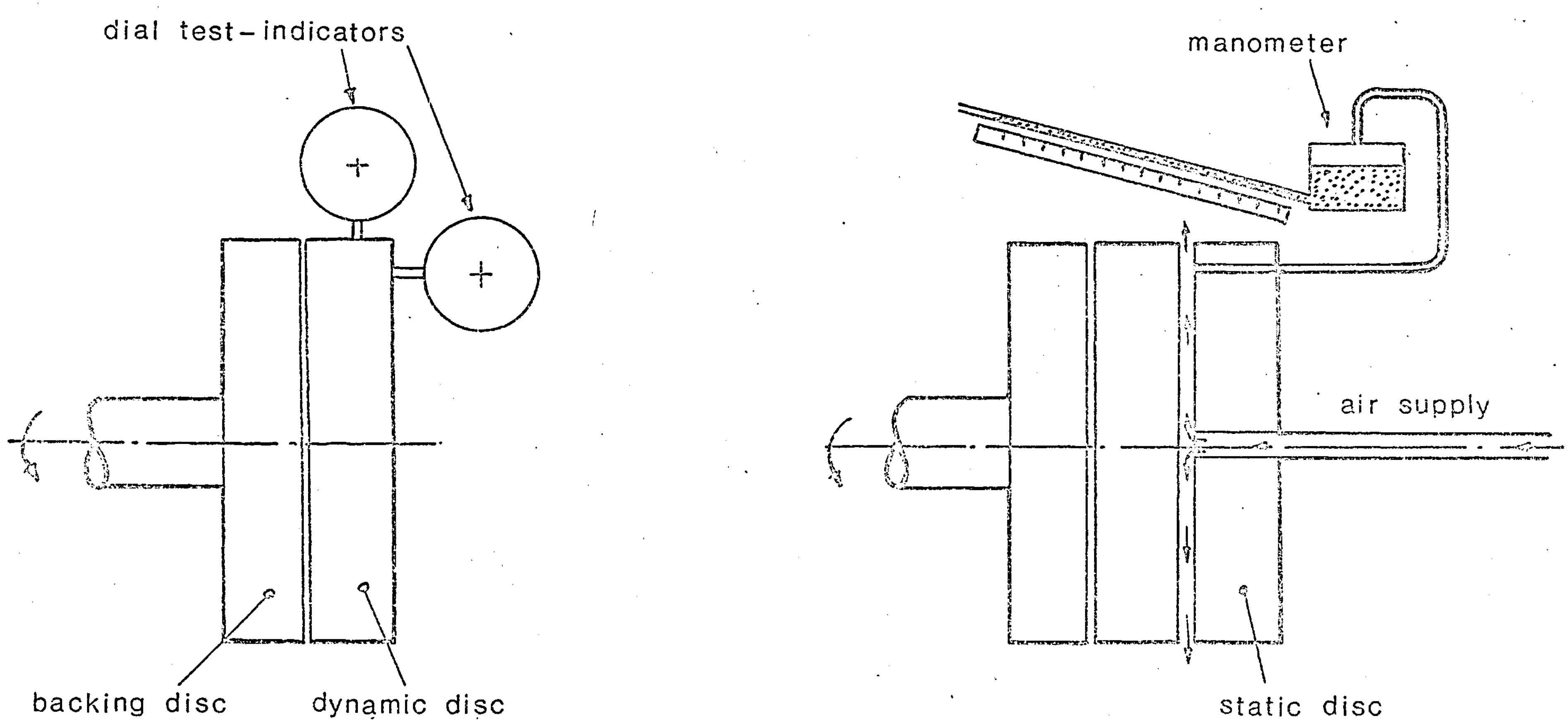
FIG. 9



DRIVE ARRANGEMENT FOR HYDROSTATIC THRUST BEARING.

SCALE: HALF FULL SIZE

FIG. 10

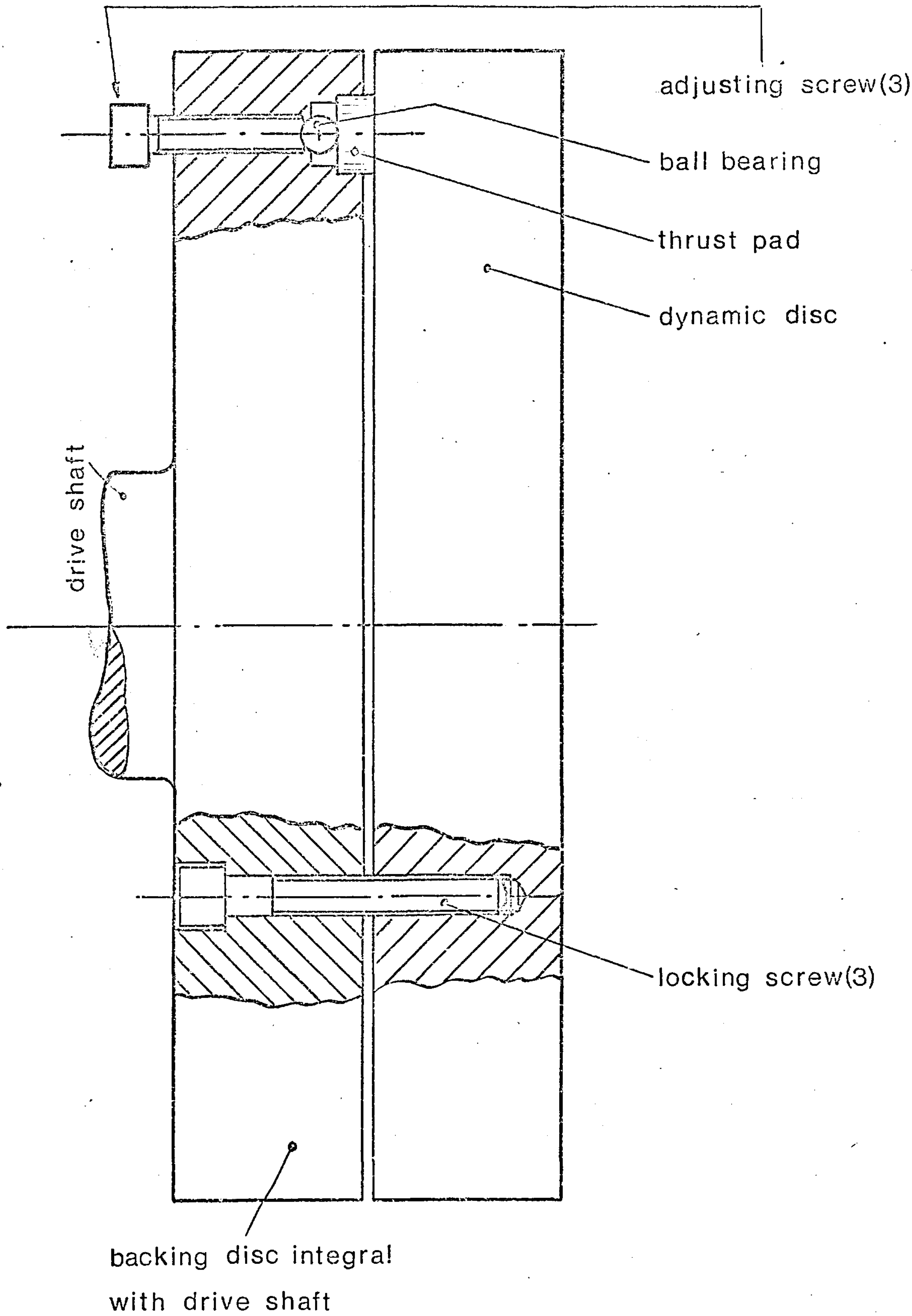


INITIAL SETTING

FINAL SETTING

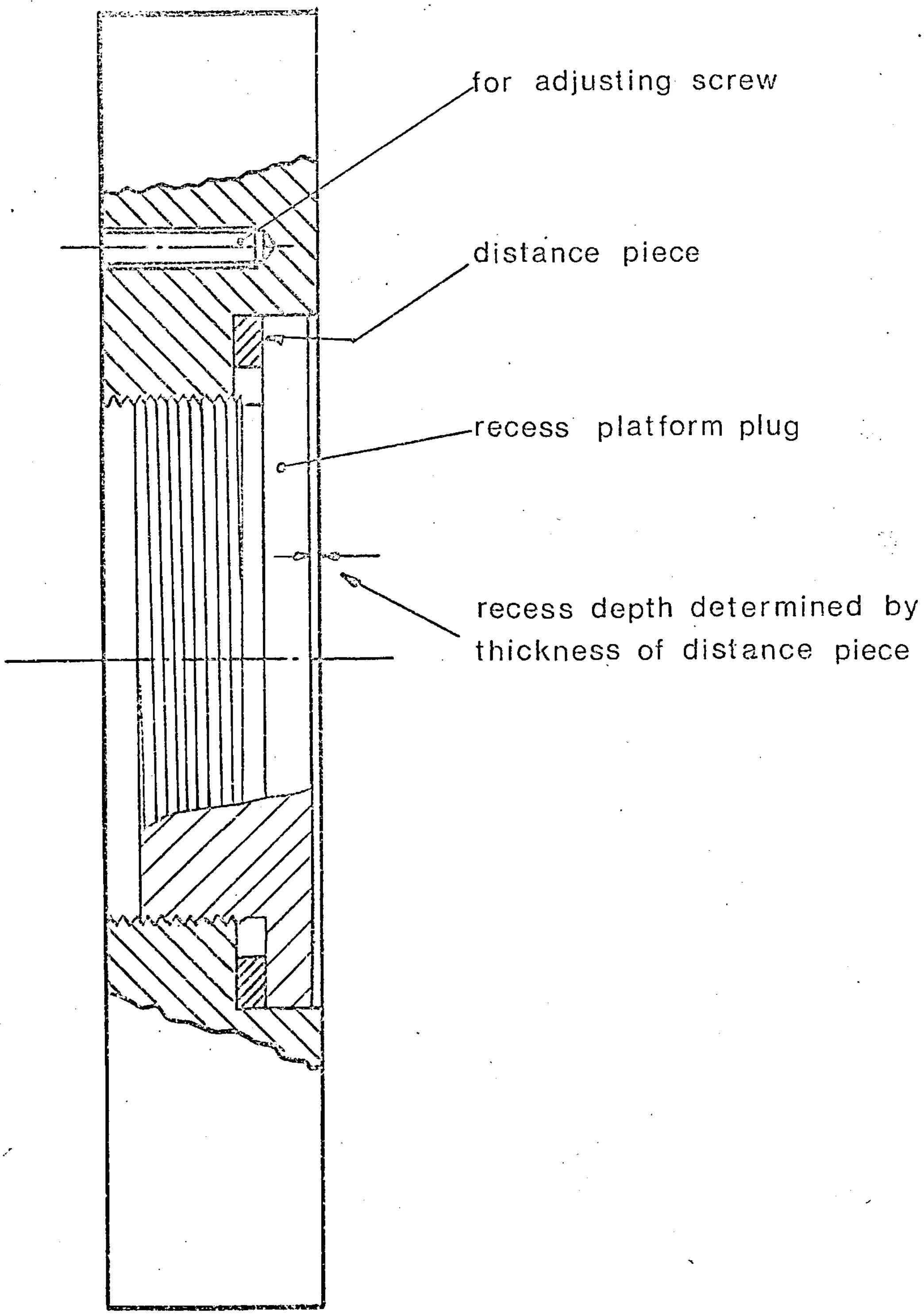
METHOD OF SETTING AIR-GAP

FIG. No 11.



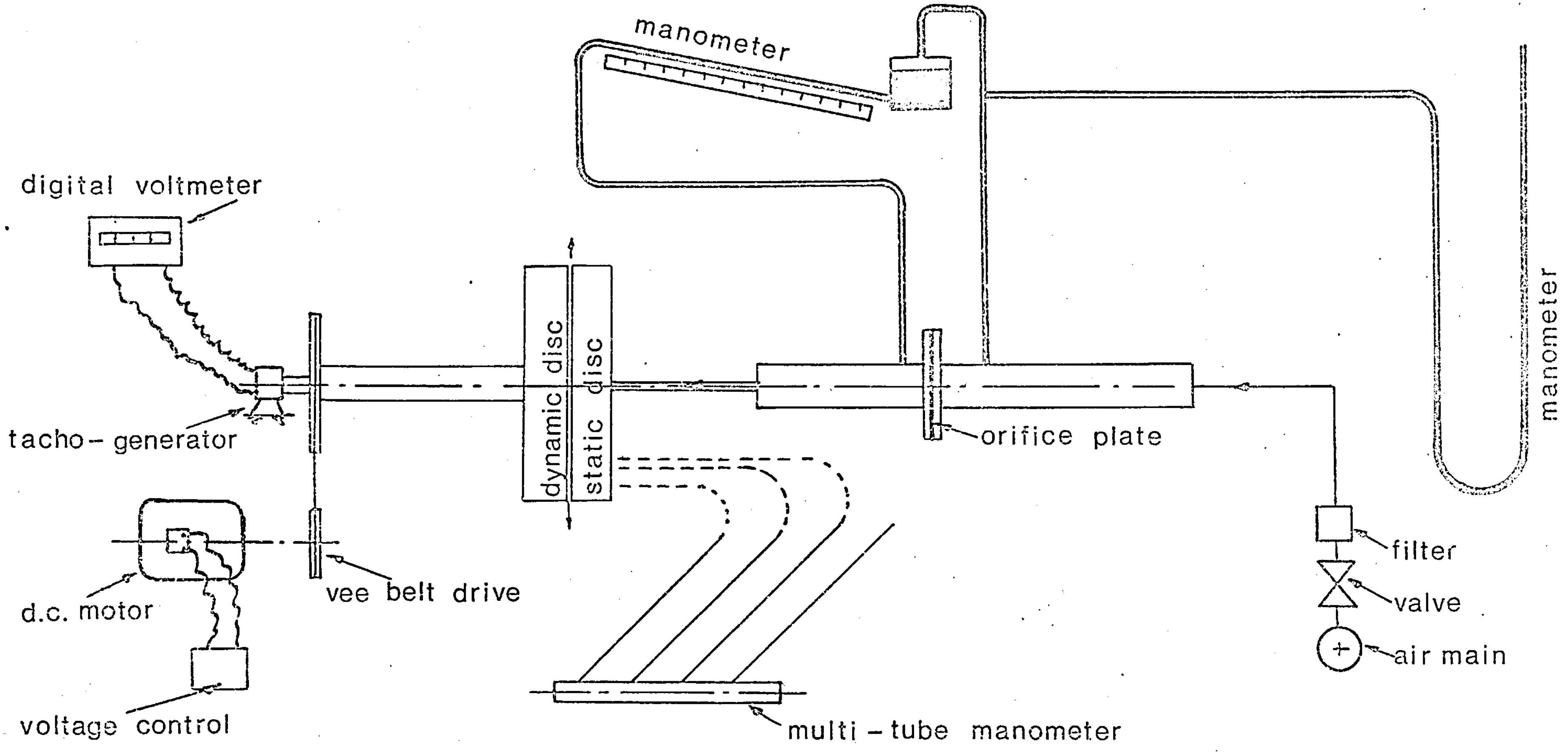
Design provision for the adjustment of the dynamic disc

FIG. N° 12.



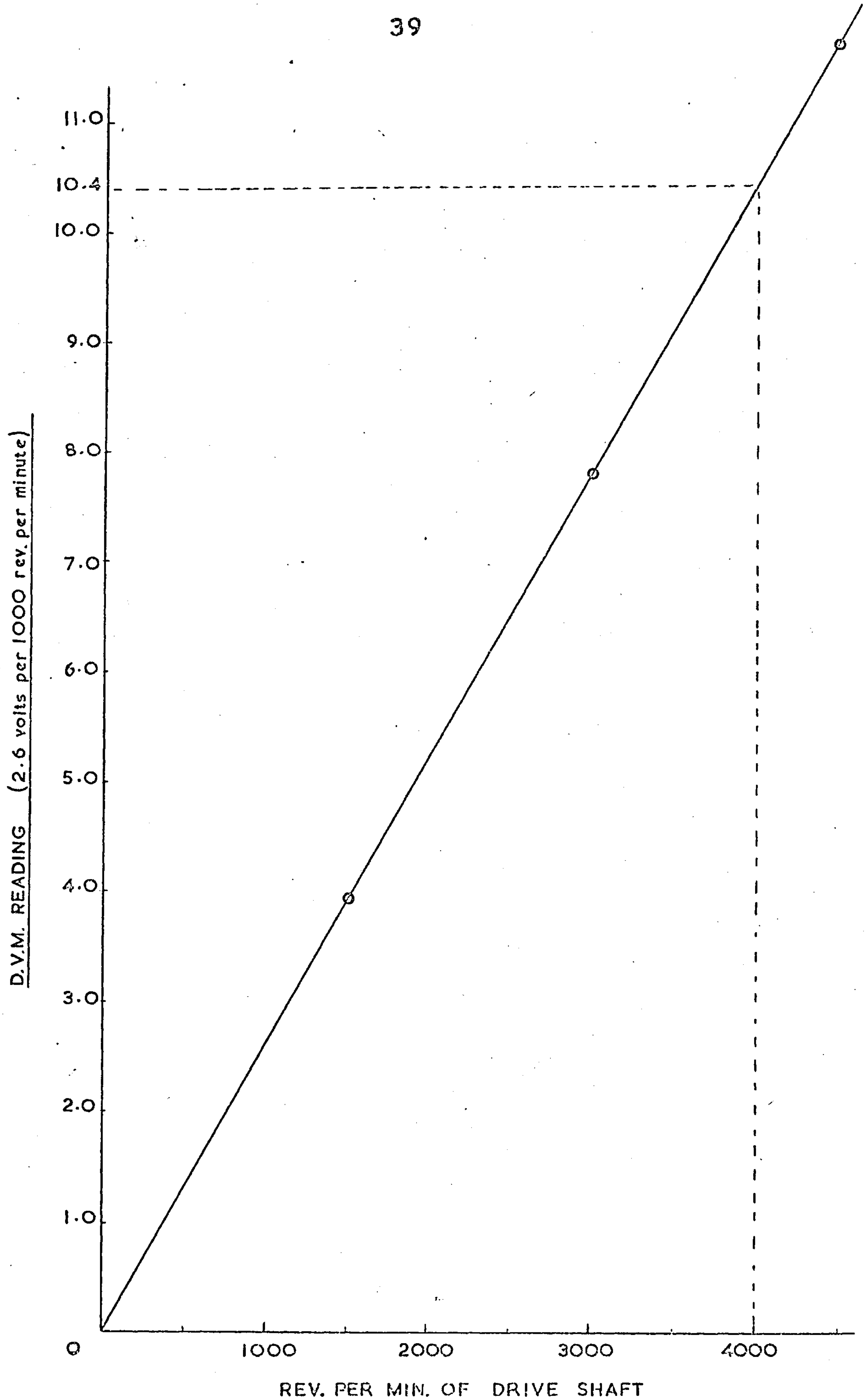
DYNAMIC DISC WITH CENTRAL RECESS

FIG. Nº 13.



INSTRUMENTATION

FIG. N°14.



CALIBRATION OF TACHO-GENERATOR OUTPUT

FIG. Nº 15.

TYPE OF TEST	SPEED Ω	AIR INLET TEMP.	ATMOS. PRESS.	ATMOS. TEMP.	TEST Nº	DATE

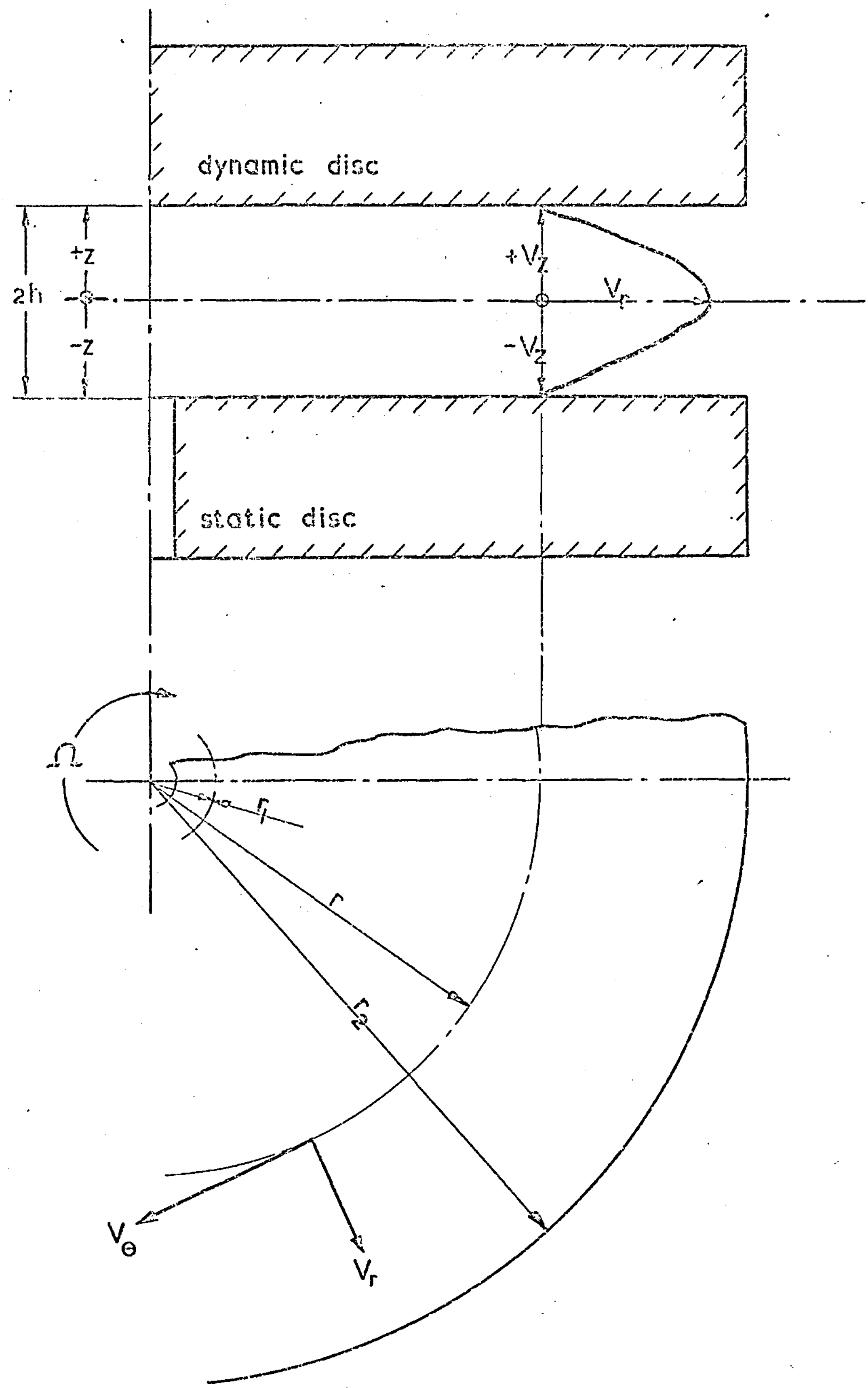
GAP (mm)	SIZE OF STEP	ORIFICE Δh (mb)	MAN. SLOPE °	APPROX. FLOW RATE kg/s

1	Av.	5	Av.	9	Av.	13	Av.
2		6		10		14	
3		7		11		15	
4	P=	8	P=	12	P=	16	P=

17	Av.	21	Av.	25	Av.	29	Av.
18		22		26		30	
19		23		27		31	
20	P=	24	P=	28	P=	32	P=

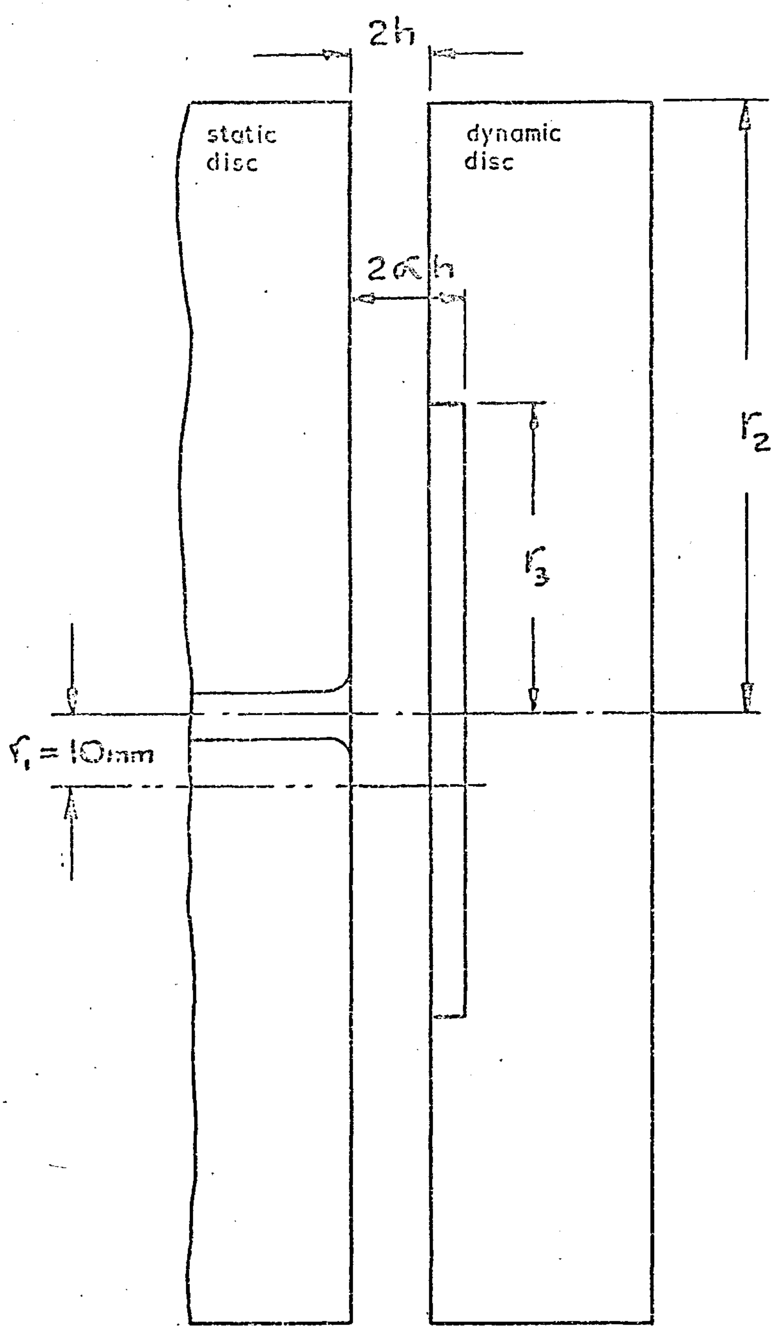
Sample Results Sheet

FIG. Nº 16.



CONFIGURATION AND CO-ORDINATE SYSTEM

FIG. Nº 17.



CONFIGURATION OF STEPPED THRUST BEARING

FIG. Nº 18.

CHAPTER 3 ANALYSIS

3.01 INERTIA EFFECTS IN FULLY DEVELOPED AXISYMMETRIC LAMINAR FLOW

Navier Stokes equations in cylindrical co-ordinates for steady state flow:

$$V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z} - \frac{V_\theta^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{\mu}{\rho}\left[\frac{\partial^2 V_r}{\partial z^2} + \frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rV_r)\right\} + \frac{1}{3}\frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rV_r) + \frac{\partial V_z}{\partial z}\right\}\right]$$

$$V_r \frac{\partial V_\theta}{\partial r} + V_r \frac{V_\theta}{r} + V_z \frac{\partial V_\theta}{\partial z} = \frac{\mu}{\rho}\left[\frac{\partial^2 V_\theta}{\partial z^2} + \frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rV_\theta)\right\}\right]$$

$$V_r \frac{\partial V_z}{\partial r} + V_z \frac{\partial V_z}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left[\frac{\partial^2 V_z}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right) + \frac{1}{3}\frac{\partial}{\partial z}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rV_r) + \frac{\partial V_z}{\partial z}\right\}\right]$$

Continuity equation in cylindrical co-ordinates

$$\frac{1}{r}\frac{\partial}{\partial r}(\rho r V_r) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho V_\theta) + \frac{\partial}{\partial z}(\rho V_z) = 0$$

When a gas is being used as the lubricating medium, the effect of compressibility should be considered. The relevance of the compressibility term in the full Navier Stokes equation, for the series of tests undertaken in this project, has been examined in Chapter 4, and found to be small enough to justify the assumption of incompressible flow.

Dowson (10) obtained a solution for the pressure distribution in a hydrostatic thrust bearing which included all but one of the predominant inertia terms, and was applicable to the case of rotating boundaries. Beginning with the Navier-Stokes equations of motion for an incompressible isoviscous fluid, neglecting body forces and allowing for axial symmetry, the equations in cylindrical co-ordinates takes the form:

$$\left.\begin{aligned}
\rho\left[V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z} - \frac{V_\theta^2}{r}\right] &= -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} + \frac{\partial^2 V_r}{\partial z^2} - \frac{V_r}{r^2}\right] \\
\rho\left[V_r \frac{\partial V_\theta}{\partial r} + V_z \frac{\partial V_\theta}{\partial z} + \frac{V_r V_\theta}{r}\right] &= \mu\left[\frac{\partial^2 V_\theta}{\partial r^2} + \frac{1}{r}\frac{\partial V_\theta}{\partial r} + \frac{\partial^2 V_\theta}{\partial z^2} - \frac{V_\theta}{r^2}\right] \\
\rho\left[V_r \frac{\partial V_z}{\partial r} + V_z \frac{\partial V_z}{\partial z}\right] &= -\frac{\partial p}{\partial z} + \mu\left[\frac{\partial^2 V_z}{\partial r^2} + \frac{1}{r}\frac{\partial V_z}{\partial r} + \frac{\partial^2 V_z}{\partial z^2}\right]
\end{aligned}\right\} \quad (1)$$

The continuity equation for an incompressible fluid in cylindrical co-ordinates is:

$$\frac{1}{r}\frac{\partial}{\partial r}(rV_r) + \frac{1}{r}\frac{\partial V_\theta}{\partial \theta} + \frac{\partial V_z}{\partial z} = 0$$

For axial symmetry this reduces to:

$$\frac{1}{r}\frac{\partial (rV_r)}{\partial r} + \frac{\partial V_z}{\partial z} = 0 \quad (2)$$

An alternative form of this equation is:

$$\frac{\partial V_r}{\partial r} + \frac{V_r}{r} + \frac{\partial V_z}{\partial z} = 0 \quad (3)$$

These equations can be nondimensionalized by making the following substitutions:

$$V_r = V_r'U \qquad V_\theta = V_\theta'X \qquad V_z = V_z'W \qquad r = \frac{r'D}{2} \qquad z = z'2h \qquad p = p'p_1$$

where the representative quantities U, X, p_1 etc. are selected so that the primed variables are always $\leqslant 1$. The equations now become:

$$\left.\begin{aligned}
&\rho\left[\frac{2U^2}{D}V_r'\frac{\partial V_r'}{\partial r'} + \frac{WU}{2h}V_z'\frac{\partial V_r'}{\partial z'} - \frac{2X^2}{D}\frac{V_\theta'^2}{r'}\right] = -\frac{2p}{D}\frac{\partial p'}{\partial r'} + \frac{4\mu U}{D^2}\left[\frac{\partial^2 V_r'}{\partial r'^2} + \frac{1}{r'}\frac{\partial V_r'}{\partial r'}\right. \\
&\qquad\qquad \left. + \left(\frac{D}{4h}\right)^2\frac{\partial^2 V_r'}{\partial z'^2} - \frac{V_r'}{r_1^2}\right] \\
&\rho\left[\frac{2UX}{D}V_r'\frac{\partial V_\theta'}{\partial r'} + \frac{WX}{2h}V_z'\frac{\partial V_\theta'}{\partial V_z'} + \frac{2UX}{D}\frac{V_r'V_\theta'}{r'}\right] = \frac{4\mu X}{D^2}\left[\frac{\partial^2 V_\theta'}{\partial r'^2}\right. \\
&\qquad\qquad \left. + \frac{1}{r'}\frac{\partial V_\theta'}{\partial r'} + \left(\frac{D}{4h}\right)^2\frac{\partial^2 V_\theta}{\partial z^2} - \frac{V_\theta'}{r'^2}\right] \\
&\rho\left[\frac{2UW}{D}V_r'\frac{\partial V_z'}{\partial r'} + \frac{W^2}{2h}V_z'\frac{\partial V_z'}{\partial z'}\right] = -\frac{p_1}{2h}\frac{\partial p'}{\partial z'} + \frac{4\mu W}{D^2}\left[\frac{\partial^2 V_z'}{\partial r'^2} + \frac{1}{r}\frac{\partial V_z'}{\partial r'}\right. \\
&\qquad\qquad \left. + \left(\frac{D}{4h}\right)^2\frac{\partial V_z'}{\partial z'^2}\right]
\end{aligned}\right\} \quad (4)$$

$$\frac{2U}{D}\frac{1}{r'}\partial\left(\frac{r'V_r'}{\partial r'}\right) + \frac{W}{2h}\frac{\partial V_z'}{\partial z'} = 0 \qquad (5)$$

The primed quantities are all of the same order of magnitude, and if only the predominant viscous terms are retained, the equations of motion are:

$$\left.\begin{aligned}
&R_n\left[V_r'\frac{\partial V_r'}{\partial r'} + \frac{WD}{4hU}V_z'\frac{\partial V_r'}{\partial z'} - \left(\frac{X}{U}\right)^2\frac{V_\theta'^2}{r'}\right] = \frac{2p'(2h)^2}{\mu UD}\frac{\partial p'}{\partial r'} + \frac{\partial^2 V_r'}{\partial z'^2} \\
&R_n\left[V_r'\frac{\partial V_\theta'}{\partial r'} + \frac{WD}{4hU}V_z'\frac{\partial V_\theta'}{\partial z'} + \frac{V_r'V_\theta'}{r'}\right] = -\frac{\partial^2 V_\theta'}{\partial z'^2} \\
&R_n\left[V_r'\frac{\partial V_z'}{\partial r'} + \frac{WD}{4hU}\frac{\partial V_z'}{\partial z'}\right] = -\frac{2p_1h}{\mu W}\frac{\partial p'}{\partial z'} + \frac{\partial^2 V_z'}{\partial z'^2}
\end{aligned}\right\} \quad (6)$$

Where the Reynolds number $R_n = \frac{\rho}{\mu} (\frac{4h}{D})$ 2hU

With oil as the lubricant in mind, Dowson argued that the representative radial velocity U would be small, and since $h << \frac{D}{4}$ the Reynolds number R_n would be considerably less than 1. Also since $\frac{W}{U} = O\ (\frac{4h}{D})$ from equation (5) all the inertia terms in the second and third equations of motion can be neglected. Similarly, two inertia terms in the first equation of motion were discounted, and the following equations obtained:

$$\left.\begin{aligned} -\frac{\rho V_\theta^2}{r} &= -\frac{\partial p}{\partial r} + \mu\frac{\partial^2 V_r}{\partial z^2} \\ 0 &= \mu\frac{\partial^2 V_\theta}{\partial z^2} \\ 0 &= -\frac{\partial p}{\partial z} + \mu\frac{\partial^2 V_z}{\partial z^2} \end{aligned}\right) \qquad (7)$$

If air is to be used as the lubricating medium then the first of equations (7) can be extended to include an additional inertia term. $\rho V_r \frac{\partial V_r}{\partial r}$ will be significant when V_r is large and r is small i.e. in the vicinity of the air inlet. From the continuity equation, $V_r \frac{\partial V_r}{\partial r}$ can be written in the form $\frac{-V_r^2}{r} - V_r \frac{\partial V_z}{\partial z}$ and of these two terms $\frac{-V_r^2}{r}$ will be the most significant. If the radial inertia term $\frac{-\rho V_r^2}{r}$ is included in the first equation of motion, the revised three equations of motion become:

$$\left.\begin{aligned} -\frac{\rho V_r^2}{r} - \frac{\rho V_\theta^2}{r} &= -\frac{\partial p}{\partial r} + \mu\frac{\partial^2 V_r}{\partial z^2} \\ 0 &= \mu\frac{\partial^2 V_\theta}{\partial z^2} \\ 0 &= -\frac{\partial p}{\partial z} + \mu\frac{\partial^2 V_z}{\partial z^2} \end{aligned}\right) \qquad (8)$$

The second of equations (8) can be integrated directly, and with the boundary conditions $z = -h$ $V_\theta = 0$, $z = +h$ $V_\theta = \Omega r$ we obtain

$$V_\theta = \frac{\Omega r}{2}\left(\frac{z}{h} + 1\right) \qquad (9)$$

If the volume flow rate is constant, ~~Then~~ then the mean velocity $= \frac{Q}{4\pi rh}$

$$\text{Let } V_r = \frac{Q}{4\pi rh} \qquad (10)$$

If the third of equations (8) is integrated twice with respect to z, the successive equations obtained are:

$$p = \mu\frac{\partial V_z}{\partial z} + A \qquad (11)$$

$$\text{and } \int p\,dz = \mu V_z + Az + B \qquad (11A)$$

where A and B are functions of r only.

The mean pressure $\bar{p}$ across the air gap (2h) $= \frac{1}{2h}\int_{-h}^{h} p\,dz$

from equation (11A) $\int_{-h}^{h} p\,dz = 2Ah$ (since $V_z = 0$ when $z = \pm h$)

$$\therefore A = \frac{1}{2h}\int_{-h}^{h} p\,dz = \bar{p}$$

combining the above relationship between A and $\bar{p}$ in equation (11)

$$p = \mu\frac{\partial V_z}{\partial z} + \bar{p} \qquad (12)$$

From equation (12) it will be seen that the pressure at any point, at a particular radius, in the air gap, will differ from the mean pressure by an amount which is dependent upon the local axial velocity gradient.

If the result expressed in equation (9) is introduced into the first of equations (8) and the expression for p in equation (12) is used to eliminate $\frac{\partial p}{\partial r}$, we find,

$$\frac{\partial \bar{p}}{\partial r} = \frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{\rho \Omega^2 r}{4}\left(\frac{z^2}{h^2} + \frac{2z}{h} + 1\right) + \mu\left(\frac{\partial^2 V_r}{\partial z^2} - \frac{\partial^2 V_z}{\partial z \partial r}\right) \qquad (13)$$

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The second viscous term in equation (13) can be re-written in terms of V_r and r from equation (2) to give,

$$\frac{\partial \bar{p}}{\partial r} = \frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{\rho \Omega^2 r}{4}\left(\frac{z^2}{h^2} + \frac{2z}{h} + 1\right) + \mu\left[\frac{\partial^2 V_r}{\partial z^2} + \frac{\partial}{\partial r}\left\{\frac{1}{r}\frac{\partial}{\partial r}(rV_r)\right\}\right] \qquad (14)$$

INERTIA TERMS VISCOUS TERMS

when the two viscous terms are non-dimensionalised they become: $\frac{U\partial^2 V_r'}{4h^2 \partial z'^2}$ and $\frac{4U}{D^2}\left\{\frac{\partial}{\partial r'}(r' V_r')\right\}$ respectively, the first viscous term is $\left(\frac{D}{4h}\right)^2$ times the second viscous term, and since $D >> 4h$, the second viscous term may be neglected, so that equation (14) becomes

$$\frac{\partial \bar{p}}{\partial r} = \frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{\rho \Omega^2 r}{4}\left(\frac{z^2}{h^2} + \frac{2z}{h} + 1\right) + \mu\frac{\partial^2 V_r}{\partial z^2} \qquad (15)$$

integrating equation (15) twice with respect to z, and re-arranging

$$V_r = \frac{z^2}{2\mu}\frac{\partial \bar{p}}{\partial r} - \frac{\rho Q^2 z^2}{32\pi^2 r^3 h^2 \mu} - \frac{\rho \Omega^2 r}{4\mu}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + Cz + D \qquad (16)$$

introducing the boundary conditions $z = -h$, $V_r = 0$ and $z = +h$, $V_r = 0$ we find

$$C = \frac{\rho\Omega^2 rh}{12\mu} \text{ and } D = -\frac{h^2}{2\mu}\frac{\partial p}{\partial r} + \frac{\rho Q^2}{32\pi^2 r^3 \mu} + \frac{7}{48}\frac{\rho\Omega^2 rh^2}{\mu}$$

The volume rate of flow, of lubricant, through the bearing can be evaluated from the integral

$$Q = 2\pi r \int_{-h}^{+h} V_r dz$$

hence $Q = 2\pi r \left[-\frac{2h^3}{3\mu}\frac{\partial \bar{p}}{\partial r} + \frac{\rho Q^2 h}{24\pi^2 r^3 \mu} + \frac{\rho\Omega^2 rh^3}{5\mu}\right]$

from the above $\frac{\partial \bar{p}}{\partial r} = -\frac{3\mu Q}{4\pi rh^3} + \frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10}$ (17)

combining equations (16) and (17) equation (16) becomes

$$V_r = \frac{1}{2\mu}(z^2 - h^2)\left(\frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{3\rho r\Omega^2}{10} - \frac{3\mu Q}{4\pi rh^3}\right) - \frac{\rho Q^2}{32\pi^2 r^3 h^2 \mu}\left(\frac{z^2}{h^2} - 1\right)$$

$$- \frac{\rho\Omega^2}{4}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7\rho\Omega^2 rh^2}{48\mu} + \frac{\rho\Omega^2 rhz}{12\mu} \qquad (18)$$

integrating (17) with respect to r and introducing the boundary conditions $\bar{p} = 0$ at $r = r_2$ we obtain:

$$\bar{p} = \frac{3\mu Q}{4\pi h^3}\log_e\left(\frac{r_2}{r}\right) - \frac{\rho Q^2}{32\pi^2 h^2}\left(\frac{1}{r^2} - \frac{1}{r_2^2}\right) - \frac{3\rho\Omega^2}{20}(r_2^2 - r^2) \qquad (19)$$

writing the above equation in dimensionless form, where $P = \frac{\pi h^3 \bar{p}}{\mu Q}$ and $R = \frac{r}{h}$

$$P = \frac{3}{4}\log_e\left(\frac{R_2}{R}\right) - \frac{\rho Q}{32\pi h\mu}\left(\frac{1}{R^2} - \frac{1}{R_2^2}\right) - \frac{3\pi h^5 \rho\Omega^2}{20\mu Q}(R_2^2 - R^2) \qquad (20)$$

A further series of equations, giving values of $\bar{p}$, P, V_z and V_r can be obtained by assuming that the radial velocity has a parabolic distribution based on the 'creeping flow' solution. In this case:

$$V_r = \frac{3Q}{8\pi h^3 r}(h^2 - z^2) \qquad (21)$$

from equations (9) and (21), also substituting $\frac{\partial \bar{p}}{\partial r}$ for $\frac{\partial p}{\partial r}$ the first of equations (8) becomes

$$\frac{\partial^2 V_r}{\partial z^2} = \frac{1}{\mu}\frac{\partial \bar{p}}{\partial r} - \frac{9Q^2\rho}{64\pi^2 h^6 r^3 \mu}(h^4 - 2h^2z^2 + z^4) - \frac{\Omega^2 r\rho}{4\mu}\left(\frac{z^2}{h^2} + \frac{2z}{h} + 1\right)$$

integrating twice with respect to z, and re-arranging

$$V_r = \frac{z^2}{2\mu}\frac{\partial \bar{p}}{\partial r} - \frac{9Q^2\rho}{64\pi^2 h^6 r^3\mu}\left(\frac{h^4 z^2}{2} - \frac{h^2 z^4}{6} + \frac{z^6}{30}\right)$$
$$- \frac{\Omega^2 r\rho}{4\mu}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + C_1 z + C_2 \qquad (22)$$

introducing the boundary conditions z = -h, V_r = 0 and z = +h, V_r = 0 we find

$$C_1 = \rho\frac{\Omega^2 rh}{12\mu} \text{ and } C_2 = \frac{-h^2}{2\mu}\frac{\partial \bar{p}}{\partial r} + \left(\frac{9Q^2}{64\pi^2 h^6 r^3\mu} \times \frac{11}{30}h^6\right) + \left(\frac{\Omega^2 r\rho}{4\mu} \times \frac{11h^2}{12}\right)$$
$$- \rho\frac{\Omega^2 rh^2}{12\mu}$$

The volume rate of flow, of lubricant, through the bearing can be evaluated from the integral

$$Q = 2\pi r\int_{-h}^{+h} V_r dz$$

hence $Q = 2\pi r\left[-\frac{2h^3}{3\mu}\frac{\partial \bar{p}}{\partial r} + \frac{9Q^2\rho h}{140\pi^2 r^3\mu} + \Omega^2 r\frac{\rho h^3}{5\mu}\right]$

from the above $\frac{\partial \bar{p}}{\partial r} = -\frac{3\mu Q}{4\pi r h^3} + \frac{27\rho Q^2}{280\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10}$ (23)

integrating equation (23) with respect to r and introducing the boundary condition $\bar{p} = 0$ at $r = r_2$ we obtain

$$\bar{p} = \frac{3\mu Q}{4\pi h^3} \log_e \left(\frac{r_2}{r}\right) - \frac{27\rho Q^2}{560\pi^2 h^2}\left[\frac{1}{r^2} - \frac{1}{r_2{}^2}\right] - \frac{3\rho\Omega^2}{20}(r_2{}^2 - r^2) \quad (24)$$

writing the above equation in dimensionless form, where
$P = \frac{\pi h^3 \bar{p}}{\mu Q}$ and $R = \frac{r}{h}$

$$P = \frac{3}{4} \log_e \left(\frac{R_2}{R}\right) - \frac{27\rho Q}{560\pi h\mu}\left(\frac{1}{R^2} - \frac{1}{R_2{}^2}\right) - \frac{3\pi h^5 \rho\Omega^2}{20\mu Q}(R_2{}^2 - R^2) \quad (25)$$

from equation (2) $\int_{-h}^{+h} -\frac{1}{r}\frac{\partial(rV_r)}{\partial r} dz = 0$ (since $V_z = 0$ when $z = \pm h$)

integrating with respect to z and introducing the boundary conditions $z = -h$, $V_z = 0$, $z = +h$, $V_z = 0$, we obtain:

$$\left[\frac{2h^3}{3\mu r}\frac{\partial}{\partial r}\left(r\frac{\partial \bar{p}}{\partial r}\right) + \frac{9Q^2\rho h}{70\pi^2 r^4 \mu} - \frac{2\Omega^2 r\rho h^3}{5\mu}\right] = 0 \quad (26)$$

from the above equation (26) $\frac{\partial \bar{p}}{\partial r} = \frac{27Q^2\rho}{280\pi^2 r^3 h^2} + \frac{3\rho r\Omega^2}{10} + \frac{C}{r}$ (27)

(from equation (24) it can be shown that $C = -\frac{3\mu Q}{4\pi h^3}$)

by combining equations (22) and (27) equation (22) becomes

$$V_r = \frac{1}{2\mu}(z^2 - h^2)\left(-\frac{3\mu Q}{4\pi r h^3} + \frac{27\rho Q^2}{280\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10}\right) - \frac{9Q^2\rho}{64\pi^2 h^6 r^3 \mu}$$

$$\left(\frac{h^4 z^2}{2} - \frac{h^2 z^4}{6} + \frac{z^6}{30} - \frac{11h^6}{30}\right) - \frac{\Omega^3 r p}{4\mu}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2} - \frac{hz}{3} -\right.$$

$$\left.\frac{11h^2}{12} + \frac{h^2}{3}\right) \quad (28)$$

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From equations (2) and (28) equation (2) can be written in the form

$$\frac{\partial V_z}{\partial z} = -\frac{1}{2\mu r}(z^2 - h^2)\frac{\partial}{\partial r}(r\frac{\partial \bar{p}}{\partial r}) - \frac{9Q^2\rho}{32\pi^2 h^6 r^4 \mu}(\frac{h^4 z^2}{2} - \frac{h^2 z^4}{6} + \frac{11h^6}{30})$$

$$+ \frac{\Omega^2\rho}{2\mu}(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2} - \frac{hz}{3} - \frac{11h^2}{12} + \frac{h^2}{3})$$

replacing $\frac{\partial}{\partial r}(r\frac{\partial \bar{p}}{\partial r})$ in the above equation by $-\frac{27Q^2\rho}{140\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{5}$

$$\frac{\partial V_z}{\partial z} = -\frac{1}{2\mu r}(z^2 - h^2)(-\frac{27Q^2\rho}{140\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{5}) - \frac{9Q^2\rho}{32\pi^2 h^6 r^4 \mu}$$

$$(\frac{h^4 z^2}{2} - \frac{h^2 z^4}{6} + \frac{11h^6}{30}) + \frac{\Omega^2\rho}{2\mu}(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2} - \frac{hz}{3} - \frac{11h^2}{12} + \frac{h^2}{2}) \quad (28A)$$

Integrating equation (28A) with respect to z and substituting the end conditions $V_z = 0$ when $z = h$, $V_z = 0$ when $z = -h$, it can be shown that

$$V_z = \frac{1}{2\mu r}(\frac{z^3}{3} - h^2 z)(-\frac{27Q^2\rho}{140\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{5}) - \frac{9Q^2\rho}{32\pi^2 h^6 r^4 \mu}$$

$$(\frac{h^4 z^3}{6} - \frac{h^2 z^5}{30} + \frac{z^7}{210} - \frac{11h^6 z}{30}) + \frac{\Omega^2\rho}{2\mu}(\frac{z^5}{60h^2} + \frac{z^4}{12h} + \frac{z^3}{6}$$

$$- \frac{hz^2}{6} - \frac{7h^2 z}{12} + \frac{h^3}{12}) \quad (29)$$

3.02 SOLUTION FOR THE STEPPED PARALLEL SURFACE HYDROSTATIC THRUST BEARING

The configuration of the hydrostatic thrust bearing is shown in FIG.18. By integrating equation (27) with respect to r

$$\bar{p} = \frac{-27Q^2\rho}{560\pi^2 r^2 h^2} + \frac{3\rho r^2\Omega^2}{20} + C \log_e r + D$$

the above expression can be used to predict the pressure distribution on either side of the step

$$\text{Let } \bar{p} = \frac{-27Q^2\rho}{560\pi^2 r^2 h^2 \alpha^2} + \frac{3\rho r^2\Omega^2}{20} + C_1 \log_e r + D_1 \qquad r_3 \geqslant r \geqslant r_1 \qquad (30)$$

$$\text{and } \bar{p} = \frac{-27Q^2\rho}{560\pi^2 r^2 h^2} + \frac{3\rho r^2\Omega^2}{20} + C_2 \log_e r + D_2 \qquad r_2 \geqslant r \geqslant r_3 \qquad (31)$$

For the boundary conditions let $\bar{p} = \bar{p}_1$ at radius r_1 and $\bar{p} = 0$ when $r = r_2$. The additional conditions needed to determine C_1, C_2, D_1 and D_2 are obtained from the requirements of flow and pressure continuity at the step. The expressions obtained are,

$$C_1 = \frac{\bar{p}_1 \left[1 + K_1\left\{\frac{1}{\alpha^2 (RD1)^2} - \frac{1}{(RD3)^2}\left(\frac{1}{\alpha^2} - 1\right) - 1\right\} - K_2\left((RD1)^2 - 1\right)\right]}{(\alpha^3 - 1)\log_e(RD3) + \log_e(RD1)} \qquad (32)$$

$$C_2 = \frac{\bar{p}_1 \alpha^3 \left[1 + K_1\left\{\frac{1}{\alpha^2 (RD1)^2} - \frac{1}{(RD3)^2}\left(\frac{1}{\alpha^2} - 1\right) - 1\right\} - K_2\left((RD1)^2 - 1\right)\right]}{(\alpha^3 - 1)\log_e(RD3) + \log_e(RD1)}$$

$$D_1 = \bar{p}_1 + \frac{K_1 \bar{p}_1}{(RD1)^2\alpha^2} - K_2\bar{p}_1 (RD1)^2 - \bar{p}_1 \log_e r_1 \frac{\left[1 + K_1\left\{\frac{1}{\alpha^2 (RD1)^2} - \frac{1}{(RD3)^2}\left(\frac{1}{\alpha^2} - 1\right) - 1\right\} - K_2\left((RD1)^2 - 1\right)\right]}{(\alpha^3 - 1)\log_e(RD3) + \log_e(RD1)}$$

$$D_2 = \bar{p}_1 (K_1 - K_2) - \bar{p}_1 \alpha^3 \log_e r_2 \frac{\left[1 + K_1\left\{\frac{1}{\alpha^2 (RD1)^2} - \frac{1}{(RD3)^2}\left(\frac{1}{\alpha^2} - 1\right) - 1\right\} - K_2\left((RD1)^2 - 1\right)\right]}{(\alpha^3 - 1)\log_e(RD3) + \log_e(RD1)}$$

where $K_1 = \frac{27\rho Q^2}{560\pi^2 h^2 \bar{p}_1 r_2^2}$, $K_2 = \frac{3\rho\Omega^2 r_2^2}{20\bar{p}_1}$, $RD1 = (\frac{r_1}{r_2})$ and $RD3 = (\frac{r_3}{r_2})$

The lubricant flow rate through the bearing can be found by solving the quadratic equation formed by combining equation (32) with the relation $C_1 = -\frac{3\mu Q}{4\pi h^3 \alpha^3}$

thus $\frac{-3\mu Q}{4\pi h^3 \alpha^3} =$

$$\frac{\bar{p}_1 \left[1 + \frac{27\rho Q^2}{560\pi^2 h^2 \bar{p}_1 r_2^2}\left\{\frac{r_2^2}{(\alpha r_1)^2} - (\frac{r_2}{r_3})^2 (\frac{1}{\alpha^2} - 1) - 1\right\} - \frac{3\rho\Omega^2 r_2^2}{20\bar{p}_1}\left\{(\frac{r_1}{r_2})^2 - 1\right\}\right]}{(\alpha^3 - 1)\log_e(\frac{r_3}{r_2}) + \log_e(\frac{r_1}{r_2})}$$

giving the final solution

$$Q = \frac{1}{2}\left[-\frac{81\mu\pi r_2^2}{2240 h\alpha^3\rho}\frac{[(\alpha^3 - 1)\log_e(\frac{r_3}{r_2}) + \log_e(\frac{r_1}{r_2})]}{[(\frac{r_2}{\alpha r_1})^2 - (\frac{r_3}{r_2})^2(\frac{1}{\alpha^2} - 1) - 1]}\right.$$
$$\pm\left\{\left(\frac{81\mu\pi r_2^2}{2240 h\alpha^3\rho}\frac{[(\alpha^3 - 1)\log_e(\frac{r_3}{r_2}) + \log_e(\frac{r_1}{r_2})]}{[(\frac{r_2}{\alpha r_1})^2 - (\frac{r_3}{r_2})^2(\frac{1}{\alpha^2} - 1) - 1]}\right)^2\right.$$
$$\left.\left. - \left(\frac{27\pi^2 h^2 \bar{p}_1 r_2^2 [1 - (\frac{3\rho\Omega^2 r_2^2}{20\bar{p}_1})\{(\frac{r_1}{r_2})^2 - 1\}]}{140\rho[(\frac{r_2}{\alpha r_1})^2 - (\frac{r_1}{r_2})^2(\frac{1}{\alpha^2} - 1) - 1]}\right)\right\}^{\frac{1}{2}}\right] \quad (33)$$

thus for a particular pressure $\bar{p}_1$ at radius r_1. there could, theoretically, be two values of flow rate Q, one of which may be negative or zero.

The above theoretical relationship between Q, $\bar{p}_1$ and r_1 etc has been shown graphically in FIGS. 53 - 58 inclusive.

These graphs have been used to provide the value of the theoretical static pressure at the datum radius r_1 in the solution of equations (30) and (31).

A computer print out of results associated with equation (33) is given in Appendix (4).

3.03 THEORETICAL THRUST - Calculated from theoretical pressure distribution

the static pressure $\bar{p} = \frac{-27Q^2\rho}{560\pi^2r^2h^2\alpha^2} + \frac{3\rho r^2\Omega^2}{20}$

$$+ C_1\log_e r + D_1 \qquad (r_3 \geqslant r \geqslant r_1)$$

and $\bar{p} = \frac{-27Q^2\rho}{560\pi^2r^2h^2} + \frac{3\rho r^2\Omega^2}{20}$

$$+ C_2\log_e r + D_2 \qquad (r_2 \geqslant r \geqslant r_3)$$

$$\text{THRUST (F)} = \pi r_1{}^2\bar{p}_1 + 2\pi\int_{r_1}^{r_3}\bar{p}r\,dr + 2\pi\int_{r_3}^{r_2}\bar{p}r\,dr$$

$$F = \pi r_1{}^2\bar{p}_1 + 2\pi\Big[\frac{-27Q^2\rho}{560\pi^2h^2\alpha^2}\log_e\left(\frac{r_3}{r_1}\right) + \frac{3\Omega^2}{80}(r_3{}^4-r_1{}^4)$$

$$+ C_1\left\{\frac{r_3{}^2}{4}(2\log_e r_3 - 1) - \frac{r_1{}^2}{4}(2\log_e r_1 - 1)\right\} + \frac{D_1}{2}(r_3{}^2 - r_1{}^2)$$

$$- \frac{27Q^2\rho}{560\pi^2h^2}\log_e\left(\frac{r_2}{r_3}\right) + \frac{3\Omega^2}{80}(r_2{}^4 - r_3{}^4) + C_2\left\{\frac{r_2{}^2}{4}(2\log_e r_2 - 1)\right.$$

$$\left. - \frac{r_3{}^2}{4}(2\log_e r_3 - 1)\right\} + \frac{D_2}{2}(r_2{}^2 - r_3{}^2)\Big] \qquad (34)$$

A computer print out employing this equation is shown in Appendix (2).

3.04 EXPERIMENTAL THRUST - Calculated from the experimental pressure distribution

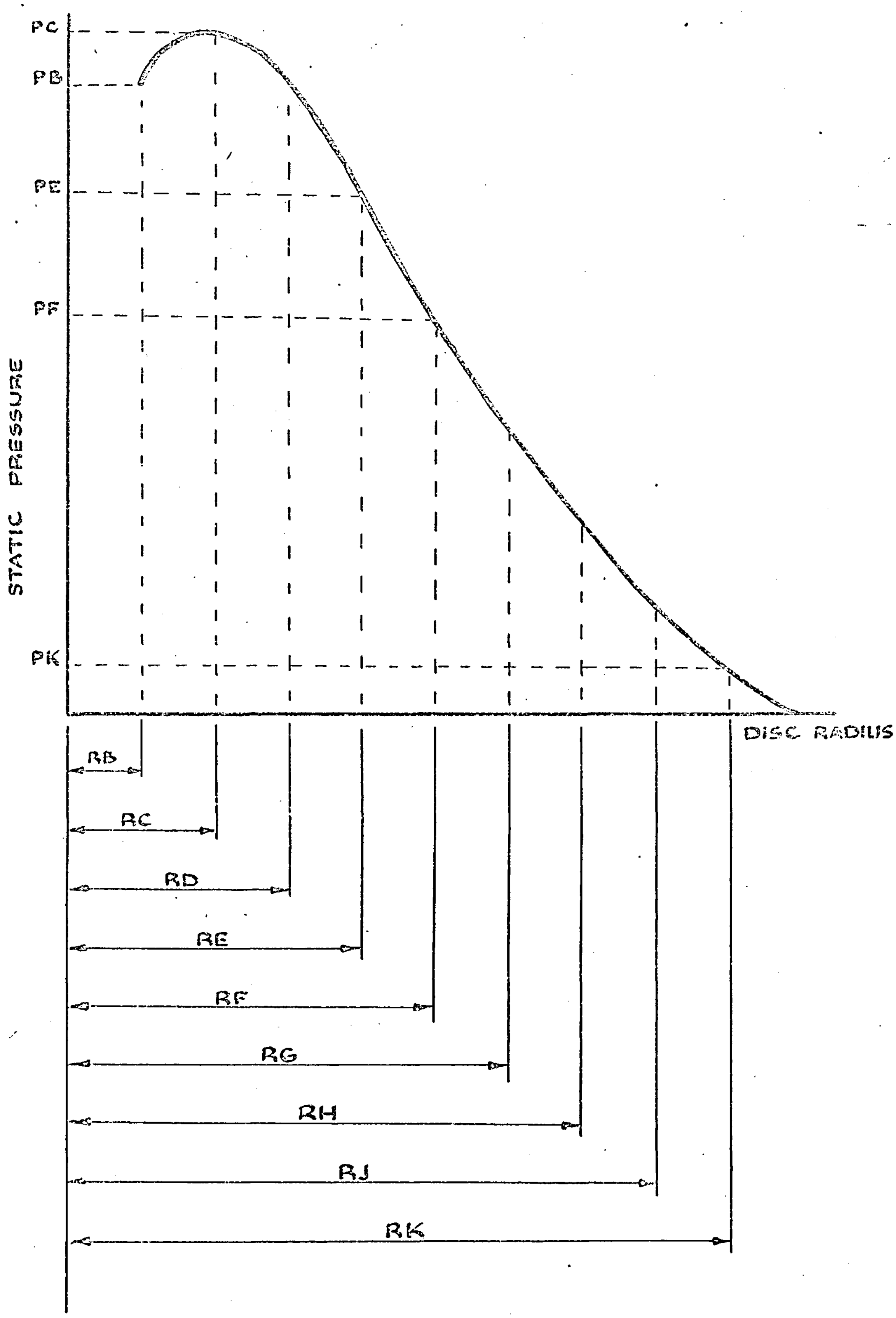
The value of the 'experimental' thrust has been calculated by using Simpson's Rule to evaluate the integral $2\pi\int\bar{p}r\,dr$, where the static pressure value $\bar{p}$ is determined experimentally. The co-ordinates used when applying Simpson's rule are shown in FIG.(19). The pressures PB, PC etc are in inches of H_2O.

B — the element width is 0.0095m.

The experimental thrust (THE) has been calculated from the equation:

$$THE = 2\pi\left[\left(\frac{249.1 \times B}{3}\right) \times \{2((PC \times RC) + (PE \times RE) + (PG \times RG) + (PJ \times RJ)) + 4.0((PB \times RB) + (PD \times RD) X (PF \times RF) + (PH \times RH) X (PK \times RK))\}\right] \text{ Newtons} \quad (35)$$

A computer print-out employing this equation is shown in Appendix (2).



CO-ORDINATES USED FOR EMPLOYING SIMPSON'S RULE TO DETERMINE EXPERIMENTAL THRUST.

FIG. Nº 19.

CHAPTER 4 COMPRESSIBILITY

4.01 THE RELEVANCE OF THE COMPRESSIBILITY TERM IN ANALYSING THE PERFORMANCE OF A HYDROSTATIC THRUST BEARING

The Navier Stokes equations (1) used in the earlier analysis (CHAPTER 3) omitted the compressibility terms, which in the r direction takes the form $\frac{\mu}{3}\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2}\right)$, the omission of this term is justified if the fluid flow is radial, and the density of the lubricant constant. Under these conditions the continuity equation takes the form $\frac{\partial V_r}{\partial r} + \frac{V_r}{r} = 0$ which when differentiated with respect to r becomes $\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2} = 0$, hence the compressibility term = 0. If the fluid is assumed to have axial as well as radial flow then the continuity equation takes the form $\frac{\partial V_r}{\partial r} + \frac{V_r}{r} + \frac{\partial V_z}{\partial z} = 0$ if this equation is non-dimensionalised, it can be shown that the omission of $\frac{\partial V_z}{\partial z}$ is justified if $\frac{4hU}{DW}$ is >> 1.

Hobson and Lawrie (8) considered the effect of inertia and compressibility in an externally pressurised gas lubrication thrust bearing, assuming the flow to be isothermal.

Starting with the Navier Stokes equation in the form

$$\rho V_r \frac{\partial V_r}{\partial r} = -\frac{\partial p}{\partial r} + \frac{\mu}{3}\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2}\right) + \mu\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial z^2}\right)$$

INERTIA PRESSURE COMPRESSIBILITY VISCOUS

and using the transverse velocity profile in parabolic form

$$V_r = \frac{3\dot{m}}{8\pi\rho r h^3}(h^2 - z^2)$$

by differentiating with respect to r they obtained:

$$\frac{\partial V_r}{\partial r} = -C(h^2 - z^2)\left(\frac{1}{pr^2} + \frac{1}{p^2 r}\frac{\partial p}{\partial r}\right),$$

$$\frac{\partial^2 V_r}{\partial r^2} = C(h^2 - z^2)\left[\frac{2}{pr^3} + \frac{2}{p^2 r^2}\frac{\partial p}{\partial r} + \frac{2}{p^3 r}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2 r}\frac{\partial^2 p}{\partial r^2}\right]$$

and $\frac{\partial^2 V_r}{\partial z^2} = -\frac{2C}{pr}$

where ρ is replaced by $\frac{p}{RT}$ and $C = \frac{3\dot{m}\bar{R}T}{8\pi h^3}$ and is constant for isothermal flow and a given film thickness and mass flow rate. When the above is substituted in the full Navier Stokes equation the following differential equation is obtained:

$$-\frac{3\dot{m}C}{8\pi h^3}(h^2 - z^2)^2\left(\frac{1}{pr^3} + \frac{1}{p^2 r^2}\frac{\partial p}{\partial r}\right) = -\frac{\partial p}{\partial r} + \frac{\mu C}{3}(h^2 - z^2)\left[\frac{1}{p^2 r^2}\frac{\partial p}{\partial r} + \frac{2}{p^3 r}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2 r}\frac{\partial^2 p}{\partial r^2}\right] + \mu C\left[(h^2 + z^2)\left(\frac{1}{p^2 r^2}\frac{\partial p}{\partial r} + \frac{2}{p^3 r}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2 r}\frac{\partial^2 p}{\partial r^2}\right) - \frac{2}{pr}\right]$$

integrating this equation over the film thickness, 2h, and substituting for C the following differential equation is obtained:

$$\underbrace{-\frac{3\dot{m}^2\bar{R}T}{40\pi^2 h}\left(\frac{1}{pr^3} + \frac{1}{p^2 r^3}\frac{\partial p}{\partial r}\right)}_{\text{INERTIA}} = \underbrace{-h\left(\frac{\partial p}{\partial r}\right)}_{\text{PRESSURE}} + \underbrace{\frac{\mu\dot{m}\bar{R}T}{12\pi}\left[\frac{1}{p^2 r^2}\frac{\partial p}{\partial r} + \frac{2}{p^3 r}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2 r}\left(\frac{\partial^2 p}{\partial r^2}\right)\right]}_{\text{COMPRESSIBILITY}} +$$

$$\underbrace{\frac{\mu\dot{m}\bar{R}T}{4\pi}\left[\frac{1}{p^2 r^2}\frac{\partial p}{\partial r} + \frac{2}{p^3 r}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2 r}\frac{\partial^2 p}{\partial r^2} - \frac{3}{h^2 pr}\right]}_{\text{VISCOUS}}$$

From their experimental radial pressure distribution, values of $(\frac{\partial p}{\partial r})$ were determined graphically and then, in turn, plotted against the radius. The second partial derivative they estimated from the resulting curve. These results were substituted in the final differential equation and the relevance of the compressibility term determined, for different radii, from the ratio compressibility term/viscous term. For their series of tests they found this ratio to be very small (less than 10^{-4} per cent).
A graph showing the relevance of the compressibility term for two values of R_e, is shown in FIG.32.

If instead of the transverse velocity profile $V_r = \frac{3\dot{m}}{8\pi\rho r h^3}(h^2 - z^2)$, we substitute equation (18) replacing ρ by $\frac{p}{RT}$ etc.

$$V_r = \frac{1}{2\mu}(z^2 - h^2)\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2 r^3 h^2 p} + \frac{3pr\Omega^2}{10RT} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3 rp}\right) - \frac{\dot{m}^2\bar{R}T}{32\pi^2 r^3 p\mu}\left(\frac{z^2}{h^2} - 1\right) -$$

$$\frac{pr\Omega^2}{4\mu\bar{R}T}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7p\Omega^2 rh^2}{48\mu\bar{R}T} + \frac{p\Omega^2 rhz}{12\mu RT}$$

which has already been shown, allows for the rotational and radial inertia effects. The following equations are obtained for the compressibility and viscous terms (see Appendix 1 for the complete solution.)

$$\text{compressibility term} = \frac{\mu}{3}\left[-\frac{2h^3}{3\mu}\left\{\frac{\dot{m}^2\bar{R}T}{16\pi^2 h^2}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \right.\right.\right.$$

$$\left.\frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10RT}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{2}{pr^3} + \frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \right.$$

$$\left.\left.\frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} + \frac{2}{rp^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r}\right)\right\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} + \frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 - \right.$$

$$\left.\frac{1}{p^2r^3}\left(\frac{\partial^2 p}{\partial r^2}\right) + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right)\left(-\frac{4h}{3}\right) - \frac{11\Omega^2 h^3}{120\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) +$$

$$\frac{7h^3\Omega^2}{24\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{1}{r}\Big\{-\frac{2h^3}{3\mu}\Big\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right) +$$

$$\frac{3\Omega^2}{10\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right) + \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{1}{pr^2} + \frac{1}{p^2r}\frac{\partial p}{\partial r}\right)\Big\} + \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(\frac{3}{pr^4} + \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right)\left(-\frac{4h}{3}\right) -$$

$$\frac{\Omega^2}{4\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\frac{11}{30}h^3 + \frac{7\Omega^2h^3}{24\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\Big\} - \frac{1}{r^2}\Big\{-\frac{2h^3}{3\mu}\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2r^3p} + \frac{3\Omega^2pr}{10\bar{R}T} -\right.$$

$$\left.\frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}\right) + \frac{\dot{m}^2\bar{R}Th}{24\pi^2\mu r^3p} - \frac{11\Omega^2prh^3}{120\mu\bar{R}T} + \frac{7\Omega^2h^3pr}{24\mu\bar{R}T}\Big\}\Big]$$

$$\text{Viscous term} = \mu\Big[-\frac{2h^3}{3\mu}\Big\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 +\right.$$

$$\left.\frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{2}{pr^3} + \frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} +\right.$$

$$\left.\frac{2}{rp^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r}\right)\Big\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\left(\frac{\partial p}{\partial r}\right) + \frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2r^3}\left(\frac{\partial^2 p}{\partial r^2}\right) +\right.$$

$$\left.\frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right)\left(-\frac{4h}{3}\right) - \frac{11\Omega^2h^3}{120\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{7h^3\Omega^2}{24\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{1}{r}\Big\{-\frac{2h^3}{3\mu}$$

$$\Big\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right) + \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{1}{pr^2} + \frac{1}{p^2r}\frac{\partial p}{\partial r}\right)\Big\} +$$

$$\frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(\frac{3}{pr^4} + \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right)\left(-\frac{4h}{3}\right) - \frac{\Omega^2}{4\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\frac{11h^3}{30} + \frac{7\Omega^2h^3}{24\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\Big\} -$$

$$\frac{1}{r^2}\Big\{-\frac{2h^3}{3\mu}\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2r^3p} + \frac{3\Omega^2pr}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}\right) + \frac{\dot{m}^2\bar{R}Th}{24\pi^2\mu r^3p} - \frac{11\Omega^2prh^3}{120\mu\bar{R}T} +$$

$$\frac{7\Omega^2h^3pr}{24\mu\bar{R}T}\Big\} + \frac{2h}{\mu}\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2r^3h^2p} + \frac{3pr\Omega^2}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}\right) - \frac{\dot{m}^2\bar{R}T}{8\pi^2r^3p\mu h} - \frac{2pr\Omega^2h}{3\mu\bar{R}T}\Big]$$

The relevance of the compressibility term compared with the viscous term can be obtained from the ratio compressibility term/viscous term.

Graphs showing the relevance of the compressibility term for four different values of R_e are shown in FIGS. 33 and 34.

4.02 THEORETICAL DETERMINATION OF PARTIAL DERIVATIVES $\frac{\partial p}{\partial r}$ and $\frac{\partial^2 p}{\partial r^2}$

For a plain thrust bearing, i.e. one without a central recess, it has been shown (23) that

$$\frac{\partial \bar{p}}{\partial r} = -\frac{3\mu Q}{4\pi r h^3} + \frac{27\rho Q^2}{280\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10} \qquad (23A)$$

If this equation is differentiated with respect to r, then,

$$\frac{\partial^2 \bar{p}}{\partial r^2} = \frac{3\mu Q}{4\pi r^2 h^3} - \frac{81\rho Q^2}{280\pi^2 r^4 h^2} + \frac{3\rho\Omega^2}{10}$$

These two equations were used to determine, theoretically, the values of $\frac{\partial \bar{p}}{\partial r}$ and $\frac{\partial^2 \bar{p}}{\partial r^2}$, enabling a check to be made on the graphically determined values shown in FIGS. 26-31 inclusive.

EXAMPLE

Test No.19

when r = 0.06m

$\frac{\partial \bar{p}}{\partial r} = -28770 \text{ N/m}^3$ (-28300 N/m^3 graphically)

$\frac{\partial^2 \bar{p}}{\partial r^2} = 391800 \text{ N/m}^4$ (382000 N/m^4 graphically)

Test No.20

when r = 0.06m

$\frac{\partial \bar{p}}{\partial r} = -25890 \text{ N/m}^3$ (-23500 N/m^3 graphically)

$\frac{\partial^2 \bar{p}}{\partial r^2} = 456500 \text{ N/m}^4$ (468000 N/m^4 graphically)

RADIAL POSITION OF MAXIMUM STATIC PRESSURE $\bar{p}$

From equation (23A)

$$\frac{\partial \bar{p}}{\partial r} = \frac{-3\mu Q}{4\pi r h^3} + \frac{27\rho Q^2}{280\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10}$$

for $\bar{p}$ to be a maximum $\frac{\partial \bar{p}}{\partial r} = 0$

$$\therefore \frac{3\mu Q}{4\pi r h^3} = \frac{27\rho Q^2}{280\pi^2 r^3 h^2} + \frac{3\rho\Omega^2 r}{10}$$

multiplying both sides of the above equation by r^3

$$\frac{3\mu Q r^2}{4\pi h^3} = \frac{27\rho Q^2}{280\pi^2 h^2} + \frac{3\rho\Omega^2 r^4}{10}$$

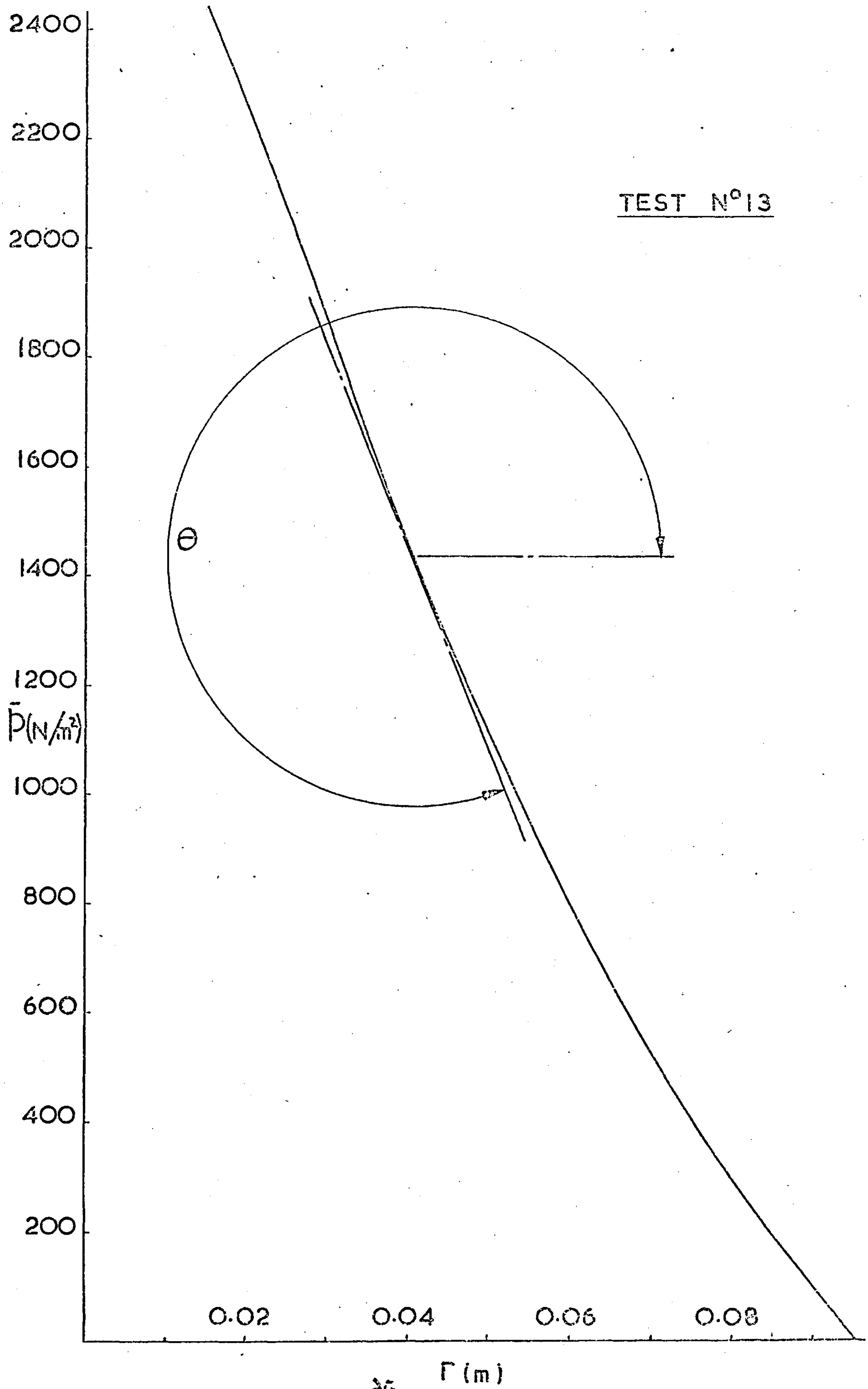
Let $A = r^2$

then $$\frac{3\rho\Omega^2 A^2}{10} - \frac{3\mu Q A}{4\pi h^3} + \frac{27\rho Q^2}{280\pi^2 h^2} = 0$$

$$\therefore A^2 - \frac{5\mu Q A}{2\pi h^3 \rho\Omega^2} + \frac{Q^2}{28\pi^2 h^2 \Omega^2} = 0$$

The solution for this quadratic equation, and hence the value of r from $r = \sqrt{A}$, for tests 19 and 20, is given in the computer print-out Appendix (3). The theoretical position of the $\bar{p}$(max) for Tests 19 and 20 is shown in FIG.44.

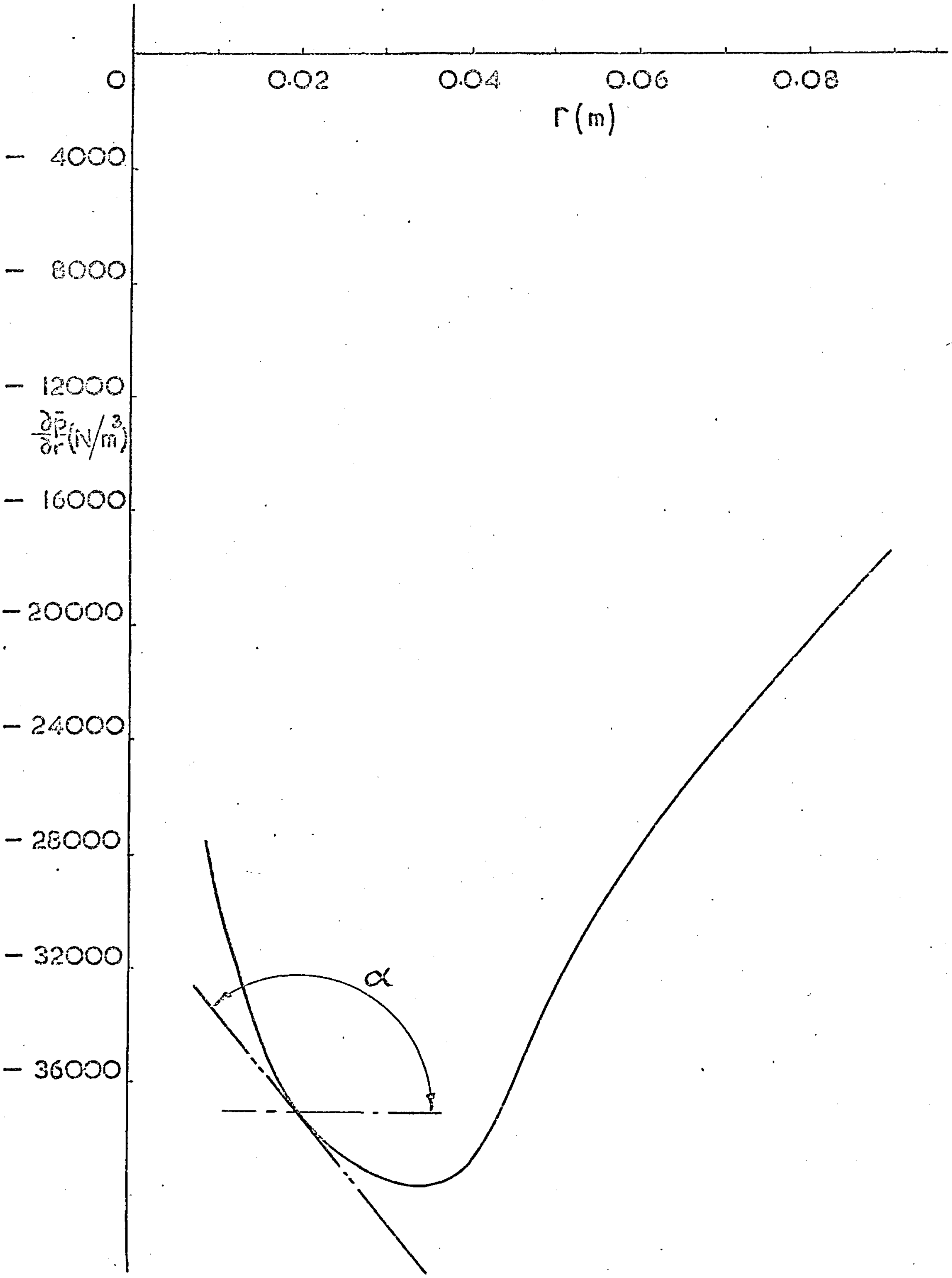
Note: $\bar{p}$(max) and P(max) will occur at the same radius for any one test.



DETERMINATION OF $\frac{d\bar{p}}{dr}$ FROM EXPERIMENTAL RESULTS

FIG. N° 20.

TEST N°13



DETERMINATION OF $\frac{\partial^2 \bar{p}}{\partial r^2}$ FROM EXPERIMENTAL RESULTS

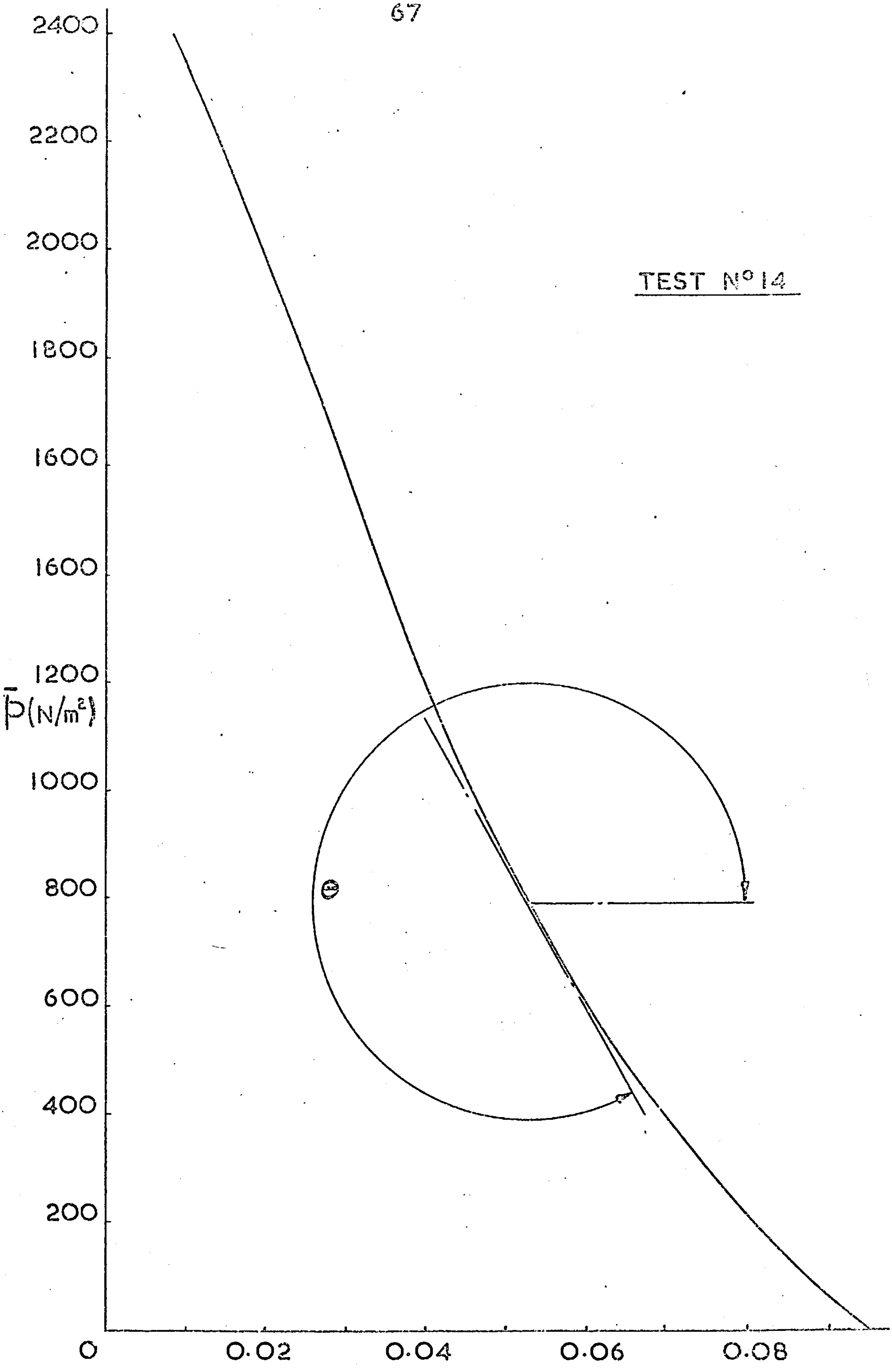
FIG. N° 21.

r (cm)	Θ (degrees)	$-\frac{\partial p}{\partial r}$ (15000 tan Θ)	α (degrees)	$-\frac{\partial^2 p}{\partial r^2} \times 10^6$ (300000 tan α)
1.0	− 62.0	− 28200	− 76.0	− 1.203
1.5	− 66.0	− 33600	− 70.5	− 0.847
2.0	− 68.0	− 37200	− 50.0	− 0.358
3.0	− 69.0	− 39100	− 29.0	− 0.166
4.0	− 69.0	− 39100	52.5	0.391
5.0	− 65.0	− 32200	61.0	0.541
6.0	− 61.0	− 27100	54.0	0.413
7.0	− 59.5	− 25400	50.0	0.358
8.0	− 54.0	− 20600	47.0	0.322
8.5	− 51.5	− 18800	46.0	0.311

COMPRESSIBILITY TEST N° 13

TABLE OF RESULTS

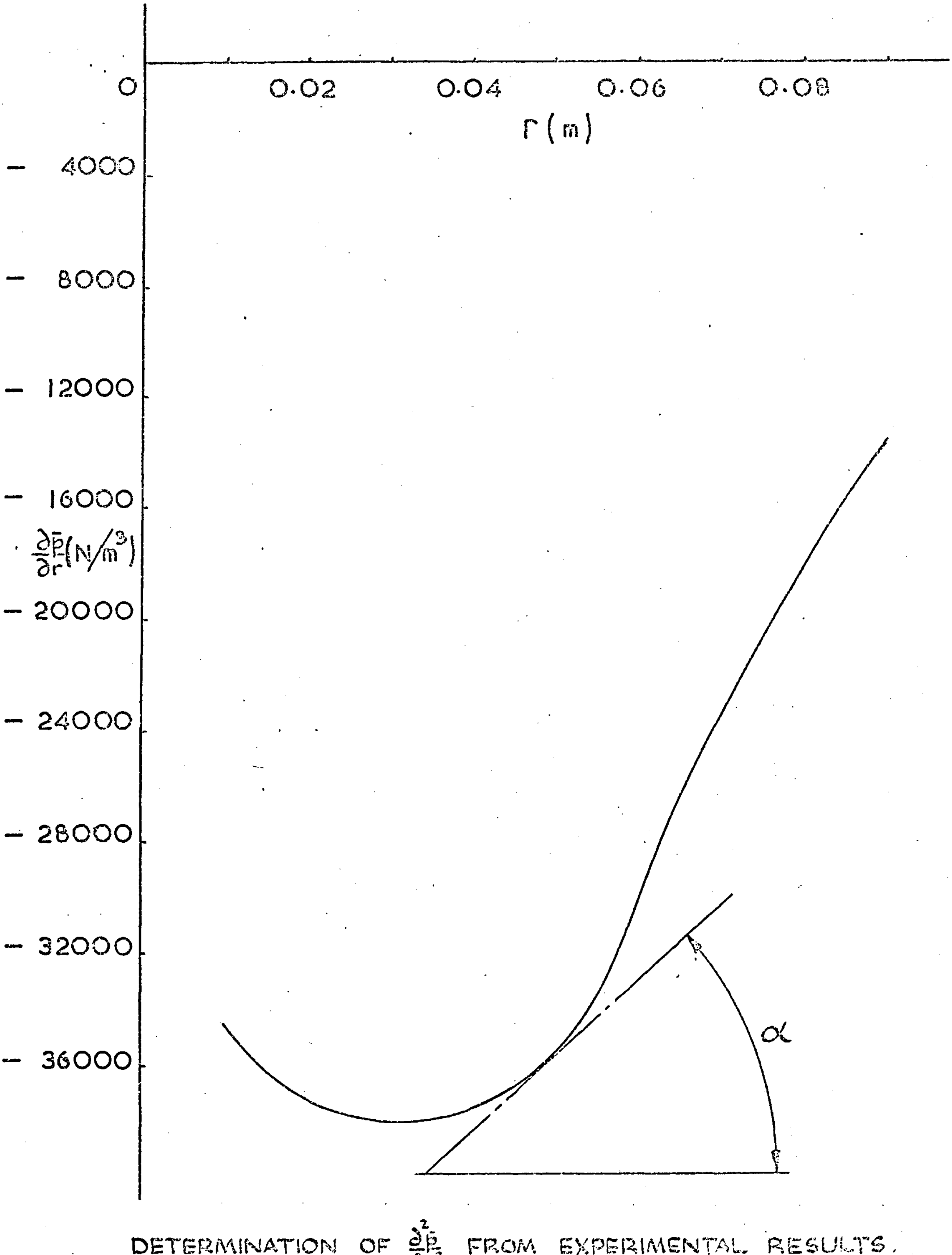
FIG. N° 22.



DETERMINATION OF $\frac{\partial \bar{p}}{\partial r}$ FROM EXPERIMENTAL RESULTS

FIG. N° 23.

TEST N° 14



DETERMINATION OF $\frac{\partial^2 \bar{p}}{\partial r^2}$ FROM EXPERIMENTAL RESULTS.

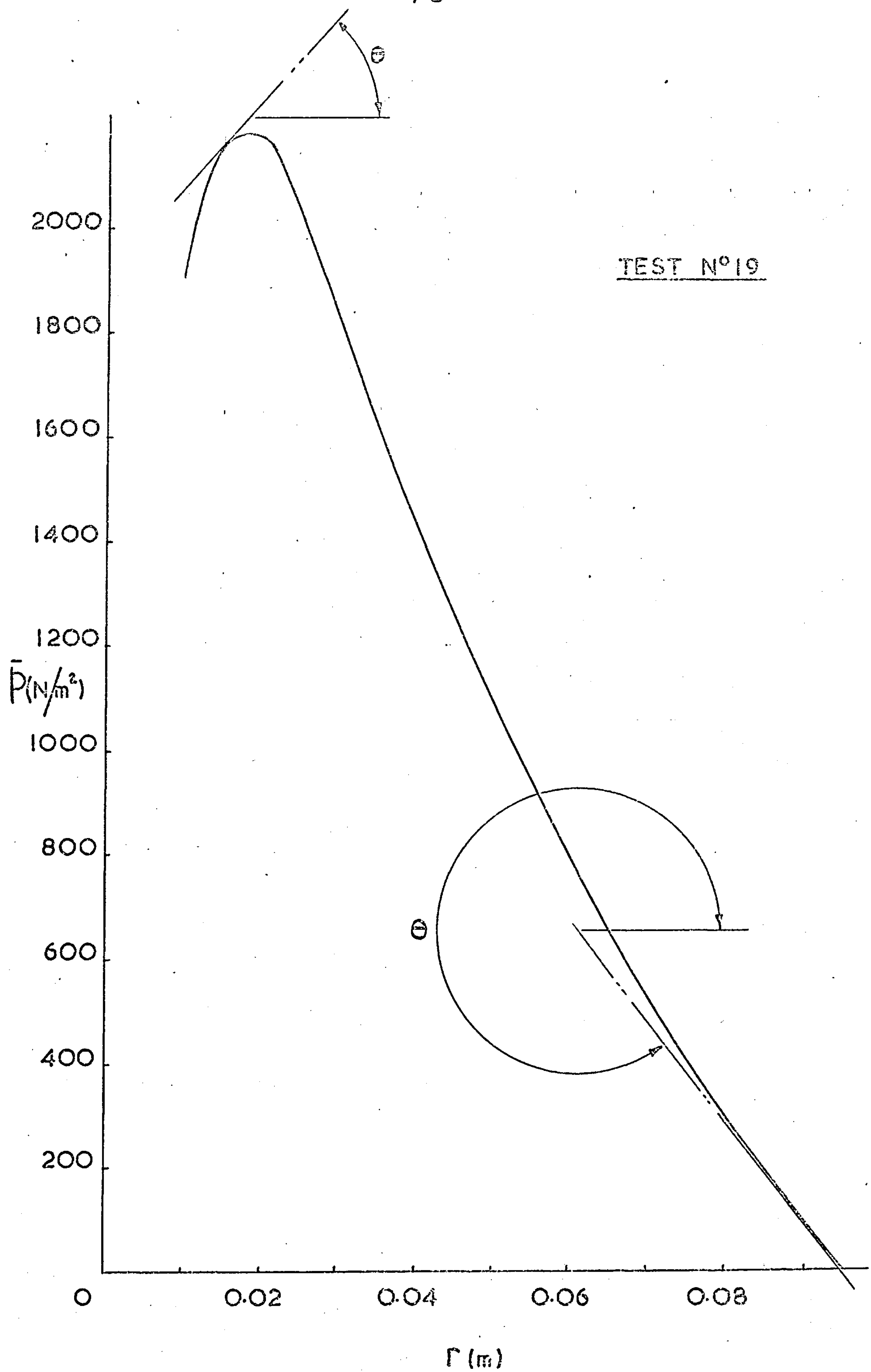
FIG. N° 24.

r (cm)	θ (degrees)	$\frac{\partial p}{\partial r}$ (15000 tan θ)	α (degrees)	$\frac{\partial^2 p}{\partial r^2} \times 10^6$ (300000 tan α)
1.0	− 66.5	− 34500	− 58.0	− 0.48
1.5	− 68.0	− 67130	− 40.5	− 0.256
2.0	− 68.5	− 38080	− 27.5	− 0.156
3.0	− 69.5	− 40120	− 3.0	− 0.016
4.0	− 67.5	− 36210	18.0	0.098
5.0	− 27.5	− 28820	42.0	0.270
6.0	− 58.5	− 24480	69.0	0.782
7.0	− 53.0	− 19900	61.5	0.552
8.0	− 48.0	− 16660	60.0	0.519
8.5	− 42.0	− 13510	57.0	0.462

COMPRESSIBILITY TEST N° 14

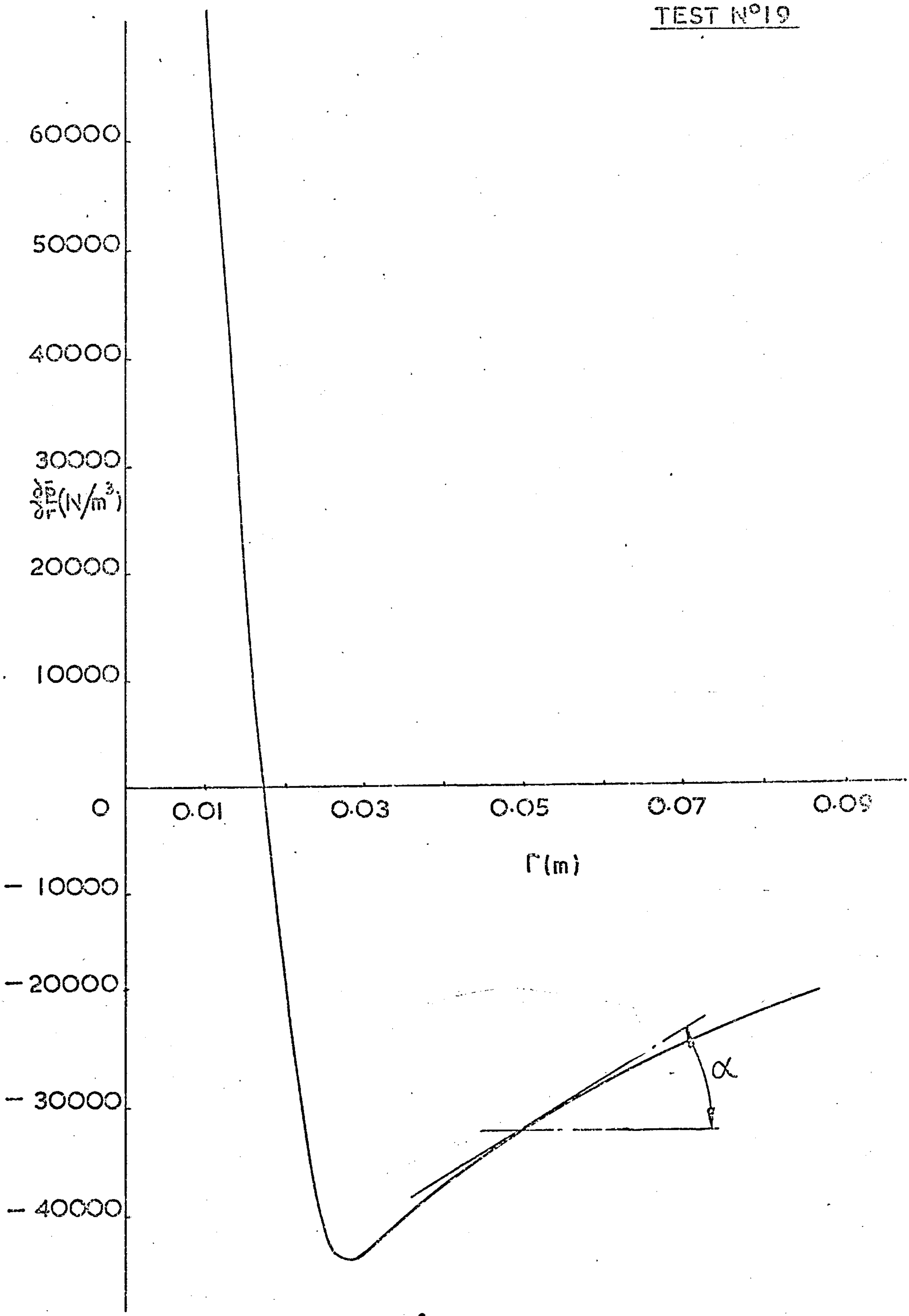
TABLE OF RESULTS

FIG. N° 25.



DETERMINATION OF $\frac{\partial \bar{p}}{\partial r}$ FROM EXPERIMENTAL RESULTS.

FIG. Nº 26.



DETERMINATION OF $\frac{\partial^2 \bar{p}}{\partial r^2}$ FROM EXPERIMENTAL RESULTS

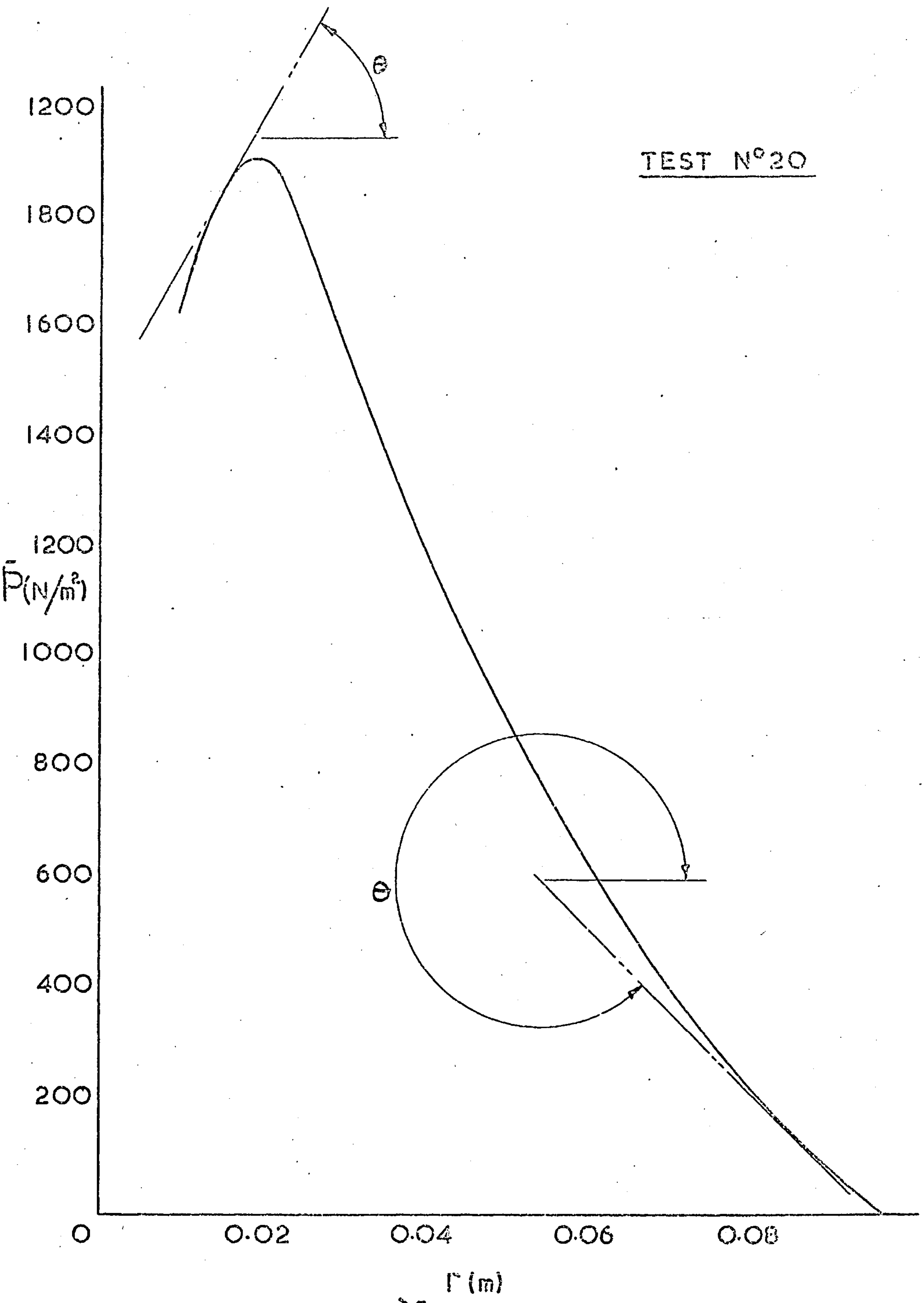
FIG. N° 27.

r (cm)	θ (degrees)	$\frac{\partial p}{\partial r}$ (15000 tan θ)	α (degrees)	$\frac{\partial^2 p}{\partial r^2} \times 10^6$ (750000 tan α)
1.0	78.0	70700	−85.0	−8.573
1.5	48.0	16670	−84.0	−7.136
2.0	−43.0	−14000	−82.0	−5.336
3.0	−71.0	−43700	30.0	0.433
4.0	−68.0	−37100	35.0	0.525
5.0	−65.0	−32200	29.0	0.416
6.0	−62.0	−28300	27.0	0.382
7.0	−58.0	−24000	25.0	0.349
8.0	−55.0	−21400	22.2	0.311
8.5	−52.0	−19200	21.0	0.288

COMPRESSIBILITY TEST N° 19

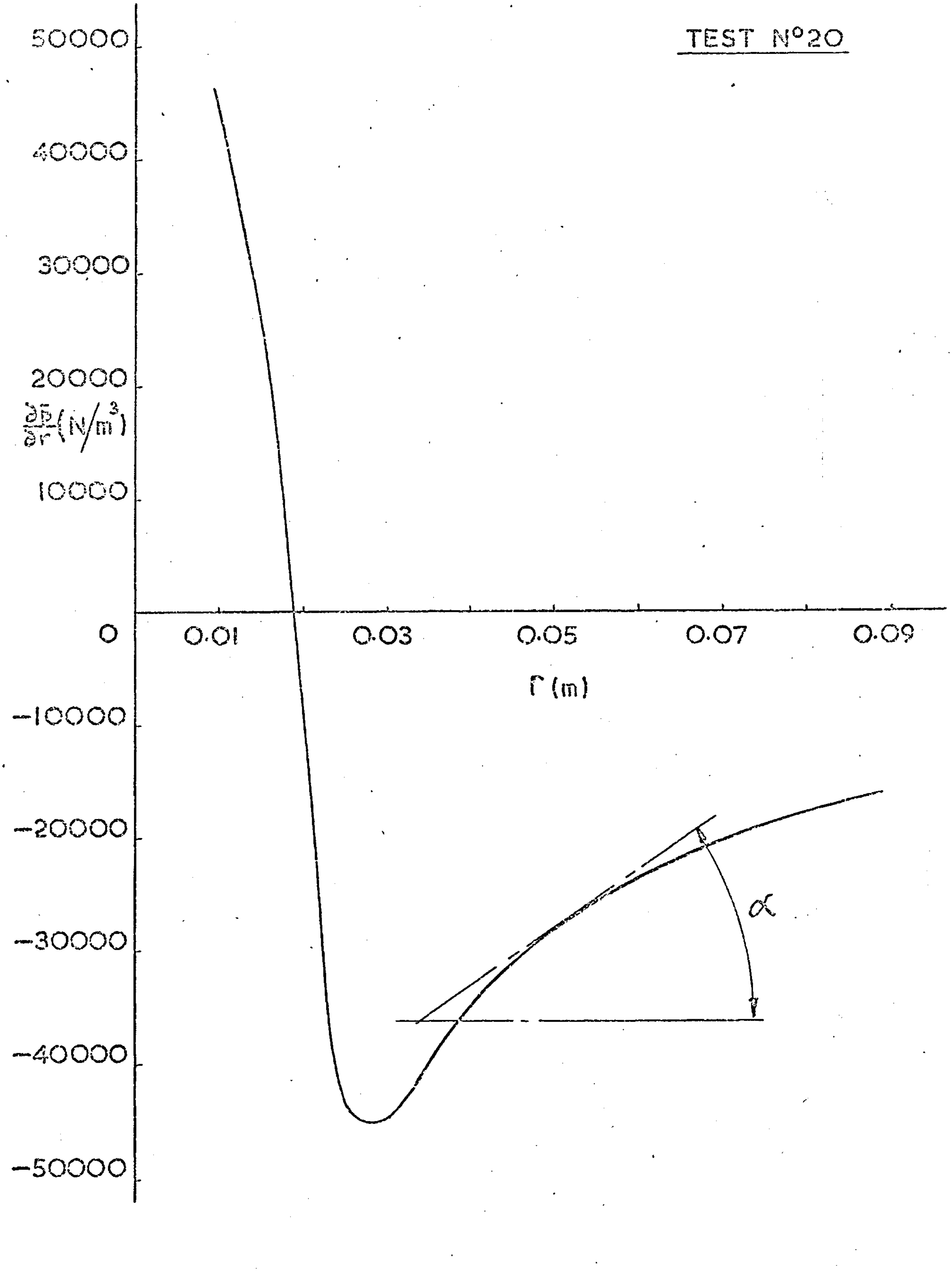
TABLE OF RESULTS

FIG. N° 28.



DETERMINATION OF $\frac{\partial \bar{p}}{\partial r}$ FROM EXPERIMENTAL RESULTS

FIG. N° 29.



DETERMINATION OF $\frac{\partial \bar{p}}{\partial r^2}$ FROM EXPERIMENTAL RESULTS

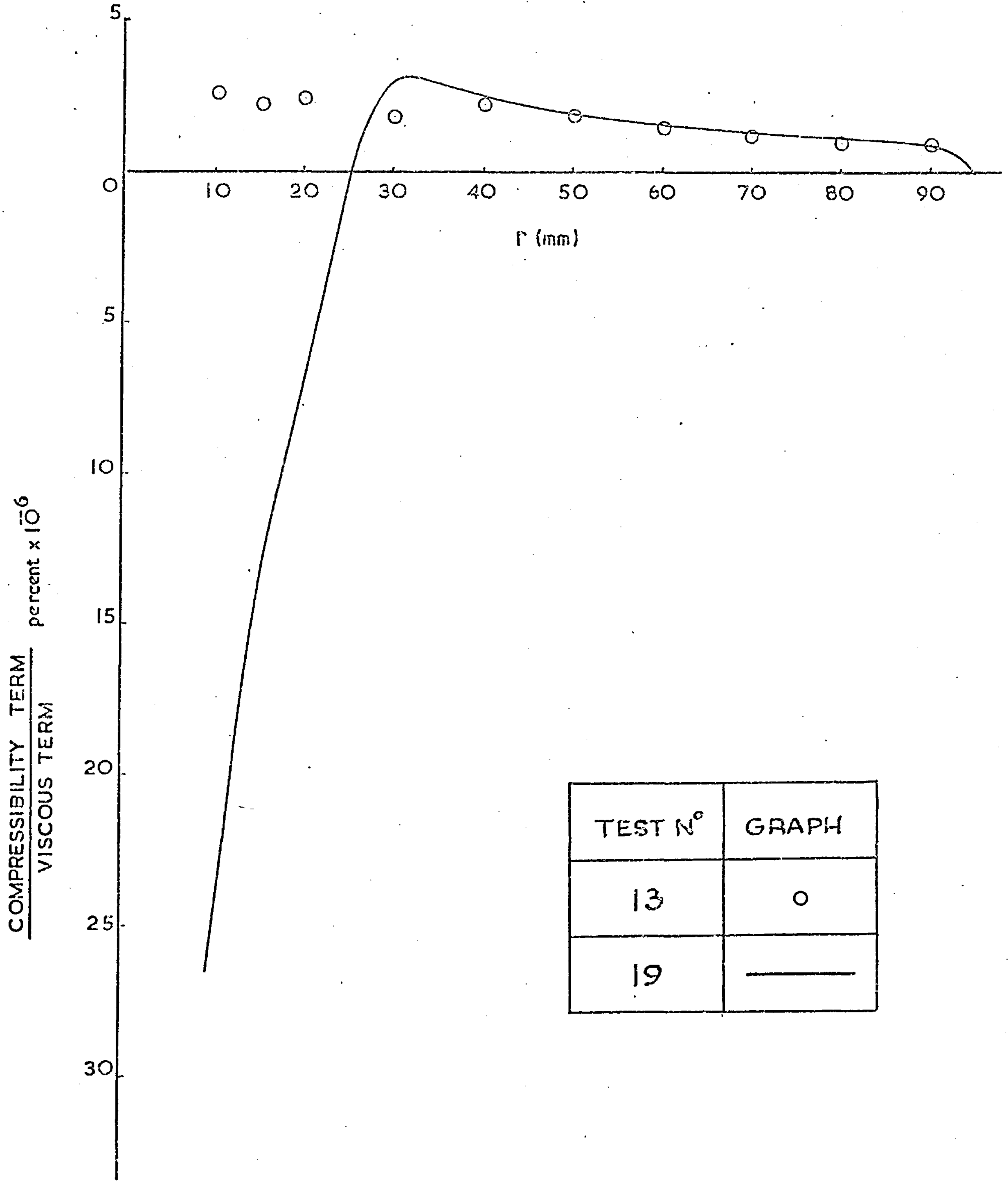
FIG. N° 30.

r (cm)	θ (degrees)	$\frac{\partial p}{\partial r}$ (15000 tan θ)	α (degrees)	$\frac{\partial^2 p}{\partial r^2} \times 10^6$ (750000 tan α)
1.0	7.25	44200	−83.0	−6.108
1.5	60.0	26000	−81.5	−5.108
2.0	−22.5	−6200	−83.5	−6.582
3.0	−71.5	−44800	30.0	0.433
4.0	−66.0	−33700	42.0	0.675
5.0	−61.5	−27600	36.0	0.545
6.0	−57.5	−23500	32.0	0.468
7.0	−53.0	−19900	32.0	0.273
8.0	−50.5	−18100	16.0	0.215
8.5	−45.0	−15000	81.5	0.201

COMPRESSIBILITY TEST N° 20

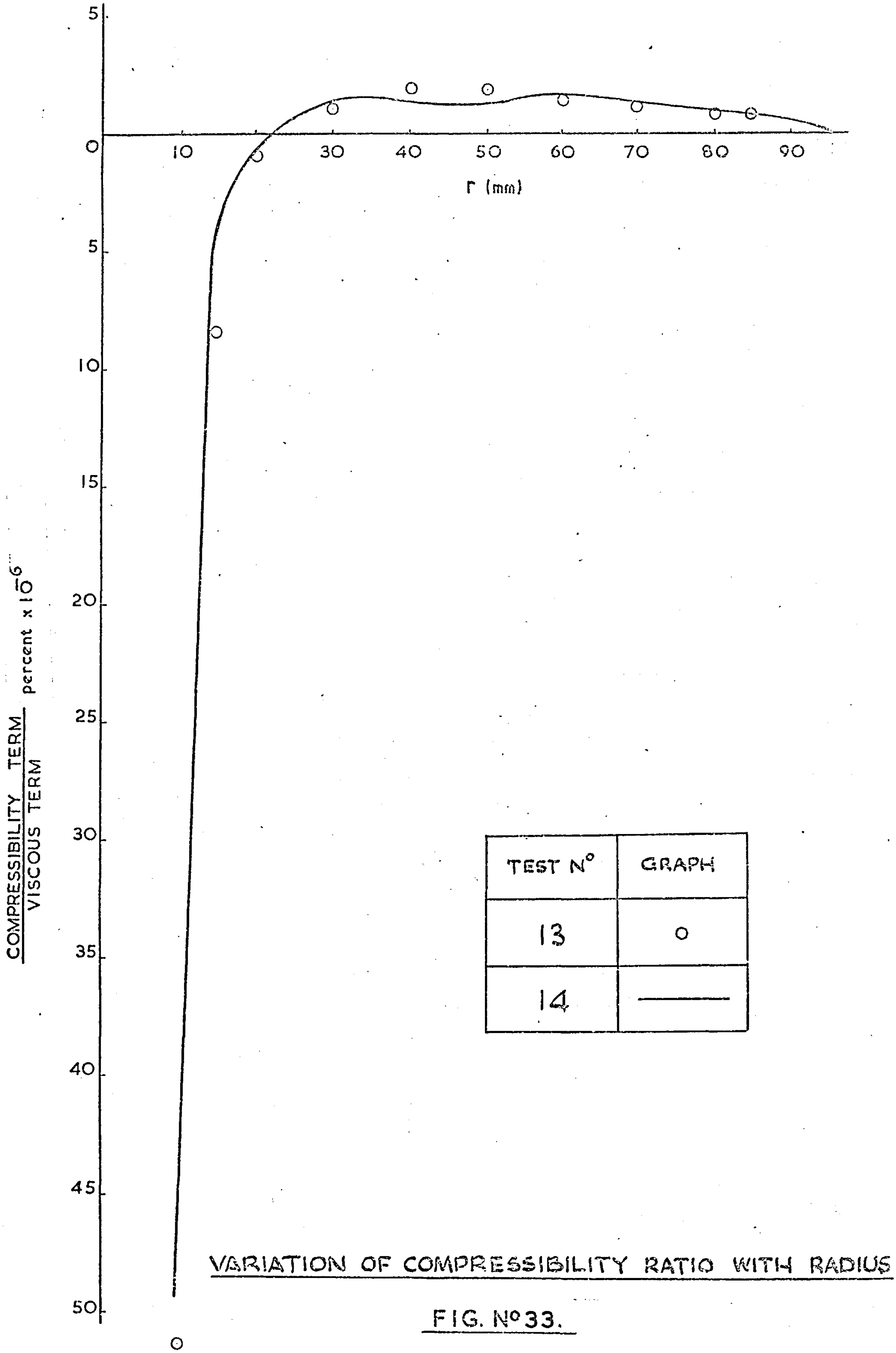
TABLE OF RESULTS

FIG. N° 31.



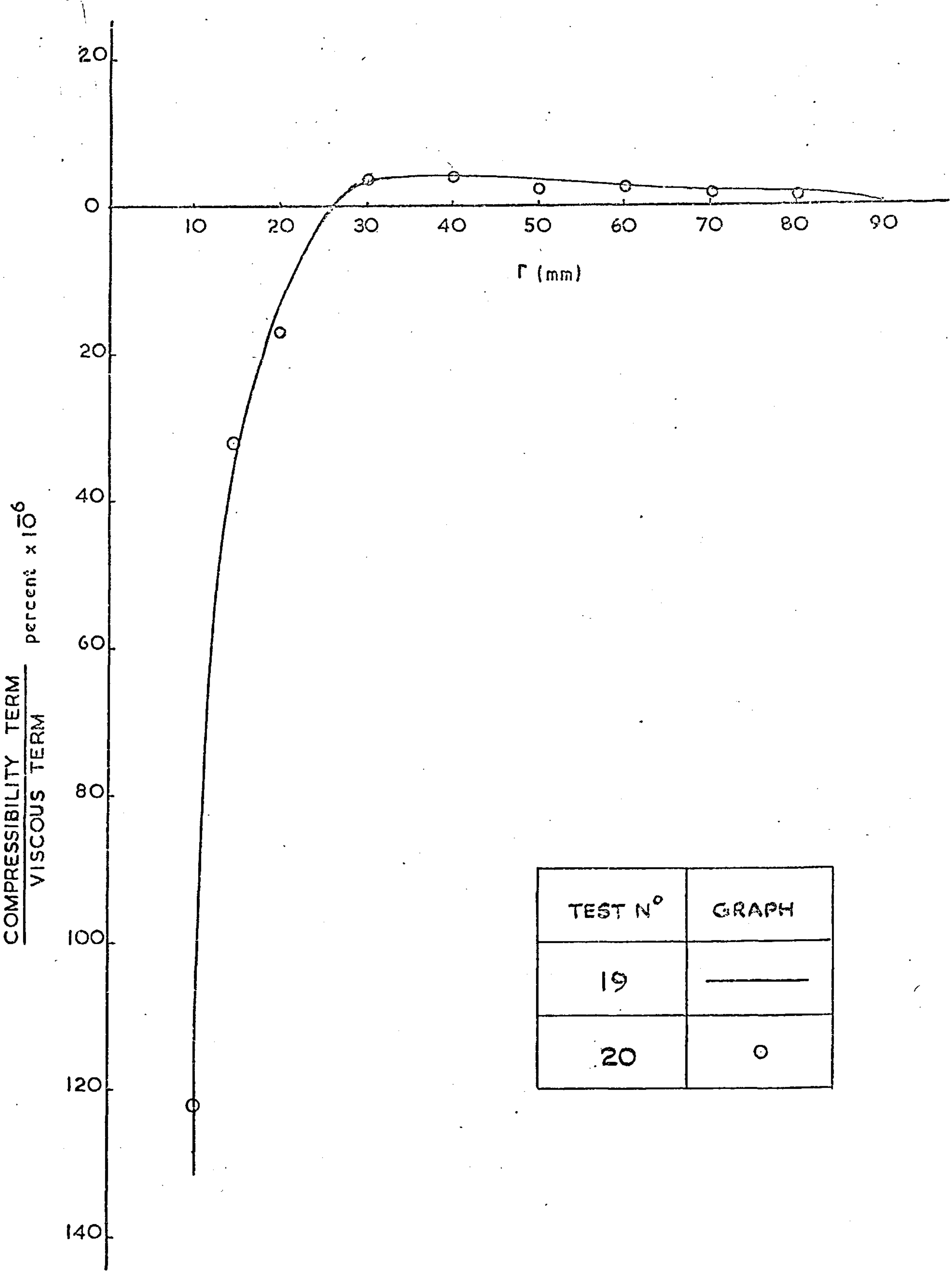
VARIATION OF COMPRESSIBILITY RATIO WITH RADIUS
(HOBSON & LAWRIE)

FIG. N° 32.



VARIATION OF COMPRESSIBILITY RATIO WITH RADIUS

FIG. N°33.



VARIATION OF COMPRESSIBILITY RATIO WITH RADIUS

FIG. N° 34.

CHAPTER 5 EXPERIMENTAL AND THEORETICAL RESULTS

5.01 INTRODUCTION

The results of 36 tests were used to test the theories outlined in Chapter 3. 12 tests were used for each of the following:

(i) Plain thrust bearing (static)

(ii) Plain thrust bearing (static/dynamic)

(iii) Stepped thrust bearing (static/dynamic)

In each of the 36 tests the theoretical determination of the dimensionless pressure distribution was calculated from equations (30) and (31). The theoretical relation between $\bar{p}_1$, r_1 and Q was evaluated using equation (33). Equation (33) has been shown in graphical form in FIGS.53-58 inclusive.

Graphs in dimensionless form, were used to show the change in pressure as the air lubricant flows through the bearing. The effect of a change in flow rate, Q, and gap thickness (2h), or alternatively the dimensionless constant $R_e = \frac{\rho Q}{\pi \mu h}$, on the dimensionless pressure profile can be seen. The viscous flow line $P - P_2 = \frac{3}{4} \log_e \frac{r_2}{r}$ was included, where appropriate, so that its limitations for the design of thrust bearings could be seen. In practice, thrust bearings would be operated with gap sizes which would be regulated by changing either the bearing load or the volume flow rate of the lubricant. The constant gap size (2h) used for this series of tests were, in general, larger than those used in practice, and this had the effect of producing extreme conditions regarding the radial inertia effect, particularly in the central area of the disc.

In the static tests, comparisons between experimental and theoretical results were made to test the effect of the radial inertia term $\frac{\rho V_r{}^2}{r}$ responsible for the deviation of the dimensionless pressure values from the viscous flow solution. In the dynamic tests there were two inertia terms to be taken into account, the radial inertia term $\frac{\rho V_r{}^2}{r}$ and a rotational inertia term $\frac{\rho V_\theta{}^2}{r}$. Tests 13-24 inclusive show the relevance of these two effects.

The value of the experimental thrust was calculated by using Simpson's Rule to determine the value $2\pi\int_{r_1}^{r_2}\bar{p}rdr$. These thrust values were based on the static pressure readings from each of the 36 tests. The theoretical thrust values, for all tests were calculated from equation (34). Theoretical thrust values for Tests 1-24 inclusive are shown graphically in FIG.66.

Thrust values from FIG.66 were used in formulating equations (1') (2') (3') shown in FIG.67, these equations were then used in predicting thrust values for flow rates in excess of those employed in Tests 1-24 inclusive, and are shown in FIG.68.

Theoretically the rotation term $\frac{3\rho\Omega^2}{20}(r_2{}^2 - r^2)$ is independent of gap size (2h) and flow rate Q. The magnitude of the rotational inertia term for the zero flow condition, at 4000 rev/min was examined experimentally. The effect of varying the gap size (2h) on the magnitude of the rotation term was investigated and the results are shown graphically in FIG.59.

Results from tests with a stepped bearing enabled equations (30) and (31) to be tested more rigorously than those obtained from the plain bearing tests. The theoretical analysis of the stepped bearing was based on the assumption that the air would expand in two stages; the inner stage through a gap width ($2\alpha h$) and the outer stage through a gap width ($2h$). FIGS. 47-52 inclusive enable the theoretical and experimental results to be compared, and the two stage expansion is clearly evident.

5.02 STATIC CASE

FIGS. 35-40 inclusive record the experimental and theoretical results for tests 1-12 inclusive. In these tests three different gap widths were used 0.2mm, 0.25mm and 0.3mm. For each gap width four different air flow rates were employed.

The significance of the Reynolds number $\frac{\rho Q}{\pi\mu h}$ in predicting the form of the dimensionless pressure distribution is readily seen — the smaller the Reynolds number, the smaller the deviation from the Viscous flow line. A high Reynolds number is therefore associated with a high value for the dimensionless radial inertia term $\frac{27\rho Q}{560\pi h\mu}(\frac{1}{R^2} - \frac{1}{R_2{}^2})$, which could be written in the form $\frac{27}{560}R_e(\frac{1}{R^2} - \frac{1}{R_2{}^2})$. The graphs shown in FIGS. 35-40 inclusive are in dimensionless form, to enable comparisons to be made between thrust bearings when different parameters are used. When actual pressure values are required however, it is preferable to use the radial inertia term in the form $\frac{27\rho Q^2}{560\pi^2 h^2}(\frac{1}{r^2} - \frac{1}{r_2{}^2})$. See equation (24). The value of the dimensionless radial inertia term is proportional to the Reynolds number, or $\frac{Q}{h}$, but the value of the radial inertia term in dimensionalised form is proportional to $(\frac{Q}{h})^2$. Therefore, for a given flow rate, if the gap width is halved, the Reynolds number is doubled and the value of the radial inertia term, in dimensionalised form, is increased by a factor 4.

The correlation between theoretical and experimental results was not the same for each test, neither was it the same at different radii for any one test. In general the lower the Reynolds number the closer the correlation between experimental and theoretical results. This can be seen by comparing FIG.35 with FIG.37. For the higher Reynolds numbers, associated with higher gap widths, the theoretical prediction of dimensionless pressure compared with experimental results was higher for the outer three-quarters of the disc, and lower for the inner quarter of the disc, as shown in FIG.37-40 inclusive. The significance of the accumulative effects of experimental error in the theoretical prediction of ~~dimensionless~~ dimensioned pressure distribution is considered in Chapter 6.

The results of the thrust calculations based on equations (34) and (35) are shown in Appendix (2). The percentage error, based on the relation:

$$\text{percentage error} = \frac{\text{theoretical thrust - experimental thrust}}{\text{theoretical thrust}}$$

ranges from 0.4% to 17%.

Theoretically, the higher the Reynolds number the greater the radius at which the maximum static pressure ($\bar{p}$) occurs. (See

4.02). Experimentally it was shown that the radial position of the $(\bar{p})$ maximum was different for each test. If Test No.2 (R_e = 78060) is compared with Test No.12 (R_e = 381500) the radial position of the $(\bar{p})$ maximum was greater for test No.12 than for Test No.2 - confirming the theoretical prediction for these two tests.

5.03 STATIC/DYNAMIC CASE

The results from Test No.13-No.24 inclusive are shown in FIGS. 41-46 inclusive. In these tests three different gap widths were used, 0.2mm, 0.25mm and 0.3mm. For each gap width two different air flow rates were employed. The dynamic tests were at 4000 rev/min.

The equation for the theoretical dimensionless pressure distribution from Chapter 3 is:

$$P - P_2 = \frac{3}{4}\log_e\left(\frac{R_2}{R}\right) - \frac{27\rho Q}{560\pi h\mu}\left(\frac{1}{R^2} - \frac{1}{{R_2}^2}\right) - \frac{3\pi^2 h^5 \rho \Omega^2}{20\mu Q}({R_2}^2 - R^2)$$

VISCOUS TERM RADIAL INERTIA TERM ROTATIONAL INERTIA TERM

The radial and rotational inertia terms, when expressed in dimensionalised form, become $\frac{27\rho Q^2}{560\pi^2 h^2}\left(\frac{1}{r^2} - \frac{1}{{r_2}^2}\right)$ and $\frac{3\rho\Omega^2}{20}({r_2}^2 - r^2)$ respectively. The form of the negative pressure distributions, due to both these terms, for Test No.13 and Test No.15 are shown in FIG.46A. This graph shows the relative importance of these two terms. In the centre of the disc i.e. when r is small, the radial term has its highest value. In one case (Test No.23) the negative pressure effect is large enough to overcome the positive pressure effect due to the Viscous term, and a pocket of sub-atmosphere pressure is induced in the centre of the disc.

The negative pressure distribution due to the rotational term also has its highest value in the centre of the disc, but the distribution of negative pressure is more ~~even~~ uniform than with the radial term. The correlation between experimental and theoretical results, for the dimensionless pressure distribution, followed a similar pattern to those in the static case. The distortion of the pressure distribution curve, due to the adverse effect of the rotational term, reduced the thrust on the bearing by 5N, which is 13.5% of the maximum thrust generated. (Theoretically if the rotation speed were 40,000 rev/min the reduction in thrust would be 500N since the magnitude of the rotation term is proportional to Ω^2).

5.04 STEPPED BEARING

Results associated with experimental Tests 25-36 inclusive are shown in graphical form in FIGS.47-52 inclusive. The effect of the introduction of a step in the bearing was to extend the area over which high pressure acted. At the same time however, in the ~~vacimity~~ vicinity of the air inlet, pronounced fall-off in static pressure could occur due to radial inertia effects.

Equations (30) and (31) were used to determine the dimensionless pressure distribution and equations (34) and (35) respectively to determine the theoretical and experimental thrusts. The percentage error in determining the bearing thrust varied from 3.3% in Test 33 to 30% in Test 36. Theoretically the suction effect induced by a rotational speed of 4000 rev/min reduced the bearing thrust by 5N, for every test. The highest thrust recorded was for Tests 27 and 28. In Test 27 (R_e = 182 200/109 300) the theoretical and experimental thrusts were 38.2 and 36.8N respectively. In Test 28 the theoretical and experimental thrusts were 33.2 and 32N respectively. This represents a 13% reduction in thrust, due to a rotation speed of 4000 rev/min, for both experimental and theoretical results.

The logical reason for providing a step is to extend the area over which the high inlet pressure of the incoming air can act before it begins to escape through the narrower air gap. Increasing the size of the air gap, by the provision of a step and for a given flow rate, results in a decrease in the Reynolds number; thus the effect of radial inertia in decreasing the static pressure is reduced. However the size of step chosen for Tests 25-36 inclusive only partly reduces the radial inertia effect. This means that some decrease in pressure across the stepped portion of the disc is unavoidable.

Where the Reynolds numbers are in excess of 200 000 (see Tests 31-36), the correlation between the experimental and theoretical pressure profiles, for the stepped area of the disc, shows considerable variation, due to an overestimation of the value of the radial inertia term. This is consistent with the pressure distribution profile for Test 23 and 24 where the Reynolds number is 31140.

5.05 THE ZERO-FLOW CONDITION

To test the significance of the rotational inertia term, as contained in equation (24), tests were carried out, in a plain thrust bearing, with the dynamic disc rotating at 4000 rev/min. The air inlet to the bearing was blocked so that a zero-flow condition (Q = 0) existed. Under these conditions equation (24) is reduced to $\bar{p} = -\frac{3\rho\Omega^2}{20}(r_2{}^2 - r^2)$ i.e. theoretically, a suction effect is produced which is independent of gap size. The instrumentation was arranged as shown in FIG.60. Tests at gap widths of 0.2mm, 0.25mm, 0.3mm, 0.35mm, 0.4mm, and 0.45mm were run. Only when a gap width of 0.45mm was tried was there a noticeable change in the suction effect, where the theoretical value tends to overestimate the suction effect. The results are tabulated in FIG.59.

5.06 THE RADIAL VELOCITY, AXIAL VELOCITY AND THE PRESSURE TERM $\frac{\mu \partial V_z}{\partial z}$

FIGS. 61-65 inclusive show how the magnitude of the theoretical radial velocity, axial velocity and the pressure term $\frac{\mu \partial V_z}{\partial z}$ are influenced by h, Ω, Q, r and z. The radial velocity components shown in FIG.61 were calculated from equation (28). The axial velocity components shown in FIG.62 and 63 were calculated from equation (29). The pressure term components ($\mu\frac{\partial V_z}{\partial z}$) shown in FIG.64 and 65 were calculated by multiplying equation (28A) by μ. These calculations are tabulated in Appendix 3.

The effect of rotation was to induce a flow in the axial direction towards the dynamic disc while at the same time the profile of the radial velocity curve was distorted so that its maximum value wa nearer the dynamic disc than the static disc. The validity of the graphs shown depend on the flow being laminar. To assist the air to flow, without swirl, into the gap separating the static and dynamic discs, a radius was machined at the exit from the air inlet port, but this could not be expected to eliminate turbulence completely. Therefore the calculated values for V_r, V_z and $\mu\frac{\partial V_z}{\partial z}$ for small values of r are 'ideal' values only.

The variation in pressure across the gap was very small. e.g. in Test 20 when z = 0 and r = 70mm (FIG.64) $\mu\frac{\partial V_z}{\partial z} = 1.99 \times 10^{-3} N/m^2$. The value of $\bar{p}$, at the same position in the air gap, was $545 N/m^2$. This justifies the interchange of $\frac{\partial p}{\partial r}$ by $\frac{\partial \bar{p}}{\partial r}$, as in the theory outlined in Chapter 1. (see the first of equations (8) and equation (15)).

5.07 BEARING THRUST AND BEARING PERFORMANCE

Curves of Reynolds number/Thrust shown in FIG.66 were based on values tabulated in Appendix (2). These graphs were replotted in dimensionless form, in FIG.67. The dimensionless thrust TD was obtained by multiplying the thrust (T) by $\frac{r_2}{\mu Q}$. The straight line laws associated with equations 1' 2' and 3' (FIG.67) were used to obtain the relationships between T and Q shown in FIG.68.

viz. consider Test No.7.

$h = 0.125\text{mm} \qquad Q = 0.00213\ \text{m}^3/\text{s} \qquad \rho = 1.24\ \text{kg/m}^3$

$\mu = 0.000018\ \text{Ns/m}^2 \qquad r_2 = 95\text{mm}$

from equation 2' $R_e = -6.15 \times 10^{-4} \times TD + 100.35 \times 10^4$

$$\therefore \frac{\rho Q}{\pi \mu h} = -\frac{6.15 \times 10^{-4} \times T \times r_2}{\mu Q} + 100.35 \times 10^4$$

substituting values for ρ, Q etc in the above equation

$$37.4 \times 10^4 = -15200T + 100.35 \times 10^4$$

$$\therefore T = 41.4\text{N}$$

(Results given in Appendix 2 are 41.1N (Theory), 38.9N (Experiment)).

In determining the performance of thrust bearings two things should be considered: (a) the thrust that the bearings can support, (b) the volume flow rate of the lubricant required. If the measure of performance is taken as the ratio Thrust/Volume flow rate per second, then the bearing giving the best performance will be one that has the smallest air gap with the smallest flow rate. See FIGS. 69, 70 and 71.

When the gap and flow rate are small we have the paradoxical situation, where, if the volume of air flowing through a rotating bearing is increased, this could result in an improvement in performance. This is because, theoretically, the suction caused by the rotational inertia effect is independent of flow rate, so that as the flow rate increases the percentage reduction in thrust due to the rotational inertia effect decreases.

For the series of tests undertaken the performance of the stepped thrust bearings was not as good as that of the plain bearings, however, the stepped bearing is able to provide initial 'lift' to separate contacting surfaces immediately before the bearing is rotated. This is an important feature if wear is to be avoided in practice.

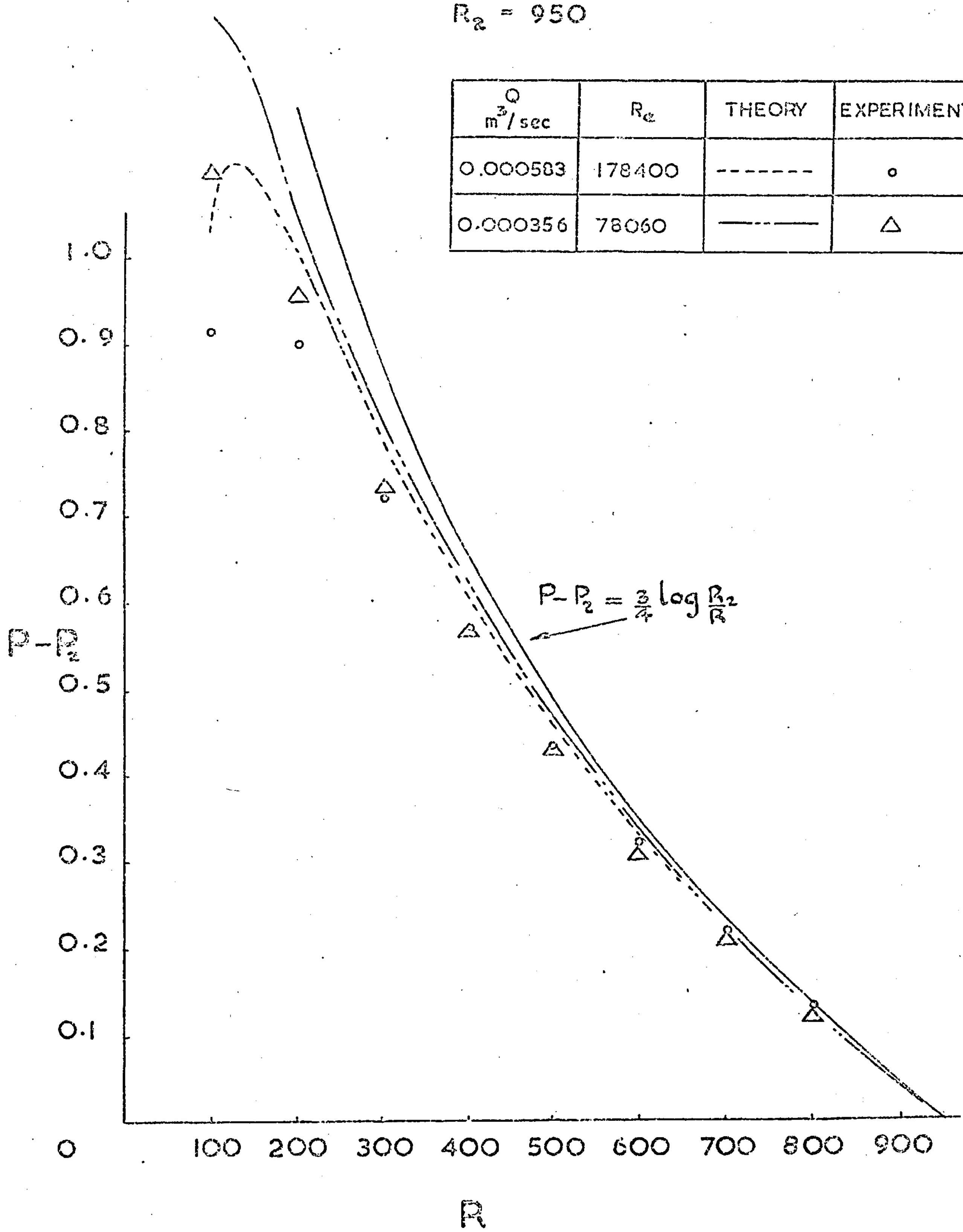
STATIC TESTS

$\alpha = 1{\cdot}0$

$h = 0{\cdot}0001\,m$

$R_2 = 950$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.000583	178400	- - - - - - -	o
0.000356	78060	——·——	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N°1 & N°2

FIG. N°35.

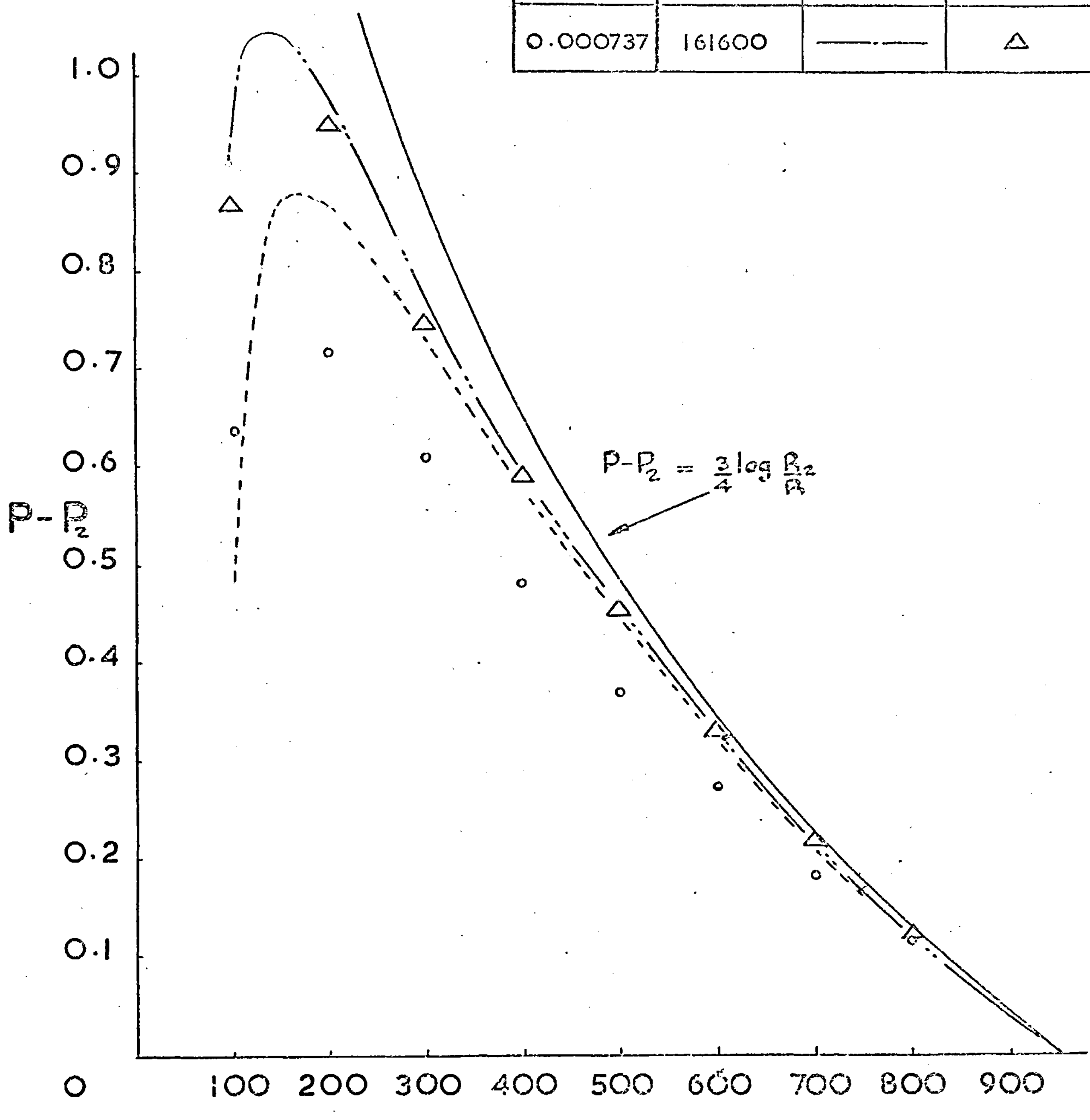
STATIC TESTS

$\alpha = 1.0$

$h = 0.0001\,m$

$R_2 = 950$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.001145	251000	--------	o
0.000737	161600	——·——	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N°3 & N°4

FIG. N° 36.

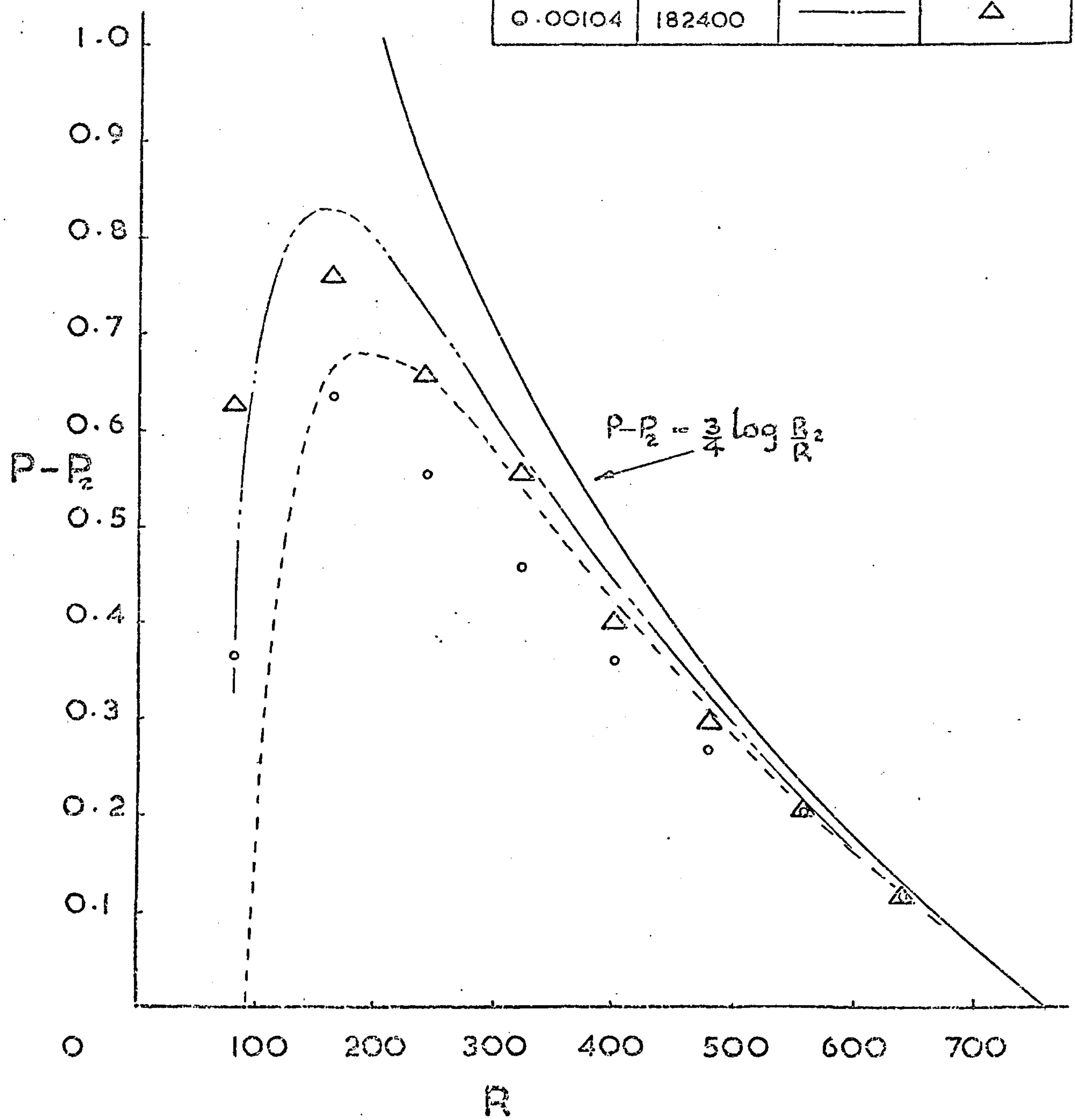
STATIC TESTS

$\alpha = 1.0$

$h = 0.000125\ m$

$R_2 = 760$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.00171	300000	- - - - - - - -	∘
0.00104	182400	——·——	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N°5 & N°6

FIG. N°37.

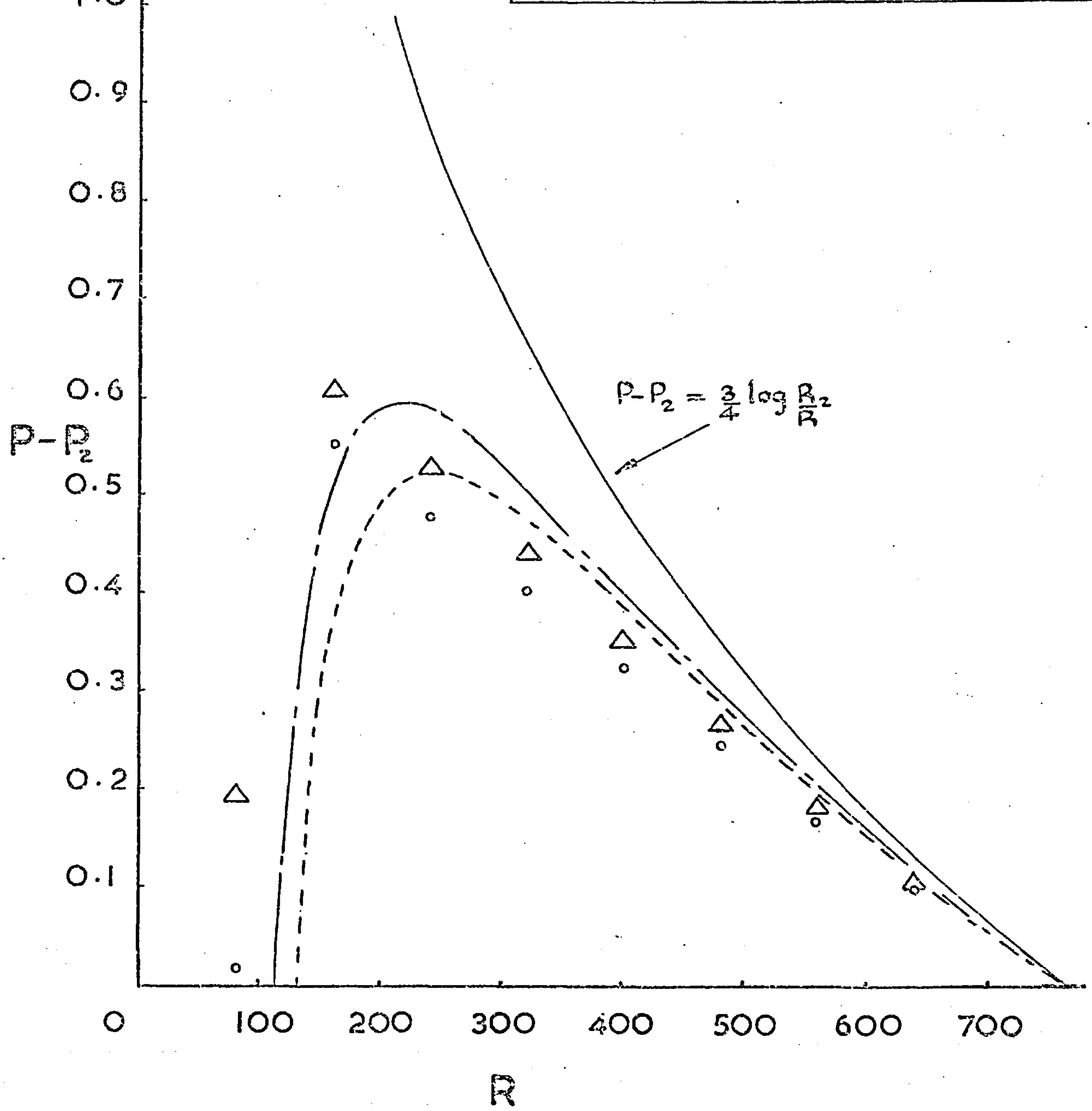
STATIC TESTS

$\alpha = 1.0$

$h = 0.000125\,m$

$R_2 = 760$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.00261	457800	------	∘
0.00213	373600	———	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 7 & N° 8

FIG. N° 38.

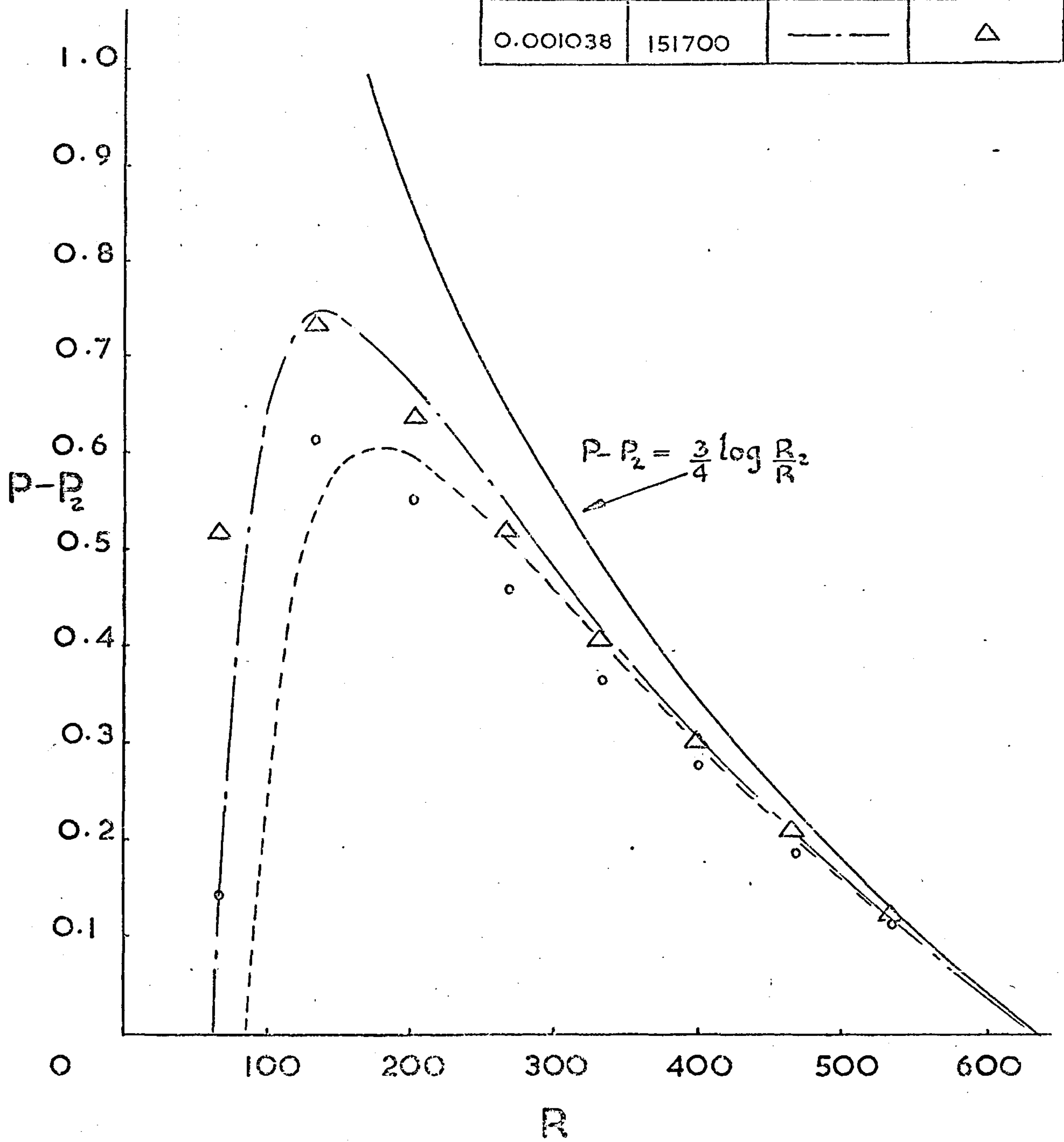
STATIC TESTS

$\alpha = 1.0$

$h = 0.00015$ m

$R_2 = 633$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.00171	250000	- - - - - - -	o
0.001038	151700	—·—	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 9 & N° 10

FIG. N° 39.

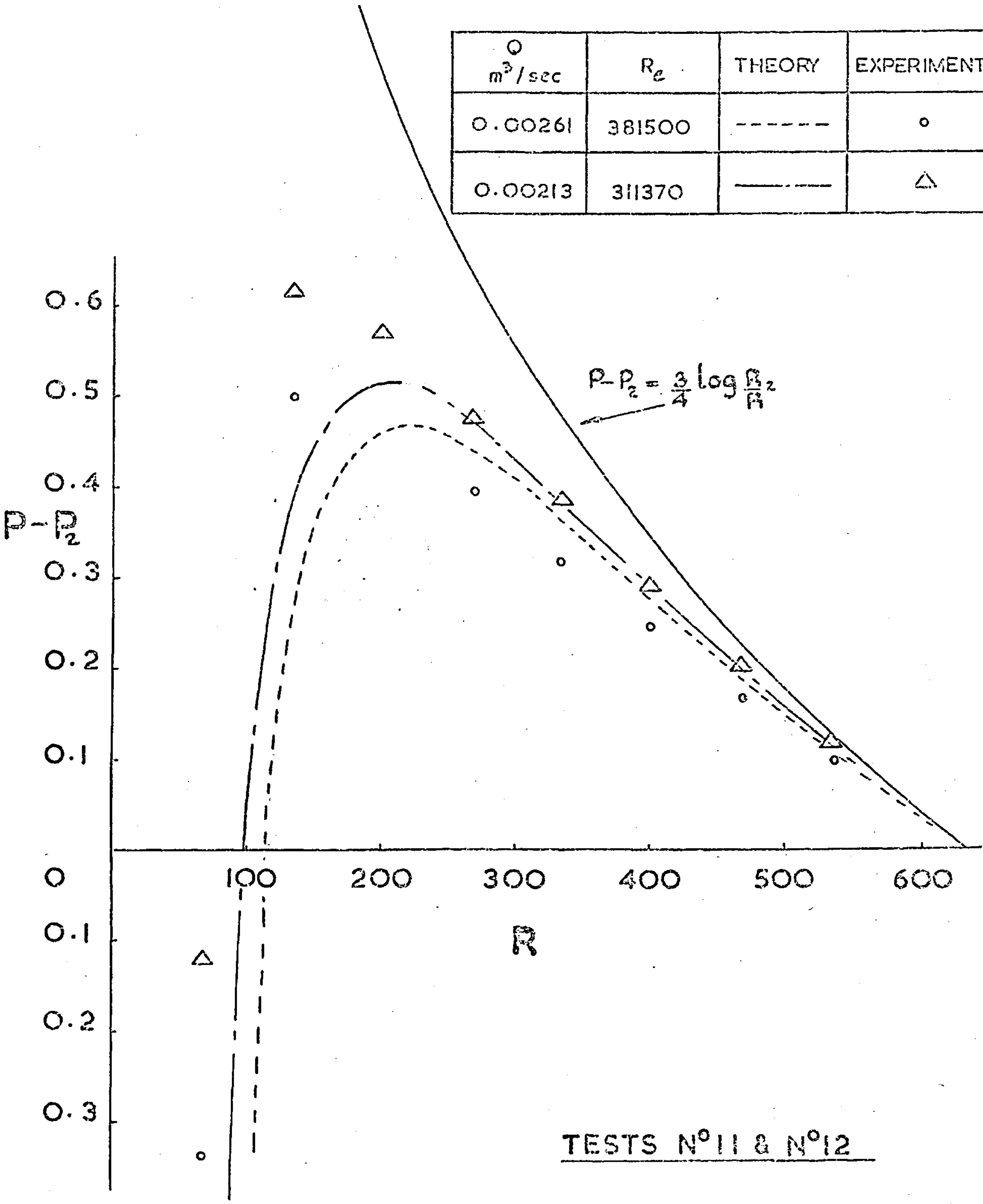
STATIC TESTS

$\alpha = 1.0$

$h = 0.00015$ m

$R_2 = 633$

Q m^3/sec	R_e	THEORY	EXPERIMENT
0.00261	381500	------	o
0.00213	311370	——·——	△



TESTS N°11 & N°12

DIMENSIONLESS PRESSURE DISTRIBUTION

FIG. N° 40.

STATIC AND DYNAMIC TESTS

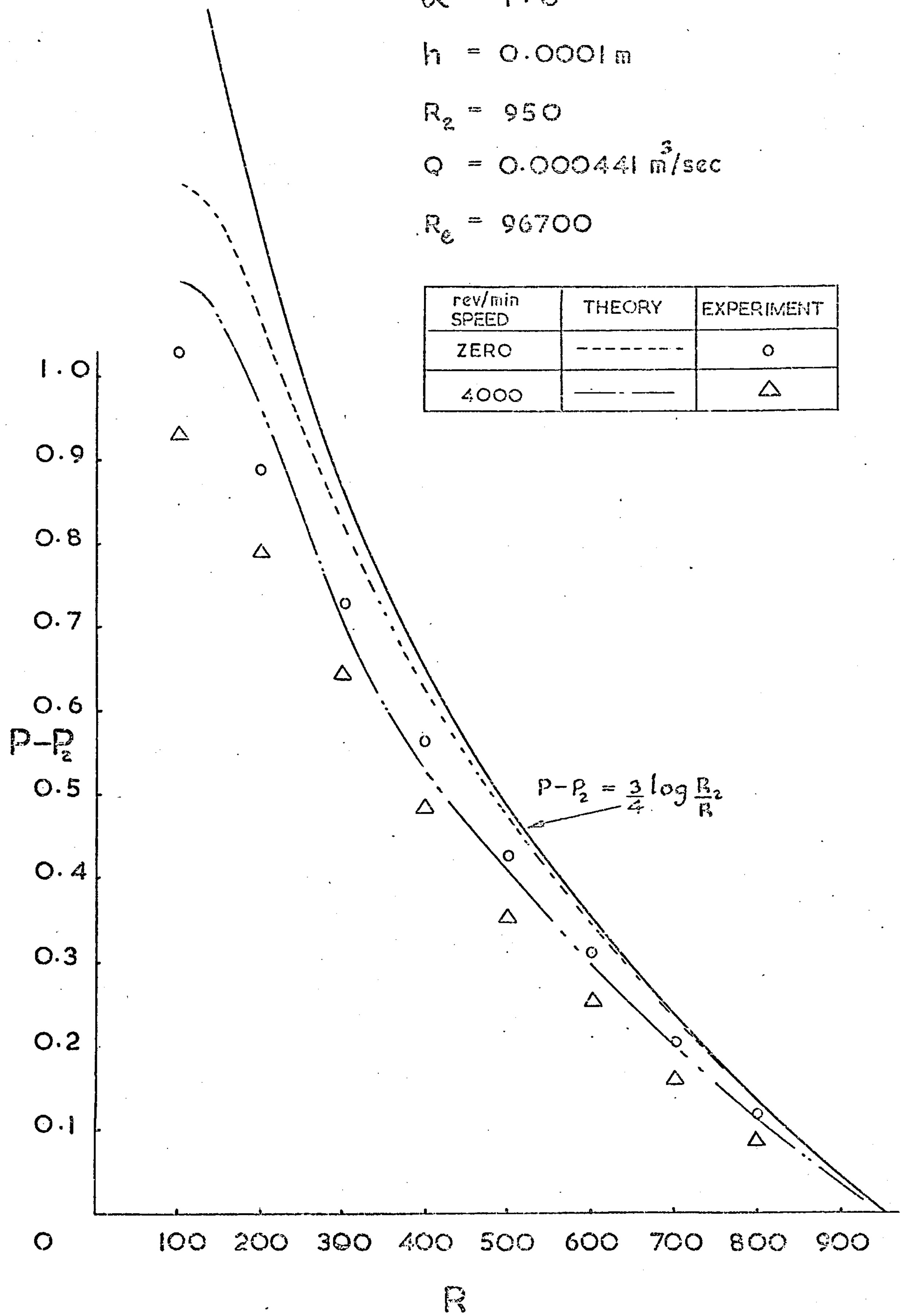
$\alpha = 1.0$

$h = 0.0001\,m$

$R_2 = 950$

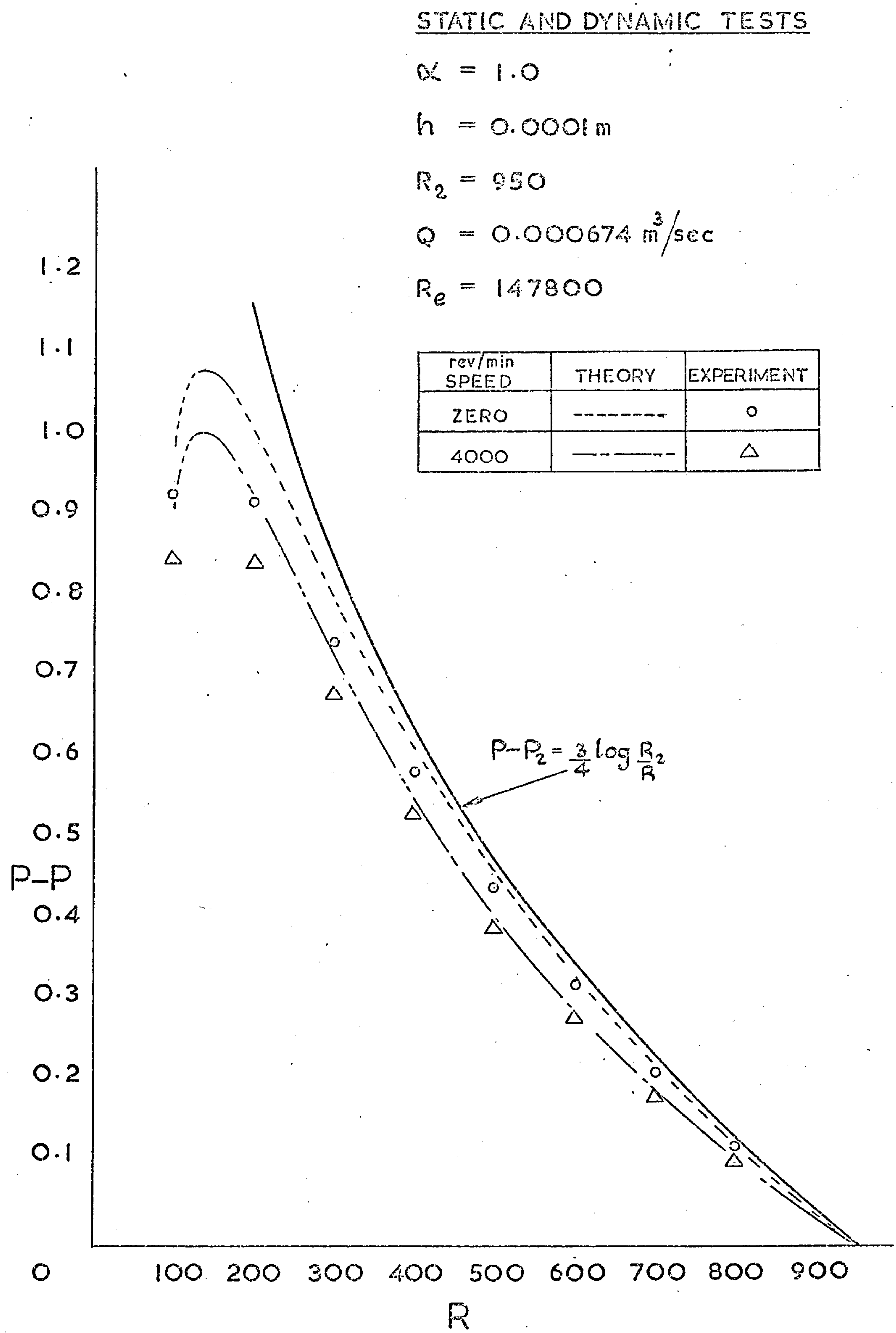
$Q = 0.000441\,m^3/sec$

$R_e = 96700$



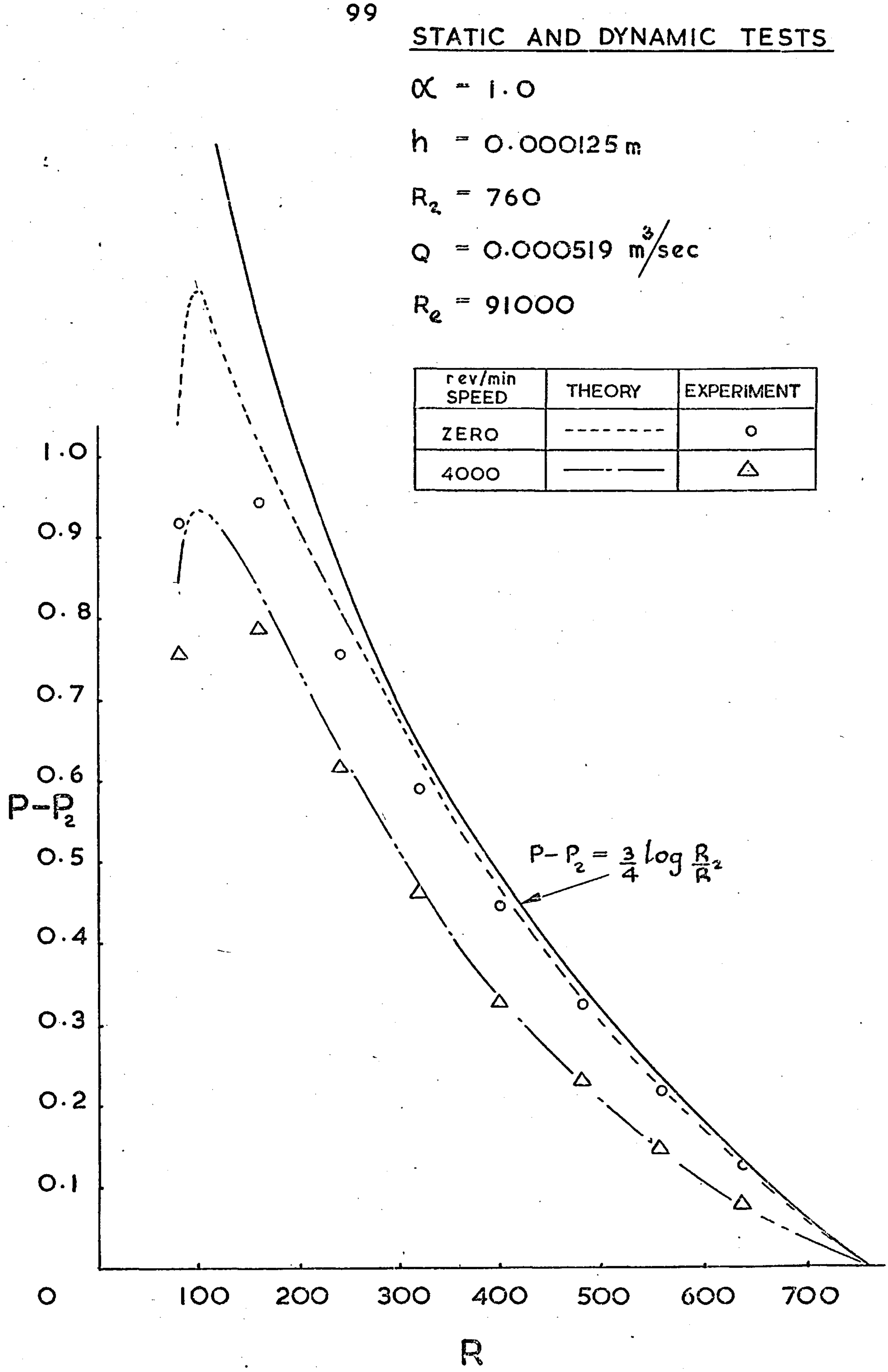
DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 13 & 14

FIG. N°41.



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N°15 & N°16

FIG. N°42.



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 17 & N° 18

FIG. N° 43.

STATIC AND DYNAMIC TESTS

$\alpha = 1.0$

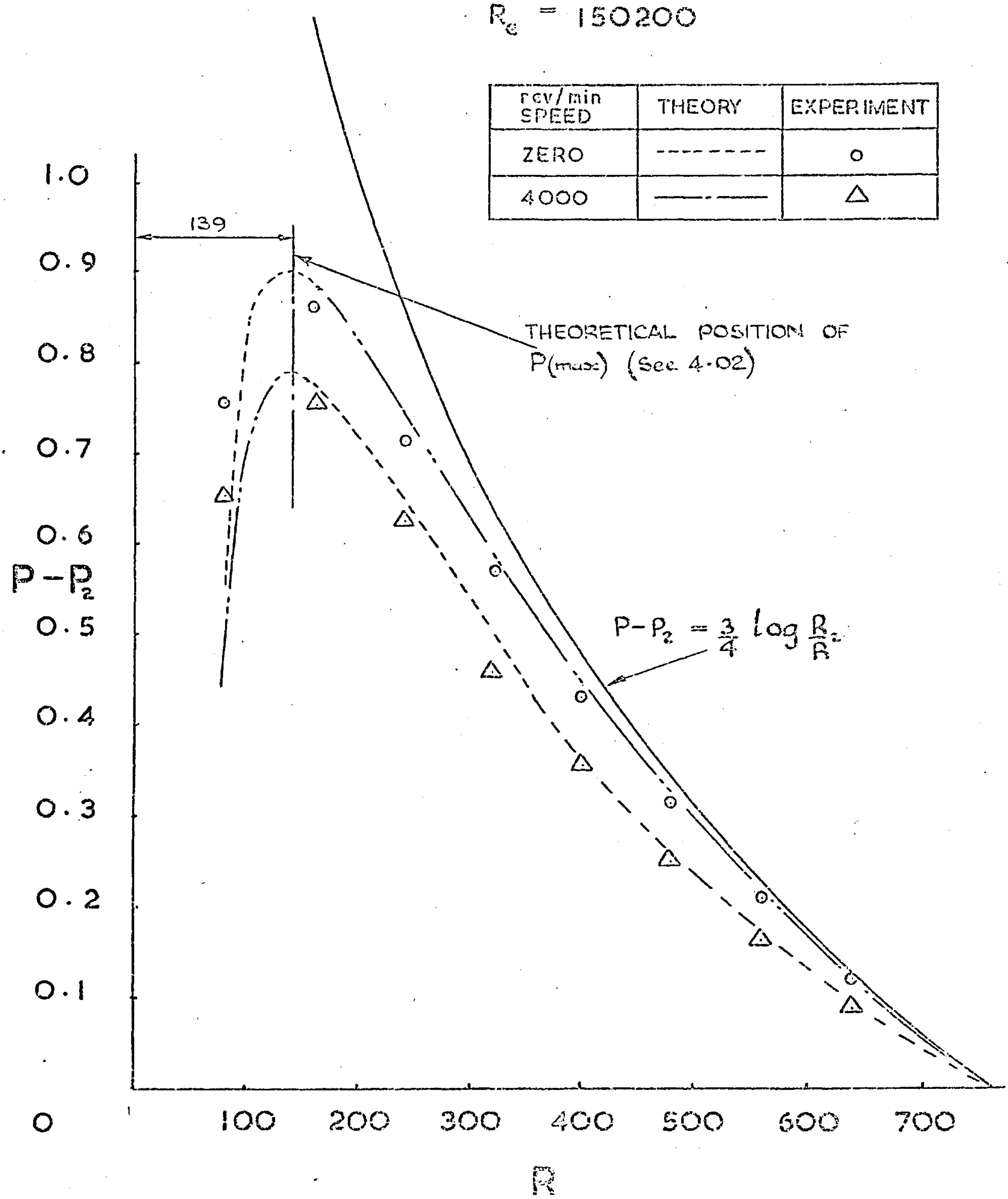
$h = 0.000125\ m$

$R_2 = 760$

$Q = 0.000856\ m^3/sec$

$R_e = 150200$

rev/min SPEED	THEORY	EXPERIMENT
ZERO	- - - - - - - -	o
4000	——·——	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 19 & N° 20

FIG. N° 44.

STATIC AND DYNAMIC TESTS

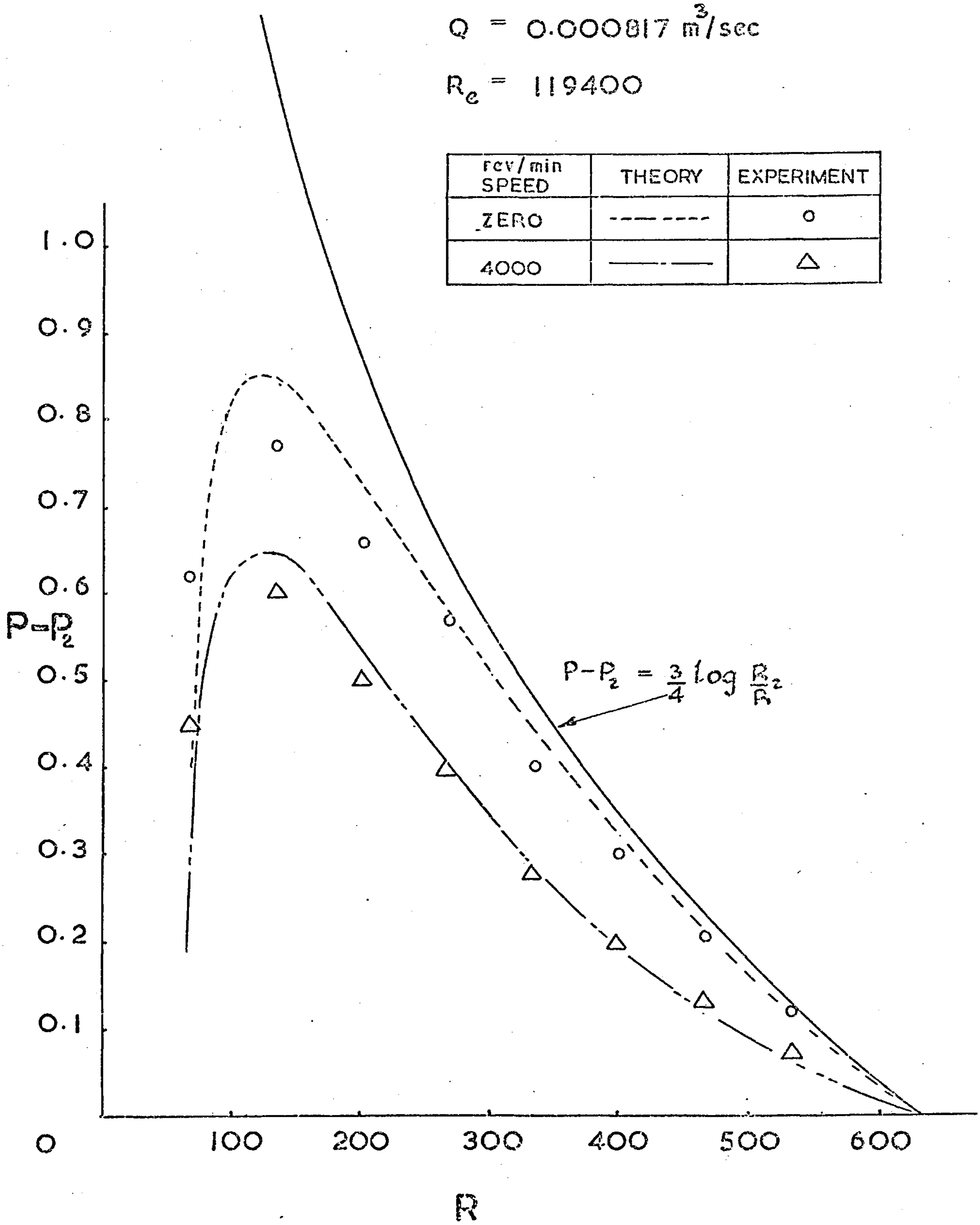
$\alpha = 1.0$

$h = 0.00015\ m$

$R_2 = 633$

$Q = 0.000817\ m^3/sec$

$R_e = 119400$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 21 & N° 22

FIG. N° 45.

STATIC AND DYNAMIC TESTS

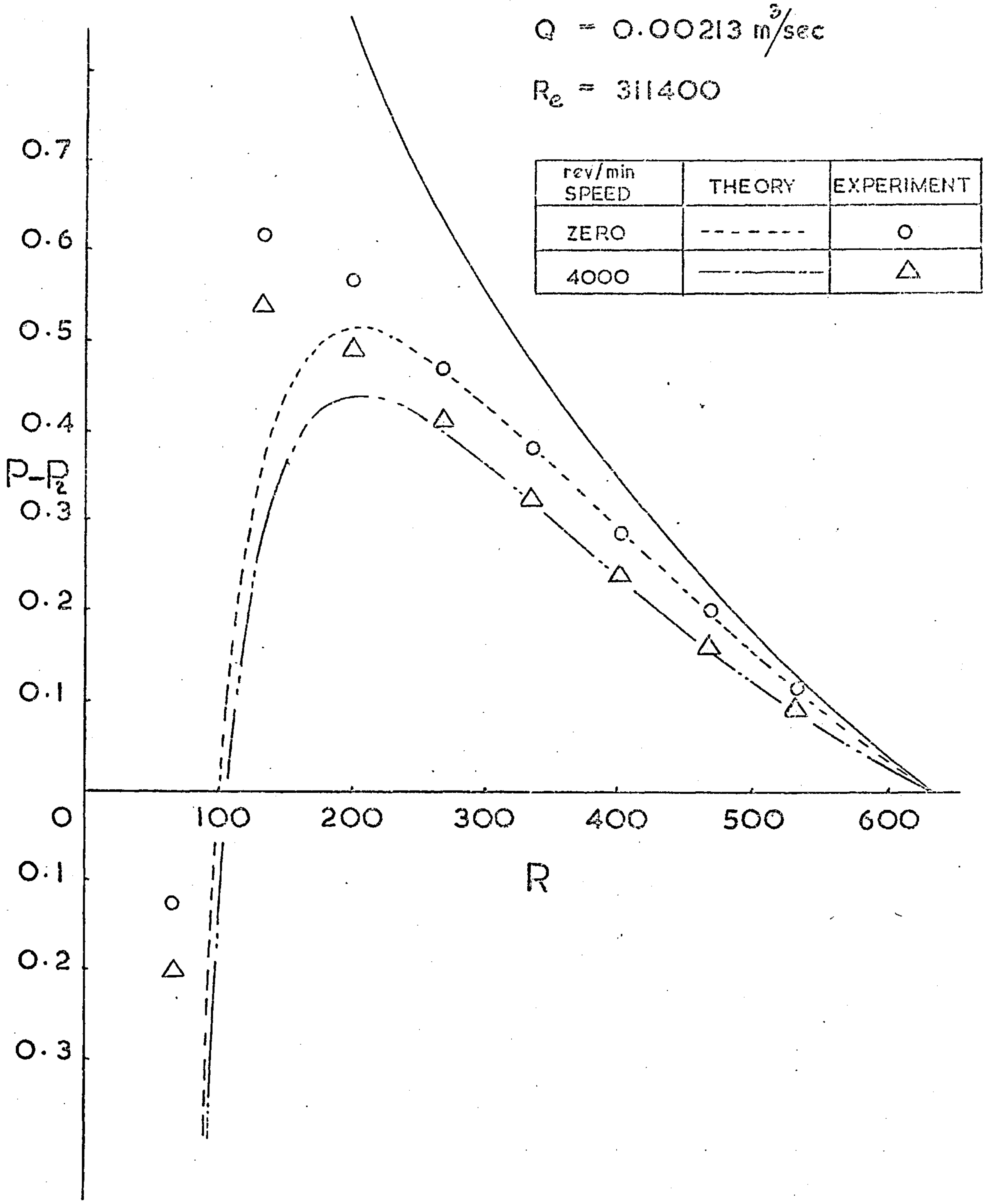
$\alpha = 1.0$

$h = 0.00015\,m$

$R_2 = 633$

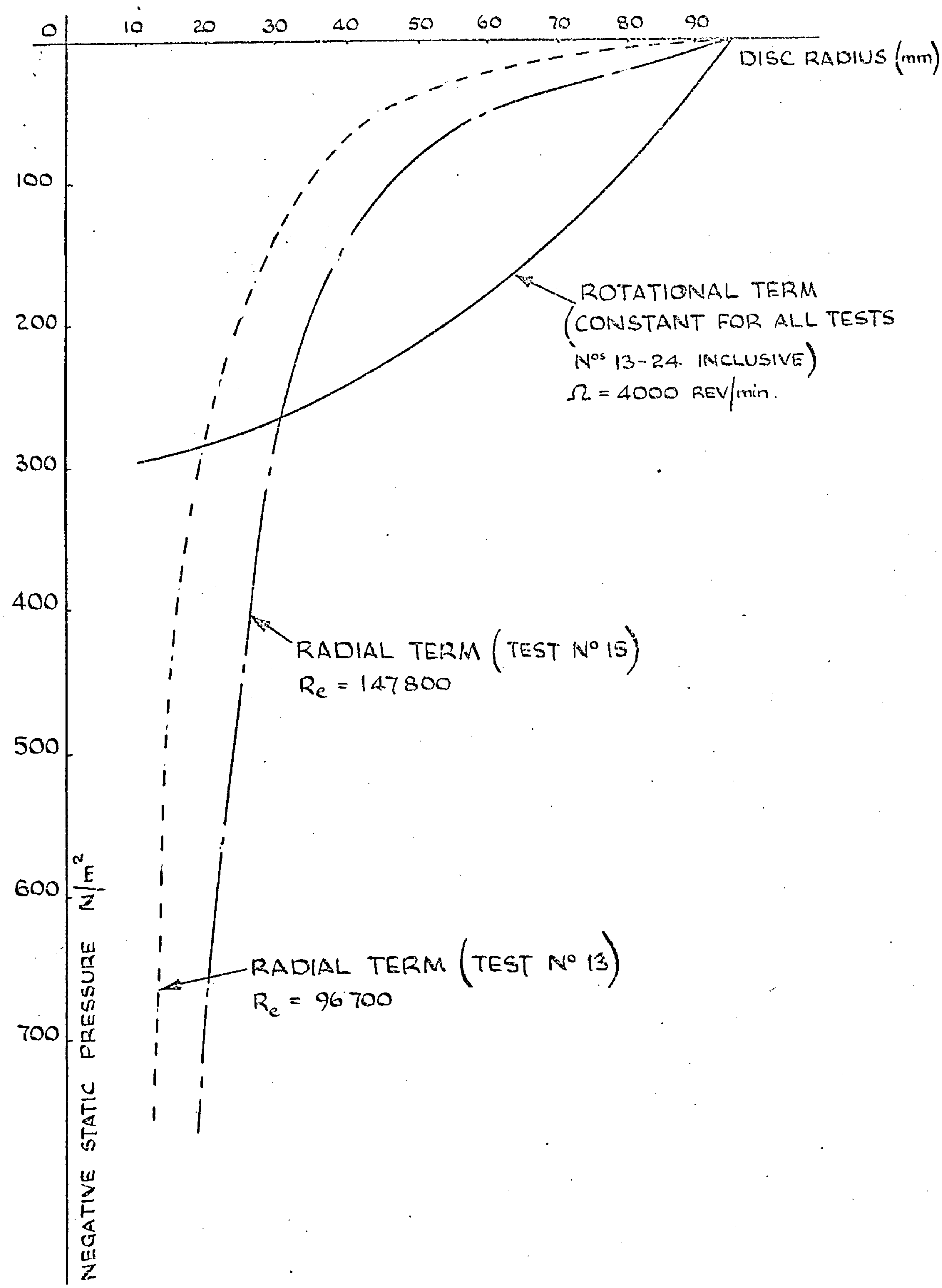
$Q = 0.00213\ m^3/sec$

$R_e = 311400$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N°23 & N°24

FIG. N°46.



NEGATIVE PRESSURE DISTRIBUTION DUE TO RADIAL & INERTIA TERMS

FIG. N°46A

STATIC AND DYNAMIC TESTS

STEPPED BEARING

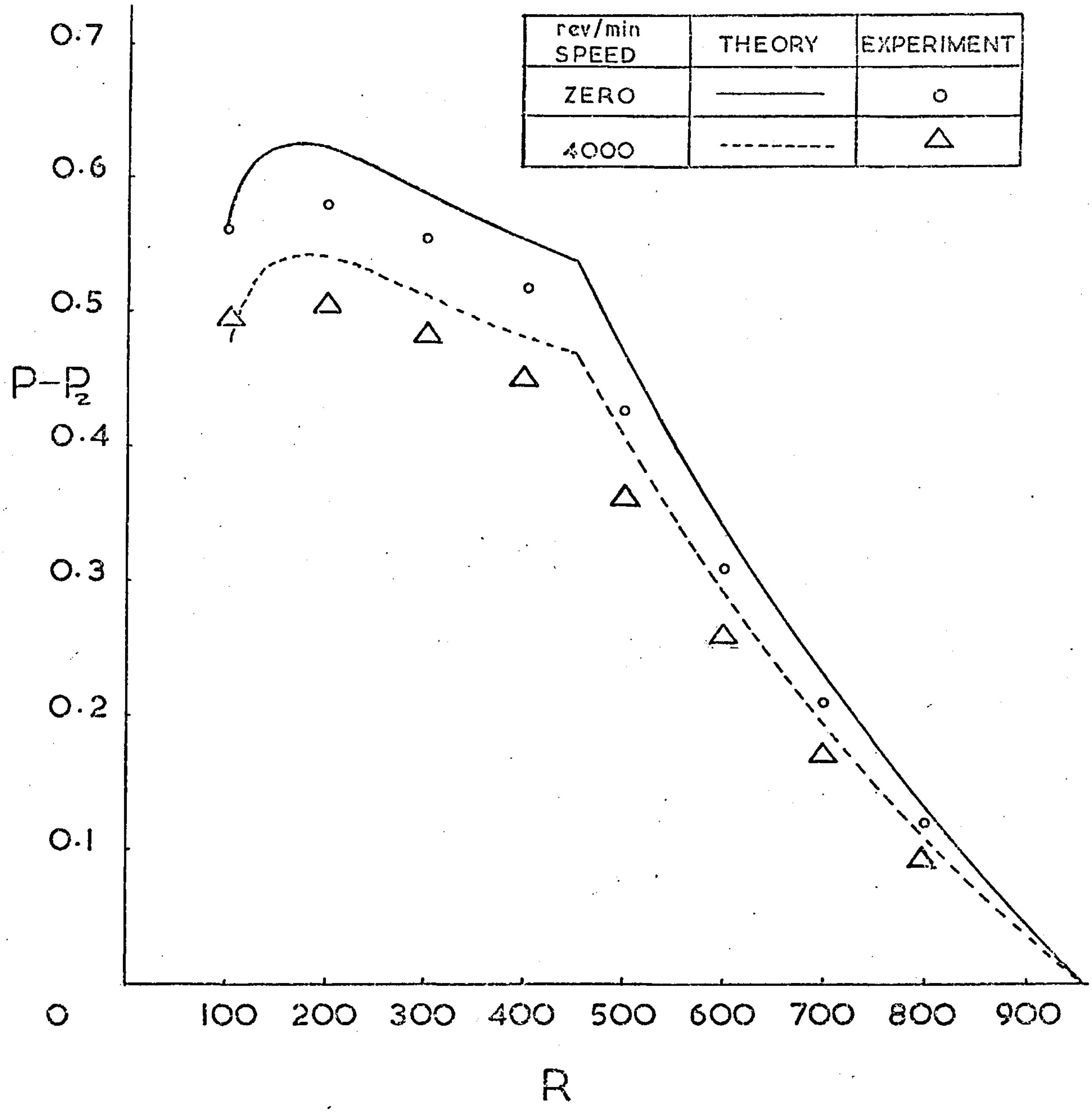
$\alpha = 1.667$ $[r_3 = 45\text{mm}]$

$h = 0.0001\text{m}$

$R_2 = 950$

$Q = 0.000587\ m^3/sec$

$R_e = 128700 / 77200$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 25 & N° 26

FIG. N° 47.

STATIC AND DYNAMIC TESTS

STEPPED BEARING

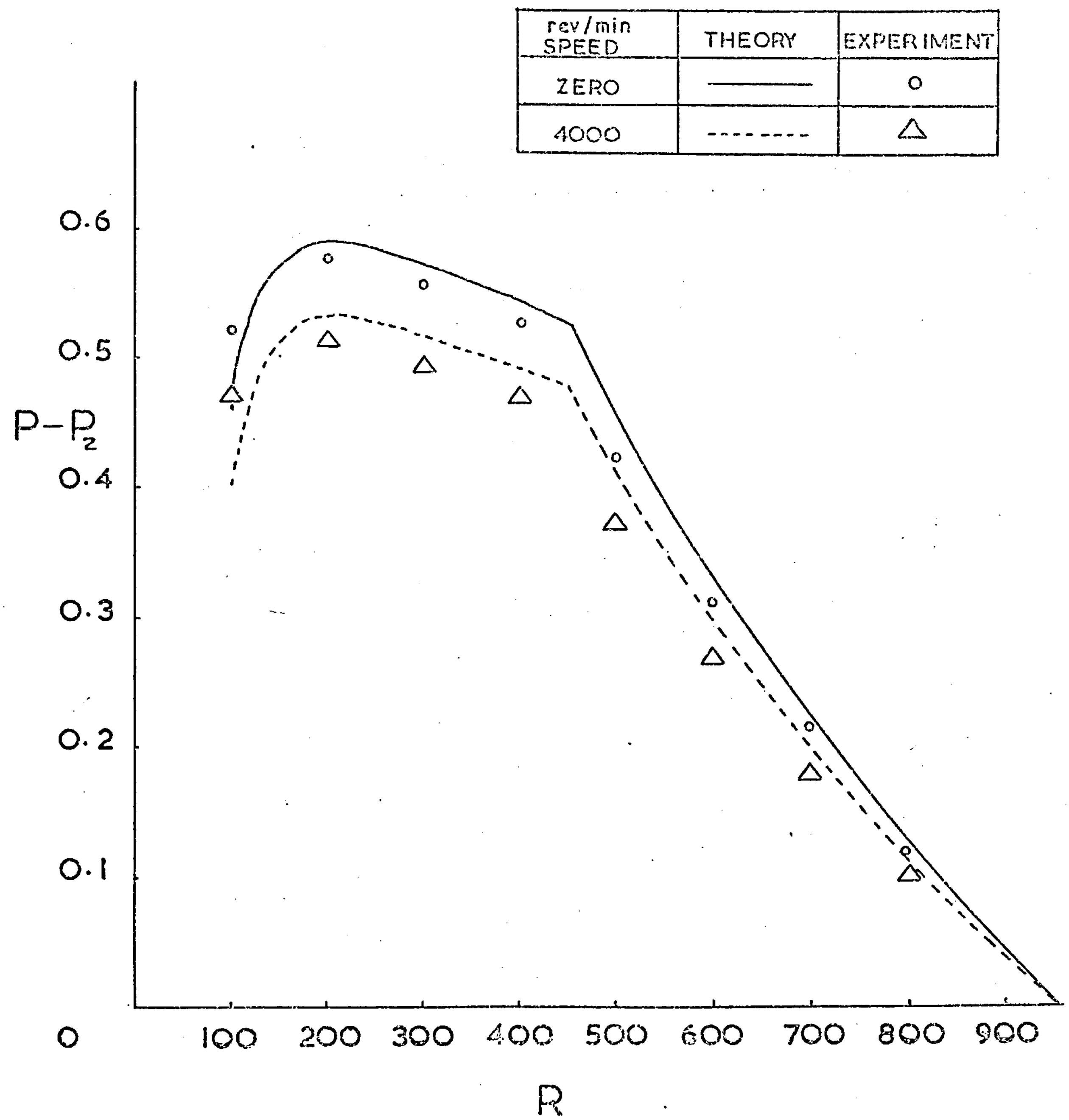
$\alpha = 1.667$ $[r_3 = 45\text{mm}]$

$h = 0.0001\text{m}$

$R_2 = 950$

$Q = 0.000831\ \text{m}^3/\text{sec}$

$R_e = 182200/109300$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 27 & N° 28

FIG. N° 48.

STATIC AND DYNAMIC TESTS

STEPPED BEARING

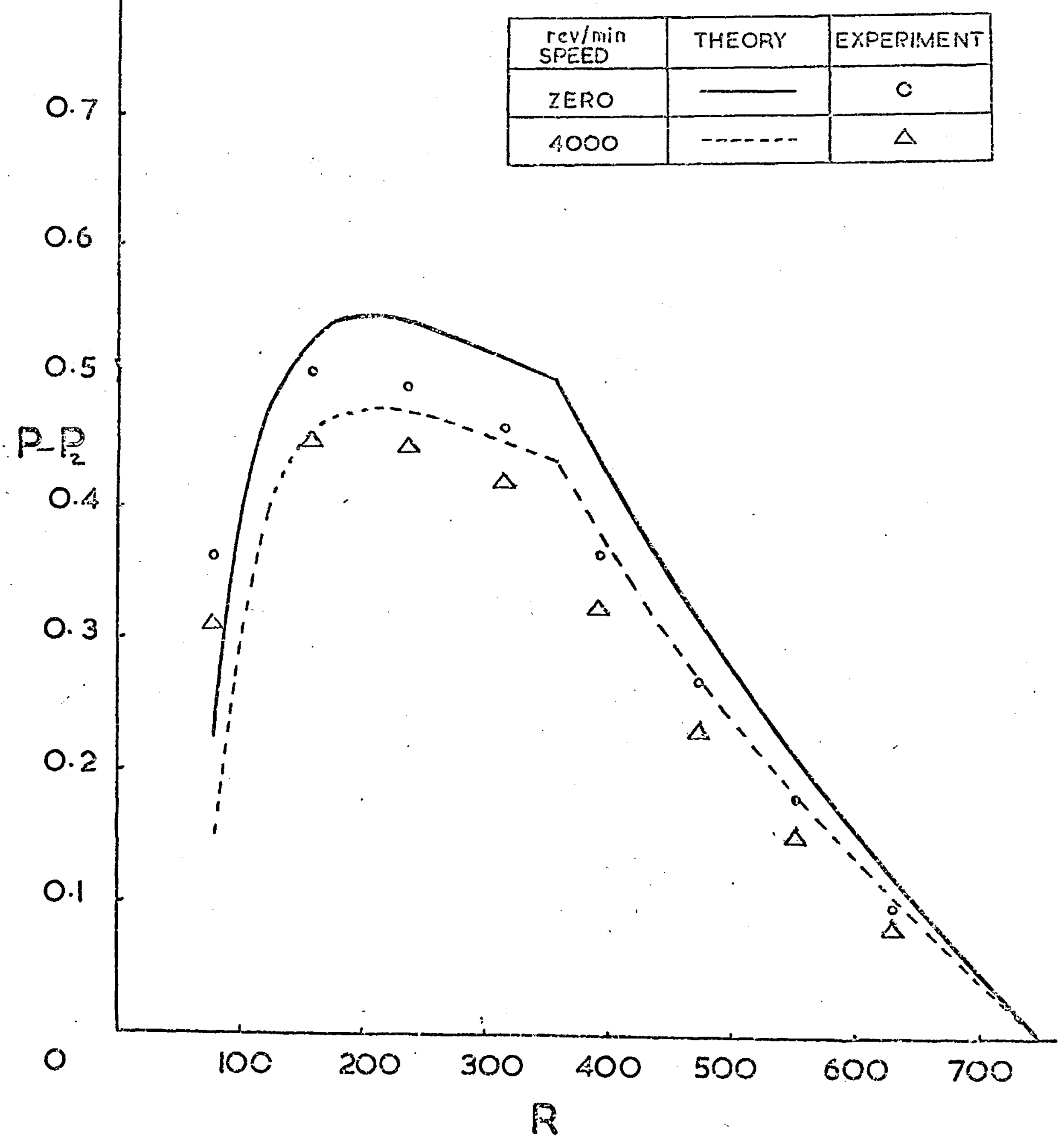
$\alpha = 1.533$ [$r_3 = 45$ mm]

$h = 0.000125$ m

$R_2 = 760$

$Q = 0.00117$ m^3/sec

$R_e = 205200 / 134000$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 29 & N° 30

FIG. N° 49.

STATIC AND DYNAMIC TESTS

STEPPED BEARING

$\alpha = 1.533$ [$r_3 = 45\,mm$]

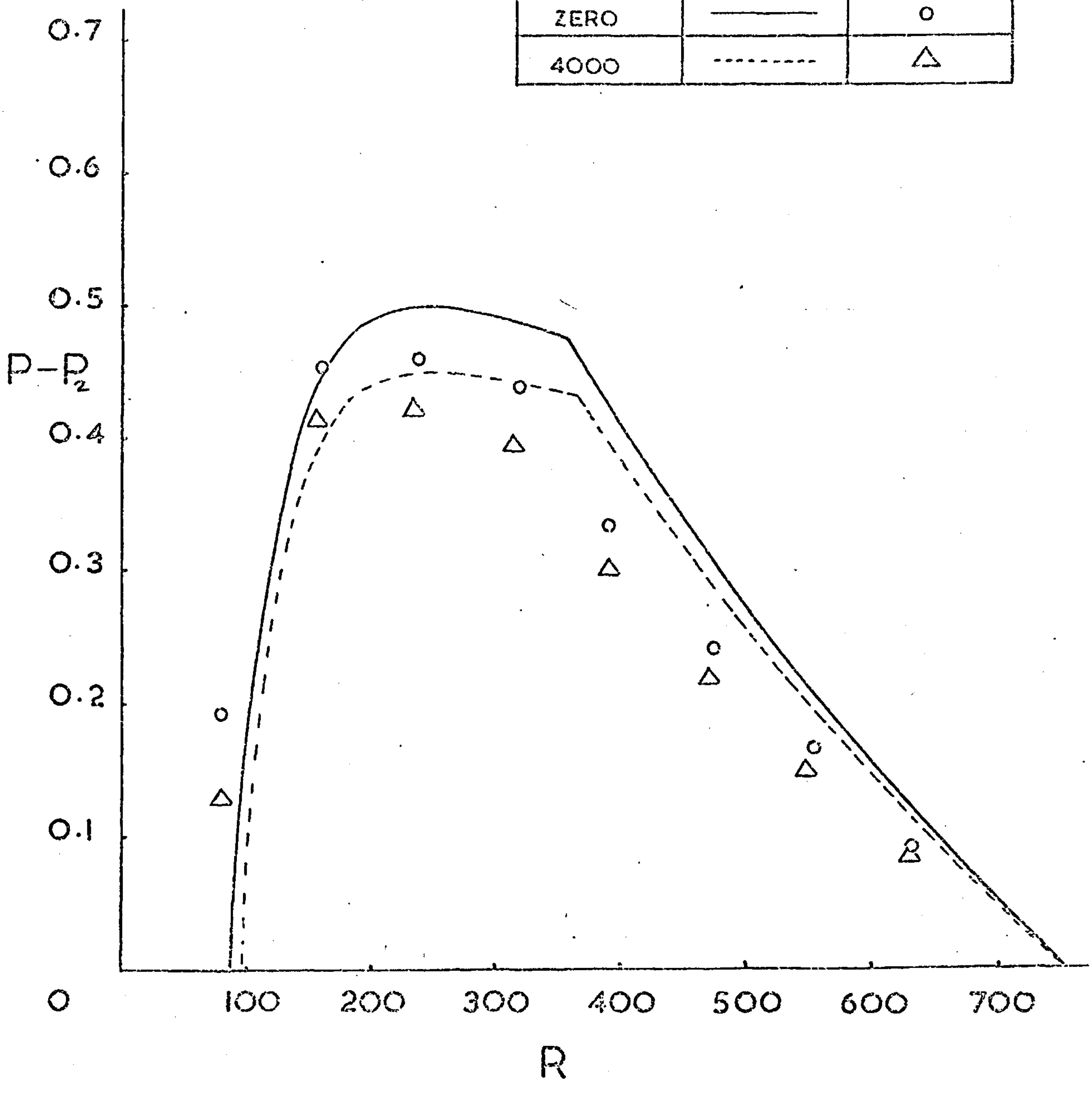
$h = 0.000125\,m$

$R_2 = 760$

$Q = 0.00184\ m^3/sec$

$R_e = 322000 / 210000$

rev/min SPEED	THEORY	EXPERIMENT
ZERO	————	o
4000	- - - - - -	△



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 31 & N° 32

FIG. N°50.

STATIC AND DYNAMIC TESTS

STEPPED BEARING

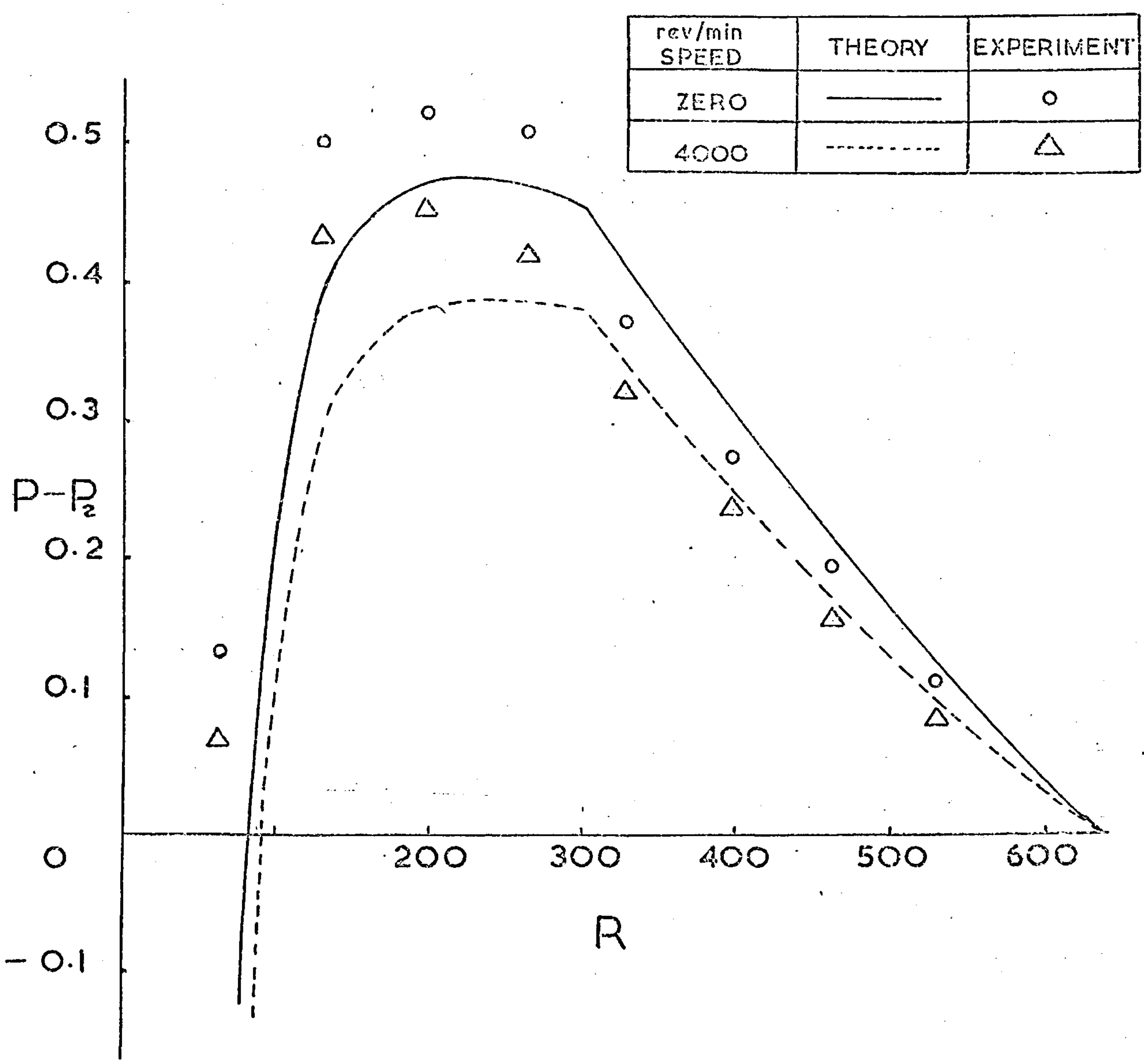
$\alpha = 1.445 \quad [r_3 = 45\,mm]$

$h = 0.00015\ m$

$R_2 = 633$

$Q = 0.00171\ m^3/sec$

$R_e = 250000 / 173000$



DIMENSIONLESS PRESSURE DISTRIBUTION TESTS N° 33 & N° 34

FIG. N° 51.

STATIC AND DYNAMIC TESTS

STEPPED BEARING

$\alpha = 1.445 \quad [r_3 = 45\text{mm}]$

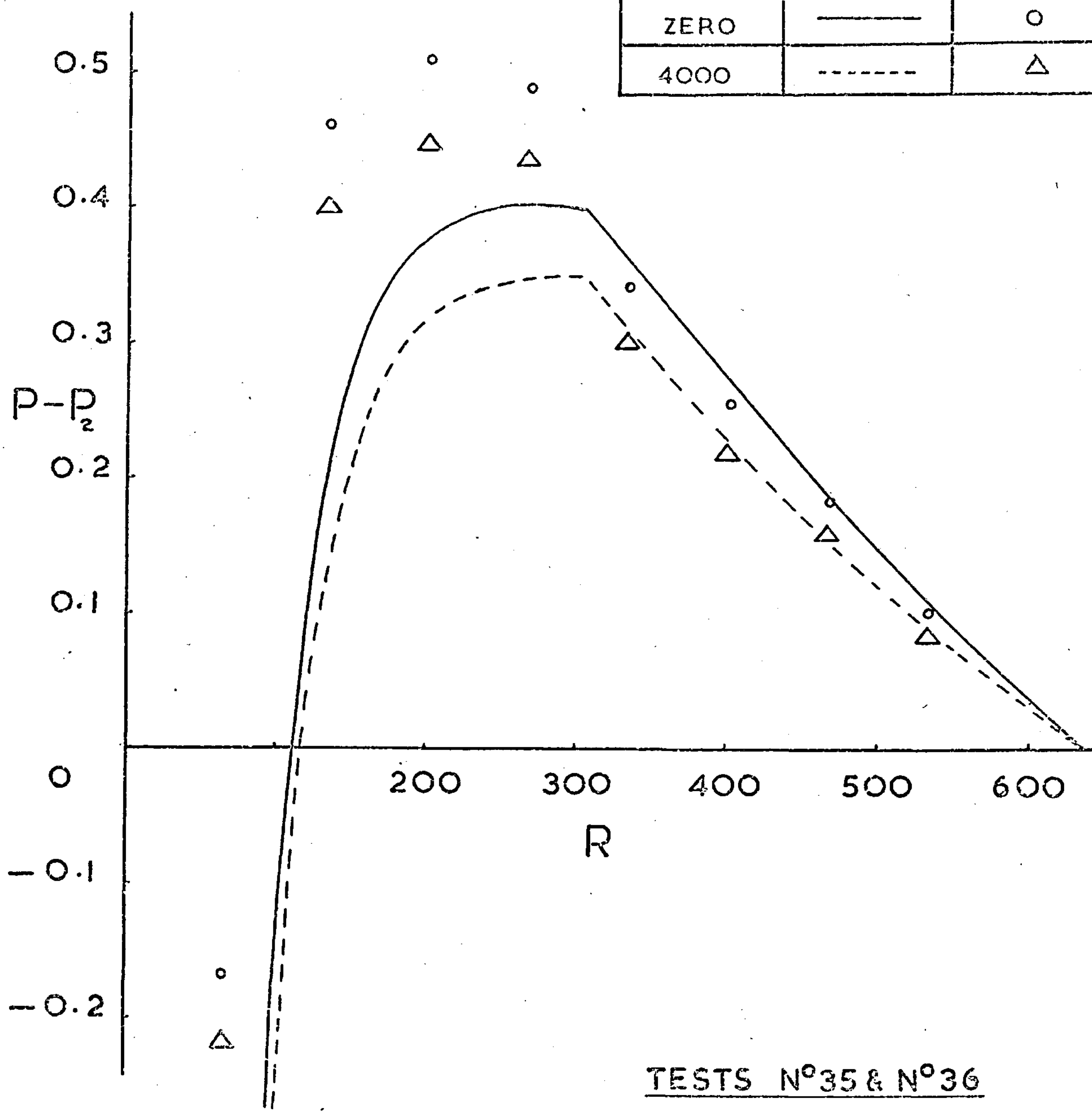
$h = 0.00015$ m

$R_2 = 633$

$Q = 0.002368$ m^3/sec

$R_e = 386000/267000$

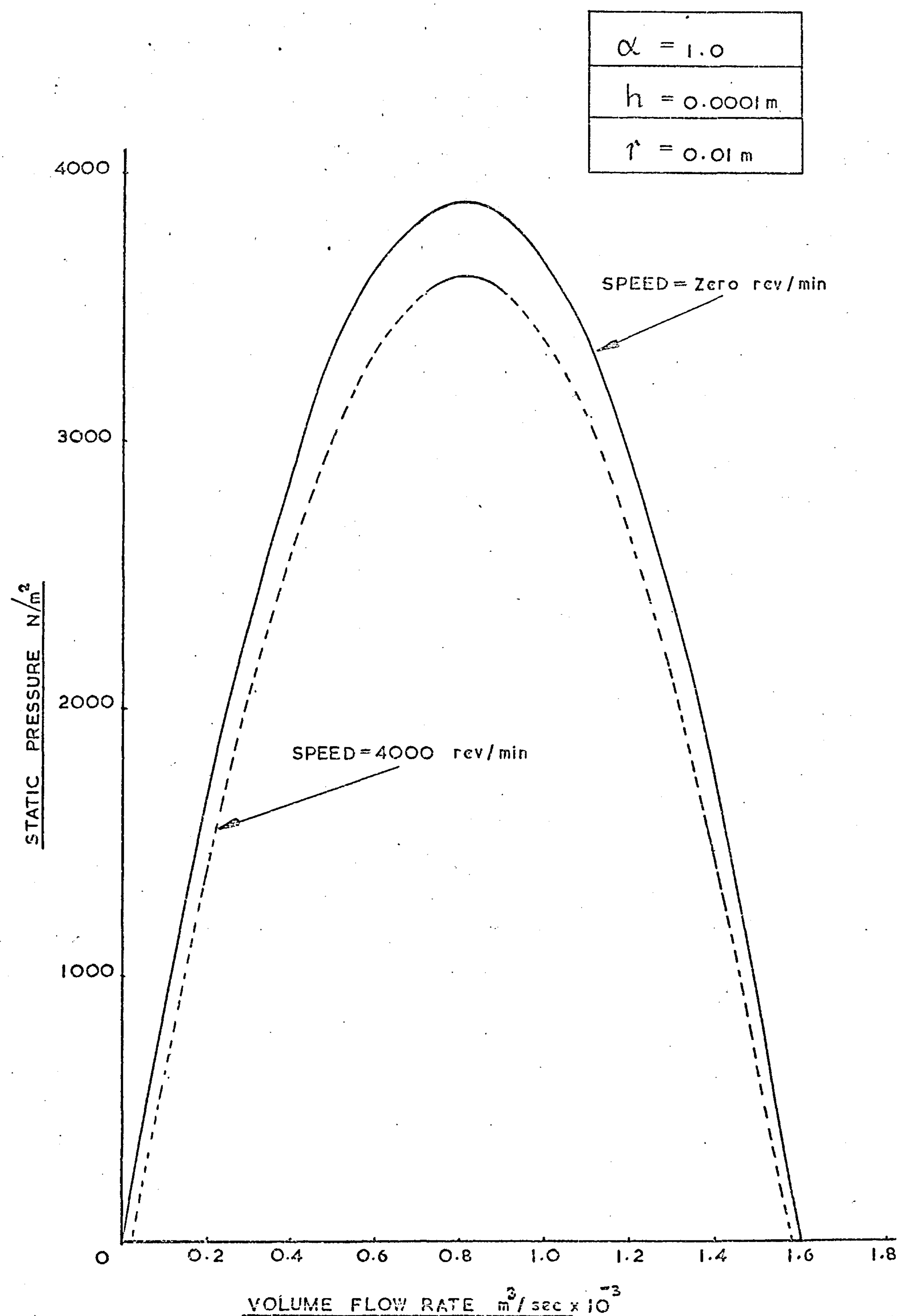
rev/min SPEED	THEORY	EXPERIMENT
ZERO	———	○
4000	- - - - - - -	△



TESTS N° 35 & N° 36

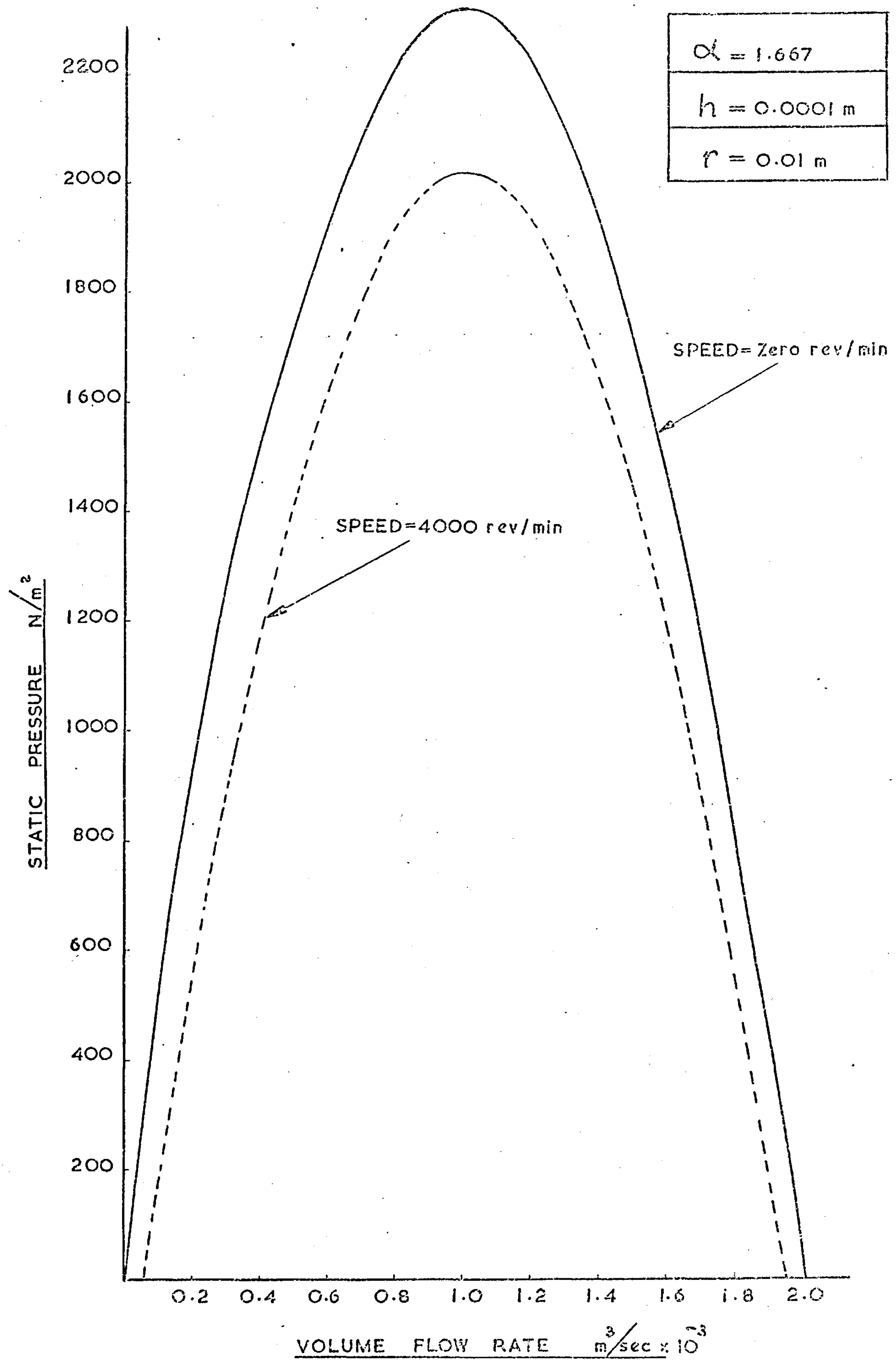
DIMENSIONLESS PRESSURE DISTRIBUTION

FIG. N° 52.



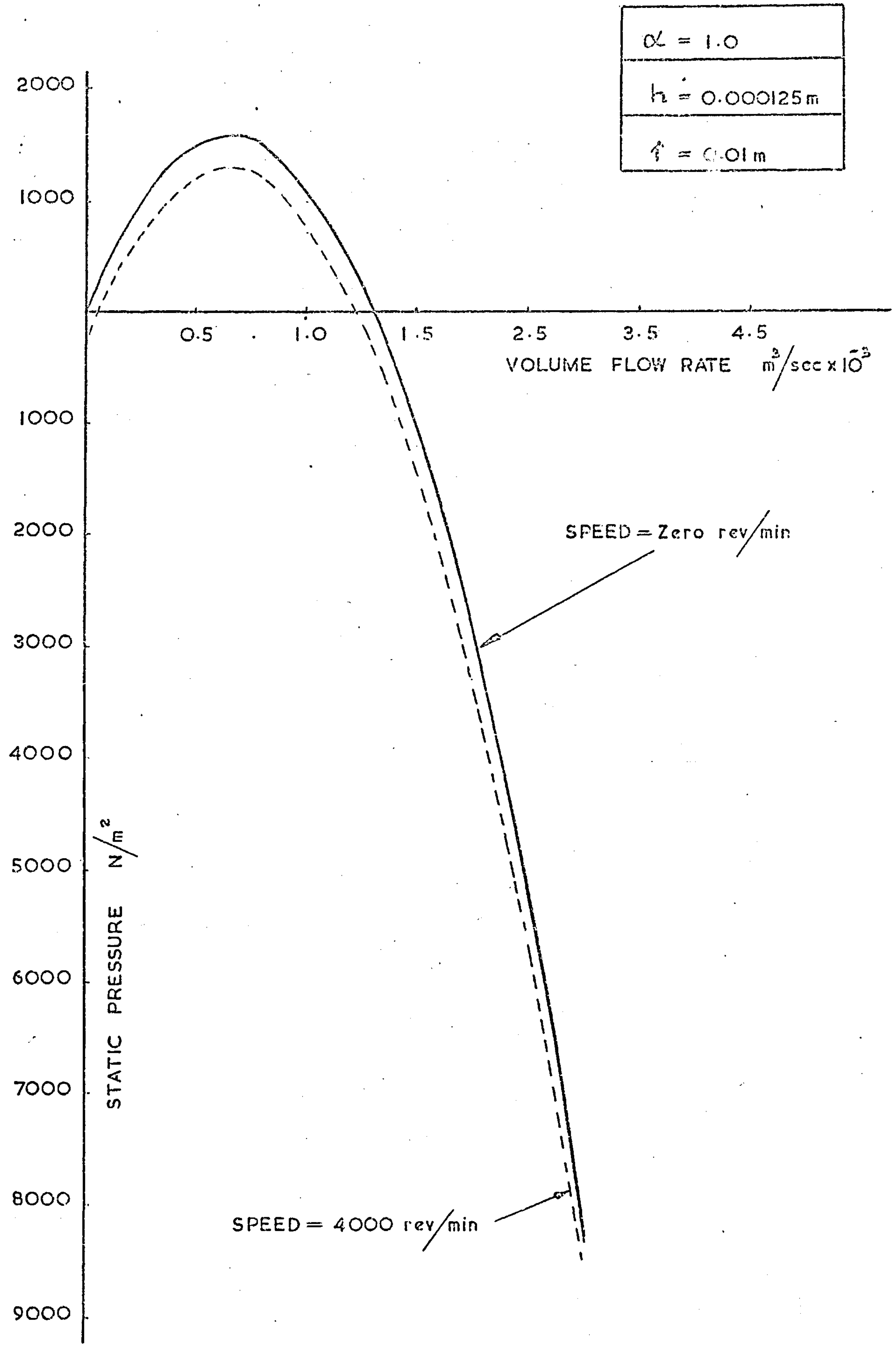
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE.

FIG. N° 53.



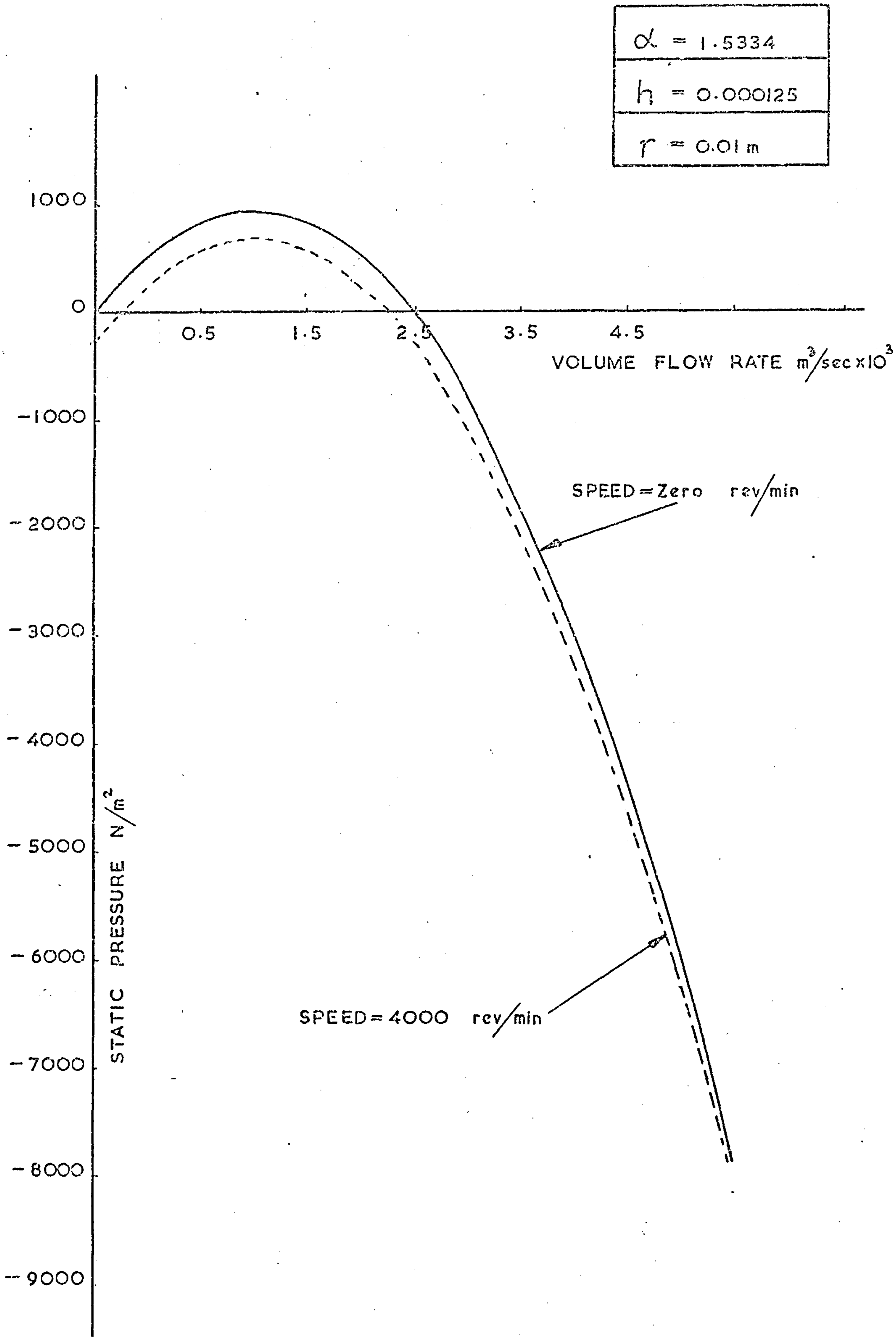
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE

FIG. N° 54.



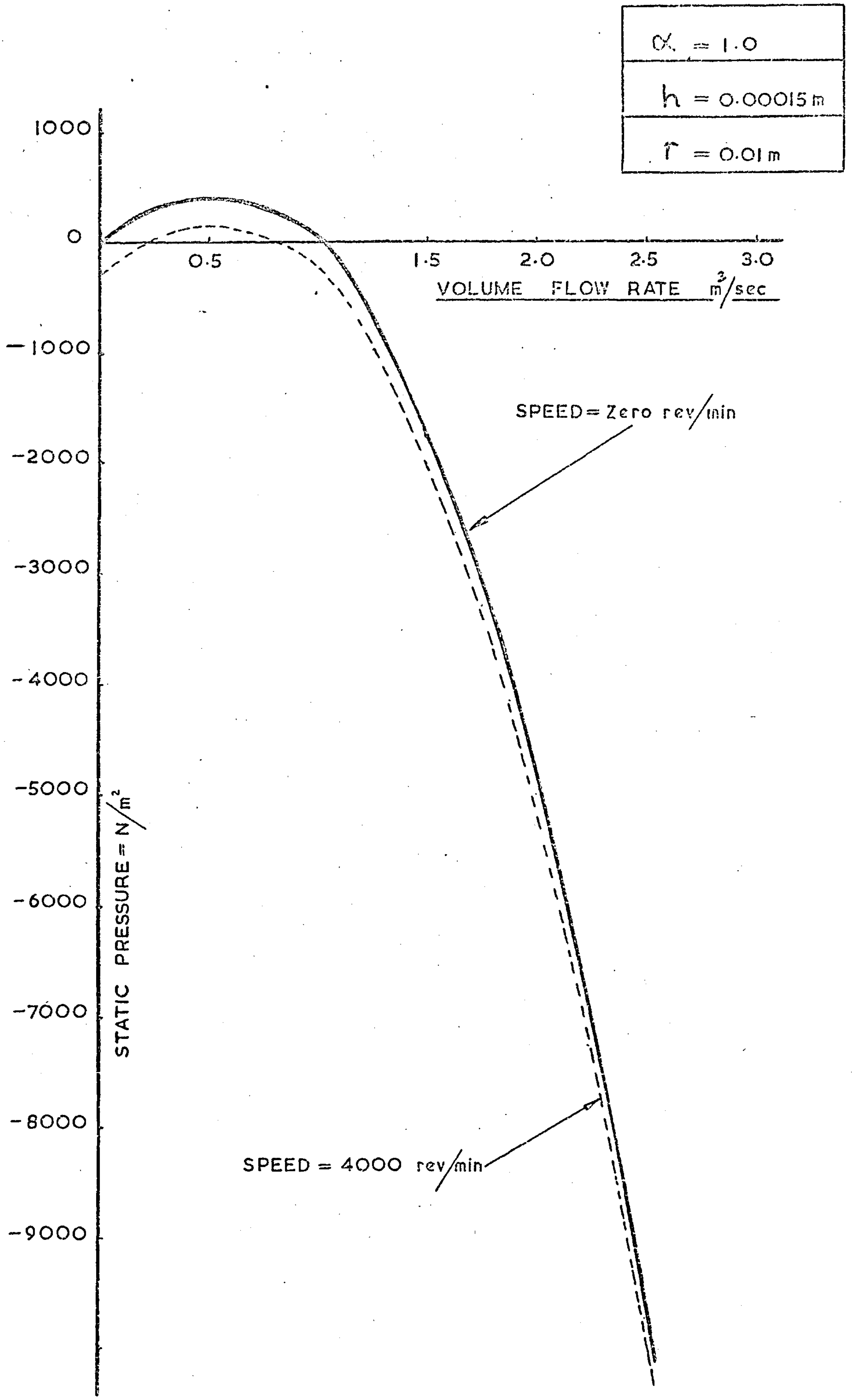
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE

FIG. N° 55.



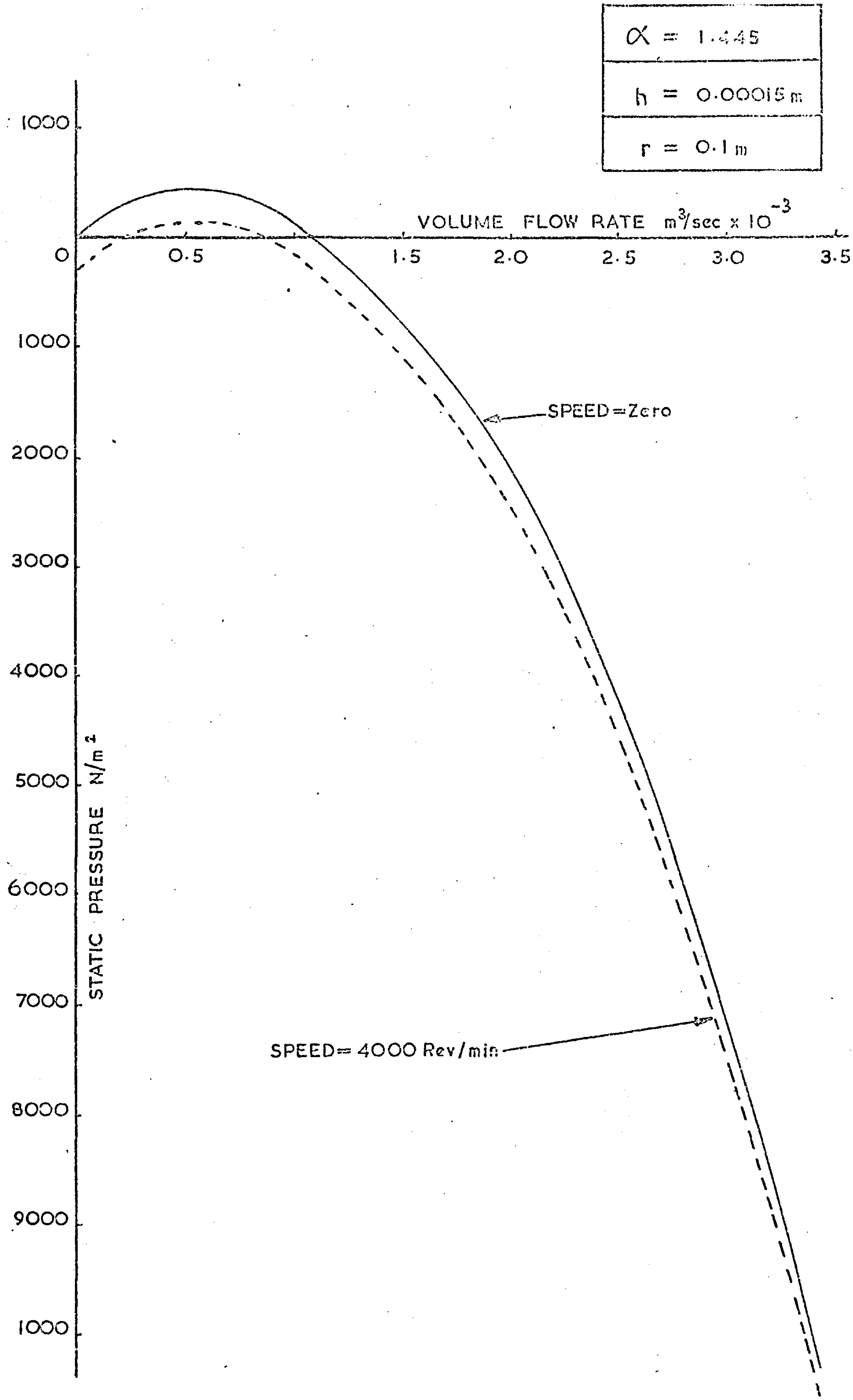
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE

FIG. N° 56.



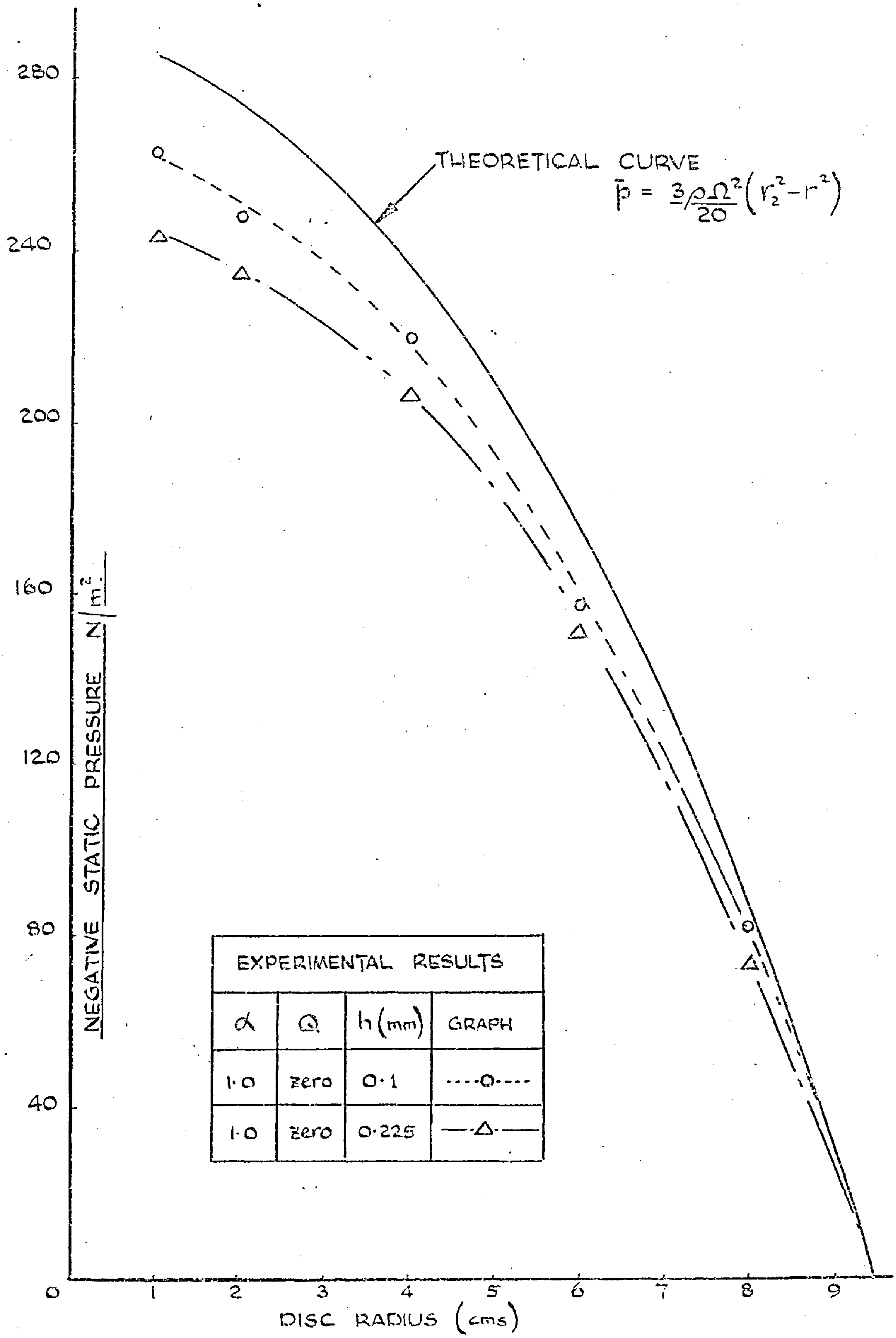
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE

FIG. N° 57.



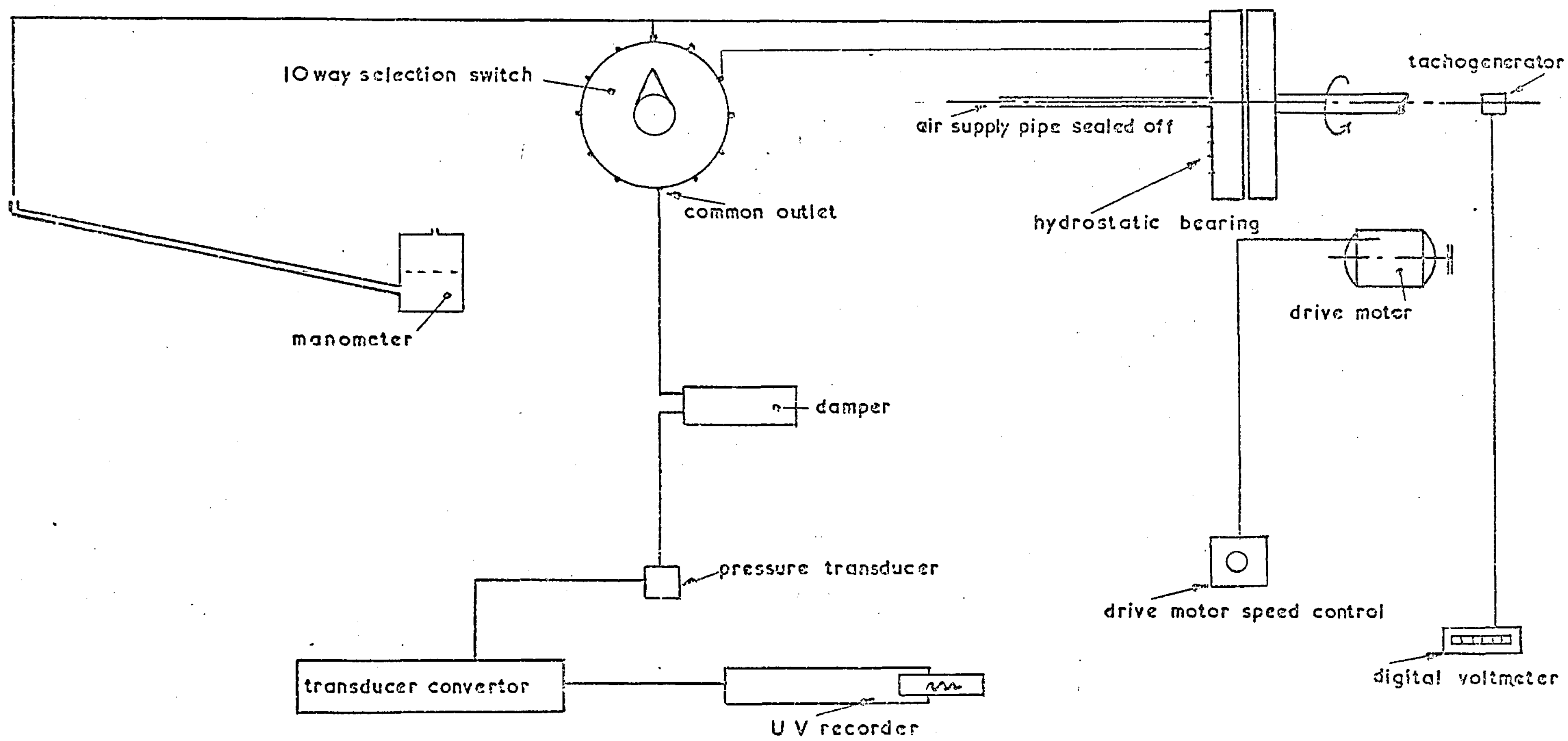
RELATION BETWEEN STATIC PRESSURE AND VOLUME FLOW RATE

FIG. N°58.



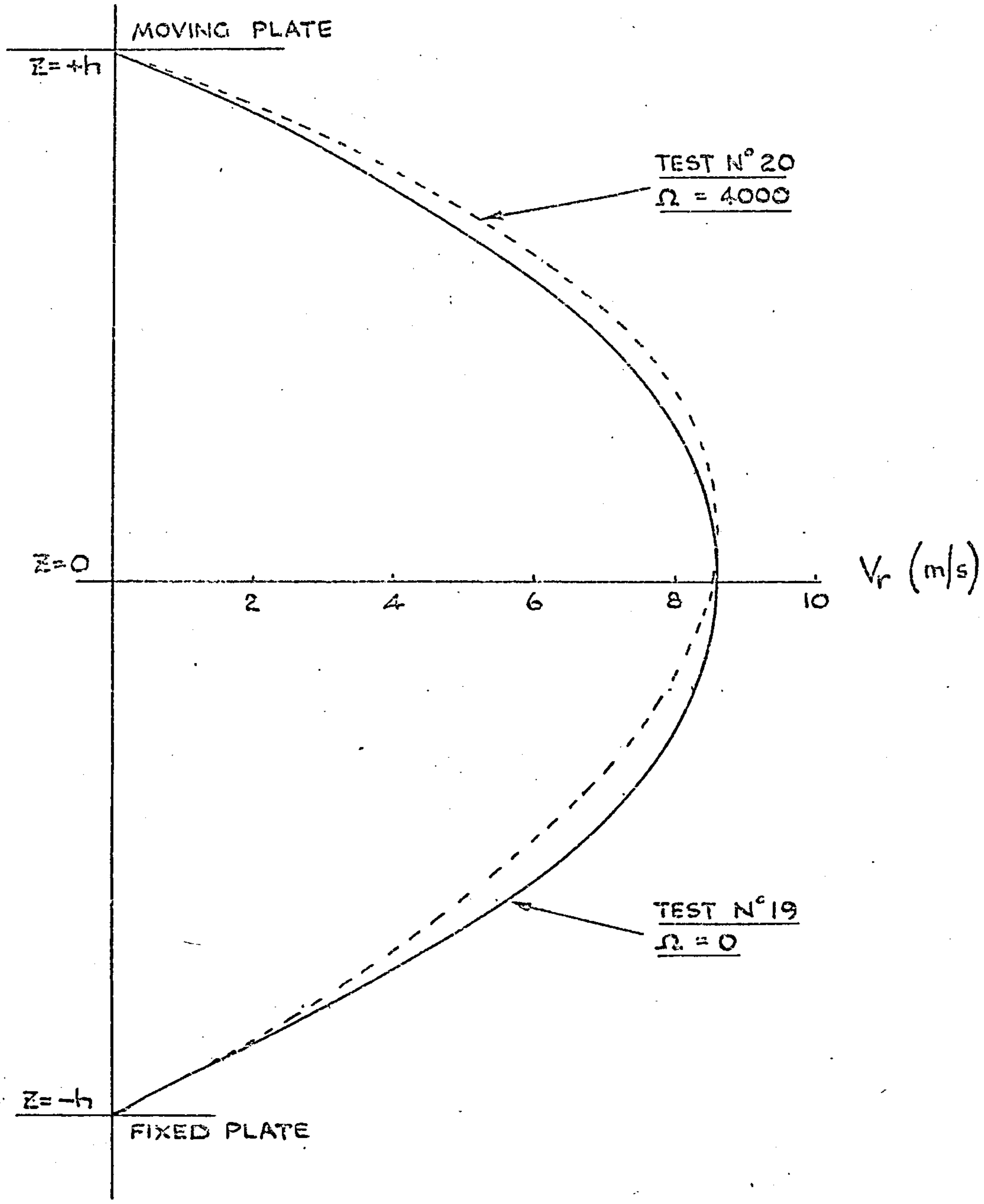
SUCTION DUE TO ROTATION SPEED OF 4000 rev/min.

FIG. No 59.



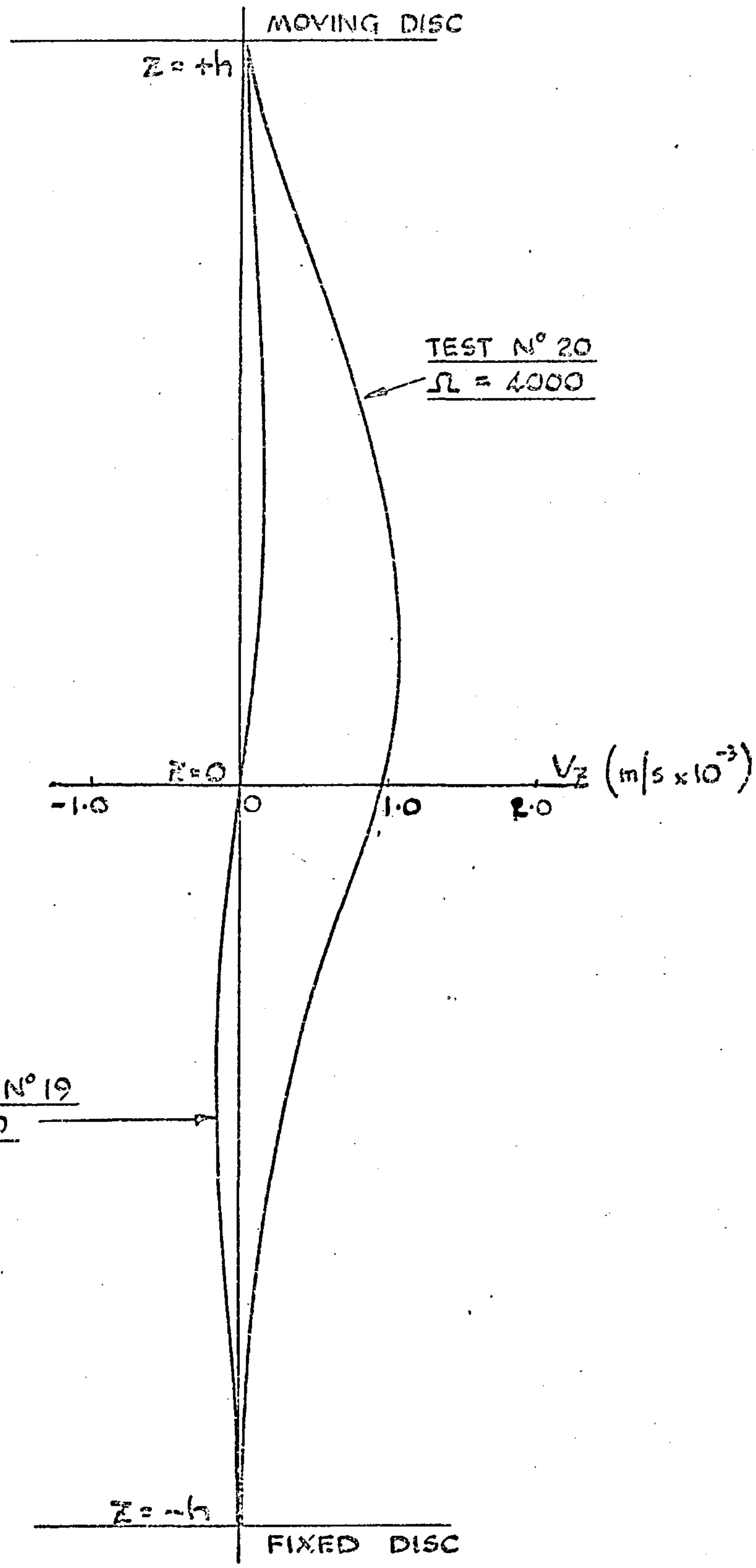
INSTRUMENTATION USED TO MEASURE SUCTION DUE TO ROTATIONAL INERTIA EFFECT

FIG. N° 60.



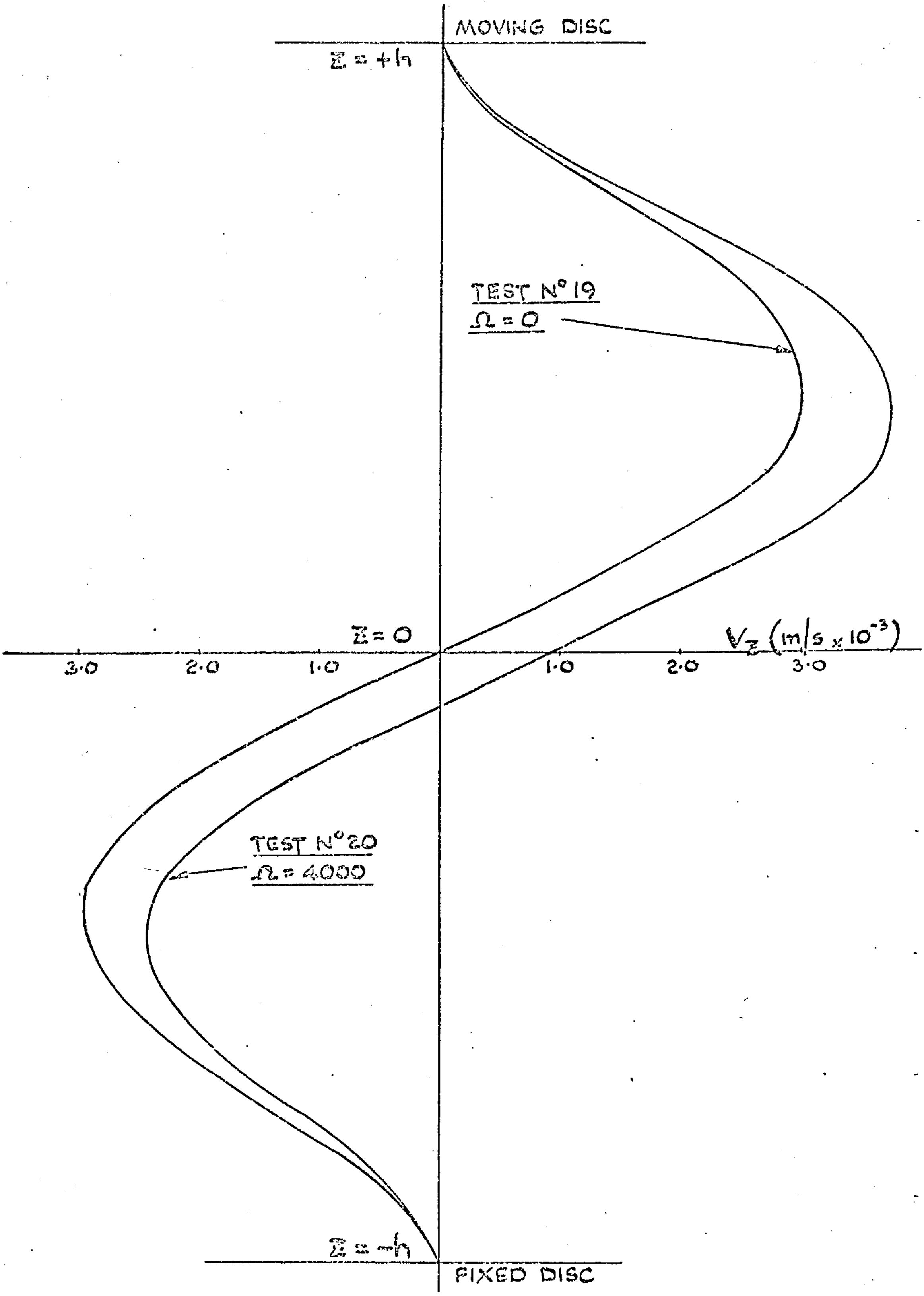
RADIAL VELOCITY DISTRIBUTION ACROSS GAP AT DISC RADIUS 95mm

FIG. N° 61.



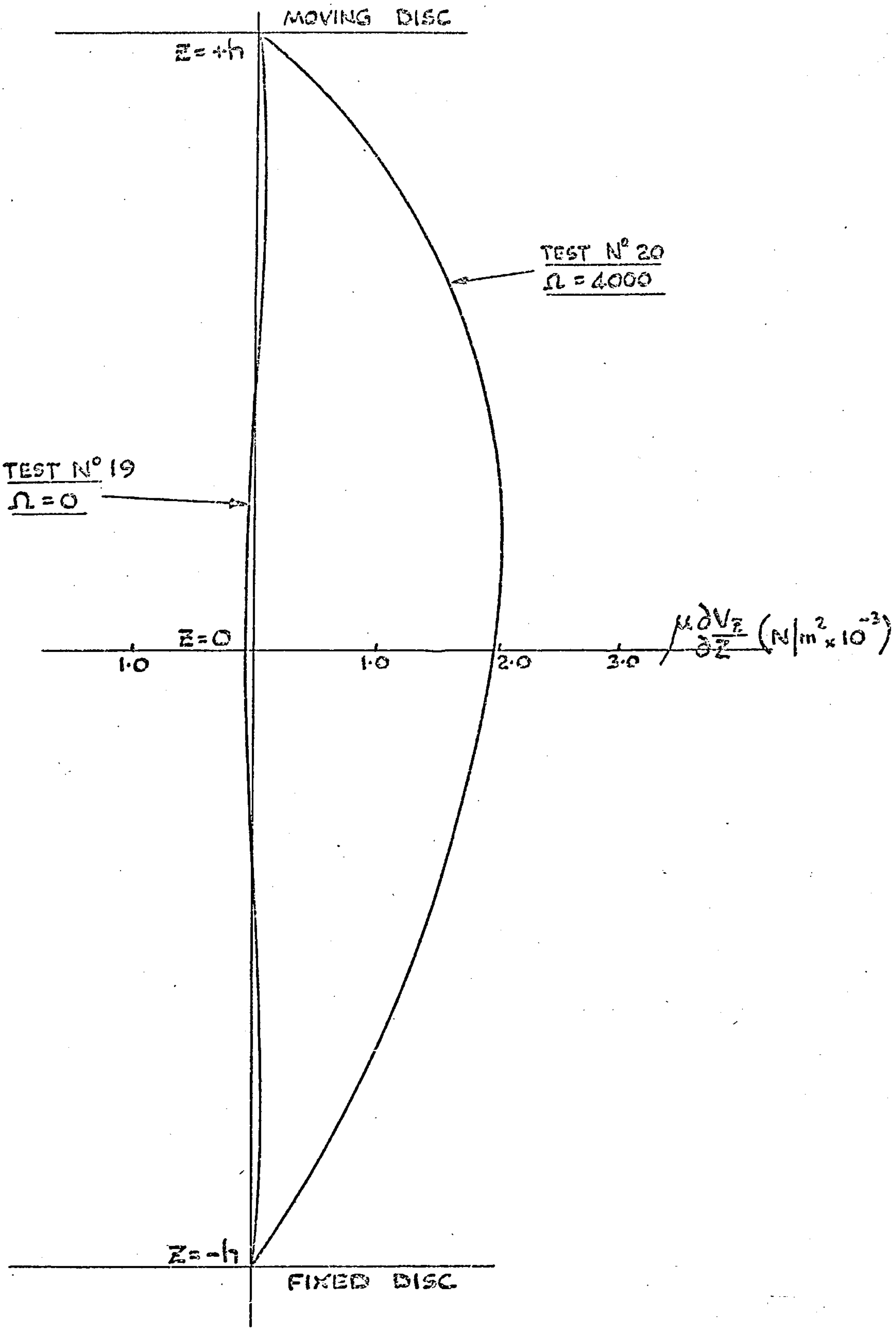
AXIAL VELOCITY DISTRIBUTION AT DISC RADIUS 50 mm

FIG. N° 62.



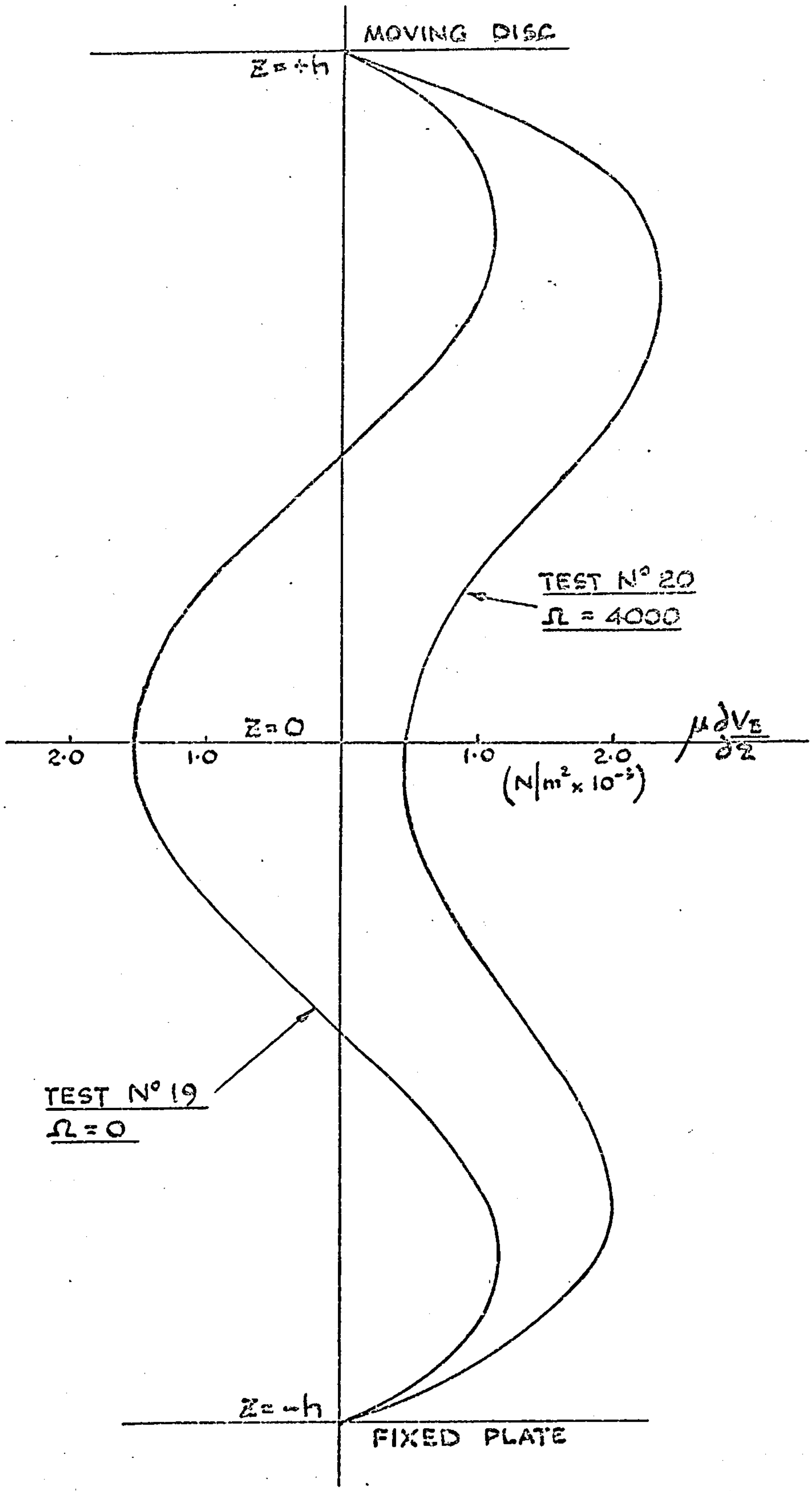
AXIAL VELOCITY DISTRIBUTION AT DISC RADIUS 25 mm.

FIG. N° 63.



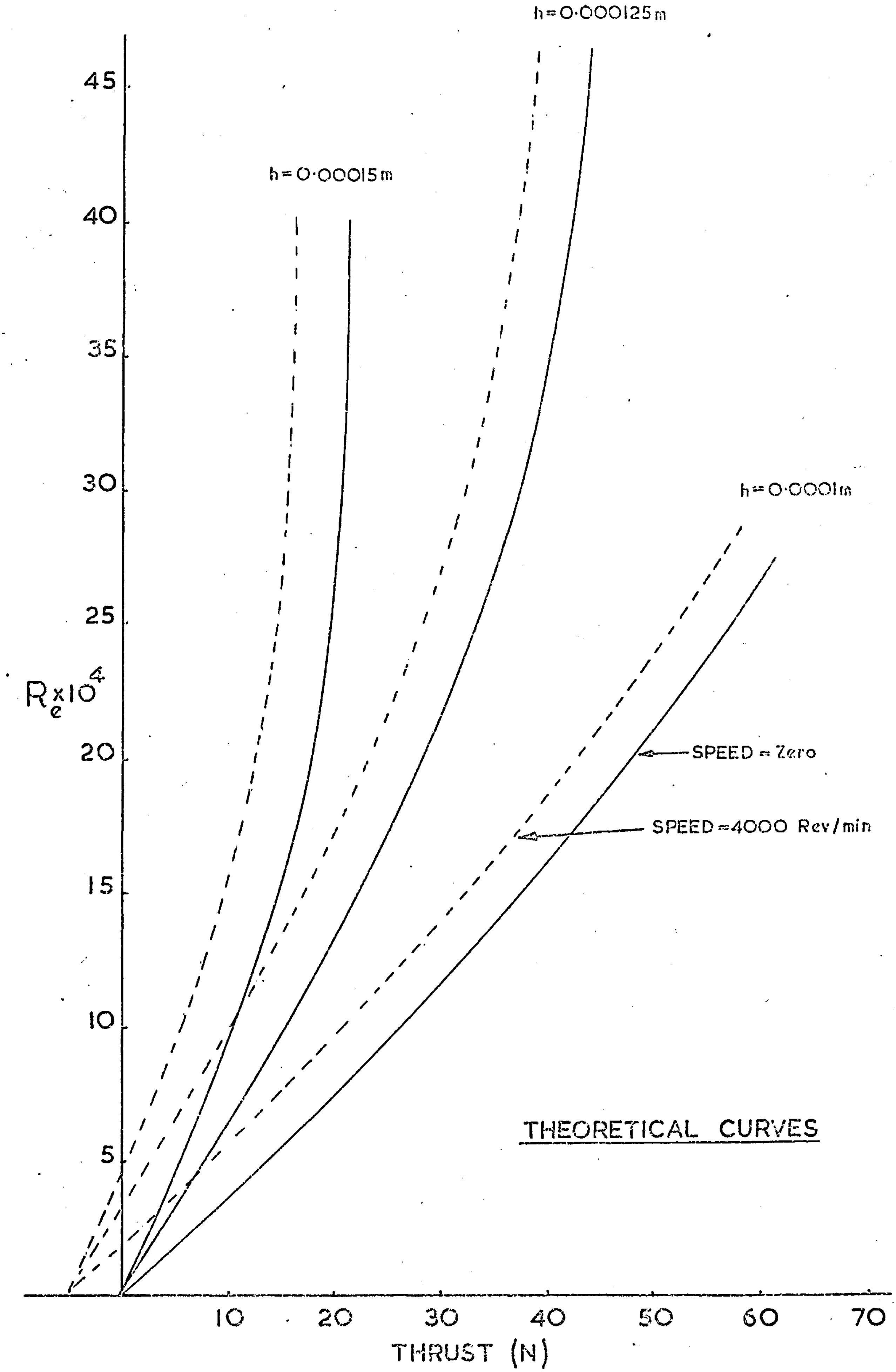
CHANGE IN PRESSURE ACROSS GAP AT DISC RADIUS 70mm

FIG. N° 64.



CHANGE IN PRESSURE ACROSS GAP AT DISC RADIUS 25 mm

FIG. N° 65.



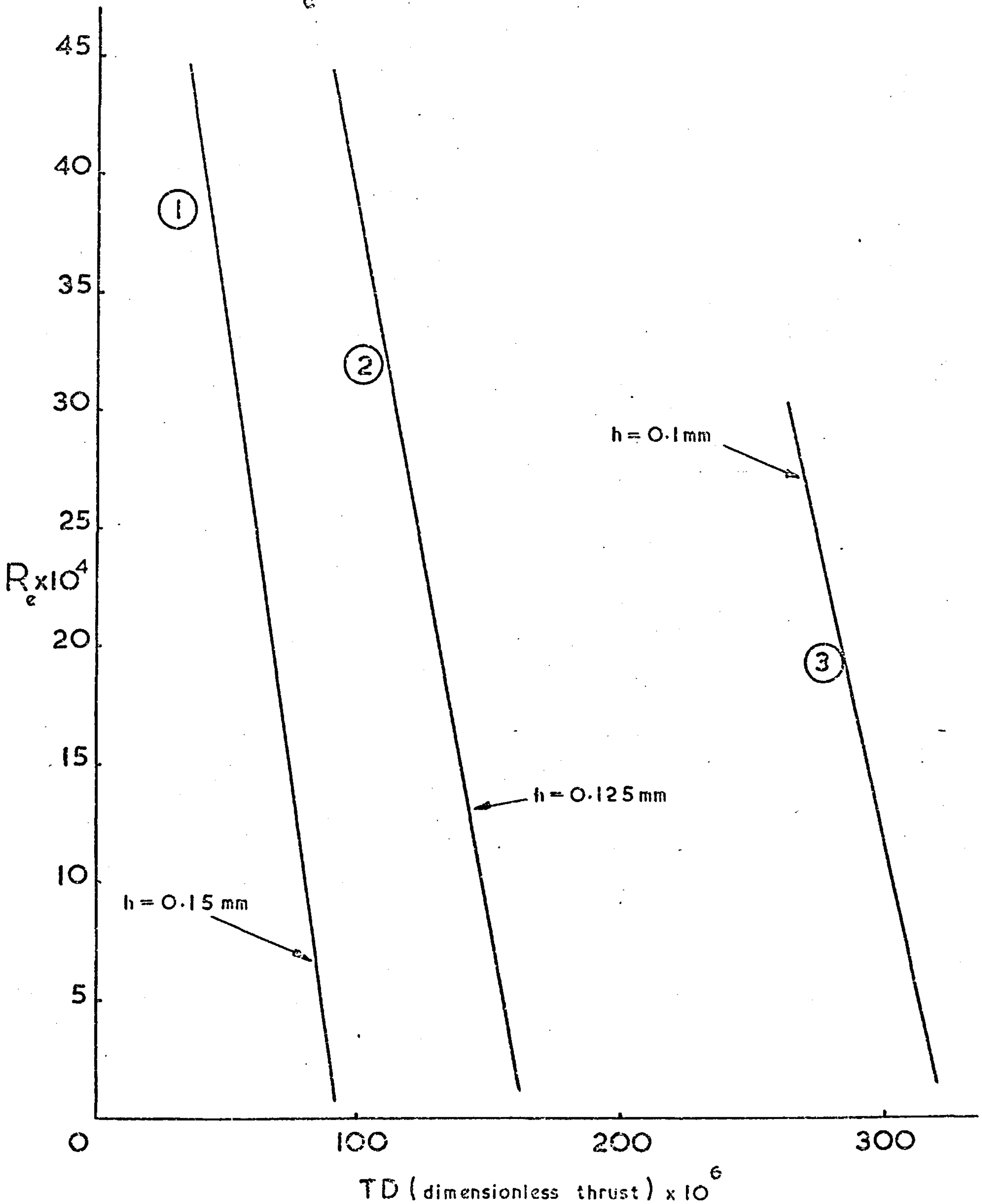
RELATION BETWEEN REYNOLDS NUMBER & THRUST.

FIG. N° 66.

(1) $R_e = -7.77 \times 10^{-3} \times TD + 71.08 \times 10^4$

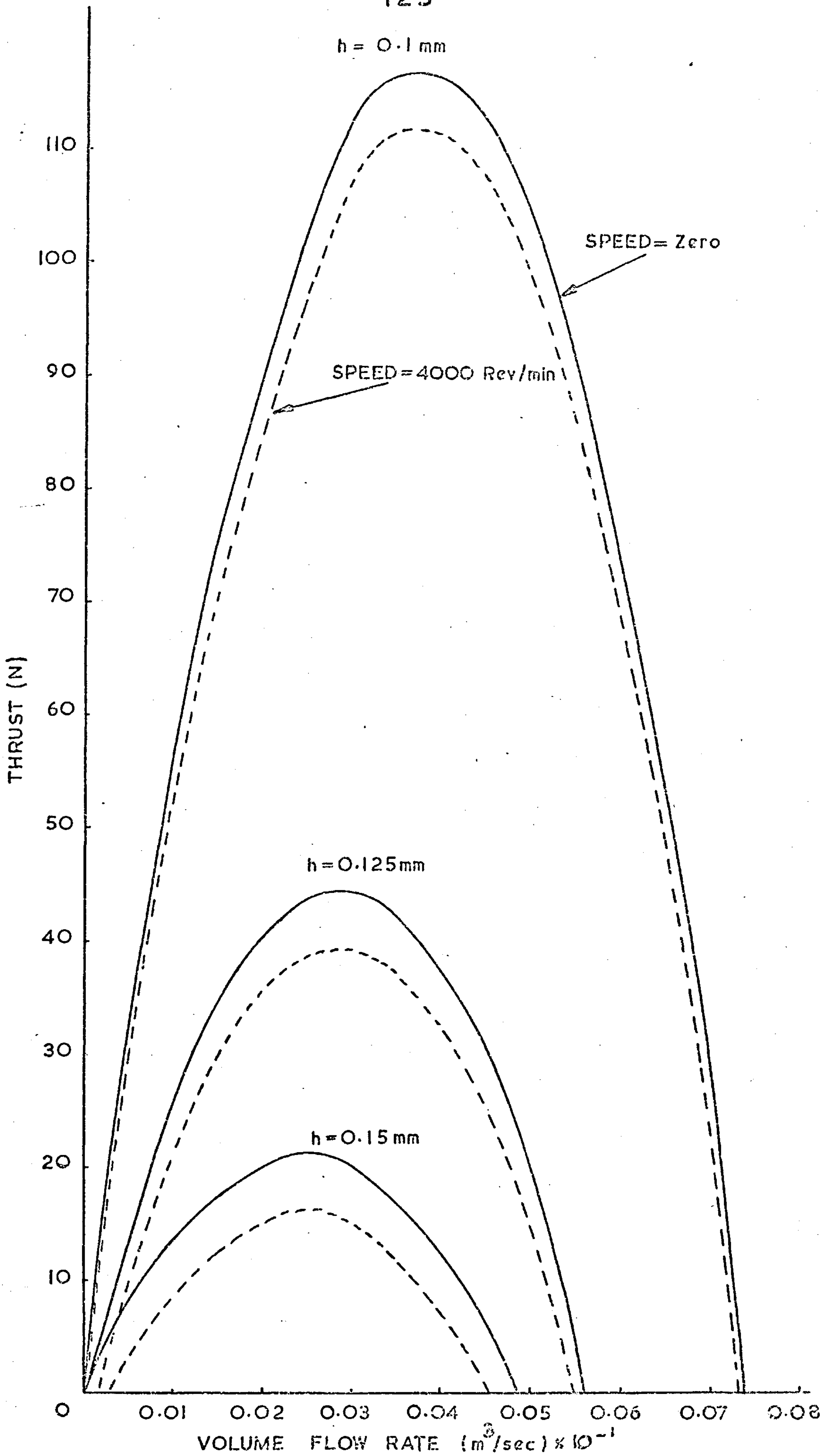
(2) $R_e = -6.15 \times 10^{-3} \times TD + 100.35 \times 10^4$

(3) $R_e = -5.04 \times 10^{-3} \times TD + 162.3 \times 10^4$



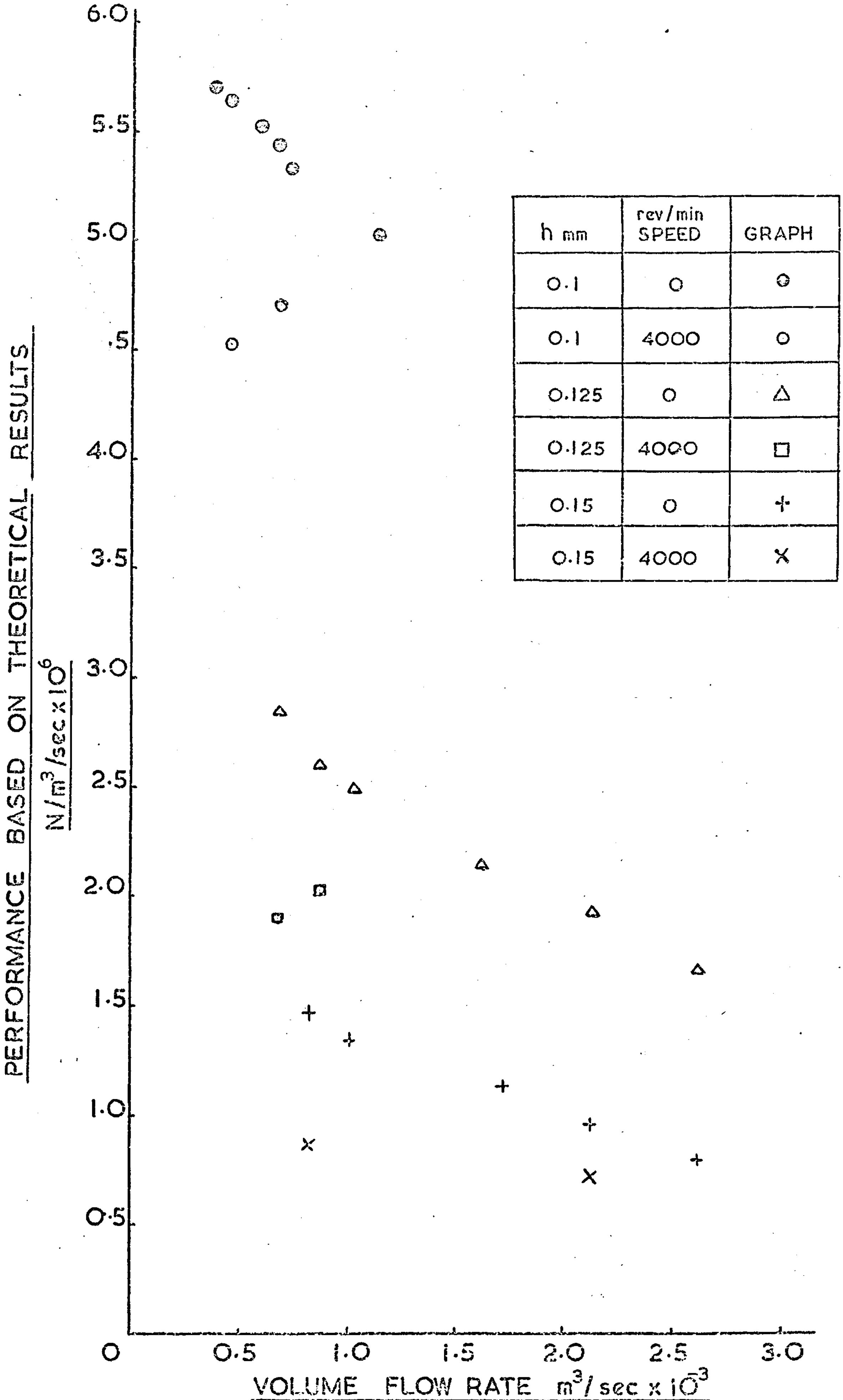
RELATION BETWEEN REYNOLDS NUMBER & DIMENSIONLESS THRUST

FIG. No 67.



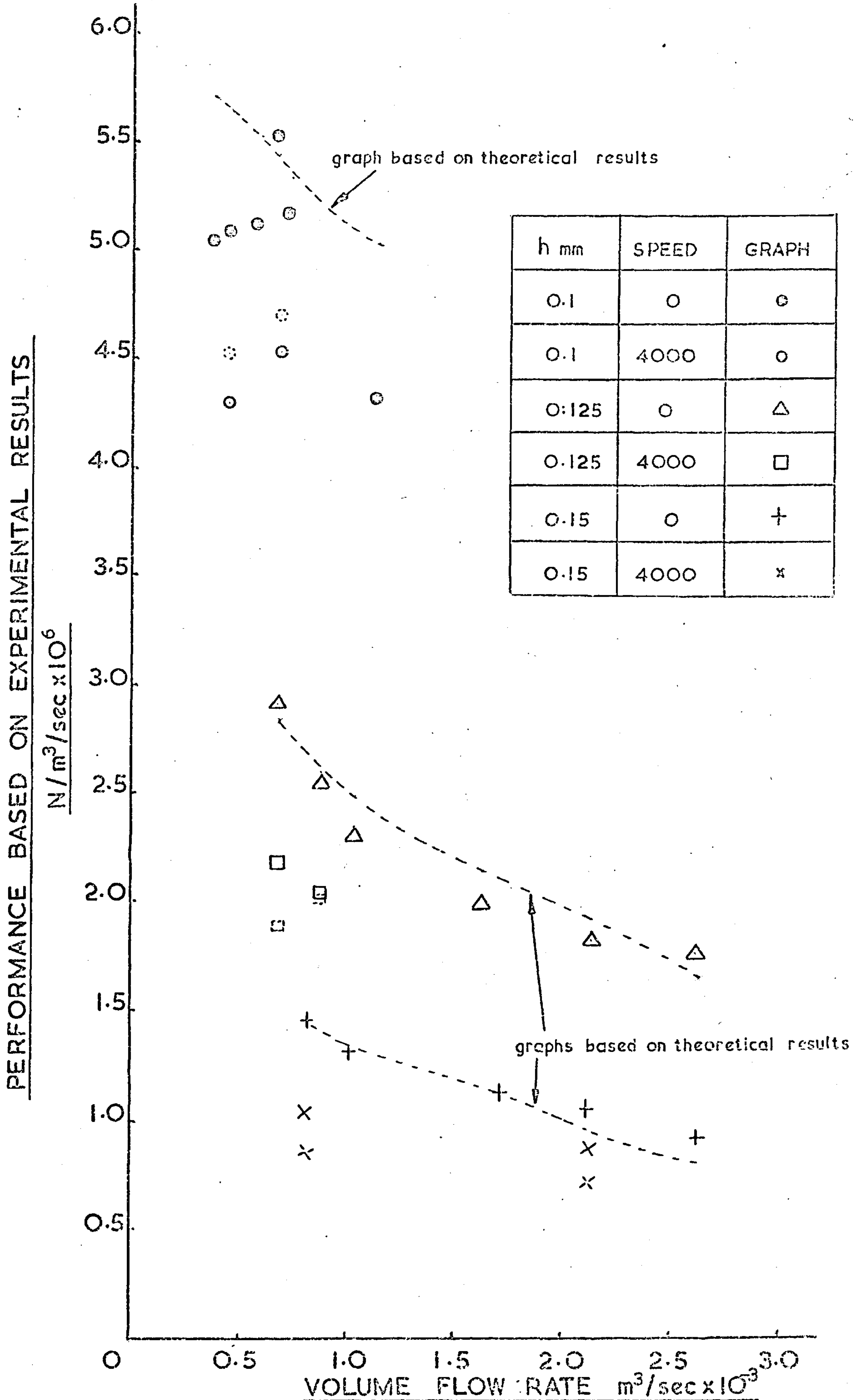
RELATION BETWEEN THRUST AND VOLUME FLOW RATE.

FIG. N° 68.



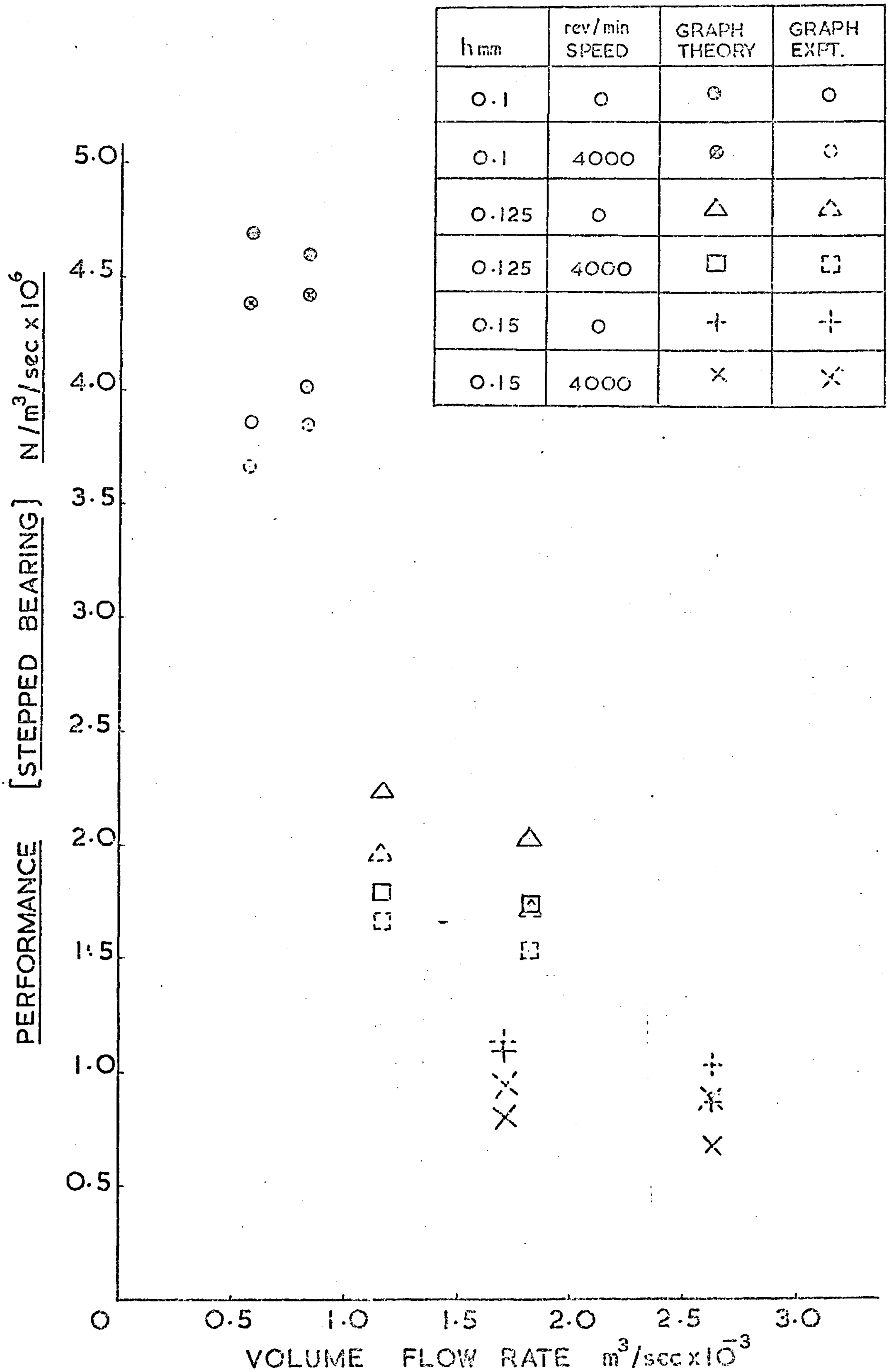
RELATION BETWEEN PERFORMANCE AND FLOW RATE (THEORY)

FIG. Nº 69.



RELATION BETWEEN PERFORMANCE & FLOW RATE (EXPERIMENTAL)

FIG. N° 70.



RELATION BETWEEN PERFORMANCE & FLOW RATE (STEPPED BEARING)

CHAPTER 6 SUMMARY

6.01 ERRORS

The errors arising from this project can be classified into two groups; namely, errors in the physical measurements and errors in the theoretical computations.

Errors in the physical measurements

If the axis of rotation of the dynamic disc is not parallel to the axis of generation of the static disc, then this misalighment can cause a vibration to be superimposed on the air passing through the bearing. A vibration of this type was detected by the pressure transducer during pressure measurements associated with the zero flow condition; but the variation in pressure produced was too small to have any significant effect on the static disc, therefore a major error, due to squeeze-film effects, can be discounted.

The volume flow rate, Q, was measured using an orifice plate whose design was based on BS 1042. From details given in Appendix D of this standard it was apparent that an error of ±1.3 per cent in the flow rate could be expected.

The setting of the distance between the discs, 2h, was subject to error from three sources (a) feeler gauge size, ±1% error, (b) error in interpreting the 'feel' when setting the gap with the feeler gauges, ±1%, (c) alignment error, ±1% error. Giving a total of ±3% error.

The speed of rotation of the dynamic disc was measured by means of a tachogenerator, the output of which was fed to a digital voltmeter. A speed tolerance of ±2% was estimated. The step in the stepped disc was set to an accuracy of ±1%. The static pressure $\bar{p}$ measured from the static disc tappings have an estimated tolerance of ±2%. The values of temperature, atmospheric pressure, density and viscosity were recorded to an estimated tolerance of 0.1%, 0.1%, 0.2% and 0.2% respectively. The tolerance on the radial positions of the static pressure tappings (set by a numerically controlled machine tool) was ±0.1%. The outer diameter of the disc r_2 was manufactured to very close limits. It will be assumed that the size attributed to r_2 is correct.

Accumulative effect of errors in physical measurements

Equation (24) is made up of three terms, if each term is considered separately, the possible error associated with each term can be calculated.

VISCOUS TERM

Let $V = \frac{3\mu Q}{4\pi h^3} \log_e \left(\frac{r_2}{r}\right)$

then $\frac{\delta V}{V} = -\frac{\delta r}{r \log_e r} + \frac{\delta Q}{Q} - 3\frac{\delta h}{h} + \frac{\delta\mu}{\mu}$

hence percentage error = ±10.3%

RADIAL INERTIA TERM

Let $U = \frac{27\rho Q^2}{560\pi^2 h^2} \left[\frac{1}{r^2} - \frac{1}{r_2^{\,2}}\right]$

then $\frac{\delta U}{U} = \frac{\delta\rho}{\rho} + 2\frac{\delta Q}{Q} - 2\frac{\delta h}{h} - 2\frac{\delta r}{r}$

hence percentage error = ±8.9

ROTATIONAL INERTIA TERM

Let $W = \frac{3\rho\Omega^2}{20}(r_2{}^2 - r^2)$

then $\frac{\delta W}{W} = \frac{\delta\rho}{\rho} + 2\frac{\delta\Omega}{\Omega} - 2\frac{\delta r}{r}$

hence percentage error = ±4.3

The above analysis suggests that in determining the value of the static pressure, theoretical predictions should correlate with experimental results to within ±10%.

Errors in the theoretical computations

The equations used for determining the static pressure in a thrust bearing at any radius, rely on the solution of a quadratic equation (33), by means of a computer program, Appendix (4), to provide the necessary relationship between $\bar{p}$ and Q at the reference radii r_1. The graphs (FIGS.53-58 inclusive) show how $\bar{p}$ and Q are related, but these graphs were not relied on exclusively to provide an accurate forecast of $\bar{p}$ and Q values. To avoid errors due to interpolation, the computer program was used to predict values of Q for particular values of $\bar{p}$ to suit each particular test run.

The graphical determination of the partial derivatives $\frac{\partial p}{\partial r}$ and $\frac{\partial^2 p}{\partial r^2}$ could be subject to considerable error particularly in the vicinity of the air inlet — where rapid changes in pressure take place, an error of 5% and 10% respectively will be assumed. (see 4.02).

6.02 DISCUSSION

Some of the theoretical and experimental curves obtained by Jackson & Symmons (7) and Shirman (12) for non-rotating hydrostatic bearings show the same general form as those found in this report. If the graph associated with the Reynolds number 174800 (Jackson & Symmons (7) FIG.3 p.63) is compared with Test 5, FIG.37, both theoretical graphs overestimate the values of the dimensionless pressure for all but the inner quarter of the disc, where the dimensionless pressure is underestimated.

The curves associated with parallel circular plates without a central recess (shown by Coombs and Dowson (11)) do not allow for radial inertia effects. This would appear to be justified if the flow rates employed were small. In their experimental tests Coombs and Dowson used a thrust bearing with an outside diameter of 5.25in (r_2 = 66.7mm) with an oil supply hole 0.25in diameter. If we assume the following: 2h = 0.25mm, ρ = 900kg/m^3, Ω = 419rad/s (4000 rev/min), μ = 0.02Ns/m^2 and Q = 0.00015m^3/s, the relative magnitudes of the Viscous, Radial, and Rotational terms, when calculated from equation (24), are:

VISCOUS	RADIAL	ROTATIONAL	
1	0.05	0.56	when r = 15mm
1	0.032	0.48	when r = 30mm

From these results it is clear that if Coomes and Dowson used the test conditions assumed above, the omission of the radial inertia term did not seriously affect their results.

If, however, air is the lubricant, its low absolute viscosity value greatly reduces the value of the viscous term. The value of the radial and rotational terms will also be reduced (because of the air's lower density value), but not by the same magnitude as the viscous term. This means that the radial term can be significant (in relation to the viscous term)——particularly when Q and h are large and r is small. The effect of omitting the radial inertia term when calculating the value of dimensionless pressure is shown in FIG.43A.

The maximum theoretical thrust of 57.4N (12.81bf), recorded in Test 4, is small by practical standards, but if higher thrusts were obtained by reducing the size of the air gap, the effect of rotation, the main interest of this thesis, would be eclipsed by the resulting high value of the viscous flow term. The low thrust values are due to the fact that the pressure change across the disc was relatively small, and so it follows that the change in gas density, which is proportional to the absolute pressure, was too small to effect the accuracy of the theory based on incompressible flow.

The use of a pressure transducer, connected to a U.V. recorder, to measure the suction effect experienced during the zero flow condition, proved very effective. The U.V. recorder was used to record the high pressures experienced in Tests 1-36, but without success; the sensitivity of the recorder had been reduced to such an extent——to cope with the higher range in pressure—— that small pressure changes could not be measured accurately. The radial pressure distribution for Tests 1-36 was therefore measured using a water filled manometer.

6.03 CONCLUSIONS

It has been established both theoretically and experimentally that the faster a hydrostatic thrust bearing is rotated, the smaller the load it can sustain for fixed flow and gap width conditions. The tests in which suction effects alone were considered were significant in showing the non-dependence of the rotational inertia term on gap thickness and flow rate.

There has not been complete agreement between experimental results and theoretical predictions, this is due mainly to the accumulative effect of errors in the physical measurements discussed in (6.01) and partly to the inadequacy of the theory employed, to really predict how the air pressure changes as it passes through the bearing——particularly in the vicinity of the air inlet where turbulence could exist. However since the theoretical results were tested under extreme conditions, sufficient accuracy exists for the designer to use these equations to include the effects of rotation on hydrostatic thrust pads.

6.04 FURTHER WORK

Modification to existing test rig

The principal error due to physical measurement was in the determination of the gap thickness (2h). This error would be reduced considerably if three pressure transducers were used (FIG.72), to monitor continuously the gap width. The three transducers could be connected via transducer converters to the same U.V. recorder and readings from each channel could be recorded simultaneously on the same trace.

Design of new test rig

The proposed rig would be arranged so that the dynamic disc rotates with its axis of rotation in a vertical plane. The dynamic disc would be above the static disc, supported only by the air which flows radially from the centre of the two discs. The thrust provided by the escaping air would always be equal to the weight of the dynamic disc. The effect of rotation would be to reduce the size of the air gap.

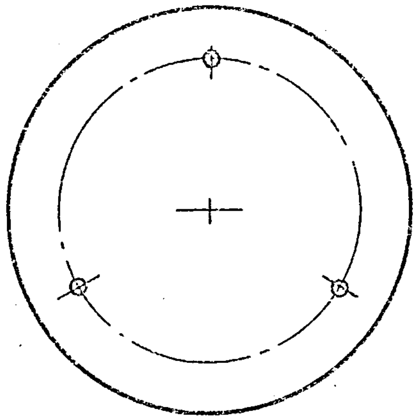
The design could include:

(a) Very high speed rotation by the use of air jets, to investigate the effects of high shear rates on viscosity.

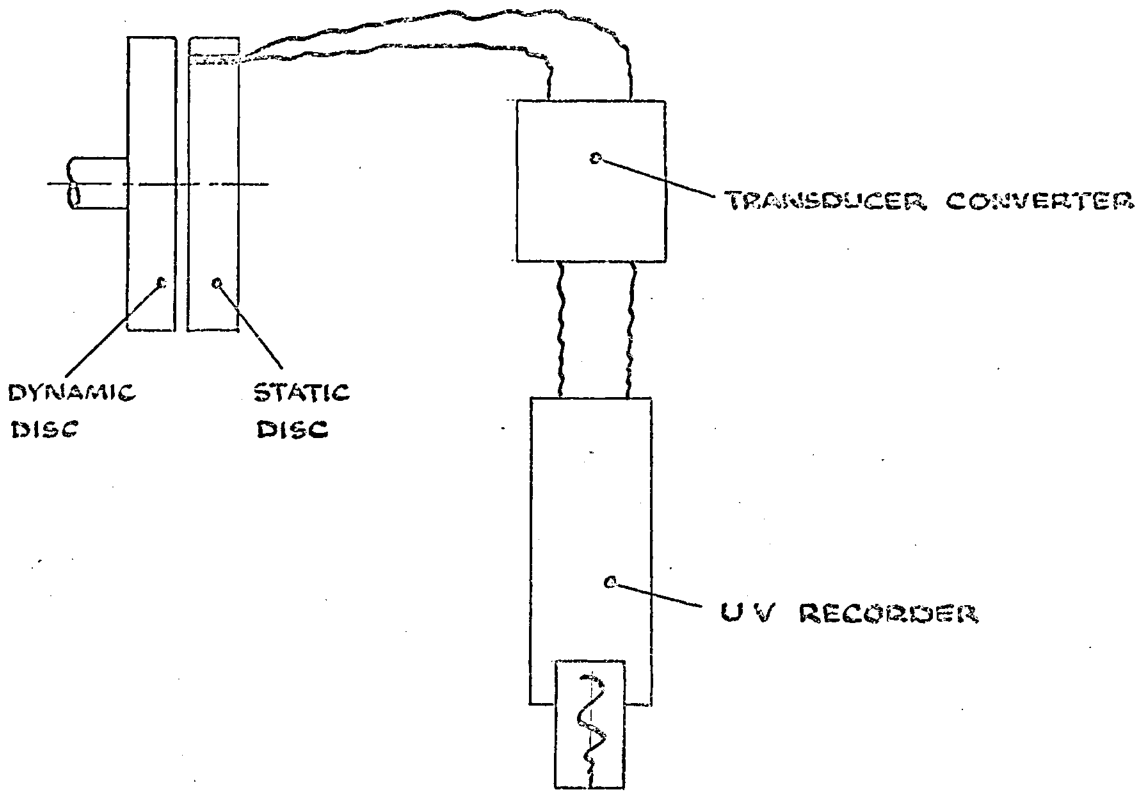
(b) Use of thermocouples, to measure changes in air temperature, to test the validity of isothermal theory.

(c) The use of pressure transducers to measure pressure, and changes in the air gap size.

(d) An electro-magnet positioned above the rotating disc which could be used to induce a pure squeeze film effect at any frequency.



RELATIVE POSITIONS OF PRESSURE TRANSDUCERS IN STATIC DISC.



PROPOSED INSTRUMENTATION FOR CONTINUOUS RECORDING OF GAP WIDTH USING PRESSURE TRANSDUCERS.

FIG. N° 72.

APPENDIX I COMPRESSIBILITY

Complete solution of compressibility and viscous terms outlined in (4.01).

From equation (18)

$$V_r = \frac{1}{2\mu}(z^2 - h^2)\left(\frac{\rho Q^2}{16\pi^2 r^3 h^2} + \frac{3r\Omega^2}{10} - \frac{3\mu Q}{4\pi h^3 r}\right) - \frac{\rho Q^2}{32\pi^2 r^3 \mu}\left(\frac{z^2}{h^2} - 1\right) -$$

$$\frac{\rho r\Omega^2}{4\mu}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7\rho\Omega^2 rh^2}{48\mu} + \frac{\rho\Omega^2 rhz}{12\mu}$$

and from the perfect gas equation $\rho = \frac{p}{\bar{R}T}$

$$V_r = \frac{1}{2\mu}(z^2 - h^2)\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2 r^3 h^2 p} + \frac{3pr\Omega^2}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3 rp}\right) - \frac{\dot{m}^2\bar{R}T}{32\pi^2 r^3 p\mu}\left(\frac{z^2}{h^2} - 1\right) -$$

$$\frac{pr\Omega^2}{4\mu\bar{R}T}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7p\Omega^2 rh^2}{48\mu\bar{R}T} + \frac{p\Omega^2 rhz}{12\mu\bar{R}T}$$

Differentiating with respect to r we obtain

$$\frac{\partial V_r}{\partial r} = \frac{1}{2\mu}(z^2 - h^2)\left\{\frac{\dot{m}^2\bar{R}T}{16\pi^2 h^2}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right) -\right.$$

$$\left.\frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(-\frac{1}{pr^2} - \frac{1}{p^2r}\frac{\partial p}{\partial r}\right)\right\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right)\left(\frac{z^2}{h^2} - 1\right) -$$

$$\frac{\Omega^2}{4\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7\Omega^2 h^2}{48\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right) + \left(p + r\frac{\partial p}{\partial r}\right)\frac{\Omega^2 hz}{12\mu\bar{R}T}$$

Differentiating again with respect to r we obtain

$$\frac{\partial^2 V_r}{\partial r^2} = \frac{1}{2\mu}(z^2 - h^2)\left\{\frac{\dot{m}^2\bar{R}T}{16\pi^2 h^2}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 +\right.\right.$$

$$\left.\frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10\bar{R}T}\left(\frac{\partial p}{\partial r} + \frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{2}{pr^3} + \frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} +\right.$$

$$\frac{2}{rp^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r})\} - \frac{\dot{m}\bar{R}T}{32\pi^2\mu}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} + \frac{2}{p^3r^3}\left(\frac{\partial p}{\partial r}\right)^2 -\right.$$

$$\left.\frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right)\left(\frac{z^2}{h^2} - 1\right) - \frac{\Omega^2}{4\mu\bar{R}T}\left(\frac{\partial p}{\partial r} + \frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right)\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) +$$

$$\frac{7\Omega^2h^2}{48\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{\Omega^2hz}{12\ \bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right)$$

Differentiating V_r twice with respect to z we obtain

$$\frac{\partial^2 V_r}{\partial z^2} = \frac{1}{\mu}\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2r^3h^2p} + \frac{3pr\Omega^2}{10RT} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}\right) - \frac{\dot{m}^2\bar{R}T}{16\pi^2r^3p\mu h^2} - \frac{pr\Omega^2}{4\mu\bar{R}T}\left(\frac{z^2}{h^2} + \frac{2z}{h} + 1\right)$$

Substituting these equations in the compressibility term we obtain

$$\frac{\mu}{3}\left(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2}\right) = \frac{\mu}{3}\left[\frac{1}{2\mu}(z^2 - h^2)\left\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} -\right.\right.\right.$$

$$\frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}\Big) + \frac{3\Omega^2}{10RT}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(\frac{2}{pr^3} +\right.$$

$$\left.\frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} + \frac{2}{rp^3}\left(\frac{\partial p}{\partial r}\right)^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r}\right)\Big\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}\left(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} +\right.$$

$$\left.\frac{2}{r^3p^3}\left(\frac{\partial p}{\partial r}\right)^2 - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}\right)\left(\frac{z^2}{h^2} - 1\right) - \frac{\Omega^2}{4\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right)\left(\frac{z^4}{12h^2} +\right.$$

$$\left.\frac{z^3}{3h} + \frac{z^2}{2}\right) + \frac{7\Omega^2h^2}{48\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{\Omega^2hz}{12\mu\bar{R}T}\left(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}\right) + \frac{1}{r}\left\{\frac{1}{2\mu}(z^2 - h^2)\right.$$

$$\left\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right) + \frac{3\Omega^2}{10RT}\left(p + r\frac{\partial p}{\partial r}\right) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}\left(-\frac{1}{pr^2} - \frac{1}{p^2r}\frac{\partial p}{\partial r}\right)\right\} -$$

$$\frac{\dot{m}\bar{R}T}{32\pi^2\mu}\left(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}\right)\left(\frac{z^2}{h^2} - 1\right) - \frac{\Omega^2}{4\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) +$$

$$\left.\frac{7\Omega^2h^2}{48\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right) + \frac{\Omega^2hz}{12\mu\bar{R}T}\left(p + r\frac{\partial p}{\partial r}\right)\right\} - \frac{1}{r^2}\left\{\frac{1}{2\mu}(z^2 - h^2)\left(\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2r^3p} +\right.\right.$$

$$\left.3\Omega^2pr - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}\right) - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu r^3p}\left(\frac{z^2}{h^2} - 1\right) - \frac{\Omega^2pr}{4\mu\bar{R}T}\left(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}\right) +$$

$$\frac{7\Omega^2 h^2 pr}{48\mu \bar{R}T} + \frac{p\Omega^2 rhz}{12\mu \bar{R}T}\}\Big]$$

Integrating the above equation over the film thickness 2h between limits of z = h and z = -h giving a final equation

$$\text{compressibility term} = \frac{\mu}{3}\Big[-\frac{2h^3}{3\mu}\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} +$$

$$\frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(\frac{2}{pr^3} + \frac{1}{p^2r^2}\frac{\partial p}{\partial r} -$$

$$\frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} + \frac{2}{rp^3}(\frac{\partial p}{\partial r})^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r})\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} + \frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 -$$

$$\frac{1}{p^2r^3}(\frac{\partial^2 p}{\partial r^2}) + \frac{3}{p^2r^4}\frac{\partial p}{\partial r})(-\frac{4h}{3}) - \frac{11\Omega^2h^3}{120\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) + \frac{7h^3\Omega^2}{24\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) +$$

$$\frac{1}{r}\{-\frac{2h^3}{3\mu}\{\frac{\dot{m}^2RT}{16\pi^2h^2}(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(p + r\frac{\partial p}{\partial r}) + \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(\frac{1}{pr^2} + \frac{1}{p^2r}\frac{\partial p}{\partial r})\} +$$

$$\frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}(\frac{3}{pr^4} + \frac{1}{p^2r^3}\frac{\partial p}{\partial r})(-\frac{4}{3}h) - \frac{\Omega^2}{4\pi\bar{R}T}(p + r\frac{\partial p}{\partial r})\frac{11}{30}h^3 + \frac{7\Omega^2h^3}{24\mu\bar{R}T}(p + r\frac{\partial p}{\partial r})\} -$$

$$\frac{1}{r^2}\{-\frac{2h^3}{3\mu}(\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2r^3p} + \frac{3\Omega^2 pr}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3 rp}) + \frac{\dot{m}^2\bar{R}Th}{24\pi^2\mu r^3p} - \frac{11\Omega^2 prh^3}{120\mu\bar{R}T} + \frac{7\Omega^2h^3pr}{24\mu\bar{R}T}\}\Big]$$

Substituting for V_r, $\frac{\partial V_r}{\partial r}$, $\frac{\partial^2 V_r}{\partial r^2}$ and $\frac{\partial^2 V_r}{\partial z^2}$ in the viscosity term we obtain

$$\mu(\frac{\partial^2 V_r}{\partial r^2} + \frac{1}{r}\frac{\partial V_r}{\partial r} - \frac{V_r}{r^2} + \frac{\partial^2 V_r}{\partial r^2}) = \mu\Big[\frac{1}{2\mu}(z^2 - h^2)\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} -$$

$$\frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 + \frac{3}{p^2r^4}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(\frac{2}{pr^3} +$$

$$\frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} + \frac{2}{rp^3}(\frac{\partial p}{\partial r})^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r})\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} +$$

$$\frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r})(\frac{z^2}{h^2} - 1) - \frac{\Omega^2}{4\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2})(\frac{z^4}{12h^2} +$$

$$\frac{z^3}{3h} + \frac{z^2}{2}) + \frac{7\Omega^2h^2}{48\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) + \frac{\Omega^2hz}{12\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) + \frac{1}{r}\{\frac{1}{2\mu}(z^2 - h^2)$$

$$\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(p + r\frac{\partial p}{\partial r}) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(-\frac{1}{pr^2} - \frac{1}{p^2r}\frac{\partial p}{\partial r})\} -$$

$$\frac{\dot{m}\bar{R}T}{32\pi^2\mu}(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r})(\frac{z^2}{h^2} - 1) - \frac{\Omega^2}{4\mu\bar{R}T}(p + r\frac{\partial p}{\partial r})(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}) +$$

$$\frac{7\Omega^2h^2}{48\mu\bar{R}T}(p + r\frac{\partial p}{\partial r}) + \frac{\Omega^2hz}{12\mu\bar{R}T}(p + r\frac{\partial p}{\partial r})\} - \frac{1}{r^2}\{\frac{1}{2\mu}(z^2 - h^2)(\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2r^3p} +$$

$$3\Omega^2pr - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}) - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu r^3p}(\frac{z^2}{h^2} - 1) - \frac{\Omega^2pr}{4\mu\bar{R}T}(\frac{z^4}{12h^2} + \frac{z^3}{3h} + \frac{z^2}{2}) +$$

$$\frac{7\Omega^2h^2pr}{48\mu\bar{R}T} + \frac{p\Omega^2rhz}{12\mu\bar{R}T}\} + \frac{1}{\mu}(\frac{\dot{m}^2\bar{R}T}{16\pi^2r^3h^2p} + \frac{3pr\Omega^2}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3rp}) - \frac{\dot{m}^2\bar{R}T}{16\pi^2r^3p\mu h^2} -$$

$$\frac{pr\Omega^2}{4\mu\bar{R}T}(\frac{z^2}{h^2} + \frac{2z}{h} + 1)\Big]$$

integrating the above equation over the film thickness 2h between limits of z = h and z = -h giving a final equation

$$\text{Viscose term} = \mu\Big[-\frac{2h^3}{3\mu}\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} - \frac{1}{p^2r^3}\frac{\partial^2 p}{\partial r^2} + \frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 +$$

$$\frac{3}{p^2r^4}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(\frac{2}{pr^3} + \frac{1}{p^2r^2}\frac{\partial p}{\partial r} - \frac{1}{p^2r}\frac{\partial^2 p}{\partial r^2} +$$

$$\frac{2}{rp^3}(\frac{\partial p}{\partial r})^2 + \frac{1}{p^2r^2}\frac{\partial p}{\partial r})\} - \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}(\frac{12}{pr^5} + \frac{3}{p^2r^4}\frac{\partial p}{\partial r} + \frac{2}{r^3p^3}(\frac{\partial p}{\partial r})^2 - \frac{1}{p^2r^3}(\frac{\partial^2 p}{\partial r^2}) +$$

$$\frac{3}{p^2r^4}\frac{\partial p}{\partial r})(-\frac{4h}{3}) - \frac{11\Omega^2h^3}{120\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) + \frac{7h^3\Omega^2}{24\mu\bar{R}T}(2\frac{\partial p}{\partial r} + r\frac{\partial^2 p}{\partial r^2}) + \frac{1}{r}$$

$$\{-\frac{2h^3}{3\mu}\{\frac{\dot{m}^2\bar{R}T}{16\pi^2h^2}(-\frac{3}{pr^4} - \frac{1}{p^2r^3}\frac{\partial p}{\partial r}) + \frac{3\Omega^2}{10\bar{R}T}(p + r\frac{\partial p}{\partial r}) + \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3}(\frac{1}{pr^2} +$$

$$\frac{1}{p^2r}\frac{\partial p}{\partial r})\} + \frac{\dot{m}^2\bar{R}T}{32\pi^2\mu}(\frac{3}{pr^4} + \frac{1}{p^2r^3}\frac{\partial p}{\partial r})(-\frac{4h}{3}) - \frac{\Omega^2}{4\mu\bar{R}T}(p + r\frac{\partial p}{\partial r})\frac{11h^3}{30} +$$

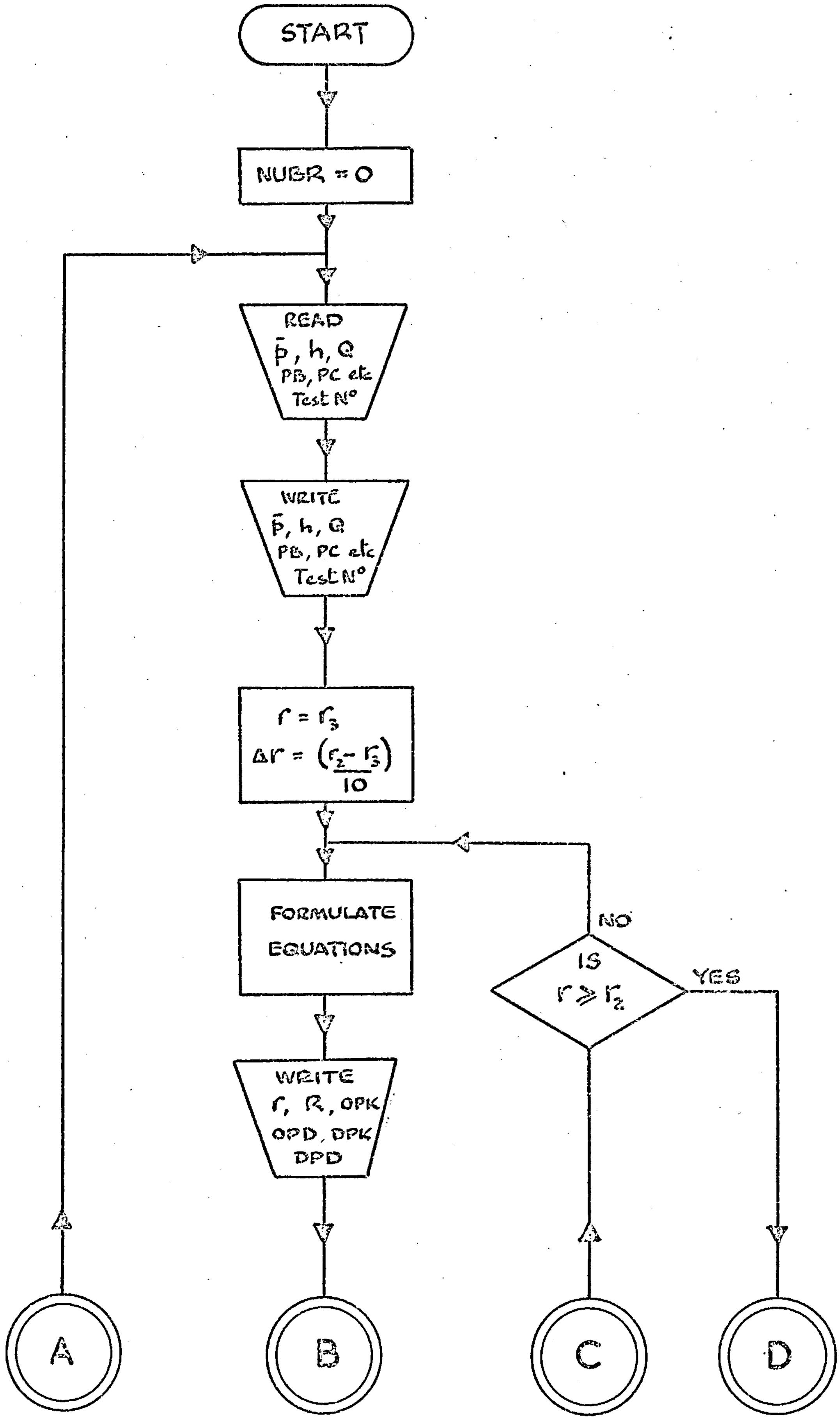
$$\frac{7\Omega^2 h^3}{24\mu\bar{R}T}(p + r\frac{\partial p}{\partial r})\} - \frac{1}{r^2}\{-\frac{2h^3}{3\mu}(\frac{\dot{m}^2\bar{R}T}{16\pi^2 h^2 r^3 p} + \frac{3\Omega^2 pr}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3 rp}) + \frac{\dot{m}^2\bar{R}Th}{24\pi^2\mu r^3 p} -$$

$$\frac{11\Omega^2 prh^3}{120\mu\bar{R}T} + \frac{7\Omega^2 h^3 pr}{24\mu\bar{R}T}\} + \frac{2h}{\mu}(\frac{\dot{m}^2\bar{R}T}{16\pi^2 r^3 h^2 p} + \frac{3pr\Omega^2}{10\bar{R}T} - \frac{3\mu\dot{m}\bar{R}T}{4\pi h^3 rp}) - \frac{\dot{m}^2\bar{R}T}{8\pi^2 r^3 p\mu h} -$$

$$\left.\frac{2pr\Omega^2 h}{3\mu\bar{R}T}\right]$$

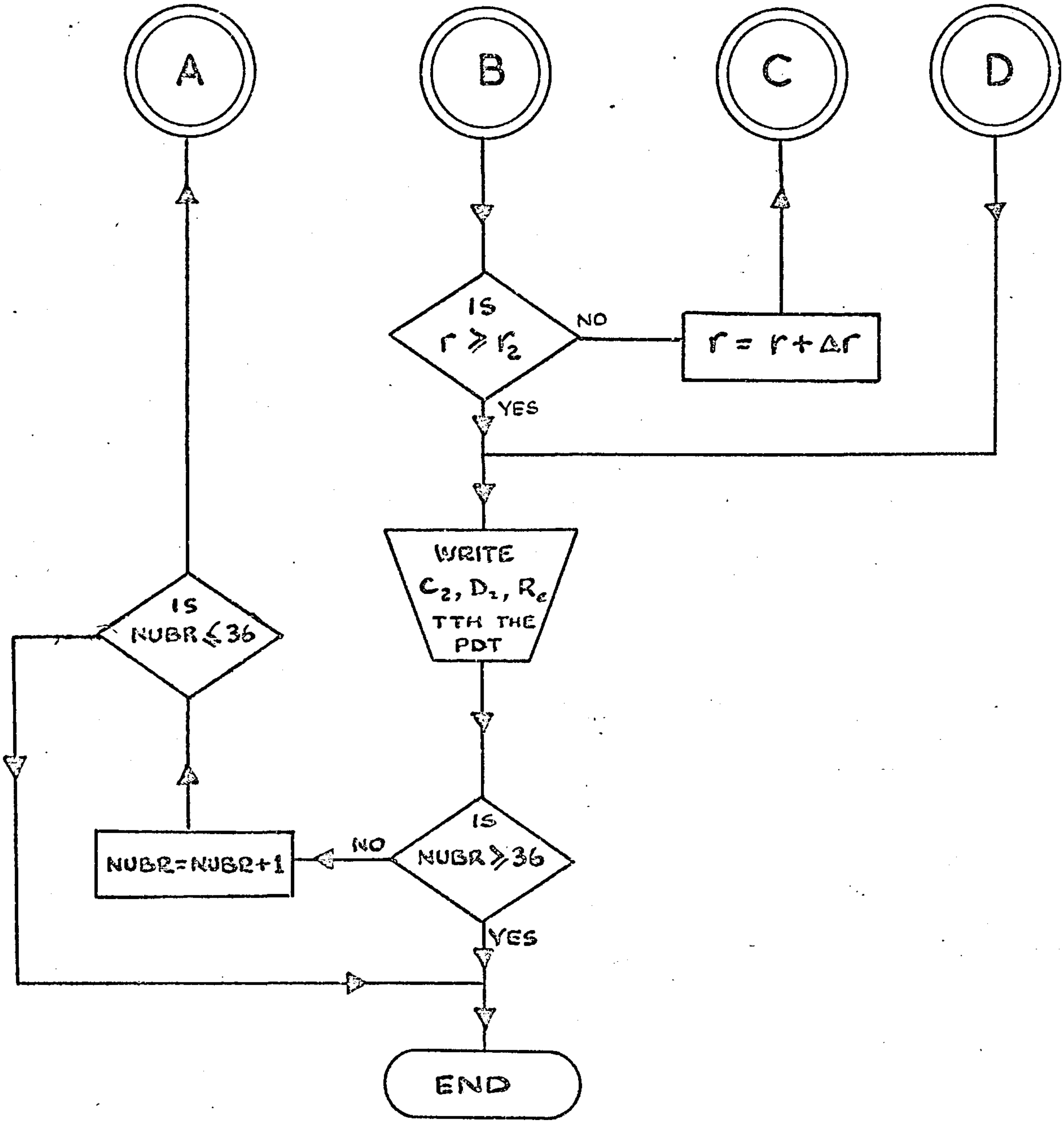
These equations have been used to calculate the ratio viscous term/compressibility term for Tests 13, 14, 19 and 20 (see Appendix 5).

COMPUTER PROGRAM & PRINT OUT OF THRUST VALUES ETC.



FLOW CHART N°1A.

APPENDIX 2



FLOW CHART N° 1 B.

```
// JOB 11S13 KLEMZ.F./THRUST BEARING INNER    *
*   JOB   1970
// OPTION LINK
// EXEC FORTRAN

               NJBR=0
      1        READ(1,50)PP,H,Q,SPEE,ALPHA,TEST
      50       FORMAT(F7.0,F7.6,F8.7,F5.1,F6.4,F4.1)
               WRITE(3,300)
      300      FORMAT('0'6X,'P',8X,'H',11X,'Q',6X,'SPEE',3X,
               'ALPHA',3X,'TEST')
               WRITE(3,400)PP,H,Q,SPEE,ALPHA,TEST
      400      FORMAT(' '3X,F8.1,2X,F8.6,2X,F9.7,2X,F5.1,2X,
               F6.4,2X,F5.2)
               R1=0.01
               R2=0.095
               R3=0.045
               RD1=R1/R2
               RD3=R3/R2
               PI=3.14159
               VIS=1.8/100000.0
               DEN=1.24
               DR1=(R3-R1)/10.0
               R=R1
               WRITE(3,10)
      10       FORMAT('0'3X,'R',8X,'R/H',8X,'IPK',8X,'IPD'8X,
               'IPRK',6X,'IPRD')
               F1=1.0/((ALPHA*RD1)**2)
               F2=(1.0/(ALPHA**2))-1.0
               F3=(RD1*RD1)-1.0
               DM=ALOG(RD3)*((ALPHA**3)-1.0)
               B4=DM+ALOG(RD1)
               FD1=-3.0*VIS*Q/(4.0*PI*((ALPHA*H)**3))
               FD2=3.0*DEN*R2*R2*SPEE*SPEE*(1.0-(RD1*RD1))/20.0
               PPD=(1.0-(FD2/(FD1*B4)))*FD1*B4
               CO1=27.0*DEN*Q*Q/(560.0*PI*PI*H*H*PP*R2*R2)
               CO2=3.0*DEN*(SPEE**2)*R2*R2/(20.0*PP)
               CD2=3.0*DEN*(SPEE**2)*R2*R2/(20.0*PPD)
               C1=PP*(1.0+CO1*(F1-F2/(RD3*RD3)-1.0)-CO2*F3)/B4
               C2=C1*(ALPHA**3)
```

```
      D1=PP*(1.0+CO1*F1-CO2*RD1*RD1)-C1*ALOG(R1)
      D2=PP*(CO1-CO2)-C2*ALOG(R2)
20    RZ=R/R2
      B1=ALOG(RZ)+DM
      B2=DM*((RZ*RZ)-(RD1*RD1))
      B3=((1.0-(RD1*RD1))*ALOG(RZ))-((1.0-(RZ*RZ))
      *ALOG(RD1))
      DK=PI*(H**3)/(VIS*Q)
      PR=-CO1/((RZ*ALPHA)**2)+(CO2*RZ*RZ)+(C1*
      (ALOG(R))/PP)+(D1/PP)
      PRID=(B1+CD2*(B2+B3))/B4
      DC=PI*H*H*H*PP/(VIS*Q)
      RE=DEN*Q/(PI*VIS*H*ALPHA)
      CPK=PR*PP
      CPD=PRID*PPD
      DPK=CPK*DK
      DPD=CPD*DK
C     IPK = STATIC PRESSURE SEE EQUATION (30)
C     IPD = STATIC PRESSURE,RADIAL INERTIA TERM
       NEGLECTED
C     IPRD = IPD IN DIMENSIONLESS FORM
C     IPRK = IPK IN DIMENSIONLESS FORM
C     RE=DEN*Q/(PI*VIS*H*ALPHA)
C      Q= CHECK ON VOLUME FLOW RATE BASED ON Q
      =QK
C     PPD=THEORETICAL PRESSURE P AT RADIUS  =1CM IF
       RADIAL INERTIA TERM
C     C1 & D1 = CONSTANTS OF INTEGRATION
      ( SEE EQUATION 30 )
      HR=R/H
      WRITE(3,13)R,HR,CPK,CPD,DPK,DPD
13    FORMAT(' '1X,F5.3,4X,F7.3,4X,F7.1,4X,F7.1,4X,
      F6.3,4X,F6.3)
      IF(R-R3)21,22,22
21    R=R+DR1
      IF(R-R3)20,22,22
22    WRITE(3,30)
30    FORMAT('0'6X,'C1',19X,'D1',19X,'Q',18X,'PPD'
      ,18X,'RE')
      QK=-(C1*4.0*PI*(H*ALPHA)**3)/(3.0*VIS)
      WRITE(3,11)C1,D1,QK,PPD,RE
11    FORMAT(' '1X,E16.8,4X,E16.8,4X,E16.8,4X,E16.8,
      4X,E16.8)
      IF(NUBR-36)150,100,100
150   NUBR=NUBR+1
      IF(NUBR-36)1,100,100
100   CONTINUE
      END
```

```
// JOB 11S13 KLEMZ.F./THRUST BEARING OUTER    *
*   JOB   1145
// OPTION LINK
// EXEC FORTRAN

                    NUBR=0
            1       READ(1,11)PP,H,Q,SPEE,ALPHA,PB,PC,PD,PE,PF,PG,PH
            11      FORMAT(F7.0,F7.6,F8.7,F5.1,F6.4,7F5.2)
                    READ(1,13)PJ,PK,TEST
            13      FORMAT(2F5.2,F4.1)
                    WRITE(3,300)
            300     FORMAT('0'6X,'P',9X,'H',7X,'Q',7X,'SPEE',3X,
                    'ALPHA',5X,'PB',4X,
                   /'PC',6X,'PD',5X,'PE',5X,'PF',5X,'PG',5X,'PH')
                    WRITE(3,200)PP,H,Q,SPEE,ALPHA,PB,PC,PD,PE,PF,PG,PH
            200     FORMAT(' '1X,F8.1,2X,F8.6,2X,F9.7,2X,F5.1,2X,F6.4,
                    7(2X,F5.2))
                    WRITE(3,400)
            400     FORMAT('0'4X,'PJ',5X,'PK',4X,'TEST')
                    WRITE(3,210)PJ,PK,TEST
            210     FORMAT(/1H ,2(2X,F5.2),2X,F4.1)
                    R1=0.01
                    R2=0.095
                    R3=0.045
                    RB=0.0095
                    RC=0.019
                    RD=0.0285
                    RW=0.0380
                    RF=0.0475
                    RG=0.057
                    RH=0.0665
                    RJ=0.076
                    RK=0.0855
                    B=0.0095
                    RD1=R1/R2
                    RD3=R3/R2
                    PI=3.14159
                    VIS=1.8/100000.0
                    DEN=1.24
                    DR2=(R2-R3)/10.0
                    R=R3
                    WRITE(3,14)
            14      FORMAT('0'3X,'R',8X,'R/H',8X,'OPK',8X,'OPD'8X,
                    'OPRK',6X,'OPRD')
                    DC=PI*H*H*H*PP/(VIS*Q)
                    RE=DEN*Q/(PI*VIS*H)
                    F1=1.0/((ALPHA*RD1)**2)
                    F2=(1.0/(ALPHA**2))-1.0
                    F3=(RD1*RD1)-1.0
                    DM=ALOG(RD3)*((ALPHA**3)-1.0)
                    B4=DM+ALOG(RD1)
                    FD1=-3.0*VIS*Q/(4.0*PI*((ALPHA*H)**3))
                    FD2=3.0*DEN*R2*R2*SPEE*SPEE*(1.0-(RD1*RD1))/20.0
                    PPD=(1.0-(FD2/(FD1*B4)))*FD1*B4
                    CD1=27.0*DEN*Q*Q/(560.0*PI*PI*H*H*PP*R2*R2)
                    CC2=3.0*DEN*(SPEE**2)*R2*R2/(20.0*PP)
                    CD2=3.0*DEN*(SPEE**2)*R2*R2/(20.0*PPD)
```

```
      C1=PP*(1.0+CO1*(F1-F2/(RD3*RD3)-1.0)-CO2*F3)/B4
      C2=C1*(ALPHA**3)
      D1=PP*(1.0+CO1*F1-CO2*RD1*RD1)-C1*ALOG(R1)
      DI=D1/2.0
      D2=PP*(CO1-CO2)-C2*ALOG(R2)

      G1=27.0*Q*Q*DEN/(560.0*((PI*H)**2))
      G2=(3.0*SPEE**2)/80.0
 24   RZ=R/R2
      B1=ALOG(RZ)+DM
      B2=DM*((RZ*RZ)-(RD1*RD1))
      B3=((1.0-(RD1*RD1))*ALOG(RZ))-((1.0-(RZ*RZ))*ALOG(RD1))
      B6=(ALPHA**3)*(1.0-(RD1*RD1))*ALOG(RZ)
      B7=(((ALPHA**3)-1.0)*ALOG(RD3))+ALOG(RD1)
      PS=-(CO1/(RZ*RZ))+(CO2*RZ*RZ)+(C2*(ALOG(R))/PP)+(D2/PP)
      PSID=((ALPHA**3)*ALOG(RZ)/B4)+(CO2/B4)*(B6-((1.0-(RZ*RZ)
      )*B7))
      TTH=PI*R1*R1*PP+2.0*PI*((-G1/(ALPHA**2))*ALOG(R3/R1)+G2*
      (R3**4-R1**4)+C1*((R3*R3/4.0)*(2.0*ALOG(R3)-1.0)-(R1*R1/
      4.0)*(2.0*ALOG(R1)-1.0))+DI*(R3*R3-R1*R1)-G1*ALOG(R2/R3)
      +G2*(R2**4-R3**4)+ C2*((R2*R2/4.0)*(2.0*ALOG(R2)-1.0)-
      (R3*R3/4.0)*(2.0*ALOG(R3)-1.0))+D2/2.0*(R2*R2-R3*R3))
      OPK=PS*PP
      OPD=PSID*PPD
      DK=PI*(H**3)/(VIS*Q)
      DPK=OPK*DK
      DPD=OPD*DK
      THE=((249.1*B/3.0)*(2.0*(PC*RC+PE*RW+PG*RG+PJ*RJ)+4.0*
     /(PB*RB+PD*RD+PF*RF+PH*RH+PK*RK)))*2.0*PI
C    PDT=PERCENT DIFF IN THRUST BASED ON THE THEORETICAL THRUST
C     RE= DEN*Q/(PI*VIS*H*ALPHA)
C     TTH=THEORETICAL THRUST (THRUST)
C     THE= EXPERIMENTAL THRUST (THRUST X )
C     C2 & D2 = CONSTANTS OF INTERGRATION ( SEE EQUATION 31 )
      PDT=(TTH-THE)*100.0/TTH
      HR=R/H
      WRITE(3,15)R,HR,OPK,OPD,DPK,DPD
C     OPK = STATIC PRESSURE SEE EQUATION (31)
C     OPD = STATIC PRESSURE,RADIAL INERTIA TERM NEGLECTED
C     OPRK =OPK  IN DIMENSIONLESS FORM
C     OPRD = OPD IN DIMENSIONLESS FORM
 15   FORMAT(' '1X,F5.3,4X,F7.3,4X,F7.1,4X,F7.1,4X,F6.3,4X,F6.3)
      IF(R-R2)23,25,25
 23   R=R+DR2
      IF(R-R2)24,25,25
 25   CONTINUE
      WRITE(3,30)
 30   FORMAT('0'8X,'C2',15X,'D2',14X,'RE',13X,'THRUST',9X,'
      THRUST X',9X,'PCT')
      WRITE(3,12)C2,D2,RE,TTH,THE,PCT
 12   FORMAT(' '1X,6E16.8)
      IF(NUBR-36)150,100,100
 150  NUBR=NUBR+1
      IF(NUBR-36)1,100,100
 100  CONTINUE
      END
```

P	H	Q	SPEE	ALPHA	TEST
2675.0	0.000100	0.0003560	0.0	1.0000	1.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	2675.0	3444.0	1.311	1.688
0.013	135.000	2563.7	2984.9	1.257	1.463
0.017	170.000	2367.6	2632.3	1.161	1.290
0.020	205.000	2165.0	2345.9	1.061	1.150
0.024	240.000	1974.0	2104.7	0.968	1.032
0.027	275.000	1798.1	1896.5	0.882	0.930
0.031	310.000	1636.9	1713.2	0.803	0.840
0.034	345.000	1489.1	1549.6	0.730	0.760
0.038	380.000	1353.1	1401.7	0.663	0.687
0.041	415.000	1227.3	1267.0	0.602	0.621
0.045	450.000	1110.4	1143.1	0.544	0.560

C1	D1	QK
-0.15254375E 04	-0.35821870E 04	0.35498501E-03

PPD	RE
0.34440234E 04	0.78063813E 05

P	H	Q	SPEE	ALPHA	TEST
3600.0	0.000100	0.0005830	0.0	1.0000	2.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3600.0	5640.1	1.078	1.688
0.013	135.000	3777.9	4888.2	1.131	1.463
0.017	170.000	3618.1	4310.7	1.083	1.290
0.020	205.000	3371.9	3841.7	1.009	1.150
0.024	240.000	3109.7	3446.8	0.931	1.032
0.027	275.000	2854.1	3105.7	0.854	0.930
0.031	310.000	2612.2	2805.6	0.782	0.840
0.034	345.000	2385.7	2537.6	0.714	0.760
0.038	380.000	2174.2	2295.5	0.651	0.687
0.041	415.000	1976.6	2074.8	0.592	0.621
0.045	450.000	1791.8	1872.0	0.536	0.560

C1	D1	QK
-0.25034893E 04	-0.58700898E 04	0.58258767E-03

PPD	RE
0.56400703E 04	0.12784050E 06

P	H	Q	SPEE	ALPHA	PB	PC
2675.0	0.000100	0.0003560	0.0	1.0000	9.00	8.10

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.30	4.90	3.80	2.80	2.00
1.20	0.40	1.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1110.4	1143.1	0.544	0.560
0.050	500.000	956.9	981.9	0.469	0.481
0.055	550.000	816.8	836.1	0.400	0.410
0.060	600.000	688.2	703.0	0.337	0.345
0.065	649.999	569.2	580.5	0.279	0.285
0.070	699.999	458.7	467.2	0.225	0.229
0.075	749.999	355.5	361.6	0.174	0.177
0.080	799.999	258.7	262.9	0.127	0.129
0.085	849.999	167.5	170.2	0.082	0.083
0.090	899.999	81.5	82.7	0.040	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.15254375E 04	-0.35821885E 04	0.78063813E 05

THRUST	THRUST X	PDT
0.20299652E 02	0.18005127E 02	0.11303273E 02

P	H	Q	SPEE	ALPHA	PB	PC
3600.0	0.000100	0.0005830	0.0	1.0000	12.00	12.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			10.00	8.00	6.30	4.70	3.40
2.20	1.10	2.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1791.8	1872.0	0.536	0.560
0.050	500.000	1547.3	1608.0	0.463	0.481
0.055	550.000	1323.0	1369.2	0.396	0.410
0.060	600.000	1116.1	1151.2	0.334	0.345
0.065	649.999	924.1	950.7	0.277	0.285
0.070	699.999	745.3	765.1	0.223	0.229
0.075	749.999	578.0	592.2	0.173	0.177
0.080	799.999	420.9	430.5	0.126	0.129
0.085	849.999	272.8	278.7	0.082	0.083
0.090	899.999	132.8	135.5	0.040	0.041
0.095	949.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.25034893E 04	-0.58700938E 04	0.12784050E 06

THRUST	THRUST X	PDT
0.32184830E 02	0.29813934E 02	0.73664989E 01

P	H	Q	SPEE	ALPHA	TEST
3860.0	0.000100	0.0007370	0.0	1.0000	3.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3860.0	7129.9	0.914	1.688
0.013	135.000	4396.6	6179.5	1.041	1.463
0.017	170.000	4335.1	5449.4	1.027	1.290
0.020	205.000	4099.1	4856.5	0.971	1.150
0.024	240.000	3812.7	4357.3	0.903	1.032
0.027	275.000	3518.7	3926.1	0.833	0.930
0.031	310.000	3232.8	3546.7	0.766	0.840
0.034	345.000	2960.7	3207.9	0.701	0.760
0.038	380.000	2704.0	2901.9	0.640	0.687
0.041	415.000	2462.4	2622.9	0.583	0.621
0.045	450.000	2235.1	2366.4	0.529	0.560

C1	D1	QK
-0.31598848E 04	-0.74015195E 04	0.73533761E-03

PPD	RE
0.71299023E 04	0.16160969E 06

P	H	Q	SPEE	ALPHA	TEST
3175.0	0.000100	0.0011450	0.0	1.0000	4.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3175.0	11077.0	0.484	1.688
0.013	135.000	5288.9	9600.4	0.806	1.463
0.017	170.000	5769.2	8466.1	0.879	1.290
0.020	205.000	5710.3	7545.0	0.870	1.150
0.024	240.000	5449.1	6769.4	0.831	1.032
0.027	275.000	5110.9	6099.6	0.779	0.930
0.031	310.000	4747.7	5510.2	0.724	0.840
0.034	345.000	4382.9	4983.8	0.668	0.760
0.038	380.000	4026.8	4508.4	0.614	0.687
0.041	415.000	3684.0	4074.9	0.562	0.621
0.045	450.000	3356.3	3676.5	0.512	0.560

C1	D1	QK
-0.48988047E 04	-0.11443188E 05	0.11400015E-02

PPD	RE
0.11076980E 05	0.25107619E 06

P	H	Q	SPEE	ALPHA	PB	PC
3860.0	0.000100	0.0007370	0.0	1.0000	14.50	16.10

PJ	PK	TEST	PD	PE	PF	PG	PH
			13.20	10.50	8.10	6.10	4.30
2.70	1.30	3.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	2235.1	2366.4	0.529	0.560
0.050	500.000	1933.0	2032.8	0.458	0.481
0.055	550.000	1654.7	1730.9	0.392	0.410
0.060	600.000	1397.1	1455.4	0.331	0.345
0.065	649.999	1157.7	1201.9	0.274	0.285
0.070	699.999	934.3	967.2	0.221	0.229
0.075	749.999	724.9	748.7	0.172	0.177
0.080	799.999	528.1	544.3	0.125	0.129
0.085	849.999	342.4	352.3	0.081	0.083
0.090	899.999	166.7	171.2	0.039	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.31598848E 04	-0.74015234E 04	0.16160969E 06

THRUST	THRUST X	PDT
0.39645432E 02	0.38157303E 02	0.37535934E 01

P	H	Q	SPEE	ALPHA	PB	PC
3175.0	0.000100	0.0011450	0.0	1.0000	16.80	19.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			17.40	13.40	10.60	8.00	5.70
3.50	1.90	4.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	3356.3	3676.5	0.512	0.560
0.050	500.000	2914.6	3158.1	0.444	0.481
0.055	550.000	2502.9	2689.1	0.382	0.410
0.060	600.000	2118.6	2261.0	0.323	0.345
0.065	649.999	1759.1	1867.2	0.268	0.285
0.070	699.999	1421.9	1502.6	0.217	0.229
0.075	749.999	1104.8	1163.1	0.168	0.177
0.080	799.999	805.8	845.6	0.123	0.129
0.085	849.999	523.0	547.3	0.080	0.083
0.090	899.999	254.8	266.0	0.039	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.48988047E 04	-0.11443195E 05	0.25107619E 06

THRUST	THRUST X	PDT
0.57444229E 02	0.49532928E 02	0.13772138E 02

P	H	Q	SPEE	ALPHA	TEST
950.0	0.000125	0.0010400	0.0	1.0000	5.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	950.0	5151.3	0.311	1.688
0.013	108.000	2163.0	4464.6	0.709	1.463
0.017	136.000	2491.0	3937.2	0.816	1.290
0.020	164.000	2520.3	3508.8	0.826	1.150
0.024	192.000	2433.2	3148.1	0.798	1.032
0.027	220.000	2298.5	2836.6	0.753	0.930
0.031	248.000	2145.5	2562.5	0.703	0.840
0.034	276.000	1987.3	2317.7	0.651	0.760
0.038	304.000	1830.5	2096.6	0.600	0.687
0.041	332.000	1677.9	1895.0	0.550	0.621
0.045	360.000	1531.0	1709.8	0.502	0.560

C1	D1	QK
-0.22639167E 04	-0.52825195E 04	0.10289773E-02

PPD	RE
0.51513320E 04	0.18244138E 06

P	H	Q	SPEE	ALPHA	TEST
-2750.0	0.000125	0.0017100	0.0	1.0000	6.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	-2750.0	8470.0	-0.548	1.688
0.013	108.000	1238.3	7340.9	0.247	1.463
0.017	136.000	2669.5	6473.6	0.532	1.290
0.020	164.000	3191.0	5769.3	0.636	1.150
0.024	192.000	3328.1	5176.2	0.663	1.032
0.027	220.000	3285.5	4664.1	0.655	0.930
0.031	248.000	3154.7	4213.3	0.629	0.840
0.034	276.000	2979.9	3810.9	0.594	0.760
0.038	304.000	2784.1	3447.3	0.555	0.687
0.041	332.000	2579.8	3115.9	0.514	0.621
0.045	360.000	2373.9	2811.2	0.473	0.560

C1	D1	QK
-0.37581487E 04	-0.87206094E 04	0.17081234E-02

PPD	RE
0.84699766E 04	0.29997575E 06

P	H	Q	SPEE	ALPHA	PB	PC
950.0	0.000125	0.0010400	0.0	1.0000	7.40	9.30

PJ	PK	TEST	PD	PE	PF	PG	PH
			8.10	6.80	5.30	4.00	2.90
1.80	0.80	5.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	1531.0	1709.8	0.502	0.560
0.050	400.000	1331.8	1468.7	0.437	0.481
0.055	440.000	1145.2	1250.6	0.375	0.410
0.060	480.000	970.3	1051.5	0.318	0.345
0.065	520.000	806.3	868.3	0.264	0.285
0.070	559.999	652.2	698.8	0.214	0.229
0.075	599.999	507.1	540.9	0.166	0.177
0.080	639.999	370.0	393.2	0.121	0.129
0.085	679.999	240.2	254.5	0.079	0.083
0.090	719.999	117.1	123.7	0.038	0.041
0.095	759.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.22639167E 04	-0.52825195E 04	0.18244138E 06

THRUST	THRUST X	PDT
0.25807266E 02	0.24069611E 02	0.67332029E 01

P	H	Q	SPEE	ALPHA	PB	PC
-2750.0	0.000125	0.0017100	0.0	1.0000	7.20	12.80

PJ	PK	TEST	PD	PE	PF	PG	PH
			10.40	9.60	7.80	6.00	4.40
2.80	1.30	6.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	2373.9	2811.2	0.473	0.560
0.050	400.000	2084.3	2414.8	0.416	0.481
0.055	440.000	1804.8	2056.2	0.360	0.410
0.060	480.000	1537.7	1728.9	0.307	0.345
0.065	520.000	1283.5	1427.7	0.256	0.285
0.070	559.999	1041.9	1148.9	0.208	0.229
0.075	599.999	812.5	889.4	0.162	0.177
0.080	639.999	594.3	646.5	0.118	0.129
0.085	679.999	386.7	418.5	0.077	0.083
0.090	719.999	188.8	203.4	0.038	0.041
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.37581487E 04	-0.87206133E 04	0.29997575E 06

THRUST	THRUST X	PDT
0.36651428E 02	0.34108017E 02	0.69394598E 01

P	H	Q	SPEE	ALPHA	TEST
-6800.0	0.000125	0.0021300	0.0	1.0000	7.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	-6800.0	10550.3	-1.088	1.688
0.013	108.000	-274.3	9143.9	-0.044	1.463
0.017	136.000	2205.8	8063.6	0.353	1.290
0.020	164.000	3225.6	7186.3	0.516	1.150
0.024	192.000	3615.5	6447.6	0.579	1.032
0.027	220.000	3702.8	5809.6	0.593	0.930
0.031	248.000	3634.5	5248.2	0.582	0.840
0.034	276.000	3483.7	4746.9	0.558	0.760
0.038	304.000	3288.7	4294.0	0.526	0.687
0.041	332.000	3070.8	3881.1	0.491	0.621
0.045	360.000	2842.5	3501.7	0.455	0.560

C1	D1	QK
-0.47057383E 04	-0.10881836E 05	0.21388144E-02

PPD	RE
0.10550320E 05	0.37365406E 06

P	H	Q	SPEE	ALPHA	TEST
-13150.0	0.000125	0.0026100	0.0	1.0000	8.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	*******	12927.9	-1.717	1.688
0.013	108.000	-2959.8	11204.5	-0.387	1.463
0.017	136.000	1065.0	9880.8	0.139	1.290
0.020	164.000	2840.7	8805.7	0.371	1.150
0.024	192.000	3632.0	7900.5	0.474	1.032
0.027	220.000	3940.8	7118.8	0.515	0.930
0.031	248.000	3994.8	6430.9	0.522	0.840
0.034	276.000	3908.0	5816.6	0.510	0.760
0.038	304.000	3741.3	5261.7	0.489	0.687
0.041	332.000	3529.3	4755.8	0.461	0.621
0.045	360.000	3292.2	4290.8	0.430	0.560

C1	D1	QK
-0.57597461E 04	-0.13265105E 05	0.26178733E-02

PPD	RE
0.12927859E 05	0.45785775E 06

P	H	Q	SPEE	ALPHA	PB	PC
-6800.0	0.000125	0.0021300	0.0	1.0000	4.60	15.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			13.50	11.40	9.20	7.20	4.20
3.30	1.50	7.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	2842.5	3501.7	0.455	0.560
0.050	400.000	2511.7	3007.9	0.402	0.481
0.055	440.000	2185.3	2561.3	0.350	0.410
0.060	480.000	1868.7	2153.5	0.299	0.345
0.065	520.000	1564.4	1778.4	0.250	0.285
0.070	559.999	1273.0	1431.1	0.204	0.229
0.075	599.999	994.6	1107.8	0.159	0.177
0.080	639.999	728.7	805.4	0.117	0.129
0.085	679.999	474.8	521.2	0.076	0.083
0.090	719.999	232.2	253.4	0.037	0.041
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.47057383E 04	-0.10881848E 05	0.37365406E 06

THRUST	THRUST X	PDT
0.41091522E 02	0.38948318E 02	0.52156830E 01

P	H	Q	SPEE	ALPHA	PB	PC
-13150.0	0.000125	0.0026100	0.0	1.0000	0.50	16.90

PJ	PK	TEST	PD	PE	PF	PG	PH
			15.50	13.00	10.60	8.20	6.10
3.90	1.90	8.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	3292.2	4290.8	0.430	0.560
0.050	400.000	2933.1	3685.8	0.383	0.481
0.055	440.000	2567.5	3138.5	0.335	0.410
0.060	480.000	2205.8	2638.8	0.288	0.345
0.065	520.000	1853.3	2179.2	0.242	0.285
0.070	559.999	1512.6	1753.6	0.198	0.229
0.075	599.999	1184.7	1357.4	0.155	0.177
0.080	639.999	869.8	986.8	0.114	0.129
0.085	679.999	567.7	638.7	0.074	0.083
0.090	719.999	278.0	310.5	0.036	0.041
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.57597461E 04	-0.13265113E 05	0.45785775E 06

THRUST	THRUST X	PDT
0.43390991E 02	0.45747330E 02	-0.54304781E 01

P	H	Q	SPEE	ALPHA	TEST
13.0	0.000150	0.0010380	0.0	1.0000	9.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	13.0	2975.4	0.007	1.688
0.013	90.000	938.0	2578.7	0.532	1.463
0.017	113.333	1230.8	2274.1	0.698	1.290
0.020	136.667	1304.7	2026.6	0.740	1.150
0.024	160.000	1289.6	1818.3	0.732	1.032
0.027	183.333	1235.3	1638.4	0.701	0.930
0.031	206.667	1163.7	1480.1	0.660	0.840
0.034	230.000	1084.9	1338.7	0.616	0.760
0.038	253.333	1004.1	1211.0	0.570	0.687
0.041	276.667	923.8	1094.5	0.524	0.621
0.045	300.000	845.3	987.5	0.480	0.560

C1	D1	QK
-0.12799824E 04	-0.29807793E 04	0.10052947E-02

PPD	RE
0.29753613E 04	0.15174213E 06

P	H	Q	SPEE	ALPHA	TEST
-2848.0	0.000150	0.0017100	0.0	1.0000	10.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-2848.0	4901.6	-0.981	1.688
0.013	90.000	46.7	4248.2	0.016	1.463
0.017	113.333	1136.7	3746.3	0.392	1.290
0.020	136.667	1576.9	3338.7	0.543	1.150
0.024	160.000	1737.7	2995.5	0.599	1.032
0.027	183.333	1765.0	2699.1	0.608	0.930
0.031	206.667	1724.0	2438.3	0.594	0.840
0.034	230.000	1647.2	2205.4	0.567	0.760
0.038	253.333	1551.5	1995.0	0.534	0.687
0.041	276.667	1446.4	1803.2	0.498	0.621
0.045	300.000	1337.1	1626.9	0.461	0.560

C1	D1	QK
-0.21930510E 04	-0.50749414E 04	0.17224152E-02

PPD	RE
0.49016055E 04	0.24997981E 06

P	H	Q	SPEE	ALPHA	PB	PC
13.0	0.000150	0.0010380	0.0	1.0000	3.60	5.18

PJ	PK	TEST	PD	PE	PF	PG	PH
			4.65	3.80	3.05	2.30	1.65
1.05	0.55	9.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	845.3	987.5	0.480	0.560
0.050	333.333	737.7	848.3	0.419	0.481
0.055	366.667	635.8	722.3	0.361	0.410
0.060	400.000	539.8	607.3	0.306	0.345
0.065	433.333	449.2	501.5	0.255	0.285
0.070	466.666	363.8	403.6	0.206	0.229
0.075	500.000	283.1	312.4	0.161	0.177
0.080	533.333	206.8	227.1	0.117	0.129
0.085	566.666	134.4	147.0	0.076	0.083
0.090	599.999	65.5	71.5	0.037	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.12799824E 04	-0.29807822E 04	0.15174213E 06

THRUST	THRUST X	PDT
0.13841306E 02	0.13782579E 02	0.42428297E 00

P	H	Q	SPEE	ALPHA	PB	PC
-2848.0	0.000150	0.0017100	0.0	1.0000	1.50	7.10

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.55	5.55	4.55	3.50	2.50
1.60	0.80	10.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1337.1	1626.9	0.461	0.560
0.050	333.333	1179.9	1397.5	0.406	0.481
0.055	366.667	1025.6	1190.0	0.353	0.410
0.060	400.000	876.3	1000.5	0.302	0.345
0.065	433.333	733.1	826.2	0.253	0.285
0.070	466.666	596.3	664.9	0.205	0.229
0.075	500.000	465.7	514.7	0.160	0.177
0.080	533.333	341.1	374.2	0.117	0.129
0.085	566.666	222.2	242.2	0.077	0.083
0.090	599.999	108.6	117.7	0.037	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.21930510E 04	-0.50749453E 04	0.24997981E 06

THRUST	THRUST X	PDT
0.19609390E 02	0.19530655E 02	0.40151858E 00

P	H	Q	SPEE	ALPHA	TEST
-6050.0	0.000150	0.0021300	0.0	1.0000	11.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-6050.0	6105.5	-1.673	1.688
0.013	90.000	-1341.2	5291.6	-0.371	1.463
0.017	113.333	517.0	4666.4	0.143	1.290
0.020	136.667	1335.6	4158.7	0.369	1.150
0.024	160.000	1699.3	3731.2	0.470	1.032
0.027	183.333	1840.2	3362.0	0.509	0.930
0.031	206.667	1863.5	3037.1	0.515	0.840
0.034	230.000	1821.8	2747.0	0.504	0.760
0.038	253.333	1743.4	2485.0	0.482	0.687
0.041	276.667	1644.1	2246.0	0.455	0.621
0.045	300.000	1533.3	2026.4	0.424	0.560

C1	D1	QK
-0.26780867E 04	-0.61685430E 04	0.21033611E-02

PPD	RE
0.61055078E 04	0.31137838E 06

P	H	Q	SPEE	ALPHA	TEST
-10650.0	0.000150	0.0026100	0.0	1.0000	12.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	*******	7481.4	-2.404	1.688
0.013	90.000	-3371.1	6484.1	-0.761	1.463
0.017	113.333	-420.7	5718.0	-0.095	1.290
0.020	136.667	938.7	5095.9	0.212	1.150
0.024	160.000	1594.5	4572.1	0.360	1.032
0.027	183.333	1900.7	4119.7	0.429	0.930
0.031	206.667	2019.0	3721.6	0.456	0.840
0.034	230.000	2030.8	3366.1	0.458	0.760
0.038	253.333	1980.3	3045.0	0.447	0.687
0.041	276.667	1892.5	2752.2	0.427	0.621
0.045	300.000	1782.4	2483.1	0.402	0.560

C1	D1	QK
-0.33255239E 04	-0.76246641E 04	0.26118574E-02

PPD	RE
0.74813984E 04	0.38154813E 06

P	H	Q	SPEE	ALPHA	PB	PC
-6050.0	0.000150	0.0021300	0.0	1.0000	-1.66	8.13

PJ	PK	TEST	PD	PE	PF	PG	PH
			7.65	6.50	5.35	4.10	3.00
1.95	0.95	11.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1533.3	2026.4	0.424	0.560
0.050	333.333	1365.7	1740.7	0.378	0.481
0.055	366.667	1195.2	1482.2	0.331	0.410
0.060	400.000	1026.7	1246.3	0.284	0.345
0.065	433.333	862.5	1029.2	0.239	0.285
0.070	466.666	703.9	828.2	0.195	0.229
0.075	500.000	551.3	641.1	0.152	0.177
0.080	533.333	404.7	466.1	0.112	0.129
0.085	566.666	264.2	301.6	0.073	0.083
0.090	599.999	129.3	146.6	0.036	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.26780867E 04	-0.61685469E 04	0.31137838E 06

THRUST	THRUST X	PDT
0.20267441E 02	0.22378342E 02	-0.10415231E 02

P	H	Q	SPEE	ALPHA	PB	PC
-10650.0	0.000150	0.0026100	0.0	1.0000	6.12	8.95

PJ	PK	TEST	PD	PE	PF	PG	PH
			8.75	7.35	5.85	4.55	3.40
2.25	1.10	12.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1782.4	2483.1	0.402	0.560
0.050	333.333	1604.1	2133.0	0.362	0.481
0.055	366.667	1414.5	1816.3	0.319	0.410
0.060	400.000	1222.0	1527.1	0.276	0.345
0.065	433.333	1031.1	1261.1	0.233	0.285
0.070	466.666	844.5	1014.8	0.191	0.229
0.075	500.000	663.3	785.6	0.150	0.177
0.080	533.333	488.1	571.1	0.110	0.129
0.085	566.666	319.3	369.6	0.072	0.083
0.090	599.999	156.6	179.7	0.035	0.041
0.095	633.333	0.0	0.0	0.000	0.000

C2	D2	RE
-0.33255239E 04	-0.76246641E 04	0.38154813E 06

THRUST	THRUST X	PDT
0.20679474E 02	0.26672455E 02	-0.28980331E 02

P	H	Q	SPEE	ALPHA	TEST
3100.0	0.000100	0.0004410	0.0	1.0000	13.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3100.0	4266.3	1.227	1.688
0.013	135.000	3063.1	3697.6	1.212	1.463
0.017	170.000	2865.2	3260.8	1.134	1.290
0.020	205.000	2637.8	2906.0	1.044	1.150
0.024	240.000	2415.0	2607.3	0.956	1.032
0.027	275.000	2205.8	2349.3	0.873	0.930
0.031	310.000	2012.1	2122.3	0.796	0.840
0.034	345.000	1833.0	1919.5	0.725	0.760
0.038	380.000	1667.4	1736.4	0.660	0.687
0.041	415.000	1513.6	1569.5	0.599	0.621
0.045	450.000	1370.5	1416.0	0.542	0.560

C1	D1	QK
-0.18944795E 04	-0.44463164E 04	0.44086482E-03

PPD	RE
0.42663281E 04	0.96702625E 05

P	H	Q	SPEE	ALPHA	TEST
2809.0	0.000100	0.0004410	419.0	1.0000	14.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	2809.0	3974.9	1.112	1.573
0.013	135.000	2774.8	3408.9	1.098	1.349
0.017	170.000	2580.2	2975.5	1.021	1.178
0.020	205.000	2357.1	2625.0	0.933	1.039
0.024	240.000	2139.4	2331.4	0.847	0.923
0.027	275.000	1936.1	2079.3	0.766	0.823
0.031	310.000	1749.0	1858.9	0.692	0.736
0.034	345.000	1577.4	1663.7	0.624	0.658
0.038	380.000	1420.0	1488.9	0.562	0.589
0.041	415.000	1275.3	1331.0	0.505	0.527
0.045	450.000	1142.0	1187.4	0.452	0.470

C1	D1	QK
-0.18946738E 04	-0.47414766E 04	0.44090999E-03

PPD	RE
0.39748916E 04	0.96702625E 05

P	H	Q	SPEE	ALPHA	PB	PC
3100.0	0.000100	0.0004410	0.0	1.0000	11.00	9.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			7.70	6.00	4.70	3.50	2.50
1.50	0.70	13.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1370.5	1416.0	0.542	0.560
0.050	500.000	1181.9	1216.3	0.468	0.481
0.055	550.000	1009.5	1035.7	0.400	0.410
0.060	600.000	850.9	870.8	0.337	0.345
0.065	649.999	704.1	719.2	0.279	0.285
0.070	699.999	567.6	578.7	0.225	0.229
0.075	749.999	439.9	448.0	0.174	0.177
0.080	799.999	320.2	325.7	0.127	0.129
0.085	849.999	207.5	210.8	0.082	0.083
0.090	899.999	100.9	102.5	0.040	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.18944795E 04	-0.44463203E 04	0.96702625E 05

THRUST	THRUST X	PDT
0.24892929E 02	0.22431076E 02	0.98897676E 01

P	H	Q	SPEE	ALPHA	PB	PC
2809.0	0.000100	0.0004410	419.0	1.0000	9.60	8.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.75	5.30	4.00	2.90	1.90
1.20	0.50	14.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1142.0	1187.4	0.452	0.470
0.050	500.000	969.0	1003.3	0.383	0.397
0.055	550.000	813.7	839.8	0.322	0.332
0.060	600.000	673.8	693.7	0.267	0.275
0.065	649.999	547.4	562.4	0.217	0.223
0.070	699.999	432.9	444.0	0.171	0.176
0.075	749.999	329.0	336.9	0.130	0.133
0.080	799.999	234.5	239.9	0.093	0.095
0.085	849.999	148.7	152.0	0.059	0.060
0.090	899.999	70.7	72.3	0.028	0.029
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.18946738E 04	-0.47414805E 04	0.96702625E 05

THRUST	THRUST X	PDT
0.19909836E 02	0.18824402E 02	0.54517469E 01

P	H	Q	SPEE	ALPHA	TEST
3800.0	0.000100	0.0006740	0.0	1.0000	15.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3800.0	6520.4	0.984	1.688
0.013	135.000	4172.6	5651.2	1.080	1.463
0.017	170.000	4062.5	4983.6	1.052	1.290
0.020	205.000	3817.6	4441.3	0.989	1.150
0.024	240.000	3538.1	3984.8	0.916	1.032
0.027	275.000	3257.6	3590.5	0.844	0.930
0.031	310.000	2988.1	3243.5	0.774	0.840
0.034	345.000	2733.4	2933.7	0.708	0.760
0.038	380.000	2494.1	2653.9	0.646	0.687
0.041	415.000	2269.7	2398.7	0.588	0.621
0.045	450.000	2059.0	2164.2	0.533	0.560

C1	D1	QK
-0.28967009E 04	-0.67879922E 04	0.67409175E-03

PPD	RE
0.65204258E 04	0.14779506E 06

P	H	Q	SPEE	ALPHA	TEST
3509.0	0.000100	0.0006740	419.0	1.0000	16.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	3509.0	6229.0	0.909	1.613
0.013	135.000	3884.2	5362.5	1.006	1.389
0.017	170.000	3777.6	4698.3	0.978	1.217
0.020	205.000	3537.0	4160.4	0.916	1.077
0.024	240.000	3262.5	3708.9	0.845	0.960
0.027	275.000	2987.9	3320.5	0.774	0.860
0.031	310.000	2725.0	2980.2	0.706	0.772
0.034	345.000	2477.8	2677.9	0.642	0.693
0.038	380.000	2246.8	2406.3	0.582	0.623
0.041	415.000	2031.4	2160.2	0.526	0.559
0.045	450.000	1830.6	1935.6	0.474	0.501

C1	D1	QK
-0.28968953E 04	-0.70831523E 04	0.67413691E-03

PPD	RE
0.62289844E 04	0.14779506E 06

P	H	Q	SPEE	ALPHA	PB	PC
3800.0	0.000100	0.0006740	0.0	1.0000	14.40	14.40

PJ	PK	TEST	PD	PE	PF	PG	PH
			12.00	9.50	7.40	5.50	3.90
2.45	1.10	15.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	2059.1	2164.2	0.533	0.560
0.050	500.000	1779.7	1859.0	0.461	0.481
0.055	550.000	1522.7	1583.0	0.394	0.410
0.060	600.000	1285.2	1330.9	0.333	0.345
0.065	649.999	1064.6	1099.1	0.276	0.285
0.070	699.999	858.9	884.5	0.222	0.229
0.075	749.999	666.3	684.7	0.173	0.177
0.080	799.999	485.3	497.7	0.126	0.129
0.085	849.999	314.6	322.1	0.081	0.083
0.090	899.999	153.1	156.6	0.040	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.28967009E 04	-0.67879883E 04	0.14779506E 06

THRUST	THRUST X	PDT
0.36717392E 02	0.34710709E 02	0.54652119E 01

P	H	Q	SPEE	ALPHA	PB	PC
3509.0	0.000100	0.0006740	419.0	1.0000	13.30	13.20

PJ	PK	TEST	PD	PE	PF	PG	PH
			10.50	8.70	6.60	4.80	3.40
2.00	0.90	16.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1830.6	1935.6	0.474	0.501
0.050	500.000	1566.7	1645.9	0.406	0.426
0.055	550.000	1326.9	1387.0	0.344	0.359
0.060	600.000	1108.1	1153.8	0.287	0.299
0.065	649.999	908.0	942.4	0.235	0.244
0.070	699.999	724.3	749.8	0.188	0.194
0.075	749.999	555.3	573.6	0.144	0.149
0.080	799.999	399.6	412.0	0.103	0.107
0.085	849.999	255.8	263.4	0.066	0.068
0.090	899.999	122.9	126.4	0.032	0.033
0.095	949.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.28968953E 04	-0.70831484E 04	0.14779506E 06

THRUST	THRUST X	PDT
0.31734207E 02	0.30642609E 02	0.34398165E 01

P	H	Q	SPEE	ALPHA	TEST
1580.0	0.000125	0.0005190	0.0	1.0000	17.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	1580.0	2570.7	1.038	1.688
0.013	108.000	1703.0	2228.0	1.119	1.463
0.017	136.000	1647.1	1964.8	1.082	1.290
0.020	164.000	1542.7	1751.0	1.013	1.150
0.024	192.000	1427.0	1571.0	0.937	1.032
0.027	220.000	1312.2	1415.6	0.862	0.930
0.031	248.000	1202.6	1278.8	0.790	0.840
0.034	276.000	1099.4	1156.6	0.722	0.760
0.038	304.000	1002.6	1046.3	0.659	0.687
0.041	332.000	912.1	945.7	0.599	0.621
0.045	360.000	827.2	853.2	0.543	0.560

C1	D1	QK
-0.11605337E 04	-0.27201814E 04	0.52747619E-03

PPD	RE
0.25707129E 04	0.91045250E 05

P	H	Q	SPEE	ALPHA	TEST
1289.0	0.000125	0.0005190	419.0	1.0000	18.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	1289.0	2279.3	0.847	1.497
0.013	108.000	1414.6	1939.3	0.929	1.274
0.017	136.000	1362.2	1679.5	0.895	1.103
0.020	164.000	1262.0	1470.0	0.829	0.966
0.024	192.000	1151.3	1295.1	0.756	0.851
0.027	220.000	1042.4	1145.6	0.685	0.752
0.031	248.000	939.5	1015.5	0.617	0.667
0.034	276.000	843.7	900.8	0.554	0.592
0.038	304.000	755.3	798.7	0.496	0.525
0.041	332.000	673.8	707.2	0.443	0.465
0.045	360.000	598.7	624.7	0.393	0.410

C1	D1	QK
-0.11607295E 04	-0.30153494E 04	0.52756560E-03

PPD	RE
0.22792734E 04	0.91045250E 05

P	H	Q	SPEE	ALPHA	PB	PC
1580.0	0.000125	0.0005190	0.0	1.0000	6.00	6.30

PJ	PK	TEST	PD	PE	PF	PG	PH
			5.10	4.10	3.20	2.40	1.70
1.10	0.50	17.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	827.2	853.2	0.543	0.560
0.050	400.000	714.7	732.9	0.469	0.481
0.055	440.000	611.3	624.1	0.402	0.410
0.060	480.000	515.9	524.7	0.339	0.345
0.065	520.000	427.3	433.3	0.281	0.285
0.070	559.999	344.7	348.7	0.226	0.229
0.075	599.999	267.3	269.9	0.176	0.177
0.080	639.999	194.7	196.2	0.128	0.129
0.085	679.999	126.2	127.0	0.083	0.083
0.090	719.999	61.4	61.7	0.040	0.041
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.11605337E 04	-0.27201846E 04	0.91045250E 05

THRUST	THRUST X	PDT
0.14792773E 02	0.15029382E 02	-0.15994864E 01

P	H	Q	SPEE	ALPHA	PB	PC
1289.0	0.000125	0.0005190	419.0	1.0000	4.90	5.30

PJ	PK	TEST	PD	PE	PF	PG	PH
			4.30	3.20	2.40	1.70	1.10
0.70	0.30	18.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	598.7	624.7	0.393	0.410
0.050	400.000	501.7	519.9	0.330	0.341
0.055	440.000	415.5	428.2	0.273	0.281
0.060	480.000	338.8	347.6	0.223	0.228
0.065	520.000	270.6	276.6	0.178	0.182
0.070	559.999	210.0	214.0	0.138	0.141
0.075	599.999	156.4	158.9	0.103	0.104
0.080	639.999	109.0	110.5	0.072	0.073
0.085	679.999	67.4	68.2	0.044	0.045
0.090	719.999	31.2	31.5	0.021	0.021
0.095	759.999	-0.0	0.0	-0.000	0.000

C2	D2	RE
-0.11607295E 04	-0.30153506E 04	0.91045250E 05

THRUST	THRUST X	PDT
0.98096495E 01	0.11262618E 02	-0.14811625E 02

P	H	Q	SPEE	ALPHA	TEST
1400.0	0.000125	0.0008560	0.0	1.0000	19.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	1400.0	4239.9	0.558	1.688
0.013	108.000	2120.9	3674.7	0.845	1.463
0.017	136.000	2265.6	3240.6	0.902	1.290
0.020	164.000	2222.6	2888.0	0.885	1.150
0.024	192.000	2110.7	2591.1	0.841	1.032
0.027	220.000	1973.7	2334.8	0.786	0.930
0.031	248.000	1829.7	2109.1	0.729	0.840
0.034	276.000	1686.7	1907.7	0.672	0.760
0.038	304.000	1547.9	1725.7	0.616	0.687
0.041	332.000	1415.0	1559.7	0.563	0.621
0.045	360.000	1288.3	1407.3	0.513	0.560

C1	D1	QK
-0.18696951E 04	-0.43695547E 04	0.84979855E-03

PPD	RE
0.42399414E 04	0.15016331E 06

P	H	Q	SPEE	ALPHA	TEST
1109.0	0.000125	0.0008560	419.0	1.0000	20.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	1109.0	3948.5	0.442	1.572
0.013	108.000	1832.6	3386.0	0.730	1.348
0.017	136.000	1980.7	2955.3	0.789	1.177
0.020	164.000	1941.9	2607.0	0.773	1.038
0.024	192.000	1835.0	2315.2	0.731	0.922
0.027	220.000	1703.9	2064.7	0.679	0.822
0.031	248.000	1566.6	1845.8	0.624	0.735
0.034	276.000	1431.0	1651.8	0.570	0.658
0.038	304.000	1300.6	1478.1	0.518	0.589
0.041	332.000	1176.7	1321.3	0.469	0.526
0.045	360.000	1059.8	1178.7	0.422	0.469

C1	D1	QK
-0.18698911E 04	-0.46647188E 04	0.84988773E-03

PPD	RE
0.39485044E 04	0.15016331E 06

P	H	Q	SPEE	ALPHA	PB	PC
1400.0	0.000125	0.0008560	0.0	1.0000	7.65	8.75

PJ	PK	TEST	PD	PE	PF	PG	PH
			7.50	5.95	4.65	3.50	2.55
1.60	0.75	19.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	1288.3	1407.3	0.513	0.560
0.050	400.000	1117.9	1208.8	0.445	0.481
0.055	440.000	959.4	1029.3	0.382	0.410
0.060	480.000	811.8	865.5	0.323	0.345
0.065	520.000	673.8	714.7	0.268	0.285
0.070	559.999	544.5	575.1	0.217	0.229
0.075	599.999	422.9	445.2	0.168	0.177
0.080	639.999	308.4	323.7	0.123	0.129
0.085	679.999	200.1	209.5	0.080	0.083
0.090	719.999	97.5	101.8	0.039	0.041
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.18696951E 04	-0.43695586E 04	0.15016331E 06

THRUST	THRUST X	PDT
0.22193481E 02	0.21762466E 02	0.19420786E 01

P	H	Q	SPEE	ALPHA	PB	PC
1109.0	0.000125	0.0008560	419.0	1.0000	6.60	7.80

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.55	5.15	3.95	2.90	1.95
1.20	0.45	20.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	1059.8	1178.7	0.422	0.469
0.050	400.000	905.0	995.8	0.360	0.397
0.055	440.000	763.6	833.4	0.304	0.332
0.060	480.000	634.7	688.3	0.253	0.274
0.065	520.000	517.1	558.0	0.206	0.222
0.070	559.999	409.8	440.4	0.163	0.175
0.075	599.999	312.0	334.2	0.124	0.133
0.080	639.999	222.7	237.9	0.089	0.095
0.085	679.999	141.4	150.7	0.056	0.060
0.090	719.999	67.3	71.6	0.027	0.029
0.095	759.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.18698911E 04	-0.46647227E 04	0.15016331E 06

THRUST	THRUST X	PDT
0.17210556E 02	0.17948624E 02	-0.42884588E 01

P	H	Q	SPEE	ALPHA	TEST
550.0	0.000150	0.0008170	0.0	1.0000	21.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	550.0	2341.9	0.397	1.688
0.013	90.000	1050.8	2029.7	0.758	1.463
0.017	113.333	1176.7	1789.9	0.848	1.290
0.020	136.667	1177.4	1595.2	0.849	1.150
0.024	160.000	1130.1	1431.2	0.815	1.032
0.027	183.333	1063.7	1289.6	0.767	0.930
0.031	206.667	990.5	1165.0	0.714	0.840
0.034	230.000	916.0	1053.7	0.660	0.760
0.038	253.333	842.6	953.2	0.608	0.687
0.041	276.667	771.7	861.5	0.556	0.621
0.045	300.000	703.6	777.3	0.507	0.560

C1	D1	QK
-0.10336912E 04	-0.24132673E 04	0.81185740E-03

PPD	RE
0.23418787E 04	0.11943475E 06

P	H	Q	SPEE	ALPHA	TEST
259.0	0.000150	0.0008170	419.0	1.0000	22.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	259.0	2050.4	0.187	1.478
0.013	90.000	762.4	1740.9	0.550	1.255
0.017	113.333	891.8	1504.6	0.643	1.085
0.020	136.667	896.7	1314.2	0.647	0.948
0.024	160.000	854.5	1155.3	0.616	0.833
0.027	183.333	794.0	1019.6	0.572	0.735
0.031	206.667	727.4	901.6	0.524	0.650
0.034	230.000	660.3	797.8	0.476	0.575
0.038	253.333	595.3	705.6	0.429	0.509
0.041	276.667	533.4	623.0	0.385	0.449
0.045	300.000	475.1	548.7	0.343	0.396

C1	D1	QK
-0.10338865E 04	-0.27084351E 04	0.81201107E-03

PPD	RE
0.20504390E 04	0.11943475E 06

P	H	Q	SPEE	ALPHA	PB	PC
550.0	0.000150	0.0008170	0.0	1.0000	3.65	4.60

PJ	PK	TEST	PD	PE	PF	PG	PH
			4.05	3.35	2.65	1.95	1.35
0.90	0.45	21.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	703.6	777.3	0.507	0.560
0.050	333.333	611.5	667.7	0.441	0.481
0.055	366.667	525.5	568.5	0.379	0.410
0.060	400.000	445.0	478.0	0.321	0.345
0.065	433.333	369.7	394.8	0.267	0.285
0.070	466.666	298.9	317.7	0.216	0.229
0.075	500.000	232.3	245.9	0.167	0.177
0.080	533.333	169.5	178.8	0.122	0.129
0.085	566.666	110.0	115.7	0.079	0.083
0.090	599.999	53.6	56.2	0.039	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.10336912E 04	-0.24132717E 04	0.11943475E 06

THRUST	THRUST X	PDT
0.11949713E 02	0.11921798E 02	0.23360389E 00

P	H	Q	SPEE	ALPHA	PB	PC
259.0	0.000150	0.0008170	419.0	1.0000	2.60	3.60

PJ	PK	TEST	PD	PE	PF	PG	PH
			3.15	2.50	1.90	1.35	0.88
0.52	0.30	22.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	475.1	548.7	0.343	0.396
0.050	333.333	398.6	454.6	0.287	0.328
0.055	366.667	329.6	372.6	0.238	0.269
0.060	400.000	267.9	300.9	0.193	0.217
0.065	433.333	213.0	238.0	0.154	0.172
0.070	466.666	164.3	183.0	0.118	0.132
0.075	500.000	121.3	134.9	0.087	0.097
0.080	533.333	83.8	93.0	0.060	0.067
0.085	566.666	51.3	56.9	0.037	0.041
0.090	599.999	23.4	26.0	0.017	0.019
0.095	633.333	-0.0	0.0	-0.000	0.000

C2	D2	RE
-0.10338865E 04	-0.27084365E 04	0.11943475E 06

THRUST	THRUST X	PDT
0.69665651E 01	0.85015755E 01	-0.22033951E 02

P	H	Q	SPEE	ALPHA	TEST
-6050.0	0.000150	0.0021300	0.0	1.0000	23.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-6050.0	6105.5	-1.673	1.688
0.013	90.000	-1341.2	5291.6	-0.371	1.463
0.017	113.333	517.0	4666.4	0.143	1.290
0.020	136.667	1335.6	4158.7	0.369	1.150
0.024	160.000	1699.3	3731.2	0.470	1.032
0.027	183.333	1840.2	3362.0	0.509	0.930
0.031	206.667	1863.5	3037.1	0.515	0.840
0.034	230.000	1821.8	2747.0	0.504	0.760
0.038	253.333	1743.4	2485.0	0.482	0.687
0.041	276.667	1644.1	2246.0	0.455	0.621
0.045	300.000	1533.3	2026.4	0.424	0.560

C1	D1	QK
-0.26780867E 04	-0.61685430E 04	0.21033611E-02

PPD	RE
0.61055078E 04	0.31137838E 06

P	H	Q	SPEE	ALPHA	TEST
-6341.0	0.000150	0.0021300	419.0	1.0000	24.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-6341.0	5814.1	-1.754	1.608
0.013	90.000	-1629.6	5002.9	-0.451	1.384
0.017	113.333	232.0	4381.2	0.064	1.212
0.020	136.667	1054.9	3877.7	0.292	1.072
0.024	160.000	1423.7	3455.3	0.394	0.956
0.027	183.333	1570.4	3092.0	0.434	0.855
0.031	206.667	1600.4	2773.8	0.443	0.767
0.034	230.000	1566.2	2491.2	0.433	0.689
0.038	253.333	1496.0	2237.4	0.414	0.619
0.041	276.667	1405.8	2007.6	0.389	0.555
0.045	300.000	1304.8	1797.9	0.361	0.497

C1	D1	QK
-0.26782830E 04	-0.64637148E 04	0.21035147E-02

PPD	RE
0.58140703E 04	0.31137838E 06

P	H	Q	SPEE	ALPHA	PB	PC
-6050.0	0.000150	0.0021300	0.0	1.0000	-1.66	8.15

PJ	PK	TEST	PD	PE	PF	PG	PH
			7.65	6.65	5.30	4.00	2.95
2.00	1.15	23.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1533.3	2026.4	0.424	0.560
0.050	333.333	1365.7	1740.7	0.378	0.481
0.055	366.667	1195.2	1482.2	0.331	0.410
0.060	400.000	1026.7	1246.3	0.284	0.345
0.065	433.333	862.5	1029.2	0.239	0.285
0.070	466.666	703.9	828.2	0.195	0.229
0.075	500.000	551.3	641.1	0.152	0.177
0.080	533.333	404.7	466.1	0.112	0.129
0.085	566.666	264.2	301.6	0.073	0.083
0.090	599.999	129.3	146.6	0.036	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.26780867E 04	-0.61685469E 04	0.31137838E 06

THRUST	THRUST X	PDT
0.20267441E 02	0.22645767E 02	-0.11734715E 02

P	H	Q	SPEE	ALPHA	PB	PC
-6341.0	0.000150	0.0021300	419.0	1.0000	-2.70	7.10

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.70	5.80	4.55	3.50	2.45
1.55	0.75	24.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1304.8	1797.9	0.361	0.497
0.050	333.333	1152.8	1527.6	0.319	0.422
0.055	366.667	999.4	1286.3	0.276	0.356
0.060	400.000	849.7	1069.1	0.235	0.296
0.065	433.333	705.9	872.4	0.195	0.241
0.070	466.666	569.3	693.5	0.157	0.192
0.075	500.000	440.3	530.1	0.122	0.147
0.080	533.333	319.0	380.3	0.088	0.105
0.085	566.666	205.4	242.9	0.057	0.067
0.090	599.999	99.1	116.4	0.027	0.032
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.26782830E 04	-0.64637148E 04	0.31137838E 06

THRUST	THRUST X	PDT
0.15284257E 02	0.18730225E 02	-0.22545853E 02

P	H	Q	SPEE	ALPHA	TEST
1900.0	0.000100	0.0005870	0.0	1.6675	25.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	1900.0	2703.1	0.565	0.804
0.013	135.000	2076.1	2539.8	0.617	0.755
0.017	170.000	2103.3	2414.4	0.625	0.718
0.020	205.000	2082.9	2312.5	0.619	0.688
0.024	240.000	2045.7	2226.8	0.608	0.662
0.027	275.000	2003.0	2152.7	0.596	0.640
0.031	310.000	1959.2	2087.6	0.583	0.621
0.034	345.000	1916.3	2029.4	0.570	0.603
0.038	380.000	1875.0	1976.8	0.557	0.588
0.041	415.000	1835.6	1928.9	0.546	0.574
0.045	450.000	1798.2	1884.8	0.535	0.560

C1	D1	QK
-0.54211279E 03	0.15413867E 03	0.58492739E-03

PPD	RE
0.27030769E 04	0.77192000E 05

P	H	Q	SPEE	ALPHA	TEST
1609.0	0.000100	0.0005870	419.0	1.6675	26.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	1609.0	2411.6	0.478	0.717
0.013	135.000	1787.7	2251.1	0.532	0.669
0.017	170.000	1818.4	2129.1	0.541	0.633
0.020	205.000	1802.3	2031.6	0.536	0.604
0.024	240.000	1770.2	1950.9	0.526	0.580
0.027	275.000	1733.3	1882.7	0.515	0.560
0.031	310.000	1696.2	1824.2	0.504	0.542
0.034	345.000	1660.7	1773.5	0.494	0.527
0.038	380.000	1627.7	1729.2	0.484	0.514
0.041	415.000	1597.4	1690.4	0.475	0.503
0.045	450.000	1569.9	1656.2	0.467	0.492

C1	D1	QK
-0.54220117E 03	-0.14053369E 03	0.58502308E-03

PPD	RE
0.24116370E 04	0.77192000E 05

P	H	Q	SPEE	ALPHA	PB	PC
1900.0	0.000100	0.0005870	0.0	1.6675	7.59	7.82

PJ	PK	TEST	PD	PE	PF	PG	PH
			7.56	7.10	6.20	4.60	3.32
2.05	0.95	25.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1798.2	1884.8	0.535	0.560
0.050	500.000	1553.0	1619.0	0.462	0.481
0.055	550.000	1327.9	1378.6	0.395	0.410
0.060	600.000	1120.2	1159.1	0.333	0.345
0.065	649.999	927.6	957.2	0.276	0.285
0.070	699.999	748.1	770.3	0.222	0.229
0.075	749.999	580.2	596.3	0.173	0.177
0.080	799.999	422.5	433.5	0.126	0.129
0.085	849.999	273.8	280.6	0.081	0.083
0.090	899.999	133.3	136.4	0.040	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.25135449E 04	-0.58934492E 04	0.12871763E 06

THRUST	THRUST X	PDT
0.27587631E 02	0.25817398E 02	0.64167633E 01

P	H	Q	SPEE	ALPHA	PB	PC
1609.0	0.000100	0.0005870	419.0	1.6675	6.64	6.88

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.56	6.15	5.15	3.90	2.60
1.60	0.72	26.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	1569.9	1656.2	0.467	0.492
0.050	500.000	1340.2	1406.0	0.398	0.418
0.055	550.000	1132.2	1182.7	0.337	0.352
0.060	600.000	943.2	982.0	0.280	0.292
0.065	649.999	771.0	800.5	0.229	0.238
0.070	699.999	613.5	635.6	0.182	0.189
0.075	749.999	469.3	485.3	0.140	0.144
0.080	799.999	336.8	347.8	0.100	0.103
0.085	849.999	215.1	221.8	0.064	0.066
0.090	899.999	103.1	106.2	0.031	0.032
0.095	949.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.25139546E 04	-0.61891172E 04	0.12871763E 06

THRUST	THRUST X	PDT
0.22606659E 02	0.21476196E 02	0.50005732E 01

P	H	Q	SPEE	ALPHA	TEST
2240.0	0.000100	0.0008310	0.0	1.6675	27.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	2240.0	3826.7	0.470	0.804
0.013	135.000	2687.6	3595.5	0.564	0.755
0.017	170.000	2814.8	3418.0	0.591	0.718
0.020	205.000	2833.0	3273.8	0.595	0.688
0.024	240.000	2808.3	3152.4	0.590	0.662
0.027	275.000	2765.6	3047.6	0.581	0.640
0.031	310.000	2715.7	2955.3	0.570	0.621
0.034	345.000	2663.3	2872.9	0.559	0.603
0.038	380.000	2611.1	2798.5	0.548	0.588
0.041	415.000	2560.0	2730.6	0.538	0.574
0.045	450.000	2510.6	2668.3	0.527	0.560

C1	D1	QK
-0.77091333E 03	0.19423608E 03	0.83179842E-03

PPD	RE
0.38266736E 04	0.10927863E 06

P	H	Q	SPEE	ALPHA	TEST
1949.0	0.000100	0.0008310	419.0	1.6675	28.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	100.000	1949.0	3535.2	0.409	0.742
0.013	135.000	2399.3	3306.8	0.504	0.695
0.017	170.000	2529.9	3132.7	0.531	0.658
0.020	205.000	2552.4	2992.8	0.536	0.629
0.024	240.000	2532.8	2876.5	0.532	0.604
0.027	275.000	2496.0	2777.6	0.524	0.583
0.031	310.000	2452.7	2692.0	0.515	0.565
0.034	345.000	2407.8	2617.1	0.506	0.550
0.038	380.000	2363.8	2550.9	0.496	0.536
0.041	415.000	2321.8	2492.2	0.488	0.523
0.045	450.000	2282.3	2439.7	0.479	0.512

C1	D1	QK
-0.77100146E 03	-0.10043628E 03	0.83189341E-03

PPD	RE
0.35352334E 04	0.10927863E 06

P	H	Q	SPEE	ALPHA	PB	PC
2240.0	0.000100	0.0008310	0.0	1.6675	10.09	11.00

PJ	PK	TEST	PD	PE	PF	PG	PH
			10.70	10.18	8.85	6.50	4.80
3.00	1.38	27.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	2510.6	2668.3	0.527	0.560
0.050	500.000	2173.3	2292.0	0.456	0.481
0.055	550.000	1861.6	1951.7	0.391	0.410
0.060	600.000	1572.7	1641.0	0.330	0.345
0.065	649.999	1303.8	1355.1	0.274	0.285
0.070	699.999	1052.5	1090.5	0.221	0.229
0.075	749.999	816.9	844.1	0.172	0.177
0.080	799.999	595.2	613.7	0.125	0.129
0.085	849.999	386.0	397.2	0.081	0.083
0.090	899.999	188.0	193.1	0.039	0.041
0.095	949.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.35743950E 04	-0.83673398E 04	0.18222206E 06

THRUST	THRUST X	PDT
0.38247925E 02	0.36786194E 02	0.38217258E 01

P	H	Q	SPEE	ALPHA	PB	PC
1949.0	0.000100	0.0008310	419.0	1.6675	8.94	9.85

PJ	PK	TEST	PD	PE	PF	PG	PH
			9.54	9.05	7.75	5.65	4.00
2.52	1.20	28.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	450.000	2282.3	2439.7	0.479	0.512
0.050	500.000	1960.5	2079.0	0.412	0.437
0.055	550.000	1665.9	1755.8	0.350	0.369
0.060	600.000	1395.7	1463.8	0.293	0.307
0.065	649.999	1147.2	1198.4	0.241	0.252
0.070	699.999	918.0	955.8	0.193	0.201
0.075	749.999	706.0	733.1	0.148	0.154
0.080	799.999	509.6	528.0	0.107	0.111
0.085	849.999	327.3	338.4	0.069	0.071
0.090	899.999	157.8	162.9	0.033	0.034
0.095	949.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.35748037E 04	-0.86630039E 04	0.18222206E 06

THRUST	THRUST X	PDT
0.33266953E 02	0.32034424E 02	0.37049637E 01

P	H	Q	SPEE	ALPHA	TEST
655.0	0.000125	0.0011700	0.0	1.5334	29.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	655.0	2997.3	0.191	0.873
0.013	108.000	1458.9	2783.1	0.425	0.811
0.017	136.000	1751.4	2618.5	0.510	0.763
0.020	164.000	1861.3	2484.8	0.542	0.724
0.024	192.000	1893.8	2372.3	0.552	0.691
0.027	220.000	1889.8	2275.1	0.551	0.663
0.031	248.000	1867.6	2189.5	0.544	0.638
0.034	276.000	1836.3	2113.2	0.535	0.616
0.038	304.000	1800.5	2044.2	0.525	0.596
0.041	332.000	1762.7	1981.3	0.514	0.577
0.045	360.000	1724.4	1923.5	0.502	0.560

C1	D1	QK
-0.71551758E 03	-0.38303442E 03	0.11725507E-02

PPD	RE
0.29973179E 04	0.13385069E 06

P	H	Q	SPEE	ALPHA	TEST
364.0	0.000125	0.0011700	419.0	1.5334	30.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	364.0	2705.9	0.106	0.788
0.013	108.000	1170.5	2494.3	0.341	0.727
0.017	136.000	1466.5	2333.2	0.427	0.680
0.020	164.000	1580.7	2203.8	0.461	0.642
0.024	192.000	1618.2	2096.4	0.471	0.611
0.027	220.000	1620.1	2005.1	0.472	0.584
0.031	248.000	1604.6	1926.2	0.468	0.561
0.034	276.000	1580.8	1857.3	0.461	0.541
0.038	304.000	1553.3	1796.6	0.453	0.523
0.041	332.000	1524.6	1742.8	0.444	0.508
0.045	360.000	1496.1	1694.9	0.436	0.494

C1	D1	QK
-0.71562207E 03	-0.67778149E 03	0.11727223E-02

PPD	RE
0.27058777E 04	0.13385069E 06

P	H	Q	SPEE	ALPHA	PB	PC
655.0	0.000125	0.0011700	0.0	1.5334	4.93	6.92

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.85	6.42	5.25	4.10	3.02
1.92	0.94	29.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	1724.4	1923.5	0.502	0.560
0.050	400.000	1502.4	1652.2	0.438	0.481
0.055	440.000	1293.3	1406.9	0.377	0.410
0.060	480.000	1096.9	1182.9	0.320	0.345
0.065	520.000	912.2	976.9	0.266	0.285
0.070	559.999	738.3	786.1	0.215	0.229
0.075	599.999	574.3	608.5	0.167	0.177
0.080	639.999	419.2	442.4	0.122	0.129
0.085	679.999	272.3	286.3	0.079	0.083
0.090	719.999	132.8	139.2	0.039	0.041
0.095	759.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.25798008E 04	-0.60137305E 04	0.20524656E 06

THRUST	THRUST X	PDT
0.25905365E 02	0.22802094E 02	0.11979261E 02

P	H	Q	SPEE	ALPHA	PB	PC
364.0	0.000125	0.0011700	419.0	1.5334	4.24	6.06

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.06	5.90	4.90	3.50	2.42
1.50	0.68	30.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	1496.1	1694.9	0.436	0.494
0.050	400.000	1289.6	1439.2	0.376	0.419
0.055	440.000	1097.6	1211.0	0.320	0.353
0.060	480.000	919.9	1005.8	0.268	0.293
0.065	520.000	755.6	820.1	0.220	0.239
0.070	559.999	603.7	651.4	0.176	0.190
0.075	599.999	463.4	497.5	0.135	0.145
0.080	639.999	333.6	356.7	0.097	0.104
0.085	679.999	213.6	227.5	0.062	0.066
0.090	719.999	102.6	109.0	0.030	0.032
0.095	759.999	0.0	0.0	0.0	0.000

C2	D2	RE
-0.25801775E 04	-0.63093203E 04	0.20524656E 06

THRUST	THRUST X	PDT
0.20924011E 02	0.19651199E 02	0.60830202E 01

P	H	Q	SPEE	ALPHA	TEST
-1010.0	0.000125	0.0018350	0.0	1.5334	31.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	-1010.0	4700.9	-0.188	0.873
0.013	108.000	1154.8	4364.9	0.215	0.811
0.017	136.000	2018.2	4106.7	0.375	0.763
0.020	164.000	2405.6	3897.1	0.447	0.724
0.024	192.000	2583.8	3720.6	0.480	0.691
0.027	220.000	2658.9	3568.2	0.494	0.663
0.031	248.000	2679.3	3434.0	0.498	0.638
0.034	276.000	2669.1	3314.2	0.496	0.616
0.038	304.000	2641.3	3206.0	0.491	0.596
0.041	332.000	2603.3	3107.4	0.484	0.577
0.045	360.000	2559.6	3016.7	0.475	0.560

C1	D1	QK
-0.11356702E 04	-0.68806641E 03	0.18610742E-02

PPD	RE
0.47009219E 04	0.20992819E 06

P	H	Q	SPEE	ALPHA	TEST
-1301.0	0.000125	0.0018350	419.0	1.5334	32.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	80.000	-1301.0	4409.5	-0.242	0.819
0.013	108.000	866.4	4076.1	0.161	0.757
0.017	136.000	1733.3	3821.5	0.322	0.710
0.020	164.000	2124.9	3616.1	0.395	0.672
0.024	192.000	2308.2	3444.7	0.429	0.640
0.027	220.000	2389.2	3298.2	0.444	0.613
0.031	248.000	2416.3	3170.7	0.449	0.589
0.034	276.000	2413.5	3058.4	0.448	0.568
0.038	304.000	2394.0	2958.5	0.445	0.550
0.041	332.000	2365.2	2868.9	0.439	0.533
0.045	360.000	2331.3	2788.1	0.433	0.518

C1	D1	QK
-0.11357744E 04	-0.98281250E 03	0.18612449E-02

PPD	RE
0.44094805E 04	0.20992819E 06

P	H	Q	SPEE	ALPHA	PB	PC
-1010.0	0.000125	0.0018350	0.0	1.5334	4.20	9.65

PJ	PK	TEST	PD	PE	PF	PG	PH
			9.93	9.57	8.00	5.70	4.00
2.55	1.20	31.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	2559.6	3016.7	0.475	0.560
0.050	400.000	2250.7	2591.3	0.418	0.481
0.055	440.000	1951.0	2206.6	0.362	0.410
0.060	480.000	1663.7	1855.3	0.309	0.345
0.065	520.000	1389.6	1532.1	0.258	0.285
0.070	559.999	1128.7	1232.9	0.210	0.229
0.075	599.999	880.5	954.4	0.164	0.177
0.080	639.999	644.3	693.8	0.120	0.129
0.085	679.999	419.4	449.1	0.078	0.083
0.090	719.999	204.9	218.3	0.038	0.041
0.095	759.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.40946621E 04	-0.94936875E 04	0.32190381E 06

THRUST	THRUST X	PDT
0.37081665E 02	0.31806534E 02	0.14225708E 02

P	H	Q	SPEE	ALPHA	PB	PC
-1301.0	0.000125	0.0018350	419.0	1.5334	3.29	8.70

PJ	PK	TEST	PD	PE	PF	PG	PH
			9.10	8.70	7.15	5.15	3.65
2.30	1.00	32.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	360.000	2331.3	2788.1	0.433	0.518
0.050	400.000	2037.8	2378.3	0.379	0.442
0.055	440.000	1755.3	2010.6	0.326	0.374
0.060	480.000	1486.7	1678.1	0.276	0.312
0.065	520.000	1233.0	1375.4	0.229	0.255
0.070	559.999	994.1	1098.2	0.185	0.204
0.075	599.999	769.6	843.3	0.143	0.157
0.080	639.999	558.7	608.1	0.104	0.113
0.085	679.999	360.7	390.3	0.067	0.073
0.090	719.999	174.7	188.1	0.032	0.035
0.095	759.999	0.0	0.0	0.000	0.000

C2	D2	RE
-0.40950381E 04	-0.97892813E 04	0.32190381E 06

THRUST	THRUST X	PDT
0.32100220E 02	0.28559601E 02	0.11029885E 02

P	H	Q	SPEE	ALPHA	TEST
-1198.0	0.000150	0.0017140	0.0	1.4445	33.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-1198.0	2719.7	-0.412	0.935
0.013	90.000	296.3	2502.4	0.102	0.860
0.017	113.333	898.4	2335.5	0.309	0.803
0.020	136.667	1173.0	2199.9	0.403	0.756
0.024	160.000	1303.2	2085.8	0.448	0.717
0.027	183.333	1361.9	1987.2	0.468	0.683
0.031	206.667	1382.4	1900.5	0.475	0.653
0.034	230.000	1381.2	1823.1	0.475	0.627
0.038	253.333	1367.5	1753.1	0.470	0.602
0.041	276.667	1346.4	1689.3	0.463	0.581
0.045	300.000	1320.9	1630.7	0.454	0.560

C1	D1	QK
-0.72101953E 03	-0.72785938E 03	0.17068244E-02

PPD	RE
0.27196973E 04	0.17346113E 06

P	H	Q	SPEE	ALPHA	TEST
-1489.0	0.000150	0.0017140	419.0	1.4445	34.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-1489.0	2428.3	-0.512	0.835
0.013	90.000	8.0	2213.7	0.003	0.761
0.017	113.333	613.5	2050.2	0.211	0.705
0.020	136.667	892.4	1919.0	0.307	0.659
0.024	160.000	1027.7	1809.9	0.353	0.622
0.027	183.333	1092.3	1717.2	0.375	0.590
0.031	206.667	1119.3	1637.2	0.385	0.563
0.034	230.000	1125.7	1567.2	0.387	0.539
0.038	253.333	1120.2	1505.5	0.385	0.517
0.041	276.667	1108.2	1450.8	0.381	0.499
0.045	300.000	1092.6	1402.1	0.375	0.482

C1	D1	QK
-0.72113696E 03	-0.10226643E 04	0.17071022E-02

PPD	RE
0.24282576E 04	0.17346113E 06

P	H	Q	SPEE	ALPHA	PB	PC
-1198.0	0.000150	0.0017140	0.0	1.4445	1.56	5.60

PJ	PK	TEST	PD	PE	PF	PG	PH
			6.20	5.84	4.80	3.50	2.55
1.62	0.75	33.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1320.9	1630.7	0.454	0.560
0.050	333.333	1166.1	1400.7	0.401	0.481
0.055	366.667	1013.9	1192.7	0.348	0.410
0.060	400.000	866.6	1002.9	0.298	0.345
0.065	433.333	725.1	828.2	0.249	0.285
0.070	466.666	589.9	666.4	0.203	0.229
0.075	500.000	460.8	515.9	0.158	0.177
0.080	533.333	337.5	375.0	0.116	0.129
0.085	566.666	219.9	242.7	0.076	0.083
0.090	599.999	107.5	118.0	0.037	0.041
0.095	633.333	0.0	0.0	0.000	0.000

C2	D2	RE
-0.21731980E 04	-0.50278008E 04	0.25056450E 06

THRUST	THRUST X	PDT
0.18780243E 02	0.19402588E 02	-0.33138275E 01

P	H	Q	SPEE	ALPHA	PB	PC
-1489.0	0.000150	0.0017140	419.0	1.4445	0.78	5.05

PJ	PK	TEST	PD	PE	PF	PG	PH
			5.20	5.06	4.02	2.95	2.10
1.30	0.65	34.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1092.6	1402.1	0.375	0.482
0.050	333.333	953.3	1187.7	0.328	0.408
0.055	366.667	818.2	996.8	0.281	0.343
0.060	400.000	689.6	825.7	0.237	0.284
0.065	433.333	568.5	671.4	0.195	0.231
0.070	466.666	455.3	531.7	0.156	0.183
0.075	500.000	349.8	404.9	0.120	0.139
0.080	533.333	251.9	289.3	0.087	0.099
0.085	566.666	161.1	184.0	0.055	0.063
0.090	599.999	77.3	87.8	0.027	0.030
0.095	633.333	-0.0	0.0	-0.000	0.000

C2	D2	RE
-0.21735520E 04	-0.53233438E 04	0.25056450E 06

THRUST	THRUST X	PDT
0.13798606E 02	0.16244156E 02	-0.17723160E 02

P	H	Q	SPEE	ALPHA	TEST
-5080.0	0.000150	0.0026380	0.0	1.4445	35.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-5080.0	4185.9	-1.134	0.935
0.013	90.000	-1361.1	3851.4	-0.304	0.860
0.017	113.333	202.6	3594.5	0.045	0.803
0.020	136.667	964.9	3385.9	0.215	0.756
0.024	160.000	1367.5	3210.3	0.305	0.717
0.027	183.333	1587.8	3058.5	0.355	0.683
0.031	206.667	1707.7	2925.0	0.381	0.653
0.034	230.000	1768.8	2805.8	0.395	0.627
0.038	253.333	1794.0	2698.2	0.401	0.602
0.041	276.667	1796.6	2600.0	0.401	0.581
0.045	300.000	1784.6	2509.7	0.398	0.560

C1	D1	QK
-0.11110264E 04	-0.12173958E 04	0.26300629E-02

PPD	RE
0.41858555E 04	0.26697231E 06

P	H	Q	SPEE	ALPHA	TEST
-5371.0	0.000150	0.0026380	419.0	1.4445	36.00

R	R/H	IPK	IPD	IPRK	IPRD
0.010	66.667	-5371.0	3894.4	-1.199	0.870
0.013	90.000	-1649.5	3562.7	-0.368	0.796
0.017	113.333	-82.3	3309.3	-0.018	0.739
0.020	136.667	684.3	3104.9	0.153	0.693
0.024	160.000	1092.0	2934.4	0.244	0.655
0.027	183.333	1318.2	2788.5	0.294	0.623
0.031	206.667	1444.7	2661.7	0.323	0.594
0.034	230.000	1513.3	2550.0	0.338	0.569
0.038	253.333	1546.8	2450.6	0.345	0.547
0.041	276.667	1558.4	2361.5	0.348	0.527
0.045	300.000	1556.3	2281.2	0.348	0.509

C1	D1	QK
-0.11111440E 04	-0.15121978E 04	0.26303409E-02

PPD	RE
0.38944192E 04	0.26697231E 06

P	H	Q	SPEE	ALPHA	PB	PC
-5080.0	0.000150	0.0026380	0.0	1.4445	-3.12	7.70

PJ	PK	TEST	PD	PE	PF	PG	PH
			9.14	8.92	6.85	5.00	3.60
2.35	1.15	35.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1784.6	2509.7	0.398	0.560
0.050	333.333	1607.6	2155.9	0.359	0.481
0.055	366.667	1418.5	1835.7	0.317	0.410
0.060	400.000	1226.0	1543.5	0.274	0.345
0.065	433.333	1034.9	1274.6	0.231	0.285
0.070	466.666	847.9	1025.7	0.189	0.229
0.075	500.000	666.1	794.0	0.149	0.177
0.080	533.333	490.3	577.2	0.109	0.129
0.085	566.666	320.7	373.6	0.072	0.083
0.090	599.999	157.3	181.6	0.035	0.041
0.095	633.333	0.0	0.0	0.0	0.000

C2	D2	RE
-0.33487031E 04	-0.76748438E 04	0.38564138E 06

THRUST	THRUST X	PDT
0.22898727E 02	0.27128235E 02	-0.18470474E 02

P	H	Q	SPEE	ALPHA	PB	PC
-5371.0	0.000150	0.0026380	419.0	1.4445	-3.98	7.23

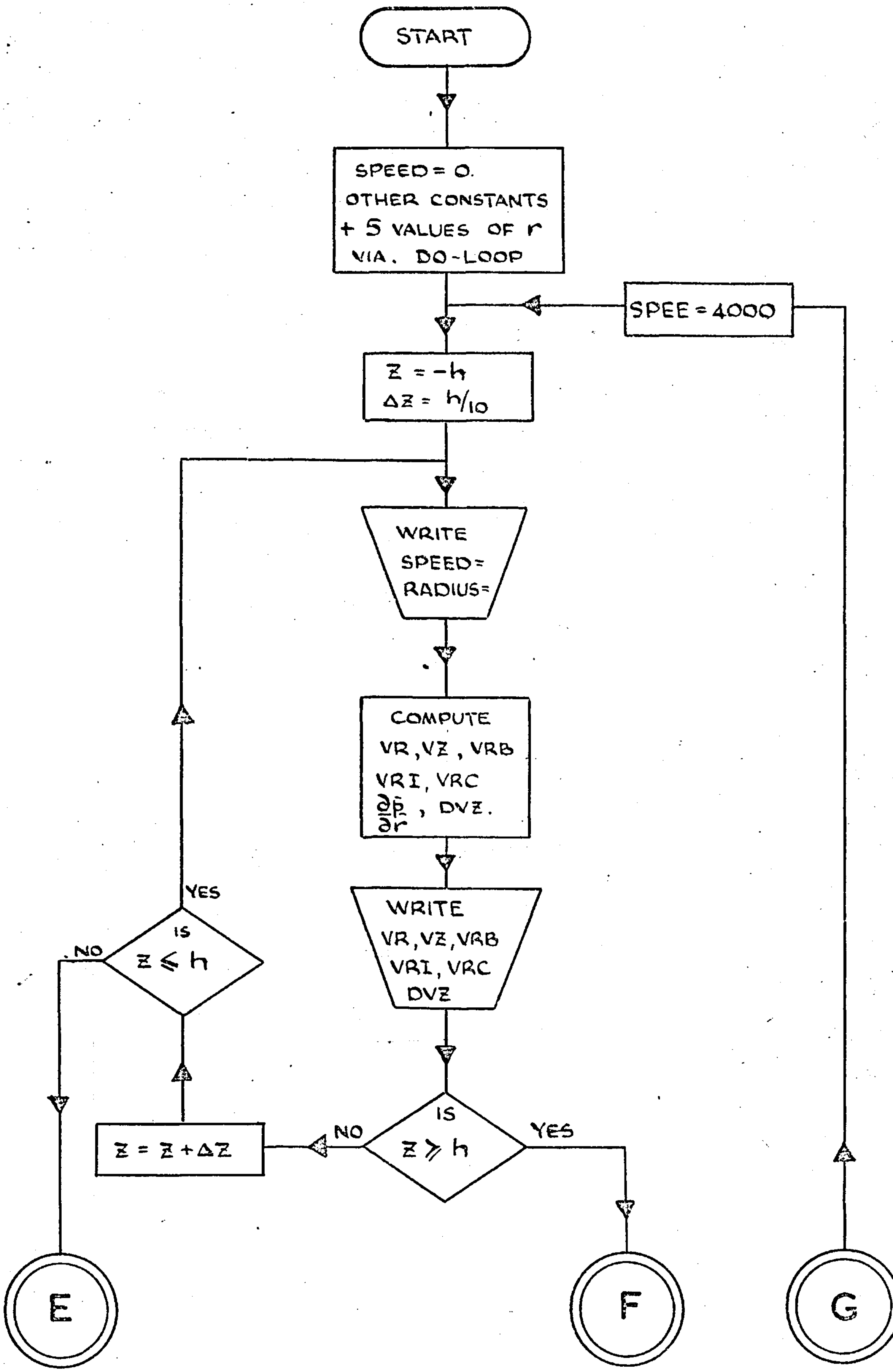
PJ	PK	TEST	PD	PE	PF	PG	PH
			8.00	7.95	5.90	4.30	3.10
2.00	0.90	36.0					

R	R/H	OPK	OPD	OPRK	OPRD
0.045	300.000	1556.3	2281.2	0.348	0.509
0.050	333.333	1394.7	1942.8	0.311	0.434
0.055	366.667	1222.7	1639.8	0.273	0.366
0.060	400.000	1049.0	1366.3	0.234	0.305
0.065	433.333	878.3	1117.9	0.196	0.250
0.070	466.666	713.3	891.0	0.159	0.199
0.075	500.000	555.2	683.0	0.124	0.153
0.080	533.333	404.7	491.5	0.090	0.110
0.085	566.666	262.0	314.8	0.059	0.070
0.090	599.999	127.2	151.4	0.028	0.034
0.095	633.333	0.0	0.0	0.000	0.000

C2	D2	RE
-0.33490579E 04	-0.79703789E 04	0.38564138E 06

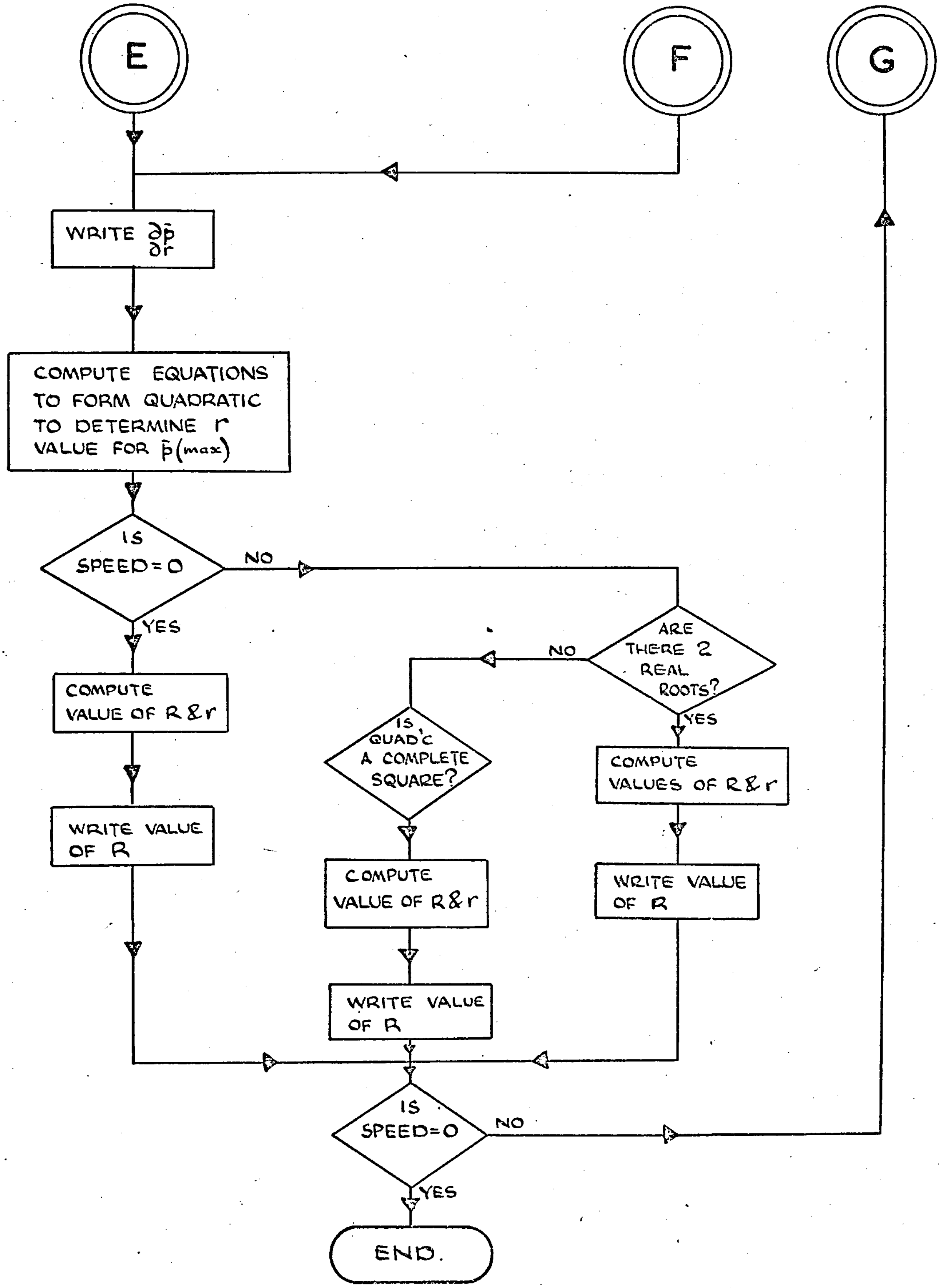
THRUST	THRUST X	PDT
0.17917282E 02	0.23231506E 02	-0.29659760E 02

COMPUTER PROGRAM AND PRINT OUT OF V_r, V_z & $\mu \frac{\partial V_z}{\partial z}$ VALUES.



FLOW CHART Nº 2A.

APPENDIX 3



FLOW CHART Nº 2B.

```
// JOB 11S13R KLEMZ F/ RADIAL VELOCITY AXIAL VELOCITY
*   JOB   2925
// OPTION LINK
// EXEC FORTRAN
C     TESTS (19) & (20)
      SPEE=0.0
      GO TO 4
 7    IF(SPEE-1.0)8,102,102
 8    SPEE=4000.0*2.0*PI/60.0
 4    Q=0.000856
      R1=0.01
      R2=0.095
      PI=3.14159
      H=0.000125
      VIS=1.8/100000.0
      DEN=1.24
      DO 100 I=1,5
      GO TO(40,41,42,43,44),I
 40   R=0.01
      GO TO 16
 41   R=0.025
      GO TO 16
 42   R=0.05
      GO TO 16
 43   R=0.07
      GO TO 16
 44   R=R2
 16   WRITE(3,80)SPEE
 80   FORMAT(' '50X,'SPEED=' F5.1)
      WRITE(3,81)R
 81   FORMAT(' '50X,'RADIUS='F5.3)
      E=0.75*VIS*Q/(PI*R*H*H*H)
      F=27.0*DEN*Q*Q/(280.0*PI*PI*R*R*R*H*H)
      G=0.3*DEN*SPEE*SPEE*R
      PR=-E+F+G
C     PR= SLOPE OF PRESSURE DISTRIBUTION CURVE
      Z=-H
      WRITE(3,15)
 15   FORMAT('0'9X,'VR'14X,'Z'22X,'VZ',14X
     /,'VRB',12X,'VRI',12X,'VRC',15X,'DVZ')
 11   A1=(Z*Z-H*H)/(2.0*VIS)
      A2=9.0*Q*Q*DEN/(64.0*PI*PI*H**6*R*R*R*VIS)
```

```
      A3=(H**4)*Z*Z/2.0
      A4=(Z**4)*H*H/6.0
      A5=(Z**6)/30.0
      A6=(H**6)*11.0/30.0
      B1=R*DEN*SPEE**2/(48.0*VIS)
      B2=(Z**4)/(H*H)+4.0*Z*Z*Z/H+6.0*Z*Z-4.0*Z*H
     -7.0*H*H
      C1=(1.0/(2.0*R*VIS))*(((Z**3)/3.0)-(H*H*Z))
      C2=27.0*Q*Q*DEN/(140.0*PI*PI*R*R*R*H*H)
      C3=3.0*DEN*SPEE*SPEE*R/5.0
      C4=9.0*Q*Q*DEN/(32.0*PI*PI*(H**6)*(R**4)*VIS)
      C5=(H**4)*(Z*Z*Z)/6.0
      C6=H*H*(Z**5)/30.0
      C7=(Z**7)/210.0
      C8=11.0*Z*(H**6)/30.0
      C9=DEN*SPEE*SPEE/(120.0*VIS)
      C10=(Z**5)/(H*H)
      C11=5.0*(Z**4)/H
      C12=10.0*(Z**3)
      C13=10.0*H*Z*Z
      C14=35.0*H*H*Z
      C15=5.0*H*H*H
      VR=A1*(-E+F+G)-A2*(A3-A4+A5-A6)-B1*B2
      VZ=-C1*(-C2+C3)-C4*(C5-C6+C7-C8)+C9*(C10+
     C11+C12-C13-C14+C15)
      VRB=(H*H-Z*Z)*3.0*Q/(8.0*PI*H*H*H*R)
      VRI=A1*(-E+F)-A2*(A3-A4+A5-A6)
      DVZ=-VIS*((A1/R)*(C2+C3)-C4*((H**4)*(Z*Z)/
     2.0-(H*H)*(Z**4)/6.0+(Z**6)/30.0-(H**6)
     *11.0/30.0)+C9*60.0*((Z**4)/(H*H*12.0)+
     (Z**3)/(3.0*H)+(Z*Z)/2.0-H*Z/3.0-(H*H)*
     11.0/12.0+(H*H)/3.0))
C      VR=RADIAL VELOCITY BASED ON EQUATION (28)
C      VZ=RADIAL VELOCITY BASED ON EQUATION (29)
C     VRB=RADIAL VELOCITY BASED ON EQUATION (21)
C     VRI=RADIAL VELOCITY BASED ON EQUATION (28)
C     (SPEED=ZERO)
C     VRC=RADIAL VELOCITY BASED ON EQUATION (18)
C     DVZ=EQUATION (28A)*VIS
      FC=DEN*Q*Q/(16.0*PI*PI*R*R*R*H*H)
      D1=(DEN*Q*Q*Z*Z)/(32.0*PI*PI*R*R*R*H*H*VIS)
      D2=DEN*SPEE*SPEE*R/(4.0*VIS)
      D3=(Z**4)/(12.0*H*H)+(Z**3)/(3.0*H)+(Z*Z)/2.0
      D4=DEN*SPEE*SPEE*R*H*Z/(12.0*VIS)
      D5=7.0*DEN*SPEE*SPEE*R*H*H/(48.0*VIS)
      D6=DEN*Q*Q/(32.0*PI*PI*R*R*R*VIS)
      PRC=-E+FC+G
      VRC=(A1*PRC)-D1-D2*D3+D4+D5+D6
```

```
      Z1=H
      ZD=H/10.0
      WRITE(3,20)VR,Z,VZ,VRB,VRI,VRC,DVZ
 20   FORMAT(' '4X,F9.4,6X,F10.7,8X,E16.4,6X,F9.4,
      6X,F9.4,6X,F9.4,
     /6X,E16.8)
      IF(Z-Z1)10,11,11
 10   Z=Z+ZD
      IF(Z-Z1)11,11,12
 12   WRITE(3,31)PR
 31   FORMAT('0'7X,'DP/DR='F8.1)
      F1=(3.0*DEN*SPEE**2)/10.0
      F3=27.0*DEN*Q*Q/(280.0*PI*PI*H*H)
      F2=3.0*VIS*Q/(4.0*PI*H*H*H)
      F4=SQRT((9.0*DEN*Q*H)/(70.0*PI*VIS))
      F5=F4/H
      IF(F1)94,94,99
 94   WRITE(3,103)F5
 103  FORMAT(22X,'P IS A MAX WHEN DIMENSIONLESS
      RADIUS =' F5.1)
      GO TO 95
 99   FK1=F2/F1
      FK2=F3/F1
      FK3=(FK1**2)-4.0*FK2
      IF(FK3)91,92,93
 93   FK4=SQRT(FK3)
      SQ1=(FK1+FK4)/2.0
      SQ2=(FK1-FK4)/2.0
      SQ3=(SQRT(SQ1))/H
      SQ4=(SQRT(SQ2))/H
      WRITE(3,98)SQ3,SQ4
 98   FORMAT(2(10X,'P IS A MAX WHEN DIMENSIONLESS
      RADIUS =' E10.4))
      GO TO 95
 92   OQ=FK1/2.0
      OQ1=OQ/H
      WRITE(3,97)OQ1
 97   FORMAT(15X,'P IS AMAX WHEN DIMENSIONLESS
      RADIUS =' F5.1)
      GO TO 95
 91   WRITE(3,96)
 96   FORMAT(10X,'NO REAL SOLUTION')
 95   CONTINUE
 100  CONTINUE
 101  GO TO 7
 102  CONTINUE
      END
```

SPEED= 0.0
RADIUS=0.010

VR	Z	VZ	VRB
0.0003	-0.0001250	-0.8583E-05	0.0
7.0151	-0.0001125	-0.1166E-01	15.5310
17.0329	-0.0001000	-0.3871E-01	29.4272
29.3934	-0.0000875	-0.7031E-01	41.6885
43.1688	-0.0000750	-0.9765E-01	52.3150
57.2933	-0.0000625	-0.1144E 00	61.3066
70.6751	-0.0000500	-0.1170E 00	68.6634
82.2915	-0.0000375	-0.1044E 00	74.3853
91.2663	-0.0000250	-0.7828E-01	78.4725
96.9309	-0.0000125	-0.4188E-01	80.9247
98.8664	0.0000000	0.2367E-06	81.7421
96.9307	0.0000125	0.4188E-01	80.9247
91.2662	0.0000250	0.7828E-01	78.4724
82.2913	0.0000375	0.1044E 00	74.3853
70.6750	0.0000500	0.1170E 00	68.6633
57.2932	0.0000625	0.1144E 00	61.3065
43.1687	0.0000750	0.9764E-01	52.3149
29.3932	0.0000875	0.7031E-01	41.6884
17.0329	0.0001000	0.3871E-01	29.4271
7.0150	0.0001125	0.1166E-01	15.5310

VRI	VRC	DVZ
0.0003	0.0000	-0.10708645E-05
7.0151	15.5311	0.30657146E-01
17.0329	29.4273	0.44619516E-01
29.3934	41.6886	0.44262610E-01
43.1688	52.3151	0.32926131E-01
57.2933	61.3067	0.14447946E-01
70.6751	68.6635	-0.72421804E-02
82.2915	74.3855	-0.28462414E-01
91.2663	78.4726	-0.46057969E-01
96.9309	80.9248	-0.57622470E-01
98.8664	81.7422	-0.61648283E-01
96.9307	80.9248	-0.57622470E-01
91.2662	78.4725	-0.46057828E-01
82.2913	74.3854	-0.28461851E-01
70.6750	68.6635	-0.72420426E-02
57.2932	61.3067	0.14448013E-01
43.1687	52.3150	0.32926060E-01
29.3932	41.6885	0.44262752E-01
17.0329	29.4272	0.44619095E-01
7.0150	15.5310	0.30657779E-01

DP/DR=379807.4
P IS A MAX WHEN DIMENSIONLESS RADIUS =138.9

SPEED= 0.0
RADIUS=0.025

VR	Z	VZ	VRB
0.0000	-0.0001250	-0.1788E-06	0.0
5.6674	-0.0001125	-0.2984E-03	6.2124
10.9776	-0.0001000	-0.9910E-03	11.7709
15.8885	-0.0000875	-0.1800E-02	16.6754
20.3406	-0.0000750	-0.2500E-02	20.9260
24.2658	-0.0000625	-0.2928E-02	24.5226
27.5941	-0.0000500	-0.2994E-02	27.4654
30.2601	-0.0000375	-0.2674E-02	29.7541
32.2077	-0.0000250	-0.2004E-02	31.3890
33.3942	-0.0000125	-0.1072E-02	32.3699
33.7928	0.0000000	0.6060E-08	32.6968
33.3942	0.0000125	0.1072E-02	32.3699
32.2077	0.0000250	0.2004E-02	31.3890
30.2601	0.0000375	0.2674E-02	29.7541
27.5940	0.0000500	0.2994E-02	27.4653
24.2657	0.0000625	0.2928E-02	24.5226
20.3406	0.0000750	0.2500E-02	20.9260
15.8885	0.0000875	0.1800E-02	16.6754
10.9776	0.0001000	0.9909E-03	11.7709
5.6674	0.0001125	0.2985E-03	6.2124

VRI	VRC	DVZ
0.0000	0.0000	-0.27414114E-07
5.6674	6.2124	0.78482740E-03
10.9776	11.7709	0.11422655E-02
15.8835	16.6754	0.11331292E-02
20.3406	20.9260	0.84292330E-03
24.2658	24.5226	0.36988733E-03
27.5941	27.4653	-0.18537881E-03
30.2601	29.7541	-0.72861277E-03
32.2077	31.3890	-0.11790565E-02
33.3942	32.3699	-0.14751072E-02
33.7928	32.6968	-0.15781675E-02
33.3942	32.3699	-0.14751116E-02
32.2077	31.3889	-0.11790565E-02
30.2601	29.7541	-0.72859973E-03
27.5940	27.4653	-0.18537881E-03
24.2657	24.5226	0.36988733E-03
20.3406	20.9259	0.84292330E-03
15.8885	16.6754	0.11331381E-02
10.9776	11.7709	0.11422567E-02
5.6674	6.2124	0.78484416E-03

DP/DR=-38972.5
P IS A MAX WHEN DIMENSIONLESS RADIUS =138.9

SPEED= 0.0
RADIUS=0.050

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	-0.7451E-08	0.0	0.0000	0.0	-0.17133821E-08
3.0381	-0.0001125	-0.1865E-04	3.1062	3.0381	3.1062	0.49051450E-04
5.7863	-0.0001000	-0.6193E-04	5.8854	5.7863	5.8854	0.71391594E-04
8.2393	-0.0000875	-0.1125E-03	8.3377	8.2393	8.3377	0.70819748E-04
10.3898	-0.0000750	-0.1562E-03	10.4630	10.3898	10.4630	0.52681615E-04
12.2292	-0.0000625	-0.1830E-03	12.2613	12.2292	12.2613	0.23116590E-04
13.7488	-0.0000500	-0.1871E-03	13.7327	13.7488	13.7327	-0.11587549E-04
14.9403	-0.0000375	-0.1671E-03	14.8771	14.9403	14.8771	-0.45539942E-04
15.7968	-0.0000250	-0.1252E-03	15.6945	15.7968	15.6945	-0.73692398E-04
16.3130	-0.0000125	-0.6700E-04	16.1849	16.3130	16.1849	-0.92195842E-04
16.4854	0.0000000	0.3788E-09	16.3484	16.4854	16.3484	-0.98637116E-04
16.3130	0.0000125	0.6700E-04	16.1849	16.3130	16.1849	-0.92195565E-04
15.7968	0.0000250	0.1252E-03	15.6945	15.7968	15.6945	-0.73692121E-04
14.9403	0.0000375	0.1671E-03	14.8771	14.9403	14.8771	-0.45538851E-04
13.7488	0.0000500	0.1871E-03	13.7327	13.7488	13.7327	-0.11587000E-04
12.2292	0.0000625	0.1830E-03	12.2613	12.2292	12.2613	0.23117143E-04
10.3898	0.0000750	0.1562E-03	10.4630	10.3898	10.4630	0.52681877E-04
8.2393	0.0000875	0.1125E-03	8.3377	8.2393	8.3377	0.70820577E-04
5.7863	0.0001000	0.6193E-04	5.8854	5.7863	5.8854	0.71390765E-04
3.0381	0.0001125	0.1865E-04	3.1062	3.0381	3.1062	0.49052527E-04

DP/DR=-33121.6
P IS A MAX WHEN DIMENSIONLESS RADIUS =138.9
SPEED= 0.0
RADIUS=0.070

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	-0.2794E-08	0.0	0.0000	0.0000	-0.44600790E-09
2.1939	-0.0001125	-0.4856E-05	2.2187	2.1939	2.2187	0.12768476E-04
4.1677	-0.0001000	-0.1612E-04	4.2039	4.1677	4.2039	0.18583698E-04
5.9197	-0.0000875	-0.2928E-04	5.9555	5.9197	5.9555	0.18435021E-04
7.4469	-0.0000750	-0.4067E-04	7.4736	7.4469	7.4736	0.13713351E-04
8.7464	-0.0000625	-0.4764E-04	8.7581	8.7464	8.7581	0.60173115E-05
9.8149	-0.0000500	-0.4871E-04	9.8091	9.8149	9.8091	-0.30165693E-05
10.6495	-0.0000375	-0.4350E-04	10.6265	10.6495	10.6265	-0.11854517E-04
11.2476	-0.0000250	-0.3260E-04	11.2103	11.2476	11.2103	-0.19182931E-04
11.6073	-0.0000125	-0.1744E-04	11.5607	11.6073	11.5607	-0.23999615E-04
11.7274	0.0000000	0.9860E-10	11.6774	11.7274	11.6774	-0.25676403E-04
11.6073	0.0000125	0.1744E-04	11.5607	11.6073	11.5607	-0.23999615E-04
11.2476	0.0000250	0.3260E-04	11.2103	11.2476	11.2103	-0.19182931E-04
10.6495	0.0000375	0.4350E-04	10.6265	10.6495	10.6265	-0.11854242E-04
9.8149	0.0000500	0.4871E-04	9.8090	9.8149	9.8090	-0.30162946E-05
8.7464	0.0000625	0.4764E-04	8.7581	8.7464	8.7581	0.60173115E-05
7.4469	0.0000750	0.4067E-04	7.4736	7.4469	7.4736	0.13713282E-04
5.9196	0.0000875	0.2928E-04	5.9555	5.9196	5.9555	0.18435094E-04
4.1677	0.0001000	0.1612E-04	4.2039	4.1677	4.2039	0.18583523E-04
2.1939	0.0001125	0.4857E-05	2.2187	2.1939	2.2187	0.12768767E-04

DP/DR=-25248.4
P IS A MAX WHEN DIMENSIONLESS RADIUS =138.9

SPEED= 0.0
RADIUS=0.095

VR	Z	VZ	VRB
0.0000	-0.0001250	-0.6985E-09	0.0
1.6249	-0.0001125	-0.1431E-05	1.6348
3.0831	-0.0001000	-0.4753E-05	3.0976
4.3739	-0.0000875	-0.8632E-05	4.3883
5.4962	-0.0000750	-0.1199E-04	5.5068
6.4486	-0.0000625	-0.1404E-04	6.4533
7.2301	-0.0000500	-0.1436E-04	7.2277
7.8393	-0.0000375	-0.1282E-04	7.8300
8.2752	-0.0000250	-0.9610E-05	8.2603
8.5371	-0.0000125	-0.5141E-05	8.5184
8.6244	0.0000000	0.2906E-10	8.6044
8.5371	0.0000125	0.5141E-05	8.5184
8.2752	0.0000250	0.9610E-05	8.2603
7.8393	0.0000375	0.1282E-04	7.8300
7.2301	0.0000500	0.1436E-04	7.2277
6.4486	0.0000625	0.1404E-04	6.4533
5.4962	0.0000750	0.1199E-04	5.5068
4.3739	0.0000875	0.8632E-05	4.3883
3.0831	0.0001000	0.4752E-05	3.0976
1.6249	0.0001125	0.1431E-05	1.6348

VRI	VRC	DVZ
0.0000	-0.0000	-0.13147418E-09
1.6249	1.6348	0.37638820E-05
3.0831	3.0976	0.54781067E-05
4.3739	4.3883	0.54342981E-05
5.4962	5.5068	0.40424857E-05
6.4486	6.4533	0.17738275E-05
7.2301	7.2277	-0.88913680E-06
7.8393	7.8300	-0.34944742E-05
8.2752	8.2603	-0.56546942E-05
8.5371	8.5184	-0.70745218E-05
8.6244	8.6044	-0.75687867E-05
8.5371	8.5184	-0.70745564E-05
8.2752	8.2603	-0.56547115E-05
7.8393	7.8300	-0.34944396E-05
7.2301	7.2277	-0.88913680E-06
6.4486	6.4533	0.17738612E-05
5.4962	5.5068	0.40424684E-05
4.3739	4.3883	0.54343154E-05
3.0831	3.0976	0.54780548E-05
1.6249	1.6348	0.37639620E-05

DP/DR=-19162.0
P IS A MAX WHEN DIMENSIONLESS RADIUS =138.9

SPEED=418.9
RADIUS=0.010

VR	Z	VZ	VRB
0.0003	-0.0001250	-0.1058E-04	0.0
6.9928	-0.0001125	-0.1163E-01	15.5310
16.9937	-0.0001000	-0.3861E-01	29.4272
29.3430	-0.0000875	-0.7009E-01	41.6885
43.1124	-0.0000750	-0.9729E-01	52.3150
57.2357	-0.0000625	-0.1139E 00	61.3066
70.6209	-0.0000500	-0.1163E 00	68.6634
82.2446	-0.0000375	-0.1037E 00	74.3853
91.2300	-0.0000250	-0.7741E-01	78.4725
96.9079	-0.0000125	-0.4093E-01	80.9247
98.8586	0.0000000	0.9839E-03	81.7421
96.9389	0.0000125	0.4286E-01	80.9247
91.2904	0.0000250	0.7922E-01	78.4724
82.3303	0.0000375	0.1053E 00	74.3853
70.7265	0.0000500	0.1177E 00	68.6633
57.3537	0.0000625	0.1150E 00	61.3065
43.2332	0.0000750	0.9809E-01	52.3149
29.4552	0.0000875	0.7060E-01	41.6884
17.0845	0.0001000	0.3886E-01	29.4271
7.0465	0.0001125	0.1171E-01	15.5310

VRI	VRC	DVZ
0.0003	0.0001	-0.10716376E-05
7.0151	15.5087	0.30964158E-01
17.0329	29.3882	0.45212954E-01
29.3934	41.6382	0.45121372E-01
43.1688	52.2587	0.34028269E-01
57.2933	61.2492	0.15770324E-01
70.6751	68.6093	-0.57242289E-02
82.2915	74.3386	-0.26775431E-01
91.2663	78.4363	-0.44230696E-01
96.9309	80.9019	-0.55686217E-01
98.8554	81.7344	-0.59637222E-01
96.9307	80.9330	-0.55574026E-01
91.2662	78.4967	-0.44012986E-01
82.2913	74.4245	-0.26465509E-01
70.6750	68.7151	-0.53433403E-02
57.2932	61.3672	0.16195331E-01
43.1687	52.3796	0.34463339E-01
29.3932	41.7506	0.45526054E-01
17.0329	29.4788	0.45538884E-01
7.0150	15.5625	0.31158563E-01

DP/DR=380460.1
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1352E 04

IS A MAX WHEN DIMENSIONLESS RADIUS =0.1397E 03
P

SPEED=418.9
RADIUS=0.025

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	-0.2086E-06	0.0	0.0000	0.0000	-0.28187074E-07
5.6115	-0.0001125	-0.2693E-03	6.2124	5.6674	6.1565	0.10919005E-02
10.8799	-0.0001000	-0.8839E-03	11.7709	10.9776	11.6731	0.17358183E-02
15.7626	-0.0000875	-0.1580E-02	16.6754	15.8885	16.5495	0.19920571E-02
20.1996	-0.0000750	-0.2145E-02	20.9260	20.3406	20.7850	0.19452677E-02
24.1219	-0.0000625	-0.2430E-02	24.5226	24.2658	24.3788	0.16925018E-02
27.4586	-0.0000500	-0.2356E-02	27.4654	27.5941	27.3298	0.13328365E-02
30.1428	-0.0000375	-0.1908E-02	29.7541	30.2601	29.6368	0.95865224E-03
32.1171	-0.0000250	-0.1134E-02	31.3890	32.2077	31.2983	0.64851530E-03
33.3368	-0.0000125	-0.1272E-03	32.3699	33.3942	32.3124	0.46145590E-03
33.7731	0.0000000	0.9837E-03	32.6968	33.7928	32.6772	0.43320027E-03
33.4147	0.0000125	0.2055E-02	32.3699	33.3942	32.3903	0.57363999E-03
32.2682	0.0000250	0.2947E-02	31.3890	32.2077	31.4494	0.86607947E-03
30.3576	0.0000375	0.3537E-02	29.7541	30.2601	29.8516	0.12680253E-02
27.7229	0.0000500	0.3744E-02	27.4653	27.5940	27.5942	0.17135814E-02
24.4170	0.0000625	0.3537E-02	24.5226	24.2657	24.6738	0.21174401E-02
20.5017	0.0000750	0.2951E-02	20.9260	20.3406	21.0871	0.23804007E-02
16.0435	0.0000875	0.2092E-02	16.6754	15.8885	16.8304	0.23966029E-02
11.1065	0.0001000	0.1139E-02	11.7709	10.9776	11.8998	0.20621624E-02
5.7460	0.0001125	0.3404E-03	6.2124	5.6674	6.2911	0.12856890E-02

DP/DR=-37340.7
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1352E 04

P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1397E 03

SPEED=418.9
RADIUS=0.050

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	-0.3725E-08	0.0	0.0000	0.0	-0.24863431E-08
2.9263	-0.0001125	0.1047E-04	3.1062	3.0381	2.9944	0.35612658E-03
5.5908	-0.0001000	0.4516E-04	5.8854	5.7853	5.6900	0.66494686E-03
7.9875	-0.0000875	0.1075E-03	8.3377	8.2393	8.0859	0.92975004E-03
10.1078	-0.0000750	0.1983E-03	10.4630	10.3898	10.1810	0.11550309E-02
11.9415	-0.0000625	0.3150E-03	12.2613	12.2292	11.9736	0.13457413E-02
13.4778	-0.0000500	0.4514E-03	13.7327	13.7488	13.4617	0.15066362E-02
14.7058	-0.0000375	0.5985E-03	14.8771	14.9403	14.6425	0.16417387E-02
15.6155	-0.0000250	0.7450E-03	15.6945	15.7968	15.5132	0.17538876E-02
16.1981	-0.0000125	0.8778E-03	16.1849	16.3130	16.0700	0.18443805E-02
16.4461	0.0000000	0.9837E-03	16.3464	16.4854	16.3091	0.19127426E-02
16.3539	0.0000125	0.1050E-02	16.1849	16.3130	16.2258	0.19565644E-02
15.9177	0.0000250	0.1068E-02	15.6945	15.7968	15.8154	0.19714558E-02
15.1354	0.0000375	0.1031E-02	14.8771	14.9403	15.0722	0.19510947E-02
14.0066	0.0000500	0.9367E-03	13.7327	13.7488	13.9905	0.18873808E-02
12.5317	0.0000625	0.7917E-03	12.2613	12.2292	12.5638	0.17706789E-02
10.7121	0.0000750	0.6075E-03	10.4630	10.3898	10.7853	0.15901679E-02
8.5494	0.0000875	0.4042E-03	8.3377	8.2393	8.6477	0.13342919E-02
6.0441	0.0001000	0.2098E-03	5.8854	5.7853	6.1432	0.99129858E-03
3.1954	0.0001125	0.6055E-04	3.1062	3.0381	3.2636	0.54989895E-03

DP/DR=-29858.1
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1352E 04

P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1397E 03

SPEED=418.9
RADIUS=0.070

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	0.0	0.0	0.0000	-0.0000	-0.12189687E-08
2.0374	-0.0001125	0.2427E-04	2.2187	2.1939	2.0622	0.31984365E-03
3.8941	-0.0001000	0.9096E-04	4.2039	4.1677	3.9302	0.61213877E-03
5.5671	-0.0000875	0.1907E-03	5.9555	5.9197	5.6029	0.87736547E-03
7.0520	-0.0000750	0.3139E-03	7.4736	7.4469	7.0787	0.11160627E-02
8.3436	-0.0000625	0.4503E-03	8.7581	8.7464	8.3553	0.13286415E-02
9.4355	-0.0000500	0.5898E-03	9.8091	9.8149	9.4296	0.15152071E-02
10.3212	-0.0000375	0.7222E-03	10.6265	10.6495	10.2981	0.16754237E-02
10.9938	-0.0000250	0.8377E-03	11.2103	11.2476	10.9565	0.18083970E-02
11.4465	-0.0000125	0.9274E-03	11.5607	11.6073	11.3998	0.19125766E-02
11.6723	0.0000000	0.9837E-03	11.6774	11.7274	11.6224	0.19857036E-02
11.6646	0.0000125	0.1001E-02	11.5607	11.6073	11.6179	0.20247602E-02
11.4169	0.0000250	0.9754E-03	11.2103	11.2476	11.3796	0.20259649E-02
10.9227	0.0000375	0.9069E-03	10.6265	10.6495	10.8997	0.19847797E-02
10.1758	0.0000500	0.7983E-03	9.8090	9.8149	10.1700	0.18959520E-02
9.1698	0.0000625	0.6563E-03	8.7581	8.7464	9.1815	0.17535789E-02
7.8981	0.0000750	0.4919E-03	7.4736	7.4469	7.9248	0.15511985E-02
6.3537	0.0000875	0.3209E-03	5.9555	5.9196	6.3895	0.12819064E-02
4.5287	0.0001000	0.1640E-03	4.2039	4.1677	4.5648	0.93849120E-03
2.4142	0.0001125	0.4676E-04	2.2187	2.1939	2.4390	0.51361532E-03

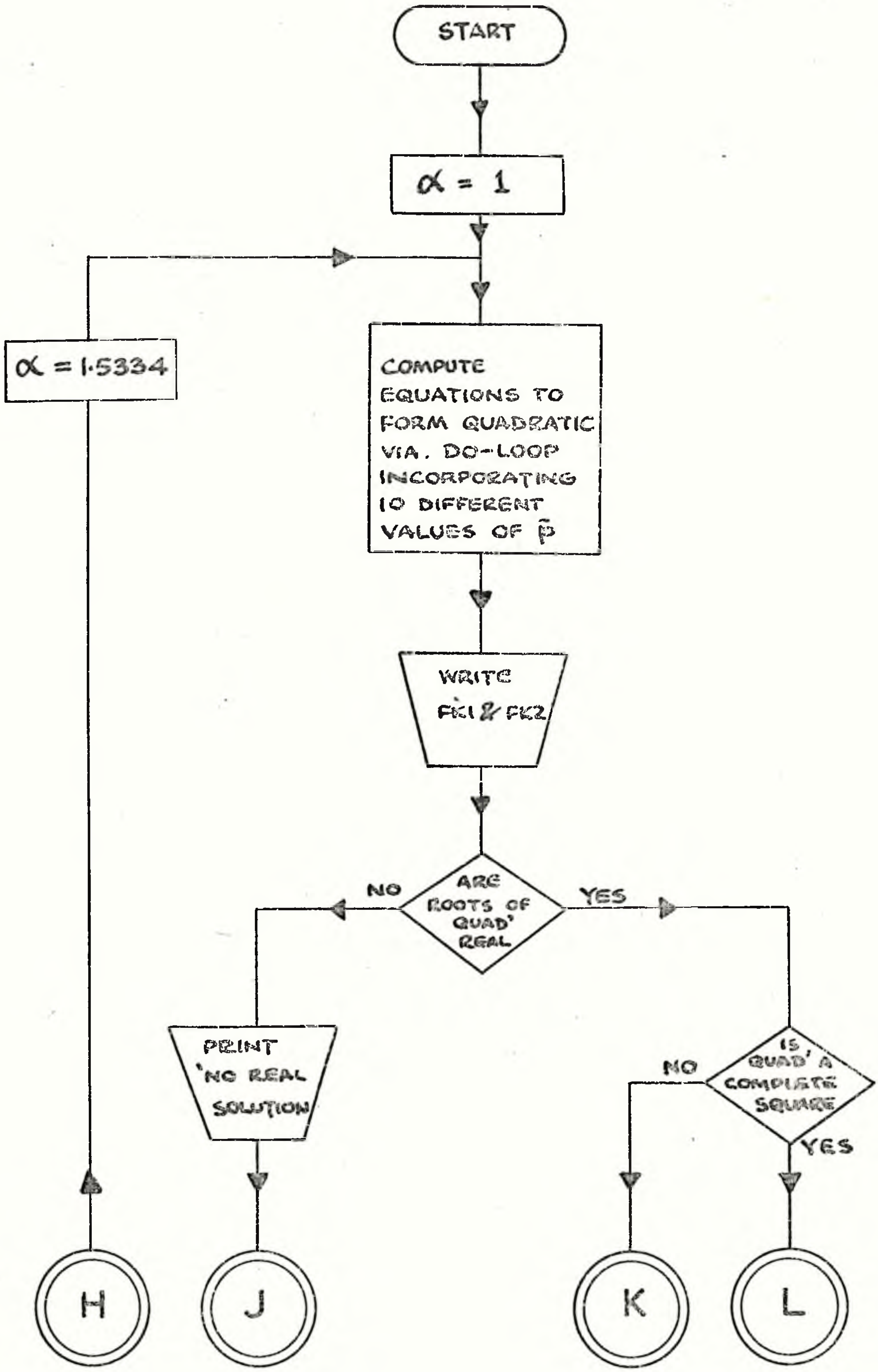
DP/DR=-20679.5
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1352E 04
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1397E 03

SPEED=418.9
RADIUS=0.095

VR	Z	VZ	VRB	VRI	VRC	DVZ
0.0000	-0.0001250	0.7451E-08	0.0	0.0000	-0.0000	-0.90443475E-09
1.4126	-0.0001125	0.2769E-04	1.6348	1.6249	1.4225	0.31083915E-03
2.7117	-0.0001000	0.1023E-03	3.0976	3.0831	2.7262	0.59903343E-03
3.8954	-0.0000875	0.2114E-03	4.3883	4.3739	3.9098	0.86436514E-03
4.9603	-0.0000750	0.3426E-03	5.5068	5.4962	4.9710	0.11063921E-02
5.9020	-0.0000625	0.4839E-03	6.4533	6.4486	5.9067	0.13243984E-02
6.7151	-0.0000500	0.6242E-03	7.2277	7.2301	6.7128	0.15173350E-02
7.3937	-0.0000375	0.7529E-03	7.8300	7.8393	7.3844	0.16837837E-02
7.9307	-0.0000250	0.8607E-03	8.2603	8.2752	7.9158	0.18219252E-02
8.3187	-0.0000125	0.9397E-03	8.5184	8.5371	8.3001	0.19295020E-02
8.5497	0.0000000	0.9837E-03	8.6044	8.6244	8.5297	0.20038113E-02
8.6148	0.0000125	0.9885E-03	8.5184	8.5371	8.5961	0.20416852E-02
8.5048	0.0000250	0.9524E-03	8.2603	8.2752	8.4899	0.20394928E-02
8.2100	0.0000375	0.8763E-03	7.8300	7.8393	8.2008	0.19931386E-02
7.7199	0.0000500	0.7640E-03	7.2277	7.2301	7.7175	0.18980789E-02
7.0233	0.0000625	0.6227E-03	6.4533	6.4486	7.0280	0.17493358E-02
6.1086	0.0000750	0.4632E-03	5.5068	5.4962	6.1193	0.15415284E-02
4.9630	0.0000875	0.3003E-03	4.3883	4.3739	4.9773	0.12689056E-02
3.5730	0.0001000	0.1526E-03	3.0976	3.0831	3.5874	0.92538586E-03
1.9239	0.0001125	0.4333E-04	1.6348	1.6249	1.9338	0.50461083E-03

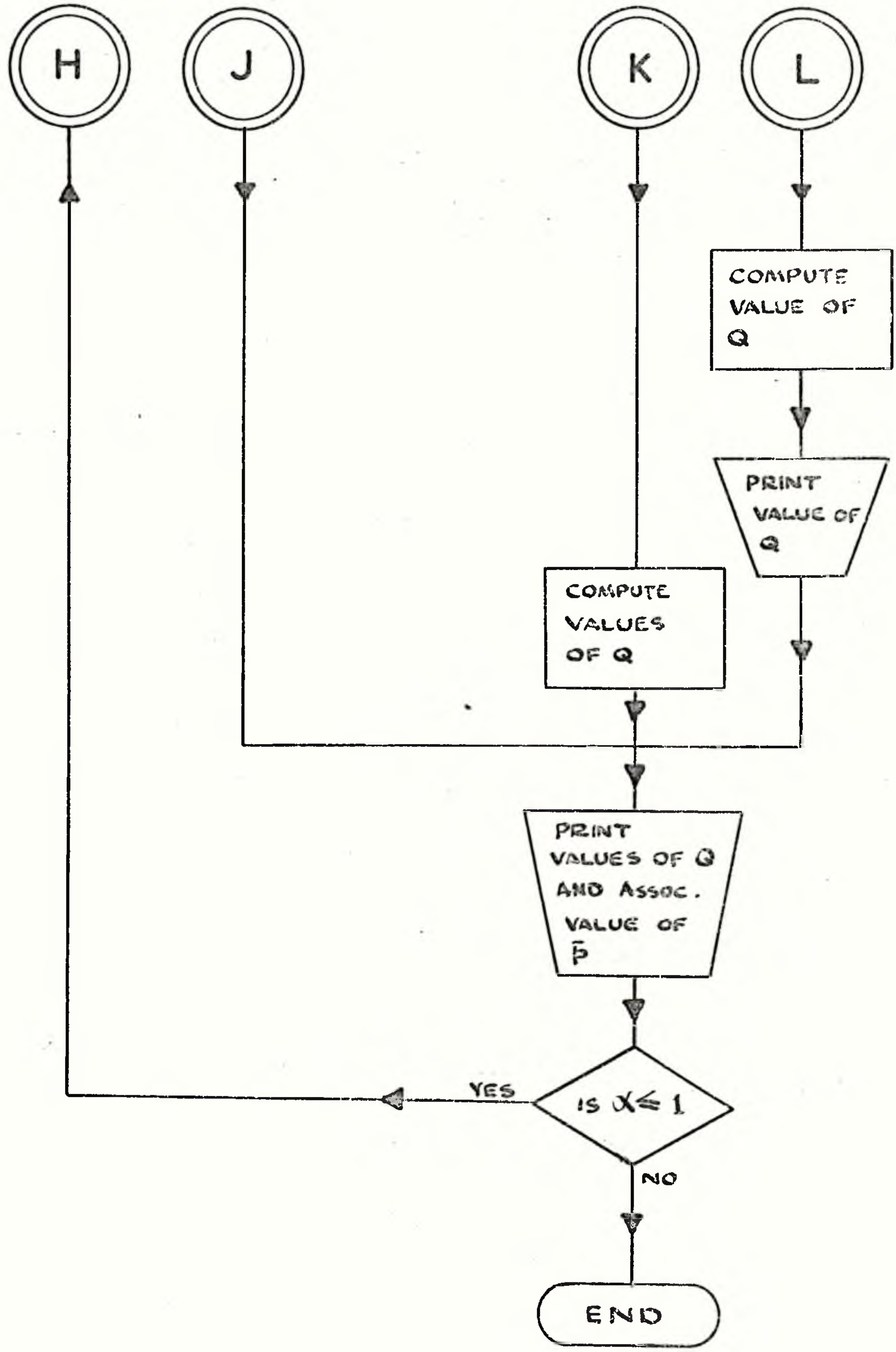
DP/DR=-12961.3
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1352E 04
P IS A MAX WHEN DIMENSIONLESS RADIUS =0.1397E 03

COMPUTER PROGRAM & PRINT OUT OF SOLUTION TO EQUATION (33)



FLOW CHART Nº 3A

APPENDIX 4



FLOW CHART N° 3B.

```
// JOB 11S13R KLEMZ.F/ VOLUME FLOW AIR BEARING    *
*   JOB   2875
// OPTION LINK
// EXEC FORTRAN
                    ALPHA=1.0
                    GO TO 71
          70        ALPHA=1.5334
          71        R1=0.01
                    R2=0.095
                    R3=0.045
                    PI=3.14159
                    SPEE=4000.0*2.0*PI/60.0
                    H=0.000125
                    DEN=1.24
                    RD1=R1/R2
                    RD3=R3/R2
                    VIS=1.8/100000.0
                    RB=(RD1*RD1)-1.0
                    DM=ALOG(RD3)*((ALPHA**3)-1.0)
                    B4=DM+ALOG(RD1)
                    RA=(1.0/(RD1*RD1))-1.0
                    DO 100 I=1,10
                    GO TO(11,12,13,14,15,16,17,18,19,20),I
          11        PP=-250.0
                    GO TO 80
          12        PP=-300.0
                    GO TO 80
          13        PP=350.0
                    GO TO 80
          14        PP=400.0
                    GO TO 80
          15        PP=450.0
                    GO TO 80
          16        PP=500.0
                    GO TO 80
          17        PP=550.0
                    GO TO 80
          18        PP=600.0
```

```
      GO TO 80
19    PP=650.0
      GO TO 80
20    PP=700.0
80    CO2=3.0*DEN*(SPEE**2)*R2*R2/(20.0*PP)
      F3=CO2*RB
      F1=-3.0*VIS*B4/(4.0*PI*PP*(H*ALPHA)**3)
      F4=27.0*DEN/((560.0*(PI*H*R2)**2)*PP)
      F5=1.0/((ALPHA*RD1)**2)
      F6=((1.0/(ALPHA**2))-1.0)/(RD3*RD3)
      F2=F4*(F5-F6-1.0)
      FK1=F1/F2
      FK2=(1.0-F3)/F2
      WRITE(3,99)FK1,FK2
99    FORMAT(10X,E10.4,20X,E10.4)
C     SOLUTION OF QUADRATIC
      FK3=FK1*FK1-4.0*FK2
      IF(FK3)91,92,93
93    FK4=SQRT(FK3)
      SQ1=(FK1+FK4)/2.0
      SQ2=(FK1-FK4)/2.0
      WRITE(3,98)SQ1,SQ2,PP
98    FORMAT(26X,E10.4,20X,E10.4,10X,F5.0)
      GO TO 100
92    DQ=FK1/2.0
      WRITE(3,97)DQ
97    FORMAT(15X,E16.8)
      GO TO 100
91    WRITE(3,96)
96    FORMAT(10X,'NO REAL SOLUTION')
100   CONTINUE
      WRITE(3,30)ALPHA
30    FORMAT('0'25X,'ALPHA= 'F6.4)
      IF(ALPHA-1.0)70,70,101
101   CONTINUE
      END
```

FK1	Q	FK2	Q	$\bar{P}_1$
0.1292E-02	0.1284E-02	0.1076E-07	0.8387E-05	-250.
0.1292E-02	0.1294E-02	-.2277E-08	-.1760E-05	-300.
0.1292E-02	0.1146E-02	0.1673E-06	0.1460E-03	350.
0.1292E-02	0.1133E-02	0.1803E-06	0.1592E-03	400.
0.1292E-02	0.1119E-02	0.1933E-06	0.1728E-03	450.
0.1292E-02	0.1105E-02	0.2064E-06	0.1867E-03	500.
0.1292E-02	0.1091E-02	0.2194E-06	0.2012E-03	550.
0.1292E-02	0.1076E-02	0.2325E-06	0.2161E-03	600.
0.1292E-02	0.1060E-02	0.2455E-06	0.2315E-03	650.
0.1292E-02	0.1044E-02	0.2586E-06	0.2476E-03	700.

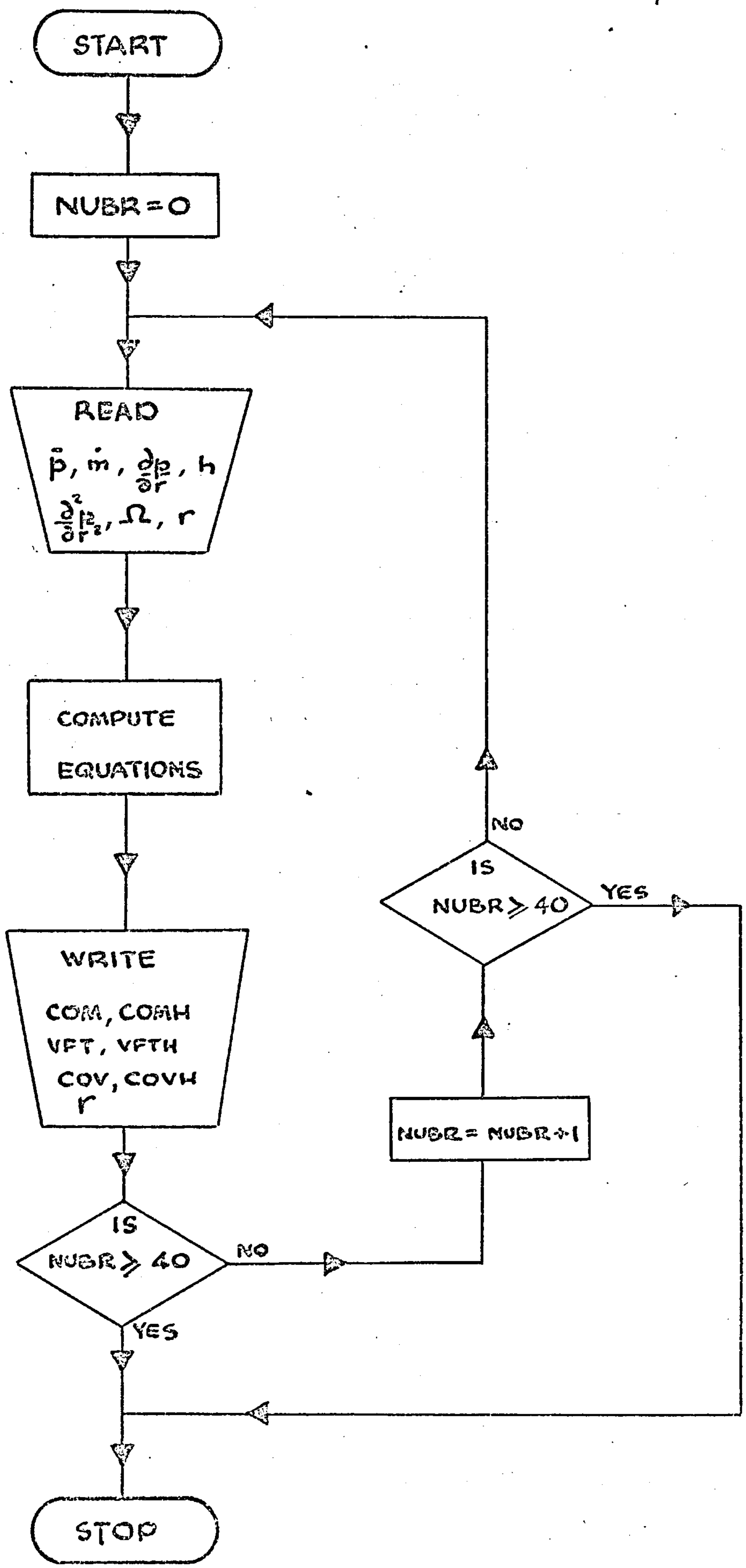
ALPHA= 1.0000

FK1	Q	FK2	Q	$\bar{P}_1$
0.1493E-02	0.1477E-02	0.2405E-07	0.1629E-04	-250.
0.1493E-02	0.1496E-02	-.5087E-08	-.3399E-05	-300.
0.1493E-02	0.1175E-02	0.3737E-06	0.3181E-03	350.
0.1493E-02	0.1139E-02	0.4029E-06	0.3536E-03	400.
0.1493E-02	0.1100E-02	0.4320E-06	0.3926E-03	450.
0.1493E-02	0.1057E-02	0.4611E-06	0.4365E-03	500.
0.1493E-02	0.1005E-02	0.4903E-06	0.4877E-03	550.
0.1493E-02	0.9410E-03	0.5194E-06	0.5520E-03	600.
0.1493E-02	0.8398E-03	0.5486E-06	0.6532E-03	650.
0.1493E-02		0.5777E-06		

NO REAL SOLUTION

ALPHA= 1.5334

COMPUTER PROGRAM & PRINT OUT OF RATIO : COMP TERM / VISCOUS TERM



FLOW CHART N° 4.

APPENDIX 5

```
// JOB 11S13R KLEMZ.F/NAVIER STOKES EQUATION
*   JOB    2721
// OPTION LINK
// EXEC FORTRAN
                    NOBR=0
                    WRITE(3,12)
          12        FORMAT('0'4X,'COM',13X,'COMH',11X,'VFT',11X,
                    'VFTH',11X,'COV',11X,'COVH',9X,'R')
          1         READ(1,11)PS,DQ,PR,PR2,S,R,H
          11        FORMAT(F8.0,F8.7,F8.0,F9.0,F5.1,F5.3,F7.6)
          C         TEST NUMBERS 13,14,19 & 20
                    PA=101300.0
                    P=PS+PA
                    PI=3.14159
                    VIS=0.000018
                    T=293.0
                    H=0.000125
                    P2R2=PR*PR
                    RR=287.0
                    DM=DQ*P/(RR*T)
                    A1=37037.0*H**3
                    A2=(1.817*DM*DM*T)/(H*H)
                    A3=12.0/(P*(R**5))
                    A4=(6.0*PR)/(P*P*(R**4))
                    A5=PR2/(P*P*(R**3))
                    A6=2.0*P2R2/((R*P)**3)
                    A7=S*S/(956.90*T)
                    A8=2.0*PR
                    A9=R*PR2
                    A10=DM*T/(811.0*(H**3))
                    A11=2.0/(P*(R**3))
                    A12=2.0*PR/(P*P*R*R)
                    A13=PR2/(P*P*R)
                    A14=2.0*P2R2/(R*(P**3))
                    A15=67313.0*DM*DM*T*H
                    A16=S*S*(H**3)*17.744/T
                    A17=56.45*S*S*(H**3)/T
                    A18=PR2/(P*P*R*R*R)
                    A19=DM*DM*RR*T/(8.0*PI*PI*R*R*R*P*VIS*H)
```

```
      A20=S*S*(H**3)*38.72/T
      B1=1.0/R
      B2=37037.0*(H**3)
      B3=3.0/(P*(R**4))
      B4=PR/(P*P*(R**3))
      B5=R*PR
      B6=1.0/(P*R*R)
      B7=PR/(P*P*R)
      C1=1.0/(R*R)
      C2=1.87*DM*DM*T/(H*H*P*(R**3))
      C3=S*S*P*R/(956.9*T)
      C4=DM*T/(811.0*(H**3)*R*P)
      C5=67313.0*DM*DM*T*H/(P*(R**3))
      C7=37037.0*(H**3)
      A=-A1*(A2*(A3+A4-A5+A6)+A7*(A8+A9)-A10*(A11
      +A12-A13+A14))+ A15*(A3+A4+A6-A18)-A16*(A8+A9)+
      A17*(A8+A9)
      B=B1*(-B2*(A2*(-B3-B4)+A7*(P+B5)+A10*(B6+B7))
      -A15*(B3+B4)+ A20*(P+B5))
      C=C1*(-C7*(C2+C3-C4)+C5+(A20*P*R))
      COM=VIS*(A+B-C)/3.0
      COMH=VIS*DM*RR*T*(A12/2.0+A14-A13)/(6.0*PI)
      V1=129.05*P*R*S*S*H/T
      V2=3.0/(H*H*P*R)
      VFTH=VIS*DM*RR*T*(A12/2.0+A14-A13-V2)/(2.0*PI)
      VT=2.0*H*(A2/(P*(R**3))+A7*P*R-A10/(R*P))/VIS-
      A19-V1
      VFT=VIS*(A+B-C+VT)
      COVH=COMH/VFTH
      COV=COM/VFT
C     COM=COMPRESSIBILITY TERM
C     COMH=COMPRESSIBILITY TERM (HOBSON & LAWRIE)
C     VFT=VISCOUS TERM
C     VFTH= VISCOUS FLOW TERM (HOBSON & LAWRIE)
C     COV=COM/VFT
C     COVH=COMH/VFTH
      WRITE(3,10)COM,COMH,VFT,VFTH,COV,COVH,R
10    FORMAT('0'1X,6(E10.4,5X),F5.3)
      IF(NUBR-40)77,345,345
77    NUBR=NUBR+1
      IF(NUBR-40)1,345,345
345   CONTINUE
      END
```

COM	COMH	VFT	VFTH	COV	COVH	R	
0.6177E-04	0.1247E-04	-.4710E 02	-.4708E 02	-.1312E-05	-.2648E-06	0.010	TEST N°19
0.1086E-04	0.4347E-05	-.3139E 02	-.3139E 02	-.3459E-06	-.1385E-06	0.015	
0.3377E-05	0.1833E-05	-.2354E 02	-.2354E 02	-.1435E-06	-.7785E-07	0.020	
-.2869E-06	-.4896E-06	-.1569E 02	-.1569E 02	0.1828E-07	0.3119E-07	0.030	
-.2357E-06	-.2836E-06	-.1177E 02	-.1177E 02	0.2003E-07	0.2409E-07	0.040	
-.1504E-06	-.1660E-06	-.9415E 01	-.9417E 01	0.1597E-07	0.1763E-07	0.050	
-.1055E-06	-.1118E-06	-.7846E 01	-.7847E 01	0.1345E-07	0.1425E-07	0.060	
-.7513E-07	-.7804E-07	-.6725E 01	-.6726E 01	0.1117E-07	0.1160E-07	0.070	
-.5578E-07	-.5727E-07	-.5884E 01	-.5885E 01	0.9479E-08	0.9731E-08	0.080	
-.4690E-07	-.4800E-07	-.5538E 01	-.5539E 01	0.8469E-08	0.8666E-08	0.085	
0.5757E-04	0.8390E-05	-.4711E 02	-.4708E 02	-.1222E-05	-.1782E-06	0.010	TEST N°20
0.1011E-04	0.3621E-05	-.3142E 02	-.3139E 02	-.3219E-06	-.1154E-06	0.015	
0.4024E-05	0.2484E-05	-.2358E 02	-.2354E 02	-.1707E-06	-.1055E-06	0.020	
-.2976E-06	-.4999E-06	-.1575E 02	-.1569E 02	0.1890E-07	0.3185E-07	0.030	
-.2502E-06	-.2931E-06	-.1184E 02	-.1177E 02	0.2113E-07	0.2532E-07	0.040	
-.9420E-06	-.9578E-06	-.9504E 01	-.9417E 01	0.9912E-07	0.1017E-06	0.050	
-.1072E-06	-.1135E-06	-.7952E 01	-.7847E 01	0.1348E-07	0.1446E-07	0.060	
-.6019E-07	-.6309E-07	-.6849E 01	-.6726E 01	0.8787E-08	0.9379E-08	0.070	
-.4227E-07	-.4376E-07	-.6026E 01	-.5885E 01	0.7015E-08	0.7436E-08	0.080	
-.3427E-07	-.3536E-07	-.5689E 01	-.5539E 01	0.6024E-08	0.6384E-08	0.085	

COM	COMH	VFT	VFTH	COV	CDVH	R	
0.1252E-04	-.6491E-06	-.2426E 02	-.2426E 02	-.5163E-06	0.2675E-07	0.010	TEST N°13
0.1361E-05	-.3711E-06	-.1617E 02	-.1617E 02	-.8415E-07	0.2295E-07	0.015	
0.1101E-06	-.3000E-05	-.1213E 02	-.1213E 02	-.9081E-08	0.2473E-07	0.020	
-.9686E-07	-.1507E-06	-.8084E 01	-.8086E 01	0.1198E-07	0.1864E-07	0.030	
-.1245E-06	-.1372E-06	-.6063E 01	-.6064E 01	0.2053E-07	0.2262E-07	0.040	
-.9166E-07	-.9582E-07	-.4850E 01	-.4851E 01	0.1890E-07	0.1975E-07	0.050	
-.5678E-07	-.5846E-07	-.4042E 01	-.4043E 01	0.1405E-07	0.1446E-07	0.060	
-.4107E-07	-.4184E-07	-.3465E 01	-.3465E 01	0.1185E-07	0.1203E-07	0.070	
-.2919E-07	-.2959E-07	-.3031E 01	-.3032E 01	0.9630E-08	0.9760E-08	0.080	
-.2534E-07	-.2564E-07	-.2853E 01	-.2854E 01	0.8881E-08	0.8984E-08	0.085	
0.1195E-04	-.1197E-05	-.2428E 02	-.2426E 02	-.4921E-06	0.4936E-07	0.010	TEST N°14
0.6061E-06	-.1121E-05	-.1620E 02	-.1617E 02	-.3742E-07	0.6933E-07	0.015	
0.5835E-07	-.3506E-06	-.1216E 02	-.1213E 02	-.4798E-08	0.2891E-07	0.020	
-.1222E-06	-.1760E-06	-.8138E 01	-.8086E 01	0.1502E-07	0.2176E-07	0.030	
-.8771E-07	-.1004E-06	-.6135E 01	-.6064E 01	0.1430E-07	0.1555E-07	0.040	
-.6428E-07	-.6842E-07	-.4940E 01	-.4851E 01	0.1301E-07	0.1410E-07	0.050	
-.7945E-07	-.8113E-07	-.4149E 01	-.4043E 01	0.1915E-07	0.2007E-07	0.060	
-.4823E-07	-.4901E-07	-.3589E 01	-.3465E 01	0.1344E-07	0.1414E-07	0.070	
-.3703E-07	-.3743E-07	-.3173E 01	-.3032E 01	0.1167E-07	0.1234E-07	0.080	
-.2986E-07	-.3015E-07	-.3004E 01	-.2854E 01	0.9941E-08	0.1057E-07	0.085	

STATEMENT OF ADVANCED COURSES OF STUDY ATTENDED

Three advanced courses of study were attended, at Sheffield Polytechnic, during the period in which the research was being carried out. These were:

(1) Instrumentation and Control.

(2) Course on Tribology: Lubrication Theories.

(3) Preparation of scientific programs in BASIC and FORTRAN IV for use on I.B.M.1130 and I.B.M. 370/135 digital computers.

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