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A UNIVERSAL CALIBRATION EQUATION FOR PRICE METERS AND SIMILAR INSTRUMENTS

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SUMMARY

A Universal Calibration Curve has been developed using theoretical and empirical methods. The analysis shows that for a meter of given rotor diameter and fixed frictional resistance, the rate of rotation of the meter rotor is dependent only on the speed of the fluid and the fluid density. It is further shown that changes in temperature and small changes in density as experienced when changing from fresh water to salt water do not have a significant effect on measurement accuracy.

A practical form of the calibration equation is given by

$$V\sqrt{\rho} = \phi\,(N\sqrt{\rho})$$

where V is the fluid velocity, ρ is the fluid density and N is the rate of rotation. Suggestions are made for applying the Universal Calibration Equation to calibrations of current meters in wind tunnels. The principles developed can be applied to other current meters used in oceanographic and lake surveys as well as anemometers used to measure wind velocities.

RÉSUMÉ

On a conçu une courbe universelle d'étalonnage selon des méthodes théoriques et empiriques. L'analyse démontre que pour un moulinet pourvu d'un rotor de diamètre donné et doté d'une résistance fixe au frottement, la vitesse de totation du rotor ne dépend que de la vitesse et de la masse volumique du fluide. On constate de plus que les changements de température et les faibles modifications de densité, notés au passage de l'eau douce a l'eau salée, n'exercent guère d'influence sur la précision des mesures.

La formule pratique de l'équation d'étalonnage se présent ainsi:

$$v\sqrt{p} = \phi\ (N\sqrt{p})$$

V représente la vitesse du fluide; p, la masse volumique du fluide et N, la vitesse de rotation. On propose d'appliquer l'équation universelle a l'étalonnage des moulinets utilisés dans les souffleries. Les principes établis peuvent aussi servir pour d'autres moulinets hydrométriques, employés en océanographic et dans les études lacustres, de même que pour les anémomètres servant à mesurer la vitesse du vent.

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1.0 INTRODUCTION

Current meters are an important part of most water oriented programmes. Surveys of national water resources, studies in marine sciences, limnological studies, power generation investigations, require the measurement of velocity. The accuracy and calibration of the current meters should be checked regularly so that reliable data are obtained because the cost of field surveys and measurements is very high.

The purpose of this report is to:

(a) develop a calibration equation for Price type current meters which will take into account the properties of the fluid.

(b) to examine the effects of fluid properties on the performance of current meters to guide users of such meters in setting standards for calibration accuracy.

This is done using the Price current meter Figure 1.1, since this is the most popular instrument for streamflow measurement in North America (Corbetts 1962, Grover, Harrington, 1966). Three Price 622A meters were calibrated in both air and water and these data together with data from Schubauer and Mason (1937)obtained with an old model Price meter were used in the analysis. The new data was obtained in the towing tank of the Hydraulics Research Division at the Canada Centre for Inland Waters, Burlington, Ontario and the wind tunnel of the Atmospheric Environment Service, Toronto, Ontario.

The writer wishes to express his appreciation to Mr. P. Mannette for providing the use of the wind tunnel and to Mr. D. Kerr for his help and guidance during the calibrations in air. Appreciation is also expressed to Mr. C. DeZeeuw and his staff of the National Calibration Service for providing the necessary calibrations in their towing tank.

The writer also wishes to thank Dr. T. M. Dick, Chief, Hydraulics Research Division and Dr. Y. L. Lau, Head Hydraulics Section, for their constructive comments which made it possible to complete this report.

2.0 THEORETICAL CONSIDERATIONS

The linear velocity of the fluid is measured by placing the current meter into the flow and recording the rate of rotation of the rotor. The relationship between the linear velocity and the revolutions per second is normally determined by calibrating the meter in a towing tank.

The forces which govern the rotation of the rotor are due to the drag on the upstream and downstream side of the cups, and the resistance of the bearings and contacts. These forces create torques which are defined schematically in Figure 2.1. The resisting drag force and the friction force, for the sake of simplicity, can be "lumped" together to produce a total resisting torque.

When the rotor turns at a constant rate the opposing torques are in equilibrium resulting in

$$\frac{1}{2} \rho \, C_{D_1} \, A \frac{D}{2} (V - rw)^2 = \frac{1}{2} \rho \, C_{D_2} \, A \frac{D}{2} (V + rw)^2 \quad . \; . \; . \; . \; . (2.1)$$

where
- ρ = density of the fluid
- A = bluff body area opposing the flow
- D = effective diameter of rotor
- V = velocity of the flow
- w = angular velocity
- r = distance from axis of shaft to centreline of cups
- $C_{D_{1,2}}$ = average drag coefficients

Equation 2.1 may be reduced to

$$V = \left[\frac{\sqrt{C_{D_1}} + \sqrt{C_{D_2}}}{\sqrt{C_{D_1}} - \sqrt{C_{D_2}}}\right] rw \quad \ldots\ldots 2.2$$

The magnitude of the linear velocity of the rotor at a distance D/2 from the centre of rotation is

$$u = w\frac{D}{2} = \pi DN \quad \ldots\ldots 2.3$$

where u = linear velocity of the rotor

N = revolutions per second of the rotor

$D = 2r$ = effective diameter of the rotor

Equation 2.2 may then be written as

$$V = \overline{C}_D \, \pi DN \quad \ldots\ldots 2.4$$

where:

$$\overline{C}_D = \left[\frac{\sqrt{C_{D_1}} + \sqrt{C_{D_2}}}{\sqrt{C_{D_1}} - \sqrt{C_{D_2}}}\right]$$

The drag coefficient is usually a function of the Reynolds number. If one considers the edges of the rotor cups to be sharp and that separation occurs at all velocities, then $\overline{C}_D$ is independent of Reynolds number. Equation 2.4 is then linear which is ideal for a current meter. For such a meter the pitch number $\frac{ND}{V}$ is constant which may be expressed by rearranging equation 2.4 as

$$\frac{ND}{V} = \frac{1}{\pi\, C_D} = k \qquad (2.5)$$

For a Price 622AA meter k varies between 0.112 to 0.115.

It is known, however, that calibration curves are non linear, in the region of lower velocities, Figure 2.2. At the lower velocities the viscous effects become significant and bearing friction becomes relatively more important.

The effects of the friction in the bearings of the rotor and the variation of drag with Reynolds number are not analytically determinable. Consequently the net effect must be found experimentally.

3.0 DIMENSIONAL CONSIDERATIONS

The variables which govern the operation of a current meter and are of importance in this treatment can be grouped under the following headings:

Fluid Characteristics:

ρ	= density of the fluid	$[ML^{-3}]$
μ	= dynamic viscosity	$[ML^{-1}T^{-1}]$
V	= average velocity	$[LT^{-1}]$
$\bar{u}^2$	= turbulence as root mean square of turbulence velocity fluctuations	$[LT^{-1}]$

Meter Characteristics:

N	= rate of revolutions of the rotor	$[T^{-1}]$
D	= effective diameter of the rotor	$[L]$
R	= resisting torque due to contacts,gears and bearing friction	$[ML^2T^{-2}]$
C_t	= long term conditioning factor	$[M^0L^0T^0]$
C_x	= geometric conditioning factor	$[M^0L^0T^0]$

Earth:

g	= acceleration due to gravity	$[LT^{-2}]$

The essence of this study is to account separately for the effects of the fluid, namely, density ρ and viscosity μ on the meter rotation. This can be conveniently done by choosing the variables D, V, R as the characteristic variables. Then N, the dependent variable, may be expressed in dimensionless form as

$$\frac{ND}{V} = \phi\left[\frac{\rho V^2 D^3}{R}, \frac{\mu VD}{R}, \frac{\sqrt{\overline{u^2}}}{V}, \frac{V}{\sqrt{gD}}, C_t, C_x\right] \quad \ldots\ldots\ldots \quad 3.1$$

The effect of gravity will have a negligible effect as long as surface waves do not affect the motion of the rotor. Therefore the Froude number $V/\sqrt{gD}$ may be omitted from further consideration. Schubauer and Mason (1937) have found that the effect of turbulence on the Price meter when rated in air is not significant. Calibration in a wind tunnel with a relative turbulence of 0.85 and 2.7 percent, with everything else unchanged, resulted in no significant change in calibration curves. Turbulence effects in the towing tank can be kept at virtually insignificant levels by having appropriate waiting times betweeen successive speed runs. Consequently the term $\frac{\sqrt{\overline{u^2}}}{V}$ may be dropped from equation 3.1. The conditioning factor C_t accounts for changes in the meter such as deterioration of lubricating oils, accumulation of marine growth etc. These conditions occur over a long period of time and with proper maintenance of the meter can be considered to be negligible. The conditioning factor C_x accounts for changes in geometry of the meter which are reflected in a change of the overall resisting torque. This includes damage to the rotor and changes in the geometry of the bearings. Significant damage to the rotor is usually an instantaneous event which can be detected and the meter repaired. It is therefore of no concern here. Changes in the geometry of the bearings is due to the wear of the meter and is the reason for regular maintenance and calibration checks. Changes in bearing geometry would cause changes in the resistance R which would otherwise be constant for a given meter. However, proper procedure such as "running in" of the meters prior to calibration will make this effect also negligible.

Upon comparison with equation 2.5 it is now clear that the calibration coefficient k may be written as

$$k = \frac{ND}{V} = \phi_1 \left[\frac{\rho V^2 D^3}{R}, \frac{\mu DV}{R}\right] = \phi_1 \left[\pi_1, \pi_2\right] \quad \ldots\ldots\ldots\ldots\ldots 3.2$$

Equation 3.2 uniquely accounts for the effects of the fluid properties. The π_1 term represents the effects of the fluid density whereas the π_2 term denotes the effects of the fluid viscosity.

The relative importance of the density and viscosity as well as the nature of the function ϕ_1 is determined by rating the current meters both in air and water.

4.0 EXPERIMENTAL PROCEDURE

Three current meters of the Price 622AA type were repaired and lubricated in a manner routinely applied to all such meters. Prior to calibration in the towing tank the meters were hung in a wind box where they were "run in" over an 8 hour period to ensure that the bearing geometry remained sensibly constant during the experiments. The meters were then rated in water and air without further adjustments.

4.1 Calibration in Water

The meters were calibrated simultaneously in a large towing tank, 122 m long, 5 m wide and 3 m deep. The towing carriage was capable of providing speeds from 0.5 cm/sec to 600 cm/sec with better than ± 1 percent accuracy at any speed. The meters were hung at a depth of 60 cm using a standard 30 Lb (14 Kg) weight - cable suspension, spacing them so that there would be no effects from the tank walls and no mutual interference. They were then calibrated over a speed range from 4.5 cm/sec to 500 cm/sec. The data were obtained through a Westinghouse data acquisition module, designed especially for current meter calibrations, which simultaneously recorded speed in cm/sec, revolutions of the rotors and time in seconds on separate channels, Figure 4.1.

4.2 Calibrations in Air

Calibrations in air were done in a wind tunnel 20 m long, 2.5 m wide and 1.8 m high. The air was circulated by an exhaust fan which drew the air through the length of the tunnel after it passed through a honeycomb screen at the entrance of the working section. The meters were hung with the same suspension used for the water calibrations, three at a time which allowed enough spacing to avoid any mutual interference and wall effects, Figure 4.2. The location of the meters was 3 m downstream from the honeycomb screen.

The air velocity was measured over a range of 280 cm/sec to 1400 cm/sec using the differential air pressure through static ports in the side of the tunnel just ahead of the suspended meters. The pressure was measured with a Betz micro-manometer which could be interpreted to 0.10 mm. The revolutions of the rotors and the time in seconds were obtained with a mechanical counter and electric timer connected in series. A strobe light was used to monitor the rotors of the meters through the observation window to ensure that their rotation was uniform and as a check for the mechanical revolution counter. Air temperature was recorded with a Digitech thermometer fitted with a YSI air probe which had a range of - $30^{\circ}C$ to $50^{\circ}C$. Relative humidity in percent was obtained using a Humeter with electronic humidity sensor. Atmospheric pressure was measured in millibars with a Fuess aneroid barometer. The instruments are given in Figure 4.3.

Tables provided by the Atmospheric Environment Service were used to make adjustments in air density to compute the true velocity of the air stream passing the current meters.

5.0 EVALUATION OF THE ϕ FUNCTION

To evaluate the function in equation 3.2 the ratings of the three Price 622AA current meters, both in air and water, were averaged in order to produce representative curves for this type of instrument, Figure 5.1. This figure illustrates the differences in the characteristic curves when fluid properties are not taken into account. The data are given in Tables 5.1 a and 5.1b.

The value of R in equation 3.2 is difficult to measure and for practical purposes here it is not necessary since R is constant for a given meter. It is convenient therefore to "lump" all constant values together into one constant which allows equation 3.2 to be written in the form of

$$\frac{ND}{V} = \phi_2 \; [\rho V^2, \; \mu V] \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 5.1$$

The effective pitch $\frac{ND}{V}$ is now plotted as a function of ρV^2, Figure 5.2a. It can be clearly seen that the curves for air and water are coincident over the entire range of plotted data. The term μV, although it has a different value for each plotted point does not affect the relationship of $\frac{ND}{V}$ vs ρV^2. This can be interpreted to mean that the viscosity has no effect on the relationship. The departure of the curves as given in Figure 5.1 is due only to the effects of the fluid density ρ. Hence equation 5.1 may be written as

$$\frac{ND}{V} = \phi_3 \; [\rho V^2] \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 5.2$$

Equation 5.2 completely defines the calibration. It does not matter whether a rating is done in air or in water or any other Newtonian fluid as long as the function ϕ can be determined over the range of velocities one is interested in.

The value of $\frac{ND}{V}$ increases with ρV^2 until a value of approximately 900 is reached. Above this value of ρV^2, $\frac{ND}{V}$ is sensibly constant and hence N varies linearly with V. These results are confirmed by data from Schubauer and Mason (1937) from an old model Price meter, Figure 5.2b.

The fact that the effective pitch $\frac{ND}{V}$ is not dependent on viscosity does not mean that it is independent of the Reynolds number. This can be demonstrated by rearranging equation 5.2, after removing all inconvenient constant terms, into the form

$$\frac{ND}{V} = \phi_4 \left[\frac{VD\rho}{\mu}, \rho V^2\right] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad 5.3$$

where: $\frac{VD\rho}{\mu}$ = Reynolds number

It should be noted that the density ρ now appears in both independent variables.

The averaged data for the 622AA Price meters are now plotted in the form $\frac{ND}{V}$ vs $\frac{VD\rho}{\mu}$ in Figure 5.3a. It is clearly seen that the curves for air and water coincide in the region where Reynolds numbers are greater than approximately 4×10^4. Below Reynolds numbers of 4×10^4 the curves are non linear and do not coincide and the curves become increasingly divergent as the Reynolds number decreases. A similar result is obtained using data from Schubauer and Mason (1937), Figure 5.3b.

Figure 5.3 shows that the calibration of a current meter is independent of the Reynolds number when this exceeds 4×10^4. For the non-linear region the Reynolds number alone does not account for the effects of fluid properties since the rating curves for air and water do not coincide. This difference in the two curves is due to the effect of the term ρV^2 and therefore it is not a good idea to use the plot of $\frac{ND}{V}$ versus Reynolds number because different curves would be obtained for different fluids.

5.1 A Practical Calibration Equation

Although N is the dependent variable the form of equation 5.2 is not convenient for direct application as a calibration curve since it would have to be solved by trial and error. It is customary to give the rating curve as V vs N. It was seen in Figure 5.1 that plotting just V or N resulted in different curves for air and water. The difference has been shown to be the effect of fluid density and viscosity did not appear to have any effect. Based on these observations one can now write

$$N = f(V, D, \rho, R) \quad \ldots\ldots\ldots\ldots\ldots 5.4$$

which can be expressed in dimensionless for as

$$\frac{N\rho^{1/2}\, D^{5/2}}{R^{1/2}} = \phi_s \left[\frac{V\rho^{1/2}\, D^{3/2}}{R^{1/2}}\right] \quad \ldots\ldots\ldots\ldots\ldots 5.5$$

Therefore for a particular meter a plot of $N\sqrt{\rho}$ vs $V\sqrt{\rho}$ should give a single curve for different fluids.

The data for air and water are now plotted in the form $V\sqrt{\rho}$ vs $N\sqrt{\rho}$ in Figure 5.4. It can be seen that one single curve satisfactorily expresses the variation between N and V.

Since such good agreement exists when applying the relationship of equation 5.5 to such vastly different fluids as air and water then it may be considered to be a Universal Calibration Equation for the Price meter for all Newtonian fluids. Such an equation is unique for a given meter and is universal in the sense that it accounts completely for the effects of fluid properties.

6.0 EFFECT OF FLUID PROPERTIES ON ACCURACY OF VELOCITY MEASUREMENT IN WATER

Current meters can be calibrated with a high degree of accuracy. Anderson (1961) found that calibrations at the Taylor model Basin and Colorado State University had variations of less than 1 percent for any one meter. Wood (1944) notes that calibrations at the American National Bureau of Standards were accurate to within 1 percent. Calibrations in the towing tank of the Hydraulics Research Division have a standard error of less than 0.5 cm/sec. For velocities greater than 45 cm/sec ratings are repeatable to within 0.5 percent. For speeds less than this the uncertainty increases as shown in Figure 6.1 (Grindley, 1971). Any errors due to fluid properties should be within the accuracy specified for a given calibration.

6.1 Errors Due to Temperature Changes

Calibrations are usually done at water temperatures which are close to the ambient conditions of the indoor environment of the towing tank. The resultant calibration curve is often applied under conditions where water temperatures are as much as 16°C lower than at the time of calibration.

The effect of the fluid manifests itself through the density as shown by equation 5.2. However the density is also a function of temperature and hence equation 5.2 can be more generally expressed as

$$\frac{ND}{V} = \phi_3 \left[\rho(\theta)V^2\right] \quad \ldots\ldots 6.1$$

where θ = temperature

For water $\rho(\theta)$ is practically constant over the temperature range of interest and hence temperature effects may be considered to be negligible. This is confirmed by the data of Robson (1954) who found that there was no change in velocities calculated to two decimal places over a speed range of 0.15 ft/sec (4.3 cm/sec) to 8.0 ft/sec (244 cm/sec) and a temperature change of 14°C.

6.2 Error due to the change in Fluid

Meters are calibrated in fresh water and then are often used to measure currents in salt water, discharges in mine tailings and other fluids of density greater than fresh water. Since $\frac{ND}{V}$ has been found to be a function of ρV^2, then the value of N for a given velocity depends on ρ. Since the change in the value of ρ for normal useage in water measurements is very small (ie. fresh water to salt water), then the effect of density is negligible. The magnitude of density change, expressed as density ratios, which result in a velocity error of 1 percent are given in Figure 6.2. It can be seen that for the normal density changes, such as going from fresh water to salt water, the effects on measurement accuracy are not significant.

7.0 APPLICATION OF UNIVERSAL CALIBRATION EQUATION

7.1 Calibration of Current Meters in Air

Towing tank facilities are relatively rare and often remote from project locations making it sometimes inconvenient to send current meters for calibration checks, especially if the number of meters available to a user are limited and time is an important factor. Under such circumstances calibration curves could be verified using a wind tunnel which may be more accessible in many cases. For this purpose the Universal Calibration Curve is a convenient tool. The meter calibration is verified if the wind tunnel data plot with acceptable accuracy on a curve such as in Figure 5.4, previously established by rating the meter in a towing tank. If the calibration is not verified the user may elect to repair the meter and have it re-calibrated in a towing tank facility.

The problem in using this method of verification is that it is difficult to accurately measure low velocities in wind tunnels in order to define the nonlinear segment of the calibration curve. It is necessary that a wind tunnel can be operated reliably to velocities as low as 150 cm/sec.

Current meter calibrations in air could be useful for meters used in oceanographic and lake surveys. These meters are often designed to record data over a period of several months with velocities recorded at intervals of several minutes on magnetic tape. In a towing tank the time at which a meter may be towed at a given velocity in the higher velocity range is limited by the length of the towing tank. Since most meters of the oceanographic type record velocities at 10 minute intervals it is awkward to calibrate these instruments directly with their data acquisition systems. But in a wind tunnel, a current meter can be subjected to a specific flow velocity for any desired length of time, thereby ensuring an adequate data sample on the magnetic tape. However, calibrations at low velocities remain a problem.

7.2 Calibration of Anemometers in Water

Anemometers are used by the Canada Department of Atmospheric Environment and similar agencies to measure the velocity of wind. Such instruments are usually calibrated in a wind tunnel but, as indicated in Section 6.2 it is often difficult to achieve accurate measurements of low velocities in a tunnel. If this is the case it would be useful to calibrate such anemometers for low velocities in an accurate towing tank facility such as the one at the Canada Centre for Inland Waters. The calibration in water is conducted until velocities are reached which are high enough to provide a sufficient overlap of the water-air data on the $V\sqrt{\rho}$ vs $N\sqrt{\rho}$ curve.

8.0 CONCLUSIONS

8.1 Theoretical and Empirical methods have been used to develop a Universal Calibration Equation. Such an equation is unique for a given meter and is universal in the sense that it takes into account the properties of the fluid.

8.2 The analysis indicates that for a current meter with a given bearing resistance the calibration coefficient k is a function of the fluid density.

8.3 Normal changes in temperature in water do not affect the accuracy of velocity measurements significantly.

8.4 Changes in density such as from fresh water to salt water affect measurement accuracy only slightly. The errors incurred are well within the accuracy usually attainable in the calibration of a current meter.

8.5 The results obtained using a Price meter are applicable in principle to other meters which use rotors or dynamic impact to record velocities.

8.6 The Universal Calibration Curve makes it possible to use a wind tunnel to verify calibrations made in a towing tank.

8.7 The Universal Calibration Curve could be used to calibrate anemometers in a towing tank.

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TABLE 5.1a

EXPERIMENTAL DATA SUMMARY FOR WATER

ρ = 1gm/cm^2 D = 7.62 cm μ = 1.011 x 10^{-2} gm/cm/sec

V cm/sec	N rev/sec	$\frac{ND}{V}$	$\rho V^2 \times 10^{-3}$ gm/cm	$V\sqrt{\rho}$ gm$^{1/2}$/cm$^{1/2}$/sec	$N\sqrt{\rho}$ rev gm$^{1/2}$/cm$^{3/2}$/sec
4.00	0.045	0.086	0.0160	4.00	0.045
5.18	0.060	0.088	0.0268	5.18	0.060
6.00	0.077	0.098	0.0360	6.00	0.077
7.08	0.092	0.099	0.0501	7.08	0.092
8.01	0.110	0.105	0.0642	8.01	0.110
9.02	0.122	0.103	0.0814	9.02	0.122
10.07	0.150	0.114	0.1014	10.07	0.150
15.08	0.224	0.113	0.2274	15.08	0.224
20.03	0.295	0.112	0.4012	20.03	0.295
25.07	0.374	0.113	0.6285	25.07	0.374
30.04	0.448	0.114	0.9024	30.04	0.448
40.01	0.600	0.114	1.601	40.01	0.600
50.01	0.750	0.114	2.501	50.01	0.750
60.02	0.882	0.112	3.602	60.02	0.882
69.96	1.025	0.112	4.894	70.00	1.025
79.59	1.172	0.113	6.335	79.60	1.177
90.07	1.333	0.113	8.113	90.07	1.333
100.02	1.475	0.112	10.004	100.02	1.475
124.28	1.777	0.109	15.446	124.28	1.777
150.00	2.218	0.113	22.500	150.00	2.218
175.07	2.593	0.113	30.650	175.07	2.593

TABLE 5.1a ....Cont'd.

EXPERIMENTAL DATA SUMMARY FOR WATER

ρ = 1gm/cm^2 D = 7.62 cm μ = 1.011 x 10^{-2} gm/cm/sec

V cm/sec	N rev/sec	$\frac{ND}{V}$	$\rho V^2 \times 10^{-3}$ gm/cm	$V\sqrt{\rho}$ gm$^{1/2}$/cm$^{1/2}$/sec	$N\sqrt{\rho}$ rev gm$^{1/2}$/cm$^{3/2}$/sec
199.28	2.956	0.113	39.952	199.88	2.956
223.36	3.321	0.113	49.890	223.36	3.321
250.012	3.701	0.113	62.506	250.01	3.701
300.02	4.469	0.113	90.012	300.02	4.469
400.91	5.919	0.113	160.729	400.91	5.919
500.40	7.426	0.113	250.490	500.79	7.426

TABLE 5.1b

EXPERIMENTAL DATA SUMMARY FOR AIR

ρ = 1gm/cm^2 D = 7.62 cm μ = 1.011 x 10^{-2} gm/cm/sec

V cm/sec	N rev/sec	$\frac{ND}{V}$	$\rho V^2 \times 10^{-3}$ gm/cm	$V\sqrt{\rho}$ gm$^{1/2}$/cm$^{1/2}$ /sec	$N\sqrt{\rho}$ rev gm $^{1/2}$ /cm$^{3/2}$/sec
194.8	2.556	0.100	0.0449	6.70	0.088
235.5	3.245	0.105	0.0657	8.1	0.112
294.11	4.170	0.108	0.1024	10.12	0.143
364.97	5.300	0.111	0.1577	12.50	0.182
430.14	6.343	0.112	0.2191	14.80	0.218
488.23	7.352	0.115	0.2822	16.80	0.253
547.84	8.330	0.116	0.3554	18.85	0.287
609.59	9.167	0.115	0.4400	20.97	0.315
677.72	10.125	0.114	0.5438	23.29	0.348
733.72	10.976	0.114	0.6374	25.24	0.378
797.94	11.961	0.115	0.7445	27.28	0.412
259.17	12.940	0.115	0.8740	29.56	0.445
916.52	13.819	0.115	0.9946	31.53	0.475
982.13	14.334	0.114	1.142	33.79	0.507
1037.63	15.567	0.114	1.275	35.70	0.536
1098.95	16.494	0.114	1.430	37.80	0.567
1169.35	17.534	0.114	1.619	40.23	0.635
1229.57	18.451	0.114	1.790	42.30	0.635
1379.50	20.583	0.114	2.253	47.46	0.708

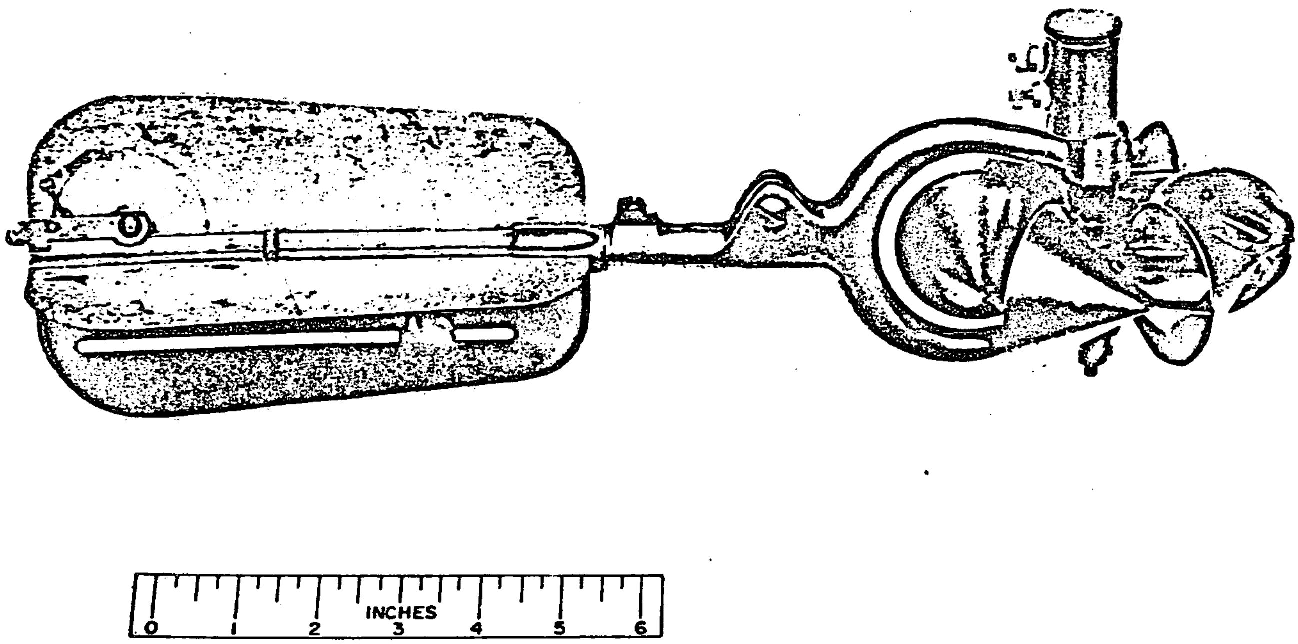


FIGURE 1·1 PRICE No.622AA CURRENT METER

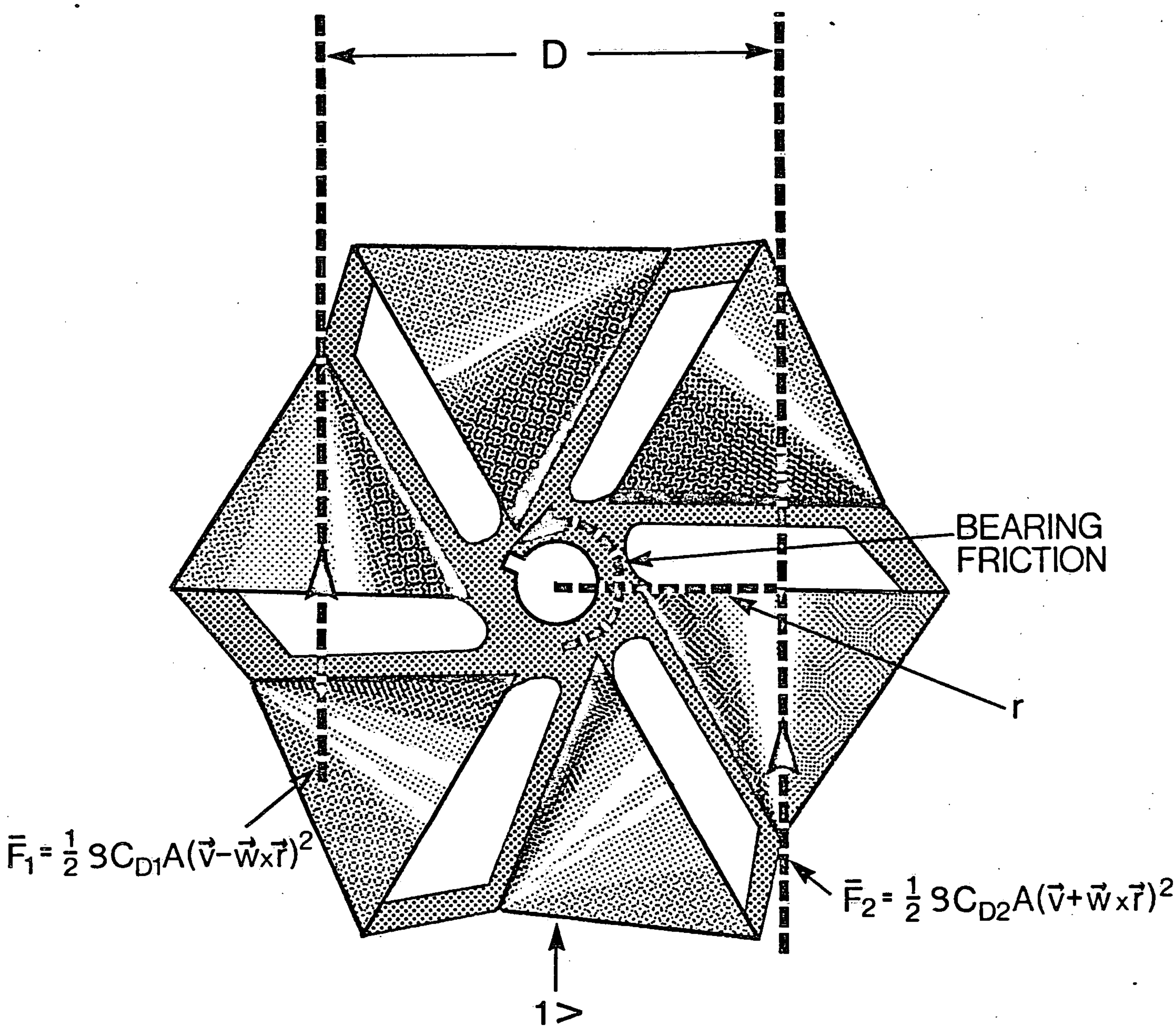
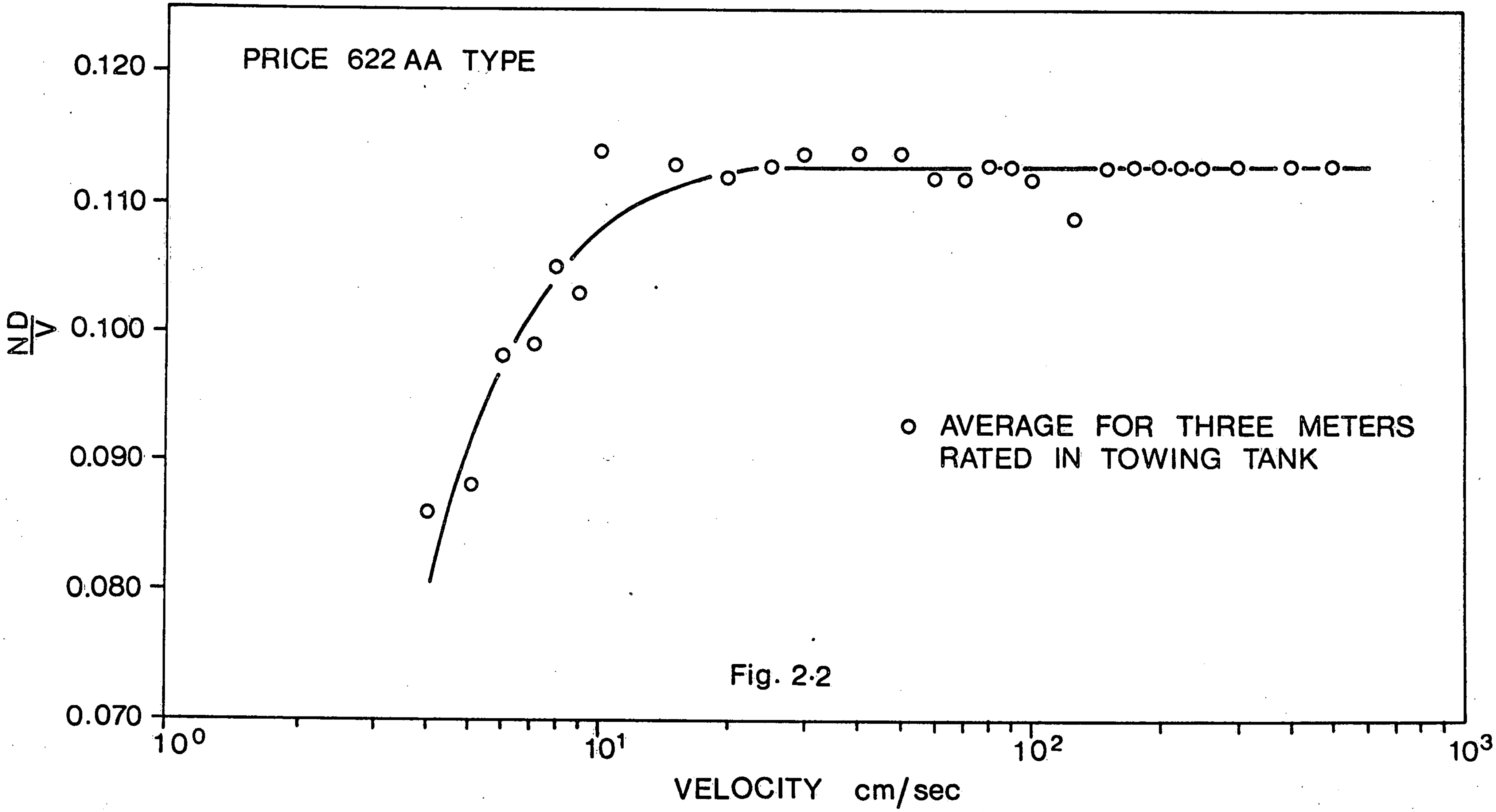


FIGURE 2-1 FORCES ACTING ON ROTOR



TYPICAL CURRENT METER CHARACTERISTICS CURVE

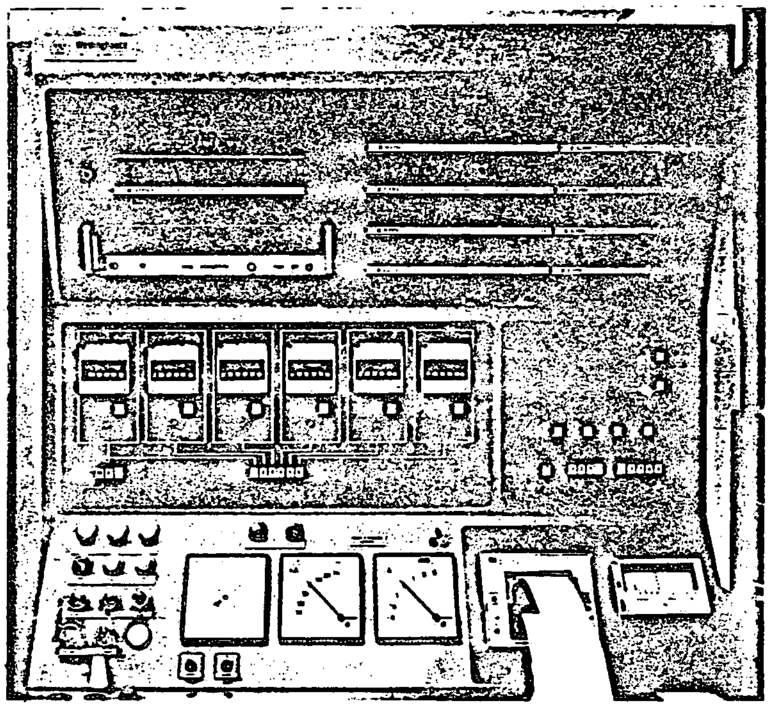


FIGURE 4·1 DATA ACQUISITION MODULE FOR TOWING CARRIAGE

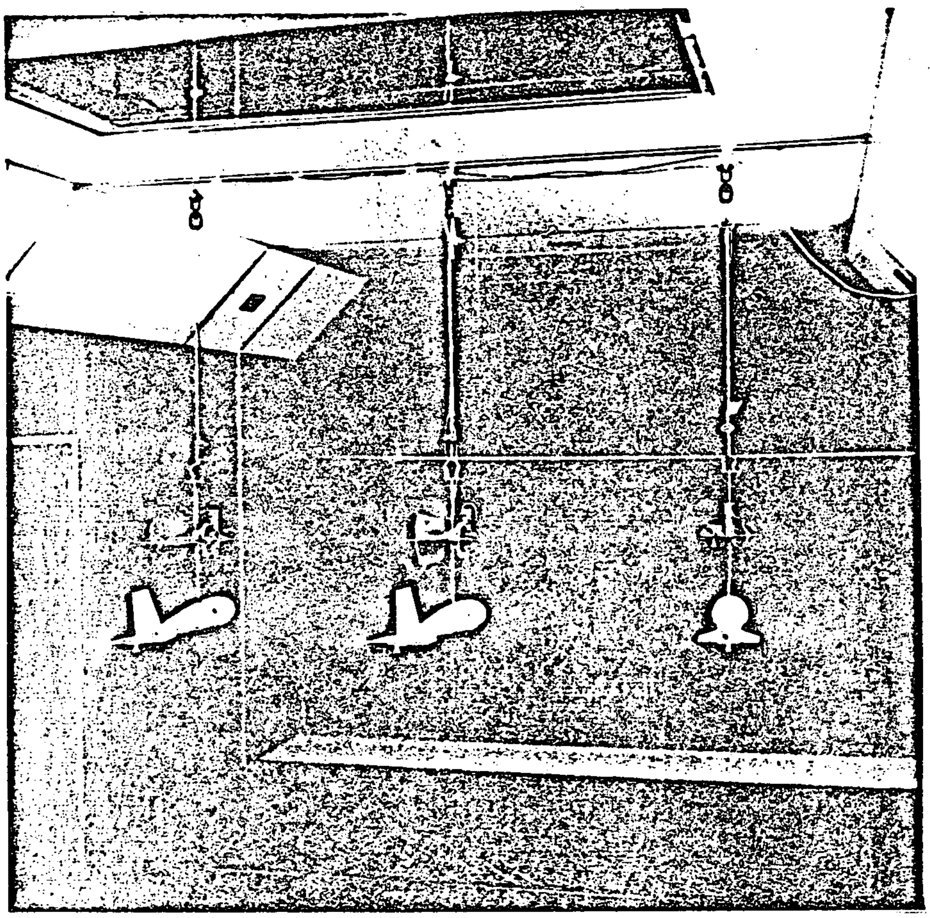


FIGURE 4·2 SUSPENSION OF PRICE METERS IN WIND TUNNEL

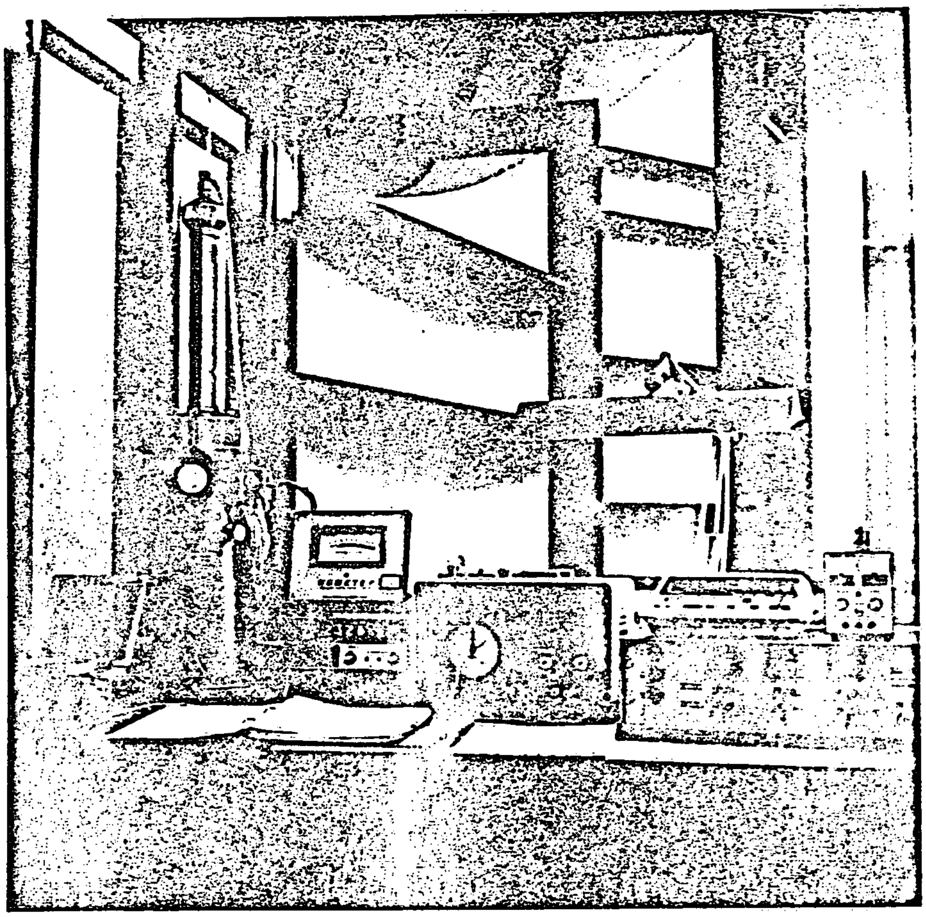
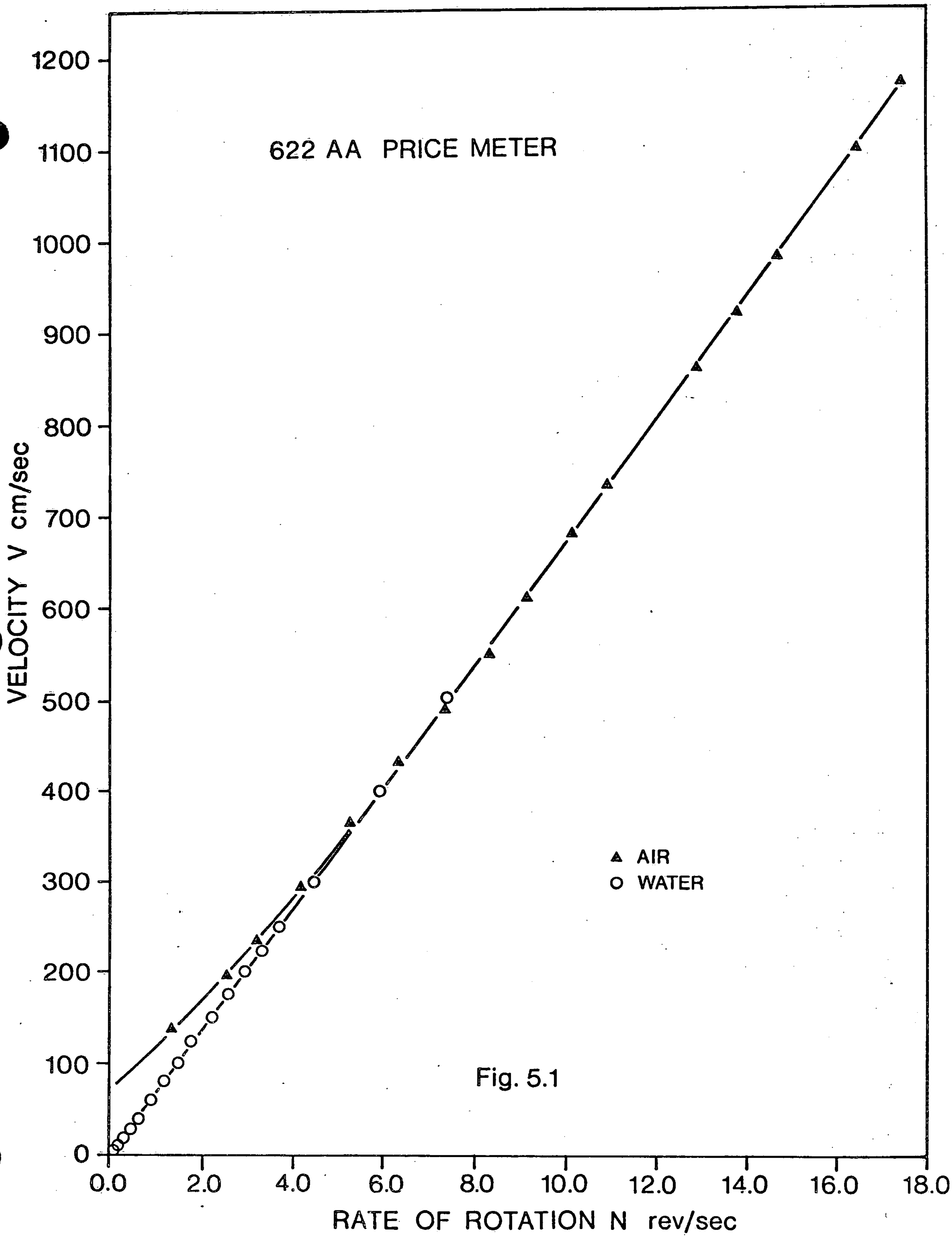


FIGURE 4·3 INSTRUMENTS TO RATE PRICE
METERS IN WIND TUNNEL



TYPICAL CALIBRATION CURVE FOR WATER AND AIR

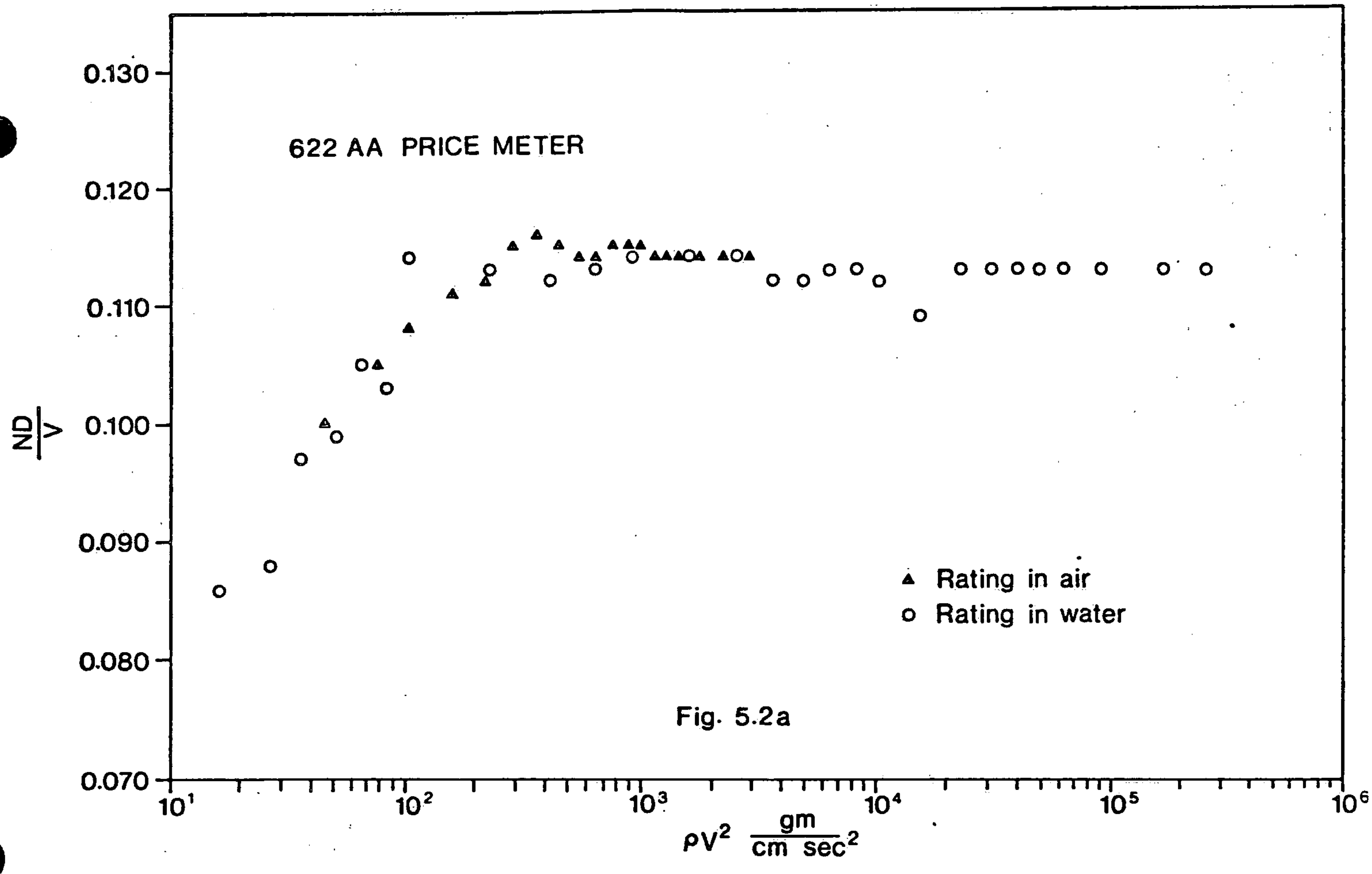


Fig. 5.2a

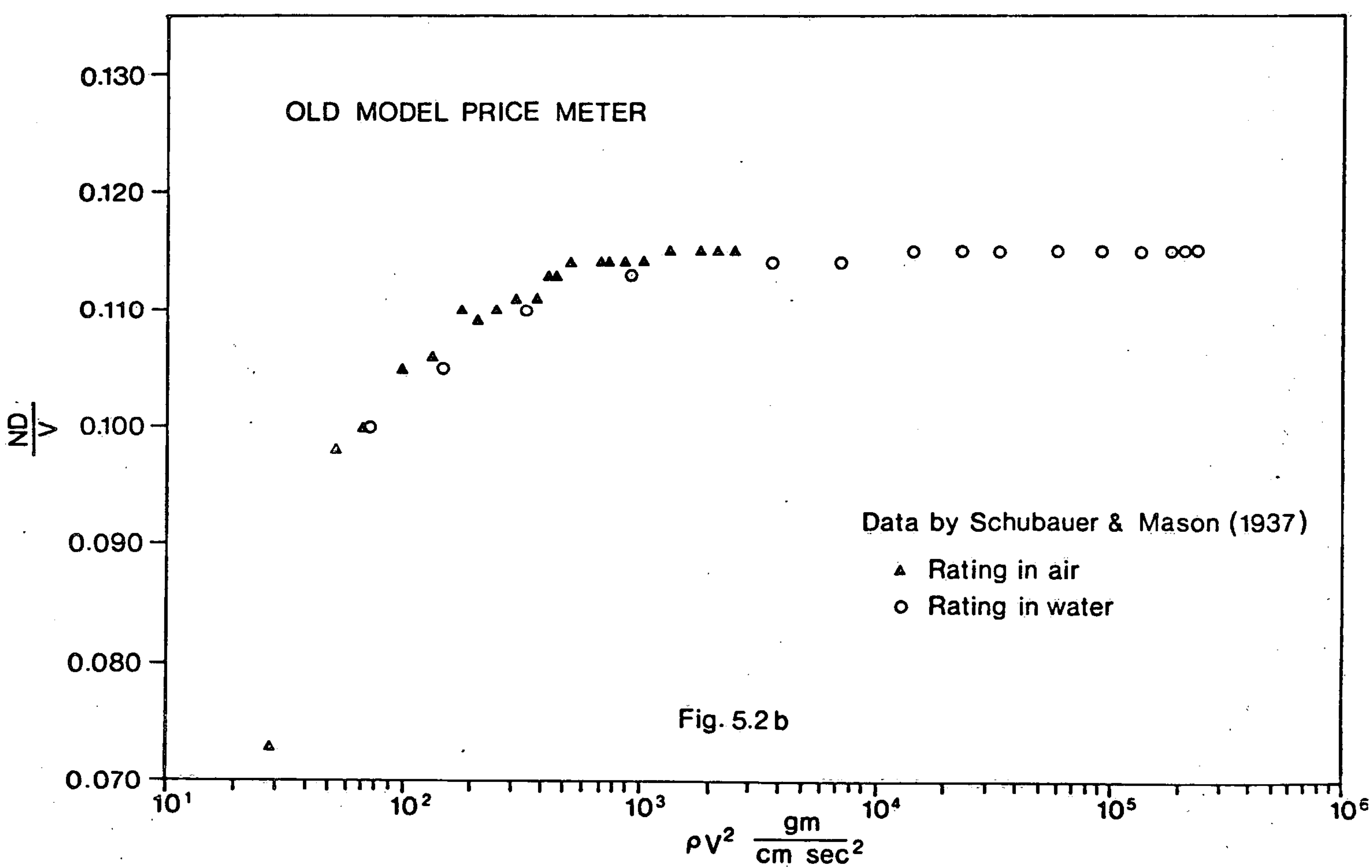


Fig. 5.2 b

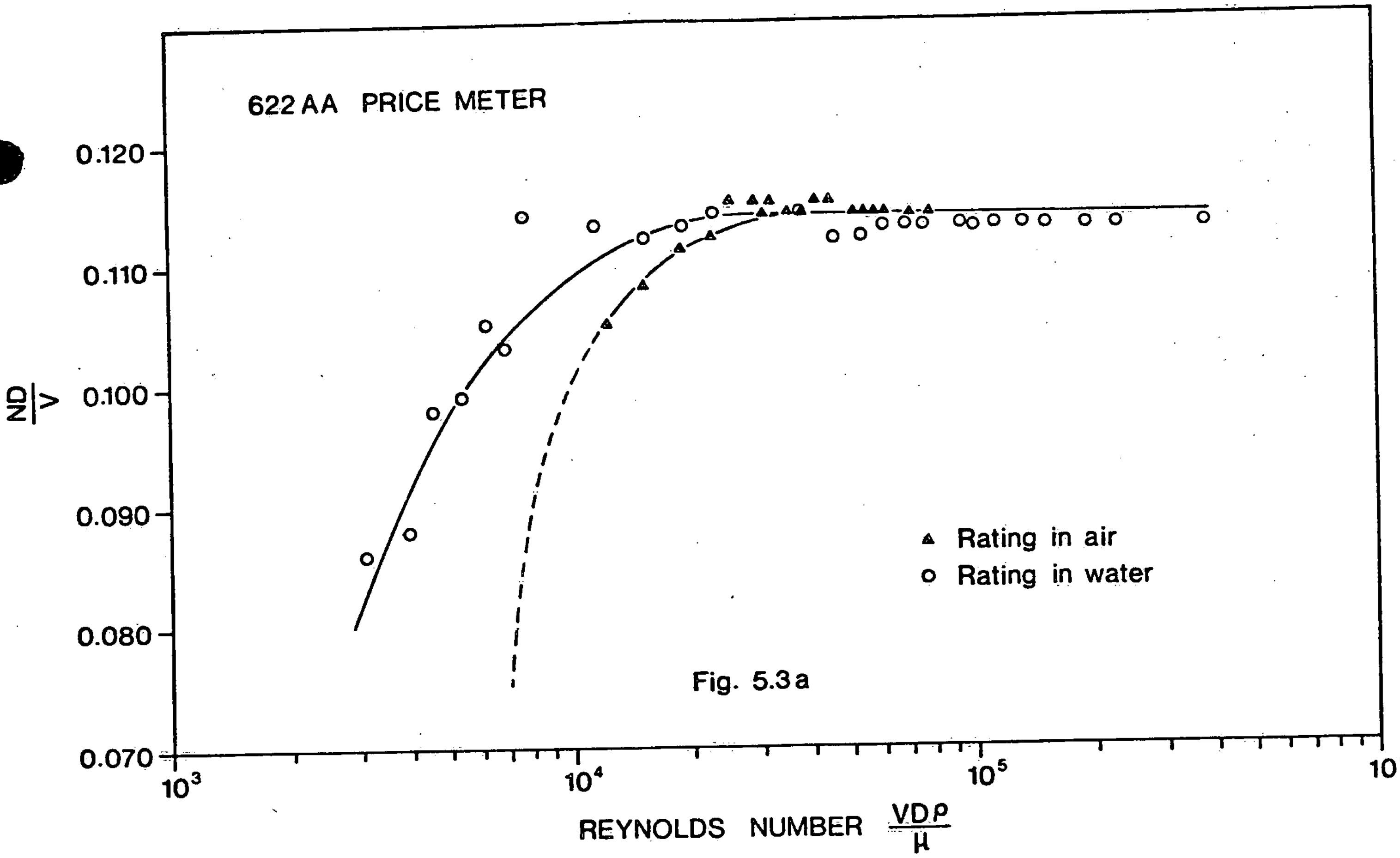


Fig. 5.3 a

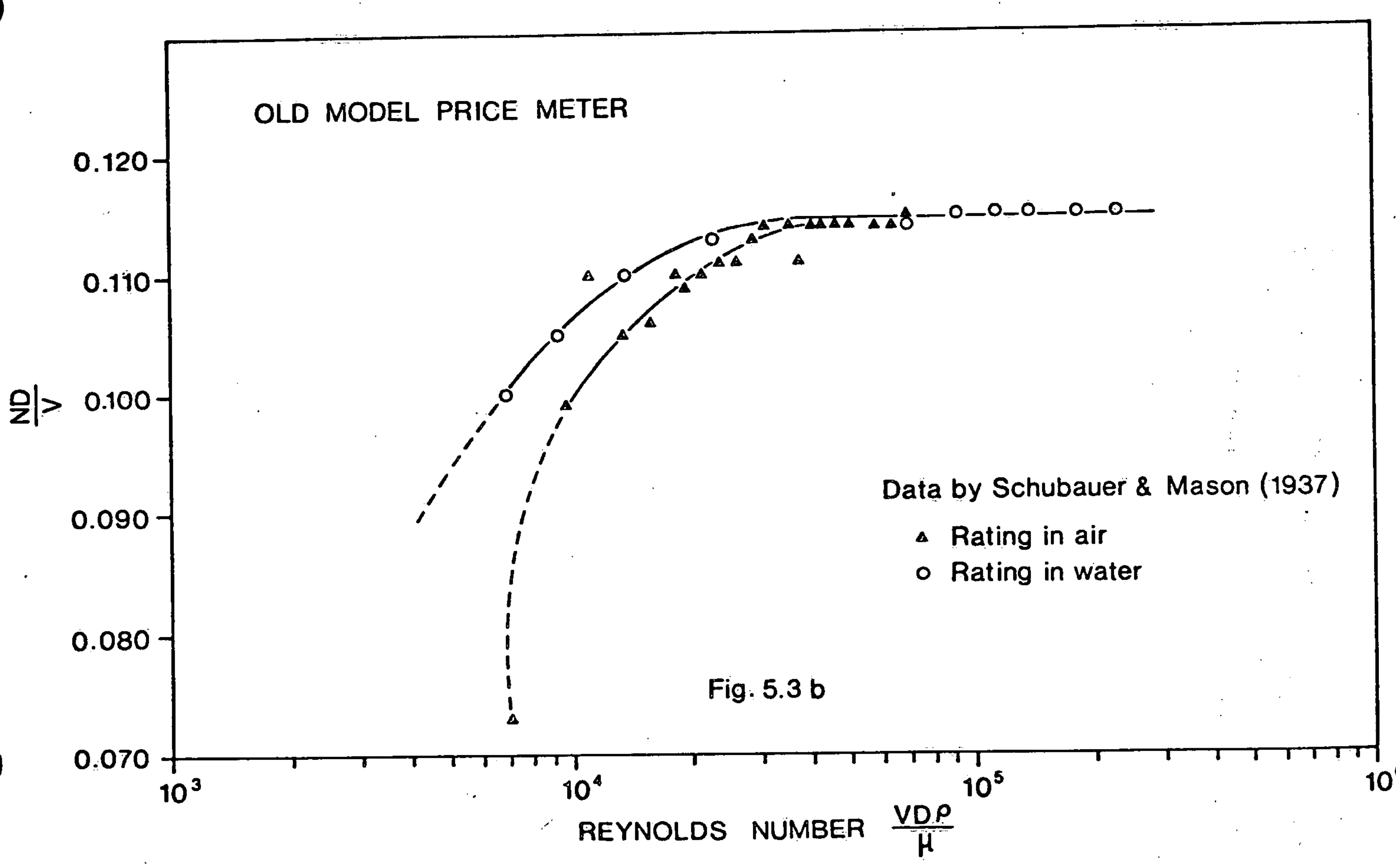
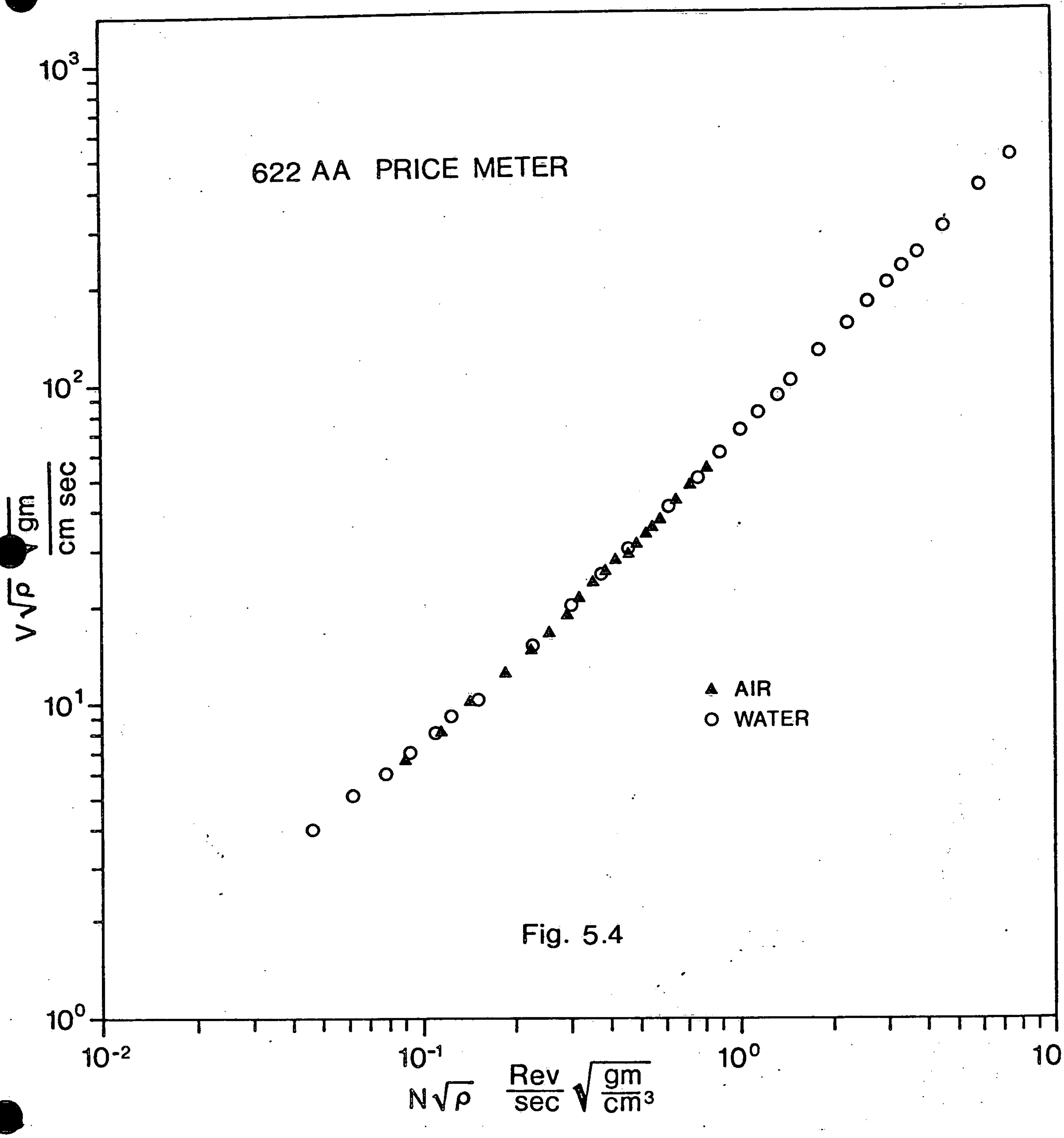
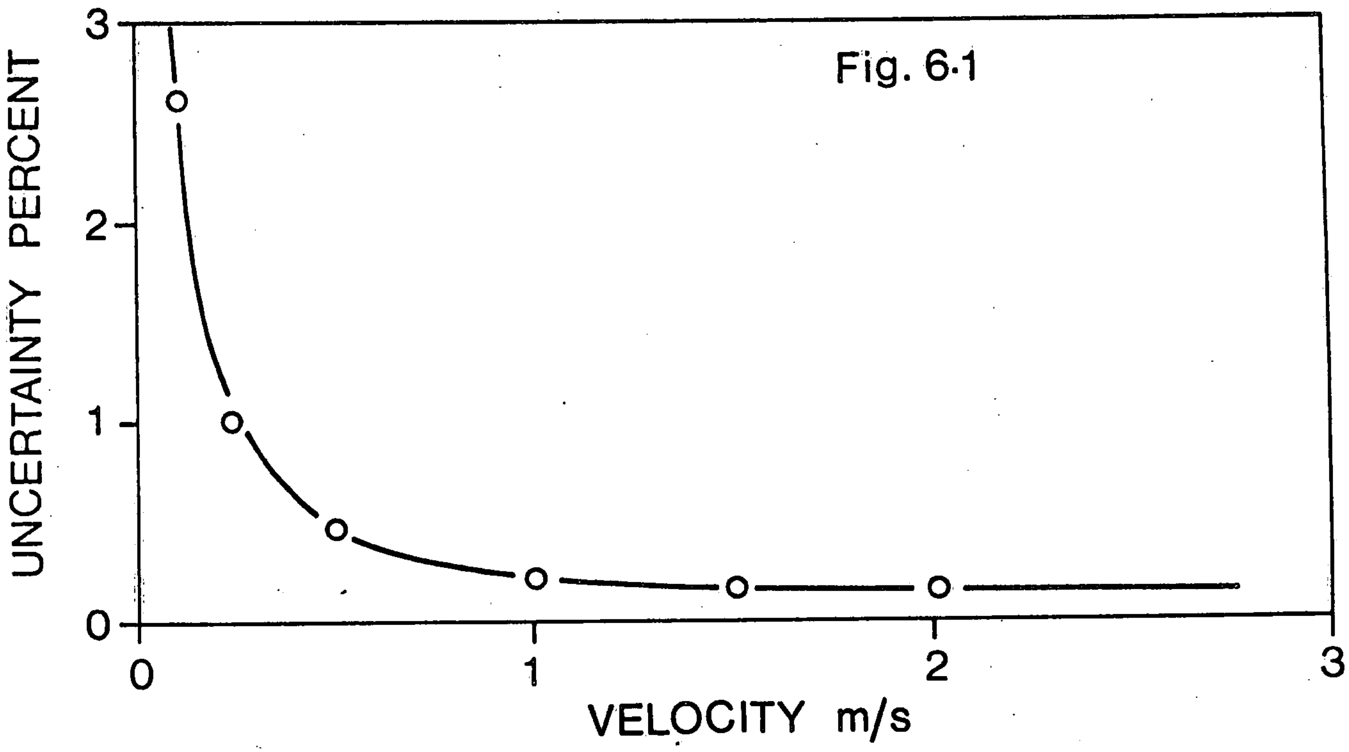


Fig. 5.3 b

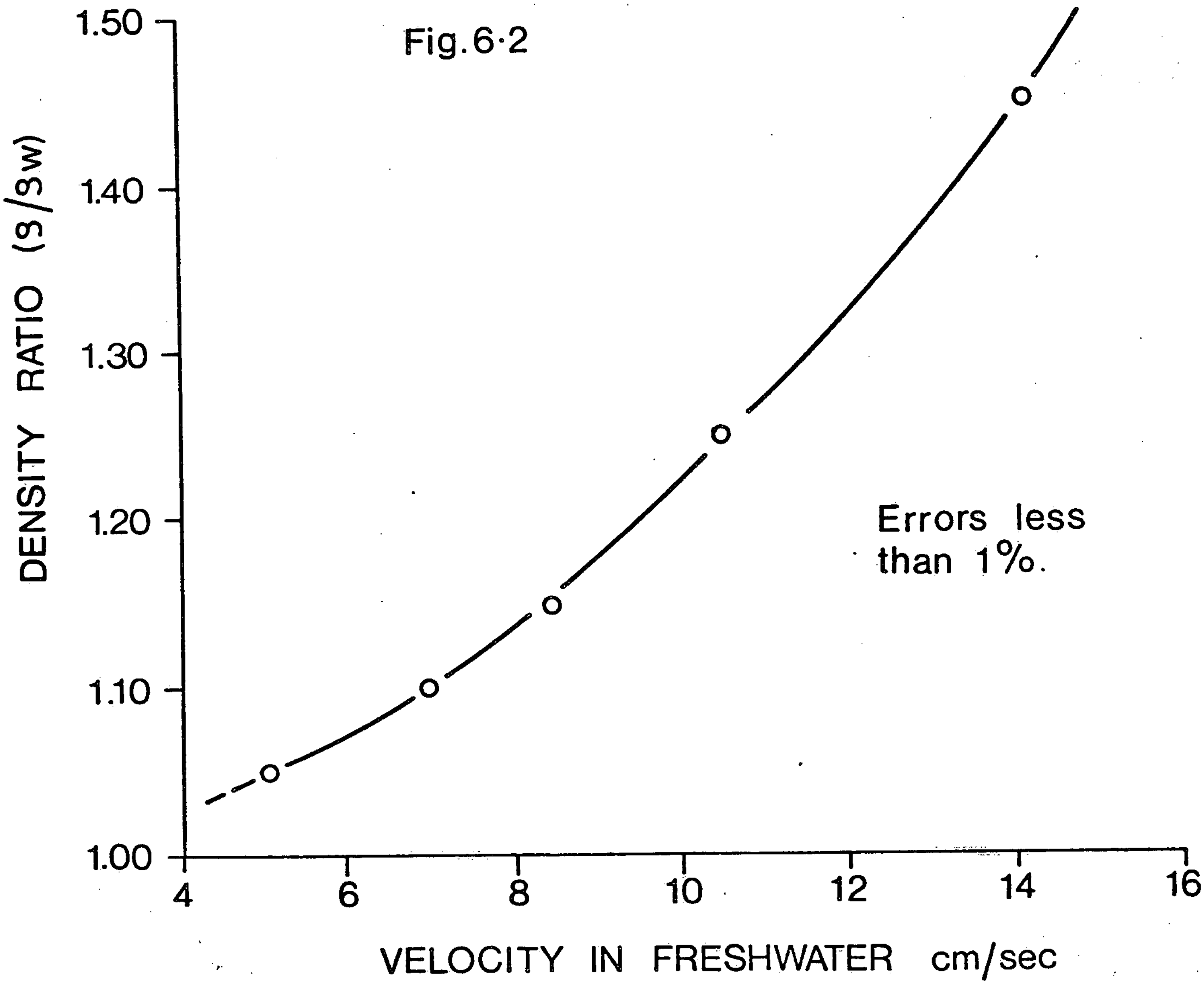
INFLUENCE OF REYNOLDS NUMBER ON CALIBRATION EQUATION



UNIVERSAL CALIBRATION CURVE



REPEATABILITY OF CALIBRATION OF PRICE CURRENT METER, (after Grindley 1971)



1% ERROR DUE TO FLUID DENSITY GREATER THAN FRESH WATER ($\rho_w = 1.0\ gm/cm^3$)