NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL de RECHERCHE sur les EAUX

PRELIMINARY EXAMINATION OF THE UNCERTAINTY IN THE REPEATABILITY OF PRICE METER CALIBRATIONS

Peter Engel

NWRI CONTRIBUTION 91-116

MANAGEMENT PERSPECTIVE

Increased awareness of river pollution and the importance of water quality monitoring has made it necessary to improve the accuracy of discharge measurements. One of the factors contributing to the error in a flow velocity measurement is the uncertainty in the current meter calibration itself. This uncertainty must be determined experimentally. In this report, repeated calibrations of ten Price winter current meters, obtained in the towing tank of the Hydraulics Laboratory at the National Water Research Institute, are examined to determine the uncertainty in their repeatability at the 99% confidence level. The results provide important information for the development of data quality control standards by the Water Survey of Canada for measurement of flow in rivers with solid ice cover.

PERSPECTIVE DE LA DIRECTION

En raison d'une sensibilisation accrue à la pollution des cours d'eau et à l'importance de la surveillance de la qualité de l'eau, il est nécessaire d'améliorer la précision des mesures du débit. L'un des facteurs responsables de l'erreur au niveau de la mesure de la vitesse du débit est l'incertitude de l'étalonnage du courantomètre lui-même. Cette incertitude doit être mesurée expérimentalement. Dans le cadre du présent rapport, des étalonnages répétés de dix courantomètres d'hiver de type Price, effectués dans le canal à chariot mobile du laboratoire d'hydraulique de l'Institut national de recherche sur les eaux, sont étudiés afin de déterminer l'incertitude de leur répétabilité pour un seuil de confiance de 99%. Les résultats fournissent des informations importantes pour la mise au point de normes pour le contrôle de la qualité des données par la Division des relevés hydrologiques du Canada pour la mesure du débit dans les rivières entièrement recouvertes de glace.

ABSTRACT

Ten Price winter meters were calibrated, each ten times, for a total of one hundred calibrations. The results show that the uncertainty in the repeatability is unexpectedly high, particularly for towing speeds less than 100 cm/s. The reason for this uncertainty is attributed to more persistent and higher residual velocities in the towing tank as a result of suspending four meters from the towing carriage at a time. Recommendations are made for additional tests to determine the effect of longer waiting periods between successive tows of the meters.

RÉSUMÉ

Dix courantomètres d'hiver de type Price ont été étalonnés, dix fois chacun, pour un total de cent étalonnages. Les résultats montrent que l'incertitude au niveau de la répétabilité est anormalement élevée, particulièrement dans le cas de vitesses du chariot mobile inférieures à 100 cm par seconde. Cette incertitude s'explique par des vitesses résiduelles plus élevées et plus persistantes dans le canal à chariot mobile en raison de la présence de quatre courantomètres suspendus au chariot en même temps. Des recommandations ont été formulées pour que d'autres essais soient effectués afin de déterminer l'effet de périodes d'attente plus longues entre les déplacements successifs des appareils.

TABLE OF CONTENTS

PRELIMINARY EXAMINATION OF THE UNCERTAINTY IN THE REPEATABILITY OF PRICE METER CALIBRATIONS

by

P. Engel

INTRODUCTION

Increased awareness of river pollution and the importance of water quality monitoring has made it necessary to improve the accuracy of discharge measurements. The determination of river discharge requires the measurement of the flow velocity. The velocity is measured by placing a meter into the flow and recording the rate of rotation of the rotor, usually in revolutions per second. The relationship between the linear velocity of the flow and the revolutions per second is determined by calibrating the meter in a towing tank. The current meter calibrations are normally expressed by some form of equation from which calibration tables are prepared for use in the field. One of the factors contributing to the error in a flow velocity measurement is the uncertainty in the current meter calibration itself (Smoot and Carter 1968). This uncertainty in the calibration is due to two reasons. Firstly, there is the uncertainty in the calibration data and secondly, there is the uncertainty due to the fit of the calibration equation to the calibration data. Before the uncertainty of the fit of the calibration equation can be considered, it is necessary to determine the uncertainty in the repeatability of the calibration data obtained in the towing tank.

In this report, repeated calibrations of ten Price winter current meters, obtained in the towing tank of the Hydraulics Laboratory (HL) at the National Water Research Institute (NWRI), are examined to determine the uncertainty in their repeatability at the 99% confidence level. The work was done for the Hydrometric Methods Section of the Water Survey of Canada (WSC) in Ottawa by the Research and Applications Branch (RAB) of NWRI in accordance with the R&D plan of the Committee for the Measurement of Flow Under Ice (MFUI).

PRELIMINARY CONSIDERATIONS

In developing a new calibration equation for the Price meter, it was shown by Engel (1989), that for a frictionless current meter, the dimensionless rotor response could be expressed as

$$\frac{ND}{V} = \frac{1}{\pi}[\frac{K-1}{K+1}] \tag{1}$$

where N = the rate of rotation of the rotor, D = the effective diameter of the rotor, V = the average flow velocity or towing speed, $K = \frac{C_{D1}}{C_{D2}}$, C_{D1} = the drag coefficient of the conical elements on the stoss-side and C_{D2} = the drag coefficient of the conical elements on the lee-side. The value of K must be determined experimentally.

Equation (1) reflects the typical response characteristics of the Price current meter in a two dimensional flow field if there is no frictional resistance in the bearings and other contact surfaces. ND/V is dependent only on the value of K which reflects primarily the shape and orientation of the conical elements of the rotor. The sensitivity of the meter is dependent on both D and K. The sensitivity can be increased by reducing D and increasing K because the rate of rotation of the rotor will be increased for a given value of the flow velocity. For a given meter the value of K and D are constant and a practical calibration equation is normally expressed in a form of V as a function of N. Therefore, equation (1) may be rearranged to give

$$V = \frac{D}{\pi}[\frac{K+1}{K-1}]N = AN \tag{2}$$

where A = the meter constant. Equation (2) is linear, with slope A and passes through the origin of a $V vs. N$ plot. Such a behaviour would be ideal for a current meter. It is known, however, that calibration curves are nonlinear, particularly in the region of lower velocities. This effect can best be illustrated with the plot of $ND/V vs. V$ in Figure 1. The average curve fitted to the data shows that the meter response is very nonlinear for velocities less than about 30 cm/s. For velocities greater than 30 cm/s the values of ND/V are approximately constant, indicating that the rotor response in this range tends to be linear. The non-linearity of the rotor response manifests itself in the standard $V vs. N$ format of the calibration plot by its departure from the curve for the frictionless meter as shown schematically in Figure 2.

The nonlinearity in the calibration equation is the result of frictional resistance due to the bearings and electrical contact brushes in the meter head, density of the fluid as well as possible effects of the meter yoke on the local flow field. The nonlinearity is not observable in a standard $V vs. N$ plot because of the scale that is normally adopted. However, the magnitude of the nonlinearity increases as the density of the fluid decreases. This was demonstrated by Engel (1976) who calibrated Price type current meters in both water and air, for which data are plotted in Figure 3. Curves fitted to the data show virtually no discernible nonlinearity when the fluid is water, whereas in the case of air, the nonlinearity is very pronounced. It is also interesting to note in Figure 3 that both curves merge into a single curve indicating that the meter behaves similarly in all Newtonian fluids in the range where the factors contributing to the nonlinearity become insignificantly small. A single, continuous calibration equation which combines the linear and the frictional components of the rotor response, was developed by Engel (1989) and is given as

$$V = AN + Be^{-KN} \tag{3}$$

where A, B and K are coefficients to be determined by calibration in a towing tank. The coefficient A accounts for the hydro-dynamic characteristics of the rotor as shown in equation (2), B acounts for the static friction of the rotor assembly and K accounts for the dynamic friction in the rotor assembly.

The dimensionless meter response $\frac{ND}{V}$, given in equation (1), may be regarded as a form of meter efficiency. It represents the number of rotations of the rotor per unit length of travel in the towing tank. For a given meter type, the rotor diameter D is constant and, therefore, for practical purposes, the meter efficiency may be designated as

$$N_* = \frac{N}{V} \tag{4}$$

where N_* denotes the meter efficiency. The meter efficiency, because of its sensitivity to changes in velocity, when the latter is less than about 60 cm/s, is used to examine the uncertainty in the repeatability of the Price winter meter calibration. Two types of uncertainty are considered. Firstly, the uncertainty in the mean efficiency of a given meter at selected speeds is examined to determine how well the average calibration for this type of meter can be determined. This information is of interest for the consideration of a single generic calibration equation for the Price winter meter. Secondly, the uncertainty in the repeatability of the meter efficiency at selected speeds is examined for each of the ten meters, to determine the quality of any given calibration of a Price winter meter. This information is required to establish realistic confidence limits for a generic calibration equation.

EXPERIMENTAL METHOD AND PROCEDURE

Towing Tank

The towing tank is constructed of reinforced concrete, is founded on piles and is 122 metres long and 5 metres wide. The full depth of the tank is 3 metres, of which 1.5 metres is below ground level. Normally the water depth is maintained at 2.7 metres. Concrete was chosen for its stability, vibration reduction and to minimize possible convection currents.

At one end of the tank is an overflow weir. Waves arising from towed current meters and their suspensions are washed over the crest, reducing wave reflections. Parallel to the sides of the tank perforated beaches serve to dampen lateral surface wave disturbances.

Towing Carriage

The carriage is 3 metres long, 5 metres wide,weighs 6 tonnes and travels on four precision machined steel wheels. The carriage is operated in three overlapping speed ranges:

0.5 cm/sec-6.0 cm/sec
5.0 cm/sec-60 cm/sec
50 cm/sec-600 cm/sec

The maximum speed of 600 cm/sec can be maintained for 12 seconds. Tachometer generators connected to the drive shafts emit a voltage signal proportional to the speed of the carriage. A feedback control system uses these signals as input to maintain constant speed during tests.

The average speed of the towing carriage is obtained by recording voltage pulses emitted from a measuring wheel. This wheel is attached to the frame of the towing carriage and travels on one of the towing tank rails, emittimg a pulse for each millimeter of travel. The pulse and measured time are collected and processed to produce an average towing speed with a micro computer data acquisition system. The accuracy of the measuring wheel is checked regularly by comparing its output over a distance of one meter against a calibrated metal bar, one metre in length (Quantum, 1981). Time is measured to an accuracy of 0.001% with a crystal clock which is calibrated with a standard clock at the National Research Council of Canada. Any errors in the computed towing carriage speed due to the measurement of time are therefore insignificant. Analysis of the towing speed variability by Engel (1989), showed that for speeds between 20 cm/s and 300 cm/s, the error in the mean speed was less than 0.15% at the 99% confidence level. Occasionally, these tolerances are exceeded as a result of irregular occurrences such as voltage "spikes" in the data transmission system of the towing carriage. Tests with such anomalies are automatically aborted.

Meter Suspension

The calibration tests were conducted using ten Price type winter meters, each fastened to a standard 20 mm diameter solid steel suspension rod. The meters were secured to the rods in accordance with standards used by the WSC for meters with rod suspensions. All meters were suspended 30 cm below the water surface. This depth was chosen to avoid surface effects and to create a minimum of drag on the suspension rods, thereby reducing undesirable vibrations. In all cases great care was taken that the meters were always aligned so that their longitudinal axis was parallel to the direction of travel of the towing carriage. Small deviations from true alignment, especially for velocities less than 30 cm/s do not affect the meter (Engel and Dezeeuw 1978) and therefore any uncertainty due to meter alignment can be considered to be insignificant.

Meter Preparation

Prior to testing each meter underwent the following inspection:

a) the penta gear was checked to ensure that it was operating freely;

b) the contact brushes were cleaned and adjusted for proper tension to provide good electrical contact;

c) all moving parts were lubricated;

Following the inspection, the meter was hung in a wind tunnel where it was spun for two hours to ensure that the bearings were properly "run in".

Test Procedure

A run of the towing carriage, with 4 meters mounted simultaneously, at a particular speed was defined as a test. To begin a set of tests each meter was carefully aligned in its specified position at the back of the towing carriage. The meters were then towed at preselected speeds. Tests were conducted beginning at velocities of 6 cm/s up to a maximum of 300 cm/s for a total of 20 tests per calibration. After each set of 20 tests, the meters were thoroughly inspected before the next set of tests was begun. Each time the meters were towed, care was taken that steady state conditions prevailed when measurements were recorded. The lengths of the waiting times between successive tests were in accordance with routine procedures used by the Nartional Calibration Service. For each test, the towing speed, revolutions of the meter rotors and the measuring time were recorded. Water temperatures were not noted because temperature changes during the tests were small and do not affect the performance of the meters (Engel, 1976). A total of 10 meters were calibrated. Each meter was calibrated 10 times, resulting in a total of 100 calibrations.

DATA ANALYSIS

Repeatability of Towing Speed

The determination of the uncertainty in the calibration of current meters at a given speed, in the strictest sense, requires that the towing speed can be repeated exactly. This is not achievable in practice and the best that can be hoped for is a mean speed with deviations as small as possible. This is particularly true for speeds less than 30 cm/s. The reason for this can be seen with reference to Figure 1. For $V < 30$, $\frac{ND}{V}$ becomes increasingly sensitive to changes in V as the latter decreases. The lowest nominal towing speed used for the present tests was 6 cm/s. Clearly, any deviations from the mean towing speed will have the greatest effect at this speed. The significance of the deviations decreases as the nominal towing speed increases. When $V > 30$, values of $\frac{ND}{V}$ are virtually independent of V and thus small deviations from the mean velocities are not so critical.

Typical mean towing speeds and their maximum deviations are given in Table 1. The deviations are expressed as percentage of the mean speed. The data in Table 1 show that the maximum percent deviation of less than 1% occurs at the lowest nominal speed of 6 cm/s. As the speed increases the percent deviation decreases until when $V \cong 30$ the deviations are no longer significant because $\frac{N_*}{V}$ is virtually constant for $V > 30$. The deviations from the mean towing speed in Table 1 are representative of all the tests conducted and their effects are considered to be small relative to other uncertainties in the calibration process.

Uncertainty in the Mean Calibration of a Meter

The true mean of the rotor efficiency N_* at each towing velocity can be expected to lie within the range

$$\mu_N = \overline{N}_* \pm \frac{t_N S_N}{\sqrt{n-1}} \tag{5}$$

where μ_N = the true mean value of N_*, $\overline{N}_*$ = the mean of n velocity coefficients obtained from the measured velocities at a given head in a particular set, t_N = the confidence coefficient from Student's "t" distribution at $(n-1)$ degrees of freedom (Spiegel 1961), S_N = the standard deviation and n = the number of tests at a particular velocity for a given meter (ie: n = 10). Equation (5) can be made dimensionless by dividing both sides by $\overline{N}_*$. In addition, by noting that the coefficient of variation, say, $K_N = \frac{S_N}{\overline{N}_*}$, one obtains

$$\frac{\mu_N}{\overline{N}_*} = 1 \pm \frac{t_N K_N}{\sqrt{n-1}} \tag{6}$$

The quantity $\frac{t_N K_N}{\sqrt{n-1}}$ in equation (6) represents the relative uncertainty of the meter efficiency obtained for n different calibrations of the same meter and is expressed as

$$E_m = \frac{100 t_N K_N}{\sqrt{n-1}} \tag{7}$$

where E_m is the relative uncertainty in the mean meter efficiency of a particular meter at a given velocity in percent. Values of E_m at the 99% confidence level were computed from the test data and are given in Tables 2 through 11. The original data are too extensive to be included in this report and can be obtained upon request.

The values of E_m in Tables 2 through 11 were plotted as a function of the towing speed V in Figures 4 and 5. The same smooth average curve was fitted to the plotted points in both figures to facilitate the analysis. The good fit shows that, on average, both sub-groups of meters behave very similarly. The uncertainty in determining the mean calibration for the Price meter, is highest at the lowest towing speed and decreases as the towing speed increases, with the rate of change decreasing, until when $V = 100$ cm/s, the rate of decrease in E_m is very small. At the lowest speed tested, the uncertainty at the 99% confidence level is as high a 6% and this decreases to about 0.5% for $V > 100$. The scatter in the plotted points about the average curve also increases as the speed decreases below values of 100 cm/s. The reason for this is not totally clear. Certainly, some of the scatter is attributable to frictional resistance in the meter assembly, which varies from meter to meter. Such errors are systematic and are unique for each meter. Some of the scatter is due to uncertainty in repeating the same towing speed. This is a random error and is small relative to other uncertainties. Probably the largest potential source of error is that due to residual movement of the water. Part of the difficulty may be caused by density currents and part by the disturbance of the previous test Grindley (1971). The relative effect of these sources is greatest at the lowest towing speed and decreases as the speed increases. This trend is reflected in the shape of the average curves in Figures 4 and 5.

The scatter in the plotted points clearly shows that for speeds less than 100 cm/s, the behaviour of each Price meter is quite unique. The impact of this behaviour on the development of a generic calibration equation needs to be determined.

Uncertainty in the Repeatability of a Single Meter Calibration

The meter efficiency at any velocity for a single meter can be expected to lie within the range

$$N_* = \overline{N}_* \pm t_N S_N \tag{8}$$

where all variables have already been defined. Equation (8) can be made dimensionless by dividing both sides by $\overline{N}_*$ and again noting that $K_N = \frac{S_N}{\overline{N}_*}$, one obtains

$$\frac{N_*}{\overline{N}_*} = 1 \pm t_N K_N \tag{9}$$

The product $t_N K_N$ in equation (9) represents the relative variability in the velocity coefficient for a single meter which is expressed as

$$E_s = 100 t_N K_N \tag{10}$$

where E_s is expressed in percent. Values of E_s at the 99% confidence level were computed from the test data and are also given in Tables 2 through 11. Once again, the original data are too extensive to be included in this report and can be obtained upon request.

Comparison of equations (7) and (10) shows that the uncertainty in the value of N_* for a single meter is greater than the uncertainty in determining $\overline{N}_*$ by a factor of $\sqrt{n-1}$. In all other respects, the behaviour of E_s is the same as E_m. For the present tests the value of n was 10 and therefore $E_s = 3.0E_m$. Values of E_s were plotted as a function of the towing speed V in Figures 6 and 7. Once again the same average curve was fitted to the plotted points in both figures to facilitate the analysis. The general behaviour of the curves is the same as that observed in Figures 4 and 5, except that the magnitudes of the uncertainties are three times larger.

The most noticable feature of Figures 6 and 7 is that E_s never reaches values less than 0.5%. This means that the calibration of a given Price winter meter cannot be repeated within ±0.5% at the 99% confidence level at any velocity at least up to 300 cm/s. At towing speeds of 6 cm/s, uncertainties E_s at the 99% confidence level are as high as 17%. Values of E_s do not reach a value of 1% until a towing speed of about 100 cm/s is reached. The implications of this is that any calibration of a given meter can differ from any other calibration of the same meter under the same conditions by as much ±1% for flow velocities at 100 cm/s to as much as ±17% or more at flow velocities of 6 cm/s. These uncertainties in current meter calibrations appear to be quite high, considering that the procedures were conducted with great care.

Tests conducted by Grindley (1971) on a new Price meter, rigidly suspended with the standard hanger bar, resulted in uncertainties at the 95% confidence level as shown in Table 12. In each case tests were repeated 10 times. It can be seen that uncertainties at about 8 cm/s are of the order of 3%. This translates into about 4.5% at the 99% confidence level which is considearbly lower than values from 8% to 12% shown in Figures 6 and 7 at the same speed. The reason for these differences needs to be addressed.

The greatest potential source of uncertainty at low speeds are residual currents (Grindley 1971). These velocities decay slowly and are most predominant at the low towing speeds. Routine procedures, used by the National Calibration Service, call for a waiting period between successive tests of 18 minutes at the lowest test speed of 6 cm/s and 3 minutes at the highest test speed of 300 cm/s. The waiting time decreases with towing speed because, as the towing speed increases, residual currents become relatively less important (Engel and Dezeeuw 1977). During performance tests of acoustic flow meters in the towing tank, Engel, Fast and Todd (1990) measured residual currents of 0.5 cm/s after a waiting period of 10 minutes. During these tests, two large transducers were towed through the water resulting in large scale disturbances in the towing tank. The present Price meter tests were conducted by towing four meters simultaneously. The disturbance created by the close proximity of the four meters may have resulted in residual velocities which persisted longer and thus longer waiting times between successive tests may be required. Tests should be conducted to determine the effect of waiting times when calibrating more than one meter at a time. The results may reveal the reason for the apparent large uncertainties shown in Figures 4, 5, 6 and 7.

CONCLUSIONS AND RECOMMENDATIONS

Calibrations of 10 different Price winter meters, repeated 10 times, has shown that the uncertainty in obtaining a calibration varies significantly for speeds less than 100 cm/s. As the speed decreases from 100 cm/s, the uncertainty increases with the rate of change increasing. The behaviour of all ten meters was very consistent and similar for speeds from about 100 cm/s to the maximum test speed of 300 cm/s. For speeds less than 100 cm/s, this similarity decreased with the differences becoming most pronounced at the lowest speed.

The uncertainty at the 99% confidence level in obtaining the mean calibration has a trend similar to that observed for single calibrations of the same meter. The mean calibration had an uncertainty as high as 6% at a speed of 6 cm/s, decreasing rapidly to a value of 0.5% at 100 cm/s. Thereafter, the uncertainty decreased gradually to a value of 0.4% at 300 cm/s.

The uncertainty at the 99% confidence level in the repeatability of any single calibration of the Price winter meter was significantly higher than results obtained for similar tests by others. The tests showed that any given calibration differed from any other calibration of the same meter, under identical conditions, by as much as ±17% when the towing speed is 6 cm/s to about ±0.5% at speeds of 300 cm/s.

Residual currents, as a result of disturbances created by towing the meters through the water, are thought to be the main reason for the large uncertainties obtained for the 10 Price winter meters tested. Calibrations of meters, suspended four at a time, may result in larger and more persistent residual velocity currents which may be the main cause for the high uncertainties observed, especially at the low speeds.

Tests should be conducted to determine the effect of longer waiting times between successive tows when four meters are suspended from the carriage at the same time. The results should be compared with existing information on the waiting times for the calibration of a single Price winter meter.

ACKNOWLEDGEMENT

The writer is grateful K. Wiebe of Water Survey of Canada and M.G. Skafel of the Hydraulics Laboratory for their careful review of the manuscript. The calibrations were conducted by B. Near and C. Bil of the Hydraulics Laboratory.

REFERENCES

Engel, P. 1976. A Universal Calibration Equation for Price Meters and Similar Instruments. Environment Canada, Inland Waters Directorate, Canada Centre for Inland Waters, Scientific Series No. 65.

Engel, P. and C. Dezeeuw 1977. Determination of Waiting Times Between Successive Runs when Calibrating Price 622 AA Type Current Meters in a Towing Tank. Technical Note, Hydraulisc Research Division, Canada Centre for Inland Waters, Burlington, Ontario.

Engel, P. and C. Dezeeuw 1978. The Effect of Horizontal Alignment on the Performance of the Price 622 AA Current Meter. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario.

Engel, P. 1989 a. A New Calibration Equation for Vertical Axis Current Meters. NWRI Contribution No. 89-131, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Canada.

Engel, P. 1989 b. Preliminary Examination of the Variability in the Towing Carriage Speed. NWRI Contribution 89 -89, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario, Canada.

Engel, P., E. Fast and J. Todd 1990. Towing Tests of the ACCUSONIC Acoustic Flow Meter. NWRI Contribution 90-142, National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario, Canada

Grindley, J. 1971 Behaviour and Calibration of Current Meters-Accuracy. Internal Report No. 95, Hydraulics Research Station, Wallingford, Berkshire, England.

Quantum 1981. Calibration Certificate No. 167-140, February. Quantum Dimensional Metrology Laboratory, Burlington, Ontario.

Smoot, G.F. and R.W. Carter 1968 Are Individual Current Meter Ratings Necessary?. Journal of the Hydraulics Division, ASCE, Vol. 94, No. HY2.

Spiegel, M.S. 1961. Theory and Problems of Statistics, Schaum Outline, Schaum Publishing Company, New York, New York, U.S.A.

Table 1
Deviations from Mean Towing Speed for Meter No. 6-226

V_m [cm/s]	$[V - V_m]$ [cm/s]	$[\frac{V-V_m}{V_m}]$ [%]
6.04	0.05	0.83
9.07	0.06	0.66
12.10	0.03	0.25
18.07	0.03	0.17
24.07	0.04	0.17
30.07	0.03	0.10
36.05	0.05	0.14
48.05	0.07	0.15
60.09	0.16	0.27
72.68	0.48	0.66
84.51	0.36	0.43
105.52	0.69	0.65
120.30	1.08	0.90
135.29	0.48	0.35
150.15	0.47	0.31
180.36	0.86	0.48
210.35	0.47	0.22
240.49	0.50	0.21
270.41	0.64	0.24
300.45	0.77	0.26

V_m = the mean towing speed for ten tests
V = the actual towing speed for a given test

TABLE 2
Calibration Data for Meter No. 6-226

V_n [cm/s]	$\overline{N}_*$ [$rev./m$]	S_N [$rev./m$]	E_s [%]	E_m [%]
6.0	1.1547	0.0554	15.59	5.20
9.0	1.3335	.0487	11¿85	3.95
12.0	1.3765	0.0488	11.55	3.85
18.0	1.4293	0.0320	7.28	2.43
24.0	1.4489	0.0171	3.87	1.29
30.0	1.4568	0.0187	4.19	1.40
36.0	1.4603	0.0156	3.49	1.16
48.0	1.4691	0.0139	3.06	1.02
60.0	1.4694	0.0091	2.04	0.68
72.0	1.4655	0.0045	1.02	0.34
84.0	1.4635	0.0056	1.23	0.41
105.0	1.4638	0.0038	0.82	0.27
120.0	1.4643	0.0030	0.68	0.23
135.0	1.4651	0.0026	0.55	0.18
150.0	1.4658	0.0033	0.75	0.25
180.0	1.4657	0.0038	0.82	0.27
210.0	1.4678	0.0028	0.62	0.20
240.0	1.4687	0.0034	0.75	0.25
270.0	1.4672	0.0025	0.55	0.18
300.0	1.4640	0.0032	0.68	0.23

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 3
Calibration Data for Meter No. 6-258

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.2820	0.0359	9.12	3.04
9.0	1.3920	0.0488	11.42	3.81
12.0	1.4087	0.0374	8.66	2.89
18.0	1.4409	0.0305	6.87	2.29
24.0	1.4684	0.0189	4.22	1.41
30.0	1.4568	0.0197	4.39	1.46
36.0	1.4653	0.0166	3.69	1.23
48.0	1.4722	0.0146	3.19	1.06
60.0	1.4680	0.0087	1.91	0.64
72.0	1.4686	0.0108	2.38	0.79
84.0	1.4613	0.0056	1.23	0.16
105.0	1.4632	0.0023	0.48	0.16
120.0	1.4650	0.0027	0.61	0.21
135.0	1.4646	0.0032	0.68	0.22
150.0	1.4657	0.0030	0.68	0.22
180.0	1.4694	0.0054	1.22	0.41
210.0	1.4671	0.0017	0.41	0.14
240.0	1.4669	0.0020	0.48	0.16
270.0	1.4663	0.0031	0.68	0.23
300.0	1.4623	0.0028	0.62	0.21

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 4
Calibration Data for Meter No. 6-273

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.3205	0.0704	17.327	5.776
9.0	1.4068	0.0541	12.498	4.166
12.0	1.4058	0.0363	8.392	2.797
18.0	1.4214	0.0254	5.808	1.936
24.0	1.4431	0.0234	5.270	1.757
30.0	1.4621	0.0207	4.601	1.534
36.0	1.4637	0.0155	3.442	1.147
48.0	1.4703	0.0132	2.918	0.973
60.0	1.4742	0.0092	2.028	0.676
72.0	1.4741	0.0081	1.786	0.595
84.0	1.4687	0.0069	1.527	0.509
105.0	1.4714	0.0067	1.480	0.493
120.0	1.4709	0.0050	1.105	0.368
135.0	1.4727	0.0048	1.059	0.353
150.0	1.4721	0.0040	0.883	0.294
180.0	1.4742	0.0026	0.573	0.191
210.0	1.4763	0.0030	0.660	0.220
240.0	1.4773	0.0030	0.660	0.220
270.0	1.4739	0.0025	0.551	0.184
300.0	1.4710	0.0031	0.685	0.228

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 5
Calibration Data for Meter No. 6-322

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.2820	0.0354	8.97	2.99
9.0	1.3790	0.0393	9.26	3.09
12.0	1.4038	0.0303	7.02	2.34
18.0	1.4312	0.0354	8.04	2.68
24.0	1.4518	0.0159	3.56	1.19
30.0	1.4585	0.0204	4.55	1.52
36.0	1.4579	0.0131	2.92	0.97
48.0	1.4642	0.0126	2.80	0.93
60.0	1.4600	0.0075	1.67	0.56
72.0	1.4591	0.0094	2.10	0.70
84.0	1.4538	0.0058	1.30	0.43
105.0	1.4578	0.0038	0.85	0.28
120.0	1.4594	0.0037	0.82	0.27
135.0	1.4617	0.0030	0.67	0.22
150.0	1.4645	0.0026	0.58	0.19
180.0	1.4640	0.0020	0.44	0.15
210.0	1.4662	0.0025	0.55	0.18
240.0	1.4660	0.0020	0.44	0.15
270.0	1.4635	0.0031	0.68	0.23
300.0	1.4601	0.0030	0.67	0.22

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 6
Calibration Data for Meter No. 6-028

V_n [cm/s]	$\overline{N}_*$ [$rev./m$]	S_N [$rev./m$]	E_s [%]	E_m [%]
6.0	1.3054	0.568	14.17	4.72
9.0	1.3727	0.0478	11.29	3.76
12.0	1.3887	0.0399	9.36	3.12
18.0	1.4372	0.0150	3.41	1.14
24.0	1.4498	0.0143	3.24	1.08
30.0	1.4572	0.0103	2.26	0.75
36.0	1.4615	0.0094	2.12	0.71
48.0	1.4583	0.0075	1.65	0.55
60.0	1.4594	0.0056	1.23	0.41
72.0	1.4565	0.0051	1.17	0.39
84.0	1.4575	0.0064	1.44	0.48
105.0	1.4599	0.0057	1.30	0.43
120.0	1.4590	0.0050	1.10	0.37
135.0	1.4618	0.0042	0.96	0.32
150.0	1.4629	0.0031	0.68	0.23
180.0	1.4641	0.0023	0.55	0.18
210.0	1.4644	0.0027	0.61	0.20
240.0	1.4649	0.0032	0.68	0.23
270.0	1.4636	0.0025	0.55	0.18
300.0	1.4604	0.0022	0.48	0.16

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 7
Calibration Data for Meter No. 6-137

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.3169	0.0528	13.06	4.35
9.0	1.3837	0.0455	10.70	3.57
12.0	1.3986	0.0385	8.94	2.98
18.0	1.4535	0.0216	4.82	1.61
24.0	1.4597	0.0123	2.74	0.91
30.0	1.4668	0.0151	3.34	1.11
36.0	1.4724	0.0094	2.11	0.70
48.0	1.4701	0.0072	1.57	0.52
60.0	1.4666	0.0049	1.09	0.36
72.0	1.4652	0.0040	0.89	0.30
84.0	1.4607	0.0058	1.30	0.43
105.0	1.4632	0.0043	0.96	0.32
120.0	1.4649	0.0058	1.30	0.43
135.0	1.4647	0.0034	0.75	0.25
150.0	1.4654	0.0035	0.75	0.25
180.0	1,4648	0.0019	0.41	0.14
210.0	1.4677	0.0024	0.55	0.18
240.0	1.4681	0.0026	0.55	0.18
270.0	1.4666	0.0026	0.55	0.18
300.0	1.4636	0.0018	0.41	0.14

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 8
Calibration Data for Meter No. 6-317

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.3120	. 0512	12.65	4.22
9.0	1.3782	0.0506	11.97	3.99
12.0	1.3961	0.0434	10.10	3.37
18.0	1.4463	0.0190	4.29	1.43
24.0	1.4572	0.0110	2.47	0.82
30.0	1.4615	0.0165	3.70	1.23
36.0	1.4640	0.0118	2.60	0.87
48.0	1.4737	0.0111	2.44	0.81
60.0	1.4660	0.0062	1.36	0.45
72.0	1.4591	0.0046	1.03	0.34
84.0	1.4612	0.0065	1.44	0.48
105.0	1.4645	0.0052	1.16	0.39
120.0	1.4643	0.0052	1.16	0.39
135.0	1.4668	0.0046	1.02	0.34
150.0	1.4672	0.0036	0.81	0.27
180.0	1.4681	0.0046	1.02	0.34
210.0	1.4705	0.0036	0.82	0.27
240.0	1.4697	0.0037	0.82	0.27
270.0	1.4686	0.0018	0.41	0.14
300.0	1.4635	0.0035	0.75	0.25

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 9
Calibration Data for Meter No. 6-487

V_n [cm/s]	$\overline{N}_*$ [$rev./m$]	S_N [$rev./m$]	E_s [%]	E_m [%]
6.0	1.2888	0.0576	14.51	4.84
9.0	1.3661	0.0441	10.47	3.49
12.0	1.3911	0.0419	9.78	3.26
18.0	1.4263	0.0156	3.58	1.19
24.0	1.4515	0.0138	3.10	1.03
30.0	1.4449	0.0143	3.25	1.08
36.0	1.4532	0.0123	2.75	0.92
48.0	1.4537	0.0090	2.00	0.67
60.0	1.4513	0.0069	1.52	0.51
72.0	1.4503	0.0059	1.31	0.44
84.0	1.4517	0.0052	1.17	0.39
105.0	1.4527	0.0060	1.38	0.46
120.0	1.4551	0.0044	0.96	0.32
135.0	1.4561	0.0040	0.89	0.30
150.0	1.4580	0.0038	0.82	0.27
180.0	1.4600	0.0026	0.55	0.18
210.0	1.4621	0.0019	0.41	0.14
240.0	1.4607	0.0021	0.48	0.16
270.0	1.4604	0.0022	0.48	0.16
300.0	1.4569	0.0037	0.82	0.27

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 10

Calibration Data for Meter No. 6-449

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.3501	0.0535	12.88	4.29
9.0	1.4024	0.0440	10.20	3.40
12.0	1.4066	0.0377	8.71	2.90
18.0	1.4205	0.0325	7.44	2.48
24.0	1.4431	0.0230	5.18	1.73
30.0	1.4533	0.0199	4.45	1.48
36.0	1.4557	0.0174	3.89	1.30
48.0	1.4626	0.0112	2.49	0.83
60.0	1.4654	0.0094	2.09	0.70
72.0	1.4656	0.0068	1.51	0.50
84.0	1.4611	0.0051	1.13	0.38
105.0	1.4618	0.0054	1.20	0.40
120.0	1.4600	0.0052	1.16	0.39
135.0	1.4601	0.0047	1.05	0.35
150.0	1.4583	0.0038	0.85	0.28
180.0	1.4595	0.0031	0.69	0.23
210.0	1.4621	0.0035	0.78	0.26
240.0	1.4628	0.0039	0.87	0.29
270.0	1.4579	0.0034	0.76	0.25
300.0	1.4554	0.0035	0.78	0.26

V_n = nominal towing speed

$\overline{N}_*$ = mean meter efficiency in revolutions per meter

S_N = standard deviation for meter efficiency

E_m = uncertainty in mean calibration at 99%level

E_s = uncertainty in single calibration of a meter at 99% level

TABLE 11
Calibration Data for Meter No. 6-466

V_n [cm/s]	$\overline{N}_*$ [rev./m]	S_N [rev./m]	E_s [%]	E_m [%]
6.0	1.3189	0.0516	12.72	4.24
9.0	1.3805	0.0391	9.21	3.07
12.0	1.4000	0.0353	8.20	2.73
18.0	1.4170	0.0263	6.03	2.01
24.0	1.4306	0.0170	3.86	1.29
30.0	1.4483	0.0182	4.08	1.36
36.0	1.4499	0.0157	3.52	1.17
48.0	1.4565	0.0087	1.94	0.65
60.0	1.4602	0.0074	1.65	0.55
72.0	1.4563	0.0057	1.27	0.42
84.0	1.4545	0.0058	1.30	0.43
105.0	1.4542	0.0055	1.23	0.41
120.0	1.4533	0.0049	1.10	0.37
135.0	1.4528	0.0029	0.65	0.22
150.0	1.4511	0.0043	0.96	0.32
180.0	1.4527	0.0025	0.56	0.19
210.0	1.4547	0.0018	0.40	0.13
240.0	1.4557	0.0021	0.47	0.16
270.0	1.4518	0.0023	0.52	0.17
300.0	1.4431	0.0036	0.81	0.27

V_n = nominal towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
S_N = standard deviation for meter efficiency
E_m = uncertainty in mean calibration at 99%level
E_s = uncertainty in single calibration of a meter at 99% level

TABLE 12
Calibration Data from Grindley (1971)

$\overline{V}$ [cm/s]	$\overline{N}_*$ [rev./m]	N_{*max} [rev./m]	N_{*min} [rev./m]	E_s [%]
7.71	0.7599	0.7718	0.7373	2.99
15.14	0.7082	0.7193	0.7026	1.31
22.82	0.6890	0.6931	0.6852	0.84
30.82	0.6885	0.6928	0.6831	1.02
46.14	0.6840	0.6855	0.6828	0.25
61.41	0.6785	0.6824	0.6767	0.58
74.77	0.6751	0.6770	0.6724	0.45
89.85	0.6745	0.6773	0.6733	0.35
246.30	0.6716	0.6727	0.6706	0.24

$\overline{V}$ = mean towing speed
$\overline{N}_*$ = mean meter efficiency in revolutions per meter
N_{*max} = maximum meter efficiency
N_{*min} = minimum meter efficiency
E_s = uncertainty in single calibration of a meter at 99% level

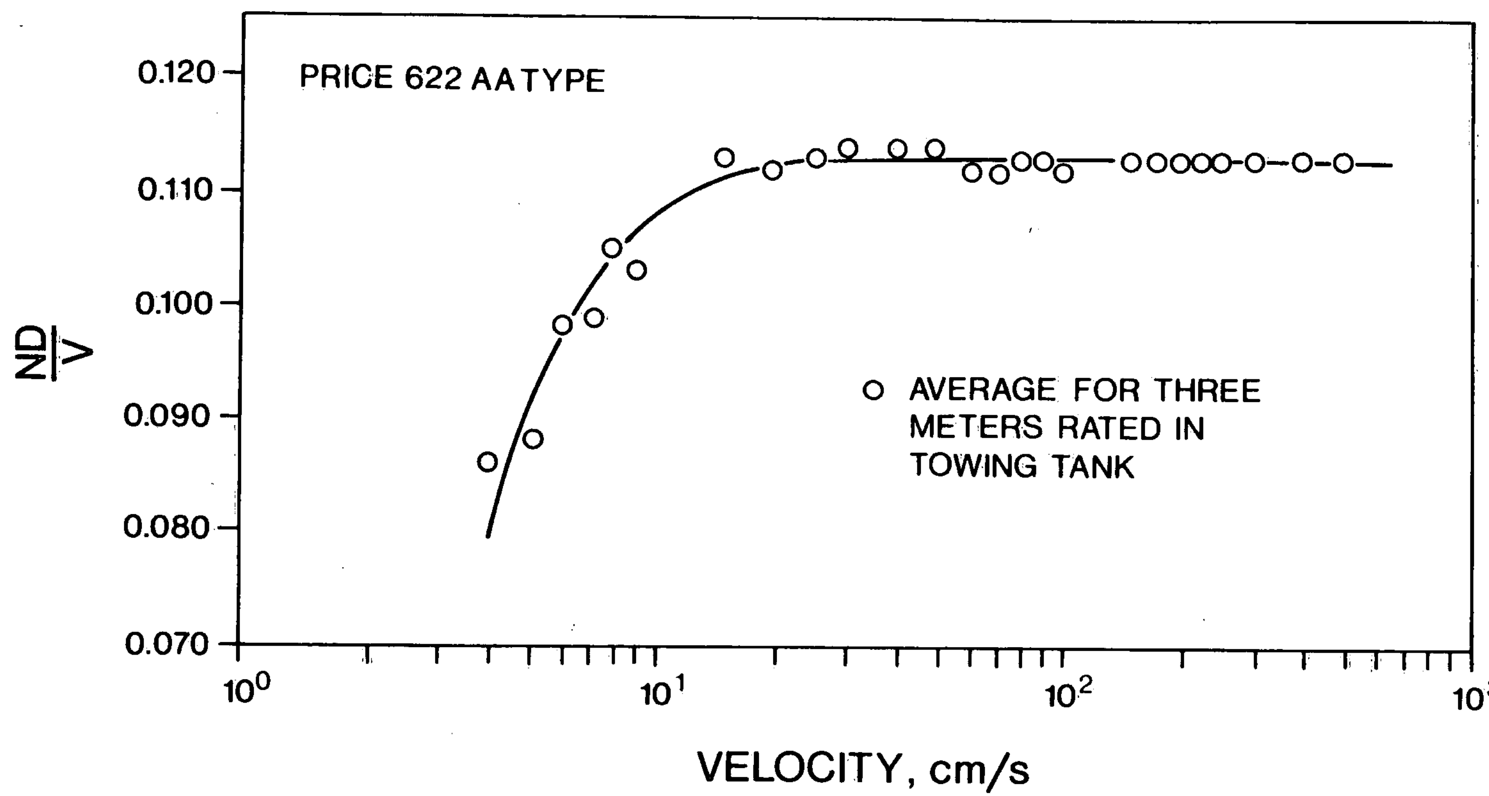

FIGURE 1. TYPICAL PRICE METER PERFORMANCE CURVE.

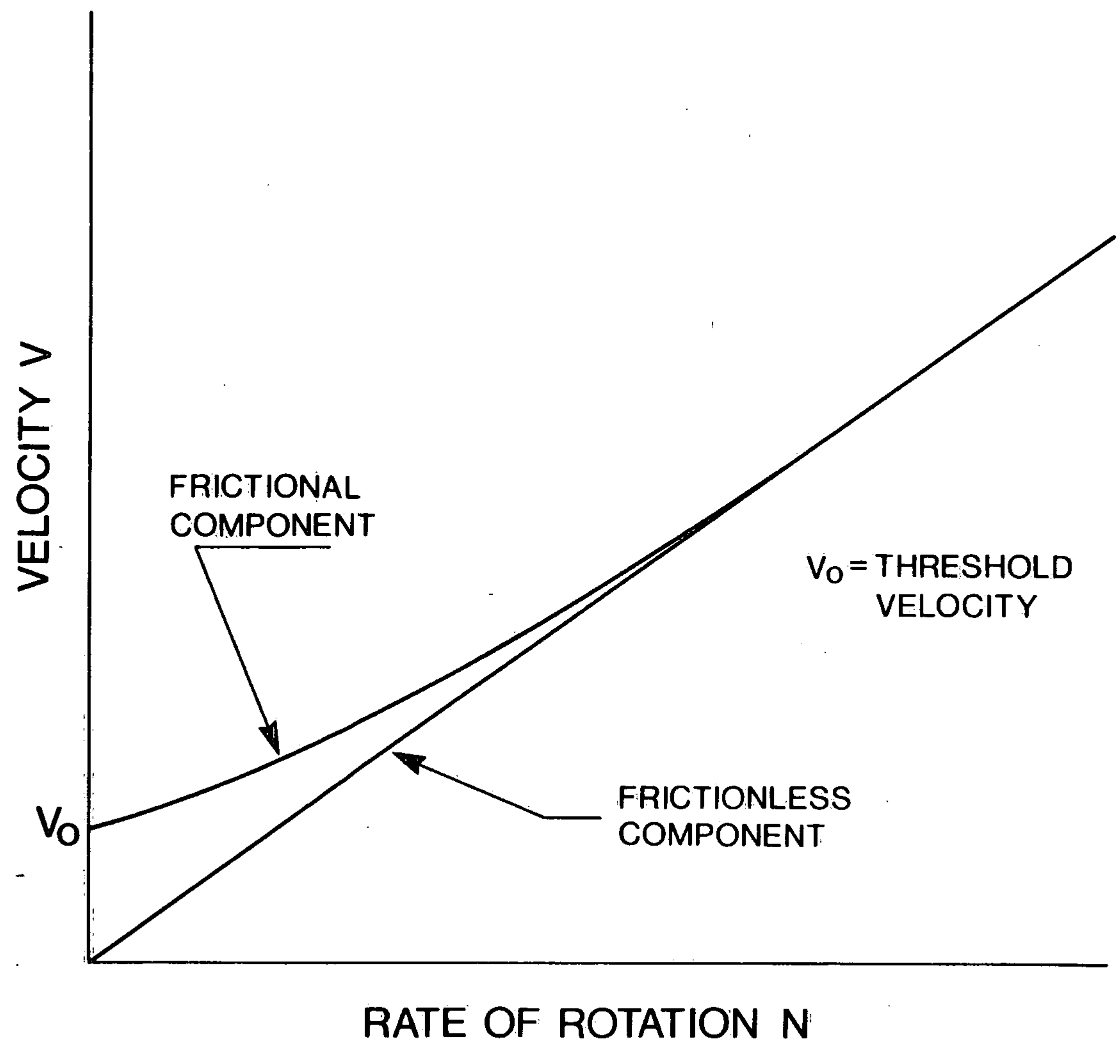

FIGURE 2. COMPONENTS OF CALIBRATION EQUATION.

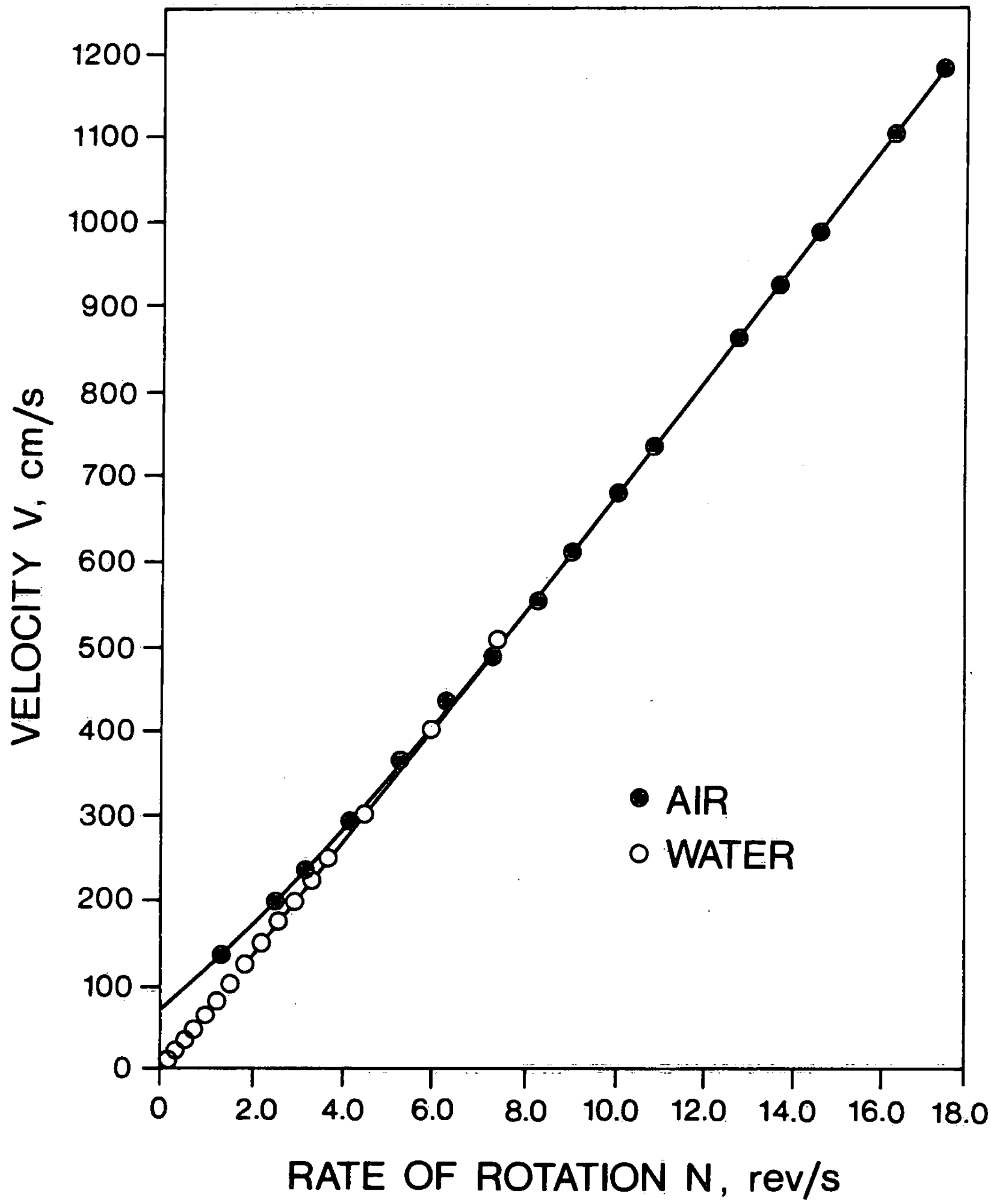

FIGURE 3. CALIBRATION CURVES FOR PRICE METER IN AIR AND WATER.

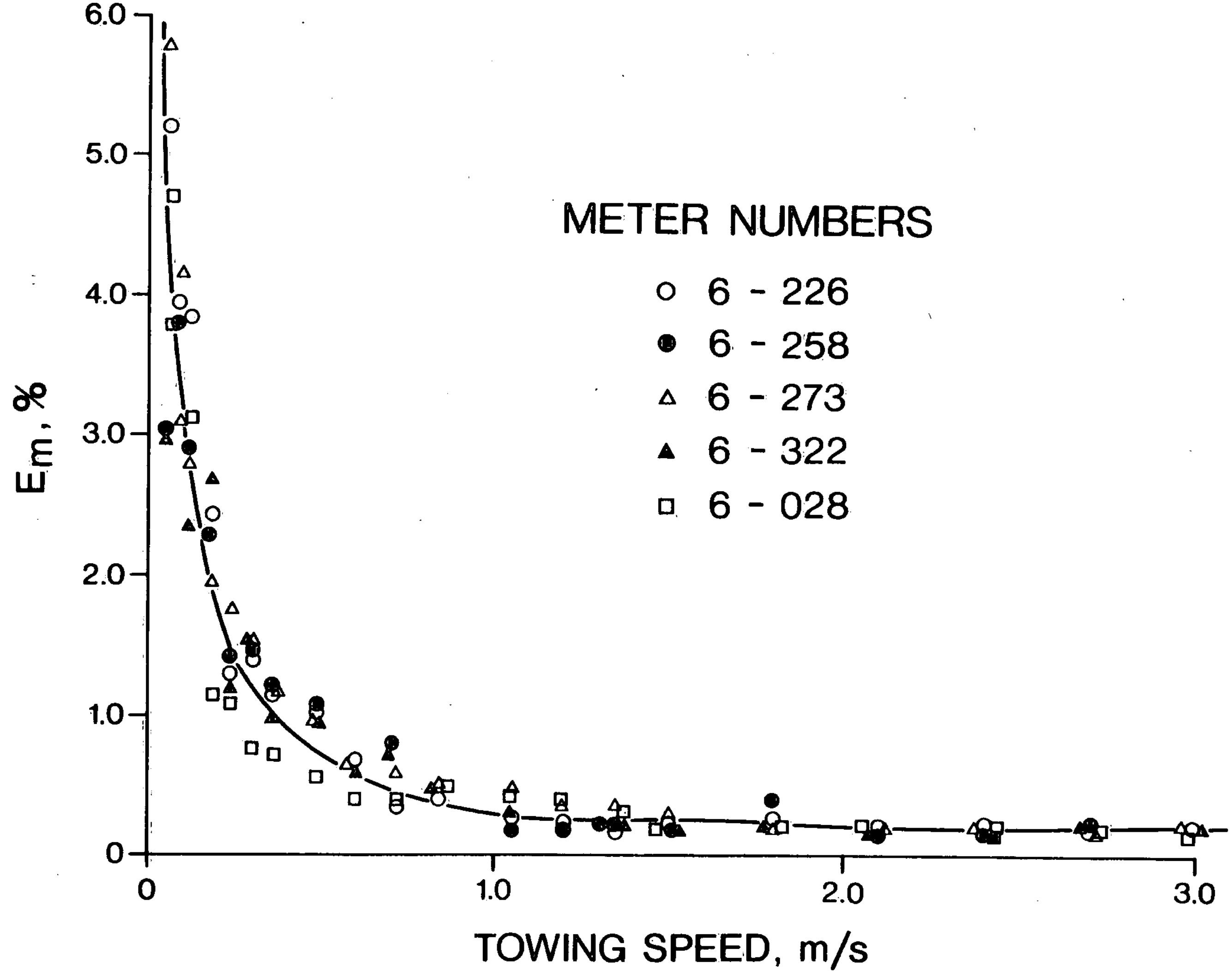

FIGURE 4. UNCERTAINTY IN MEAN CALIBRATION AT 99% CONFIDENCE LEVEL.

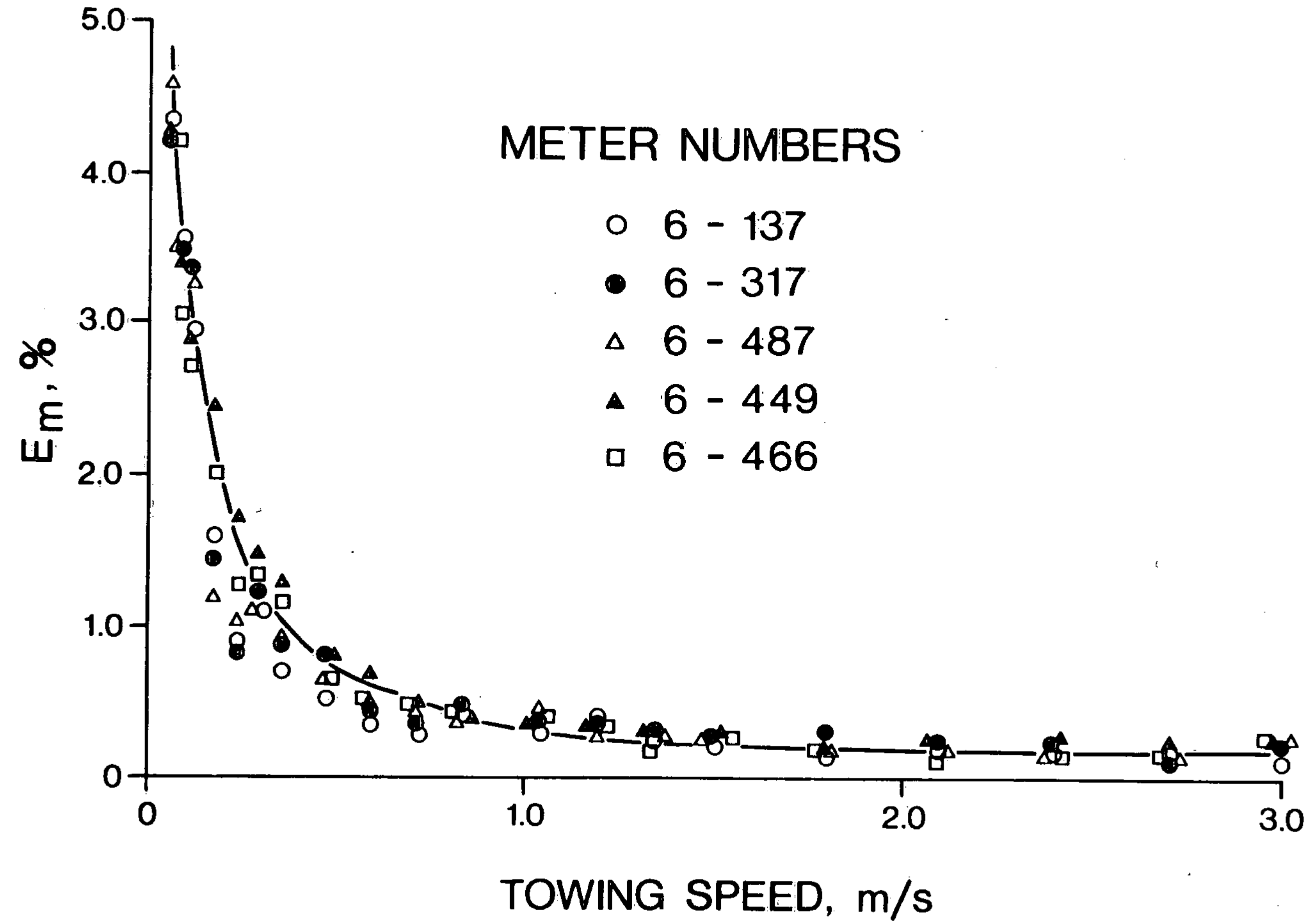

FIGURE 5. UNCERTAINTY IN MEAN CALIBRATION AT 99 % CONFIDENCE LEVEL.

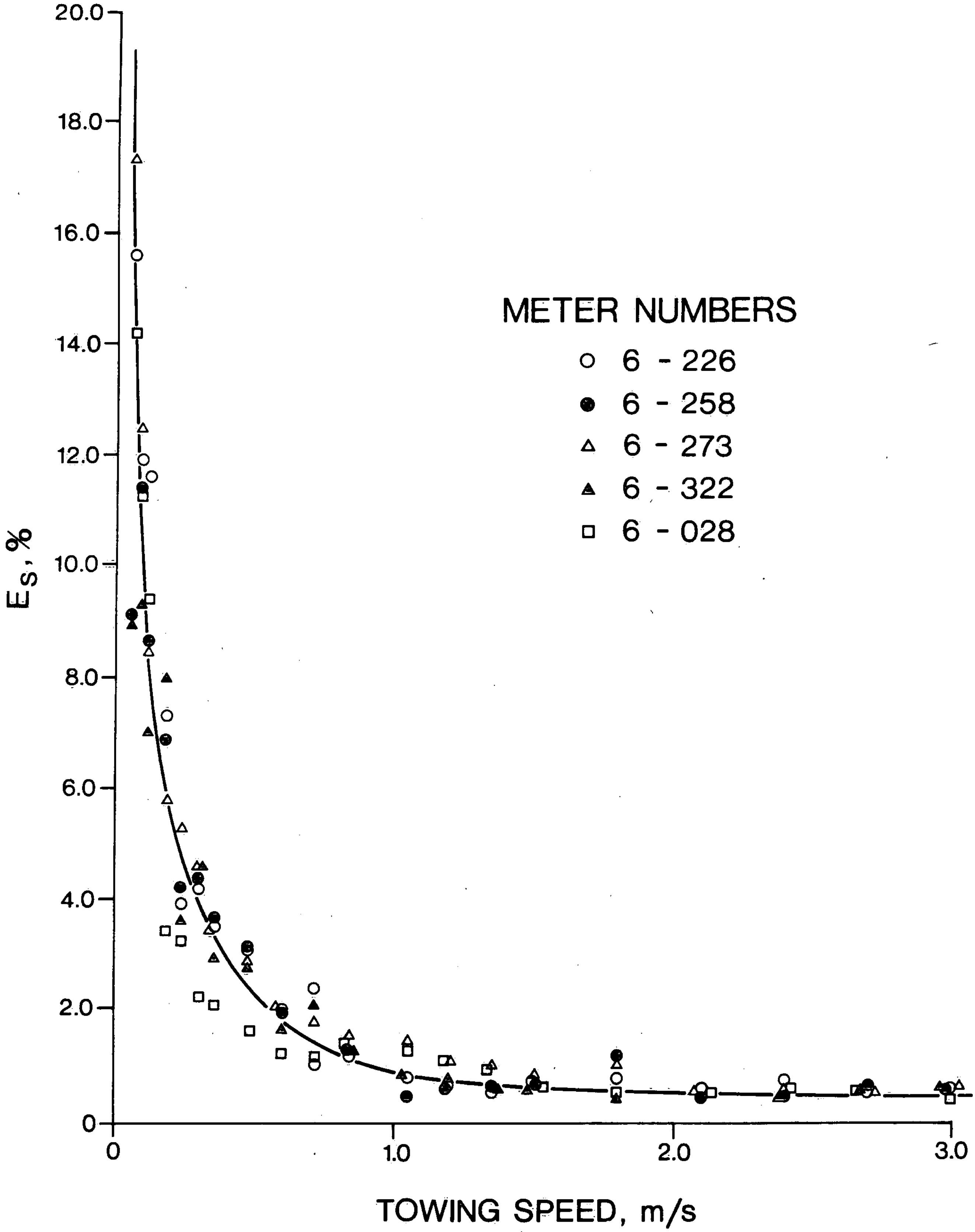

FIGURE 6. UNCERTAINTY IN REPEATABILITY OF A GIVEN CALIBRATION AT 99% CONFIDENCE LEVEL.

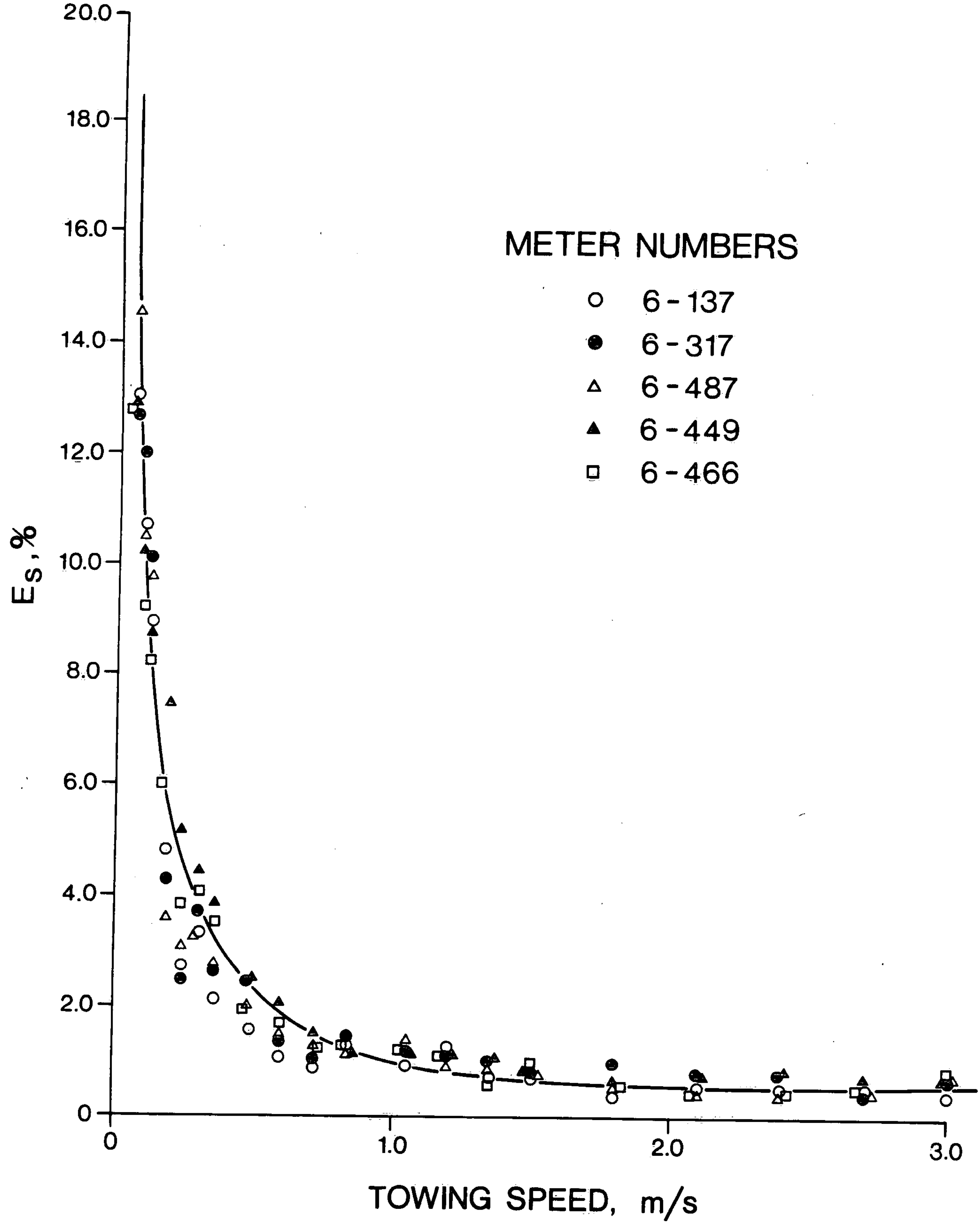

FIGURE 7. UNCERTAINTY IN REPEATABILITY OF A GIVEN CALIBRATION AT 99% CONFIDENCE LEVEL.

NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

Environment Canada Environnement Canada

Canada

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6