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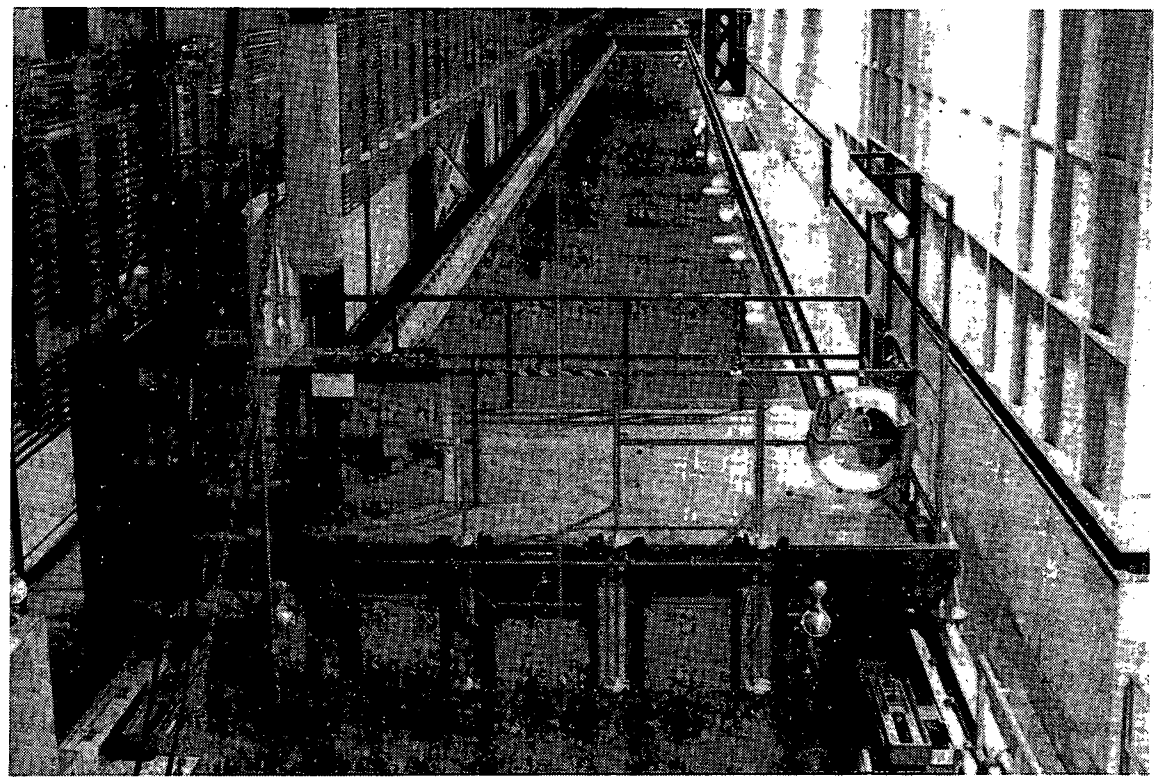

Calibration of the SIAP ME4001 current meter

Étalonnage du moulinet SIAP ME4001

by

par

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CALIBRATION OF THE SIAP ME4001 CURRENT METER

By

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SUMMARY

Owing to the initiative of Quebec Hydro engineers, comparative ratings of five Siap ME40001 type were made at four institutes including the National Water Research Institute (NWRI).

Because specified procedures were not used at NWRI, the tests were repeated as well as some additional work. This analysis shows that the meter may be calibrated to an accuracy of .4% at the 99% confidence level. Analysis of the data indicates that calibrations at the NWRI towing tank are least prone to error.

MANAGEMENT PERSPECTIVE

Quebec Hydro initiated an interlaboratory comparison of the calibration of current meters.

This report gives an analysis of the calibrations which indicates that the towing tank and equipment in the hydraulics laboratory of the National Water Research Insitute at the Canada Centre for Inland Waters will calibrate meters consistently within 0.4% error.

This performance equals or exceeds other well known calibration facilities in France, Switzerland and Italy.

The Quebec Hydro engineers are to be congratulated on their initiative in organizing this intercomparison.

T. Milne Dick
Chief, Hydraulics Division
October 21, 1982

1.0 INTRODUCTION

1.1 Background

Hydro-Quebec uses the Siap ME4001 current meter, which is a propeller-type meter, to measure the turbine discharge at their hydro-electric power generating stations. The measurements are used to determine the efficiency of the turbines. It is very important to make accurate flow measurements because even small errors can result in considerable losses in revenue for the utility company. In order to achieve this required accuracy, it is necessary that the current meters are carefully calibrated. Hydro-Quebec hopes to obtain a calibration accuracy of 0.25 percent.

In 1979, Hydro-Quebec sent five of their current meters - numbered 600591, 600592, 600593, 600594 and 600595 - to four different rating stations to determine to what accuracy these meters could be calibrated. These rating facilities were: Institute Di Idraulica, University of Perdua, Italy; Station D'êtalonnage de moulinets hydromêtrique de Beauvert, Grenoble, France; Eidgenossiches Amt fÜr Wasserwirtschaft, Berne, Switzerland; and the National Water Research Institute, Burlington, Canada. The results were analyzed by Levesque (1). The analysis indicated that the Canadian calibrations contained a systematic error which was attributed to the meter suspension. In addition, the Canadian calibrations extended only over a velocity range of 3 m/s whereas in the European facilities the meters were calibrated up to velocities of 4 m/s or better. Because of these differences, it was not possible to make a good comparison between the Canadian calibrations and those obtained in the European facilities. The meters were subsequently returned to the National Water Research Institute for recalibration. This was done using the meter suspension and velocity increments up to 6 m/s recommended by Levesque (1).

1.1 Scope of the Study

In this report, new calibrations of the five current meters are analyzed and compared with those from the European calibration facilities. The work is divided into three parts: (1) accuracy of calibration, (2) comparison of calibrations, and (3) effect of meter position on suspension rod.

1.2.1 Accuracy of calibration

Current meter no. 600594 is calibrated five times to obtain five separate sets of calibration equations. The results are used to determine the accuracy of the calibration of a single Siap type current meter at the 99% confidence level attainable at the towing tank facility of the National Water Research Institute.

1.2.2 Comparison of calibrations

Each of the five current meters is calibrated once to obtain one set of calibration equations for each meter. These equations are then compared with those obtained for the same meters in the European calibration facilities.

1.2.3 Effect of suspension rod

In the report by Levesque (1), it was stated that there was a systematic error in the initial calibrations conducted in the towing tank at the National Water Research Institute. This was attributed to the fact that the meter was positioned on the suspension rod with its axis of rotation only 2 cm from the base of the rod. In contrast to this, the European facilities calibrated the meters with the suspension rod extending from 20 cm to 30 cm past the rotational axis of the meter. The effect of this is being examined using new calibration data obtained with meter number 600594.

2.0 PRELIMINARY CONSIDERATIONS

When a current meter is towed through a body of still water at a given speed, the propeller rotates in response to the drag and lift forces exerted on its blades by the fluid. The number of revolutions that a propeller will undergo depends on the friction in the bearings, the coupling between fluid and propeller blades and their pitch. For an ideal meter, there is no bearing friction, and the coupling between the fluid and blades is perfect (i.e. no slippage). For such a meter, the distance it can be towed for a given number of revolutions can be expressed by the relationship

$$S = kR \qquad (1)$$

in which S = distance towed in cm, k = true pitch of propeller and R = number of revolutions of the propeller. Dividing both sides of equation by the time t over which the number of revolutions are counted gives the rate of advance in terms of the rate of revolutions, which represents the calibration equation for an ideal meter given by

$$V = kN \qquad (2)$$

where V = velocity in cm/s and N = rate of propeller response in rev/s. Equation 2 states that when V = 0, N = 0 which means that there is no threshold velocity. This result arises directly from the initial assumption that there is no bearing friction and slippage between the fluid and propeller blades. In reality, however, meters do not behave in this way and this is the reason they have to be calibrated. Because of bearing friction and slippage between the fluid and the propeller blades, both of which vary somewhat from meter to meter, each meter has an "effective" pitch, which is greater than the true pitch, and a different threshold velocity. The effective pitch is the distance that the meter is towed through still water during one complete revolution of the propeller. The threshold velocity is the speed at which the meter must be towed in order to obtain the minimum, uniform rate of revolution of the propeller. As a result, Equation 2 has to be modified to accommodate these characteristics. Experience has shown that a suitable form of the equation is

$$V = mN + a \qquad (3)$$

in which m = effective pitch and "a" is an intercept. Both m and a are determined by calibrating the meter in a towing tank. The effective pitch m in Equation 3 can be written in terms of the true pitch by using the relationship

$$m = \alpha k \qquad (4)$$

where α is a slippage factor, the magnitude of which depends on the degree of coupling between the fluid and propeller blades. For the ideal meter (i.e. perfect coupling or no slippage), $\alpha = 1$. Clearly, for a real meter, one must always have the condition $\alpha > 1$. Therefore, the closer α is to 1, the more consistent and precise one can expect a meter to be.

Experience has shown that for the ME4001 type Siap meter with the no. 1 propeller, two linear equations of the type given as Equation 3, must be used to relate the measured towing speed to the propeller response. The need for two linear equations arises from the abrupt change in the meter response to the towing speed when the value of N is in the vicinity of 9 to 10 rev/s. At this point, there is a reduction in the value of the slippage α giving the propeller a smaller effective pitch from this point to the upper limit of the operating range of the meter. In order to have a well defined calibration, it is important to accurately determine the point where the value of α changes from a higher to a lower value. Since the slippage α represents the coupling between the fluid and propeller blades, it is most probable that the value of N at which α changes should depend to some degree on the propeller Reynolds number given by $V_m D/\nu$ (V_m = measured towing speed, D = diameter of propeller, ν = kinematic viscosity of the fluid). This value of N may for the sake of convenience be denoted as N_c, the critical value of N, since this is the point where the two linear calibration equations intersect.

It is the established practice to determine the point of intersection N_c graphically by plotting the measured calibration data as ΔV vs N. The value of ΔV is computed from the relationship

$$\Delta V = V_m - m'N \qquad (5)$$

where ΔV = speed difference in cm/s, V_m = the measured towing speed, m' = nominal pitch which is the rounded off value of the effective pitch m, and is given by the manufacturer of the Siap model as 25.0 cm/rev for the no. 1 propeller. A typical plot of ΔV vs N for the Siap ME4001 meter with the no. 1 propeller is shown in Figure 1. The plot of ΔV vs N gives a good picture of the behaviour of the meter over its operating range. The primary purpose of this plot, however, is to enlarge the scale in the vertical axis, thus making it possible to obtain a pronounced change in slope at the value $N = N_c$ (see Figure 1). Once the value of N_c has been obtained from such a plot, the two calibration equations can be determined from the measured values V_m and N. These equations can be expressed in general terms as

$$V = m_1 N + a_1 \qquad 0 < N \leq N_c \qquad (6)$$

$$V = m_2 N + a_2 \qquad N_c \leq N < N_{max} \qquad (7)$$

where the subscripts 1 and 2 denote first and second equation and N_{max} = the upper operating limit of the meter. Equations 6 and 7 are shown schematically in Figure 2. The diagram shows that a_1 is less than V_0. This is a direct consequence of the fact that Equation 6 is a linear approximation of the true V vs N relationship which is slightly nonlinear for small values of N.

The above concepts are used in this report to define the calibration equations for the Siap ME4001 meter with no. 1 propeller. No attempts have been made to determine a relationship between N_C and $V_m D/\nu$ nor to explore this effect on the overall calibration accuracy.

3.0 EQUIPMENT AND TOWING PROCEDURE

3.1 Towing Tank

The tank, constructed of reinforced concrete, founded on piles, is 122 metres long and 5 metres wide. The full depth of the tanks 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 reduce possible convection currents.

At one end of the tank is an overflow weir. Waves arising from towed current metres 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. The large cross section of the tank also inhibits the generation of waves by the towed object.

3.2 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 the constant speed within specified tolerances.

3.3 Data Acquisition

3.3.1 Towing Speed

The average speed data for the towing carriage is obtained from electronic 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, emitting a pulse for each millimeter of travel. The frequency of these pulses is measured using the 5323A Hewlett Packard automatic counter. The frequency is converted to speed in cm/s by dividing the frequency by 10 since the frequency of the pulses is the same as speed in mm/s. The automatic counter determines the frequency over very short time increments and therefore a large number of average velocity determinations are made as the towing carriage travels down the tank. These "speed samples" are processed directly as they are produced by a Hewlett Packard 85 computer. The computer determines the overall average towing speed and the standard deviation about this average to make sure that the specified tolerances are met.

3.3.2 Rate of revolution of propeller

The Siap ME4001 current meter is equipped with a magnetic switch. The revolutions of the propeller are measured by counting the electric pulses emitted from this switch. Each pulse represents a half a revolution of the propeller. In order to compute the revolutions per second, the pulses and the length of time over which they were counted were recorded on the Siap digital counter and timer supplied with the meter and shown in Figure 3. This data acquisition module is capable of monitoring 30 current meters simultaneously over the same preset length of time. This system, however, has the disadvantage that it can overcount by as much as a half a revolution at the beginning of the measuring sequence and undercount by as much as a half a revolution at the end. In the most ideal case, these errors would offset each other. In the worst case, the total count of revolutions could be in error by a half revolution. The significance of this error varies with the number of revolutions counted. It is greatest for small numbers of revolutions and decreases as the number of revolutions increase.

3.4 Meter Suspension

The meter suspension system consisted of the 75/35 mm standard rod which was supplied with the meters. The rod was tightly fitted to a rigid, compact mounting frame which was bolted to the rear of the towing carriage near the centreline of the tank as shown in Figure 4. The compact configuration of the mounting frame was chosen to minimize the effects of vibrations generated by the carriage drive and the drag on the meter and suspension rod. The meter was fastened to the suspension rod by a clamp which was designed so that the propeller of the meter was well ahead of the suspension rod.

3.5 Test Procedure

Before testing a particular meter, it was carefully fastened to the suspension rod with the clamp, taking care that the meter was truly aligned with longitudinal axis parallel to the sides of the towing tank. Care was also taken that the axis of rotation of the meter was 40 cm below the surface of the water and 30 cm above the bottom end of the suspension rod as recommended by Levesque (1). The meter was then connected to the Siap revolutions counter and timer. When this procedure was completed, the calibration of the meter began. The calibration was begun with a speed of about 10 cm/sec, proceeding to the next higher speed, using the speed increments recommended by Levesque (1) up to 600 cm/sec. At the end of a run for a particular speed, the water in the tank was allowed to come to rest and the length of these waiting times varied somewhat with the towing speed. For speeds up to 60 cm/s, the waiting time was 10 minutes, from 60 cm/s to 140 cm/s, the waiting time was 15 minutes, from 140 cm/s to 500 cm/s, the waiting time was 25 minutes and, from 500 cm/s to 600 cm/s the waiting time was 35 minutes. In all, 29 different towing speeds were used. The data are given in Tabes 1, 2, 3, 4 and 5 for the consecutive calibrations of meter number 600594. The data for the single calibrations of meters no. 600591, 600592, 600593, 600594 and 600595 are given in Tables 6, 7, 8, 9 and 10. Finally, the data for meter number 600594 positioned 2 cm above the end of the suspension rod are given in Table 11.

3.6 Preliminary Analysis of the Data

A preliminary analysis of the calibration data in Tables 1 through 11 was conducted to determine the value of $N = N_c$ at the point of change in the propeller response as well as the slopes and intercepts of the pairs of equations for each calibration.

The data were plotted as ΔV vs N. These plots are shown in Figures 5, 6, 7, 8 and 9, for the five meters, in Figures 10, 11, 12, 13 and 14 for the five successive calibrations of meter 600594, and in Figure 15 for meter 600594 mounted 2 cm above the end of the suspension post. Each plot shows the two regimes of the propeller response. In the regime before the transition point, there is some difference for each meter in the overall alignment of the data points. For example, for meter no. 600593 in Figure 7 the plot indicates some systematic variation rather than random measurement error. This is most likely due to some characteristic unique to the meter at the time it was calibrated. For values of N past the transition point, the variation of ΔV with N is more consistent for all meters until N reaches a values of about 20. When $N > 20$, the plots become noticeably more erratic. This may be partly due to the fact that propeller no. 1 is only recommended for use up to 500 cm/s which corresponds to a value of $N \approx 20$. As a result, only the data for $N \leq 20$ were used in the analysis.

The plots of ΔV vs N, in keeping with adopted practice, were used to determine the critical value of $N = N_c$. Straight lines were fitted by eye through the data, after any obviously erratic data points were discarded. The point of intersection of the two straight lines was then taken as the value of N_c. Although the fitting of curves in this manner is rather subjective, this procedure is adequate to obtain N_c, since its only purpose is to define the range $0 < N \leq N_c$ for the first calibration equation and $N_c \leq N \leq 20$ for the second calibration equation.

Once the values of N_c were determined, linear equations were fitted to the data. This was accomplished by using linear regression methods which, when used with good judgement, yield consistent results. In all cases, the coefficient of correlation was very close to 1. Values of N_c, slopes and intercepts for the five meters are given in Table 12. The results for the five consecutive calibrations of meter no. 600594 are given in Table 13 and those for the calibration of meter no. 600594 mounted 2 cm above the end of the suspension rod are given in Table 14.

4.0 ACCURACY OF THE CALIBRATION EQUIPMENT

Accuracy is defined as the degree of conformity of a measurement to the true value. However, the true value of the quantity being measured is not known. Therefore, the best one can do is to estimate the true value at some level of confidence which is normally referred to as the uncertainty of the measurement. The level of confidence depends on the precision required. In the case of current meter calibrations, the uncertainty should be taken at the 99% level of confidence.

When a current meter is calibrated, one wishes to know how accurately one can make a velocity measurement using the resulting calibration equations. As shown earlier, the typical form of the calibration equations for the Siap meter is given as

$$V = mN + a \qquad (m = ak) \tag{8}$$

in which all the parameters have been previously defined. In determining these equations, the slope m and intercept a are obtained from measurements of V and N, both of which contain measurement errors. Therefore, in order to know how accurately one can obtain a velocity measurement with a calibrated meter (i.e. use of calibration equations), one must know how accurately the meter can be calibrated. This accuracy depends on how well one can determine V and N over the operating range of the meter during its calibration.

4.1 Accuracy of Towing Speed V

The towing speed is the average of a number, say n, velocity samples measured with the frequency counter as described in section 3.3.1. The values of n range from 20 to about 270 with the higher values of n corresponding to the lower values of speed and decreasing as the towing speed increases. Values of average speed, say V, and the standard deviation S_V, are determined for each run. There are no known systematic errors in the data acquisition equipment and therefore the standard deviation about the mean speed is an indication of the random error in the speed measurement. Such errors are normally distributed and hence the uncertainty in the mean speed of the carriage at the 99% confidence level can be computed from the quantity $(3\ S_v/\sqrt{n})$.

Values of the uncertainty in the mean speed expressed as a percentage of the mean speed are plotted versus the mean speed in Figure 16 for values of v from 10 cm/s to 600 cm/s. Data from three separate calibrations of meter no. 600594 were used. The three sets of data show considerable scatter but there is a clearly definable trend and this is shown by an average curve drawn through the points. The shape of the curve is a reflection of the performance characteristics of the data acquisition system. The curve shows that the uncertainty decreases sharply from 0.045% at 10 cm/s to about 0.015% at 30 cm/s. It then rises sharply to about 0.09% at 100 cm/s and thereafter decreases quite smoothly to about 0.03% at 600 cm/s. These results are very encouraging. The uncertainty at the 99% level of confidence of the towing speed used for the meter calibration is seen to be well below 0.1% throughout the entire speed range. This makes it possible to use the towing carriage for very precise current meter calibrations.

4.2 Accuracy of Rate of Rotation of Propeller

The rate of rotation in rev/s is determined by counting the number of revolutions and measuring the time during which the revolutions are counted. The time is measured very accurately and errors in the time measurement may be taken to be insignificant. Therefore, the error in measuring the meter response arises from the counting of the revolutions only. It was shown in section 3.3.2 that the maximum error in counting the revolutions of the meter propeller is 0.5 revolutions. The percentage error in the revolutions depends on the number of revolutions and decreases as the number of revolutions increases. This is shown in Figure 17, where the maximum error in percent (0.5/R) 100% is plotted versus the number of revolutions R. The curve shows that about 240 revolutions must be counted in order to ensure that the uncertainty in R is less than 0.2% 99% of the time. For values of R < 240, the rate of increase in the uncertainty increases progressively as R is decreased. When R is increased above 240, the extra reduction in the uncertainty is relatively small compared to the extra effort expended. Since the error in the time measurement is negligible, then the error in determining R is also the error in determining the rate of rotation of the propeller N. Therefore,the value of N is accurate to within 0.20% when R > 240, 99% of the time.

5.0 ACCURACY OF CURRENT METER CALIBRATION

The accuracy of the calibration equipment indicates that it should be possible to calibrate the current meters very accurately. If the calibration accuracy depended on the calibration equipment alone, then an accuracy of the order of 0.25% sought by Hydro Quebec should be attainable. However, the calibration accuracy depends also on the performance of the meter itself, the calibration procedure and the goodness of the fit of linear equations to the calibration data. To assess the accuracy of the meter calibration, the set of five calibration equations obtained for meter number 600594 and given in Table 13 were used. Although five separate calibrations is a small sample from a statistical point of view, it was considered sufficient for the scope of this report. In keeping with small sample theory the "student's t" distribution was used to determine the uncertainty in the calibration of meter no. 600594 at the 99% confidence level.

For each of the five pairs of calibration equations, velocities were computed for the same fixed values of N. The values of N were taken in increments of 2 rev/s from 2 rev/sec to the upper operating limit of the meter of 20 rev/s. The computed velocities for each complete calibration are given in Table 15. Once the velocities were determined, the mean velocities and standard deviation at each velue of N were computed and these are also given in Table 15. The percent uncertainty at the 99% confidence level were then computed as a percentage of the mean velocity using the relationship

$$E = \frac{t_{.995}\, S_v}{\bar{V}_5 \sqrt{n-1}} \times 100\% \qquad (9)$$

where: E = uncertainty of the mean velocity at the 99% confidence in percent of the mean velocity, S_v = standard deviation computed as $S_v = \sqrt{\Sigma(V_i - \bar{V}_5)^2/n}$ in which i = ith calibration equation, t.995 = confidence coefficient for (n - 1) degrees of freedom, n = number of separate calibrations, and V_5 = the mean computed velocity from the five calibrations at a given value of N. In Equation 9 $t_{.995} = 4.60$ from student's t distribution (2) and n = 5. Therefore Equation 9 can be reduced to

$$E = \frac{2.30\ S_v}{V_5} \times 100\% \qquad (10)$$

The computed values of E are also given in Table 15.

Examinations of the values of E in Table 15 show that the uncertainty in the velocity computed from the calibrations varied from a minimum of about 0.14% when N = 9 to a maximum of about 0.40% for values of N = 20. In order to obtain a better picture of the variation of E with N, values of E were plotted versus N, in Figure 18.

The plot shows that the uncertainty E varies smoothly, decreasing from E = 0.36% at N = 2 rev/s to the minimum value of 0.14% at N = 9. The high uncertainty at the low values of N is primarily due to the uncertainty in the intercept a of the first calibration equation. This effect becomes progressively less as N increases with the result of lowering the overall calibration uncertainty in the range $0 < N \leq N_c$ (N_c = point of intersection of the two calibration curves). When $N \approx 9$, there is a sudden transition toward higher values of uncertainty with a smooth variation from a value of 0.31% at N = 10 to 0.40% at the upper operating limit of N = 20. The sudden increase in the uncertainty occurs at the average value of $N = N_c$. Therefore, there is a higher uncertainty in the calibration of the meter given as the second equation. The higher uncertainties in the second equation indicate the occurrence of some phenomenon not encountered for values of $N < N_c$. It is possible that since the meter is towed with a rod suspension,the vibrations arising from the fluid drag on the meter and rod may be a contributing factor. However, considering that throughout the testing all important conditions, such as testing procedure, meter suspension, waiting times between sucessive tows, etc., were always exactly the same, it is unlikey that the effects of the drag alone could be the cause of the increased uncertainty.

Another possible source of inaccuracy in the calibration is the meter itself. Examination of Figures 10 - 14, which show the plots of ΔV vs N for the five successive calibrations of meter 600594, reveals that for $N > N_C$ there is indeed less consistency in the calibration data and that this inconsistency increases as N increases. In fact, for values of $N > 20$, the response of the meter becomes quite erratic. This demonstrates that the meter performs less well at the higher speeds and hence the calibration accuracy that can be achieved is limited to some extent by the performance characteristics of the meter itself. Therefore, based on the above results, it is unlikely that the overall calibration accuracy of 0.25% anticipated by Quebec Hydro, can be achieved. Instead, a more realistic accuracy for the Siap ME 4001 meter is about 0.4% which is the greatest uncertainty determined from the present tests.

6.0 COMPARISON OF METER CALIBRATIONS FROM DIFFERENT TOWING TANKS

Levesque's (1) report on analysis was made to determine the accuracy with which the Siap current meters used by Hydro-Quebec could be calibrated in different towing tanks. Five meters numbered 600591 through 600595, were sent to Italian, French, Swiss and Canadian (NWRI) calibration facilities, to have each meter calibrated once. The analysis by Levesque (1) showed that the meter suspension used for the Canadian calibrations differed substantially from that used in Europe and as a result a meaningful comparison between the European and Canadian calibration was not possible.

In his analysis, the calibration equations provided for each meter were used to compute velocities at values of N = 2, 4, 6, 8, 10 and 12 rev/s. For each value of N, the mean velocity and standard deviation was computed for the group of five meters. The standard deviation was then used to compare the accuracy of the calibration at the different facilities. This procedure, although useful, is not quite precise enough for good quantitative results. Firstly, the standard deviation was used as an indicator of accuracy which gives the accuracy to a confidence level of only 68%, which is not quite precise enough in this application. Secondly, the data from five different meters was used. Each meter is slightly different from the others and thus the average and standard deviations reflect the quality of a group calibration rather than the accuracy to which a single meter can be calibrated. Instead of calibrating each of the five meters once, a better result would have been obtained by calibrating a single meter five times and then analyzing the results.

Despite the reservations above, comparisons of the calibrations at four different institutions are possible.

In this section, the data presented by Levesque (1) are used together with results from new calibrations of the five meters obtained in the Canadian towing tank. Two approaches are used to compare the calibrations from the four different towing tanks. In the first approach, the calibration of meter no. 600594 from each facility is compared against the average calibration of meter no. 600594 obtained in Section 5.0. In the second approach, the group calibrations for the five meters from each facility are compared.

6.1 Single Meter Calibration

In comparing the calibration of meter 600594 obtained at the four facilities, it is necessary to have a common reference standard against which they can be compared. For present purposes, the average calibration obtained from the five separate calibrations for meter no. 600594 was used. Velocities were computed from the calibration equations provided by each of the four calibration facilities for values of N from 2 to 20 rev/s in increments of N = 2 rev/s. For each velocity thus computed, the percent deviation from the average velocity V_5 (Table 15) was then obtained from the relationship

$$E_v = \frac{V - \bar{V}_5}{V_5} \times 100\% \qquad (11)$$

where: E_V = the percent deviation in velocity from the reference standard V_5 at a given value of N, V = computed velocity from calibration equations supplied by calibration facilities. V_5 = average velocity obtained from average of five calibrations of meter no. 600594 in Table 15. For the Canadian facility, a different calibration (calibration no. 4 in Table 12) from the five comprising the reference standard was used. The computed values of E_V for the Italian, French, Swiss and Canadian calibrations of meter no. 600594 are given in Table 16. The results in Table 16 show that the values of E_V for the Italian calibration are much larger in magnitude than those computed for the other facilities, and that these magnitudes in all cases exceed the uncertainty at 99% level of the meter calibration obtained in the Canadian facility. In addition, all values of E_V are negative, indicating that the Italian calibration always gives a velocity which is too low. The values of E_V for the French, Swiss and Canadian facilities in Table 16 overall appear to be quite similar with all values, except at N = 18 for the French calibration, being positive, and considerably smaller in absolute value than found for the Italian calibration. In order to obtain a better relative picture of the calibrations, values of E_V for each facility over the range of N for which the meters were calibrated were plotted in Figure 19. For the sake of convenience, the uncertainty at the 99% level in the reference calibration determined in Section 5.0 is also shown.

The plots for the French, Swiss and Canadian calibrations may be considered to form a group and for each the deviation E_V from the reference calibration is within the uncertainty of 0.4%. All the curves behave similarly for values of $N < 10$. When $N > 10$, the values of E_V for the Swiss and Canadian calibrations increase as N increases whereas in the case of the French calibration E_V drops sharply over the same range of N. The reason for the different behaviour in the French calibration is not known but it may be due to some undesirable characteristics in the calibration equipment, possibly vibrations. Although this sudden drop in E_V in the French calibration results in an error reduction, one would be inclined to give more credence to the Swiss and Canadian calibrations. In comparing these two calibrations, it can be seen from Figure 16 that the Canadian calibration gives lower values of E_V throughout the entire range of N tested. Therefore, the Canadian calibration is preferable to the Swiss and French calibrations. Consequently, the calibrations may be ranked in order of reliability as 1) Canadian, 2) Swiss, 3) French.

In assessing the Italian calibration, it can be seen in Figure 19 that its curve of E_V vs N is far removed from the other three curves, with most of the values of E_V being outside of 0.4% uncertainty on the negative side of the plot. There is no information available to indicate why the Italian calibration should be so different, although it is quite possible that the departure of this curve from the others is due to some systematic error which may be corrected in future calibration.

6.2 Group Calibration

To compare the group calibrations of the five meters numbered 600591 through to 600595 inclusive, the group average velocities V_g and their corresponding standard deviations at a given value of N were computed from the calibration equations obtained at each facility. The values of N were taken in increments of 2 rev/s from 2 rev/s to 12 rev/s which was the upper limit for the information from the European facilities supplied by Levesque (1). The percent uncertainty in the mean velocities at the 99% confidence level for each value of N were then computed as a percentage of the group mean velocity using Equation 9. Since there are five meters in each group, the degrees of freedom are 4 and the confidence coefficient from the Student's "t" distribution (2) is again $t_{.995}$ = 4.60. Therefore, Equation 9, for the case of the group calibrations, may be written as

$$Eg = \frac{2.30 \; S_v}{\overline{V}_g} \times 100\% \qquad (12)$$

The computed values of Eg are given in Table 17.

The values of Eg were plotted versus N in Figure 20. The plot clearly shows that the Italian results again are vastly different from those of the other three facilities. In this case, the departure of the Italian curve relative to the other three curves is much greater than was the case for the single meter comparison in Figure 19, while at the same time the position of the curves of the the other three curves relative to each other did not change appreciably. This indicates that the Italian data contains other errors.

Upon examining the plots for the French, Swiss and Canadian group calibrations, one notes again that they are closely grouped. On the average, as one would expect, the uncertainties in the group calibrations using five meters are higher than those for a single meter calibrated five times. This is because each meter has its own particular characteristics which varies from that of any other meter of the same type. The degree of difference depends on the quality of workmanship of the meter. These differences are systematic and hence using a group average of several meters is tantamount to randomizing systematic errors. Therefore, group calibrations should not be used to determine the accuracy of a particular type of meter. The results in Figure 20 show again that the Swiss and Canadian calibrations are better than those from the French facility, but the results are not as reliable as that of comparing the single meter calibration in Figure 19.

7.0 EFFECT OF SUSPENSION ROD

Levesque (1) suggested that there was a systematic error in the initial calibration of the five meters conducted in the towing tank at the National Water Research Institute. This error was estimated to be about -0.4% which means that velocities computed with the calibration equations would be consistently low by this amount. The systematic error was, as mentioned in Section 1.2.3, attributed to the fact that the meter was positioned on the suspension rod with its axis of rotation only 2 cm from the base of the rod. In contrast to this, the meters in the European facilities were calibrated with the suspension rod extending from 20 to 30 cm past the rotational axis of the meter. To examine the effect of this difference in suspension on the meter calibration more directly, meter 600594 was calibrated once when positioned 2 cm from the end of the rod. This calibration was compared with that of the meter in the recommended position, 30 cm above the end of the suspension rod.

Velocities were computed for each case from the appropriate calibration equations for values of N from 2 rev/s to 20 rev/s in increments of 2 rev/s. The percent deviations in velocities obtained with the meter at the 2 cm position was then obtained from the relationship

$$E_2 = \left(\frac{V_2 - V_{30}}{V_{30}}\right) \times 100\% \qquad (13)$$

in which E_2 = the percent difference in the computed velocities, V_2 = computed velocities for the case of meter 2 cm from end of rod, V_{30} = computed velocities for the case of meter 30 cm from end of rod. The results are given in Table 18.

The values of E_2 were plotted versus N in Figure 21 showing the regions over which each of the two calibration equations apply. The plot shows that when $N \leq 9$ the values of E_2 are virtually constant at -0.34% which agrees quite closely with the value of -0.4% estimated by Levesque (1). However, when $N \geq 9$ the values of E_2 are considerably larger than -0.4% having an average value of -0.57%. It is interesting to note that the difference obtained with the second equation is so much larger, although one can expect the end effect of the suspension rod to be greater at the higher towing speeds. The systematic errors are quite significant since they are of the same order as the uncertainty in the calibration of the meter at the 99% level of confidence. It is therefore very important to ensure that during calibration of the Siap meter the recommended specifications for meter suspension are respected.

8.0 CONCLUSIONS

8.1 The average towing speed of the carriage can be determined to better than 0.1% at the 99% level of confidence.

8.2 The accuracy of determining the number of revolutions of the meter propeller with the data acquisition equipment supplied can be obtained to an accuracy of 0.2% when the number of revolutions counted is greater than 240.

8.3 The Siap meter can be calibrated to an accuracy of 0.4% at the 99% level of confidence at the NWRI calibration facility.

8.4 Based on limited data, the quality of the calibrations of the Siap calibrations analysed in this report may be ranked in decreasing order as:

1. Canadian
2. Swiss
3. French
4. Italian

8.5 The uncertainty of calibrating five meters once at the 99% level of confidence is higher than the uncertainty in calibrating one meter five times because each meter is slightly different from another.

8.6 Tests show that positioning of the meter 2 cm from the end of the suspension rod, instead of 30 cm from the end, results in systematic errors which are incorporated in the calibration equations. These errors are constant. In the first calibration equation the error is -0.34% and in the second equation the error is -0.57%. The magnitude of these errors is close to the error of -0.4% estimated by Levesque (1) for the first set of calibrations conducted at the National Water Research Institute.

ACKNOWLEDGEMENT

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REFERENCES

(1) Levesque, J. M., 1980. "Moulinets Hydromêtriques comparaisons des êtalonnages effectués en Italie, France, Canada et Suisse". Rapport no. 8091, Division Machines, Hydro Québec.

(2) Spiegel, M. R., 1961. "Theory and Problems of Statistics". Schaum Publishing Company, New York.

TABLES

TABLE 1. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600594, WATER TEMPERATURE 18.8°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	101	280.00	10.033	0.361	0.010
2	10	147.5	195.00	20.065	0.756	0.012
3	10	201	170.00	30.109	1.182	0.006
4	10	317	200.00	40.111	1.585	0.005
5	10	323.5	135.00	60.160	2.396	0.003
6	15	320	100.00	80.137	3.200	0.001
7	15	320	80.00	99.820	4.000	-0.002
8	15	314	65.00	120.559	4.831	-0.002
9	15	337.5	60.00	140.222	5.625	-0.004
10	25	321.5	50.00	160.290	6.430	-0.005
11	25	326.5	45.00	181.971	7.256	-0.004
12	25	281	35.00	199.863	8.029	-0.009
13	25	311	35.00	220.646	8.886	-0.015
14	25	292	30.00	240.747	9.733	-0.026
15	25	304.5	30.00	250.863	10.150	-0.029
16	25	301	27.00	275.071	11.148	-0.036
17	25	305	25.00	300.625	12.200	-0.044
18	25	291	22.00	325.676	13.227	-0.050
19	25	300	21.00	351.032	14.286	-0.061
20	25	298.5	19.50	375.748	15.308	-0.069
21	25	294	18.00	400.951	16.333	-0.074
22	25	261	15.00	425.713	17.400	-0.093
23	25	277	15.00	450.410	18.467	-0.113
24	25	273.5	14.00	476.319	19.536	-0.121
25	25	288.5	14.00	500.539	20.607	-0.146
26	35	249.5	11.50	525.619	21.696	-0.168
27	35	227	10.00	550.845	22.700	-0.167
28	35	225	9.50	576.044	23.684	-0.162
29	35	224.5	9.00	600.346	24.944	-0.233

TABLE 2. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600594, WATER TEMPERATURE 18.8°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	101.5	280.00	10.049	0.363	0.010
2	10	148 5	195.00	20.080	0.762	0.010
3	10	200	170.00	30.020	1.176	0.006
4	10	315	200.00	40.094	1.575	0.007
5	10	322	135.00	60.117	2.385	0.005
6	15	319.5	100.00	80.019	3.195	0.001
7	15	321	80.00	100.302	4.013	-0.000
8	15	313.5	65.00	120.417	4.823	-0.002
9	15	336.5	60.00	139.976	5.608	-0.002
10	25	322	50.00	160.321	6.440	-0.007
11	25	325.5	45.00	180.061	7.233	-0.008
12	25	281	35.00	199.326	8.029	-0.014
13	25	310.5	35.00	219.836	8.871	-0.019
14	25	292.5	30.00	241.111	9.750	-0.026
15	25	304.5	30.00	250.597	10.150	-0.032
16	25	301.5	27.00	275.569	11.167	-0.036
17	25	305	25.00	300.544	12.200	-0.045
18	25	291.5	22.00	325.772	13.250	-0.055
19	25	300	21.00	351.075	14.286	-0.061
20	25	298	19.50	375.540	15.282	-0.065
21	25	294.5	18.00	401.129	16.361	-0.079
22	25	261.5	15.00	426.366	17.433	-0.095
23	25	276.5	15.00	450.520	18.433	-0.103
24	25	273.5	14.00	476.485	19.536	-0.119
25	25	288.5	14.00	500.847	20.607	-0.143
26	35	248	11.50	526.356	21.565	-0.128
27	35	227.5	10.00	551.377	22.750	-0.174
28	35	226.5	9.50	576.636	23.842	-0.194
29	35	223.5	9.00	601.226	24.833	-0.196

TABLE 3. CALIBRATION DATA FOR SIAP CURRENT METER

METER NO. 600594, WATER TEMPERATURE 19.6°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	101.5	280.00	10.077	0.363	0.010
2	10	148 5	195.00	20.115	0.762	0.011
3	10	200.5	170.00	30.093	1.179	0.006
4	10	314.5	200.00	40.001	1.573	0.007
5	10	323	135.00	60.089	2.393	0.003
6	15	318.5	100.00	79.883	3.185	0.003
7	15	320.5	80.00	100.182	4.006	0.000
8	15	313.5	65.00	120.252	4.823	-0.003
9	15	338	60.00	140.401	5.633	0.004
10	25	320.5	50.00	159.978	6.410	-0.003
11	25	325	45.00	179.656	7.222	-0.009
12	25	281	35.00	199.686	8.029	-0.010
13	25	311.5	35.00	220.352	8.900	-0.021
14	25	291.5	30.00	240.179	9.717	-0.027
15	25	305.5	30.00	251.287	10.183	-0.033
16	25	301	27.00	274.993	11.148	-0.037
17	25	305	25.00	300.459	12.200	-0.045
18	25	290.5	22.00	325.065	13.205	-0.050
19	25	299.5	21.00	350.455	14.262	-0.061
20	25	299	19.50	375.226	15.333	-0.081
21	25	294.5	18.00	400.880	16.361	-0.081
22	25	261.5	15.00	426.034	17.433	-0.098
23	25	277	15.00	450.876	18.467	-0.108
24	25	273.5	14.00	476.541	19.536	-0.119
25	25	288	14.00	500.688	20.571	-0.136
26	35	249.5	11.50	525.801	21.696	-0.166
27	35	228.5	10.00	550.922	22.850	-0.203
28	35	226	9.50	576.630	23.789	-0.181
29	35	223.5	9.00	601.048	24.833	-0.198

TABLE 4. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600594, WATER TEMPERATURE 12.2°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	108.5	300.00	10.082	0.362	0.010
2	10	227	300.00	20.108	0.757	0.012
3	10	311	267.00	30.073	1.165	0.010
4	10	313.5	200.00	40.084	1.568	0.009
5	10	316	133.00	60.064	2.376	0.007
6	15	319.5	100.00	80.409	3.195	0.005
7	15	320	80.00	100.064	4.000	0.001
8	15	322.5	67.00	120.213	4.813	-0.001
9	15	321	57.00	140.287	5.632	-0.005
10	25	320.5	50.00	159.999	6.410	-0.003
11	25	318	44.00	180.522	7.227	-0.002
12	25	322	40.00	200.568	8.050	-0.007
13	25	319.5	36.00	220.644	8.875	-0.012
14	25	319.5	33.00	240.451	9.682	-0.016
15	25	322	32.00	250.130	10.063	-0.014
16	25	322.5	29.00	275.647	11.121	-0.024
17	25	328.5	27.00	300.462	12.167	-0.037
18	25	290.5	22.00	325.741	13.205	-0.044
19	25	285	20.00	350.402	14.250	-0.058
20	25	290	19.00	375.447	15.263	-0.061
21	25	293.5	18.00	400.576	16.306	-0.071
22	25	277.5	16.00	425.402	17.344	-0.082
23	25	275.5	15.00	450.418	18.367	-0.087
24	25	272.5	14.00	475.971	19.464	-0.106
25	25	267	13.00	502.762	20.538	-0.107
26	35	259	12.00	527.969	21.583	-0.116
27	35	226	10.00	550.784	22.600	-0.142
28	35	212	9.00	575.925	23.556	-0.130
29	35	221	9.00	599.870	24.556	-0.140

TABLE 5. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600594, WATER TEMPERATURE 12.5°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	110.5	300.00	10.107	0.368	0.009
2	10	229	300.00	20.131	0.763	0.011
3	10	316	267.00	30.103	1.184	0.005
4	10	315	200.00	40.032	1.575	0.007
5	10	316	133.00	60.103	2.376	0.007
6	15	319	100.00	80.353	3.190	0.006
7	15	320.5	80.00	100.065	4.006	-0.001
8	15	323	67.00	120.068	4.821	-0.005
9	15	321	57.00	140.214	5.632	-0.006
10	25	321.5	50.00	160.371	6.430	-0.004
11	25	317.5	44.00	180.234	7.216	-0.002
12	25	322	40.00	200.416	8.050	-0.008
13	25	319.5	36.00	220.515	8.875	-0.014
14	25	319.5	33.00	240.445	9.682	-0.016
15	25	322.5	32.00	250.423	10.078	-0.015
16	25	323	29.00	275.662	11.138	-0.028
17	25	328.5	27.00	300.605	12.167	-0.036
18	25	290.5	22.00	325.765	13.205	-0.043
19	25	284.5	20.00	350.209	14.225	-0.054
20	25	290	19.00	375.388	15.263	-0.062
21	25	293.5	18.00	400.389	16.306	-0.072
22	25	277.5	16.00	425.482	17.344	-0.081
23	25	275.5	15.00	450.298	18.367	-0.089
24	25	272.5	14.00	476.107	19.464	-0.105
25	25	265.5	13.00	500.098	20.423	-0.105
26	35	257.5	12.00	525.074	21.458	-0.114
27	35	225.5	10.00	550.582	22.550	-0.132
28	35	212	9.00	575.819	23.556	-0.131
29	35	220.5	9.00	599.968	24.500	-0.126

TABLE 6. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600591, WATER TEMPERATURE 12.9°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	105	300.00	10.113	0.350	0.014
2	10	227	300.00	20.139	0.757	0.012
3	10	308.5	267.00	30.127	1.155	0.012
4	10	310.5	200.00	40.100	1.553	0.013
5	10	315	133.00	60.218	2.368	0.010
6	15	319.5	100.00	80.417	3.195	0.005
7	15	321	80.00	100.703	4.013	0.004
8	15	322	67.00	120.220	4.806	0.001
9	15	319.5	57.00	140.407	5.605	0.003
10	25	321 5	50.00	160.681	6.420	0.002
11	25	317.5	44.00	180.604	7.216	0.002
12	25	321	40.00	200.576	8.025	0.000
13	25	317.5	36.00	220.638	8.819	0.002
14	25	319	33.00	240.745	9.667	-0.009
15	25	321.5	32.00	250.561	10.047	-0.006
16	25	321	29.00	275.924	11.069	-0.008
17	25	327	27.00	300.789	12.111	-0.020
18	25	289.5	22.00	325.882	13.159	-0.031
19	25	283	20.00	350.638	14.150	-0.031
20	25	289	19.00	375.764	15.211	-0.045
21	25	292.5	18.00	400.746	16.250	-0.055
22	25	276.5	16.00	425.828	17.281	-0.062
23	25	275	15.00	450.738	18.333	-0.076
24	25	270.5	14.00	475.422	19.321	0.076
25	25	265	13.00	500.697	20.385	-0.089
26	35	257	12.00	525.315	21.417	-0.101
27	35	225.5	10.00	550.805	22.550	-0.129
28	35	211.5	9.00	575.771	23.500	-0.117
29	35	221.5	9.00	600.862	24.611	-0.144

TABLE 7. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600592, WATER TEMPERATURE 12.9°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	106.5	300.00	10.094	0.355	0.012
2	10	224	300.00	20.115	0.747	0.014
3	10	310.5	267.00	30.164	1.163	0.011
4	10	310.5	200.00	40.060	1.553	0.012
5	10	314	133.00	60.007	2.361	0.010
6	15	317.5	100.00	80.922	3.175	0.005
7	15	317.5	80.00	100.472	3.969	0.002
8	15	322	67.00	120.223	4.806	0.001
9	15	320	57.00	140.385	5.614	0.000
10	25	320	50.00	160.121	6.400	0.001
11	25	317	44.00	180.030	7.205	-0.001
12	25	320	40.00	200.099	8.000	0.001
13	25	318	36.00	220.336	8.833	-0.005
14	25	318.5	33.00	240.219	9.652	-0.011
15	25	322.5	32.00	250.706	10.078	-0.012
16	25	320.5	29.00	274.791	11.052	-0.015
17	25	326.5	27.00	300.142	12.093	-0.022
18	25	289.5	22.00	325.620	13.159	-0.034
19	25	283.5	20.00	350.204	14.175	-0.042
20	25	289	19.00	375.058	15.211	-0.052
21	25	292.5	18.00	400.285	16.250	-0.060
22	25	276.5	16.00	425.147	17.281	-0.069
23	25	274.5	15.00	449.966	18.300	-0.075
24	25	270.5	14.00	475.224	19.321	0.078
25	25	264.5	13.00	500.505	20.346	-0.081
26	35	256.5	12.00	525.397	21.375	-0.090
27	35	224.5	10.00	550.513	22.450	-0.107
28	35	211	9.00	575.781	23.444	-0.103
29	35	219.5	9.00	600.447	24.389	-0.093

TABLE 8. CALIBRATION DATA FOR SIAP CURRENT METER

METER NO. 600593, WATER TEMPERATURE 13.8°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	98.5	300.00	10.103	0.328	0.019
2	10	223.5	300.00	20.160	0.745	0.015
3	10	310.5	267.00	30.059	1.163	0.010
4	10	316.5	200.00	40.131	1.583	0.006
5	10	318.5	133.00	60.195	2.395	0.003
6	15	321	100.00	80.465	3.210	0.002
7	15	321.5	80.00	100.739	4.019	0.003
8	15	323.5	67.00	120.964	4.828	0.003
9	15	320	57.00	140.470	5.614	0.001
10	25	320	50.00	160.232	6.400	0.002
11	25	316.5	44.00	180.058	7.193	0.002
12	25	321.5	40.00	200.806	8.038	-0.001
13	25	318	36.00	220.251	8.833	-0.006
14	25	318.5	33.00	240.265	9.652	-0.010
15	25	321.5	32.00	250.984	10.047	-0.012
16	25	321.5	29.00	274.284	11.086	-0.019
17	25	327	27.00	300.471	12.111	-0.023
18	25	289.5	22.00	325.584	13.159	-0.034
19	25	284	20.00	350.026	14.200	-0.050
20	25	289.5	19.00	375.063	15.237	-0.059
21	25	293.5	18.00	400.416	16.306	-0.072
22	25	277.5	16.00	425.313	17.344	-0.083
23	25	276	15.00	449.837	18.400	-0.092
24	25	271.5	14.00	475.216	19.393	0.096
25	25	265.5	13.00	500.248	20.423	-0.103
26	35	257.5	12.00	525.223	21.458	-0.112
27	35	225	10.00	550.553	22.500	-0.119
28	35	211.5	9.00	575.692	23.500	-0.118
29	35	221.5	9.00	600.051	24.611	-0.152

TABLE 9. CALIBRATION DATA FOR SIAP CURRENT METER

METER NO. 600594, WATER TEMPERATURE 16.4°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	107.5	300.00	10.101	0.358	0.011
2	10	228	300.00	20.100	0.760	0.011
3	10	311	267.00	30.064	1.165	0.009
4	10	312.5	200.00	40.042	1.563	0,010
5	10	316.5	133.00	60.068	2.380	0.006
6	15	320	100.00	80.215	3.200	0.002
7	15	321.5	80.00	100.504	4.019	0.000
8	15	323.5	67.00	120.660	4.828	0.000
9	15	320.5	57.00	140.128	5.623	-0.004
10	25	320	50.00	160.695	6.400	-0.003
11	25	317.5	44.00	180.293	7.216	-0.001
12	25	322.5	40.00	200.919	8.063	-0.006
13	25	319.5	36.00	220.407	8.875	-0.015
14	25	319.5	33.00	240.233	9.682	-0.018
15	25	323.5	32.00	250.583	10.109	-0.022
16	25	323	29.00	274.589	11.138	-0.029
17	25	328.5	27.00	300.427	12.167	-0.037
18	25	290.5	22.00	325.616	13.205	-0.045
19	25	284.5	20.00	350.653	14.225	-0.050
20	25	290	19.00	375.683	15.263	-0.059
21	25	293.5	18.00	401.048	16.306	-0.066
22	25	277.5	16.00	425.897	17.344	-0.077
23	25	276	15.00	451.291	18.400	-0.087
24	25	272	14.00	475.714	19.429	0.100
25	25	266	13.00	500.644	20.462	-0.109
26	35	259	12.00	525.842	21.583	-0.137
27	35	226	10.00	550.960	22.600	-0.140
28	35	213	9.00	575.918	23.667	-0.157
29	35	223	9.00	600.864	24.778	-0.186

TABLE 10. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600595, WATER TEMPERATURE 13.8°C

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	105.5	300.00	10.102	0.352	0.013
2	10	223.5	300.00	20.113	0.745	0.015
3	10	308.5	267.00	30.101	1.155	0.012
4	10	310 5	200.00	40.078	1.553	0.013
5	10	315	133.00	60.045	2.368	0.008
6	15	320	100.00	80.515	3.200	0.005
7	15	320.5	80.00	100.654	4.006	0.005
8	15	322.5	67.00	120.760	4.813	0.004
9	15	319	57.00	140.218	5.596	0.003
10	25	319	50.00	160.826	6.380	0.003
11	25	316	44.00	180.888	7.182	0.003
12	25	320.5	40.00	200.655	8.013	0.003
13	25	318	36.00	220.192	8.833	-0.006
14	25	318.5	33.00	240.069	9.652	-0.012
15	25	321.5	32.00	250.315	10.047	-0.009
16	25	321	29.00	275.068	11.069	-0.017
17	25	327	27.00	300.144	12.111	-0.026
18	25	289.5	22.00	325.563	13.159	-0.034
19	25	283.5	20.00	349.828	14.175	-0.045
20	25	289	19.00	374.991	15.211	-0.053
21	25	292.5	18.00	400.004	16.250	-0.062
22	25	276.5	16.00	424.976	17.281	-0.071
23	25	275	15.00	450.536	18.333	-0.078
24	25	271	14.00	474.991	19.357	0.089
25	25	266.5	13.00	501.737	20.500	-0.108
26	35	257.5	12.00	525.323	21.458	-0.111
27	35	224.5	10.00	550.469	22.450	-0.108
28	35	211	9.00	575.377	23.444	-0.107
29	35	221	9.00	600.247	24.556	-0.136

TABLE 11. CALIBRATION DATA FOR SIAP CURRENT METER
METER NO. 600594, WATER TEMPERATURE 14.7°C
METER MOUNTED 2 CM FROM END OF SUSPENSION ROD

Run No.	Waiting Time (min)	Revs	Time sec	Actual Speed cm/s	N rev/s	ΔV m/s
1	10	110	300.00	10.093	0.367	0.009
2	10	228.5	300.00	20.113	0.762	0.011
3	10	310.5	267.00	30.100	1.163	0.010
4	10	314	200.00	40.049	1.570	0.008
5	10	317	133.00	59.991	2.383	0.004
6	15	322	100.00	80.432	3.220	-0.001
7	15	322	80.00	100.548	4.025	-0.001
8	15	325.5	67.00	120.874	4.858	-0.006
9	15	322	57.00	140.440	5.649	-0.008
10	25	322	50.00	160.149	6.440	-0.009
11	25	319	44.00	180.032	7.250	-0.012
12	25	323.5	40.00	200.645	8.088	-0.015
13	25	320.5	36.00	220.253	8.903	-0.023
14	25	320.5	33.00	240.976	9.712	-0.028
15	25	324.5	32.00	250.060	10.141	-0.035
16	25	324.5	29.00	275.216	11.190	-0.045
17	25	330	27.00	300.259	12.222	-0.053
18	25	292	22.00	325.567	13.273	-0.063
19	25	285.5	20.00	349.219	14.275	-0.067
20	25	291.5	19.00	374.470	15.342	-0.081
21	25	295	18.00	400.404	16.389	-0.093
22	25	279	16.00	424.402	17.438	-0.105
23	25	277.5	15.00	450.029	18.500	-0.115
24	25	273.5	14.00	474.651	19.536	0.127
25	25	267	13.00	501.935	20.538	-0.125
26	35	259.5	12.00	527.648	21.625	-0.130
27	35	226.5	10.00	551.260	22.650	-0.150
28	35	213	9.00	576.060	23.667	-0.156
29	35	223	9.00	600.939	24.778	-0.185

TABLE 12. CALIBRATION EQUATION FOR ALL FIVE METERS

Calibration No.	Meter No.	N_c rev/s	Equation for $0 < N < N_c$			Equation for $N_c<N<20$		
			m_1	a_1	r_1	m_2	a_2	r_2
1	600591	10.6	24.8047	1.3865	0.999996	24.1486	8.4572	0.999993
2	600592	9.9	24.7779	1.4001	0.999996	24.1812	7.3799	0.999996
3	600593	10.3	24.7752	1.3552	0.999982	24.0243	9.0818	0.999978
4	600594	8.9	24.7417	1.2315	0.999990	24.1636	6.5912	0.999988
5	600595	8.9	24.8153	1.4042	0.999990	24.1399	7.8028	0.999998

TABLE 13. EQUATIONS FOR FIVE CONSECUTIVE CALIBRATIONS OF METER 600594

Calibration No.	Meter No.	N_c rev/s	Equation for $0 < N < N_c$			Equation for $N_c<N<20$		
			m_1	a_1	r_1	m_2	a_2	r_2
1	600594	8.9	24.7730	0.9524	0.999992	24.0181	7.6409	0.999947
2	600594	9.1	24.7195	1.1271	0.999996	23.9850	8.0044	0.999932
3	600594	8.9	24.7424	1.0585	0.999995	24.0031	7.6016	0.999973
4	600594	9.6	24.7490	1.2331	0.999992	24.0999	7.4590	0.999987
5	600594	9.6	24.7576	1.0593	0.999986	24.1146	7.2402	0.999993

TABLE 14. CALIBRATION EQUATION TO STUDY EFFECT OF SUSPENSION ROD

Calibration No.	Meter No.	N_c rev/s	Equation for $0 < N < N_c$			Equation for $N_c<N<20$		
			m_1	a_1	r_1	m_2	a_2	r_2
1	600594	8.9	24.6552	1.2396	0.999996	24.0227	8.5865	0.999995

TABLE 15. ACCURACY OF CALIBRATION FOR METER NO. 600594
AT 99% CONFIDENCE

N rev/s	Towing Speed cm/s Calibration No. 1	Calibration No. 2	Calibration No. 3	Calibration No. 4	Calibration No. 5	Mean Speed V cm/s	Standard Deviation S_V cm/s	E %
2	50.498	50.566	50.543	50.731	50.575	50.583	0.079	0.359
4	100.044	100.005	100.028	100.229	100.090	100.079	0.080	0.184
6	149.590	149.444	149.513	149.727	149.605	149.576	0.095	0.146
8	199.136	198.883	198.998	199.225	199.120	199.072	0.119	0.138
8-9	221.432	221.131	221.266	221.499	221.402	221.346	0.132	0.137
10	247.822	247.854	247.633	248.458	248.386	248.031	0.329	0.305
12	295.858	295.824	295.639	296.658	296.615	296.119	0.429	0.333
14	343.894	343.794	343.645	344.858	344.845	344.207	0.532	0.356
16	391.931	391.764	391.651	393.057	393.074	392.295	0.635	0.372
18	439.967	439.734	439.657	441.257	441.303	440.384	0.739	0.386
20	488.003	487.704	487.664	489.457	489.532	488.472	0.843	0.397

TABLE 16. COMPARISON OF CALIBRATIONS FOR METER NO. 600594 IN DIFFERENT TOWING TANK

Average for 5 Calibrations			Percent Difference from Reference Calibration E_v			
N rev/s	V_5 cm/s	*E%	Italian	French	Swiss	Canadian
2	50.583	0.359	-0.994	0.192	0.330	0.271
4	100.079	0.184	-0.519	0.181	0.171	0.121
6	149.576	0.146	-0.358	0.177	0.116	0.070
8	199.072	0.138	-0.318	0.175	0.089	0.049
10	248.031	0.305	-0.577	0.391	0.290	0.080
12	296.119	0.333	-0.459	0.230	0.291	0.146
14	344.204	0.356	-0.373	0.115	0.301	0.197
16	392.295	0.372	-	0.027	0.307	0.233
18	440.384	0.386	-	-0.042	0.313	0.262
20	488.472	0.397	-	-	0.317	0.285

*E = % uncertainty at 99% confidence level in the reference calibration from Table 15

TABLE 17. UNCERTAINTY OF GROUP CALIBRATIONS

N rev/s	Uncertainty In Group Mean Velocity % Eq			
	Italian	French	Swiss	Canadian
2	2.51	0.46	0.20	0.50
4	1.92	0.42	0.25	0.37
6	1.75	0.41	0.35	0.33
8	1.66	0.37	0.40	0.30
10	1.79	0.69	0.41	0.38
12	1.88	0.62	0.48	0.42

TABLE 18. PERCENT CHANGE IN CALIBRATION AS A RESULT OF METER POSITION ON SUSPENSION ROD

N rev/s	V_{30} cm/s	V_2 cm/s	E_2%
2	50.715	50.550	-0.325
4	100.198	99.860	-0.337
6	149.682	149.171	-0.342
8	199.165	198.481	-0.343
	221.433	220.671	-0.344
10	248.227	246.814	-0.569
12	296.554	294.859	-0.572
14	344.882	342.904	-0.573
16	393.209	390.950	-0.575
18	441.536	438.995	-0.576
20	489.863	487.041	-0.576

Subscript "30" indicates meter position 30 cm above end of rod.

Subscript "2" indicates meter position 2 cm above end of rod.

FIGURES

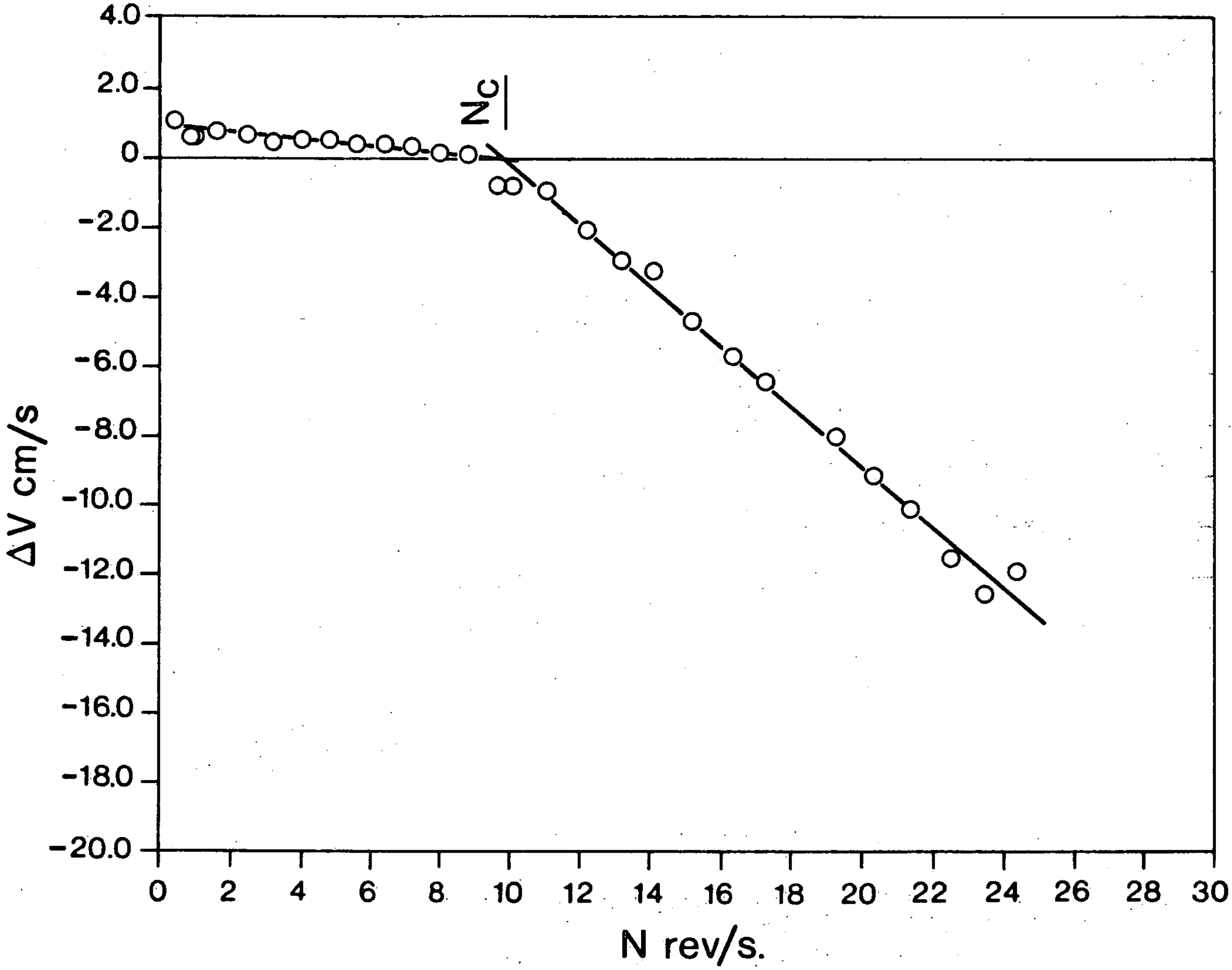


FIGURE 1. TYPICAL PLOT OF ΔV vs N

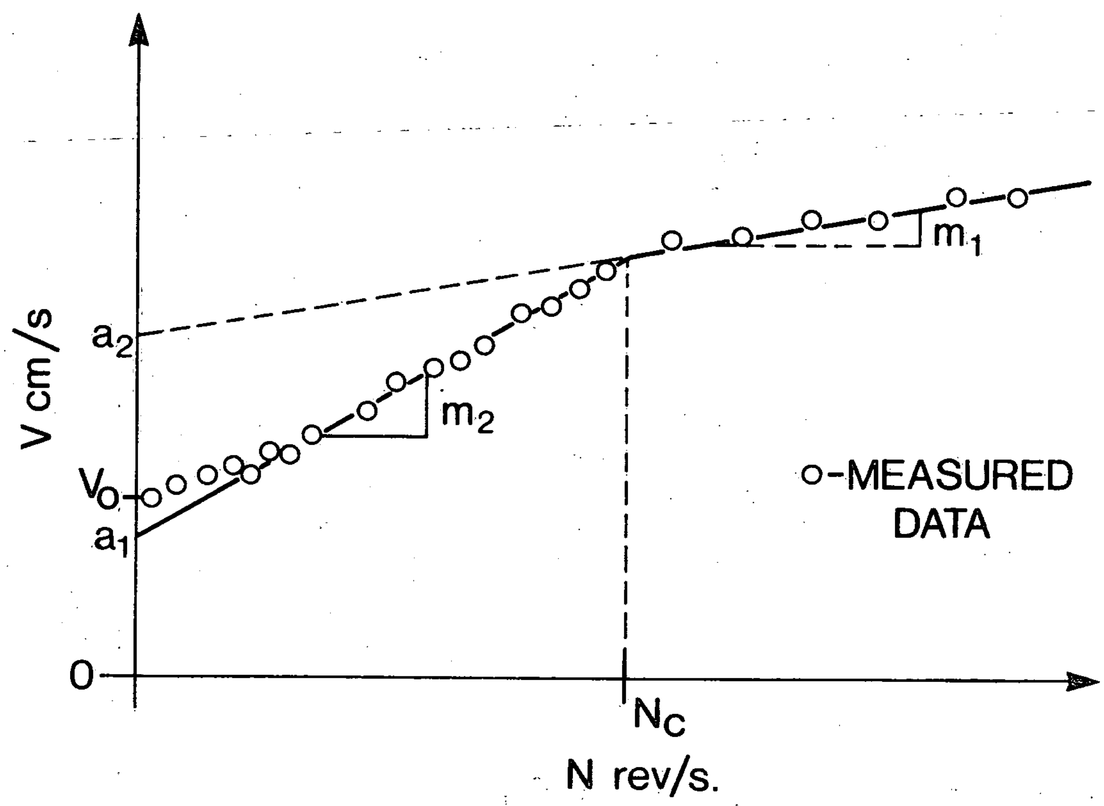


FIGURE 2. SCHEMATIC REPRESENTATION OF CALIBRATION EQUATIONS

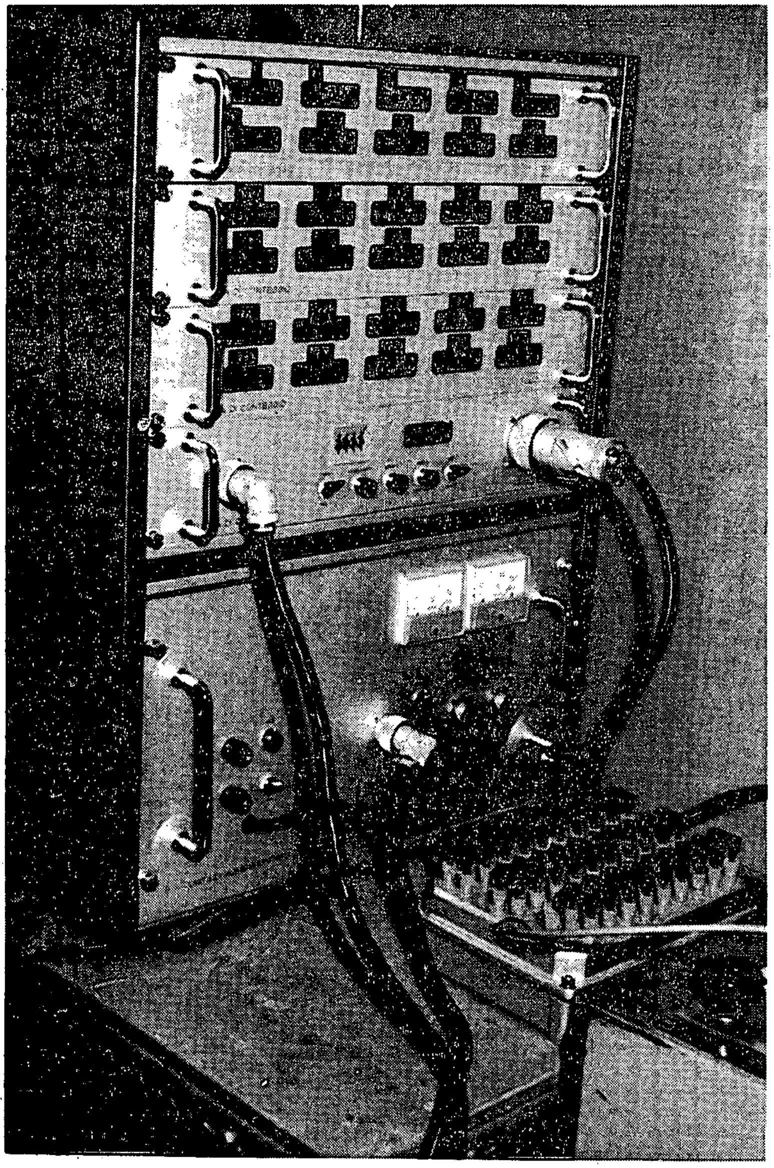


FIGURE 3. SIAP REVOLUTION COUNTER AND TIMER

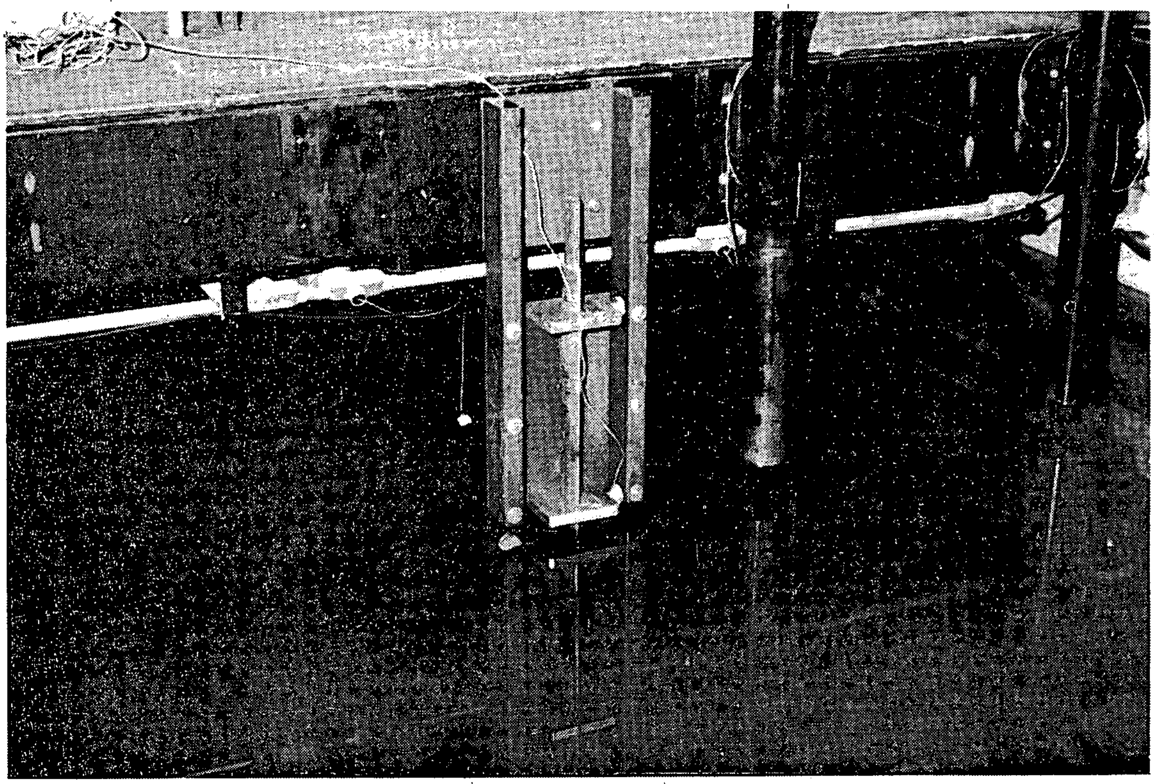


FIGURE 4. METER SUSPENSION POST AT REAR OF TOWING CARRIAGE

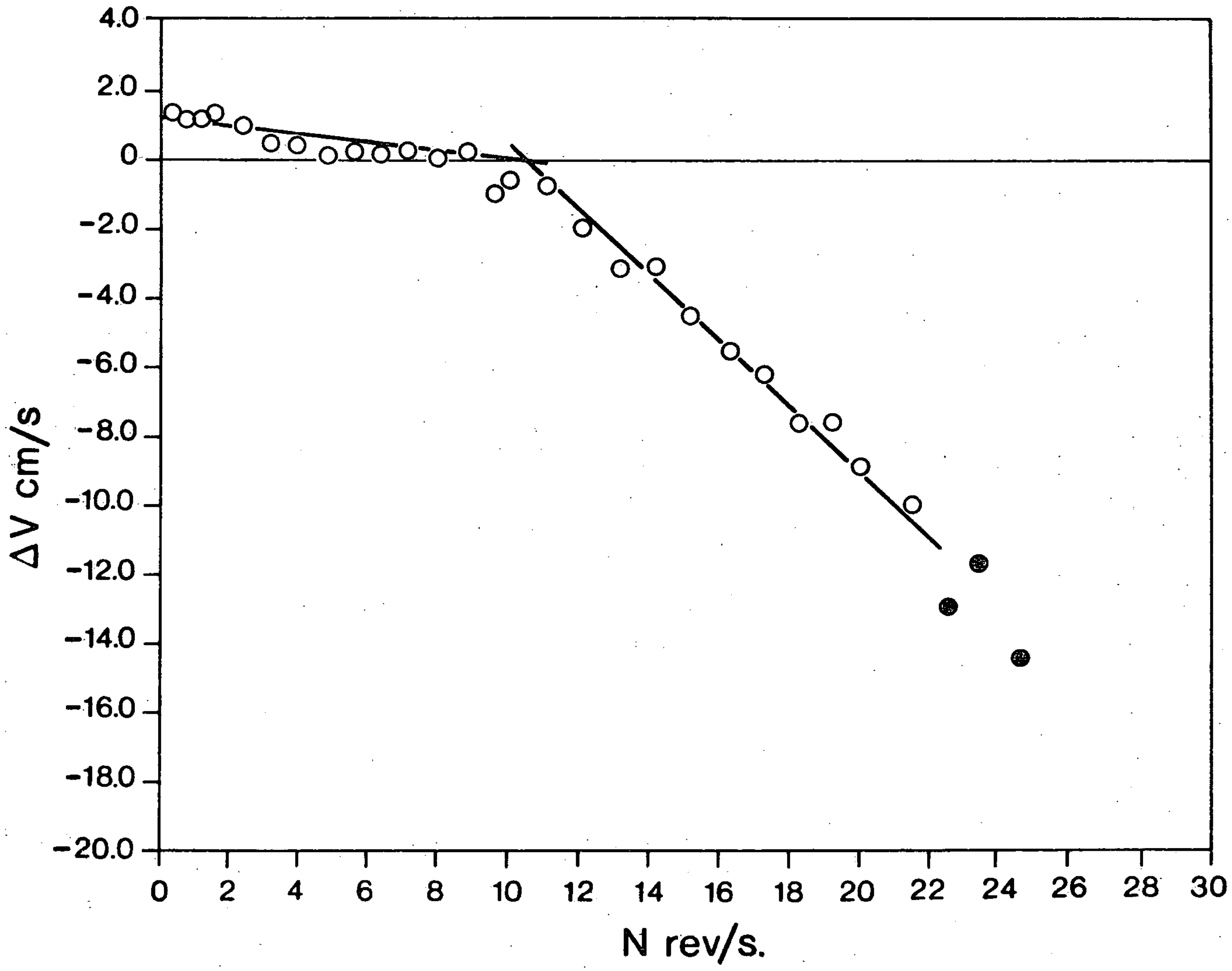


FIGURE 5. CALIBRATION FOR METER No. 600591

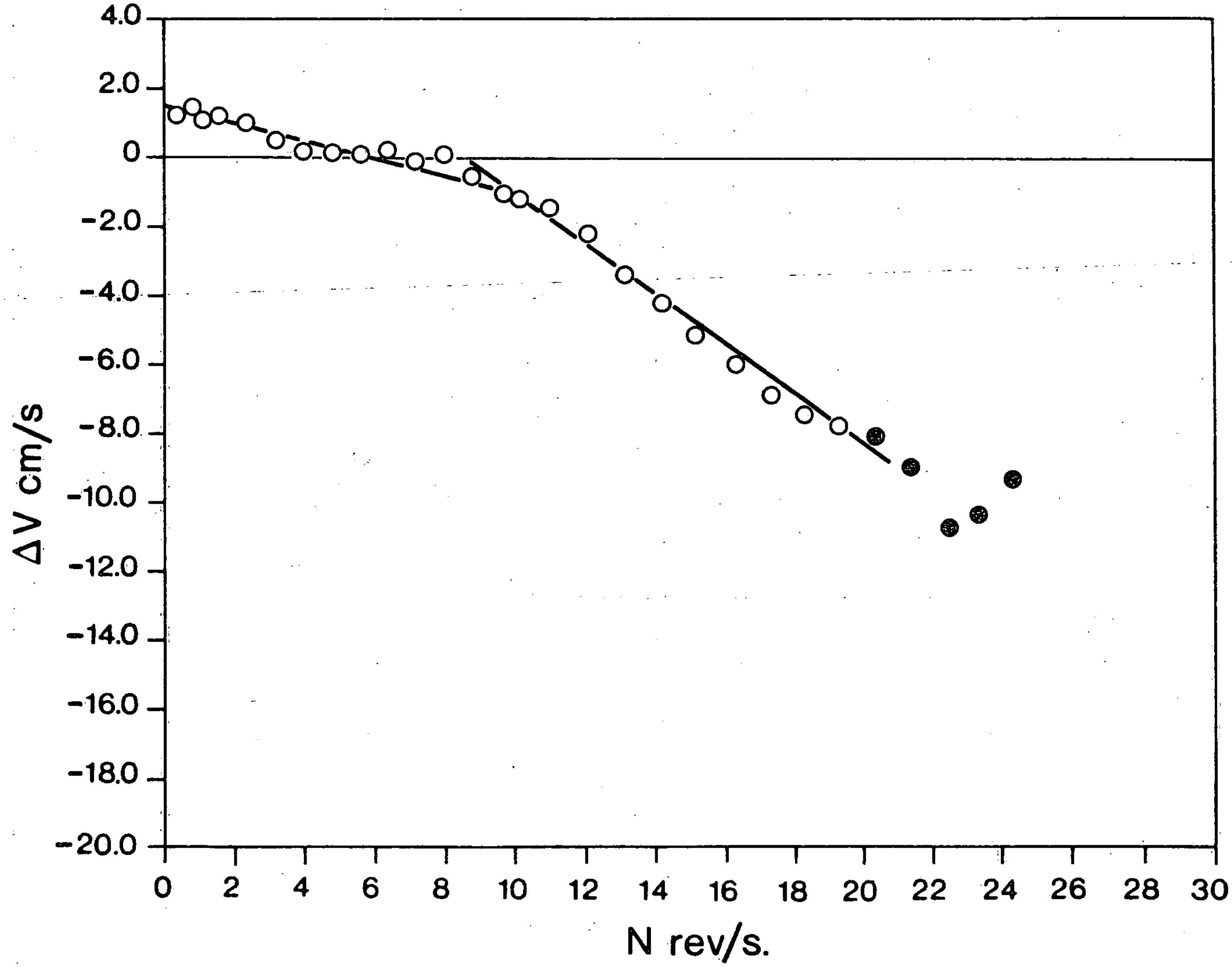


FIGURE 6. CALIBRATION FOR METER No. 600592

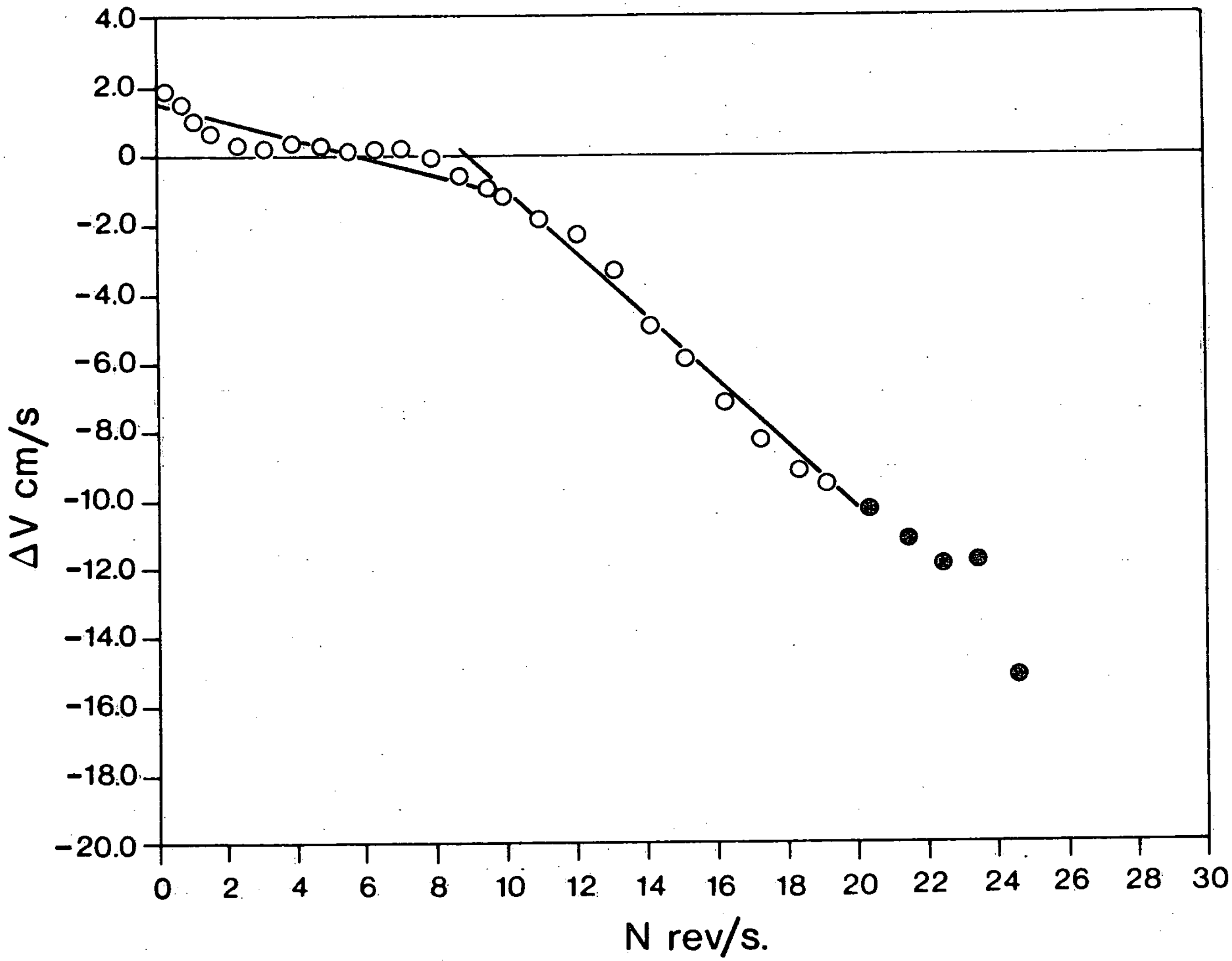


FIGURE 7. CALIBRATION FOR METER No. 600593

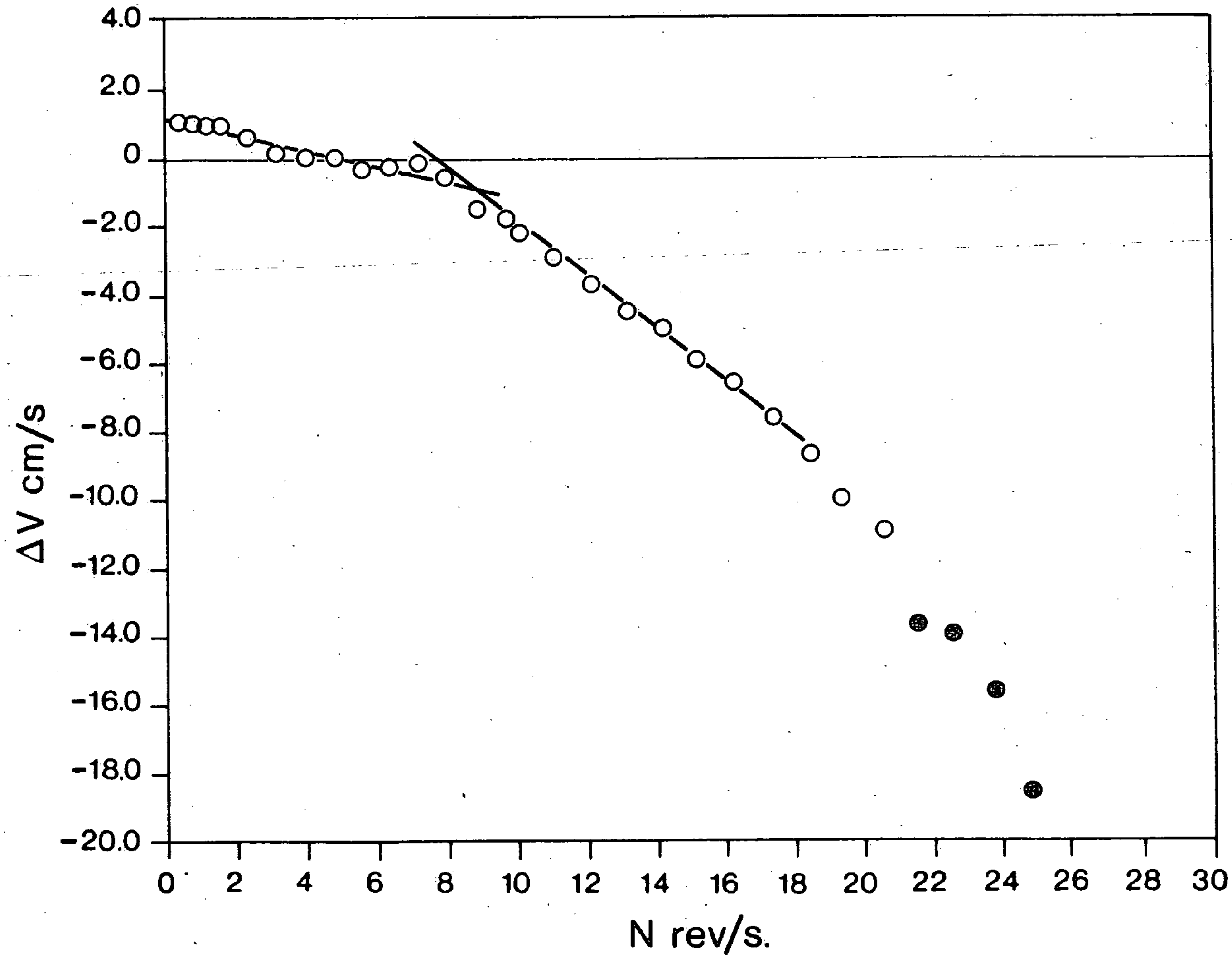


FIGURE 8. CALIBRATION FOR METER No. 600594

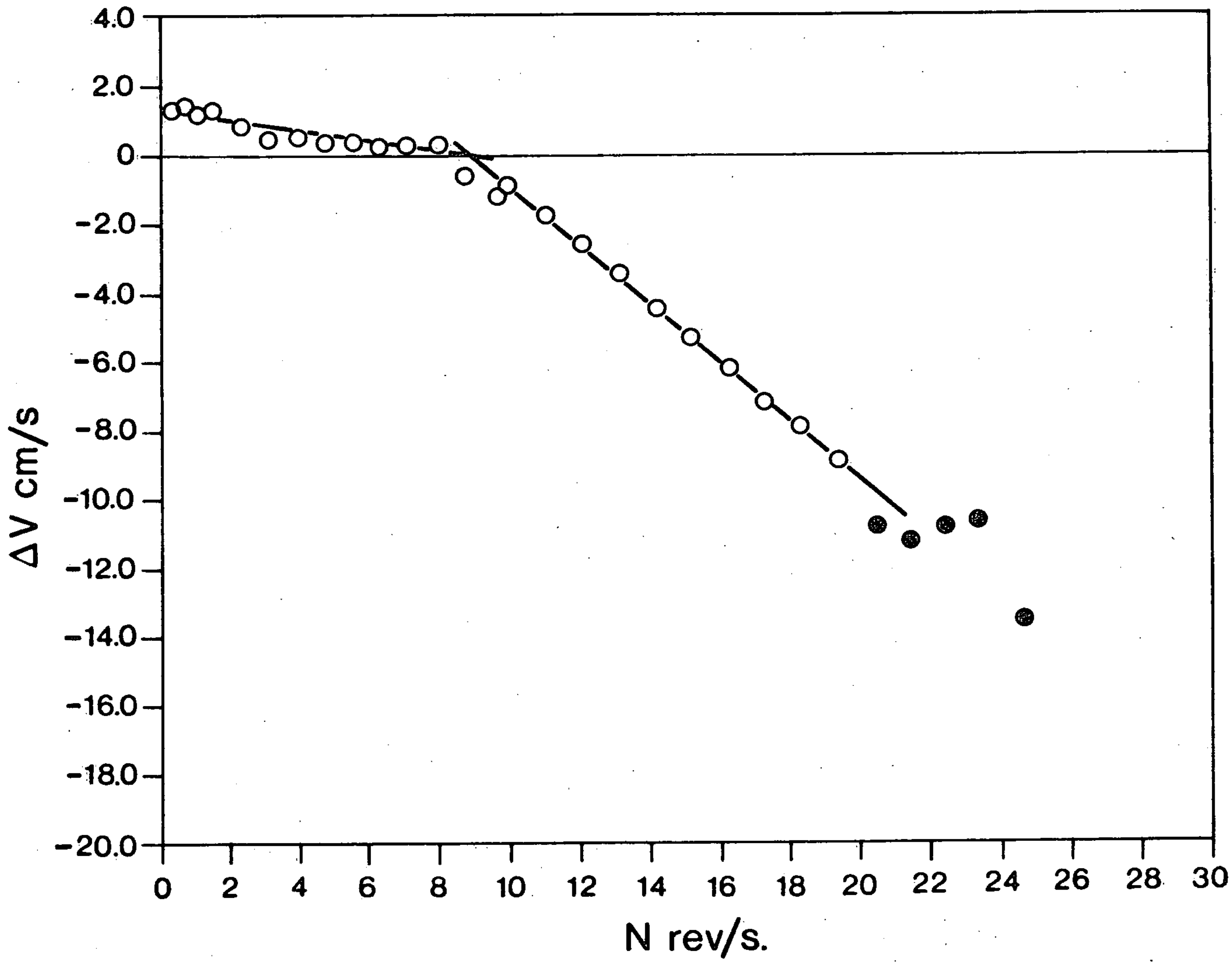


FIGURE 9. CALIBRATION FOR METER No. 600595

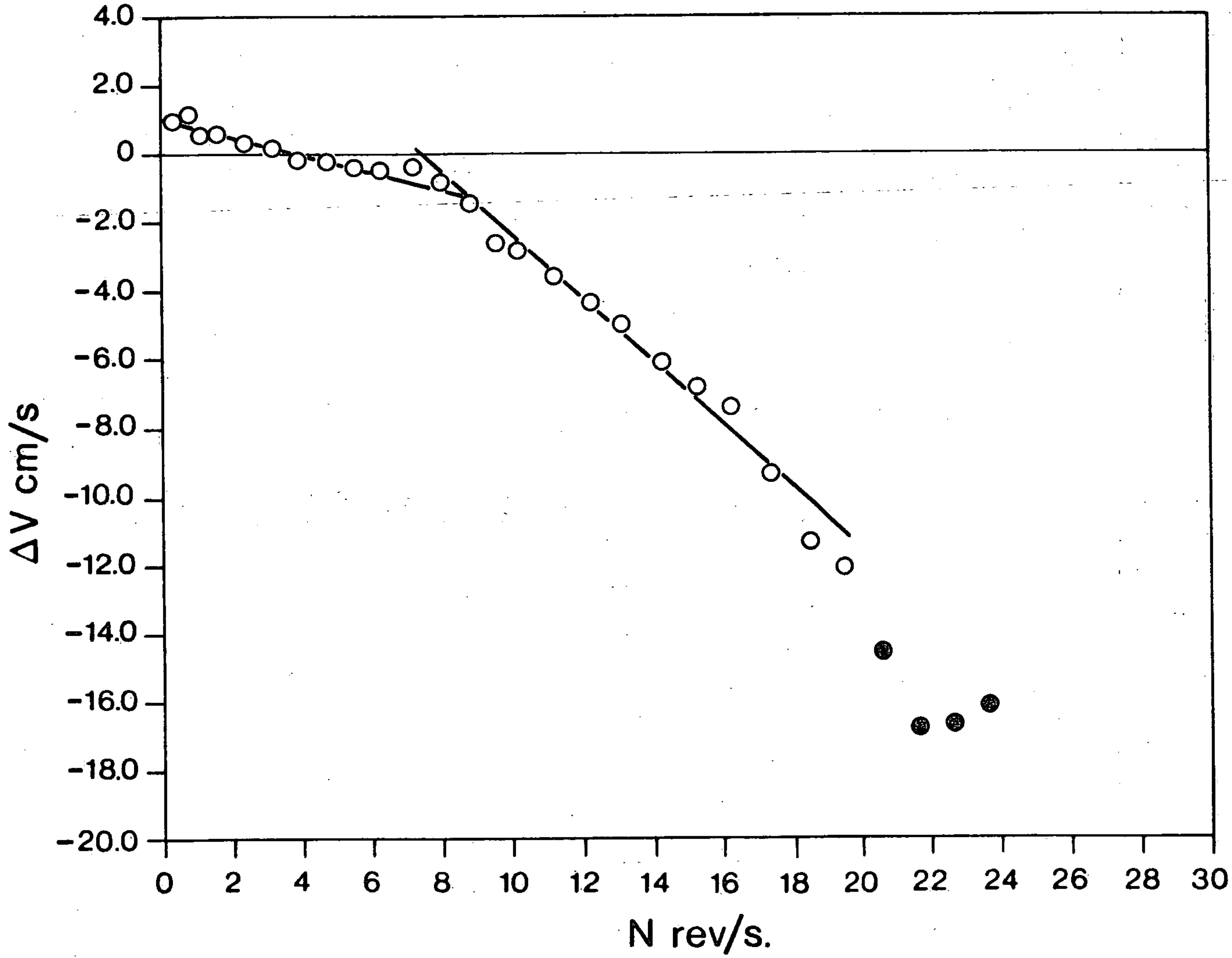


FIGURE 10. CALIBRATION No. 1 FOR METER No. 600594

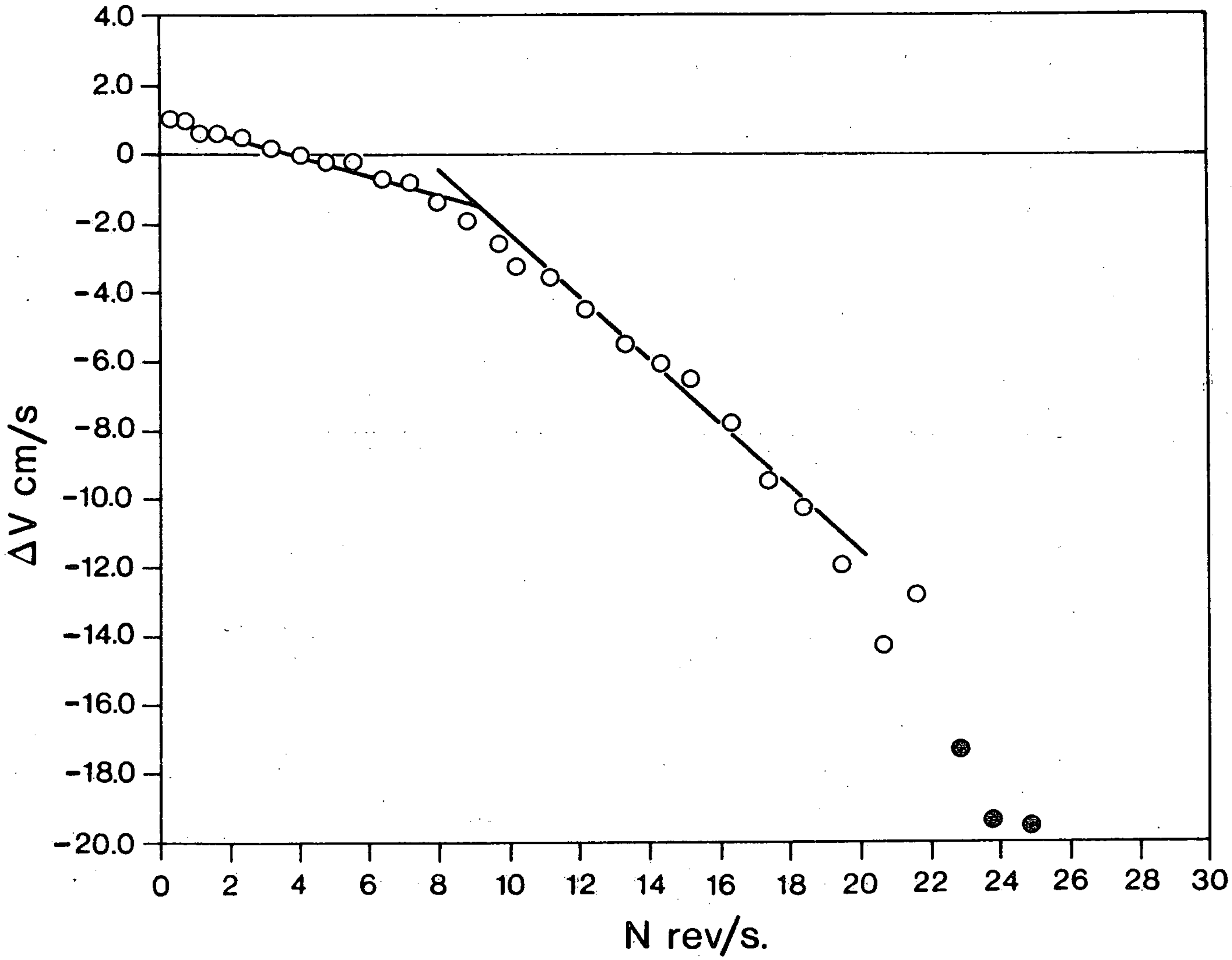


FIGURE 11. CALIBRATION No. 2 FOR METER No. 600594

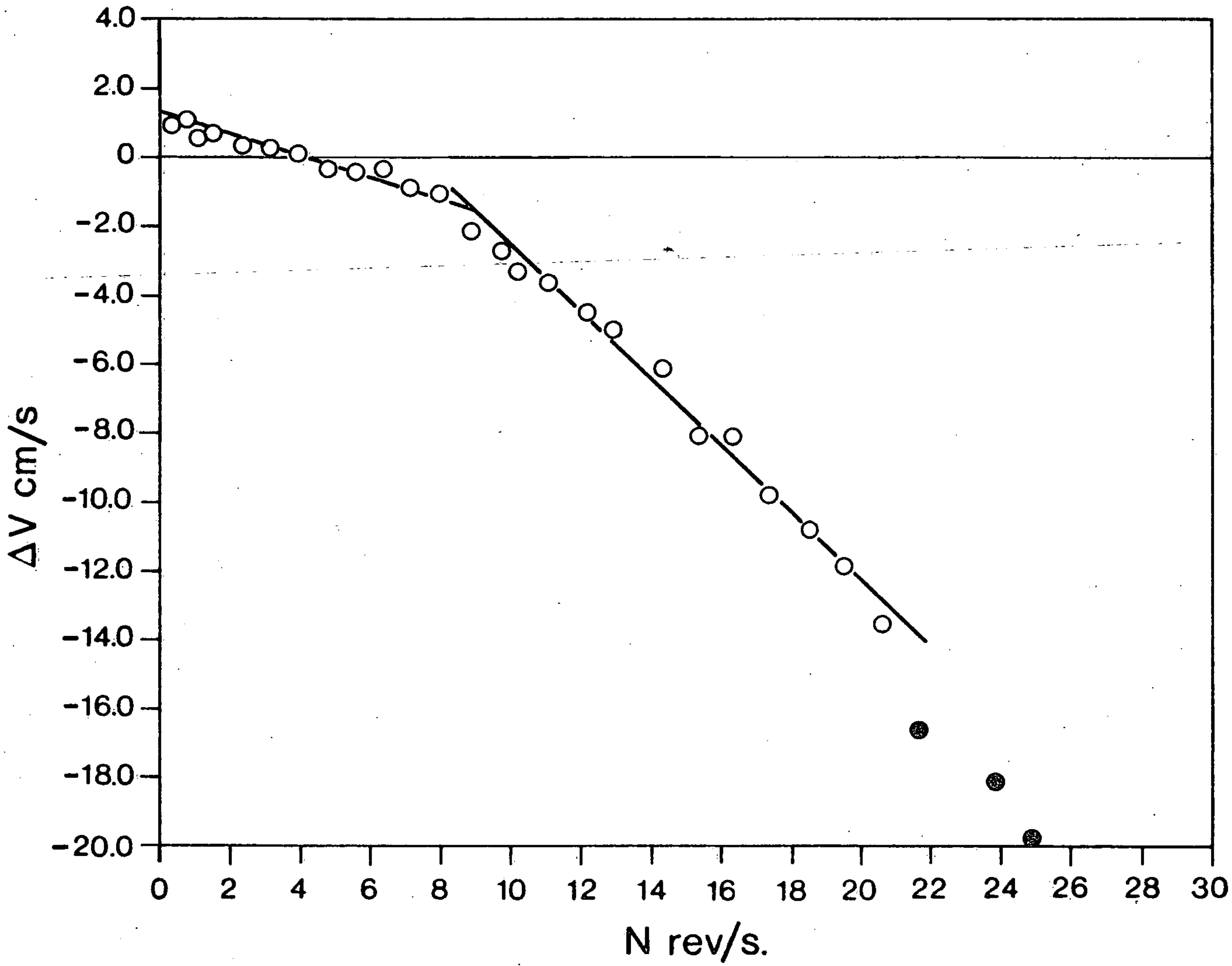


FIGURE 12. CALIBRATION No. 3 FOR METER No. 600594

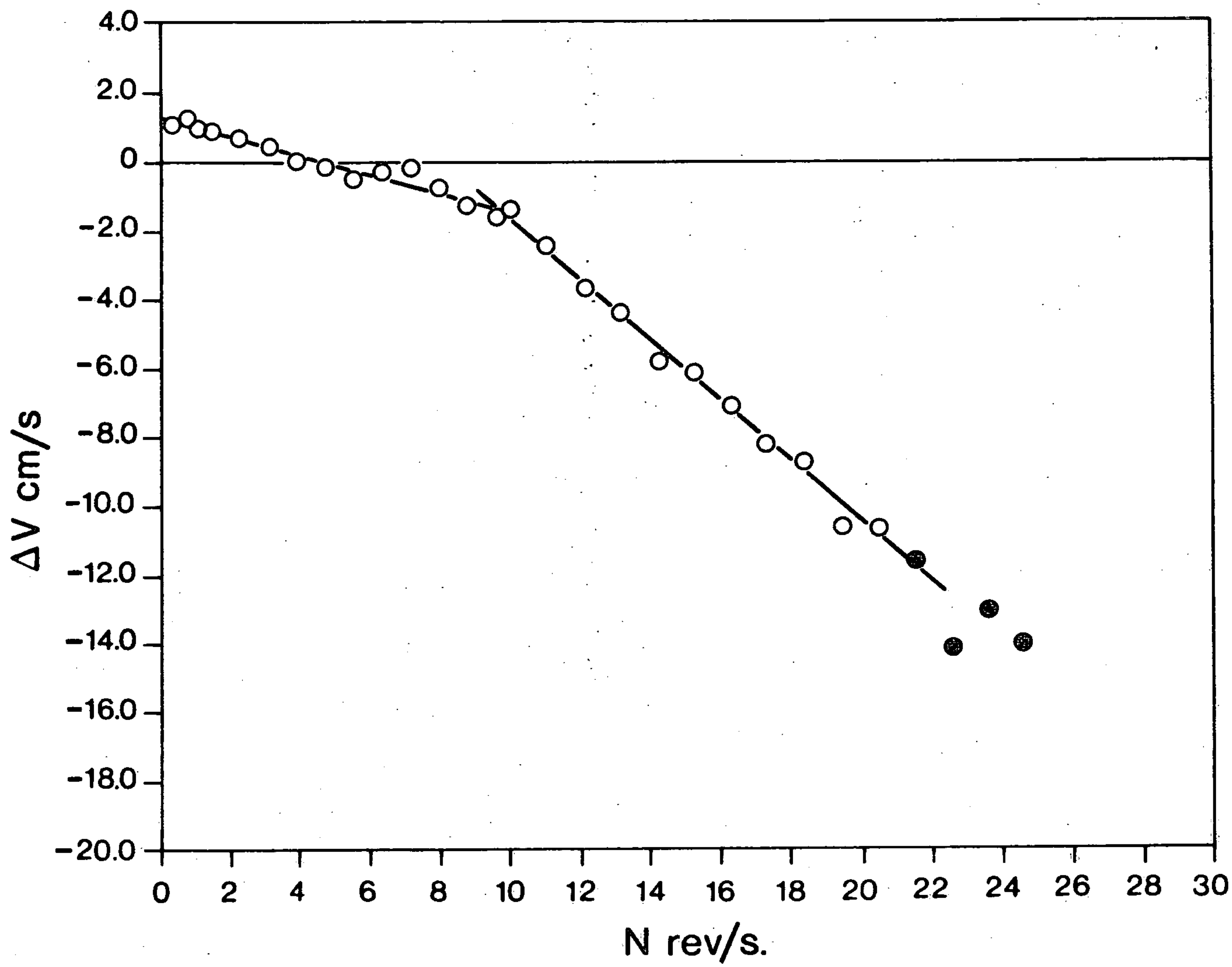


FIGURE 13. CALIBRATION No.4 FOR METER No.600594

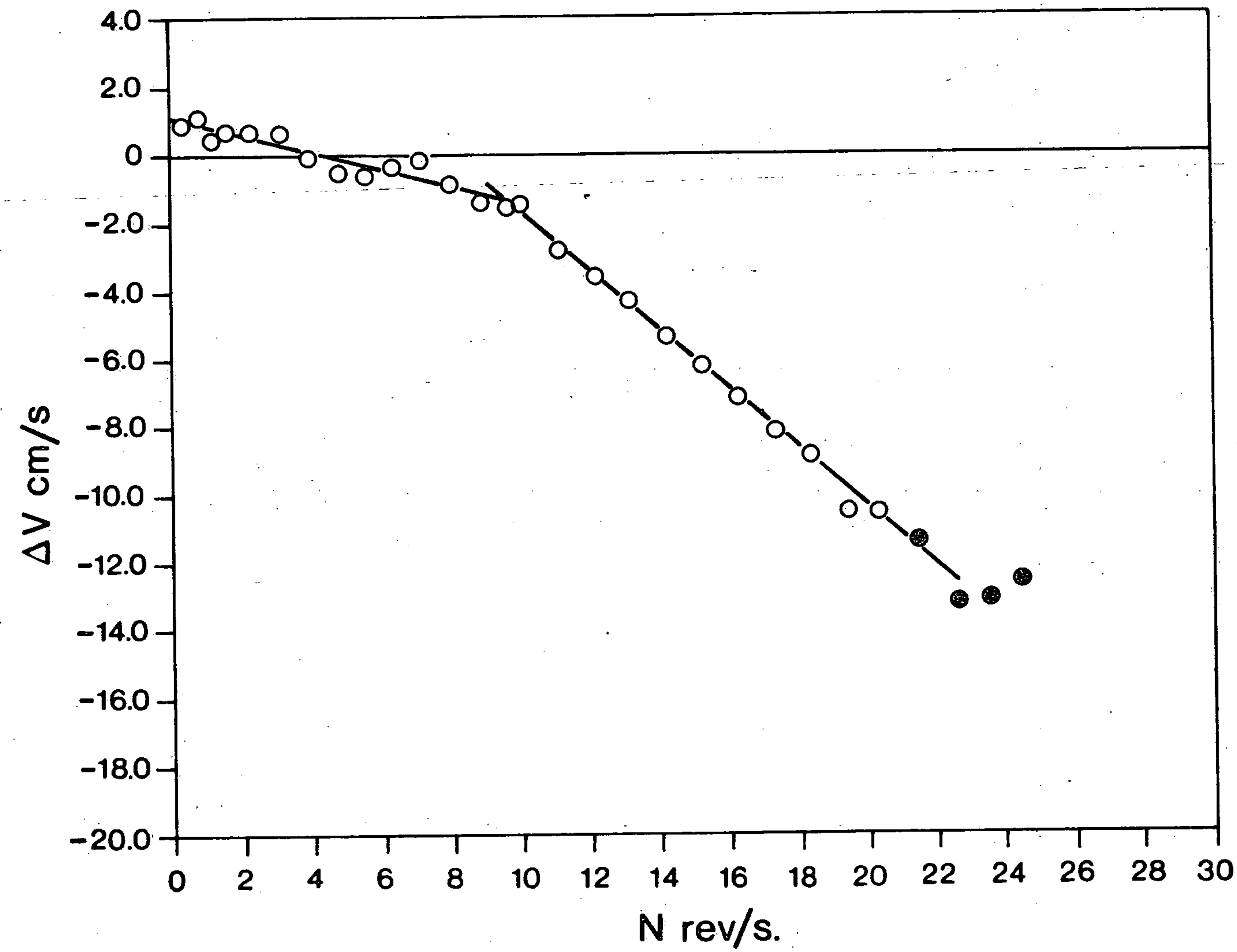


FIGURE 14. CALIBRATION No. 5 FOR METER No. 600594

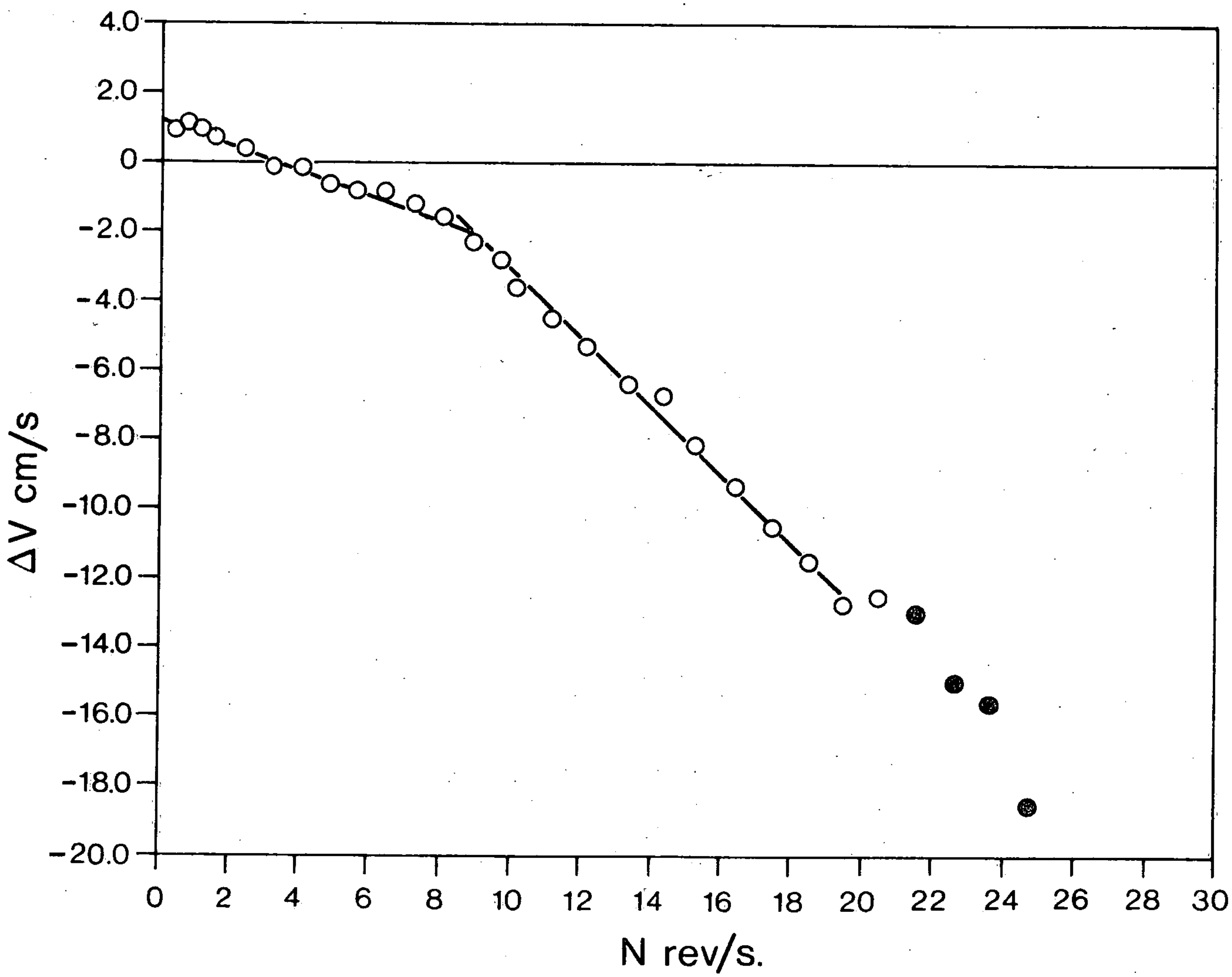


FIGURE 15. CALIBRATION FOR METER No. 600594 POSITIONED 2 cm FROM END OF SUSPENSION ROD

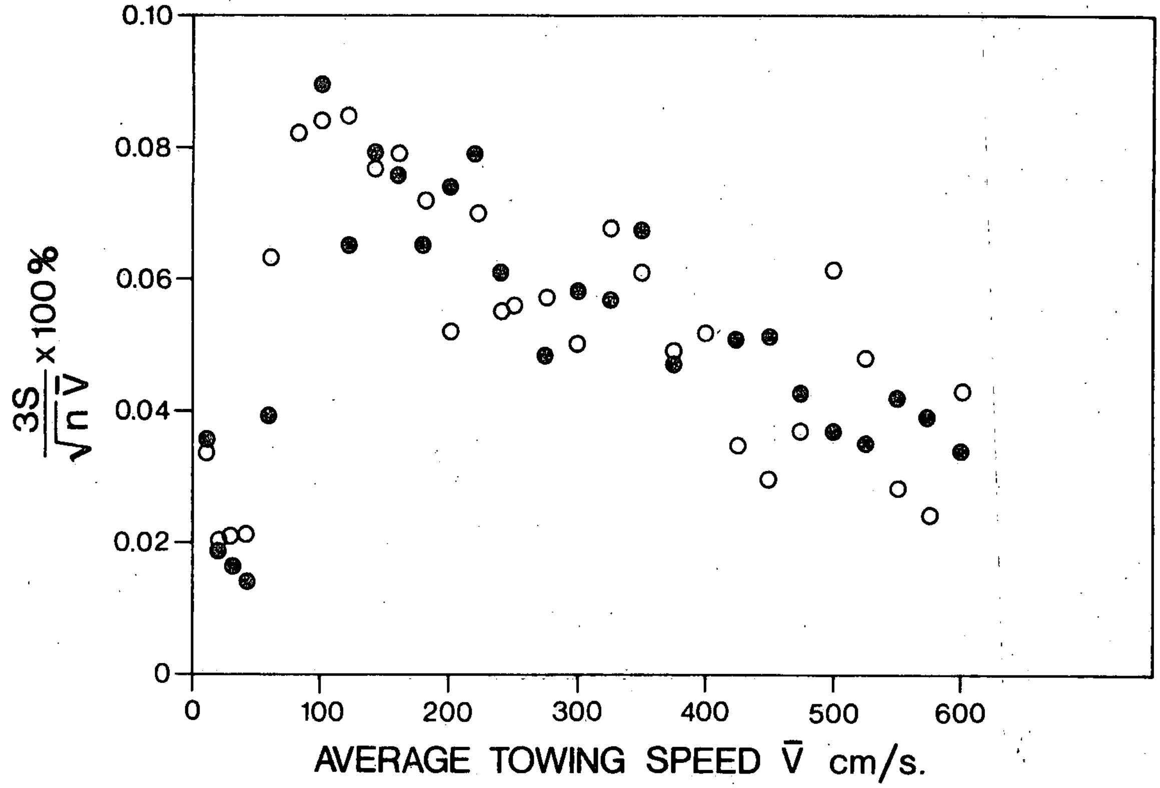


FIGURE 16. UNCERTAINTY IN MEAN TOWING SPEED AT 99 % CONFIDENCE LEVEL

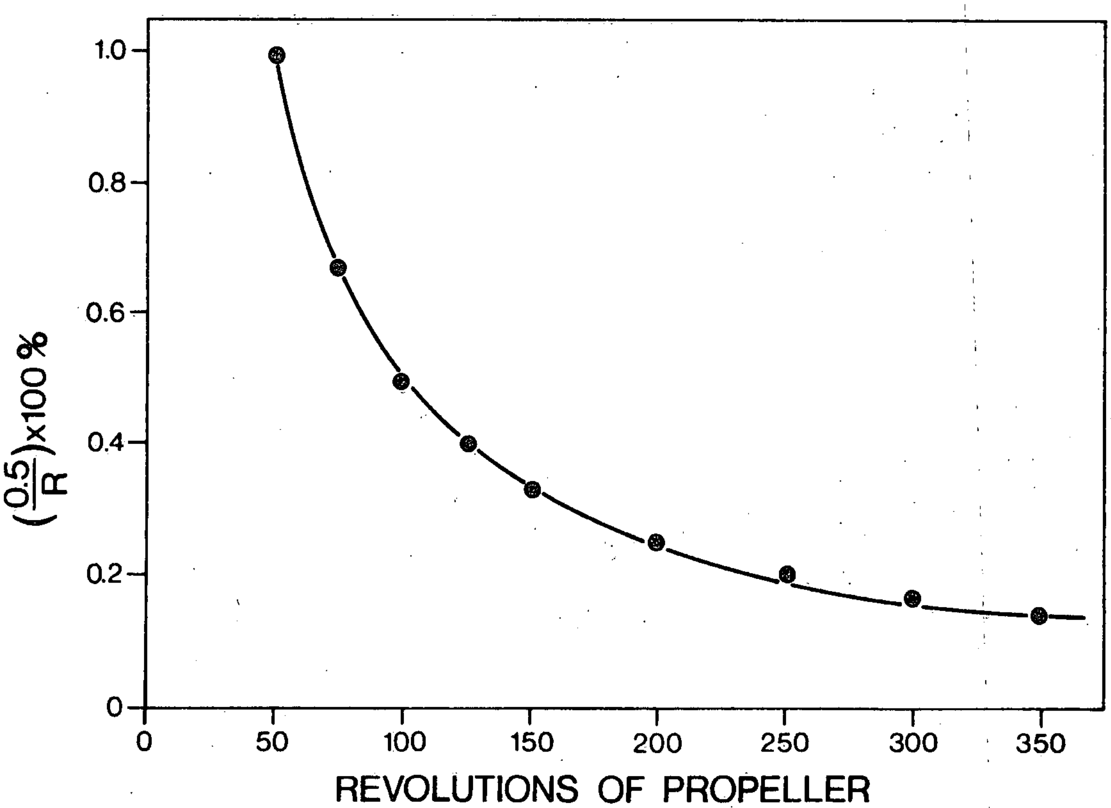


FIGURE 17. UNCERTAINTY IN COUNTING REVOLUTIONS AT 99 % CONFIDENCE LEVEL

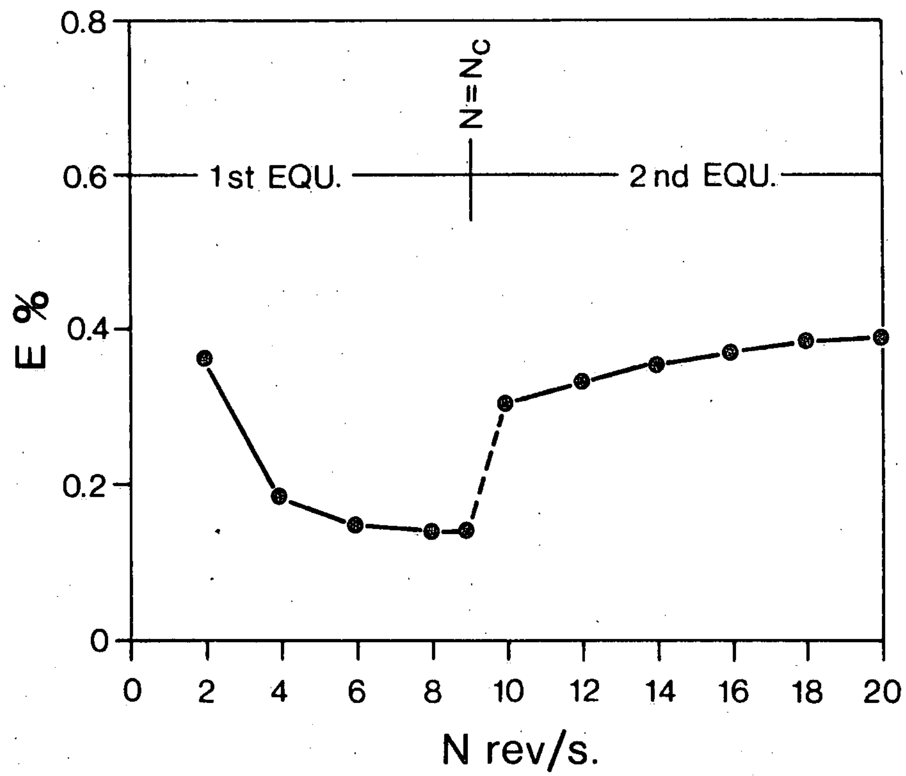
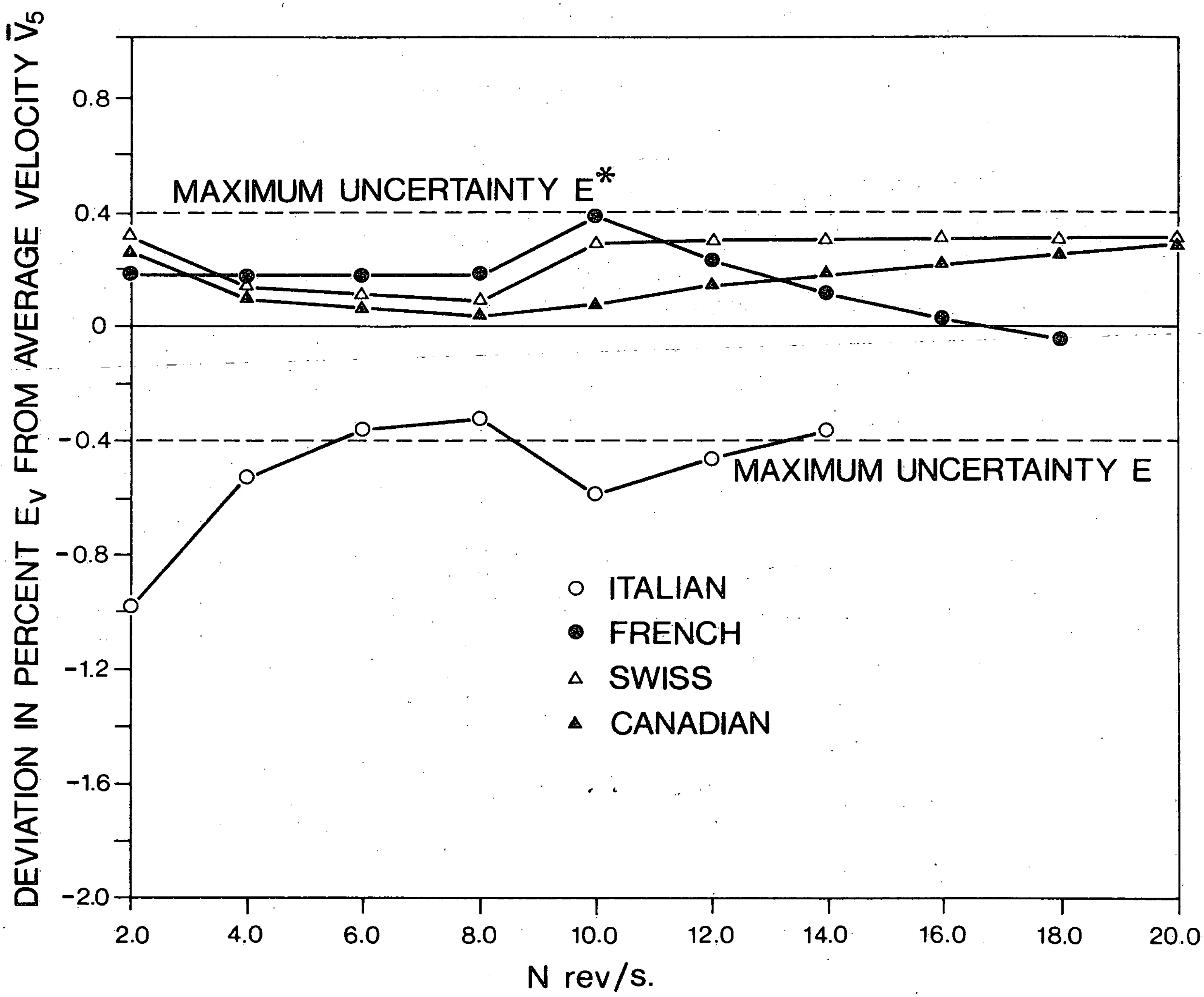


FIGURE 18. UNCERTAINTY IN CALIBRATION OF METER No. 600594 AT 99 % LEVEL OF CONFIDENCE



* E IS OBTAINED FROM 5 CALIBRATIONS OF METER 600594

FIGURE 19. COMPARISON OF CALIBRATION FOR METER No. 600594 OBTAINED IN DIFFERENT TOWING TANKS

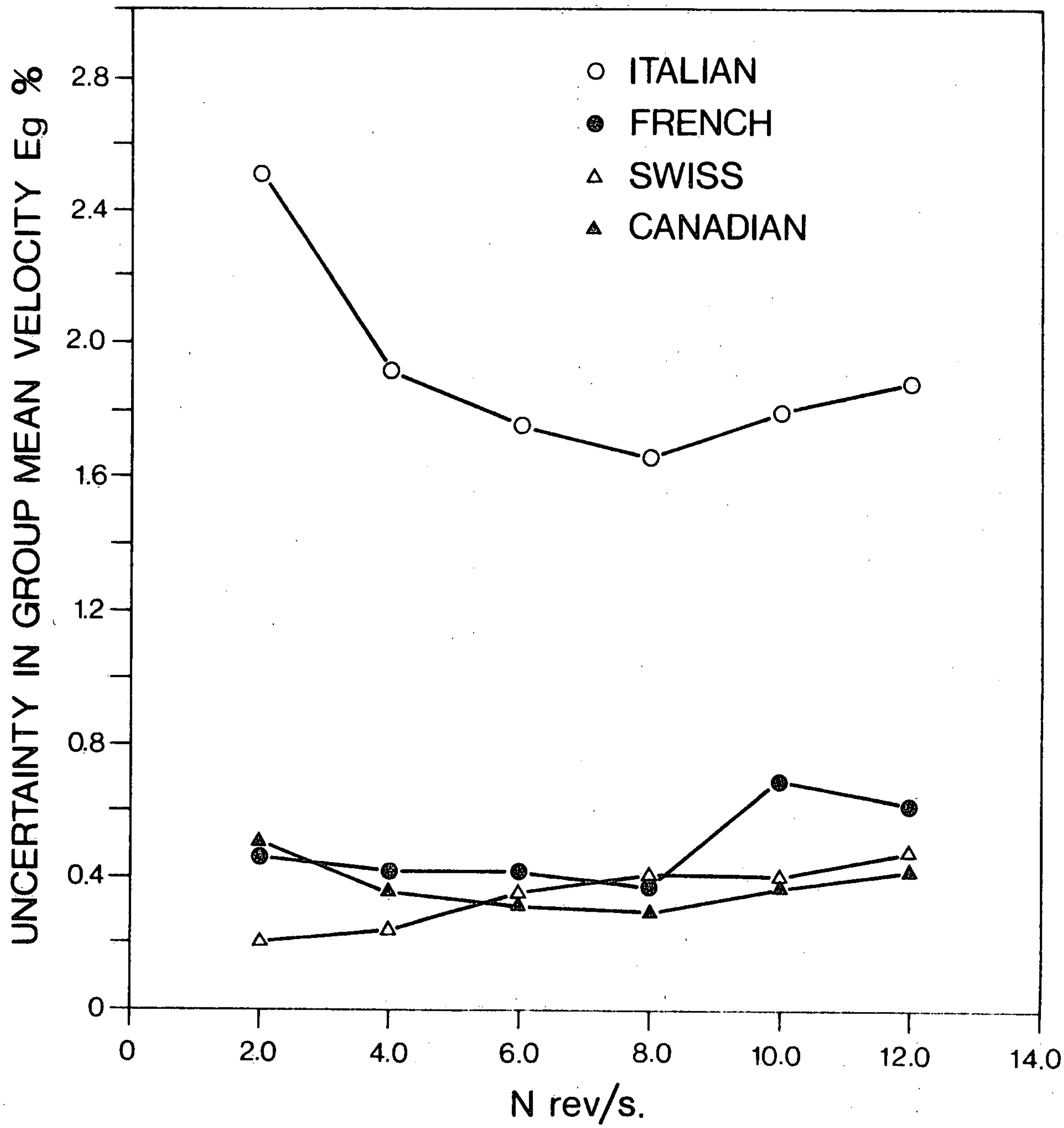


FIGURE 20. COMPARISON OF UNCERTAINTIES IN GROUP CALIBRATIONS OF FIVE METERS AT 99 % CONFIDENCE LEVEL

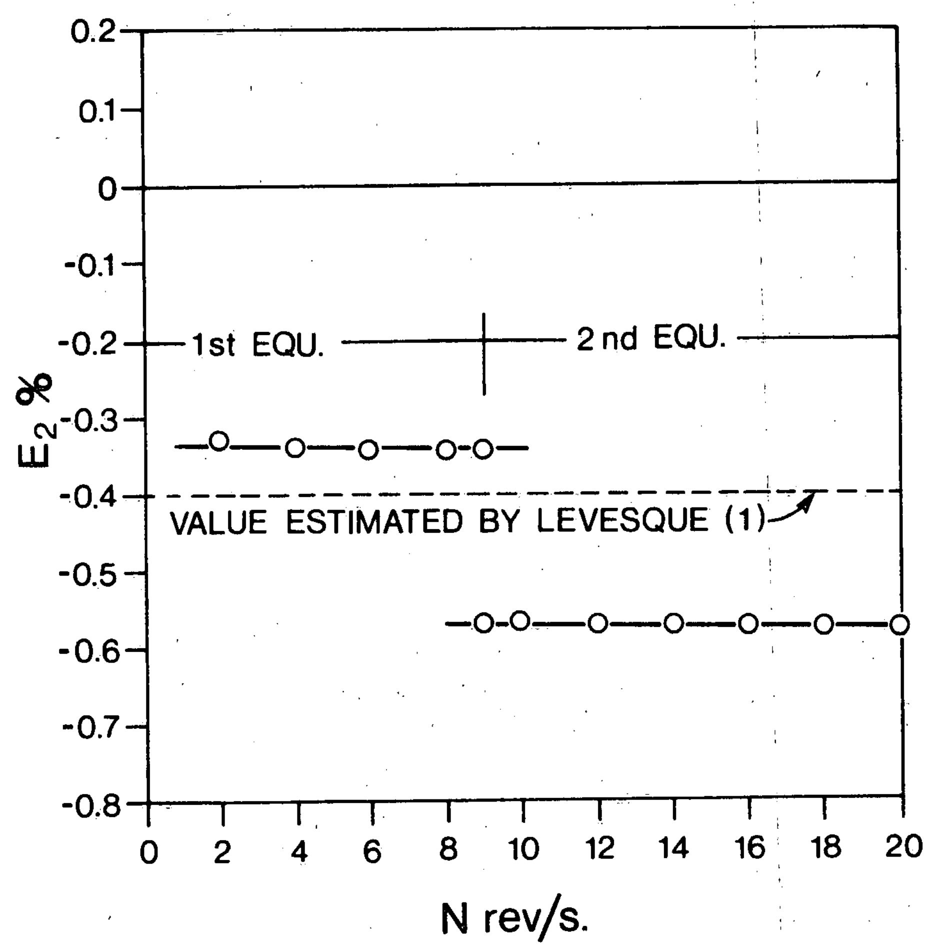


FIGURE 21. EFFECT OF POSITION OF METER ON SUSPENSION ROD