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CALIBRATION OF CURRENT METERS FOR TURBINE EFFICIENCY TESTS

by

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SUMMARY

At the request of Hydro-Québec Engineers, calibrations were provided for 30 SIAP ME 4001 current meters. Investigations of sources of uncertainties in the calibrations revealed that there may be a small systematic error due to the Epper Effect, a small random error due to towing speed variability and a significant error as a result of using proeller No. 1 which is not applicable for speeds greater than 500 cm/s. Theoretical analyses and tests indicated that satisfactory calibrations could be produced by towing three meters at a time and using 48 data pairs to determine the calibration equations. Tests conducted to determine the effect of replacing lubricating oil in the meter's bearing chambers with water showed that this procedure did not significantly change the calibrations for speeds greater than 50 cm/s.

RÉSUMÉ

Les résultats de l'étalonnage de 30 moulinets SIAP ME4001 ont été fournis aux ingénieurs de l'Hydro-Québec. Après enquête sur les sources d'incertitudes dans l'étalonnage, on a découvert qu'une légère erreur systématique pouvait être reliée à l'effet Epper, une erreur aléatoire aux variations dans la vitesse de déplacement du chariot et une erreur significative à l'utilisation de l'hélice n^{o} 1, qui n'est pas adaptée aux vitesses supérieures à 500 cm/s. Des analyses théoriques et des essais ont démontré qu'on pourrait en arriver à un étalonnage satisfaisant en faisant déplacer trois moulinets à la fois et en utilisant 48 paires de données pour établir les équations d'étalonnage. Les essais effectués pour déterminer les avantages à remplacer l'huile de lubrification des roulements par de l'eau indiquent que cette mesure n'a pas grand effet sur les résultats de l'étalonnage lorsque la vitesse dépasse 50 cm/s.

MANAGEMENT PERSPECTIVE

Efficiency tests of hydro-electric turbines require accurately calibrated current meters to measure the velocities of the turbine discharge. This report shows the various sources of uncertainties that arise in meter calibrations and how they can be minimized with an appropriate calibration strategy. The results in this report indicate that calibrations with a high degree of accuracy can be obtained at the towing tank facility of the National Water Research Institute, Burlington, Ontario, Canada.

T. Milne Dick
Chief
Hydraulics Division

PERSPECTIVE-GESTION

On détermine l'efficacité des turbines hydro-électriques en mesurant leur vitesse de débit; pour y parvenir, il est essentiel de disposer de moulinets étalonnés avec une grande précision. Ce rapport traite des diverses sources d'incertitude dans l'étalonnage des moulinets et propose des façons de les réduire en utilisant les techniques appropriées. Les résultats de l'étude démontrent qu'il est possible d'obtenir un étalonnage extrêmement précis dans le bassin de traction de l'Institut national de recherche sur les eaux à Burlington (Ontario), Canada.

Le Chef,

T. Milne Dick
Division de l'hydraulique

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1.0 INTRODUCTION

Hydro-Québec uses the SIAP ME4001 current meter, which is a propeller type meter, to measure the turbine discharges at their hydro electric power generating stations. The measurements are used to determine the efficiencies of the turbines and therefore, it is necessary that the meters are carefully calibrated.

In 1981, calibrations of five SIAP ME4001 current meters were conducted by the Hydraulics Division of the National Research Institute at Burlington, Ontario. The results reported by Engel and Dezeeuw (1982) showed that calibrations in the range from about 50 cm/s to 500 cm/s were repeatable to within 0.4%. However, it was not possible to obtain a stable calibration for turning speeds greater than 500 cm/s. As a result calibrations by Engel and Dezeeuw (1982) were given only for speeds up to 500 cm/s.

Hydro-Québec requires the calibration of 30 of their SIAP ME4001 meters and their calibration certificates to be made available by June 25, 1985. These meters will be used to measure flow velocities in excess of 600 cm/s at water temperatures which may be less than 10°C. There is concern about the instability in the calibrations for speeds from 500 cm/s to 600 cm/s and the effects of changes in water temperature from about 21°C in the towing tank to less than 10°C of the turbine discharge. To answer these questions and to provide the necessary calibration certificates, the Hydraulics Division was asked to conduct the following investigation.

1. To determine the cause of the scatter in the calibration data for towing speeds from about 500 cm/s to 600 cm/s as reported by Engel and Dezeeuw (1982).
2. To determine the most suitable way to calibrate the SIAP ME4001 meters and to provide calibration equations together with a suitable indication of their accuracy for 30 of these meters.
3. To examine the effect of replacing the standard lubricating oil in the bearing chamber with water.

This report presents the results of these investigations together with the calibration equations for 30 SIAP ME4001 current meters.

2.0 EQUIPMENT

2.1 Towing Tank

The tank, constructed of reinforced concrete, founded on piles, is 122 m long and 5 m wide. The full depth of the tank is 3 m of which 1.5 m is below ground level. Normally, the water depth is maintained at 2.7 m. 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 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. The large cross section of the tank also inhibits the generation of waves by the towed object.

2.2 Towing Carriage

The carriage is 3 m long, 5 m 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 up to 12 sec. 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.

2.3 Micro Computer Data Acquisition System

The hardware configuration of the micro computer is based on a S-100 bus card cage into which has been installed the following:

* one SBC-200 single board computer (This is a Z80 microprocessor operating under CP/M 2.2).
* three Expandoram memory cards (each card has 256K bytes of memory giving a total of 768K).
* a SA-1000 disk controller card which drives one 10 Megabyte hard disk drive and one 8" double-sided double density floppy drive.
* a MPC-4 intelligent buffered four channel input-output expansion card.

In addition to the computer chassis, there is the input manifold, which contains one small circuit card on which are located the data input registers. The current meter signals (4 max) are connected to these input registers which are interrogated by the parallel input-output port of the SBC-100 computer under program control. For each run at a given speed a data array is stored in memory which has a record for every millimeter of travel of the towing carriage. In the maximum case a file could contain 95,000 observations. The actual calculations of carriage velocity and the rate of rotation of the meter rotor takes place after the run is completed. In the case of meters which emit voltage pulses to indicate revolutions, noise pickup in the form of voltage "spikes" is illiminated by the software when the revolutions per second for the meters are computed.

2.4 Meter Suspension

The meter suspension system consisted of a 75/35 mm standard airofoil rod which was supplied with the meters. Each rod was tightly fitted to a rigid, compact mounting frame which was bolted to the rear of the towing carriage as shown in Figure 1. 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.

3.0 SOURCES OF CALIBRATION UNCERTAINTY

During earlier calibration of the SIAP ME4001 meters, Engel and Dezeeuw (1982) reported that there was excessive scatter in the calibration data when towing speeds were greater than about 500 cm/s. In this section an attempt is made to determine the reason for the anomaly.

3.1 <u>Variability in the Towing Speed</u>

The accuracy of the towing speed was examined by Engel and Dezeeuw (1982) over the full calibration speed range from 10 cm/s to 600 cm/s. Mean speeds together with standard deviations were computed and the uncertainties in the mean speed at the 99% confidence level were determined. The results are shown in Figure 2. It can be seen that the percent errors for speeds greater than 500 cm/s are lower than those for speeds less than 500 cm/s. Indeed, throughout the full speed range the error is always less than 0.1%. These results were considered to be sufficiently accurate for the meter calibrations provided by Engel and Dezeeuw (1982). For these calibrations, errors in towing speed cannot be considered to contribute significantly to the observed data scatter for speeds greater than 500 cm/s.

The variability of the towing speed was again examined prior to conducting the present calibrations. Considering the possibility of calibrating the meters one at a time or three at a time, the speed tests were conducted while towing meters in either of these modes. The percent errors E_v at the 99% confidence level are plotted in Figure 3 for the single meter mode and in Figure 4 for the three meter mode as a function of the towing speed v. In each case four separate sets of tests were used ranging over a period of one month. The method of measuring the towing speed was the same as that used by Engel and Dezeeuw (1982). This was necessary because the present Microcomputer Data Acquisition System does not have a means of determining the variability in the towing speed.

The plots show that there appears to have been a change in the behaviour of the towing carriage, particularly for speeds greater than about 300 cm/s. For speeds less than this the errors in the towing speed for both suspension modes are approximately comparable, never exceeding a value of 0.12% at the 99% level of confidence. This may be considered to be not too much different from the results reported by Engel and Dezeeuw (1982). When speeds are greater than 300 cm/s errors reach values as high as about 0.4% in the case of the single meter mode while errors for the three meter mode reach values slightly lower or just under 0.3%. However, these errors are very erratic and not consistent from one data set to another. For example in Figure 4 when v = 550 cm/s the errors E_v vary from a low of 0.074% for the data of April 3 to a maximum error of 0.266% for the data of April 2. This inconsistency is attributed to electrical noise which creates spikes in the voltage signal received from the "fifth wheel" of the towing carriage. The presently used Micro Computer Data

Acquisition System eliminates all such spikes and thus the apparent variability in the towing speeds should be minimized. Indeed, if one looks at the bulk of the plotted data in Figure 3 and Figure 4 it can be seen that on the whole errors are less than 0.12%, and this error can be expected to be about the maximum at the 99% confidence level. Therefore, velocity variability should be within tolerable limits.

3.2 Variability in Counting Revolutions of Propellers

The SIAP ME4001 current meters come equipped with new magnetic transducers (Hall effect devices) to replace the less precise Reed switches. The revolutions of the propeller are measured by counting the magnetic pulses emitted and each pulse is interpreted as one revolution. In order to compute the revolutions per second, the magnetic pulses and the length of time over which they are counted are recorded on a data acquisition module supplied by Hydro-Québec with the meters. Although this module counts the magnetic pulses precisely as they occur, it has the disadvantage that it can over-count by one full revolution because the counting sequence is terminated by the timer, . When the meter is used in the field, this error is of little significance because one can make the revolution count and the corresponding length of time as large as one likes. However, this error is significant for the calibration of the meter because at the high speeds, the length of time over which constant towing speed can be maintained is approximately 10 sec. This means that an over count of one revolution results in an error in the rate of rotation of the propeller of 1/10 rev/s. Considering that the nominal pitch of the propeller is 25 cm/rev, an error of 0.1 rev/sec would give an error in the computed speed of 2.5 cm/s. This error is of the same order as that observed in the data scatter reported by Engel and Dezeeuw (1982) for speeds greater than 500 cm/s, and therefore in that case, errors in determining the revolutions definitely contributed to the reported scatter.

In order to eliminate this source of uncertainty during the present calibration, an interface between the meter pulse transducers and the Micro Computer Data Acquisition System was fabricated with the co-operation of Hydro-Québec Engineers. With this new feature the measuring time is initiated by a pulse from the magnetic transducer in the meter. The revolutions are then counted until a pre-set value has been reached after which the measuring time is terminated by the last pulse. This ensures that the number of revolutions is counted precisely. With this system the counting of the revolutions should be a negligible source of uncertainty for the meter calibrations.

3.3 Vibration in the Meter Suspension

Vibrations are generated partly by the carriage drive and partly by the action of the water on the meter and the suspension post. Such vibrations are not likely to affect the actual rotation of the propeller, but instead interfere with the revolution counting device inside the meter body. Initially, during the calibrations reported by Engel and DeZeeuw (1982), Reed switches were used, and some vibration effects could have contributed to the reported scatter in the calibration data at the high speeds. However, for the present calibrations, all meters have been equipped with new magnetic transducers and they are not affected by vibrations. Therefore, contributions of vibrations in the meter suspension system to calibration uncertainty should be considered to be insignificant.

3.4 Epper Effect

The Epper effect occurs for a range of towing speeds having values near to $V = \sqrt{gd}$ (d = depth of water, g = acceleration due to gravity) which is the speed of a shallow water wave in water of depth d. For the NWRI towing tank the maximum Epper effect ($V = \sqrt{gd}$ exactly) occurs at a speed of about 525 cm/s. When the carriage travels at this speed the disturbance caused by the meter and suspension post moves along the tank with the meters and reduces the rate of rotation of the propellers. The magnitude of the reduction in rate of rotation and the range of speeds over which it is observed vary somewhat with the size of the meter and the dimensions of the towing tank. Grindley (1971) investigated the Epper effects on an Ott Texas type current meter using the same type of 35/75 mm suspension post as used in the present tests. The results are given in Figure 5 as a plot of mean values of effective pitch V/N versus V (V = towing speed, N = rev/s). The plot shows over the speed range of 20 cm/s to 600 cm/s, there was a reduction in the rate of rotation (increase in V/N) for speeds between about 300 cm/s and 500 cm/s with the maximum occurring at a speed of 370 cm/s. The deviation in V/N at the peak of the Epper effect is about 0.1 cm/rev which translates approximately into an absolute speed of 2 cm/s. However, it should also be noted that for a given meter, the effect is larger in a smaller tank then it is in a large one (Grindley, 1971). The width and depth of the tank used for the data in Figure 5 were 1.83 m and 1.83 m respectively. The corresponding dimensions for the NWRI towing tank are 2.9 m and 5 m. In view of this, one would expect that the magnitude of the Epper effect would be somewhat less than that observed in Figure 5. Nevertheless, one must accept the fact that there may be some small systematic error in the calibrations of the order of about 0.1%.

3.5 Meter Properties

The last plausible source of the calibration anomaly observed by Engel and Dezeeuw (1982) must be looked for in the meter itself. It has already been shown that the revolution counting system used by Hydro-Québec contributed some of the uncertainty to the calibrations, but the new interface with the Micro Computer Data Acquisition System, has eliminated this problem. The body of the meter is smooth and streamlined, and since vibrations are not a problem, then the meter body itself may be ruled out as a source of trouble. This leaves the propeller itself. The nominal pitch of the SIAP No. 1 propeller is 25 cm/rev. Examination of documentation for the Ott C-31 (Table 1) type current meter shows that its propeller with a pitch of 25 cm/rev is only recommended for speeds up to 500 cm/s. If flows with speeds greater than 500 cm/s are likely to be encountered a propeller with a pitch of 50 cm/rev is recommended for any speed up to 600 cm/s. The fact that a propeller with a larger pitch is required for speeds greater than 500 cm/s indicates that there must be a significant change in the propeller dynamics. Additional research by Hydro-Québec revealed that indeed the SIAP No. 1 propeller should only be used for speeds up to 500 cm/s and that a propeller No. 2 with a pitch of 50 cm/rev should be used for speeds greater than 500 cm/s. However, such propellers could not be obtained by Hydro-Québec and they requested that calibrations of their meters should proceed with only propeller No. 1 used over the full available towing speed range of 600 cm/s.

The scatter (uncertainty) in the calibrations between 500 cm/s and 600 cm/s observed by Engel and Dezeeuw (1982) must therefore be largely attributed to the effect of propeller No. 1 which was not designed for these speeds. This uncertainty will also significantly affect the present calibrations.

4.0 DEVELOPMENT OF CALIBRATION PROCEDURE

The calibration of current meters must take into account both accuracy and economy. A program must be designed so that sufficient accuracy is obtained for the lowest cost per meter. Towards this goal two factors are considered in this section: (1) to determine if three meters can be calibrated simultaneously as opposed to a single meter and (2) to determine the number data pairs (i.e., measurements of speed and rate of rotation of propeller) required per calibration. These two questions are addressed using theoretical considerations and data from preliminary tests.

4.1 Towing Tests

Before testing, each meter was carefully fastened to a 35/75 Aerofoil suspension post taking care that alignment of the propellers' axes of rotation was always parallel to the sides of the towing tank. Care was also taken that the axis of rotation was always 40 cm below the surface of the water and 30 cm above the bottom end of the suspension post. The meters were then connected to the data acquisition system and the calibration begun. A tow of a meter at a pre-set speed was defined as a test. During each test the Micro Computer Data Acquisition System ensured that steady state conditions prevailed when towing speed and rate of rotation of the propeller were measured. In all cases the water temperature in the towing tank was between 15°C and 22°C.

4.2 Single and Simultaneous Calibrations

Preliminary tests were conducted using meters numbers 600508, 600509 and 600510, one at a time and all three simultaneously. For the single meter calibration, each meter was positioned on the centre line of the towing tank. For the simultaneous calibrations all three meters were mounted in such a way that the distances between the meters and distance from the towing tank wall were equal. The data for the single calibrations are given in Tables 2, 3 and 4 and for the simultaneous calibrations in Tables 5, 6 and 7.

4.2.1 Preliminary Data Analysis

The data from each table were plotted as ΔV versus V in which ΔV is computed from the relationship

$$\Delta V = V - kN \quad (1)$$

where ΔV is a speed difference in cm/s, V = measured towing speed in cm/s, k = the nominal pitch for the No. 1 propeller which is given as 25 cm/rev and N = rate of rotation of the propeller in rev/s. Equation (1) expresses the difference between the measured towing speed and the speed computed from the rate of rotation of the propeller if the meter behaved like an ideal meter (i.e., no bearing friction and perfect coupling between the fluid and propeller blades). If, indeed, the meter were to behave this way, then ΔV would always be zero over the full speed range. This, of course, is not the case and therefore the ΔV versus V plot gives a good picture of the behaviour of the meter. The plotted data are given in Figures 6, 7 and 8 for the single meter calibrations and in Figures 9, 10 and 11 for the simultaneous calibrations. It can be seen in each plot that there is a significant increase in the scatter of the plotted data, commencing just below a speed of 500 cm/s. This effect is primarily due to the instabilities in the behaviour of the No. 1 propeller in this part of the speed range.

Straight lines were fitted to the plotted data in keeping with established practice, resulting in three linear segments for each of the six calibrations. Comparison of the plots for single and simultaneous calibrations shows that in each case the points of intersection are shifted towards lower values of speed than those observed with single calibrations. This resulted in shorter ranges for equations (1) and (2) and considerably extended the range of equation (3). The reason for this is not clear. It is possible that when three meters are towed together there is some mutual interference between adjacent meters, although this should be quite small, since they are separated by a distance of 125 cm. A better and more direct comparison can be made by comparing the standard errors of estimate and the calibration equations themselves. Therefore, using the minimum speeds for each linear segment from Figures 6 to 11 together with the data in Tables 2 to 7, linear regressions, together with their standard errors of estimate, were obtained. The linear equations are of the form

$$V = a_n N + b_n \qquad (2)$$

where a = the effective pitch of the propeller in cm/rev, b = an intercept and n takes on values 1, 2, 3 denoting equations (1), (2) and (3). The slopes, intercepts and standard errors of estimates are given in Table 8 for the single calibrations and in Table 9 for the simultaneous calibrations. The standard errors of estimate are a measure of the uncertainty of the calibration whereas the equations themselves can be used to examine the repeatability of the single meter calibration with the 3 meter calibration.

4.2.2 Standard Errors of Estimate

Examination of Tables 8 and 9 shows that for equations (1) and (2) the standard errors of estimate are lower for the three meter calibrations. The one exception is equation (1) for meter number 600508. In this case the standard error of estimate is larger but its value is not excessive. Therefore for these two equations, the three meter method provides results which are at least equally as good as those obtained with the single meter method. However, for equation (3) the standard errors of estimate is consistently larger, by an average factor of about 1.5, when three meters are used simultaneously. This is a reflection of greater scatter in the measured data and this can be seen in Figures 6 to 11, by comparing plots of single and simultaneous calibrations for each meter at the high speeds. The increase in the standard error of estimate when meters are calibrated three at a time must be due to the mutual interference caused primarily by the flow separation around the 35/75 suspension posts in the speed range at which the Epper effect occurs. This would be in the speed range of about 450 cm/s to about 550 cm/s. It is also possible that the situation has been aggravated by the fact that propeller No. 1 operating beyond its recommended speed range, may be quite vulnerable to the interference and thus enhance their effect.

4.2.3 Repeatability of Calibrations

The repeatability of the single meter calibration with the three meter calibration was examined by computing values of speed V for even values of propeller rotation rate N using the calibration equations in Tables 8 and 9. Percent differences given as $\delta V = (V_3 - V_s)/V_s \times 100\%$, in which 3 and s denote three meter and single meter calibration, were computed for each of the three meters. The results are given in Tables 10, 11 and 12. In the case of meter number 600508 the absolute percent differences never exceed 0.31% and similar results are obtained for meter number 600509. These results indicate that calibrations with three meters at a time give satisfactory results. However, in the case of meter 600510 percent differences are much higher for speeds less than 175 cm/s and reaches a maximum of 0.81% when the speed is 125 cm/s. It is not clear why there should be such a difference for one meter out of three, given that all conditions were held constant. One possibility is that there was a slight horizontal misalignment of meter number 600510. The effect of which may be more significant at the low to medium speeds.

4.2.4 Summary

Considering the above results, there is no compelling reason why the meters should not be calibrated three at a time as long as propeller No. 1 is used. Tests using propeller No. 2, applicable to the higher speeds, must be conducted before it can be determined if single calibrations would give a significant improvement. Unfortunately, Hydro-Québec is not able to provide the required propellers at this time. Another consideration is the fact that the cost of single calibrations is three times that of calibrating three meters at a time. The increased costs would be greater than the cost of acquiring the proper propellers. Therefore, until such propellers are procured, meters should be calibrated three at a time.

4.3 Data Requirements

The linear calibration equations of V versus N are used to compute values of V given measured values of N. The standard error of the computed value of V can be written as

$$S_V = S_e \sqrt{1 + \frac{1}{n} + \frac{1}{n}\left(\frac{N-\bar{N}}{S_N}\right)^2} \tag{3}$$

where S_V = the standard error in the computed velocity, S_e = the standard error of estimate, n = the number of data points, N = rate of rotation of the propeller for which the velocity is computed, $\bar{N}$ = the mean rate of rotation for all the measured data used to define the calibration equation, S_N = standard deviation for all the data used to to determine $\bar{N}$. The standard error S_V is used to determine the upper and lower confidence limits between which the true value of V will be found a specified percent of the time. These limits can be written as

$$\delta V_N = \pm t_p S_v = \pm t_p S_e \sqrt{1 + \frac{1}{n} + \frac{1}{n}\left(\frac{N-\bar{N}}{S_N}\right)^2} \tag{4}$$

where t_p are the percentile values of the Student's "t" distribution for (n-2) degrees of freedom (Spiegel, 1961). Over the range of N, the values of $V \pm \delta V_N$ form an upper and lower envelope for a given level of confidence as shown schematically in Figure 12.

Given the confidence limits one can determine the maximum percent error in the computed velocity for any value of N from the relationship

$$E_N = \frac{100\ t_p\ S_e}{V}\sqrt{1 + \frac{1}{n} + \frac{1}{n}\left(\frac{N-\bar{N}}{S_N}\right)^2} \tag{5}$$

where E_N = the maximum percent error at some specified level of confidence determined by t_p. Equation (5) shows that the smallest value of E_N occurs when $N = \bar{N}$ whereas the greatest value of E_N coincides with the smallest value of N over the data range for a given value of n. Clearly, for a calibration equation with which the velocity is always to be computed within a given percent error, E_N must not be exceeded even at the lowest value of the range of N for which the equation applies. Therefore the greatest maximum percentage error may be expressed as

$$E_1 = \frac{100\ t_p\ S_e}{V_1}\sqrt{1 + \frac{1}{n} + \frac{1}{n}\left(\frac{N_1-\bar{N}}{S_N}\right)^2} \tag{6}$$

where V_1 and N_1 are the minimum values of V and N for which the calibration equation applies. This means, that in this report, a calibration equation having an accuracy of say, 0.5%, is one for which $E_1 \leq 0.5\%$.

It can be seen from equation (6) that E_1 depends on both the standard error of estimate S_e and the size of the data sample n. Therefore, equation (6) can be used to estimate the number of data points required to obtain a calibration equation having an accuracy E_1, for a given standard error of estimate. To do this, one must first express both $\bar{N}$ and S_N in terms of n.

When using linear regression methods the best results are obtained when the measured values of the independent variable are equally spaced over the full range of the equation. If one considers n data pairs, with values of N equally spaced at some interval m beginning with the smallest value N_1, it can be shown that

$$\bar{N} = \frac{1}{2}\left[2N_1 + (n - 1)\ m\right] \qquad (7)$$

and

$$S_N = \sqrt{\frac{n(n + 1)\ m^2}{12}} \qquad (8)$$

Now substituting $\bar{N}$ and S_N into equation (6) one obtains

$$E_1 = 100\ t_p \frac{S_e}{V_1} \sqrt{1 + \frac{1}{n} + \frac{3(n - 1)}{n^2}} \qquad (9)$$

Equation (9) is plotted as a dimensionless family of curves of E_1 versus S_e/V_1 with n as a parameter, in Figure 13. The curves show that for a given value of n there is a rapid increase in E_1 with the rate of change in E_1 increasing smoothly as S_e/V_1 increases. This clearly shows the importance of having precise measuring equipment as well as the effect of having an improper propeller, which tends to increase values of S_e at higher speeds. As can be seen from Figure 13, even a small increase in S_e/V_1 results in a significant increase in E_1 and this is virtually the same for all values of n from 5 to 30, shown in Figure 13. One can also see from the curves that for a given value of S_e/V_1 one can improve the accuracy (i.e., reduce E_1) by increasing the number of data pairs n and this is dependent on the initial value of n and the given value of S_e/V_1. For example, given a value of $S_e/V_1 = 0.001$ one can reduce E_1 from 0.75% when n = 5 to about 0.39% when n = 10. The effect of increasing n is greatest when changing from n = 5 to n = 10. Thereafter, additional increases yield progressively less reduction in E_1 until when n ≈ 20 to 25 any further increase in n results in insufficient decrease in E_1.

The concepts embodied in Figure 13 were used to examine the preliminary calibrations of meters 600508, 600509 and 600510 suspended simultaneously. Values of n, V_1, were noted and are given in Table 13 for equations (1), (2) and (3). Values of S_e/V_1 and E_1 at the 95% level of confidence were computed and these too are given in

Table 13. The results show that for equation (1) values of E_1 are always very high and as can be seen from Figure 13, this situation cannot be improved by increasing n because values of n are already quite large. However, this problem is not too serious because equation (1) for the SIAP meters covers the lower end of the speed range, whereas the meters will be primarily used to measure much faster flows. In the case of equation (2) the number of data pairs varied from 5 to 7 giving values of E_1 which are quite low, the largest value being 0.51% for meter number 600508. These results are quite acceptable, indicating that the value of n is about right for the given values of standard errors of estimates. Finally, as observed in previous sections, S_e for equation (3) of all three meters are high. Because of this, values of E_1 are high, having values of from 0.98, 0.86 and 1.20 for meters 600508, 600509, 600510 respectively. In the case of meter number 600508 the value of E_1 could be reduced to 0.75% from 0.98% by increasing n from 10 to 25. For meter 600509, E_1 can be reduced from 0.86% to 0.78% by increasing n from 16 to 25 and for meter 600510, E_1 can be reduced from 1.20% to only 1.1% by increasing n from 16 to 25. Clearly, the increase of n for meter 600508 was beneficial, because n was increased from 10 to 25. In the case of the other two meters the reduction in E_1 was much less, because the value of n was already higher having a value of 16. However, considering the uncertainties discussed in Section 3.0, one should strive to obtain all the advantage possible. Therefore, in the case of equation (3), values of n should be kept close to 25.

The number of data points for a given calibration depends on the range of speed for each of the separate equations. If the range of each equation is known then the number of data pairs n for a given meter calibration can be determined from

$$m = \frac{N_n - N_1}{(n - 1)} \tag{10}$$

where N_n = the nth and largest value of N. However, the precise range of each equation is not known a priori and experience has shown that there can be considerable variation. For example, in Table 13, values of V_1 respresenting the lowest value or speed for each equation vary from about 147 cm/s to 202 cm/s for the lower limit of equation (2) and from 262 cm/s to 348 cm/s for the upper limit of equation (2). Of course, the other limits are given by the lowest value and largest value of the overall speed range of the calibration. Some consideration must be given to these variations when determining the best distribution of data pairs.

The calibrations given in Table 13 were obtained by taking speed intervals of 10 cm/s for equations (1) and (2) and intervals of 20 cm/s for equation (3). This resulted in a total of 38 points for each meter. As indicated earlier the number of data pairs in equation (1) can be reduced, thus increasing the speed interval m, while for equation (3), n should be increased, resulting in a decrease in m. It can be seen from Figures 9, 10 and 11 that there is a wide variation in the magnitudes of speeds defining the range limits of equation (2). To minimize subjective judgement in assigning speed intervals to equations (1) and (2), it was decided to maintain a single value of m up to a speed of about 360 cm/s, and a second value for speeds greater than 360 cm/s. Because of the large values of the standard error of estimate at the high speeds it was decided to increase n to 24 in accordance with criteria contained in Figure 13, resulting in a new speed interval of m = 10 cm/s for speeds greater than 360 cm/s. For speeds less than 360 cm/s it was decided to increase the speed interval slightly, reducing the value of n for equations (1) while at the same time not seriously reducing the number of data pairs for equation (2). A speed interval of m = 15 cm/s was chosen for all speeds less than 360 cm/s resulting in another 24 data pairs. Therefore, 48 data points will be used for the present calibrations, summarized by the following ranges:

for m = 15 cm/s

$$15 \text{ cm/s} \leq V \leq 360 \text{ cm/s}$$

for m = 10 cm/s

$$360 \text{ cm/s} < V \leq 600 \text{ cm/s}$$

These distributions of data points were applied to 30 meters given in the next section of this report.

5.0 EFFECT OF CHANGING LUBRICATION FLUIDS

The meter will be used in water having temperatures which may be less than 10°C. Calibrations in the towing tank are conducted with water temperatures around 20°C. Some concern has been expressed that such temperature differences may increase the viscosity of the oil sufficiently to affect the calibration, whereas water is affected much less. It has, therefore been suggested by Hydro-Québec, that for cold water applications, the oil in the meter bearing chamber be replaced with water. This means that meters calibrated in the normal way would be used after oil has been replaced with water. In order to see if the same calibration would still apply, tests were conducted.

Three meters numbers 600592, 600593 and 600594 were calibrated once with the standard oil and once with water in their bearing cavity. The data are given in Tables 14 through 19. Values of ΔV were computed and plotted as ΔV versus V in Figures 14 to 16 for the case of oil and Figures 17 to 19 for the case of water. Linear regression equations were developed together with their standard errors of estimate and these are given in Table 20 and Table 21 for oil and water respectively. In all cases the speed intervals recommended in Section 4.3 were used.

On the whole, there are only small differences in the calibrations for the two types of lubricants. In the case of meter number 600594, three equations were required when oil is used and only two equations in the case of water. The standard errors of estimate are comparable and are not much different in magnitude from those observed with meter numbers 600508, 600509 and 600510 in Table 13.

The equations given in Tables 20 and 21 were used to compute speeds for even values of N from 2.0 to 24. These data were used to compute percent differences $\delta V/V_o$ using the relationship

$$\frac{\delta V}{V_o} = \left(\frac{V_w - V_o}{V_o}\right) \times 100\% \qquad (11)$$

in which w and o denote water and oil in the bearing chambers, respectively. The results are given in Tables 22, 23 and 24 for meters 600592, 600593 and 600594 respectively. In all cases absolute values of $\delta V/V_o$ are within acceptable limits. Therefore, meters which have been calibrated with oil in the bearing chambers can be used when the oil is replaced with water. However, the lower speed limit of equation (1) is about 50 cm/s. For speeds less than 50 cm/s, it can be seen from Figures 17, 18 and 19 that values of ΔV are much higher than those in Figures 14, 15 and 16, indicating that for the same towing speed the propeller with water in the bearings turns slower and this reduction in the rate of rotation increases rapidly as V decreases from about 50 cm/s.

Although, from a calibration point of view, there is little difference caused by the two modes of lubrication, there is another factor to be considered. The meters will be running, primarily at high speeds, for a considerable length of time. The meter bearings and associated fittings are very precisely made and prolonged high speed operation, with water as the bearing fluid, may increase wear. This in turn may change the calibration relationship significantly. Therefore, although the results in Tables 22 to 24 show little difference between the oil and water calibrations, there is no guarantee how long this agreement will last. Therefore, it is not recommended that water be used to replace standard meter lubricating oil.

6.0 CALIBRATION EQUATIONS

A computer program called METCAL was developed which produced the linear regression equations, the limits of the equations, the standard errors of estimate and the confidence intervals at the 95% and 99% confidence levels. A typical example of the calibration certificates obtained with METCAL is given in Table 25. A calibration certificate together with the original data was included with each meter. Calibration equations for 30 meters are given in Table 26. It can be seen in Table 26 that in some cases only two equations are required for a complete calibration. The standard errors of estimate fluctuate from meter to meter and this probably reflects the characteristics of the individual meters.

The maximum errors E_1 at the 99% level of confidence were computed and these together with the number of data pairs n and the minimum flow speed V_1 for each calibration equation are given in Table 27. Each value of E_1 represents the error at the minimum speed V_1 for each equation. As the speeds increase above V_1, the errors gradually decrease in accordance with equation 5 in section 4.3. It can be seen from Table 27 that the largest values of E_1 occur for equation no. 1. This is because of a small non-linearity at the very low speeds due to bearing friction, etc. However, as pointed out earlier, this is not serious because the meters will be used to measure flow with very high velocities. In equations no. 2 and no. 3, the values of E_1 are much lower with most of them being less than 0.5%.

These equations represent the best calibrations that can be obtained at a reasonable cost, considering the constraints imposed by propeller No. 1 which is not suited for speeds greater than 500 cm/s.

7.0 CONCLUSIONS

1. The average towing speed of the towing carriage can be determined with an accuracy of about 0.12% at the 99% confidence level.
2. The error in counting the revolutions of the propeller with the new meter-computer interface developed jointly with Hydro-Québec is negligible.
3. Vibrations in the meter suspension should not contribute significantly to the observed scatter in the calibrations at speeds greater than 500 cm/s.
4. There is likely to be a small systematic error as a result of the Epper Effect for speeds between about 500 cm/s to 550 cm/s. This error is thought to be of the order of 0.1% or less.
5. The primary cause of the scatter in the calibration for speeds greater than 500 cm/s is the use of propeller No. 1 in this speed range. This propeller is recommended only for speeds less than 500 cm/s. A second propeller with a pitch of 50 cm/rev is recommended for speeds greater than 500 cm/s.
6. Tests showed that the meters could be calibrated three at a time.
7. Theoretical considerations and tests indicated that a total of 48 data pairs should be used for the complete calibration of each meter.

8. There is no significant difference in the calibrations of meters when lubrication oil in the bearing chamber was replaced with water, for all speeds greater than about 50 cm/s. For speeds less than 50 cm/s, the meters with water in the bearing chamber rotate at a slower rate. This effect increases as speed decreases.
9. It is not recommended to replace the lubricating oil in the bearing chambers with water. The use of water may affect the rate of wear of the moving meter parts and thus change the calibration while the meter is in use.
10. The calibration equations provided in Table 27 represent the best possible at reasonable cost. If greater accuracies are to be achieved, the meters must be provided with the appropriate propeller to cover the full available towing speed range of 600 cm/s.

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TABLES

TABLE 1

Recommended Propellers for OTT C-31 Universal Current Meter

Propeller Number Engraved	Propeller Size	Maximum Water Velocity (m/sec)	Starting Speed (m/sec)	Range of Component Effect	Material
1 1	125 mm dia., 0.25 m pitch	5.0	0.025	5°	Brass
1	125 mm dia., 0.25 m pitch	5.0	0.035	5°	Plastic
2	125 mm dia., 0.50 m pitch	6.0	0.040	5°	Brass
2	125 mm dia., 0.50 m pitch	6.0	0.060	5°	Plastic
3	125 mm dia., 1.00 m pitch	10.0	0.055	5°	Brass

TABLE 2

Data for Single Calibration of Meter No. 600508

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	10.07	271.62	100	.368	0.866
2	15.04	194.87	110	.564	0.940
3	20.11	193.56	150	.775	0.735
4	25.05	181.46	175	.964	0.950
5	30.11	170.93	200	1.170	0.860
6	34.94	182.65	250	1.369	0.715
7	39.96	200.14	315	1.574	0.610
8	44.89	160.66	285	1.774	0.540
9	49.94	149.82	295	1.969	0.715
10	54.97	139.10	300	2.157	1.045
11	59.96	135.53	320	2.361	0.935
12	70.12	119.07	330	2.771	0.870
13	80.99	93.49	300	3.209	0.765
14	90.52	84.18	320	3.588	0.820
15	100.12	75.62	300	3.967	0.945
16	110.33	69.74	305	4.373	1.005
17	120.26	64.98	310	4.771	0.985
18	130.33	61.80	320	5.178	0.888
19	140.56	59.92	335	5.591	0.785
20	150.49	54.29	325	5.986	0.840
21	160.33	50.17	320	6.378	0.880
22	170.36	47.31	320	6.764	1.260
23	180.24	44.75	320	7.151	1.465
24	190.18	39.78	300	7.541	1.655
25	200.16	34.60	275	7.948	1.460
26	210.34	34.69	290	8.360	1.340
27	220.05	34.31	300	8.744	1.450
28	230.80	32.68	300	9.180	1.300
29	240.60	30.82	295	9.572	1.300
30	250.24	29.11	290	9.962	1.190

TABLE 2 (continued)

Data for Single Calibration of Meter No. 600508

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	271.52	24.92	270	10.835	+0.645
32	290.34	24.11	280	11.613	+0.015
33	311.57	23.26	290	12.468	-0.130
34	331.67	21.81	290	13.297	-0.755
35	351.42	20.91	295	14.108	-1.280
36	371.41	20.11	300	14.918	-1.540
37	390.96	19.09	300	15.713	-1.865
38	409.61	17.90	295	16.480	-2.390
39	431.28	15.85	275	17.350	-2.470
40	450.76	15.12	275	18.188	-3.940
41	472.55	14.17	270	14.054	-3.800
42	484.49	13.62	270	19.824	-6.110
43	510.38	12.60	260	20.635	-5.495
44	530.57	10.94	235	21.481	-6.455
45	550.23	10.53	235	22.317	-7.695
46	571.65	9.06	210	23.179	-7.825
47	591.50	8.73	210	24.050	-9.750

TABLE 3

Data for Single Calibration of Meter No. 600509

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	10.07	268.90	100	.372	0.770
2	15.05	190.92	110	.576	0.650
3	20.09	193.26	150	.776	0.690
4	25.01	180.05	175	.972	0.710
5	30.06	170.91	200	1.175	0.685
6	34.97	182.83	250	1.367	0.795
7	39.96	200.81	315	1.569	0.735
8	44.88	161.26	285	1.767	0.705
9	49.96	149.68	295	1.971	0.685
10	54.86	138.05	300	2.173	0.535
11	59.95	134.72	320	2.375	0.575
12	69.69	119.22	330	2.768	0.490
13	80.62	93.56	300	3.206	0.470
14	90.18	89.37	320	3.581	0.655
15	99.87	75.57	300	3.969	0.620
16	110.18	69.66	305	4.378	0.730
17	120.09	64.86	310	4.780	0.590
18	130.12	61.81	320	5.177	+0.695
19	140.53	59.97	335	5.586	+0.880
20	150.49	54.31	325	5.984	+0.890
21	160.19	50.07	320	6.391	+0.415
22	170.07	47.20	320	6.780	+0.570
23	180.03	44.59	320	7.176	+0.630
24	190.17	39.53	300	7.589	+0.445
25	200.30	34.38	275	7.999	+0.329
26	210.38	34.47	290	8.413	+0.520
27	220.15	34.06	300	8.808	-0.005
28	230.51	31.95	295	9.233	-0.319
29	240.86	30.59	295	9.644	-0.232
30	250.52	28.90	290	10.035	-0.345

TABLE 3 (continued)

Data for Single Calibration of Meter No. 600509

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	271.34	24.77	270	10.900	-1.167
32	290.50	23.97	280	11.681	-1.532
33	311.37	23.12	29	12.543	-2.211
34	331.11	21.72	290	13.352	-2.684
35	350.87	20.83	295	14.162	-3.187
36	371.41	19.98	300	15.015	-3.965
37	390.48	18.98	300	15.806	-4.673
38	409.18	17.79	295	16.582	-5.379
39	431.07	15.73	275	17.483	-5.993
40	450.72	15.01	275	18.321	-7.308
41	471.95	14.07	270	19.190	-7.794
42	491.35	13.02	260	19.969	-7.882
43	510.62	11.54	240	20.797	-9.311
44	531.67	11.09	240	21.641	-9.358
45	549.73	10.47	235	22.445	-1.397
46	569.70	9.01	210	23.307	-2.986
47	590.48	8.71	210	24.110	-2.275

TABLE 4

Data for Single Calibration of Meter No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	10.08	266.37	100	.375	+0.705
2	15.05	193.08	110	.570	+0.800
3	20.09	194.07	150	.773	+0.765
4	25.04	180.04	175	.972	+0.740
5	30.06	170.65	200	1.172	+0.760
6	34.99	182.79	250	1.368	+0.790
7	39.95	200.25	315	1.573	+0.625
8	44.92	160.54	285	1.775	+0.545
9	49.97	149.41	295	1.974	+0.620
10	54.91	138.40	300	2.168	+0.710
11	59.99	134.66	320	2.376	+0.590
12	69.64	119.02	330	2.773	+0.375
13	80.55	93.25	300	3.217	+0.125
14	90.09	88.91	320	3.599	+0.115
15	99.72	75.29	300	3.985	+0.095
16	110.01	69.35	305	4.398	+0.060
17	119.99	64.51	310	4.805	-0.135
18	130.06	61.43	320	5.209	-0.165
19	140.22	59.61	335	5.620	-0.280
20	150.43	53.92	325	6.027	-0.245
21	160.04	49.93	320	6.409	-0.185
22	170.14	47.00	320	6.809	-0.085
23	179.78	44.48	320	7.194	-0.070
24	189.80	39.48	300	7.599	-0.175
25	200.03	34.27	275	8.025	-0.595
26	210.24	34.32	290	8.450	-1.010
27	219.72	33.96	300	8.834	-1.130
28	230.56	32.31	300	9.285	-1.565
29	240.29	30.46	295	9.685	-1.835
30	249.87	28.79	290	0.073	-1.955

TABLE 4 (continued)

Data for Single Calibration of Meter No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	271.16	24.69	270	10.936	-02.240
32	290.28	23.86	280	11.735	-03.095
33	311.17	23.05	290	12.581	-03.350
34	330.84	21.63	290	13.402	-04.335
35	350.75	20.75	295	14.217	-04.675
36	370.82	19.93	300	15.053	-05.505
37	390.36	18.91	300	15.865	-06.190
38	409.20	17.72	295	16.648	-07.000
39	431.12	15.67	275	17.549	-07.600
40	450.62	14.96	275	18.382	-08.939
41	470.77	14.03	270	19.244	-10.342
42	490.20	13.50	270	20.000	-09.800
43	509.91	12.48	260	20.833	-10.923
44	531.93	10.82	235	21.719	-11.046
45	550.59	10.43	235	22.531	-12.689
46	570.75	8.97	210	23.411	-14.534
47	490.00	8.67	210	24.221	-15.536

TABLE 5

Data for Simultaneous Calibration of Meter No. 600508 with No. 600509 and No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	9.93	268.08	100	.373	0.605
2	14.99	193.47	110	.569	0.765
3	20.13	190.97	150	.785	0.505
4	25.09	178.46	175	.981	0.565
5	30.13	169.71	200	1.178	0.680
6	35.07	182.53	250	1.370	0.820
7	40.10	200.47	315	1.571	0.825
8	44.96	161.63	285	1.763	0.885
9	50.03	149.63	295	1.965	0.905
10	54.98	138.84	300	2.161	0.955
11	59.95	135.69	320	2.358	0.100
12	70.09	119.29	330	2.766	0.940
13	80.99	93.46	300	3.210	0.740
14	90.53	89.04	320	3.594	0.680
15	100.17	75.47	300	3.975	0.795
16	110.37	69.62	305	4.381	0.845
17	120.49	64.71	310	4.790	0.740
18	130.44	61.64	320	5.191	0.665
19	140.59	59.86	335	5.591	0.815
20	150.75	54.18	325	5.998	0.800
21	160.34	50.16	320	6.380	0.840
22	170.48	47.19	320	6.781	0.955
23	180.28	44.62	320	7.172	0.980
24	190.22	39.65	300	7.566	1.070
25	200.35	34.49	275	7.973	1.025
26	210.41	34.59	290	8.384	0.810
27	230.79	32.00	295	9.217	0.365
28	240.39	30.73	295	9.600	0.390
29	249.82	29.09	290	9.968	0.620

TABLE 5 (continued)

Data for Simultaneous Calibration of Meter No. 600508 with No. 600509 and No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
30	270.92	24.93	270	10.831	-00.145
31	289.47	24.19	280	11.575	-00.095
32	311.37	23.26	290	12.470	-00.380
33	330.87	21.85	290	13.270	-00.880
34	350.73	20.96	295	14.077	-01.195
35	370.62	20.11	300	14.918	-02.330
36	408.67	17.89	295	16.490	-03.580
37	429.38	15.87	275	17.328	-03.820
38	449.13	15.15	275	18.152	-04.670
39	471.14	14.21	270	19.001	-03.885
40	489.81	13.64	270	19.795	-05.065
41	509.65	12.62	260	20.602	-54.000
42	529.39	11.17	240	21.486	-77.605
43	548.91	10.55	235	22.274	-79.405
44	586.86	8.78	210	23.907	-10.815

TABLE 6

Data for Simultaneous Calibration of Meter No. 600509 with No. 600508 and No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	9.93	267.52	100	.374	0.580
2	14.99	193.38	110	.569	0.765
3	20.13	191.71	150	.782	0.580
4	25.09	179.18	175	.977	0.665
5	30.13	169.57	200	1.179	0.655
6	35.07	181.31	250	1.379	0.595
7	40.10	199.45	315	1.579	0.625
8	44.96	161.30	285	1.767	0.785
9	50.03	149.44	295	1.974	0.680
10	54.98	138.28	300	2.169	0.755
11	59.95	135.26	320	2.366	0.800
12	70.09	119.01	330	2.773	0.765
13	80.99	93.42	300	3.211	0.715
14	90.53	89.09	320	3.592	0.730
15	100.17	75.43	300	3.977	0.745
16	110.37	69.55	305	4.385	0.745
17	120.49	64.71	310	4.791	0.715
18	130.44	61.63	320	5.192	0.640
19	140.59	59.84	335	6.003	0.615
20	150.75	54.14	325	5.999	0.675
21	160.34	50.07	320	6.392	0.540
22	170.48	47.03	320	6.804	0.380
23	180.28	44.51	320	7.204	0.180
24	190.22	39.45	300	7.604	0.120
25	200.35	34.31	275	8.014	0.000
26	210.41	34.43	290	8.422	-0.140
27	219.87	32.92	290	8.810	-0.380
28	230.79	31.88	295	9.254	-0.560
29	240.39	30.60	295	9.641	-0.635
30	249.82	29.94	290	10.020	-0.680

TABLE 6 (continued)

Data for Simultaneous Calibration of Meter No. 600509 with No. 600508 and No. 600510

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	270.92	24.82	270	10.880	-01.080
32	289.47	24.05	280	11.642	-01.580
33	311.37	23.12	290	12.544	-02.230
34	330.87	21.70	290	13.362	-03.180
35	350.73	20.81	295	14.176	-03.670
36	370.62	19.99	300	15.006	-04.530
37	389.84	18.97	300	15.814	-05.510
38	408.67	17.79	295	16.582	-05.880
39	429.38	15.76	275	17.449	-06.845
40	449.13	15.06	275	18.260	-07.370
41	471.14	14.12	270	19.122	-06.660
42	489.81	13.56	270	19.912	-07.990
43	509.65	12.54	260	20.734	-08.700
44	529.39	11.16	240	21.622	-11.160
45	548.91	10.49	235	22.411	-11.365
46	570.16	9.47	220	23.233	-10.665
47	586.86	8.73	210	23.042	-14.190

TABLE 7

Data for Simultaneous Calibration of Meter No. 600510 with No. 600508 and No. 600509

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	9.93	264.75	100	.378	0.480
2	14.99	193.47	110	.569	0.765
3	20.13	193.23	150	.776	0.730
4	25.09	180.47	175	.920	0.840
5	30.13	170.87	200	1.170	0.880
6	35.07	182.95	250	1.366	0.920
7	40.10	201.39	315	1.564	1.000
8	44.96	161.86	285	1.761	0.935
9	50.03	149.44	295	1.967	0.855
10	54.98	138.83	300	2.161	0.955
11	59.95	135.44	320	2.363	0.875
12	70.09	119.31	330	2.766	0.940
13	80.99	93.67	300	3.203	0.915
14	90.53	89.38	320	3.580	1.030
15	100.17	75.58	300	3.969	0.945
16	110.37	69.74	305	4.373	1.045
17	120.49	64.83	310	4.781	0.965
18	130.44	61.75	320	5.182	0.865
19	140.59	59.92	335	5.591	0.815
20	150.75	54.18	325	5.999	0.775
21	160.34	50.14	320	6.382	0.790
22	170.48	47.11	320	6.792	0.680
23	180.28	44.51	320	7.189	0.555
24	190.22	39.50	300	7.595	0.345
25	200.35	34.34	275	8.007	0.175
26	210.41	34.47	290	8.414	0.060
27	230.79	31.87	295	9.255	- 0.585
28	240.39	30.58	295	9.647	- 0.785
29	249.82	28.93	290	10.026	- 0.830

TABLE 7 (continued)

Data for Simultaneous Calibration of Meter No. 600510 with No. 600508 and No. 600509

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
30	270.92	24.79	270	10.891	-01.355
31	289.47	24.04	280	11.647	-01.705
32	311.37	23.06	290	12.577	-03.055
33	330.87	21.65	290	13.393	-03.955
34	350.73	20.77	295	14.202	-04.320
35	370.62	19.93	300	15.053	-05.705
36	389.84	18.90	300	15.873	-06.985
37	408.67	17.75	295	16.620	-06.830
38	429.38	15.72	275	17.494	-07.970
39	449.13	15.03	275	18.297	-08.295
40	471.14	14.09	270	19.163	-07.935
41	489.81	13.53	270	19.956	-09.090
42	509.65	12.55	260	20.717	-08.275
43	529.39	11.09	240	21.641	-11.635
44	548.91	10.47	235	22.446	-12.240
45	570.16	9.45	220	23.274	-11.690
46	586.86	8.72	210	24.089	-15.365

TABLE 8

Calibrations for Single Meters

Meter Number	Equation (1) a_1	b_1	S_e (cm/s)	Equation (2) a_2	b_2	S_e (cm/s)	Equation (3) a_3	b_3	S_e (cm/s)
600508	0.596	25.089	0.189	6.410	24.466	0.122	13.508	24.057	0.568
600509	0.696	24.987	0.133	5.189	24.418	0.185	10.635	24.037	0.528
600510	0.820	24.837	0.145	4.691	24.345	0.154	10.077	23.975	0.568

TABLE 9

Calibrations for Three Meters at a Time

Meter Number	Equation (1) a1	b1	S_e (cm/s)	Equation (2) a2	b2	S_e (cm/s)	Equation (3) a3	b3	S_e (cm/s)
600508	0.662	25.038	0.123	3.493	24.687	0.212	11.083	24.143	0.864
600509	0.643	25.014	0.069	2.800	24.645	0.049	9.002	24.105	0.754
600510	0.806	25.019	0.138	4.222	24.489	0.079	8.366	24.096	0.950

TABLE 10.

Difference Between Single and Group Calibrations

for Meter 600508

N rev/s	V_s cm/s	V_3 cm/s	$\frac{\delta V}{V_s}$ %
0.5	13.14	13.18	0.30
1.0	25.69	25.70	0.04
2.0	50.78	50.74	-0.08
3.0	75.86	75.78	-0.11
4.0	100.95	100.81	-0.14
5.0	126.04	125.85	-0.15
6.0	151.13	150.89	-0.16
7.0	176.22	175.93	-0.16
8.0	201.31	200.96	-0.17
9.0	226.40	225.68	-0.31
10.0	251.07	250.37	-0.28
12.0	300.00	299.74	-0.09
14.0	348.93	349.08	0.04
16.0	397.86	397.36	-0.13
18.0	446.53	445.65	-0.20
20.0	494.65	493.93	-0.15
22.0	542.76	542.22	-0.09
24.0	590.88	590.51	-0.06

TABLE 11.

Difference Between Single and Group Calibrtions for Meter 600509

N rev/s	V_s cm/s	V_3 cm/s	$\frac{\delta V_{\%}}{V_s}$
0.5	13.19	13.15	-0.30
1.0	25.68	25.66	-0.08
2.0	50.67	50.67	0.00
3.0	75.66	75.69	0.04
4.0	100.64	100.70	0.06
5.0	125.63	125.71	0.06
6.0	150.62	150.67	0.03
7.0	175.61	175.31	-0.17
8.0	200.54	199.96	-0.29
9.0	224.95	224.60	-0.16
10.0	249.37	249.25	-0.05
12.0	298.21	298.27	0.02
14.0	347.05	346.48	-0.16
16.0	395.22	394.69	-0.13
18.0	443.29	442.90	-0.09
20.0	491.37	491.11	-0.05
22.0	539.44	539.32	-0.02
24.0	587.51	587.53	0.00

TABLE 12.

Difference Between Single and Group Calibrations

for Meter 600510

N rev/s	V_s cm/s	V_3 cm/s	$\frac{\delta V\%}{V_s}$
0.5	13.24	13.32	0.60
1.0	25.66	25.82	0.62
2.0	50.49	50.84	0.69
3.0	75.33	75.86	0.70
4.0	100.17	100.88	0.70
5.0	125.00	125.90	0.81
6.0	149.84	150.92	0.72
7.0	174.68	175.65	0.56
8.0	199.45	200.14	0.35
9.0	223.50	224.63	0.37
10.0	248.14	249.12	0.39
12.0	296.83	297.52	0.23
14.0	345.52	345.71	0.05
16.0	393.68	393.90	0.06
18.0	441.63	442.10	0.11
20.0	489.59	490.29	0.14
22.0	537.54	538.48	0.17
24.0	585.49	586.67	0.20

TABLE 13

Simultaneous Calibrations of Test Meters

Parameters	Meter 600508			Meter 600509			Meter 600510		
	Eq. #1	Eq. #2	Eq. #3	Eq. #1	Eq. #2	Eq. #3	Eq. #1	Eq. #2	Eq. #3
n	21	7	10	15	7	16	16	5	16
V_1 cm/s	9.93	202.86	347.47	9.93	146.79	286.10	9.93	162.11	262.31
S_e cm/s	0.123	0.212	0.864	0.069	0.049	0.754	0.138	0.079	0.950
S_e/V_1	0.0123	0.00104	0.00249	0.00695	0.00033	0.0026	0.0139	0.00049	0.00362
a_n	0.662	3.493	11.083	0.643	2.800	9.002	0.806	4.222	8.366
b_n	25.038	24.687	24.143	25.014	24.645	24.105	25.019	24.489	24.096
E_1 %	3.82	0.51	0.98	2.34	0.16	0.86	4.61	0.37	1.20
m	10	10	20	10	10	20	10	10	20

TABLE 14

Data for Simultaneous Calibration of Meter No. 600592 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	15.10	194.99	110	.564	0.99671
2	30.12	171.23	200	1.168	0.91951
3	45.13	160.15	285	1.780	0.64046
4	60.03	134.26	320	2.383	0.44412
5	74.85	110.66	330	2.982	0.29732
6	90.54	88.58	320	3.613	0.22616
7	105.35	71.21	300	4.213	0.02771
8	120.71	64.30	310	4.821	0.18123
9	134.91	59.39	320	5.388	0.20719
10	150.34	54.12	325	6.005	0.21066
11	164.82	48.40	320	6.612	-0.46926
12	180.24	44.34	320	7.217	-0.18399
13	195.20	37.04	290	7.829	-0.53434
14	210.27	34.32	290	8.450	0.97709
15	224.73	32.04	290	9.051	-1.54965
16	240.25	30.48	295	9.678	-1.71194
17	255.18	29.14	300	10.295	-2.19818
18	270.05	24.73	270	10.918	-2.89784
19	284.91	24.27	280	11.537	-3.51192
20	299.52	23.90	290	12.134	-3.82728
21	315.12	22.69	290	12.781	-4.40402
22	329.76	21.68	290	13.376	-4.64959
23	345.48	21.04	295	74.021	-5.04281
24	360.43	20.48	300	14.648	-5.75094
25	371.33	19.90	300	15.075	-5.55442
26	380.74	19.40	300	15.464	-5.85794
27	390.23	18.92	300	15.856	-6.17592
28	401.12	18.39	300	16.313	-6.71034
29	410.82	17.93	300	16.732	-7.47336
30	421.13	16.93	290	17.129	-7.10390

TABLE 14 (continued)

Data for Simultaneous Calibration of Meter No. 600592 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	431.32	15.69	275	17.527	-6.85718
32	440.63	15.33	275	17.939	-7.83706
33	451.04	14.95	275	18.395	-8.82622
34	462.32	14.58	275	18.861	-9.21635
35	472.34	14.02	270	19.258	-9.11506
36	482.68	13.74	270	19.651	-8.58638
37	491.54	12.97	260	20.046	-9.61652
38	502.01	12.71	260	20.456	-9.39834
39	510.35	11.52	240	20.833	-10.48333
40	520.01	11.29	240	21.258	-11.43376
41	531.22	11.07	240	21.680	-10.78542
42	540.08	10.65	235	22.066	-11.56319
43	549.70	10.46	235	22.467	-11.96348
44	561.10	9.60	220	22.917	-11.81667
45	569.89	9.00	210	23.333	-13.44333
46	581.33	8.85	210	23.729	-11.89034
47	592.67	8.68	210	24.194	-12.16871
48	604.19	8.49	210	24.735	-14.18456
49	571.74	8.97	210	23.411	13.54428
50	550.02	10.46	235	22.467	11.64348

TABLE 15

Data for Simultaneous Calibration of Meter No. 600593 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	15.24	183.48	110	.600	0.25199
2	30.14	168.10	200	1.190	0.39580
3	45.14	159.27	285	1.789	0.40465
4	60.06	133.97	320	2.389	0.34514
5	75.32	109.89	330	3.003	0.24493
6	90.23	88.51	320	3.615	-0.15527
7	105.80	70.73	300	4.241	-0.23704
8	120.53	64.19	310	4.829	-0.20532
9	135.12	59.16	320	5.409	-0.10650
10	149.97	54.07	325	6.011	-0.29817
11	164.36	48.52	320	6.595	-0.52046
12	179.87	44.29	320	7.225	-0.75768
13	195.23	36.95	290	7.848	-0.98109
14	210.32	34.26	290	8.465	-1.29705
15	224.45	32.07	290	9.043	-1.61798
16	239.95	30.50	295	9.672	-1.85328
17	255.98	29.04	300	10.331	-2.28446
18	270.26	24.67	270	10.944	-3.35168
19	284.48	24.27	280	11.537	-3.94192
20	299.98	23.81	290	12.180	-4.51391
21	315.00	22.64	290	12.809	-5.22968
22	329.66	21.58	290	13.438	-6.29922
23	344.96	20.63	290	14.057	-6.46996
24	360.51	20.01	295	14.743	-8.05572
25	371.89	19.80	300	15.152	-6.89788
26	380.12	19.33	300	15.520	-7.87793
27	390.04	18.86	300	15.907	-7.62702
28	399.54	18.33	300	16.367	-9.62530
29	410.21	17.88	300	16.779	-9.25309
30	420.99	16.84	290	17.221	-9.53257

TABLE 15 (continued)

Data for Simultaneous Calibration of Meter No. 600593 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	431.59	15.58	275	17.651	- 9.68086
32	439.96	15.24	275	18.045	-11.15549
33	451.28	14.89	275	18.469	-10.43927
34	460.20	14.58	275	18.861	-11.33635
35	469.84	14.02	270	19.258	-11.61506
36	480.45	13.71	270	19.694	-11.89136
37	490.10	13.42	270	20.119	-12.88063
38	500.33	12.65	260	20.553	-13.50399
39	508.98	12.41	260	20.951	-14.79115
40	521.68	11.21	240	21.409	-13.55640
41	531.53	11.01	240	21.798	-13.42913
42	542.27	10.55	235	22.275	-14.60204
43	561.98	9.53	220	23.085	-15.14487
44	572.65	8.90	210	23.596	-17.23764
45	582.42	8.77	210	23.945	-16.21170
46	589.73	8.65	210	24.277	-17.20642
47	603.80	8.47	210	24.793	-16.03471
	Reruns				
48	549.95	10.38	235	22.640	-16.04229
49	529.78	11.03	240	21.759	-14.19099
50	510.62	11.47	240	20.924	-12.48375
51	439.86	15.24	275	18.045	-11.25549
52	591.41	8.66	210	24.249	-14.82557

TABLE 16

Data for Simultaneous Calibration of Meter No. 600594 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	15.24	181.33	110	.607	0.07428
2	30.14	166.45	200	1.202	0.10095
3	45.14	158.28	285	1.801	0.12484
4	60.06	133.31	320	2.400	0.04950
5	75.32	108.94	330	3.029	-0.40976
6	90.23	88.74	320	3.606	+0.07889
7	105.80	70.94	300	4.229	+0.07685
8	120.53	64.27	310	4.823	-0.05503
9	135.12	59.22	320	5.404	+0.03050
10	149.97	54.14	325	6.003	-0.10388
11	164.36	48.56	320	6.590	-0.38465
12	179.87	44.33	320	7.219	-0.59469
13	195.23	36.94	290	7.851	-1.03421
14	210.32	34.23	290	8.472	-1.48251
15	224.45	32.01	290	9.060	-2.04172
16	239.95	30.41	295	9.701	-2.56891
17	255.98	28.96	300	10.359	-2.99790
18	270.26	24.67	270	10.944	-3.35168
19	284.48	24.26	280	11.542	-4.06081
20	299.98	23.84	290	12.161	-4.13074
21	315.00	22.67	290	12.792	-4.80591
22	329.66	21.62	290	13.414	-5.67765
23	344.96	20.69	290	14.016	-5.45083
24	360.51	20.09	295	14.691	-6.77088
25	371.89	19.86	300	15.106	-5.75351
26	380.12	19.39	300	15.472	-6.67732
27	390.04	18.92	300	15.856	-6.36592
28	399.54	18.42	300	16.287	-7.62612
29	410.21	17.94	300	16.722	-7.85020
30	420.99	16.90	290	17.160	-8.00408

TABLE 16 (continued)

Data for Simultaneous Calibration of Meter No. 600594 with Oil in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	431.59	15.63	275	17.594	- 8.26925
32	439.96	15.29	275	17.986	- 9.68029
33	451.28	14.93	275	18.419	- 9.20225
34	460.20	14.64	275	18.784	- 9.40383
35	469.84	14.08	270	19.176	- 9.56341
36	480.45	13.76	270	19.622	-10.10233
37	490.10	13.47	270	20.045	-11.01359
38	500.33	12.70	260	20.472	-11.45102
39	508.98	12.46	260	20.867	-12.68934
40	521.68	11.26	240	21.314	-11.17968
41	531.53	11.05	240	21.719	-11.45643
42	542.27	10.59	235	22.191	-12.49865
43	549.48	10.40	235	22.596	-15.42385
44	561.98	9.57	220	22.989	-12.73265
45	572.65	8.93	210	23.516	-15.25594
46	582.42	8.79	210	23.891	-14.84962
47	603.80	8.46	210	24.823	-16.76738
	Reruns				
48	549.95	10.40	235	22.596	-14.95385
49	529.78	11.06	240	21.700	-12.71548
50	510.62	11.49	240	20.888	-11.57321
51	439.86	15.30	275	17.974	- 9.48641
52	591.41	8.65	210	24.277	-15.52642

TABLE 17

Data for Simultaneous Calibration of Meter No. 600592 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	15.23	221.89	110	.496	2.83647
2	30.17	172.75	200	1.158	1.22644
3	45.20	159.90	285	1.782	0.64090
4	60.06	134.40	320	2.381	+0.53619
5	75.18	109.96	330	3.001	+0.15272
6	90.28	88.56	320	3.613	-0.05424
7	105.78	70.77	300	4.239	-0.19711
8	120.40	64.19	310	4.829	-0.33532
9	135.09	59.08	320	5.416	-0.31961
10	150.07	54.02	325	6.016	-0.33726
11	164.45	48.49	320	6.599	-0.53247
12	179.86	44.32	320	7.220	-0.64542
13	195.58	36.89	290	7.861	-0.95023
14	210.11	34.27	290	8.462	-1.44530
15	224.39	32.03	290	9.054	-1.96030
16	239.96	30.44	295	9.691	-2.31989
17	255.56	29.01	300	10.341	-2.97154
18	270.21	24.68	270	10.940	-3.29081
19	284.94	24.23	280	11.556	-3.95806
20	300.25	23.81	290	12.180	-4.24391
21	313.83	22.76	290	12.742	-4.71130
22	330.70	21.55	290	13.457	-5.72692
23	344.39	21.05	295	14.014	-5.96630
24	360.52	20.10	295	14.677	-6.39542
25	370.98	19.86	300	15.106	-6.66351
26	380.35	19.36	300	15.496	-7.04670
27	389.95	18.90	300	15.873	-6.87540
28	400.34	18.39	300	16.313	-7.49034
29	410.82	17.90	300	16.760	-8.17441
30	420.91	16.91	290	17.150	-7.83039

TABLE 17 (continued)

Data for Simultaneous Calibration of Meter No. 600592 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/Sec	ΔV (cm/s)
31	431.35	15.65	275	17.572	- 7.94712
32	441.45	15.25	275	18.033	- 9.36967
33	450.48	14.91	275	18.444	-10.61993
34	460.87	14.63	275	18.797	- 9.05481
35	470.66	14.04	270	19.231	-10.10923
36	480.52	13.77	270	19.608	- 9.67608
37	489.13	13.47	270	20.045	-11.98359
38	502.36	12.69	260	20.489	- 9.85434
39	510.86	12.47	260	20.850	-10.39100
40	521.52	11.27	240	21.295	-10.86687
41	529.89	11.07	240	21.680	-12.11542
42	541.64	10.62	235	22.128	-11.56151
43	550.86	10.42	235	22.553	-12.95958
44	559.87	9.61	220	22.893	-12.45050
45	571.98	8.98	210	23.385	-12.65252
46	580.00	8.84	210	23.756	-13.89140
47	589.07	8.71	210	24.110	-13.68545
48	599.20	8.56	210	24.533	-14.11776
49	451.27	14.90	275	18.456	9.63940
50	490.35	12.98	260	20.031	10.42942

TABLE 18

Data for Simultaneous Calibration of Meter No. 600593 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
1	15.23	210.10	110	.524	2.14099
2	30.17	170.27	200	1.175	0.80487
3	45.20	159.22	285	1.790	0.45060
4	60.06	133.92	320	2.389	0.32284
5	75.18	110.05	330	2.999	+0.21408
6	90.28	88.67	320	3.609	+0.05783
7	105.78	70.83	300	4.235	-0.10734
8	120.40	64.38	310	4.815	+0.02100
9	135.09	59.21	320	5.404	-0.02231
10	150.07	54.10	325	6.007	-0.11484
11	164.45	48.54	320	6.593	-0.36253
12	179.86	44.33	320	7.219	-0.60470
13	195.58	36.92	290	7.855	-0.79053
14	210.11	34.35	290	8.443	-0.95259
15	224.39	32.14	290	9.023	-1.18561
16	239.96	30.52	295	9.666	-1.68482
17	255.56	29.10	300	10.309	-2.17196
18	270.21	24.75	270	10.909	-2.51727
19	284.94	24.31	280	11.518	-3.00735
20	300.25	23.85	290	12.159	-3.73323
21	313.83	22.80	290	12.719	-4.15246
22	330.70	21.63	290	13.407	-4.48262
23	344.39	21.09	295	13.988	-5.30180
24	360.52	20.11	295	14.669	-6.21297
25	370.98	19.89	300	15.083	-6.09391
26	380.35	19.38	300	15.480	-6.64691
27	389.95	18.89	300	15.881	-7.08547
28	400.34	18.38	300	16.322	-7.71223
29	410.82	17.90	300	16.760	-8.17441
30	420.91	16.89	290	17.170	-8.33808

TABLE 18 (continued)

Data for Simultaneous Calibration of Meter No. 600593 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
31	431.35	15.65	275	17.572	- 7.94712
32	441.45	15.24	275	18.045	- 9.66549
33	450.48	14.90	275	18.456	-10.92940
34	460.87	14.61	275	18.823	- 9.69810
35	470.66	14.02	270	19.258	-10.79506
36	480.52	13.75	270	19.636	-10.38909
37	489.13	13.45	270	20.074	-12.72874
38	502.36	12.67	260	20.521	-10.66289
39	510.86	12.45	260	20.884	-11.22835
40	521.52	11.26	240	21.314	-11.33968
41	529.89	11.05	240	21.719	-13.09643
42	541.64	10.60	235	22.170	-12.60528
43	550.86	10.41	235	22.574	-13.50119
44	559.87	9.60	220	22.917	-13.04667
45	571.98	8.96	210	23.438	-13.95750
46	580.00	8.82	210	23.810	-15.23810
47	589.07	8.68	210	24.194	-15.76871
48	599.20	8.52	210	24.648	-16.99718
49	451.77	14.87	275	18.494	-10.57028
50	490.35	12.95	260	20.077	-11.58050

TABLE 19

Data for Simultaneous Calibration of Meter No. 600594 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/Sec	ΔV (cm/s)
1	30.17	173.15	200	1.155	1.29330
2	45.20	159.22	285	1.790	0.45060
3	60.06	133.87	320	2.390	0.30054
4	75.18	110.08	330	2.998	0.23451
5	90.28	88.68	320	3.608	+0.06800
6	105.78	70.73	300	4.241	-0.25704
7	120.40	64.35	310	4.817	-0.03512
8	135.09	59.15	320	5.410	-0.15937
9	150.07	54.06	325	6.012	-0.22597
10	164.45	48.51	320	6.597	-0.46445
11	179.86	44.32	320	7.220	-0.64542
12	195.58	36.84	290	7.872	-1.21696
13	210.11	34.25	290	8.467	-1.56883
14	224.39	31.98	290	9.068	-2.31419
15	239.96	30.41	295	9.701	-2.55891
16	255.56	28.99	300	10.348	-3.14990
17	270.21	24.67	270	10.944	-3.40168
18	284.94	24.23	280	11.556	-3.95806
19	300.25	23.78	290	12.195	-4.62805
20	313.83	22.73	290	12.758	-5.13173
21	330.70	21.54	290	13.463	-5.88310
22	344.39	21.04	295	14.021	-6.13281
23	360.52	20.08	295	14.691	-6.76088
24	370.98	19.85	300	15.113	-6.85375
25	380.35	19.34	300	15.512	-7.44731
26	389.95	18.86	300	15.907	-7.71702
27	400.34	18.39	300	16.313	-7.49034
28	410.82	17.90	300	16.760	-8.17441
29	420.91	16.90	290	17.160	-8.08408

TABLE 19 (continued)

Data for Simultaneous Calibration of Meter No. 600594 with Water in Bearing Chamber

Test No.	Velocity (cm/s)	Time (sec)	Revs.	Revs/ Sec	ΔV (cm/s)
30	431.35	15.65	275	17.572	- 7.94712
31	441.45	15.25	275	18.033	- 9.36967
32	450.48	14.90	275	18.456	-10.92940
33	460.87	14.61	275	18.823	- 9.69810
34	470.66	14.03	270	19.244	-10.45190
35	480.52	13.75	270	19.636	-10.38909
36	489.13	13.45	270	20.074	-12.72874
37	502.36	12.67	260	20.521	-10.66289
38	510.86	12.44	260	20.900	-11.64804
39	521.52	11.25	240	21.333	-11.81333
40	529.89	11.04	240	21.739	-13.58826
41	541.64	10.60	235	22.170	-12.60528
42	550.86	10.41	235	22.574	-13.50119
43	571.98	8.97	210	23.411	-13.30428
44	580.00	8.81	210	23.837	-15.91373
45	451.27	14.87	275	18.494	-10.57028
46	490.35	12.94	260	20.093	-11.96839

TABLE 20

Calibrations for Meters with Oil Lubrication

Meter Number	Equation (1)			Equation (2)			Equation (3)		
	a_1	b_1	S_e (cm/s)	a_2	b_2	S_e (cm/s)	a_3	b_3	S_e (cm/s)
600592	0.974	24.825	0.188	5.675	24.229	0.492	-	-	-
600593	0.514	24.864	0.146	2.498	24.549	0.054	7.445	24.008	0.677
600594	0.072	24.477	0.159	4.601	24.268	0.131	8.556	24.018	0.772

TABLE 21

Calibrations for Meters with Water Lubrication

Meter Number	Equation (1)			Equation (2)			Equation (3)		
	a_1	b_1	S_e (cm/s)	a_2	b_2	S_e (cm/s)	a_3	b_3	S_e (cm/s)
600592	0.913	24.775	0.131	5.102	24.222	0.502	-	-	-
600593	0.753	24.828	0.133	3.786	24.433	0.128	8.173	24.032	0.652
600594	0.752	24.818	0.104	5.715	24.154	0.617	-	-	-

TABLE 22

Difference in Calibrations of Meter No. 600592

When Oil is Replaced with Water

N rev/s	V_{oil} cm/s	V_{water} cm/s	$\frac{\delta V}{V_s}$%
2.0	50.62	50.46	-0.32
3.0	75.45	75.24	-0.28
4.0	100.27	100.01	-0.26
5.0	125.10	124.79	-0.25
6.0	149.92	149.56	-0.24
7.0	174.75	174.34	-0.23
8.0	199.51	198.88	-0.32
9.0	223.33	223.10	-0.28
10.0	247.96	247.32	-0.26
12.0	296.42	295.77	-0.22
14.0	344.88	344.21	-0.19
16.0	393.34	392.66	-0.17
18.0	441.79	441.10	-0.16
20.0	496.25	489.54	-0.15
22.0	538.31	537.99	-0.13
24.0	597.17	536.43	-0.13

$$\frac{\delta V}{V_{oil}} = \left(\frac{V_{water} - V_{oil}}{V_{oil}}\right) \times 100\%$$

TABLE 23

Difference in Calibrations of Meter No. 600593

When Oil is Replaced with Water

N rev/s	V_{oil} cm/s	V_{water} cm/s	$\frac{\delta V_{\%}}{V_s}$
2.0	50.24	50.41	0.34
3.0	75.11	75.24	0.17
4.0	99.97	100.06	0.09
5.0	124.84	124.89	0.04
6.0	149.70	149.72	0.01
7.0	174.34	174.55	0.12
8.0	198.89	199.24	0.18
9.0	223.44	223.67	0.10
10.0	247.52	248.11	0.24
12.0	295.54	296.56	0.35
14.0	343.55	344.63	0.31
16.0	391.53	392.69	0.29
18.0	439.59	440.35	0.26
20.0	489.60	488.82	0.25
22.0	535.62	536.88	0.24
24.0	553.63	584.95	0.23

$$\frac{\delta V}{V_{oil}} = \left(\frac{V_{water} - V_{oil}}{V_{oil}}\right) \times 100\%$$

TABLE 24

Difference in Calibrations of Meter No. 600594

When Oil is Replaced with Water

N rev/s	V_{oil} cm/s	V_{water} cm/s	$\frac{\delta V}{V_s}$%
2.0	50.03	50.39	0.72
3.0	75.00	75.20	0.27
4.0	99.98	100.02	0.04
5.0	124.96	124.84	0.10
6.0	149.93	149.66	-0.18
7.0	174.48	174.47	0.01
8.0	198.75	198.95	0.10
9.0	203.01	223.10	0.04
10.0	247.28	247.26	0.01
12.0	295.82	295.57	-0.09
14.0	344.36	343.87	-0.14
16.0	392.85	293.18	-0.17
18.0	440.88	440.49	-0.09
20.0	488.92	488.80	-0.02
22.0	536.95	537.11	0.03
24.0	584.99	585.41	0.07

$$\frac{\delta V}{V_{oil}} = \left(\frac{V_{water} - V_{oil}}{V_{oil}}\right) \times 100\%$$

TABLE 25

Typical Calibration Certificate

(a) EQUATION (1)

Meter No.: 600594 Date: June 20, 1985

Hydro-Québec SIAP ME4001 Meters with 35/75 Aerofoil Post (Water)

Range of values is Minimum V(cm/s) = 45.20 N(rev/s) = 1.790
Maximum V(cm/s) = 186.43 N(rev/s) = 7.482
V = 0.752 + 24.818 *N

Standard Error of Estimate = 0.1041 cm/s

		Confidence Intervals			
		95%		99%	
N REV/S	V CM/S	V- CM/S	V+ CM/S	V- CM/S	V+ CM/S
2.000	50.39	50.11	50.66	49.99	50.78
2.500	62.80	62.53	63.06	62.41	63.18
3.000	75.20	74.95	75.46	74.83	75.58
3.500	87.61	87.36	87.87	87.24	87.98
4.000	100.02	99.77	100.27	99.65	100.39
4.500	112.43	112.18	112.68	112.06	112.80
5.000	124.84	124.59	125.09	124.47	125.21
5.500	137.25	136.99	137.50	136.88	137.62
6.000	149.66	149.40	149.92	149.28	150.03
6.500	162.07	161.80	162.33	161.68	162.45
7.000	174.47	174.20	174.75	174.08	174.87

STE = 0.10406 NMEAN = 4.51 SN = 1.82345 T95 = 2.306 T99 = 3.35

TABLE 25

Typical Calibration Certificate

(b) EQUATION (2)

Meter No.: 600594 Date: June 20, 1985

Hydro-Québec SIAP ME4001 Meters with 35/75 Aerofoil Post (Water)

Range of values is Minimum V(cm/s) = 186.43 N(rev/s) = 7.482
Maximum V(cm/s) = 580.00 N(rev/s) = 23.837

V = 5.715 + 24.154 *N

Standard Error of Estimate = 0.6165 cm/s

		Confidence Intervals					
N REV/S	V CM/S	V- CM/S	95%	V+ CM/S	V- CM/S	99%	V+ CM/S
7.500	186.87	185.54		188.20	185.09		188.65
8.000	198.95	197.62		200.27	197.18		200.72
8.500	211.03	209.71		212.34	209.26		212.79
9.000	223.10	221.79		224.41	221.35		224.86
9.500	235.18	233.88		236.48	233.43		236.93
10.000	247.26	245.96		248.56	245.52		249.00
10.500	259.33	258.04		260.63	257.60		261.07
11.000	271.41	270.12		272.70	269.69		273.14
11.500	283.49	282.20		284.77	281.77		285.21
12.000	295.57	294.28		296.85	293.85		297.28
12.500	307.64	306.37		308.92	305.93		309.35
13.000	319.72	318.45		320.99	318.01		321.42
13.500	331.80	330.53		333.07	330.10		333.50
14.000	343.87	342.60		345.14	342.18		345.57
14.500	355.95	354.68		357.22	354.26		357.65
15.000	368.03	366.76		369.29	366.33		369.72
15.500	380.10	378.84		381.37	378.41		381.80
16.000	392.18	390.92		393.45	390.49		393.87
16.500	404.26	403.00		405.52	402.57		405.95
17.000	416.34	415.07		417.60	414.65		418.03
17.500	428.41	427.15		429.68	426.72		430.11
18.000	440.49	439.22		441.76	438.80		442.18
18.500	452.57	451.30		453.83	450.87		454.26
19.000	464.64	463.38		465.91	462.95		466.34
19.500	476.72	475.45		477.99	475.02		478.42
20.000	488.80	487.52		490.07	487.09		490.50
20.500	500.88	499.60		502.15	499.17		502.58
21.000	512.95	511.67		514.23	511.24		514.67
21.500	525.03	523.75		526.31	523.31		526.75
22.000	537.11	535.82		538.40	535.38		538.83
22.500	549.18	547.89		550.48	547.45		550.91
23.000	561.26	559.96		562.56	559.52		563.00
23.500	573.34	572.03		574.64	571.59		575.08

STE = 0.61653 NMEAN = 16.54 SN = 4.55434 T95 = 2.021 T99 = 2.704

TABLE 26

Calibration Equations

Meter Number	Equation (1)			Equation (2)			Equation (3)		
	a1	b1	S_e	a2	b2	S_e	a3	b3	S_e
600508	0.596	25.089	0.1888	6.410	24.466	0.1218	13.508	24.057	0.5680
600509	0.696	24.987	0.1328	5.189	24.418	0.1850	10.635	24.037	0.5279
600510	0.820	24.837	0.1445	4.691	24.345	0.1543	10.077	24.975	0.5676
600511	0.751	24.868	0.2161	4.333	24.343	0.1860	8.836	24.008	0.5047
600512	0.715	25.009	0.2209	3.178	24.648	0.1333	10.881	24.138	0.7815
600513	0.978	25.198	0.1280	4.585	24.746	0.2039	10.598	24.341	0.8802
600514	0.932	24.727	0.3187	8.181	23.914	0.6038	-	-	-
600515	0.756	24.939	0.1095	4.342	24.439	0.1199	9.827	24.004	0.7078
600516	0.217	25.046	0.3056	5.032	24.450	0.2113	7.177	24.290	0.6690
600517	0.558	25.064	0.1586	6.023	24.356	0.3527	11.946	23.989	0.6704
600518	0.455	25.095	0.1894	4.616	24.563	0.3472	9.099	24.291	0.7700
600519	0.673	25.025	0.1608	6.498	24.274	0.3081	10.164	24.051	0.6963
600520	0.910	24.921	0.2000	6.052	24.295	0.3212	10.385	24.004	0.5347
600521	0.848	25.047	0.1500	6.878	24.296	0.5570	-	-	-
600522	0.977	25.073	0.1250	6.671	24.322	0.5300	-	-	-
600523	0.834	24.997	0.0977	6.141	24.353	0.2679	10.142	24.112	0.4500
600524	0.841	24.961	0.1336	3.857	24.566	0.3062	11.125	24.140	0.5562
600525	0.678	25.084	0.1448	4.495	24.537	0.2178	11.514	24.105	0.5409
600526	0.869	25.007	0.1053	5.377	24.436	0.3406	10.946	24.027	0.4620
600530	0.776	25.004	0.1353	3.704	24.608	0.2237	9.022	24.236	0.6126
600532	0.842	25.004	0.1278	4.596	24.488	0.2370	10.364	24.061	0.4990
600533	0.736	24.790	0.1291	5.387	24.207	0.2260	9.788	23.873	0.4891
600534	0.517	25.163	0.1535	4.034	24.699	0.2728	13.653	24.138	0.5313
600535	0.828	24.705	0.1158	7.928	23.718	0.4425	-	-	-
600536	0.491	25.049	0.1054	1.604	24.855	0.2600	6.367	24.517	0.6649
600539	0.579	24.846	0.1169	5.689	24.279	0.2401	7.180	24.183	0.6080
600540	0.485	24.677	0.1570	6.930	23.725	0.6110	-	-	-
600541	0.607	24.926	0.1210	4.586	24.353	0.1500	7.745	24.110	0.7280
600542	0.687	24.824	0.0935	4.980	24.250	0.2116	10.034	23.968	0.7866
600543	0.976	24.835	0.1165	5.432	24.219	0.2016	8.356	24.043	0.7195

a = intercept (cm/s).
b = effective pitch of propeller (i.e., slope of equation) (cm/rev).
S_e = standard error of estimate (cm/s).

TABLE 27

Maximum Error of Calibrations at 99% Level of Confidence

Meter Number	Equation (1)			Equation (2)			Equation (3)		
	n	V_1 cm/s	E_1 %	n	V_1	E_1 %	n	V_1	E_1 %
600508	21	10.67	5.83	9	234.43	0.22	10	431.41	0.51
600509	21	10.07	4.10	8	198.14	0.42	13	353.45	0.52
600510	18	10.07	4.61	9	196.43	0.33	13	359.28	0.55
600511	17	10.06	7.01	9	170.33	0.45	14	331.98	0.52
600512	18	10.06	7.06	11	190.06	0.26	13	351.31	0.79
600513	18	10.06	4.09	11	202.00	0.38	12	371.43	0.86
600514	14	15.06	7.30	34	221.64	0.79	-	-	-
600515	12	15.06	2.64	11	179.61	0.25	25	312.39	0.68
600516	13	15.06	7.17	10	202.70	0.41	25	331.67	0.61
600517	14	15.05	3.63	13	194.07	0.64	24	398.78	0.51
600518	14	15.05	4.34	15	196.88	0.59	23	408.67	0.58
600519	14	15.05	3.69	14	194.68	0.55	25	405.24	0.52
600520	13	15.00	4.71	15	205.60	0.53	27	368.54	0.43
600521	13	15.00	3.53	40	201.88	0.78	-	-	-
600522	12	15.00	3.03	42	191.05	0.78	-	-	-
600523	13	15.03	2.30	14	206.59	0.44	22	410.68	0.34
600524	12	15.03	3.23	18	191.40	0.51	20	422.85	0.41
600525	11	15.03	3.62	15	175.79	0.42	24	402.91	0.41
600526	13	15.02	2.48	9	198.27	0.71	28	337.97	0.41
600530	12	15.02	3.27	12	185.60	0.44	30	355.12	0.51
600532	12	15.02	3.09	10	182.52	0.46	29	335.31	0.44
600533	13	15.01	3.04	8	198.29	0.51	31	324.64	0.44
600534	12	15.01	3.71	18	191.42	0.46	21	427.30	0.39
600535	11	15.01	2.90	40	178.54	0.71	-	-	-
600536	9	15.12	2.89	14	143.49	0.62	27	351.96	0.56
600539	15	15.12	2.61	12	224.65	0.39	26	382.99	0.48
600540	11	15.12	3.90	41	167.65	1.02	-	-	-
600541	11	15.10	3.01	10	173.80	0.34	33	321.01	0.66
600542	12	15.10	2.25	19	186.30	0.36	21	440.09	0.56
600543	12	15.10	2.80	16	180.90	0.37	23	407.48	0.54

n = no. of data pairs
V_1 = minimum velocity
E_1 = percent error at 99% confidence at V_1

FIGURES

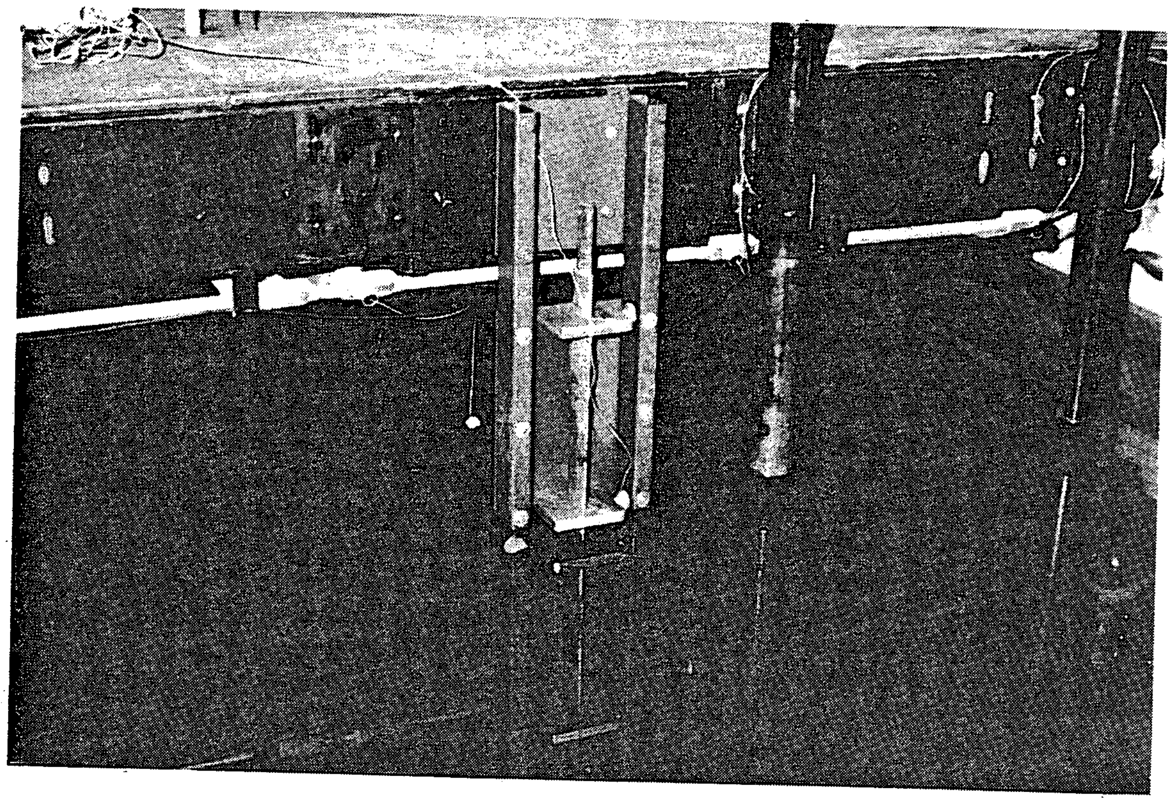

FIGURE 1. METER SUSPENSION POST AT REAR OF TOWING CARRIAGE

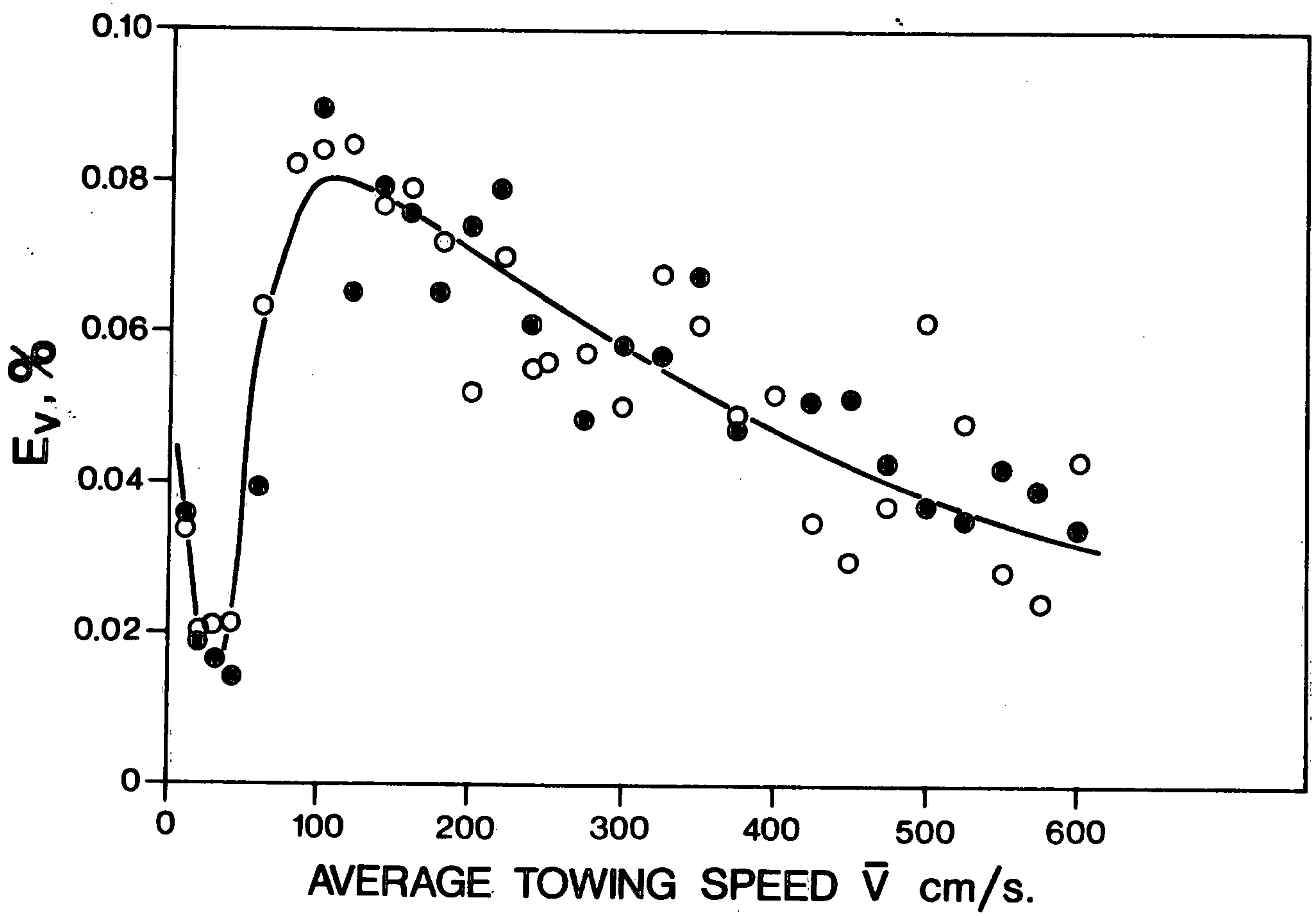

FIGURE 2. UNCERTAINTY IN MEAN TOWING SPEED AT 99 % CONFIDENCE LEVEL (Engel, Dezeeuw, 1982)

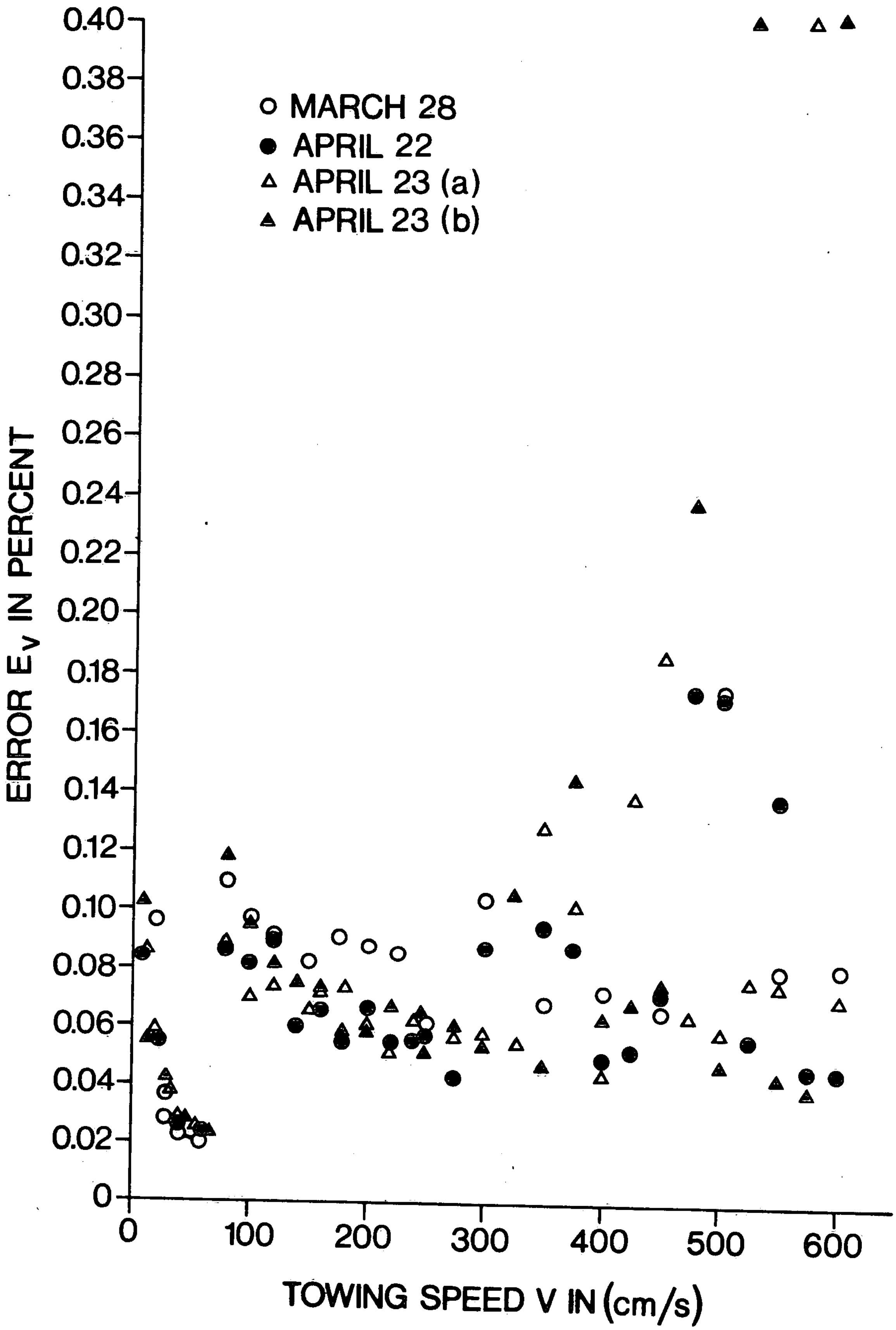

FIGURE 3. MAXIMUM ERROR IN TOWING SPEED AT 99% CONFIDENCE LEVEL WHEN SINGLE METER IS TOWED

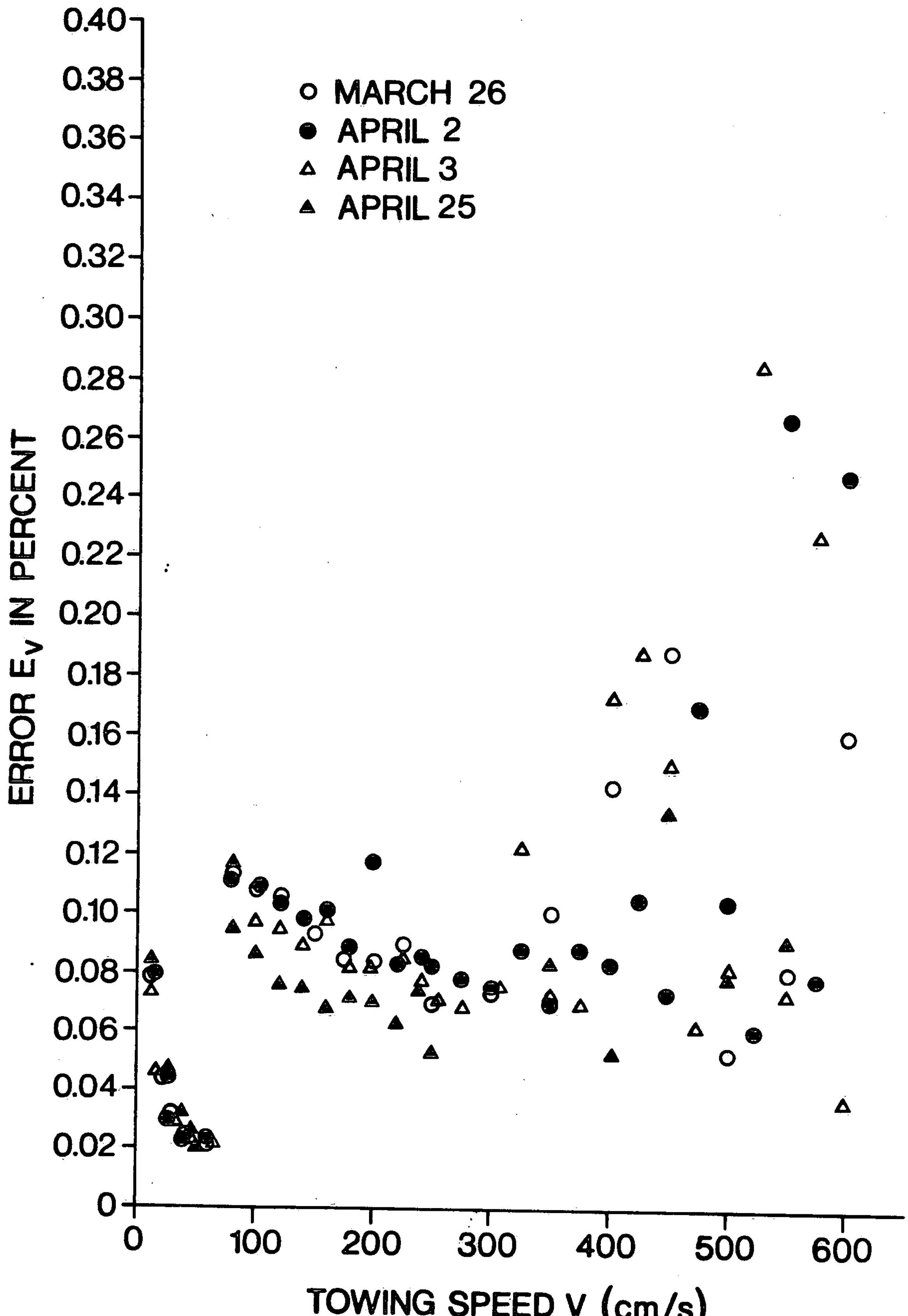

FIGURE 4. MAXIMUM ERROR IN TOWING SPEED AT 99% CONFIDENCE LEVEL WITH 3 METERS TOWED SIMULTANEOUSLY

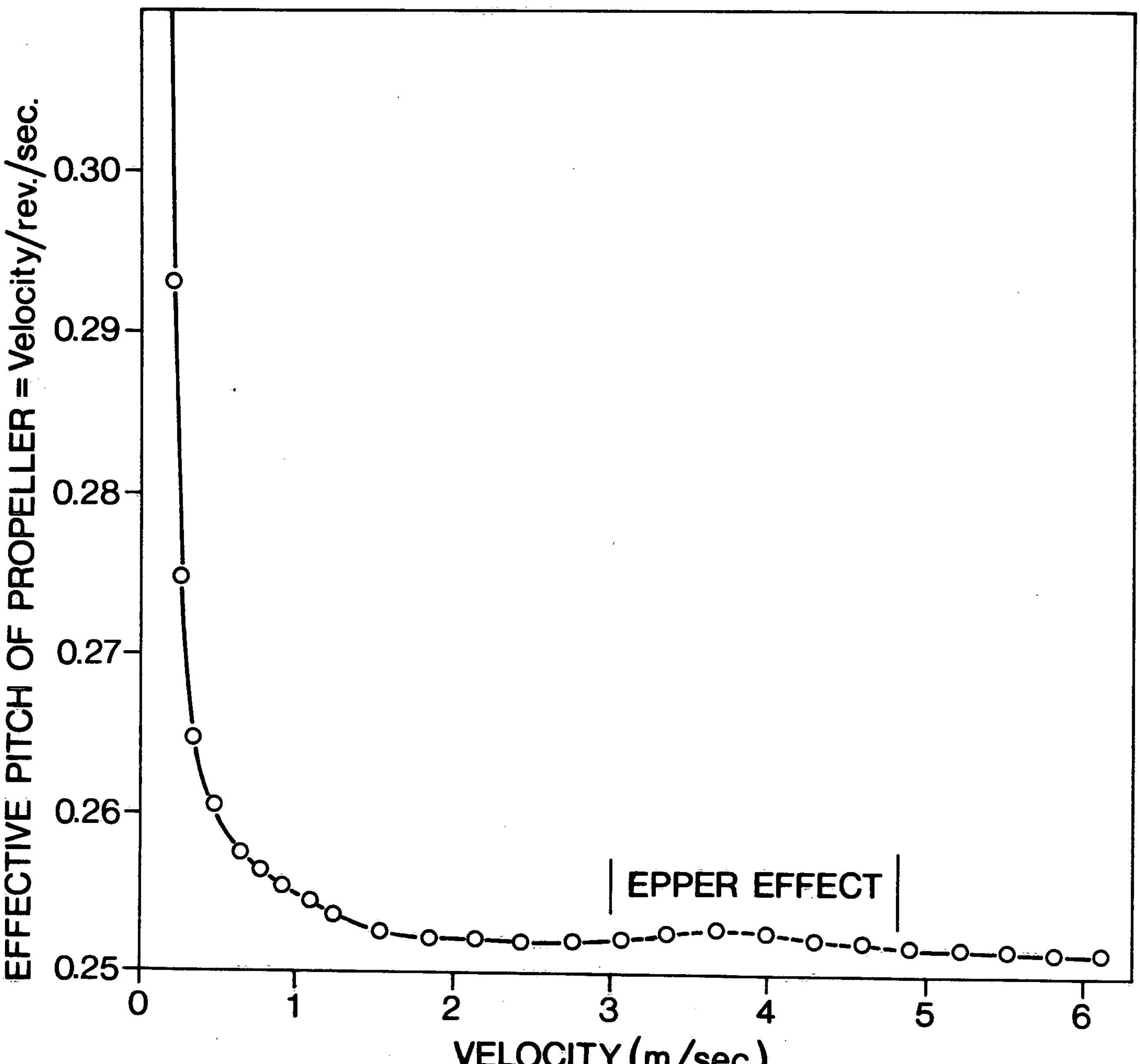

FIGURE 5. EPPER EFFECT FOR OTT CURRENT METER (GRINDLEY, 1971)

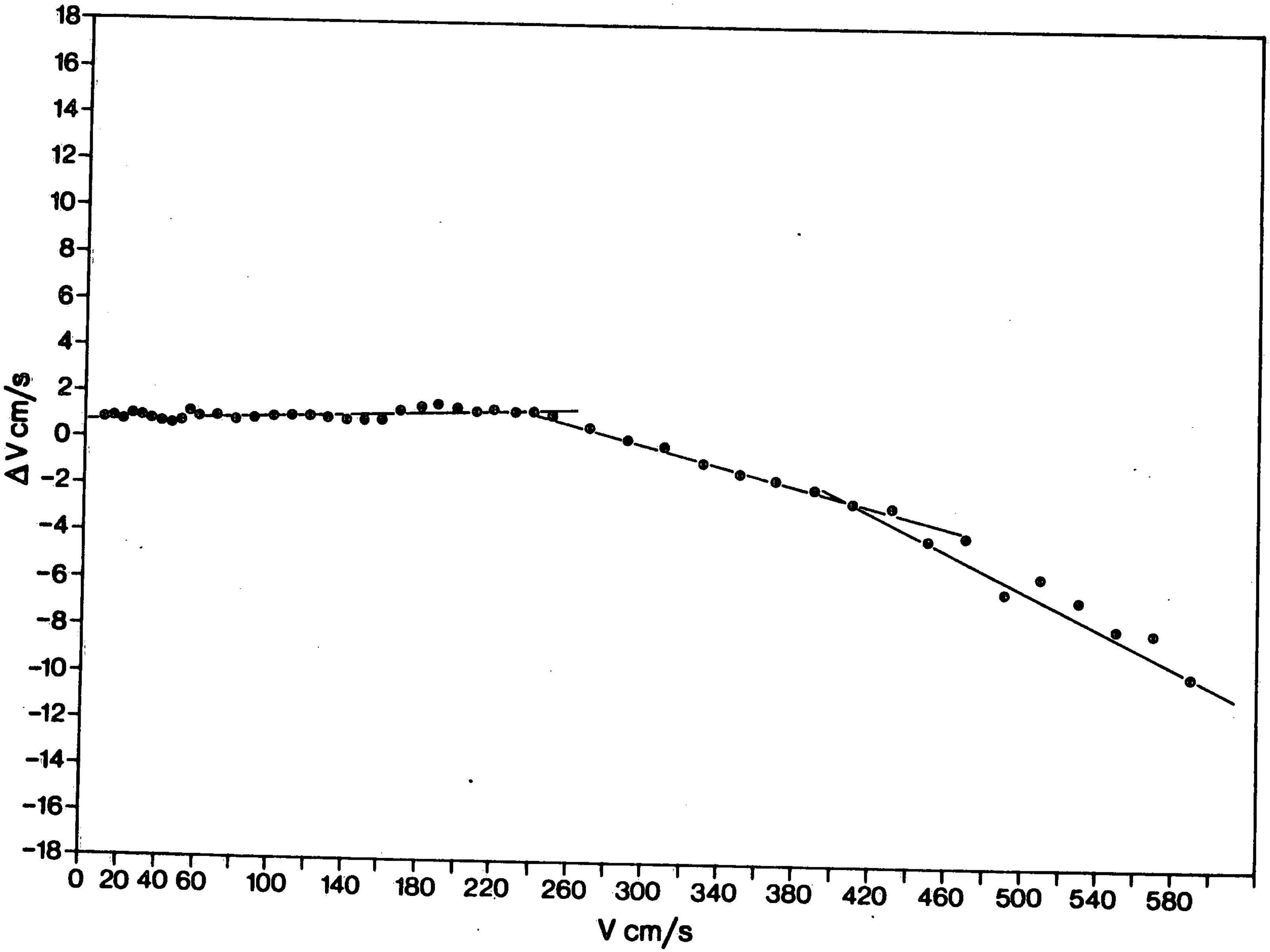

FIGURE 6. SINGLE CALIBRATION FOR METER No. 600508

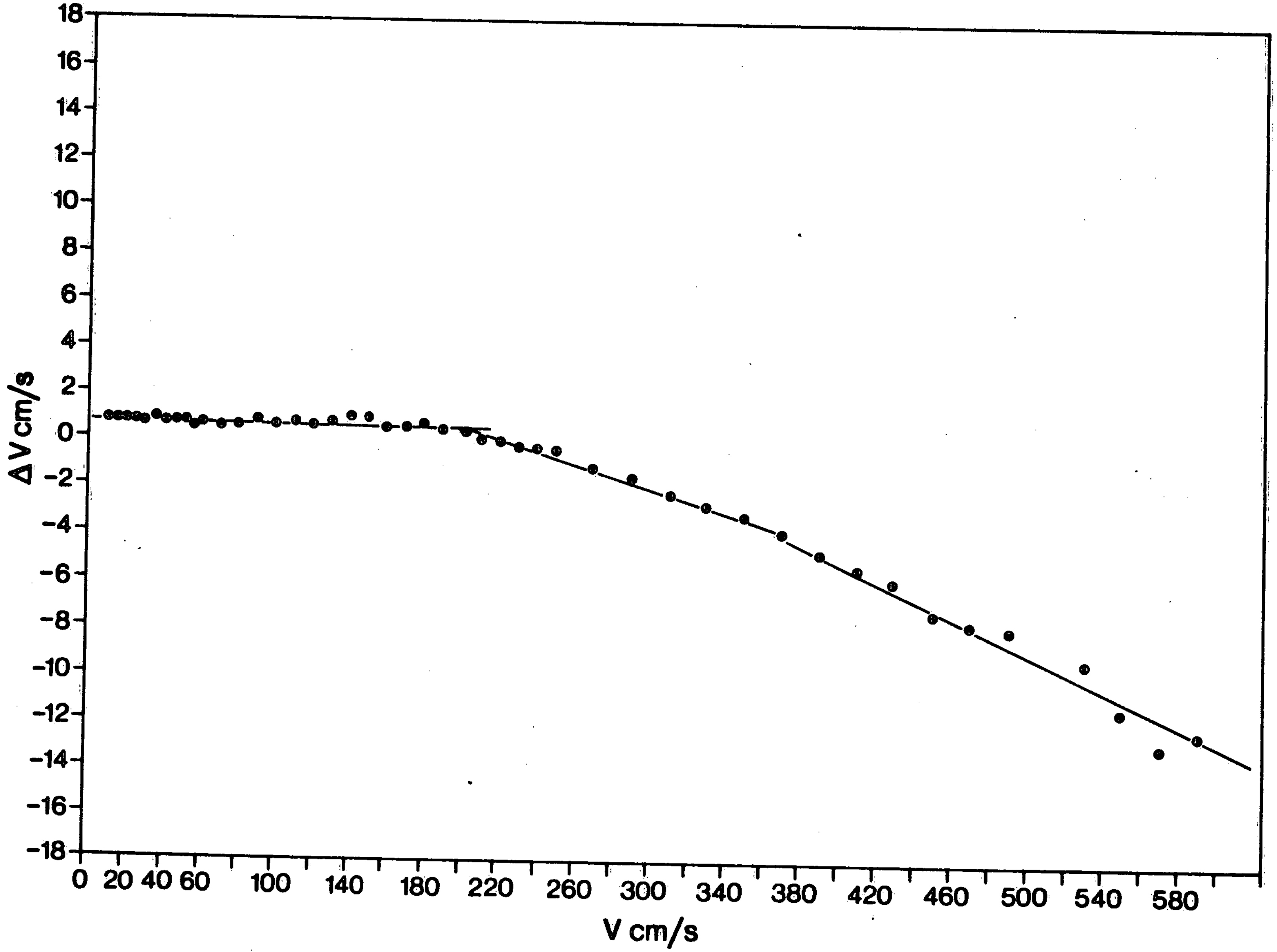

FIGURE 7. SINGLE CALIBRATION FOR METER No. 600509

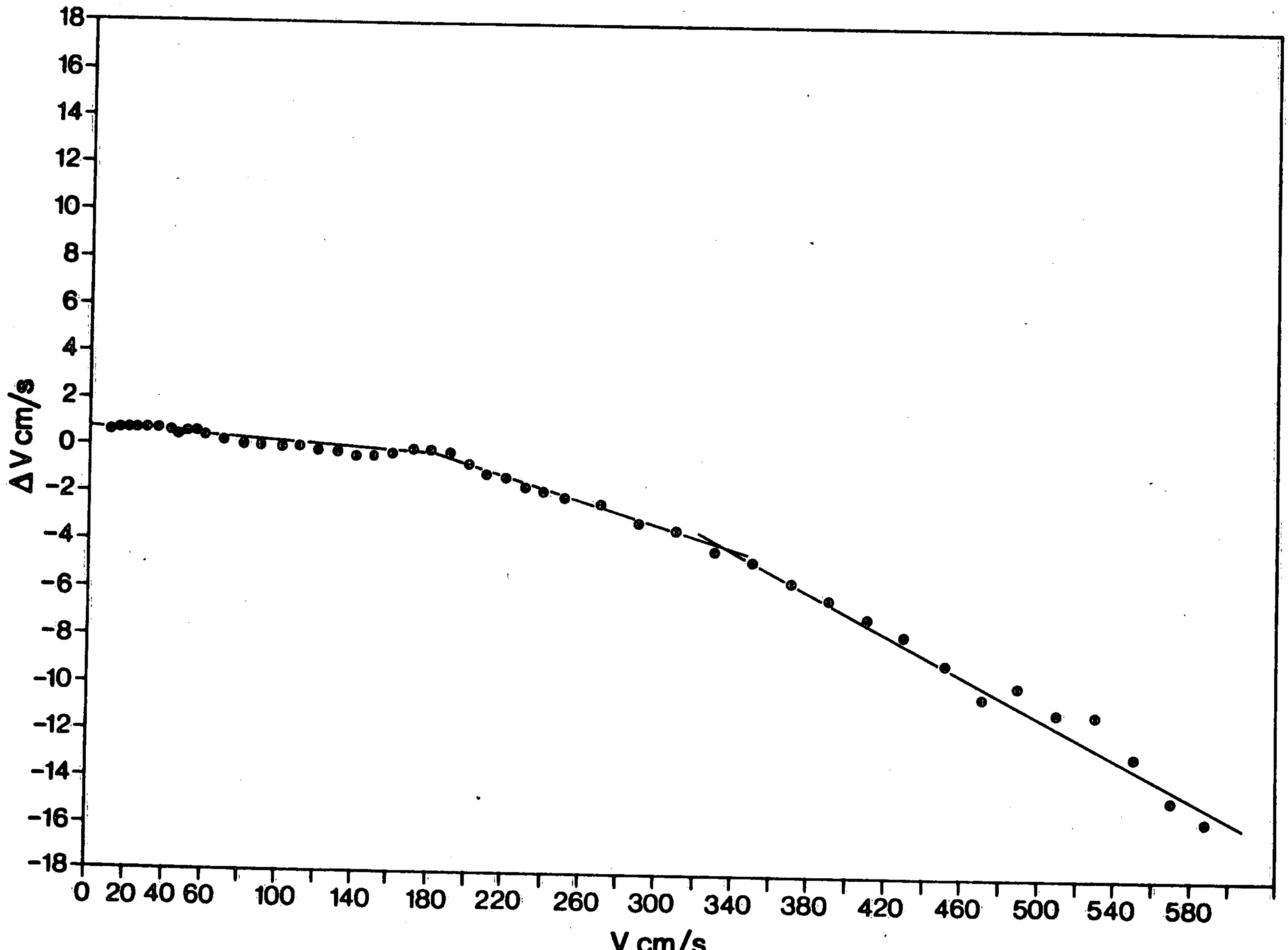

FIGURE 8. SINGLE CALIBRATION FOR METER No. 600510

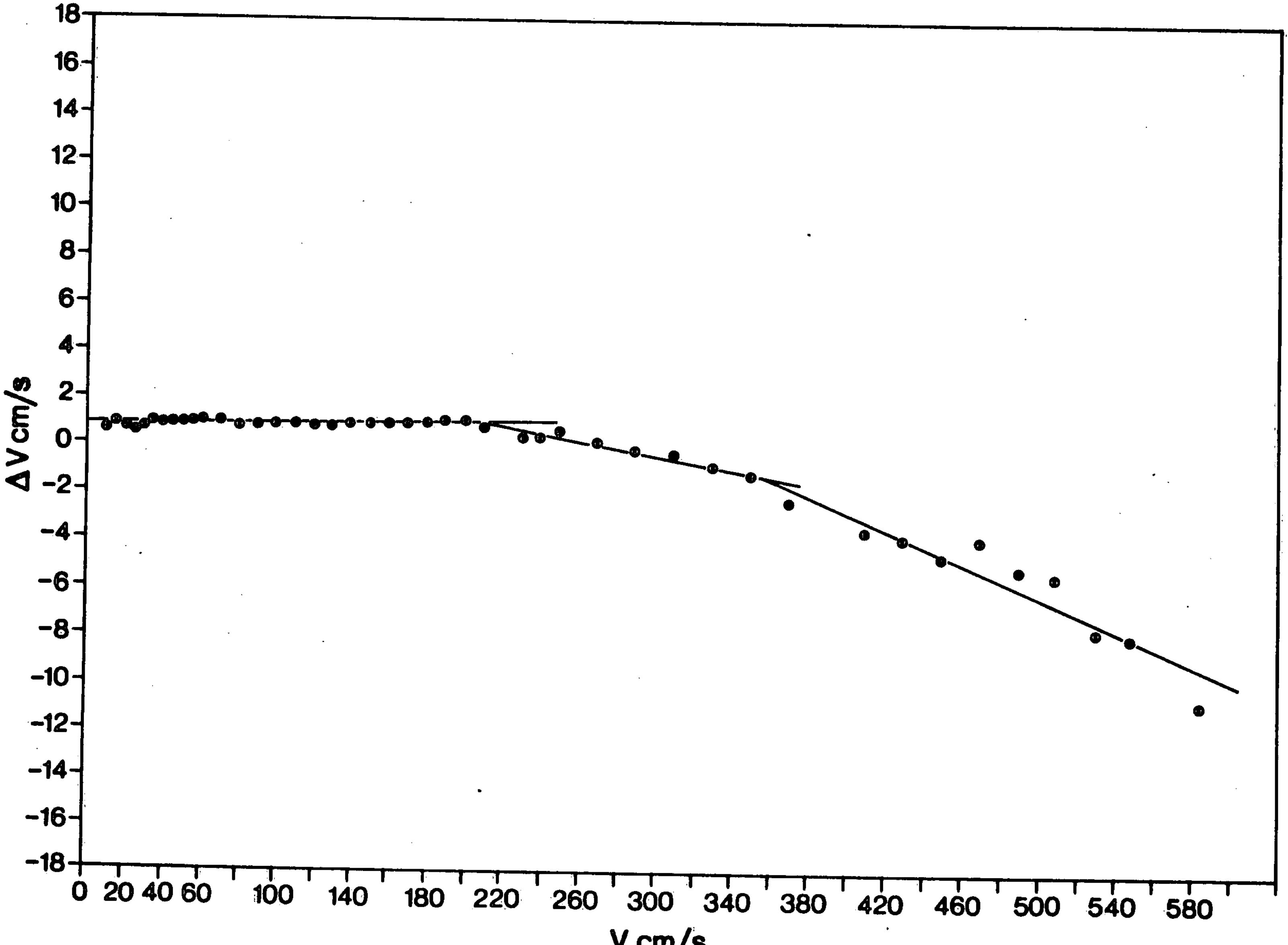

FIGURE 9. CALIBRATION OF METER No. 600508 TOWED WITH METERS No. 600509 AND No. 600510

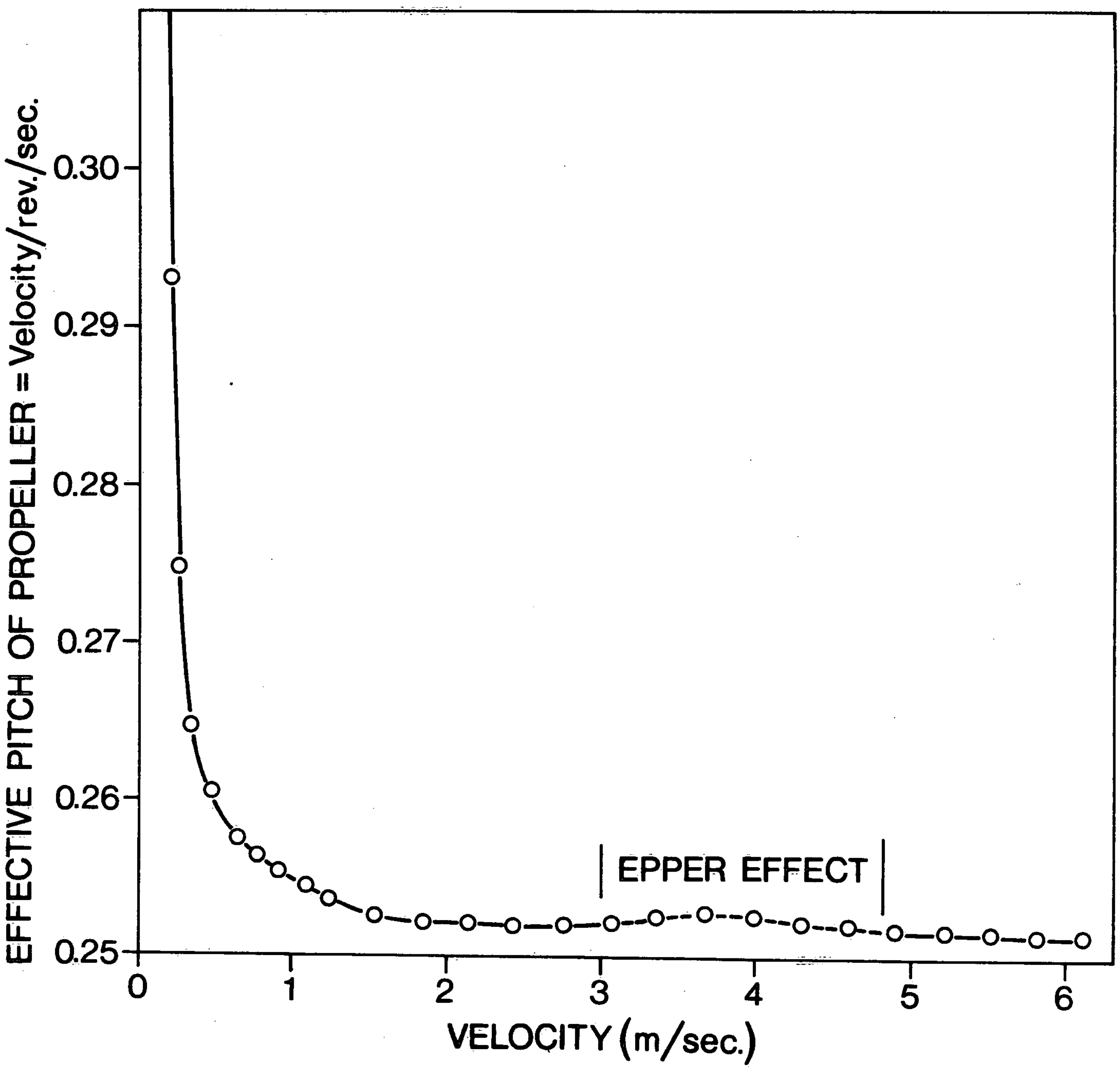

FIGURE 5. EPPER EFFECT FOR OTT CURRENT METER (GRINDLEY, 1971)

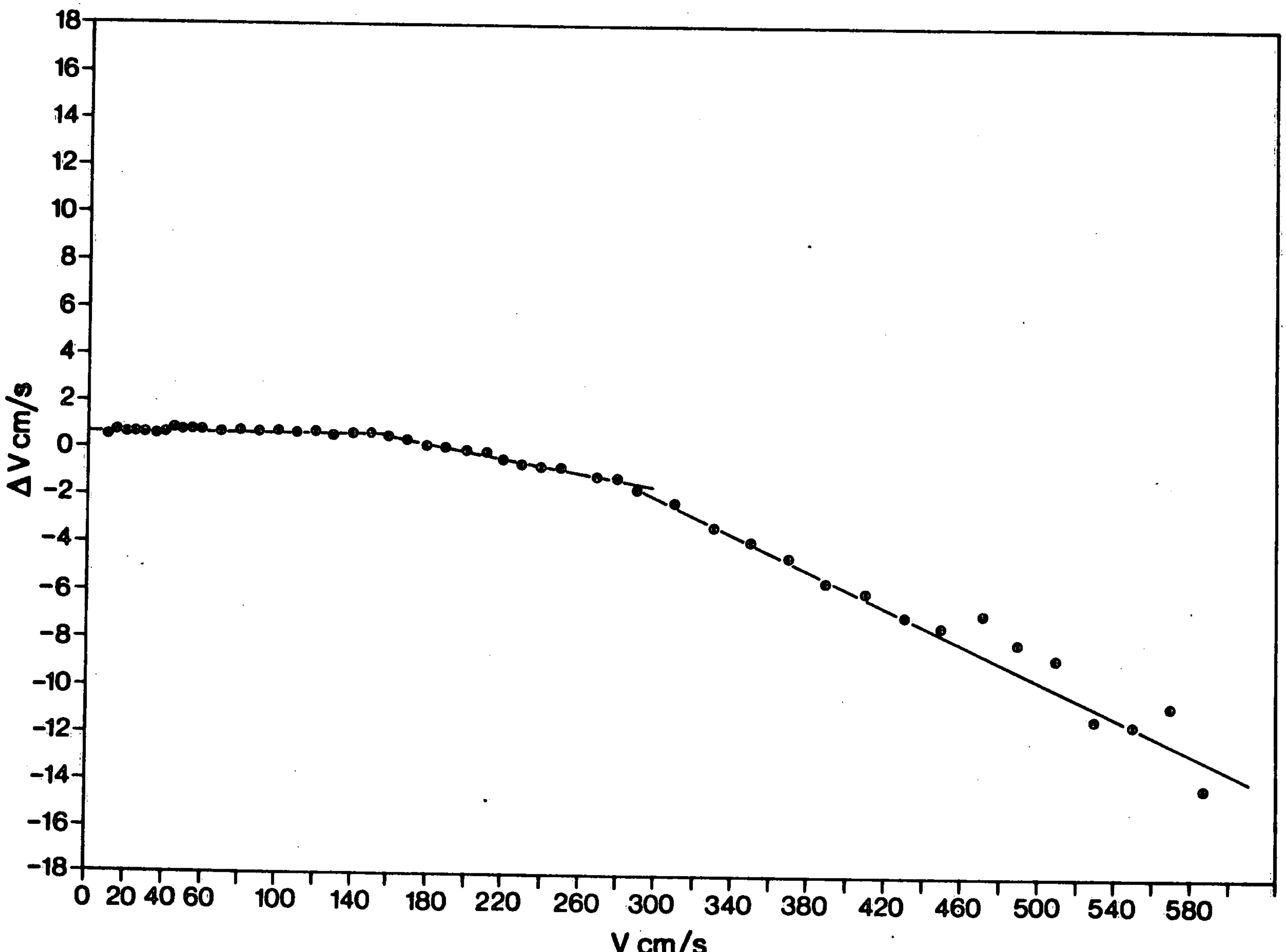

FIGURE 10. CALIBRATION OF METER No. 600509 TOWED WITH METERS No. 600508 AND No. 600510

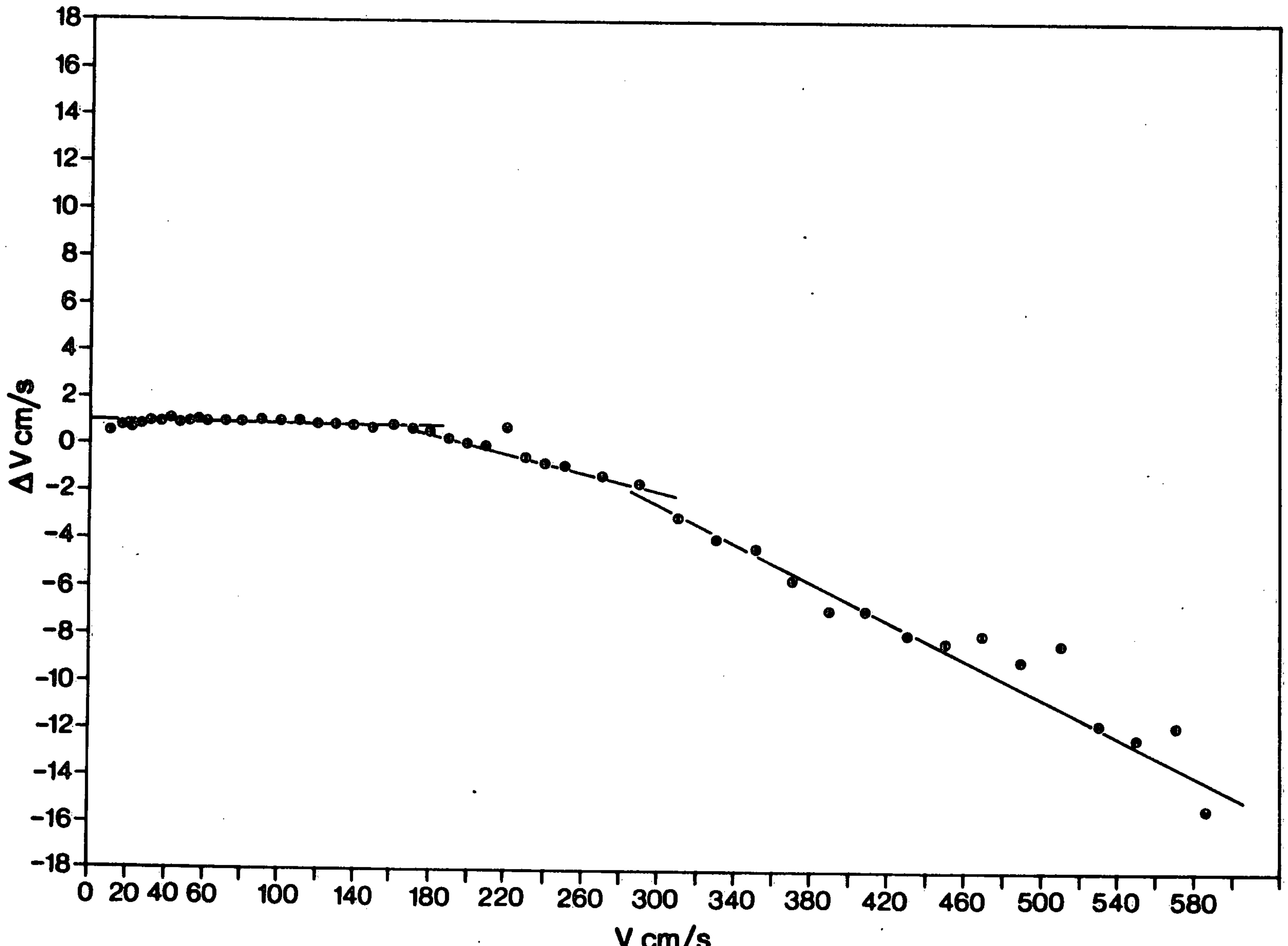

FIGURE 11. CALIBRATION OF METER No. 600510 TOWED WITH METERS No. 600508 AND No. 600509

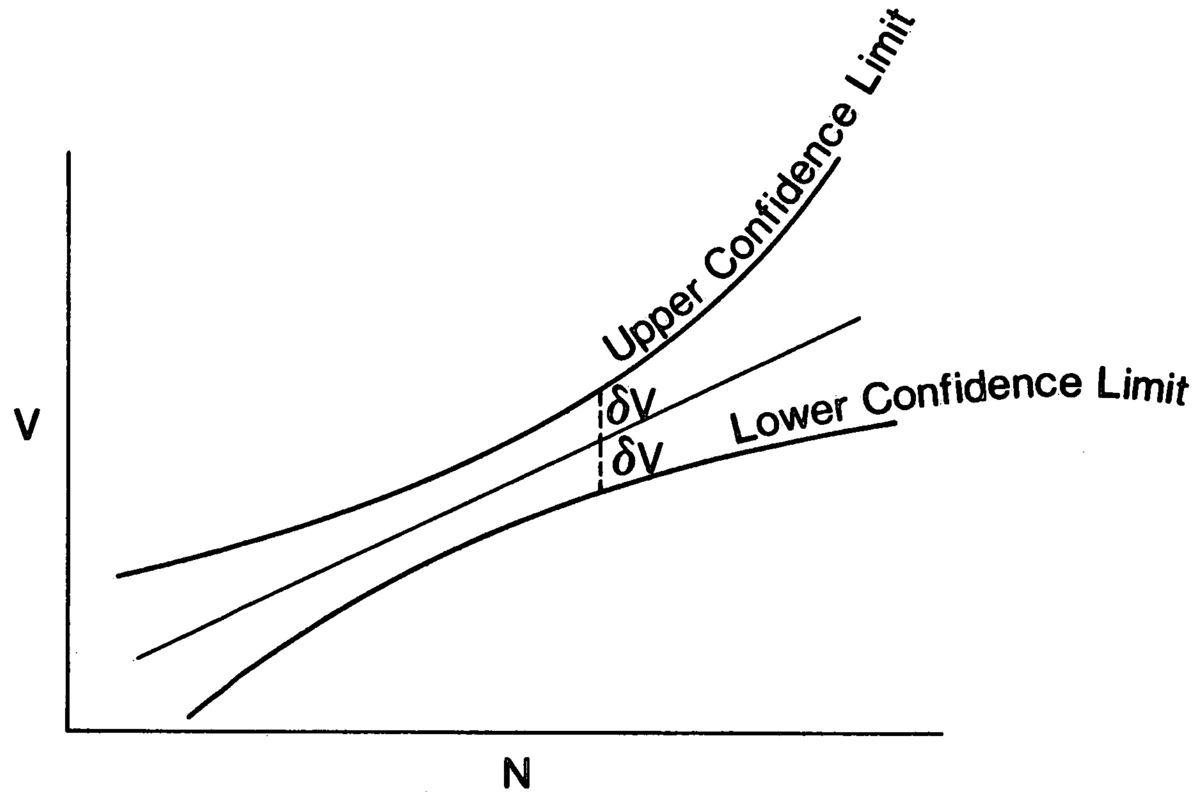

FIGURE 12. SCHEMATIC DEFINITION OF CONFIDENCE INTERVAL

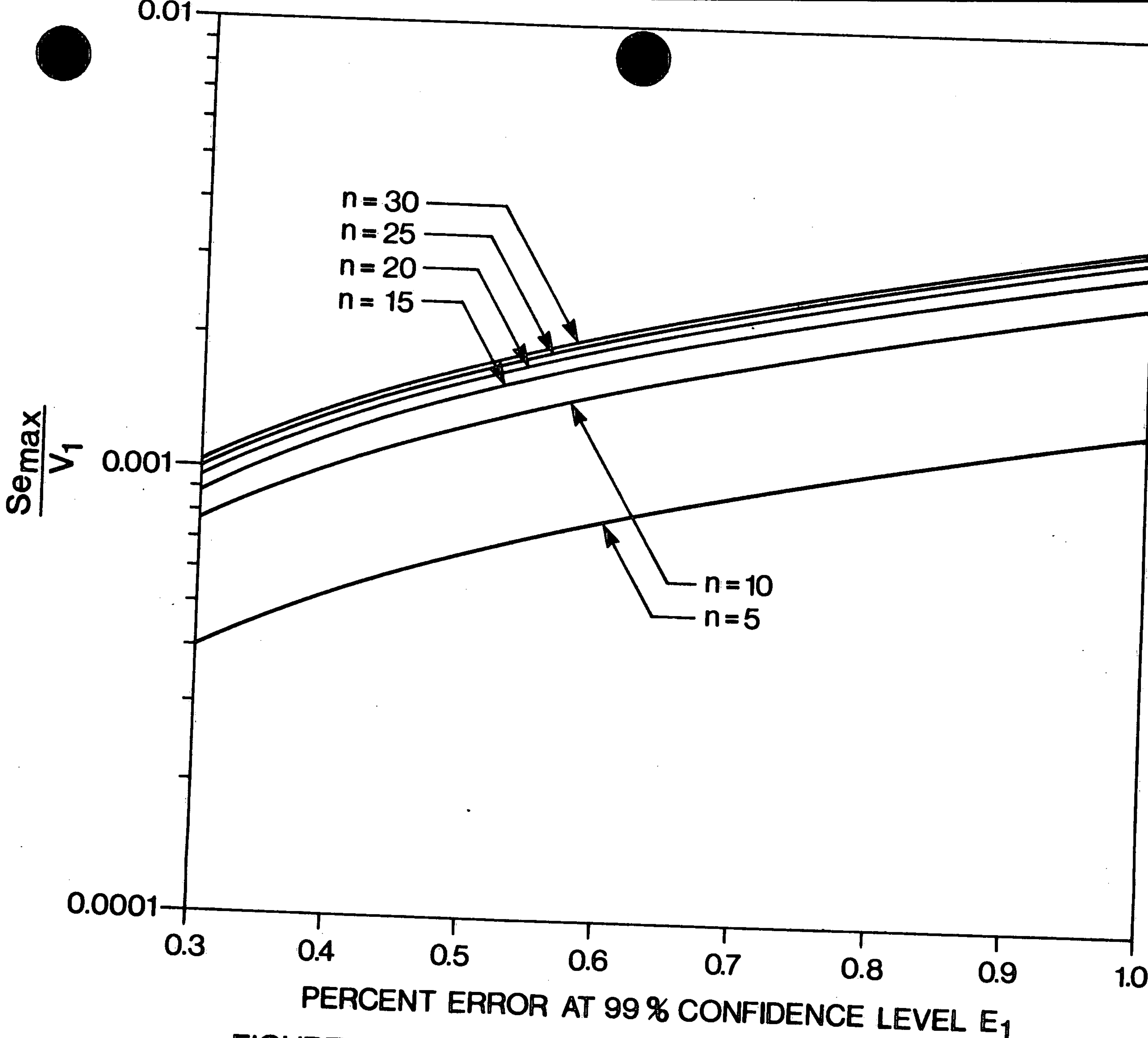

FIGURE 13. EFFECT OF NUMBER OF DATA POINTS ON CALIBRATION ACCURACY

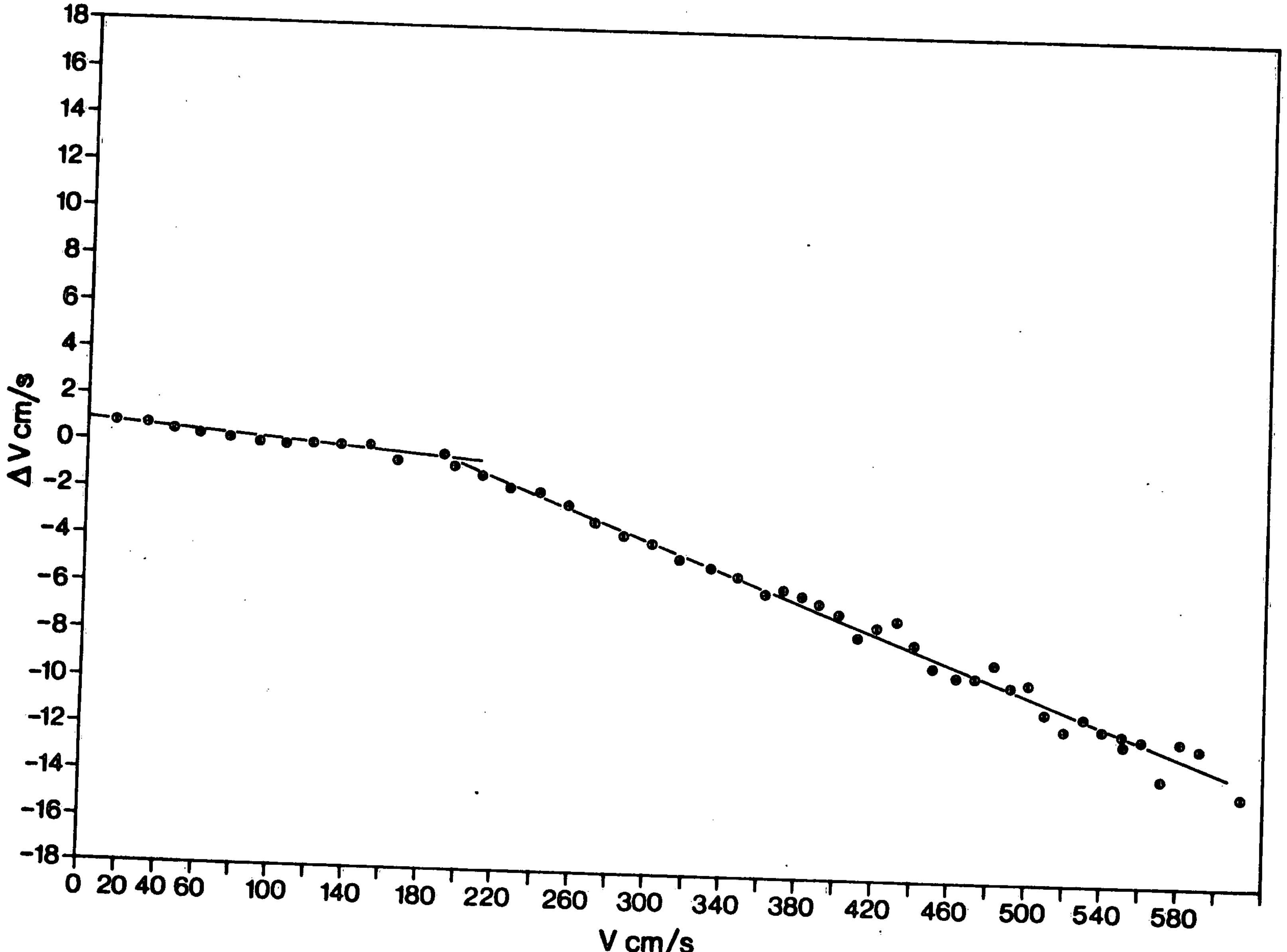

FIGURE 14. CALIBRATION OF METER No.600592 WITH OIL IN BEARING CHAMBER

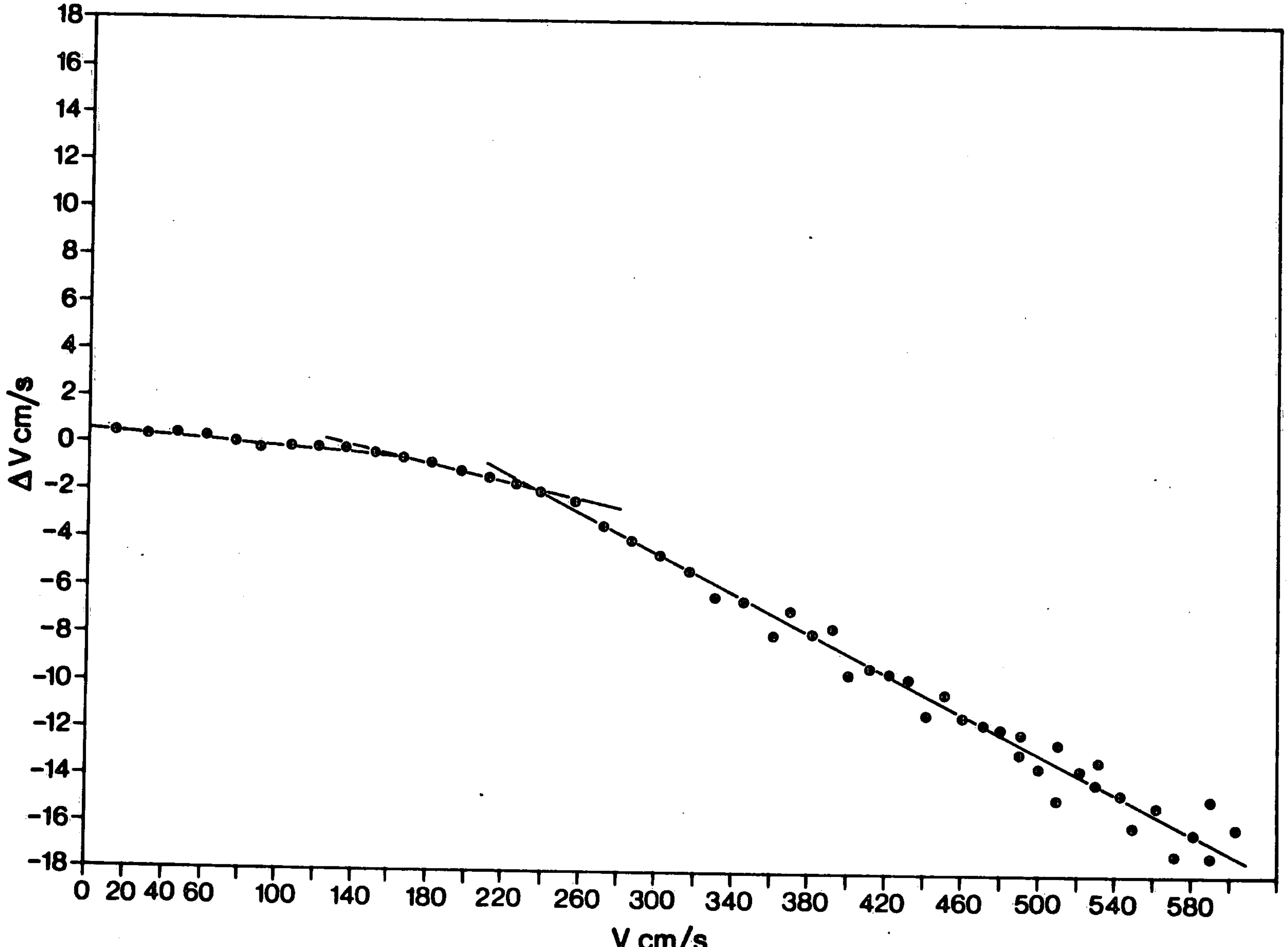

FIGURE 15. CALIBRATION OF METER No.600593 WITH OIL IN BEARING CHAMBER

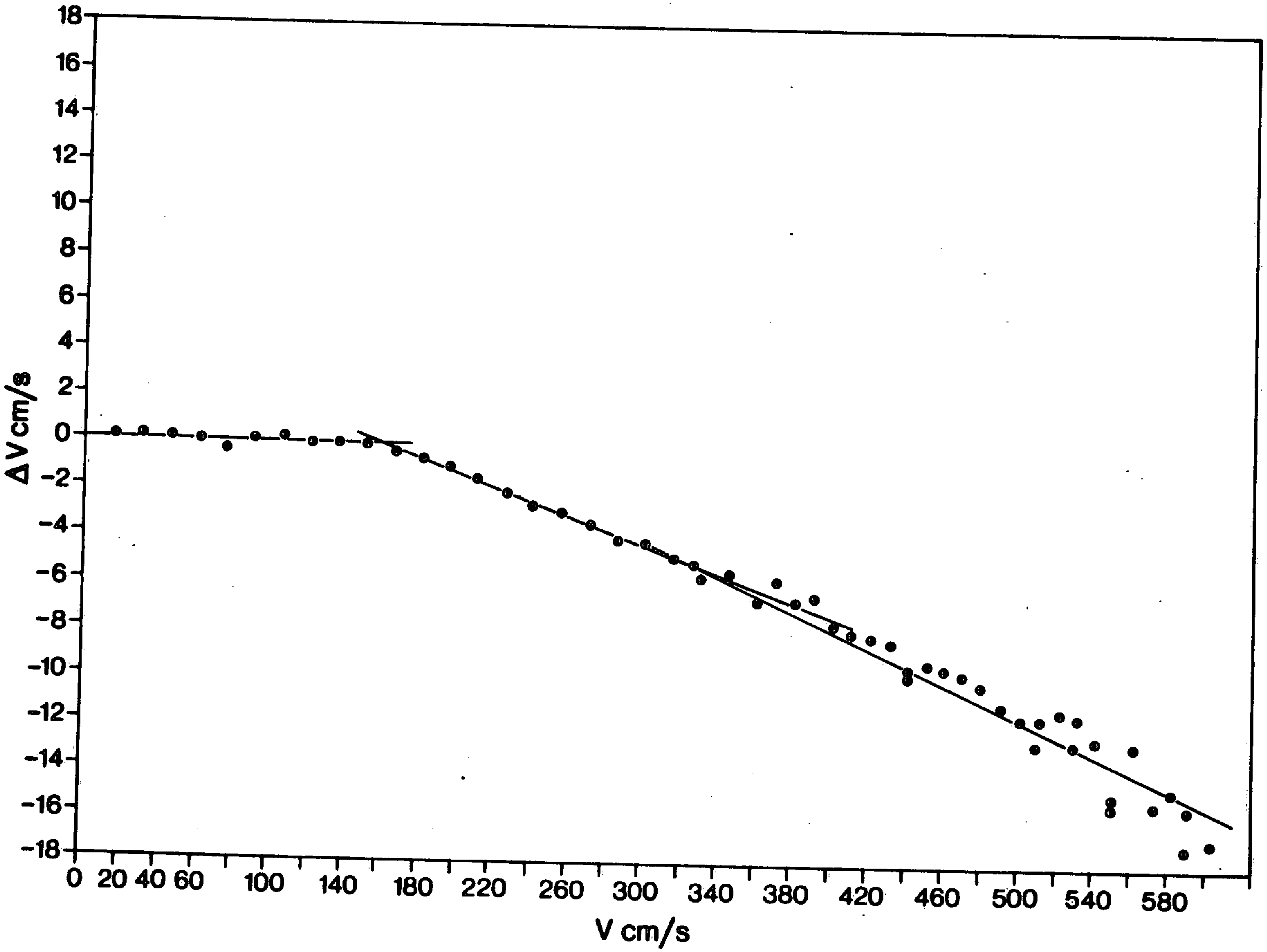

FIGURE 16. CALIBRATION OF METER No.600594 WITH OIL IN BEARING CHAMBER

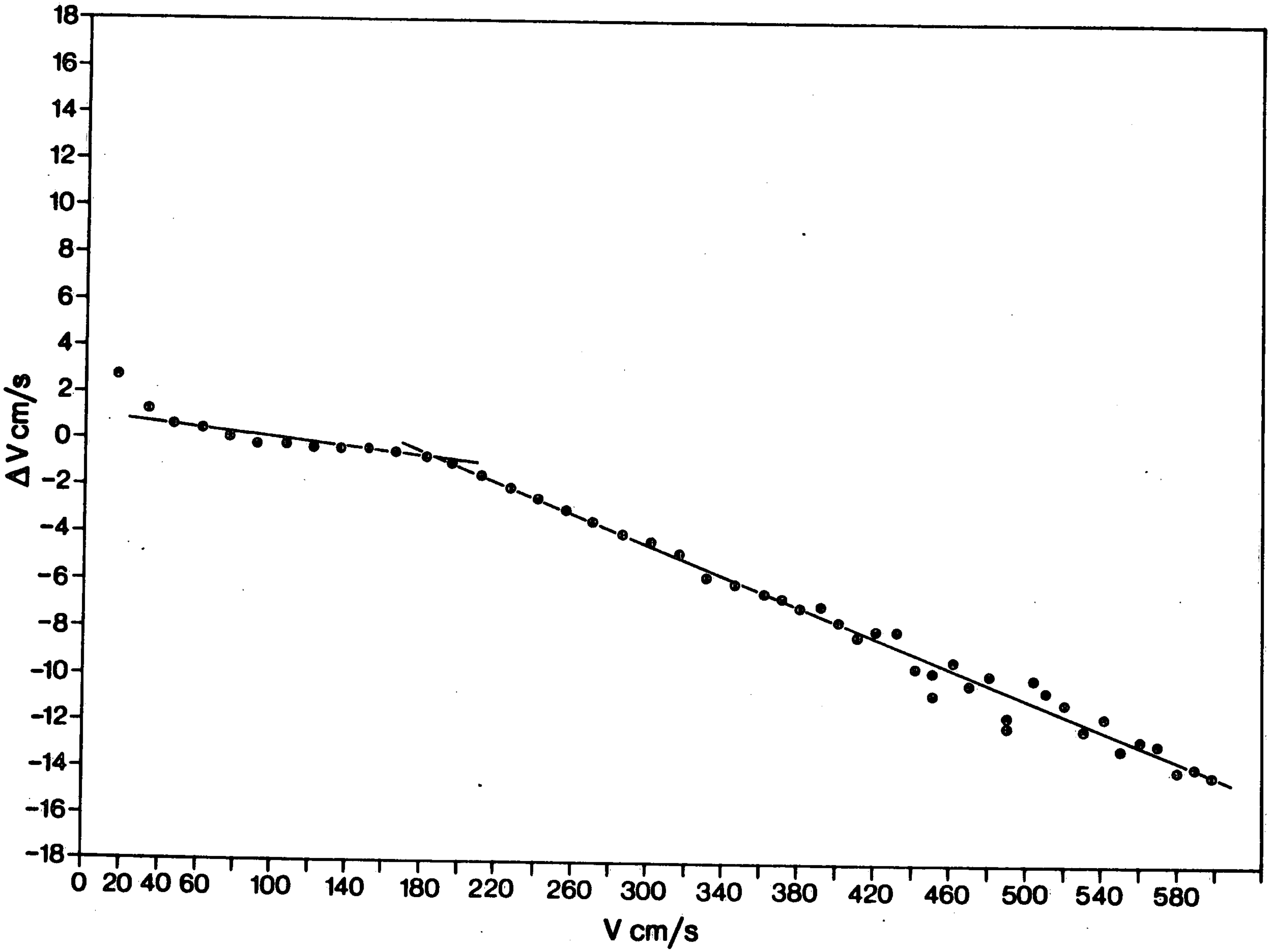

FIGURE 17. CALIBRATION OF METER No.600592 WITH WATER IN BEARING CHAMBER

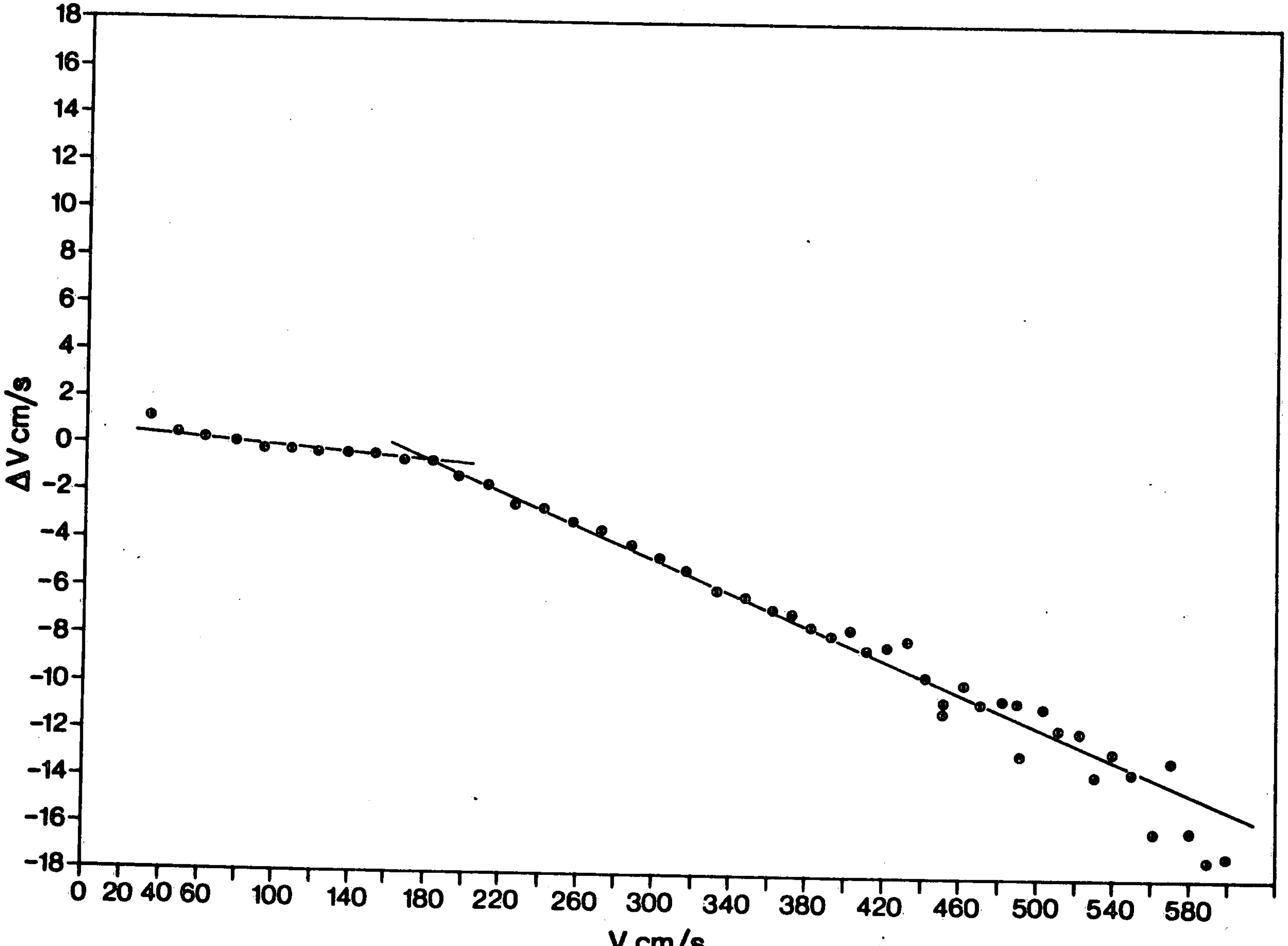

FIGURE 19. CALIBRATION OF METER No.600594 WITH WATER IN BEARING CHAMBER

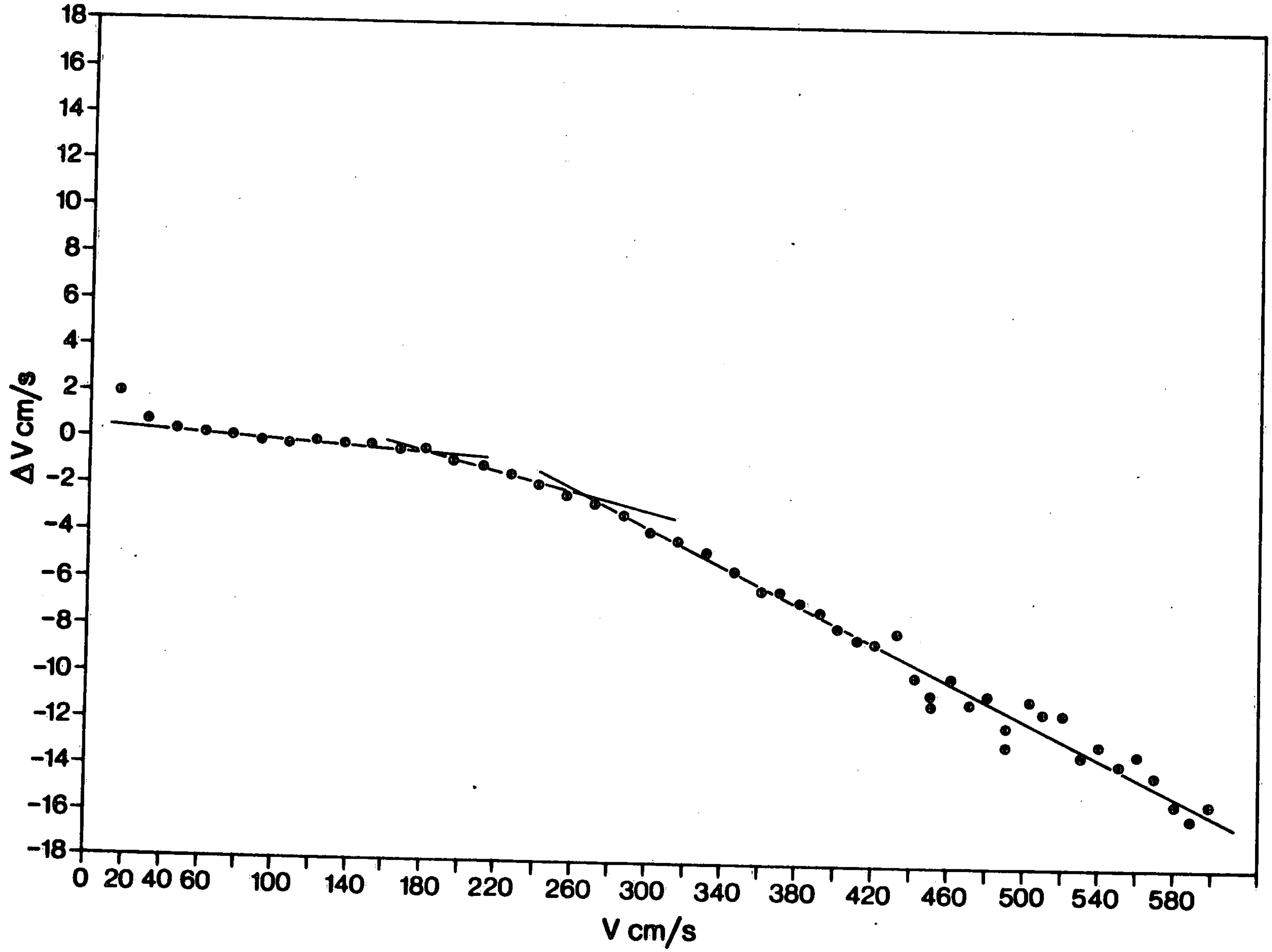

FIGURE 18. CALIBRATION OF METER No.600593 WITH WATER IN BEARING CHAMBER