FLOW MEASUREMENT OF FLUIDS
H.H. Dijstelbergen, E.A. Spencer (eds.)
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STEPS TOWARD AN IDEAL TRANSFER STANDARD FOR FLOW MEASUREMENT

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In flow measurement, acceptable traceability to primary standards depends upon more than the static checking of mass, volume, and timing measurements. Such checks are necessary, but must be complemented by dynamic checks on actual flow measurements using specific transfer standards and test procedures.

This paper demonstrates the validity of dynamic checking methods and describes the evolution of ideal transfer standards and techniques. Such knowledge should be the basis for flow measurement assurance programmes, which will benefit instrument manufacturers, calibration laboratories, and flowmeter users both nationally and internationally. Although the present results pertain to experiments which use a particular choice of transfer standard - namely a "turbine meters in tandem" package, the concept is readily extended to other packages where other (or mixed) types of meters are used. In this manner, the sensitivity of the transfer standard can be adapted to a particular type of metering or adjusted to a specific precision that is desired for acceptable dynamic flow traceability.

1. INTRODUCTION

Fluid flow measurements can be the basis for actions taken in a very wide variety of situations affecting health and safety, environmental quality, industrial productivity and national economies. Examples of this are in measurements to control pollutant laden flows which can seriously affect the quality of life; or to monitor feedback and input flows which can critically affect industrial productivity; or to determine totals for payment in custody transfer transactions on, say, imported fuel quantities. In all such cases the acceptability of the measurement is clearly seen to be dependent on a knowledge of its claimed accuracy.

The establishment of reasonable and attainable accuracy levels is then of immense importance. Equally important is the continued assurance that the quoted flow measurement accuracies are in fact as good as they are claimed to be. For example, in the case of a litigation which is critically based on a fluid flow measurement, the "shadow of doubt" surrounding the measurement must be acceptably small and be proven to be so. Although legal action is not always involved by any means, the requirement to prove that the measurements are within the claimed levels is essential to an orderly system.

Thus traceability from the actual measurement through to known standards is an essential path which must be followed if claims are to be substantiated. In the USA, programmes on traceability links which produce this "proof of quality" are termed Measurement Assurance Programmes (MAPs) [1]. In the UK Quality Assurance requires the same concepts.

In situations where there is a unique artifact which, by definition, establishes a nation's standard for a particular measurement, MAPs can be devised by which all measurements are traceable through transfer standards to the national standard. Classic examples are the one kilogram mass standard or the platinum metre bar with its scratches one metre apart or its present day equivalent wavelength standard.

In the case of most derived standards, however, such as fluid flowrate which is expressed as a fluid volume or mass flowing per unit of time, there is no discrete national standard. Hence there is no simple artifact which can be passed through a fluid flowmeter to see if it registers "unity". The flow MAP is necessarily therefore more complicated and depends on the selection of a satisfactory "substitute artifact" or transfer standard which can act as a replacement for the simple classical models.

This transfer standard has however to aim at the same characteristics as its direct counterpart. It must have a known stability of value, longevity and predictable response to reasonable changes in environmental conditions. With such an artifact it is also necessary to have a testing algorithm. This requires one to specify the set of conditions under which the artifact can be used with known confidence. It can then be moved from one laboratory to another and to specific metering installations to provide the link in the traceability chain.

Over the past century the need for such transfer standards has grown steadily. 100 years ago the first measurements with an orifice plate were being made to measure natural gas in Ohio. Still today the orifice plate is being used for most of the high pressure measurements of natural gas round the world. Predicting the accuracy of such measurements imposes the highest self-examination by the laboratories providing the data for the coefficients on which the calculations are based.

The search for the ideal flow measurement transfer standard, which will enable laboratories to assess the overall accuracy of their facilities continues. All the individual components in the laboratory's measuring system can be checked statically against higher standards which themselves through sound traceability chains link back to the national primary standards. Yet it has been shown many times that the overall uncertainty obtained by summing these individual component uncertainties is not the complete story - it does not adequately identify the performance of the facility in its active mode. What is required is "dynamic traceability" in which the transfer standard is subjected to normal usage in the facility since a derived quantity like flowrate is not and can never be static in time.

This paper describes work initiated at the National Bureau of Standards (NBS) in the USA and at the National Engineering Laboratory (NEL) in the UK to set up a transfer standard package and testing algorithm which can be used with greater confidence than previous packages to obtain this "dynamic traceability" effectively. Extra elements have been introduced to provide built-in controls and checks on the meter performance making up the transfer standard artifact.

2. TRANSFER STANDARD PACKAGES

Over the past 25 years the NEL has been involved in a number of exchange programmes on flow measurement with other laboratories. One of the earliest [2] was with Liege University in Belgium where Professor Schlag carried out so much research in the period from 1930-1955 on the performance of venturi meters. The reason for the exchange was to provide a link which would assure that the results each laboratory obtained separately in its study of the coefficients of venturi meters could be cross-related and hence acceptable to the Technical Committee then drafting the international standard on these devices. The transfer standard packages used in this exchange were two venturi meters tested separately.

An important exercise which was reported at the Pittsburgh Symposium in 1971 established the level of agreement between NEL and one of the best-known laboratories in the USA [3]. Here four orifice plates were used as transfer devices each being separately tested in a single carrier with an upstream and downstream length of straight pipe. It was found that there was a susceptibility to installation effects in the two test facilities.

The most recent NEL exchange programme to be reported [4] used a single turbine meter with lengths of straight pipe as the transfer package. While the results of these tests in three UK laboratories were very successful there must always be a problem if a single transfer standard is used.

This problem is to decide whether the evidence is sufficiently strong to establish without doubt the uncertainty level between the results. It is clear that if there is a difference between the measurements obtained in the two laboratory facilities being compared using the transfer standard, then there must be an uncertainty level equivalent at least to this difference. Indeed it is mandatory as part of any testing algorithm for such a programme that there should be a repeat calibration of the transfer standard back at the first laboratory after the exchange. It can then be argued successfully - if the initial calibration and the recalibration agree - that the transfer standard has not been damaged in the course of the programme.

This is not the whole story, however, for it is not possible on the basis of this information alone, to conclude that the difference found is solely a bias which would be systematic for all tests using these two facilities. It is possible that the transfer standard package is itself sensitive to the flow patterns in the test sections where it was installed in the two facilities. In this case it could be that the flowrates were measured correctly in the two test facilities but the transfer standard responded differently.

From this it follows that even if no difference had been found it still would not be absolute proof that the bias between the two facilities was zero and that the overall uncertainty levels of the two could be equated. A systematic bias in the one could be offset by an installation effect which would vary with the characteristics of the transfer standard being used. Bringing in a third facility will increase the confidence level in the conclusions being made from the data but still leaves the separation of the estimated uncertainty into its constituent parts unresolved.

Thus the use of a single artifact on its own can be inconclusive without considerable backup testing. This is expensive both in time and the quality of the staff effort required. Testing two or more transfer standards sequentially can widen the range of flowrates being covered and narrow down the uncertainties but does not solve the problem. It was at this point that the NBS development took off.

3. TWIN-TURBINE METERS AS TRANSFER STANDARDS

3.1. The NBS Package

A concerted effort at the NBS to establish a MAP for flow measurement has involved the use of a pair of turbine meters in tandem. Commercially available meters were selected for this project and each was equipped with matched meter tubes consisting of straight upstream and downstream sections sized to the manufacturers specifications. Tube bundle flow straighteners sized and located according to AGA/ASME recommendations [5,6] could be installed in the upstream pipe sections. These sections were bolted, via pinned flanges, to their respective turbine meters so as to assure repeatably aligned joints.

3.2. The Test Programme

These turbine meter units were tested according to a particular algorithm in the NBS water flow facility over an extended period of time [7]. The data obtained were statistically analyzed using conventional control chart techniques and the performance of one meter relative to the other was determined. Typical results are shown in Figures 1 and 2.

The ratio of the turbine meter frequencies when the units are arranged in a particular configuration provides a quantitative check on the performance of the two meters. If this ratio is not reproduced in any test it must be presumed that something has impaired the performance of one of the meters. At the same time it is assumed that the probability that simultaneous and identical impairment of both meters over an extended period of time is negligibly small. Hence so long as the ratio remains within a defined small tolerance the resulting data obtained from the tests are regarded as valid.

The testing algorithm stipulated that each meter in its own pipeline be tested in the upstream position followed by the other meter unit in the downstream position. Four sets of results were obtained therefore, two at each of two flowrates. These flowrates were carefully set using a specified Reynolds number criteria.

Results for each meter when it occupies the upstream position at a specific flow can be regarded as being independent of the other meter in the same position. These sets will then conform to the assumptions required for a Youden analysis of variation [8] that there is statistical independence between the meters. The Youden concept, developed at the NBS in the late 1950s, is that if samples of two different materials were sent to a number of laboratories, each of which is asked to make one test on each material, then a graph could be prepared in which the axes are scaled to include the measurements on each material. A single point is then obtained for each laboratory and from the disposition of the points on the graph much can be deduced about the test procedures, care and accuracy of the laboratories staff and equipment. If not many laboratories were involved Youden recommended circulating a second pair of materials at a later date, thus doubling the number of points on which the analysis could be based.

In the flow application the measurements of the turbine meter constants become the paired samples referred to above. Repeated measurements can in fact be made to build a record of the performance of a test facility. Typical results can be seen in Figure 3 for one particular flowrate.

3.3. The Youden Analysis

The Youden analysis is performed by drawing vertical and horizontal lines through the medians of the data plotted on the abscissa and ordinate axes, respectively. The intersecting median lines then divide the data into four quadrants about the origin. Using Cartesian notation, data lying in the first of these quadrants is, to some extent, "systematically" inaccurate since each point is "high" relative to the best available estimate of the true values for each turbine meter constant, namely the coordinates of the median intersection. Similarly, points lying in the third quadrant are "systematically low". In the second and fourth quadrants, the data are termed "inconsistent" or random since the points in these areas are "low-high" and "high-low" relative to the origin. Thus, the degree to which the data lie in a circular pattern about the origin or are distributed elliptically with the major axis at a slope of +1 or -1 quantifies the nature of the variation in the flow facility and turbine meter systems.

The total variation in the data can be categorized by calculating standard deviations based upon the parallel and perpendicular projection of all the data points onto a line drawn through the median intersection with a slope of +1. Then the ratio of these parallel to perpendicular standard deviations gives the degree and orientation of the ellipticality of the data.

If this ratio is larger than unity it can be interpreted that the variation is predominantly systematic. Depending on its magnitude, possible causes for this variation can be sought in either the meter's performance or in the flow facility, or both.

If the ratio is very much less than unity it would indicate that the transfer standard package is not capable of having sufficient resolution and other metering devices need to be selected. Alternatively there could be insufficient resolution in the flow facility or there are operator inconsistencies. In practice this pattern has not been observed in the NBS studies thus far.

On the other hand, if the ratio is close to unity then systematic and random variations are similar. Decisions can then be made on whether the magnitude of the radius of the circle covering the data spread is acceptable or whether an improvement is desirable.

3.4. Discussion of NBS Programme

The tandem turbine testing procedure can thus be used to generate sets of data which can quantify the systematic and random components of variation obtained in a particular flow facility. Improvements to reduce the components of variation can then be investigated. One of the ways which has been examined at the NBS has been to develop effective flow conditioning so that the package will be unaffected by upstream disturbances. The flow conditioner used in these tests is described in Reference [6] where it is shown that with this device even severe swirl induced just upstream had no effect on the results obtained with the tandem meter package. By testing with and without this conditioner it became feasible to separate the total meter variation into (a) that due to the flow profile entering the upstream meter tube and (b) everything else.

This total package could thus be used to measure the dynamic performance of a flow facility. It has in fact been used in inter-laboratory testing where by carrying out exactly the same programme of tests on a number of facilities it is possible to assess the amount of systematic variation found among the participating laboratories.

A more effective utilization of a flow conditioner with the tandem turbine meter package has now been evolved. This innovation by the last named author at NEL in the UK permits an equivalent test and data base to be obtained in half the time required to carry out the NBS algorithm with and without flow conditioning. Some useful information has to be sacrificed to achieve this time saving but the essential objective of setting up a transfer standard package which is more controlled and less susceptible to the vagaries and uncertainties which apply to single metering devices is retained.

4. TESTS ON THE NEL TWIN TURBINE-METER PACKAGE

4.1. The NEL Package

The layout of the NEL package is shown in Figure 4 and a photograph of the unit when installed in the test line of the NEL oil primary flow facility [9] is shown in Figure 5. The difference between it and the NBS package preceded by the NBS flow conditioner is that here while the downstream test meter is isolated from the influence of the system the upstream meter is not. This is achieved by placing the NEL flow conditioner between the two test meters rather than installing the conditioner upstream of the pair. Equally though the conditioner to be used must be shown to remove effectively whatever swirl or asymmetry that may exist in the test section of the facility being examined.

The downstream position is thus used to measure the absolute accuracy of the calibration facility while the upstream position is sensitive to the flow pattern in the test line. When the results of the intercomparison are analysed the uncertainties from these two sources can be separately gauged in addition to finding out the information accruing from the NBS package.

The layout of this particular NEL package which was first tested in the Laboratory early in 1978 was suited to a 100 mm (4 inch) test line. Each meter's upstream pipe is about 4.6D long while the pipework downstream of each meter measures about 3D. The two test meter sections are separated by a length of 100 mm diameter pipe about 1.25D long at the entrance of which is located the flow conditioner held between flanges. This conditioner consists of a perforated plate and a tube bundle flow straightener. The straightener for this preliminary investigation was of the conventional concentric 19 tube bundle type, while the plate, 5 mm thick, was drilled with 73 x 9.5 mm holes. The overall length of the NEL package was thus a little over 3 m.

4.2. Test Procedure and Programme

The basic test algorithm consisted of a series of calibrations of meter 'a' and meter 'b' against the NEL oil calibration facility. This was carried out by independently calibrating a positive displacement reference meter, which was fitted with a pulse generator, against the NEL oil gravimetric standard using a standing start-and-finish method. While this calibration was taking place the turbine meters were calibrated against this reference meter using a flying start-and-finish method. For this feasibility study four series of results were taken. Series C and D were repeats of series B and A respectively and were taken after the meters had been removed from the line, cleaned and stored for about six weeks. Series A and D were taken with the package installed immediately downstream of a bend and a rubber bellows while in series B and C the package was proceeded by approximately eight metres of straight upstream length equivalent to 75D of 100 mm line. The upstream location which was deliberately selected as probably being too near to a disturbance, was chosen to create a different flow pattern. In this way the sensitivity of the NEL method could be judged.

Each series of calibrations was made up of two sets; set A was the package with meter 'a' upstream of meter 'b' while set B was the opposite way round; meter 'a' being downstream of meter 'b'. Three flowrates were chosen for the study. These were a low flow at approximately 7.5 l/s, a middle flow, at 24 l/s and a high flow, at 37 l/s.

Each set consisted of 3 batches of results, one at each flowrate, followed, after a shut down, by three further batches at as close as possibly the same flowrates. Batches were numbered as subdivisions of the test, and normally consisted of five points taken at one flowrate.

4.3. Results of NEL Tests

The results of the NEL study are presented in two ways. First the ratios of the meter factors of the two meters are plotted for each position in the line. These ratios are shown in Figures and , which correspond to the upstream and downstream line positions respectively.

The second way of presenting the NEL results is by means of the 'Youden' plot described in 3.3. Here the meter factors of the two meters are plotted as percentage deviations from their separate mean values for that particular pipe line position. Figures 8 and 9 thus each contain four separate plots, the first containing all the points at that line position and the other three corresponding to the three different flowrates used. Figure 8 refers to the upstream location and Figure 9 to the downstream position in the line.

4.4. Discussion of NEL Test Results

From the evidence of the meter ratio plots at the upstream position, Figure 6, it appears that the performance of the meters depends on their position relative to each other. This would indicate a disturbance upstream which affects the first meter but which is removed by the time the second meter is reached. This indicates further that the 'isolating device' of perforated plate and flow straightener is effective in 'protecting' the second meter from the upstream disturbance. Since the package was deliberately installed immediately downstream of 90° bend, the likelihood of a disturbance was to be expected. The pattern observed when the meters were reversed at the upstream position was repeated when they were returned to the upstream position after an interval of about three months, for the series D tests.

When the package was removed to the downstream position, downstream of about 75 diameters of straight pipe, the dependence on the relative positions of the meters disappears. Figure 7 shows no significant difference in meter factor ratio for the different meter configurations, and there is a considerable improvement in both the overall scatter and in the within-batch scatter of the results. It appears therefore that the effect of the disturbance which was so evidently present at the upstream location, Figure 6, has disappeared by the time the downstream location is reached. This in turn indicates the suitability of this part of the line as a flow measurement test section.

Each of the points symbolized in Figures 6 and 7 consists of the mean and scatter band of two batches of results, taken before and after shutdown. It will be seen that no significant change in meter factor ratio was observed before and after shut-down of the flow when the meter was in a fixed position, either upstream or downstream, in the line.

When the results are plotted in the manner of a "Youden" plot, further conclusions may be drawn.

At the upstream position there is a fairly random scatter of points about the overall mean, Figure 8 (i), although it was interesting to note for this study that there was almost a complete absence of any points in the top right-hand quadrant. When the points are plotted according to flowrate, however, while the mid-flowrate and high flowrate graphs show a similar pattern, Figure 8 (iii) and (iv), the low flowrate points appear almost entirely in the bottom left-hand quadrant, Figure 8 (ii). This is a result of the turbine meter characteristics being different for the two meters at the lower flowrates, as can be seen from the sample calibration curves for both meters which is shown in Figure 10.

The overall scatter of the points about the mean is, at the upstream position, about ±0.5 per cent.

At the downstream position there appears to be a significant cluster of points around a line at 45° between Ma and Mb, Figure 9 (i). However, when the points are separated according to flowrate, two facts emerge. First the two points in set B show a systematic shift from the other points at each of the three flowrates, Figure 9 (ii), (iii) and (iv). On checking the records, it was found that there was some doubt about the validity of the measurement of oil density at the time these particular tests were done, and the evidence of the graphs points to some kind of systematic error. The second fact to be observed is that as with the upstream position plotted in Figure 8, the low flowrate points are confined to the bottom left-hand quadrant, because of the nonlinear meter characteristic at this flowrate, (see again Figure 10).

Thus at the middle and high flowrates, if the two spurious points are ignored, the points appear to lose their affinity for the 45° line. The scatter of the points is also much improved in Figure 9, where the middle and high flowrate points, ignoring the spurious ones, all lie within ±0.1 per cent of the mean. Inclusion of the low flowrate points extends this scatter to about ±0.25 per cent, which is still however considerably better than the scatter at the upstream position.

5. CONCLUSIONS

The general conclusion which can be drawn from the results of the NBS and NEL projects is that a transfer standard artifact can be produced which when coupled to a suitable testing algorithm is capable of giving detailed information about the performance of a flow test facility.

At the present time this development has been confined to internal laboratory studies at NBS and NEL though an inter-laboratory round robin programme has been set up which is based on the tandem turbine meter package.

It has been shown that these turbine meter packages are capable of separating out the components of the variation arising from random and systematic sources. Where these packages will be most useful is that they will be able to discriminate between the absolute performance of different test facilities and also be able to quantify the effect of flow pattern variations in the metering test section of such facilities.

The further objective can then be envisaged of having transfer standards available which can be used to check and calibrate metering installations on site. At present dedicated meter prover calibration systems are incorporated into liquid petroleum custody transfer lines at considerable expense. Most metering installations however are operated on the assumption that the meters performance remains unchanged in both space and time regimes from that obtained or predicted when it was manufactured. To have the capability to check this belief in critical situations has long been the goal: it is now considered to be in sight.

6. ACKNOWLEDGEMENTS

The last named author gratefully acknowledges the special effort of his NEL co-authors in the race against time to produce preliminary results described here for a special meeting with the first author. The efforts too of J. Chapman and Miss S. McFarlane who assisted in the tests at NEL are fully appreciated.

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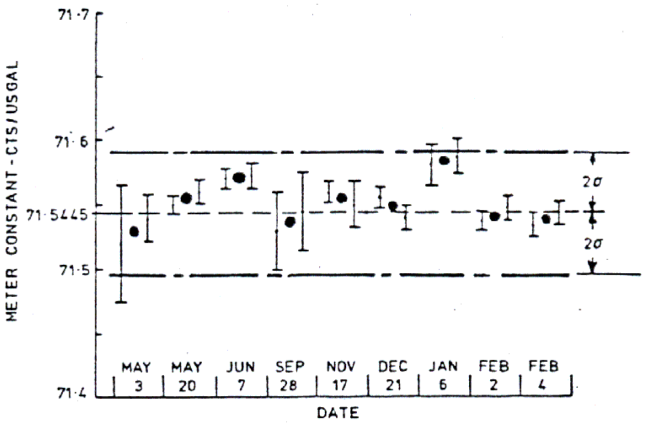


FIG.1 CONTROL CHART FOR TURBINE METER CONSTANTS-NBS RESULTS - LOW FLOW

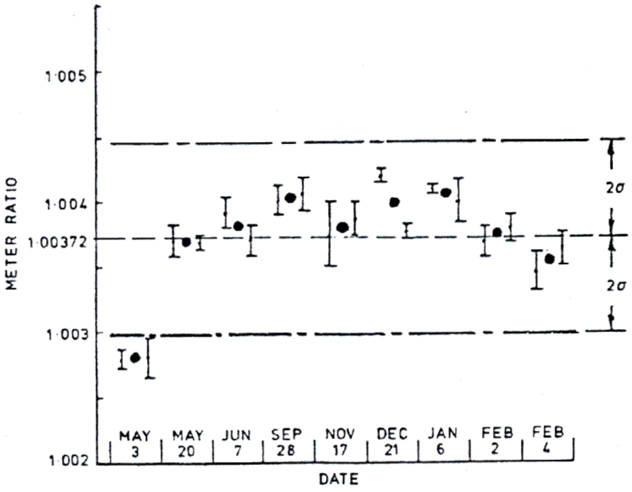


FIG. 2 CONTROL CHARTS FOR RATIOS OF METER CONSTANTS-
NBS RESULTS - LOW FLOW

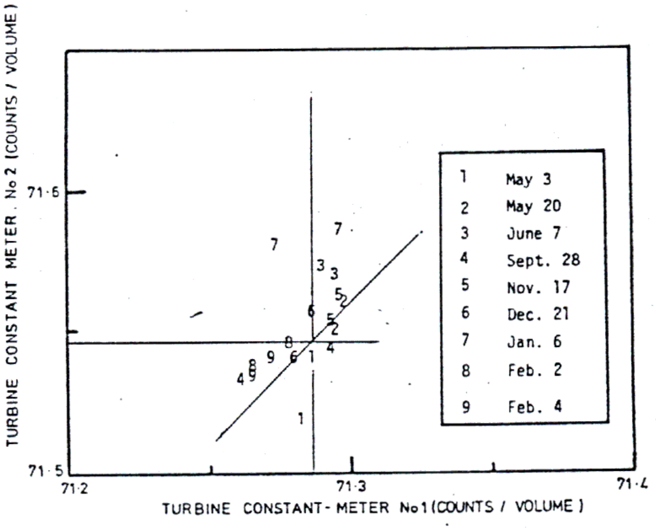


FIG. 3 YOUDEN PLOT FOR METER CONSTANTS-
NBS RESULTS - LOW FLOW

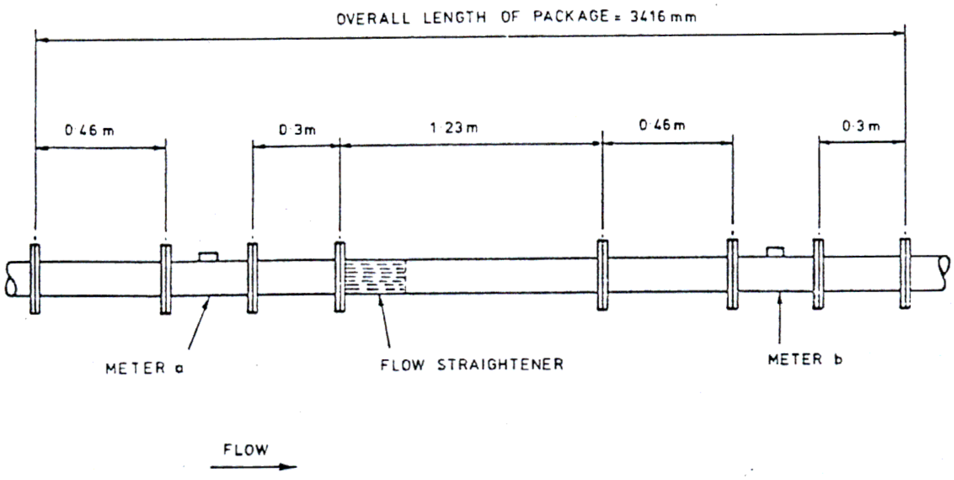


FIG.4 LAYOUT OF NEL TRANSFER PACKAGE

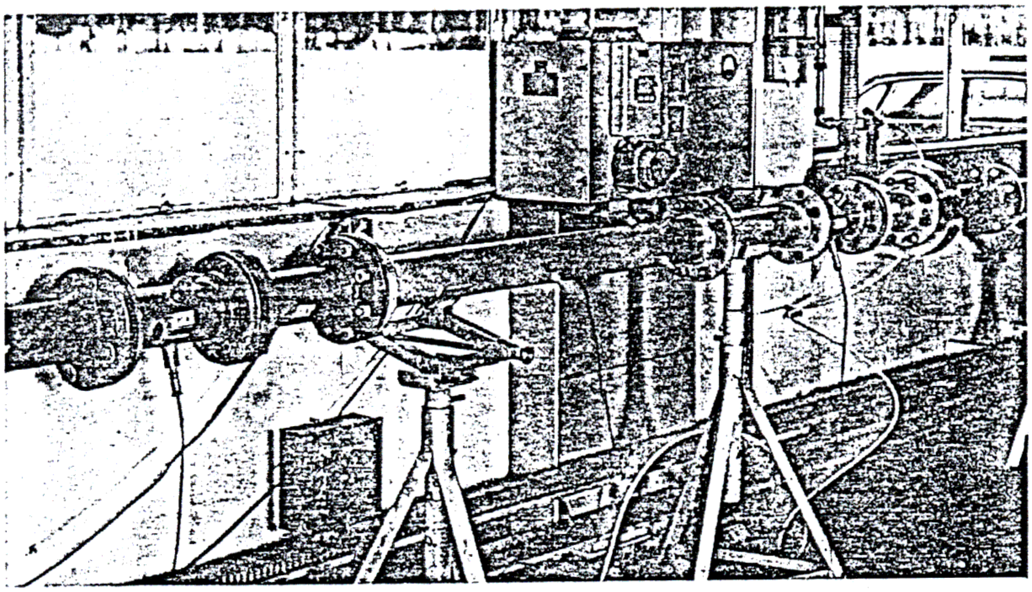


FIG.5 UNIT INSTALLED IN NEL OIL CALIBRATION LINE

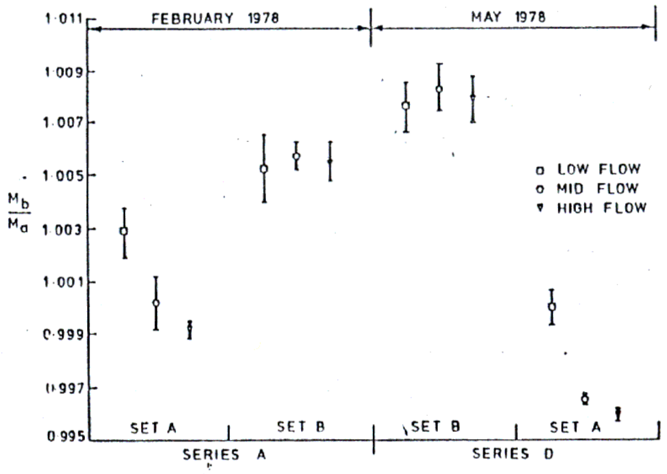


FIG.6 METER RATIO VARIATION FOR NEL SERIES A AND D

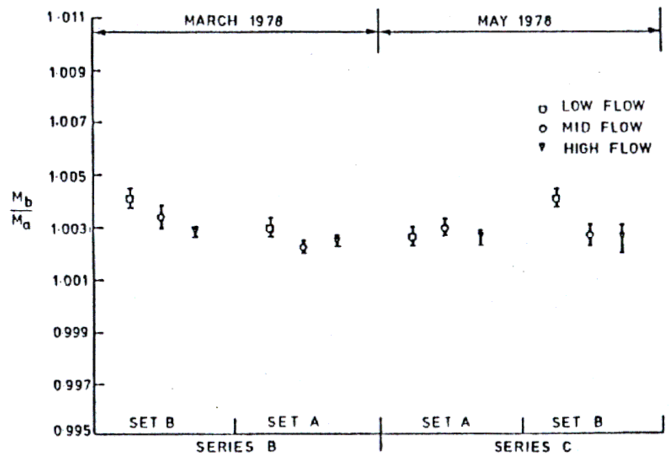


FIG.7 METER RATIO VARIATION FOR NEL SERIES B AND C

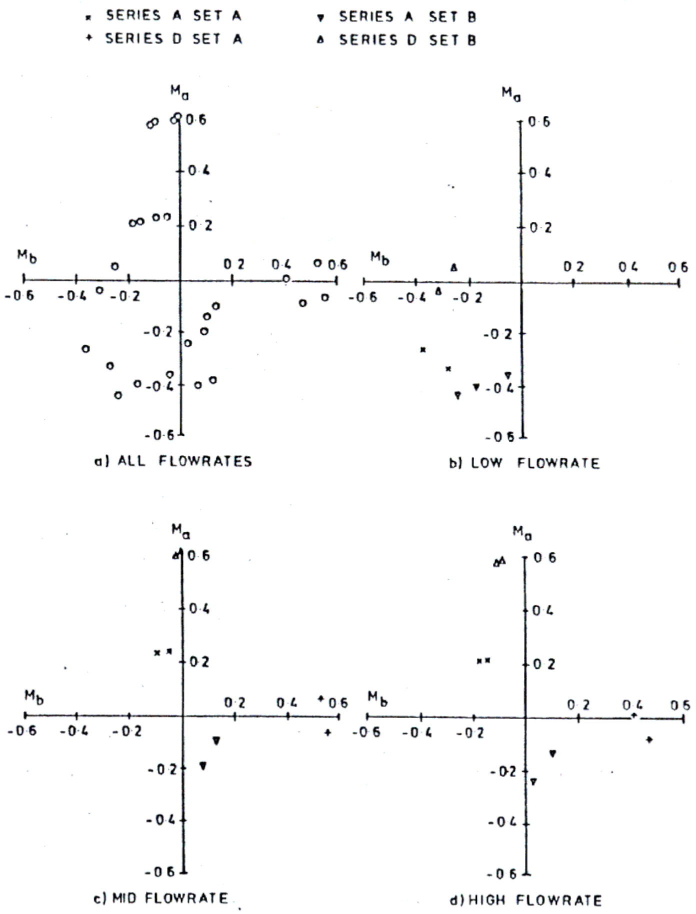
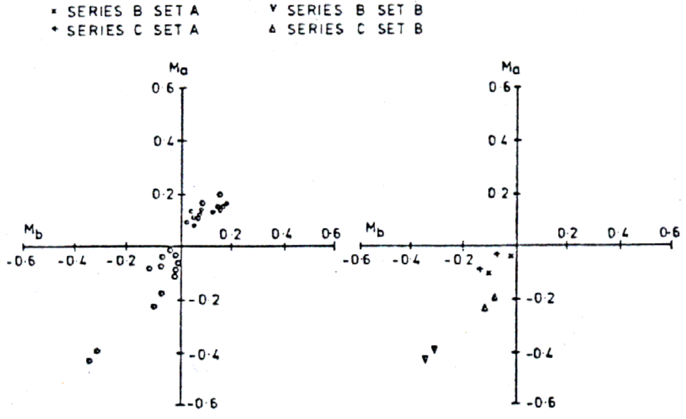
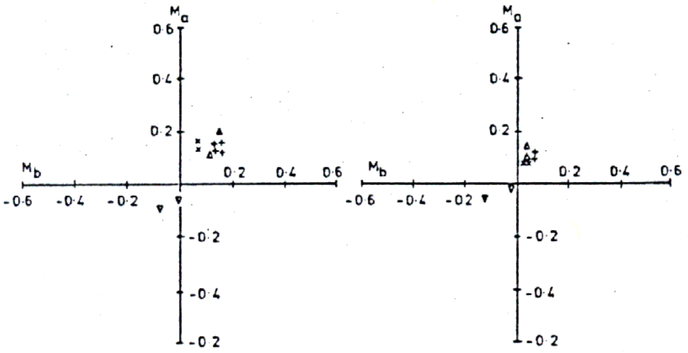


FIG.8 MEAN PERCENTAGE ERROR IN METER FACTOR OF METER a AGAINST THAT OF METER b FOR NEL SERIES A AND D

FIG.9
MEAN PERCENTAGE ERROR IN METER FACTOR OF METER a AGAINST THAT OF METER b FOR NEL SERIES B AND C



a) ALL FLOWRATES b) LOW FLOWRATE



c) MID FLOWRATE d) HIGH FLOWRATE

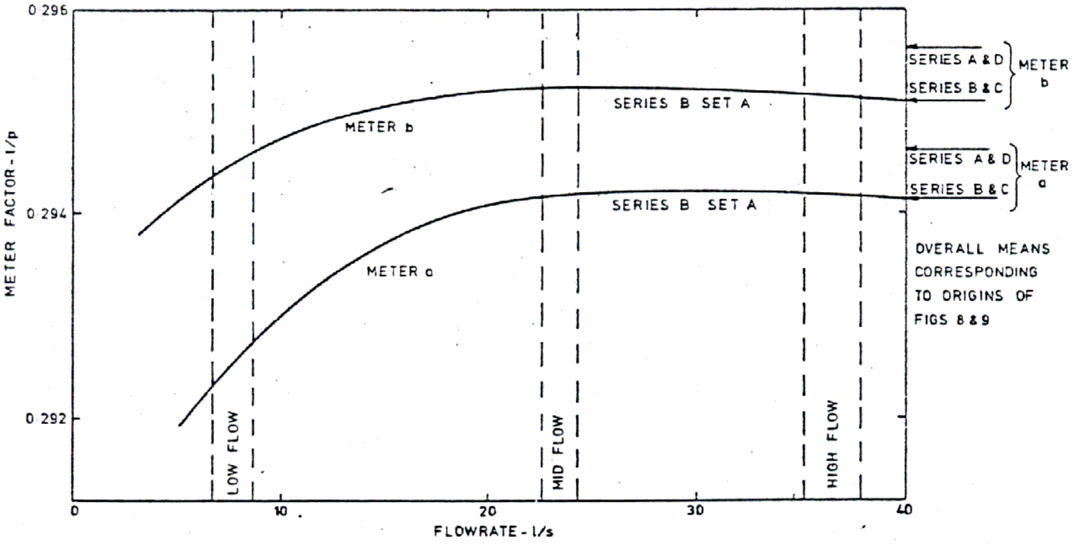


FIG.10 TYPICAL CALIBRATION CURVES FOR METER a and METER b - NEL RESULTS