

Guide for

Statistical control of dynamic liquid hydrocarbon volumetric metering systems

Committees responsible for this British Standard

The preparation of this British Standard was entrusted to Technical Committee PTI/12, Petroleum measurement and sampling, upon which the following bodies were represented:

- Department of Trade and Industry (National Engineering Laboratory)
- Department of Trade and Industry (Oil and Gas Office)
- Institute of Petroleum
- Salvage Association

The following body was also represented in the drafting of the standard, through subcommittees and panels:

- GAMBICA (BEAMA Ltd.)

This British Standard, having been prepared under the direction of the Sector Board for Materials and Chemicals, was published under the authority of the Standards Board and comes into effect on 15 June 1995

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The following BSI references relate to the work on this standard:
Committee reference PTI/12
Draft for comment 88/52423 DC

ISBN 0 580 24139 4

Amendments issued since publication

Amd. No.	Date	Comments

Contents

	Page
Committees responsible	Inside front cover
National foreword	iii
Section 1. General	
1.1 Scope	1
1.2 Definitions	1
1.3 Symbols and units	1
1.4 Central proving	2
1.5 On-line proving	2
Section 2. Statistical measurements	
2.1 Principles of statistical measurement	3
2.2 Measurement procedure	6
Section 3. Central proving	
3.1 Collection of data	9
3.2 Reliability of data collected and resulting values	10
3.3 Performance charts	11
3.4 Control charts and tests	18
3.5 Worked examples	21
Section 4. On-line proving	
4.1 Collection of data	45
4.2 Reliability of data collected	47
4.3 Performance charts	47
4.4 Control charts	48
4.5 Worked examples	52
Section 5. Secondary control	
5.1 Comparison between meter and tank	63
Annex A (informative) Statistical tables	67
Annex B (informative) <i>t</i> -distribution values for 95 % and 99 % probability (two-sided)	70
Annex C (informative) Normal (Gaussian) distribution	71
Annex D (informative) Outlier tests	73
Annex E (informative) Random uncertainty of polynomial approximation	75
Annex F (informative) Bibliography	75
Figure 1 — Performance chart: <i>K</i> -factor versus flowrate [showing scatter (range) of 5 to 10 consecutive runs]	8
Figure 2 — Control chart (general)	8
Figure 3 — Performance chart No. 1	13
Figure 4 — Performance chart No. 2	14
Figure 5 — Performance chart No. 3, $E = f(Q)$	14
Figure 6 — Performance chart No. 4 — UCC polynomial	15
Figure 7 — Control chart No. 1	19
Figure 8 — Control chart No. 2	19
Figure 9 — Control chart No. 3	20
Figure 10 — Control chart No. 4	20
Figure 11 — Double chronometer method of pulse interpolation	24
Figure 12 — Performance chart, turbine No. 310, 1978	28
Figure 13 — Log (<i>Q/v</i>) vs. meter factor, turbine No. 310, 1978	29
Figure 14 — Performance chart, turbine No. 310, 1979	33
Figure 15 — Log (<i>Q/v</i>) vs. meter factor, turbine No. 310, 1979	34

	Page
Figure 16 — Performance chart, turbine No. 310, 1980	38
Figure 17 — Log (Q/v) vs. meter factor, turbine No. 310, 1980	39
Figure 18 — Comparison of 1978 data with 1979 data, log (Q/v) vs. meter factor, turbine No. 310	43
Figure 19 — Comparison of 1979 data with 1980 data, log (Q/v) vs. meter factor, turbine No. 310	44
Figure 20 — Permissible change in flowrate during proving	46
Figure 21 — Performance chart from series of on-line provings	48
Figure 22 — K -factor (mean of 5 or 10 consecutive runs) versus time	49
Figure 23 — Combined performance/control chart	51
Figure 24 — Moving-average meter factor versus time	52
Figure 25 — Control chart for meter operating within linear range	56
Figure 26 — Chart A — Meter performance curves — Meter turbine proved with pipe prover	59
Figure 27 — Control chart — Meter operating outside linear range	61
Figure C.1 — Frequency histogram	72
Figure C.2 — Bell-shaped distribution curve	72
Table 1 — Performance chart No. 5 — Direct matrix	16
Table 2 — Performance chart No. 6	17
Table 3 — Example 5: test results for turbine meter	25
Table 4 — Performance chart, meter No. 310 test report, 1978	30
Table 5 — Meter factor for turbine meter No. 310, 1978	31
Table 6 — Random uncertainty of polynomial for turbine No. 310, 1978	32
Table 7 — Performance chart, meter No. 310 test report, 1979	35
Table 8 — Meter factor for turbine meter No. 310, 1979	36
Table 9 — Random uncertainty of polynomial for turbine No. 310, 1979	37
Table 10 — Performance chart, meter No. 310 test report, 1980	40
Table 11 — Meter factor for turbine meter No. 310, 1980	41
Table 12 — Random uncertainty of polynomial for turbine No. 310, 1980	42
Table 13 — Example 4 — Normalizing meter factor	58
Table 14 — Computed uncertainty for vertical cylindrical tanks at 15 °C	65
Table 15 — Computed meter uncertainty at 15 °C	65
Table 16 — Combined values of transfer uncertainty for tank and meter	66
Table A.1 — Distribution of the range	67
Table A.2 — Limiting values $E_2(n, \phi)$, $P = 0,95$	68
Table A.3 — Limiting values $E_2(n, \phi)$, $P = 0,99$	69
Table B.1 — t -distribution values	70
Table D.1 — For use with Dixon's Test for outliers	73
Table D.2 — For use with Grubb's Test for outliers	74
List of references	Inside back cover

National foreword

This British Standard has been prepared by Technical Committee PTI/12. It is identical with ISO 4124:1994, *Liquid hydrocarbons — Dynamic measurement — Statistical control of volumetric metering systems*, published by the International Organization for Standardization (ISO). ISO 4214 was prepared by Subcommittee 2, Dynamic petroleum measurement, of Technical Committee, Petroleum products and lubricants, in which the United Kingdom participated.

Cross-references

International Standard	Corresponding British Standard
	BS 6866 <i>Proving systems for meters used in dynamic measurement of liquid hydrocarbons</i>
ISO 7278-3:1986	Part 3:1987 <i>Methods for pulse interpolation</i> (Identical)

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Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 76, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

1.1 Scope

In dynamic measuring systems the performance of meters for liquid hydrocarbons will vary with changes in flow conditions, viz. flowrate, viscosity, temperature, pressure, density of product, and with mechanical wear.

This International Standard has been prepared as a guide for establishing and monitoring the performance of such meters, using appropriate statistical control procedures for both central and on-line proving. These procedures may be applied to measurements made by any type of volumetric or mass metering system.

The procedures to be followed for collecting data, on which the control limits are based, are described. An alternative method for establishing the reliability of these data is described in ISO 7278-3.

Methods are described for calculating the warning and action control limits for the charts covering the selected performance characteristics, the application of these control charts to subsequent routine measurements, and their interpretation. Worked examples are given in the appropriate central and on-line proving sections.

1.2 Definitions

For the purposes of this International Standard, the following definitions apply.

1.2.1

proving; proof; calibration

determination of the meter performance via the relationship between the volume of liquid actually passing through a meter and the reference volume of the pipe prover

1.2.2

K-factor

relationship between the number of pulses (N) generated by the meter during the proving run and the volume of liquid (V) displaced by the sphere or piston in the pipe prover between detectors

normally, $K = N/V$; it is recommended that this value be corrected by the pulse interpolation technique described in ISO 7278-3

1.2.3

meter factor

ratio of the actual volume passed through a meter, as derived from the pipe prover, to the volume indicated by the meter totalizer

1.3 Symbols and units

1.3.1 General symbols

h_1	high liquid level in tank	metres
h_2	low liquid level in tank	metres
E_h	gauging error	millimetres
E_m	meter volumetric error	percent
E_t	temperature error	degrees Celsius
K	<i>K</i> -factor	pulses per unit volume
ΔK	change in <i>K</i> -factor	pulses per unit volume
MF	meter factor	dimensionless
MF _m	mean meter factor	dimensionless
MF _{max}	maximum meter factor in a set of measurements	dimensionless
MF _{min}	minimum meter factor in a set of measurements	dimensionless
N	number of pulses generated by meter during proving run	dimensionless
P	pressure at line conditions	kilopascals (1 bar = 100 kPa)
P_0	pressure at standard conditions (101,325 kPa)	kilopascals
t	temperature at line conditions	degrees Celsius

t_0	temperature at standard conditions (15 °C or 20 °C)	degrees Celsius
T_1	elapsed time	seconds
Q	volume rate of flow	cubic metres per hour
V_p	reference volume of pipe prover at standard conditions (15 °C or 20 °C and 101,325 kPa)	litres or cubic metres
ν	kinematic viscosity of the fluid	millimetres squared per second [centistoke (cSt)]

1.3.2 Statistical symbols

X	true value of quantity
μ	mean value
σ	standard deviation
x	value of measurement
$\bar{x}$	mean of a set of measurements
n	number of repeated measurements
m	number of quantities
s	estimate of standard deviation
w	range of a set of measurements
$\bar{w}$	mean of a set of ranges
t	value of Student's t -distribution
r	estimate of repeatability
Φ	degrees of freedom

1.4 Central proving

With the method of central proving, the performance of a meter is established at a testing station by proving the meter over its entire operating range of flowrate, viscosity, temperature and oil density used in service.

Meter performance charts are then prepared from the proving data, and are used to establish the relationship between the meter factor and flowrate or flow and viscosity.

Any large deviation in meter performance on site can be detected by secondary control procedures, which monitor the output of two meters in series or in parallel. Long-term deviations in meter factors can be established by statistical control charts. The latter method can also be used in on-line proving.

1.5 On-line proving

With the method of on-line proving, the meter is proved under operating conditions with a portable or fixed installation pipe prover. Where significant changes in flowrate, viscosity, temperature or density occur, the meter can be reproved.

Any marked deviation or abnormal trend in meter factor can be monitored by use of statistical control charts.

By statistical analysis it is possible to establish whether the deviations are due to changes in flow conditions, random error or some other assignable cause.

Section 2. Statistical measurements

2.1 Principles of statistical measurement

2.1.1 Introduction

Measurements taken via central or on-line meter proving provide information on the random variability of the parameters of hydrocarbon flow through the meter (for example meter factor, flowrate, temperature, Reynolds number). Using this information, it is possible to assign a level of probability to a deviation observed in practice, and thereby differentiate between a normal or “allowable” deviation and one that has been caused by an external and systematic influence, such as meter component wear.

The true value of the meter characteristic in question, and its range of variability, can be represented diagrammatically on a control chart (see 2.2.5). This will indicate the deviation (warning limit) which should be taken as an early indication of malfunction, and the deviation (action limit) at which it is almost certain that meter failure has occurred. It is standard practice to assign a probability of 95 % to warning limits, and 99 % to action limits. This means, for example, that there is only a 1 % chance that a measurement falling outside the action limits did so as a result of normal variation when the process is under statistical control. Once a control chart is established, the measurements from subsequent meter provings can be entered periodically onto the control chart, from which it is possible to monitor trends in meter performance over a period of time.

In order to establish control through this means, reliable estimates should be obtained of the statistics to be used. The initial period in which data is collected, and against which the performance of the meter is to be monitored, is called the “learning period”. This should be long enough to provide a reliable assessment of the true value of the meter characteristic in question.

Before considering the steps to be followed in the creation, use and maintenance of control charts, it is first necessary to understand the statistical treatment which is to be applied.

2.1.2 Distribution of measurements

The measurement of any physical quantity, be it direct (for example temperature by thermometer) or indirect (for example meter factor) is always subject to error. The error is sometimes systematic and assignable to a definite cause, for example a large change in temperature may result in a large change in meter factor. If that is not the case, however, data scatter can be regarded as random, and is thus amenable to statistical treatment.

Random errors often vary in magnitude with the quantity being measured (in which case they are expressed as percentages) or with some other external factor. The error in K -factor, for example, will change in magnitude according to the flowrate (see performance chart in Figure 1). For this reason it is vital that operating conditions are controlled while measurements are being taken (see 2.2.2). In practice, the distribution of errors approximates a Gaussian (normal) distribution, and this is fully defined if its two parameters are known. The parameters in this case are mean value, represented by μ , and standard deviation, represented by σ . The Gaussian distribution is described in more detail in Annex C.

Each of the parameters of a distribution of measurements is assumed to have a true value, and is represented algebraically by a Greek or capital Roman letter. Estimates of the parameters, or statistics, are represented algebraically by small Roman letters. When necessary these will be qualified algebraically by the use of brackets. For example the standard deviation estimate of a measurement x will be shown as $s(x)$ (see 2.1.4). The statistics which are of primary interest are mean, standard deviation, range of a set of measurements, and uncertainty.

2.1.3 Estimate of true quantity

Given a set of measurement x_i , for $i = 1$ to n , the estimate of the true quantity which is most likely to be correct is the mean $\bar{x}$ (termed “ x bar”) of the set of measurements, where

$$\bar{x} = \frac{1}{n} (x_1 + x_2 + \dots + x_n) = \frac{1}{n} \sum_{i=1}^n x_i \quad \dots (2.1)$$

As n tends to infinity, so the estimate $\bar{x}$ will tend towards the true value μ , provided there are no systematic errors.

2.1.4 Estimate of standard deviation

The standard deviation $\sigma(x)$ is a measure of the random error of a single measurement x . The usual unbiased estimate of $\sigma(x)$ is $s(x)$, where:

$$s(x) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n x_i^2 - \frac{n}{(n-1)}} \quad \dots(2.2)$$

Another estimate is given by:

$$s(x) = \frac{\bar{w}}{D(n)} \quad \dots(2.3)$$

where

$\bar{w}$ is the mean range difference between the maximum and minimum values of x , using a number of sets of n measurements;

$D(n)$ is a conversion factor (see Annex A).

This estimate becomes less reliable as the number of ranges on which it was based becomes smaller, and should only be regarded as a rough check when based on a single range.

The standard deviation estimate of a mean, sometimes called standard error, is derived from this as:

$$s(\bar{x}) = s(x)/\sqrt{n} \quad \dots(2.4)$$

It is evident that as the number n of measurements is increased, so the standard error is decreased, leading to greater confidence in the estimate $\bar{x}$ of the true quantity.

2.1.5 Estimate of the uncertainty

The reliability of an estimate can be expressed as an *uncertainty interval* in which the true value should be expected to fall with a specified level of confidence or probability. In statistical terminology this is called a confidence interval. The uncertainty interval which contains an estimate x is $x \pm u(x)$, where $u(x)$ is called the *uncertainty*, $x - u(x)$ and $x + u(x)$ are called the *uncertainty limits*, and the difference $2u(x)$ between these limits is called the *range of uncertainty*. Normally the probability levels are 95 % and 99 %.

A true quantity estimate of $\bar{x}$, the mean of n measurements, could then be stated as:

True quantity = $\bar{x} \pm u(\bar{x})$, n measurements, 95 % probability;

when $n = 1$, $\bar{x}$ becomes the single measurement x .

If the standard deviation σ is known from long experience, then the uncertainty is also known. That referring to 95 % probability is given by:

$$u(\bar{x}) = 1,96\sigma(\bar{x}) = 1,96\sigma(x)/\sqrt{n} \quad \dots(2.5)$$

As before, $\bar{x}$ becomes the single measurement x when $n = 1$. The value 1,96 is the value of the standard normal deviate for a two-sided probability of 95 % (see Annex C).

If, however, the standard deviation of individual measurements has been estimated as $s(x)$, based on Φ degrees of freedom, then the uncertainty should be estimated as:

$$u(\bar{x}) = t_{95, \Phi} s(\bar{x}) = t_{95, \Phi} s(x)/\sqrt{n} \quad \dots(2.6)$$

Once again, when $n = 1$, $\bar{x}$ becomes the single measurement x .

Here $t_{95, \Phi}$ is the value of the t -distribution for a two-sided probability of 95 %, corresponding to a standard deviation estimate based on Φ degrees of freedom (see Annex B). In this context, degrees of freedom should be regarded as the number of independent measurements from which the standard deviation was estimated. Given n measurements, therefore, s would be based on $\Phi = (n - 1)$ degrees of freedom, since one degree of freedom was already accounted for in estimating the mean.

The t -distribution is a function of the degrees of freedom, and the t -value for a given probability will decrease in magnitude as Φ increases. As Φ tends towards infinity, so the t -distribution tends towards a Gaussian distribution. Values of 2 and 3 are sometimes used as approximations of the t -values corresponding to 95 % and 99 % probability respectively. These values are appropriate for estimates based on 10 to 20 measurements.

2.1.6 Estimate of repeatability

Repeatability is the term used for uncertainty which relates not to individual measurements or measurement means as in 2.1.5, but to the *difference* between two individual measurements. Since the standard deviation of the difference between two measurements x_1 and x_2 (see 2.1.8) is:

$$\sigma(x_1 - x_2) = \sqrt{2} \sigma(x_1) = \sqrt{2} \sigma(x_2) \quad \dots(2.7)$$

then the repeatability estimate r is given by:

$$r = \sqrt{2} u(x) \quad \dots(2.8)$$

In this case $u(x)$ refers to individual measurements x_i rather than the mean $\bar{x}$, and equations (2.5) and (2.6) would become:

$$U(x) = 1,96\sigma(x) \quad \dots(2.9)$$

and

$$u(x) = t_{95, \phi} s(x) \quad \dots(2.10)$$

Note that a repeatability value, to be used in practice, should be derived from an independent set of measurements which excludes the pair of values in question. The standard deviation estimate should be based on at least 20 and preferably 30 or more degrees of freedom

2.1.7 Estimate of maximum range

It is possible to extend the concept of repeatability (the uncertainty for the difference between two measurements) by considering the distribution of a range of three or more measurements. For this it is necessary to refer to the limiting values $E_1(n)$ or $E_2(n, \Phi)$ of a range of measurements with unit standard deviation corresponding to chosen probability level (see Annex A).

The upper limit of the range of n measurements, knowing the standard deviation $\sigma(x)$, is given by:

$$W = \sigma(x) E_1(n) \quad \dots(2.11)$$

Where the standard deviation is estimated as $s(x)$ (see 2.1.4) based on ϕ degrees of freedom, from an independent exercise excluding the measurements in question, the limit is estimated to be:

$$w = s(x) E_2(n, \Phi) \quad \dots(2.12)$$

In either case, the limit calculated corresponds to the maximum range (n measurements) to be expected in practice with the given probability. The limit corresponding to 95 % probability may be used as a test to establish statistical control (see 2.2.2). A rogue value can also be identified in this way (see 2.2.3), but should be confirmed by the use of one of the outlier tests given in Annex D. As with repeatability, an estimate of maximum range to be used in practice should be based on at least 20 and preferably 30 or more degrees of freedom, and should exclude the measurements in question.

2.1.8 Combination of errors

Consider an indirect measurement y which is calculated from, say, m intermediate measurements $x_1, x_2 \dots x_m$ according to the function:

$$y = F(x_1, x_2 \dots x_m) \quad \dots(2.13)$$

If the m intermediate measurements are algebraically independent, that is, no one can be calculated from the others, then the statistics of the indirect measurement may be derived as shown below.

2.1.8.1 The estimate $\bar{y}$ of the true value (see 2.1.3) can be calculated by substitution of the appropriate means into equation (2.13), that is:

$$\bar{y} \simeq F(\bar{x}_1, \bar{x}_2 \dots \bar{x}_m) \quad \dots(2.14)$$

This approximation applies to functions F which are approximately linear.

2.1.8.2 The estimate $s(y)$ of the standard deviation of y (see **2.1.4**) is given by:

$$s^2(y) = \left[\frac{\partial F}{\partial x_1} s(x_1) \right]^2 + \left[\frac{\partial F}{\partial x_2} s(x_2) \right]^2 + \dots + \left[\frac{\partial F}{\partial x_m} s(x_m) \right]^2 \quad \dots (2.15)$$

where the sensitivity coefficients $\partial F/\partial x_i$ are evaluated at the known or mean values of x_i .

Note that the standard deviation estimates used in this expression could be in terms of either individual measurements [equation (2.2)] or mean values [equation (2.4)]. Furthermore, the expression is valid if one or more of the standard deviation values is known as $\sigma(x_i)$, rather than estimated as $s(x_i)$.

2.1.8.3 The estimate $u(y)$ of the uncertainty of y (see **2.1.5**) is similar in form to equation (2.13), that is:

$$u^2(y) = \left[\frac{\partial F}{\partial x_1} u(x_1) \right]^2 + \left[\frac{\partial F}{\partial x_2} u(x_2) \right]^2 + \dots + \left[\frac{\partial F}{\partial x_m} u(x_m) \right]^2 \quad \dots (2.16)$$

Once again, the uncertainty estimates used in this expression can be in terms of individual measurements or mean values, and could include known values of uncertainty $u(x_i)$.

2.2 Measurement procedure

2.2.1 Introduction

In order to monitor meter performance through a statistically based control chart, in general terms the procedure should be carried out as follows:

- a) establish statistical control;
- b) take measurements in the proving run conducted under the operating conditions required;
- c) test the measurements for reliability and use them to create new performance charts, or add to performance charts previously created;
- d) add the measurements to control charts in progress, or use the measurements to create new control charts if sufficient measurements have been accumulated in the "learning period".

2.2.2 Statistical control

A measurement taken under undefined or variable operating conditions will not yield meaningful statistics. In order to establish statistical control, great care should be taken that factors such as temperature and flowrate are correctly measured, and that all external influences have been identified.

It is very often difficult to establish statistical control quantitatively. It may be possible, however, to examine performance charts and calculate the maximum allowable range for a set of measurements obtained under the given operating conditions (see **2.1.7**). At the very least, it is essential that the measurement procedure is clearly understood and that equipment is operating correctly.

2.2.3 Measurement reliability

A set of n repeated measurements having been obtained, they should be examined for outliers (rogue values). It should be stressed, however, that measurements should not freely be discarded. An attempt should always be made to find a reason for the extreme values, after which corrective action can be taken. Given no further information on the scatter of the measurements, Dixon's or Grubbs' outlier test may be used (see Annex D). In the event that an outlier is detected by this means, then it should be disregarded and further measurements obtained. It should also be confirmed that the extreme value was not due to a change in an uncontrolled variable such as temperature or flowrate (see **2.2.2**).

The scatter of the K -factor may have already been determined for the operating conditions under which the set of measurements was obtained (see **2.2.4**). In that case the uncertainty limits are known, and if a measurement were to fall outside the limit corresponding to 95 % probability, it should be regarded as a rogue value. When only two measurements are available, and their difference exceeds the repeatability (see **2.1.6**), then both measurements are suspect. Similarly, the extreme values of a range of n measurements would be suspect if an observed range exceeded the maximum (see **2.1.7**).

2.2.4 Performance charts

The performance of a meter can be represented diagrammatically on a performance chart. Figure 1 is an example, in which mean meter factor is given as a function of only one operating condition, namely flowrate. Variability is expressed in Figure 1 as the range of n repeated measurements (typically, $n = 5$ or 10), but could also have been expressed as the uncertainty interval.

A separate performance chart should be drawn for each meter and product, and should refer to a stated set of operating conditions (for example range of temperature). In the case of central proving, however, in which it is possible to take measurements covering a wide range of operating conditions on the same class of meter, the “performance charts” may take the form of a matrix or surface in which meter factor is a function of two or more operating variables. (See 3.3.)

2.2.5 Control charts

2.2.5.1 Chart preparation

Following a sufficient learning period (for example 15 sets of proving runs), the true value estimate of K -factor can be represented on a control chart. Figure 2 is an example, in which each entry is a mean of 5 K -factors from four proving runs. The warning and action limits are the uncertainty limits, estimated at the end of the learning period, corresponding to 95 % and 99 % probability, respectively. It would be reasonable to expect that 5 % of the results would lie outside the warning limits and 1 % outside the action limits if the process were in statistical control.

Figure 2 shows entries which indicate whether the measurements are “in control” or not, and also gives an example of a systematic trend with time or volume throughput. It should be noted that if a systematic trend is evident, the control chart can be recreated with an appropriate shift in mean value and control limits. This would, for example, take account of meter component wear over a long period of time.

2.2.5.2 Parallel control charts

Control charts referring to different measurements, for example K -factor and flowrate, can be constructed with a common scale of time or volume throughput. This will allow the correlation of one measurement with another, and may indicate a reason for major deviations in K -factor.

2.2.5.3 Moving-average control charts

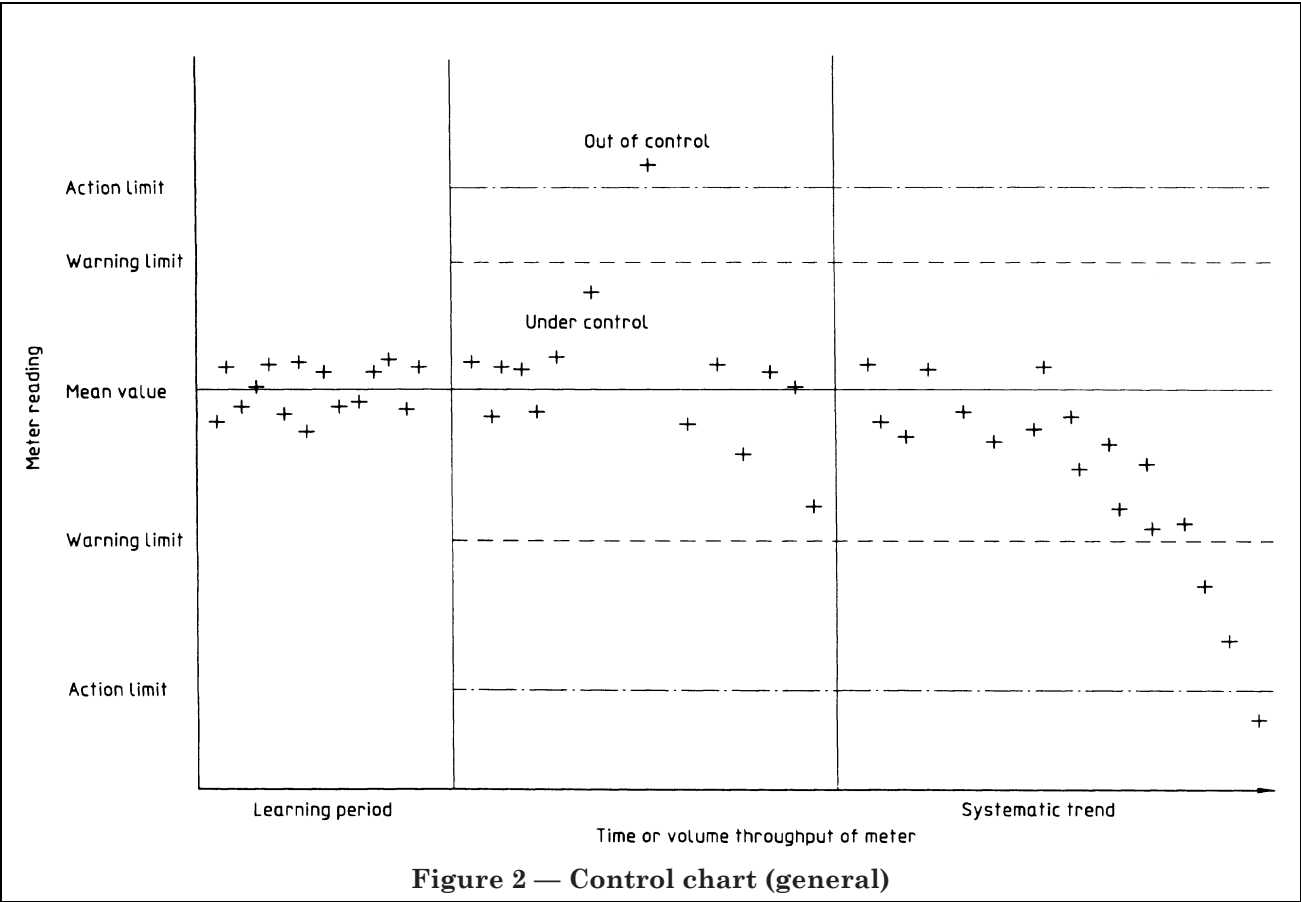
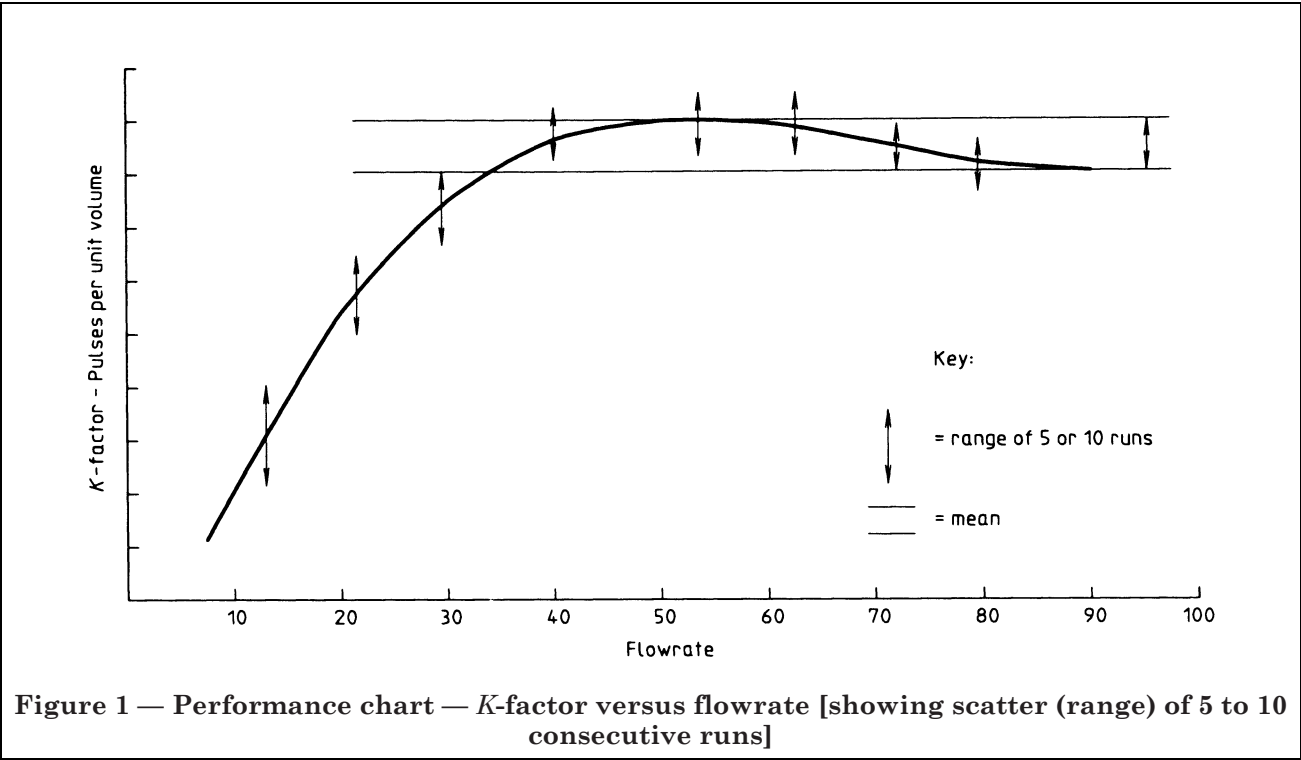
Long-term meter performance can be monitored by using moving averages. After the learning period, each entry on the control chart (see Figure 2) will be the average of, say, the last ten sets of proving runs. This will provide a moving “window” which will be less affected by short-term deviations, and from which it is possible to identify a slope change (long-term drift) or a step change (constant shift in K -factor).

2.2.5.4 Non-linear control charts

The performance chart in Figure 1 becomes a control chart if warning and action limits are placed on each side of the line. In this case the learning period includes the measurements on which the performance chart was based. From these measurements, and previous experience when available, it is possible to estimate the standard deviation of K -factor for a given range of flowrates. Control limits can then be estimated and drawn on the chart.

2.2.5.5 Reconciliation charts

Long-term meter performance can be monitored in meter/tank or meter/meter comparisons of volume throughput. When a meter’s readings are regularly compared with another measuring technique (for example tank gauging) on the same volume of liquid, then the volume of throughput is accumulated for each measuring device and the difference between them expressed as a percentage of the cumulative sum. The true value on a reconciliation chart will be zero, and as the cumulative sums of volume increase, so the percentage difference will be expected to tend towards zero. If not, meter failure or bias would be indicated.



Section 3. Central proving

3.1 Collection of data

3.1.1 Proving conditions

3.1.1.1 General

Initial and periodic provings may be carried out on different oils which are stored in the centralized proving station in order to cover, when required, a wide range of viscosities.

During the proving operation, the meter factor of the meter versus flowrate and of the meter versus viscosity should be established. As the meter factor will depend upon pressure p , temperature t and flowrate Q , it is necessary to maintain the pressure and temperature as constant as possible.

During the proving operation, the meter factor of a positive displacement meter versus flowrate shall be established. If the meter will be used on products covering a wide range of viscosities < 20 cSt, a curve of meter factors for each product type shall be established.

Turbine- and other inferential meters are in essence Reynolds-number related in their behaviour. The meter factor should therefore preferentially be established versus Reynolds number or Q/D .

If there is any variation in the pressure and temperature it should be sufficiently small to ensure that it does not contribute more than $\pm 0,01$ % to the overall uncertainty in meter factor. The variation should be less than the uncertainty of the pipe prover reference volume, which is usually of the order of 0,02 % to 0,05 %.

3.1.1.2 Pressure

The pressure should be measured at (or close to) the meter and at the prover outlet. Its value should be kept constant within the limits ± 50 kPa.

3.1.1.3 Temperature

The temperature of the liquid should be measured at (or close to) the meter and at the prover. Sufficient product should be passed or circulated through the system initially in order to ensure thermally stable conditions. Any variations in temperature of less than 0,1 °C between the meter and prover may be considered as instrument errors rather than variations in liquid temperature.

3.1.1.4 Flowrate

The mean flowrate should be computed from the volume of the prover at reference conditions of temperature and pressure using the time interval between the first and last detector signals.

3.1.1.5 Viscosity

Determine the density and viscosity (at a minimum of two different temperatures, e.g. 20 °C and 40 °C) of the oil for each proving operation.

3.1.1.6 Meter data

The number of pulses generated by the meter at the various flowrates is totalled by an electronic counter which is started and stopped by the two detector signals respectively. In order to achieve a maximum uncertainty of 0,01 %, a suitable pulse interpolation technique may be used.

3.1.1.7 Number of provings

Each calibration for the same flowrate should be repeated at least twice, further measurements being required if the scatter is unacceptably large (see 3.2.2).

3.1.1.8 Number of flowrates required

For any given fluid the meter should be tested at no less than five flowrates, which will include the maximum and minimum flowrates. The minimum number of flowrates covering the operating range is defined in relation to the actual performance of the meter; for example, if the meter factor varies considerably with flowrate then a larger number of flowrates will be required in the test procedure.

3.1.1.9 Number of viscosities

Where possible, tests should be carried out on the actual fluids and over the flow range and under the same conditions of temperature and pressure that would be experienced in operation. The choice of the viscosities and their spacings depends on the type of meter being proved, i.e. the sensitivity of meter factor to viscosity variation, and the range of viscosities encountered in operation.

Although the viscosities normally chosen should be equally spaced over the operating range of the meter, it may be necessary to select additional viscosities at points where the meter factor is particularly sensitive to viscosity variation.

3.1.2 Test report

The results and conditions concerning the initial and periodic proving tests should be set down in a report that includes the following information:

- a) identification of the centralized proving station;
- b) reference volume of the pipe prover used;
- c) meter characteristics (manufacturer, model and serial number);
- d) exact details of the conditions under which the various tests were performed.

3.2 Reliability of data collected and resulting values

3.2.1 Central proving operational conditions

Although it is implied in 3.1.1.1 that conditions are held constant within a test in a central proving station, products are often recycled with slight variations in temperature. However, it is possible to compute the viscosity from the temperature.

If the uncertainty in meter factor (see 3.2.3) is known, during a test any variation in the parameters should not produce a variation in meter factor greater than a given percentage of this uncertainty. A typical value of this percentage is 30 %.

3.2.2 Reliability of data collected

The reliability of the data collected should be checked by means of the following tests before estimating the meter factor and the scatter on this estimate.

3.2.2.1 Outlier test

At each flow and viscosity (Q , v) n ($n \geq 3$) provings are made.

Dixon's test (see D.1) or Grubbs' test (see D.2) can be used to discard outliers (rogue values).

3.2.2.2 Tests for short-term variability or scatter

There are two methods for testing the scatter or variation in the meter factor: a repeatability test and a range test.

3.2.2.2.1 Test for repeatability

The absolute difference between two measurements at each (Q , v) point can be tested against the repeatability r . If r is unknown, then a given percentage of the mean MF_m of the measurements should be used in its place. A typical value is 0,05 %.

If the absolute value of the difference is less than or equal to r , then the two measurements shall be retained. If the absolute difference exceeds r , then at least three additional measurements should be obtained, giving a total of n measurements. The test is repeated, but now using the absolute difference between the most divergent value and the average of the remaining $n - 1$ measurements.

If the absolute difference is less than or equal to

$$r \cdot \sqrt{\frac{n}{2(n-1)}}$$

then all the measurements shall be retained. If the absolute difference exceeds

$$r \cdot \sqrt{\frac{n}{2(n-1)}}$$

the most divergent measurement shall be rejected and the procedure repeated until an acceptable set of measurements is obtained. However, if two or more measurements out of 20 have been rejected, then the proving run should be stopped for investigation.

3.2.2.2.2 Test of the range

The range of $n > 2$ measurements at each (Q, v) point can be tested against a maximum value of w , where $MF_{\max}$ and $MF_{\min}$ are respectively the largest and smallest measurements. If the standard deviation of the meter factor measurements is known or can be estimated from previous measurements, then w can be calculated from equation (2.11) or equation (2.12) (see 2.1.7), using tabulated values of $E_1(n)$ or $E_2(n, \Phi)$ corresponding to 95 % probability. If the standard deviation is unknown, then a given percentage of the mean value MF_m of the measurements should be used in place of w . A typical value is 0,05 %.

If $(MF_{\max} - MF_{\min})$ is less than or equal to w , then all the measurements shall be retained.

If $(MF_{\max} - MF_{\min})$ exceeds w , then the most divergent measurement shall be rejected and the procedure repeated until an acceptable set of measurements is obtained. In that event w will require recalculation to take account of the new value of n . However, if two or more measurements out of not more than 20 have been rejected, then the proving run should be stopped for investigation.

If σ or s is not known, then test the measurements by applying the ratio:

$$\frac{MF_{\max} - MF_{\min}}{MF_{\max} + MF_{\min}}$$

If the ratio is less than 0,000 25 then the results are acceptable.

3.2.3 Resulting values

At each proving point (Q, v) the meter factor value is the arithmetic mean of the retained measurements after the tests defined in 3.2.2.

The uncertainty on meter factor determination (arithmetic mean), estimated as described above, is calculated with equations (2.5) and (2.6) of 2.1.5 (Section 2).

3.2.4 Variation in meter factor with (Q, v)

When meter factors have been established over the entire range of the flowrate and viscosity, tests should be performed in order to check the variation of the meter factor. Different ranges of flowrates are considered as corresponding to different ranges of viscosities.

The ratio

$$\frac{MF_{\max} - MF_{\min}}{MF_{\max} + MF_{\min}}$$

is computed.

The ratio should be less than a given limit, which is typically 0,025 %, where $MF_{\max}$ and $MF_{\min}$ are the maximum and minimum values of meter factor, respectively, over the entire range of proving.

3.3 Performance charts

3.3.1 General

A centralized proving station is a fixed installation comprising a number of pipe provers for proving and testing turbine and displacement meters.

Measurements are carried out in order to establish the performance characteristic for the meter under test. The appropriate meter factors, which are determined for different oil flowrates and ratios Q/v , can be represented by means of polynomials, tables or a matrix.

3.3.2 Preparation of data

3.3.2.1 Flowrate Q

The flowrate Q , expressed in cubic metres per hour, is calculated from the time T_1 (in seconds) required to displace the prover spheroid between the two detectors which define the prover loop volume, V_p (in litres) at the standard conditions of temperature t_{0p} and pressure P_{0p} . The flowrate at temperature t and pressure p is given by

$$Q = 3,6 \frac{V_p}{T_1} [1 + C_{tp}(t - t_{0p}) + C_{pp}(p - p_{0p})] \quad \dots (3.17)$$

where C_{tp} and C_{pp} are the temperature and pressure corrections, respectively, of the prover.

3.3.2.2 Viscosity

The oil viscosity ν , expressed in centistokes, at proving temperature t is either directly measured at the proving temperature or computed from a formula such as

$$\log_{10} \log_{10}[\nu + f(\nu)] = A - B \log_{10}(t + 273,15) \quad (3.18)$$

where A and B are constants calculated from the oil viscosity at two different temperatures (see ANSI/ASTM D341).

3.3.2.3 Meter characteristics

3.3.2.3.1 K -factor

The K -factor, which is expressed in pulses per unit volume (here pulses per cubic metre), is calculated from equation (3.19) on the assumption that the temperature and pressure at the meter and prover are the same.

$$K = \frac{N}{V_p} \cdot \frac{1 + C_{tm}(t - t_{0m}) + C_{pm}(p - p_{0m})}{1 + C_{tp}(t - t_{0p}) + C_{pp}(p - p_{0p})} \quad \dots (3.19)$$

where

- N is the number of pulses counted during a proving run;
- V_p is the base volume of the prover at standard conditions;
- C_{tm} is the correction for the expansion of the meter due to temperature;
- C_{pm} is the correction for the expansion of the meter due to pressure;
- C_{tp} is the correction for the expansion of the prover due to temperature;
- C_{pp} is the correction for the expansion of the prover due to pressure;
- t is the temperature of the liquid at the meter and prover;
- p is the pressure of the liquid at the meter and prover;
- t_0 is the reference temperature (at standard conditions);
- P_0 is the reference pressure (at standard conditions).

3.3.2.3.2 Meter correction factor

The meter correction factor, which is dimensionless, is normally the ratio between a nominal K -factor permanently stored in the meter processor and the new K -factor.

$$\text{Meter correction factor} = \frac{K_{\text{nominal}}}{K} \quad \dots (3.20)$$

3.3.2.3.3 Relative error

The relative error (E) of the turbine meter is normally defined as:

$$E = \frac{\text{indicated volume} - \text{true volume}}{\text{true volume}} \quad \dots (3.21)$$

It can be expressed as:

$$E = \frac{1 - MF}{MF} \quad \dots (3.22)$$

3.3.3 Meter calibration and performance charts

3.3.3.1 Calibration curve for turbine and displacement meters

3.3.3.1.1 PD meters

As positive displacement (PD) meters are little influenced by the viscosity of the product above 20 cSt, the meter factors can be considered to be mainly a function of flowrate Q .

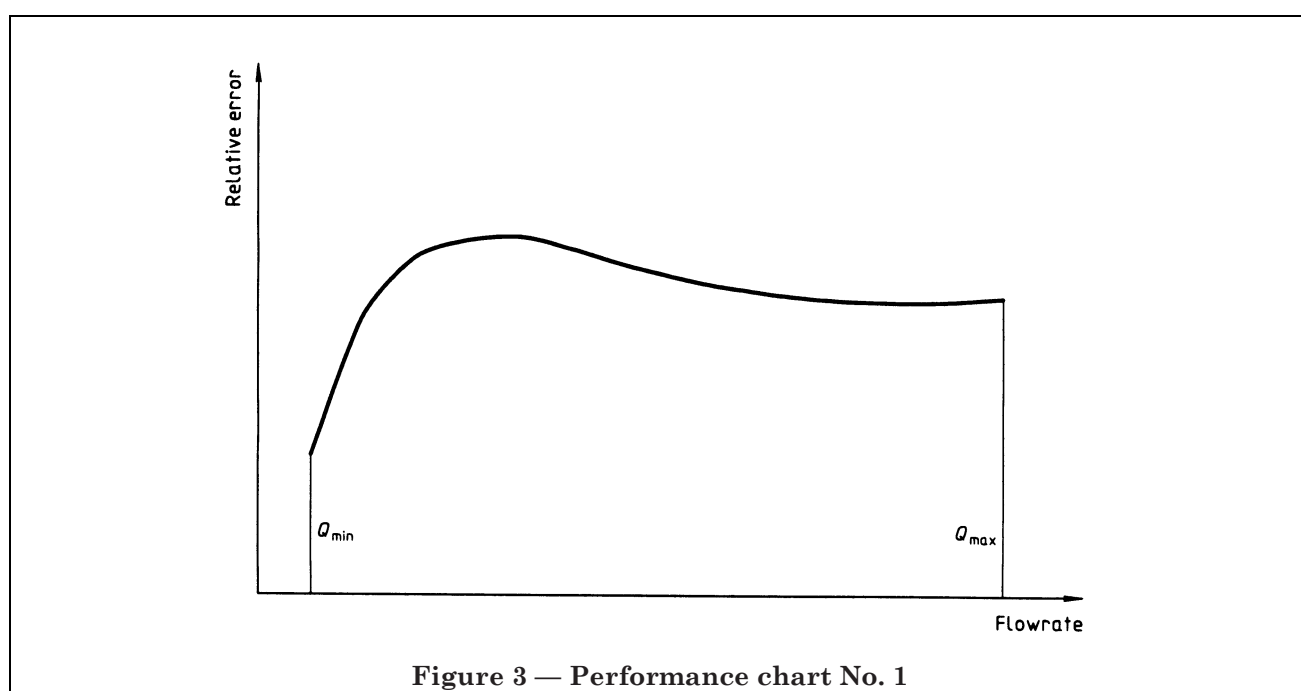
These meters are proved with an oil of the same category as that for which they are used. The performance charts can represent MF, K or E as a function of flowrate. See performance chart No. 1 (Figure 3) showing relative error versus flowrate.

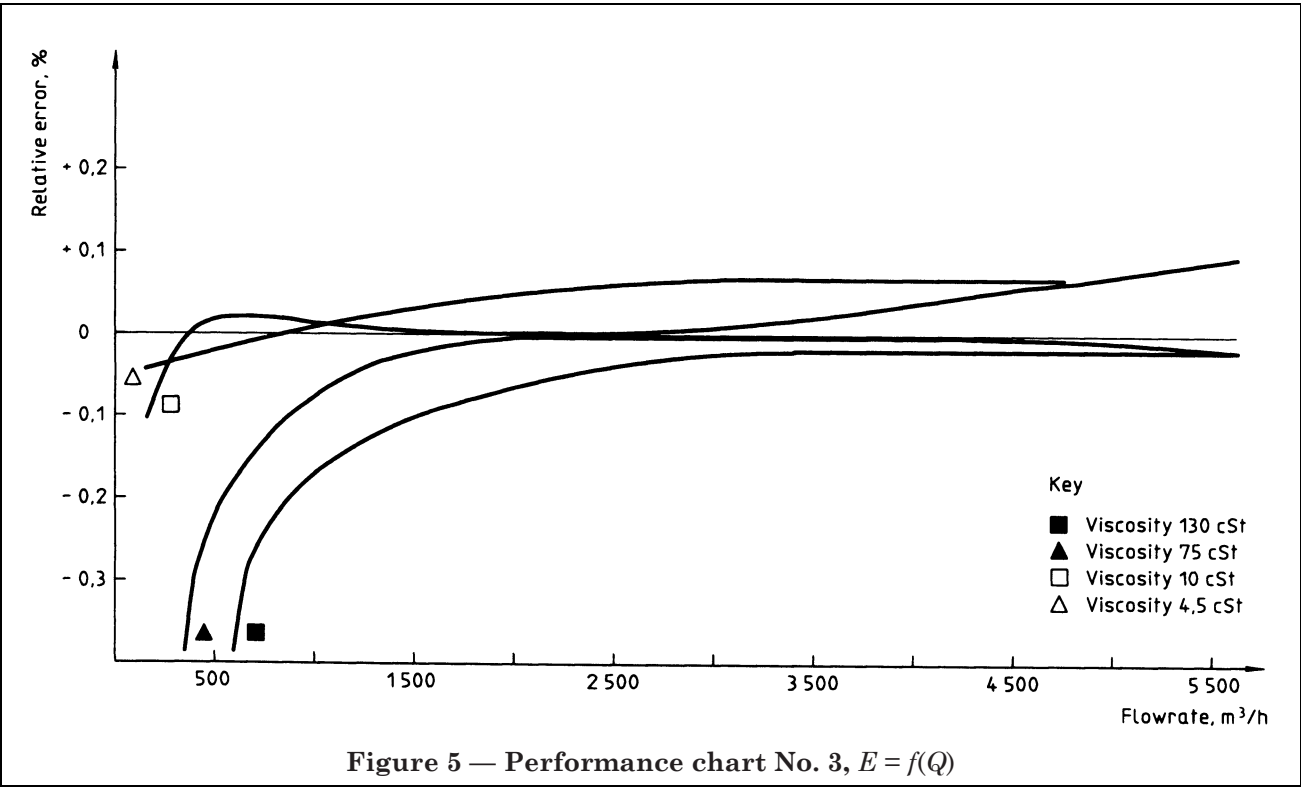
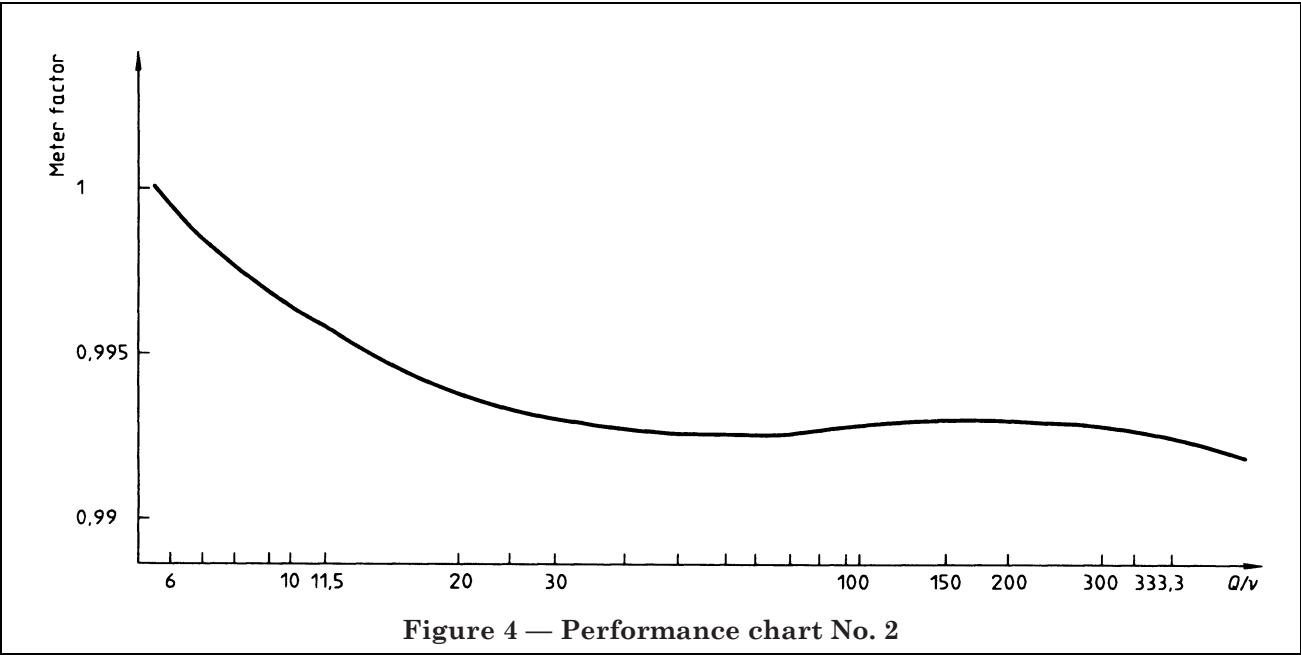
3.3.3.1.2 Turbine meters

When using oil of the same category with a kinematic viscosity less than 1 cSt or when viscosity variations are small, i.e. oils that do not produce meter factor variations greater than 0,1 %, then the meter factor is only a function of flowrate. The performance charts can represent MF, K or E as a function of flowrate. See performance chart No. 1 (Figure 3) showing relative error versus flowrate.

On multiproduct oils or when large viscosity variations occur, for turbine meters, for instance helicoidal two-blade turbine meters, a universal calibration curve (UCC) may be plotted (see 3.3.3.2). The performance charts can represent MF as a function of Q/v (see Figure 4).

With meters for which it is not possible to plot a UCC, tables can be established as a function of flowrate and viscosity. The performance charts can represent MF, K or E as a function of flowrate at a given viscosity (see Figure 5).

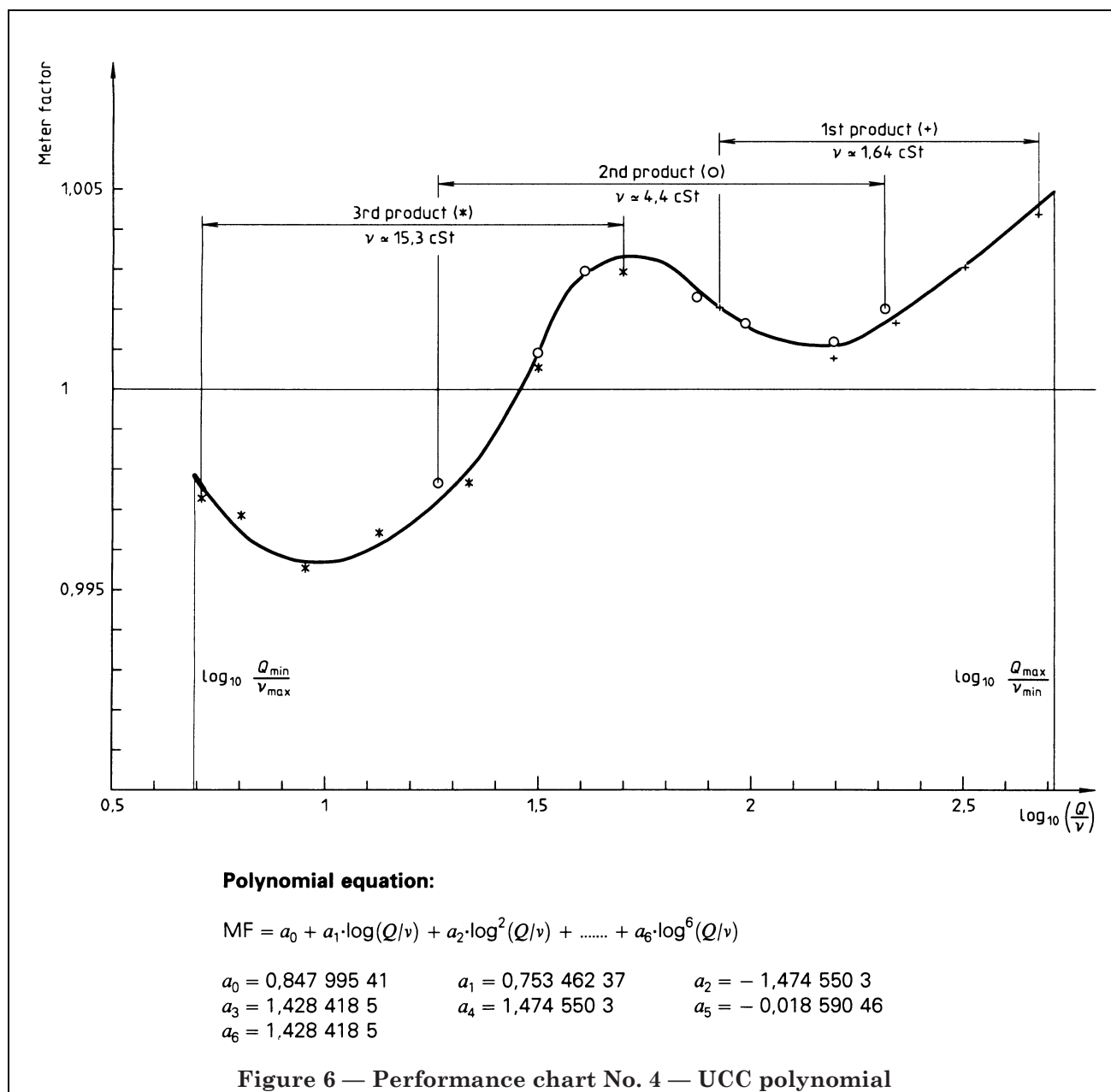




3.3.3.2 Universal calibration curve for turbine meters

The results obtained for different products, flowrates and viscosities are used to establish a curve (UCC) giving MF versus the ratio Q/v . This curve can be represented by a polynomial depending on the variable Q/v (see Figure 6).

Results can also be presented as a direct matrix (see Table 1 or Table 2).



3.3.3.2.1 Polynomial method

For a given pair $[\log_{10}(Q/v), MF]$, a polynomial of a given degree can be established to produce the best fit for these points. The method generally used is that of least squares (see Annex E).

The polynomial degree should be chosen in accordance with the curve shape; generally polynomials of degree 4 to degree 6 are sufficient. The random uncertainty of the polynomial should be less than $\pm 0,1\%$ (see Annex E).

It is necessary to check that the number of points (n) in function of the retained degree (d) is sufficient. A good choice is to take at least twice the polynomial degree plus one $[n = 2(d + 1)]$. The point spacing should be as regular as possible.

3.3.3.2.2 Direct matrix

From the UCC, a double-entry table (Q, v) can be established giving meter factor as a function of flowrate and viscosity.

To obtain a meter factor for a flowrate or viscosity value which does not appear in the matrix, an interpolation will be necessary between the nearest appropriate values.

3.3.3.2.3 Table

A table may be prepared from the data for calibration of a turbine meter, which is similar to a direct matrix but has smaller viscosity increments.

Table 1 — Performance chart No. 5 — Direct matrix

Viscosity ν (cSt)	Meter factor							
	Flowrate (m ³ /h)							
	100	200	300	400	500	600	700	800
1,00	1,001 7	1,001 3	1,002 8	1,004 2	1,004 4	1,003 2	1,000 5	0,996 3
2,00	1,002 5	1,001 7	1,001 1	1,001 3	1,002 0	1,002 8	1,003 6	1,004 2
4,00	1,000 1	1,002 5	1,002 3	1,001 7	1,001 3	1,001 1	1,001 1	1,001 3
6,00	0,997 9	1,001 5	1,002 5	1,002 5	1,002 1	1,001 7	1,001 4	1,001 2
8,00	0,996 8	1,000 1	1,001 9	1,002 5	1,002 5	1,002 3	1,002 0	1,001 7
10,00	0,996 4	0,998 9	1,001 0	1,002 1	1,002 5	1,002 6	1,002 4	1,002 2
12,00	0,996 5	0,997 9	1,000 1	1,001 5	1,002 2	1,002 5	1,002 6	1,002 5
14,00	0,996 8	0,997 2	0,999 2	1,000 8	1,001 7	1,002 3	1,002 5	1,002 6
16,00	0,997 1	0,996 8	0,998 5	1,000 1	1,001 2	1,001 9	1,002 3	1,002 5
NOTE The polynomial chart is the same as for performance chart No. 4.								

Table 2 — Performance chart No. 6

Viscosity <i>v</i> (cSt)	Meter factor								
	Flowrate (m ³ /h)								
	50	100	150	200	250	300	350	400	450
1	0,997 3	0,997 9	0,998 9						
2	0,996 6	0,997 3	0,997 2	0,997 9	0,998 7				
3	0,994 4	0,997 4	0,997 3	0,997 1	0,997 4	0,997 9	0,998 5	0,998 9	0,998 9
4	0,992 9	0,996 6	0,997 5	0,997 3	0,997 1	0,997 2	0,997 5	0,997 9	0,998 3
5	0,992 4	0,995 5	0,997 2	0,997 5	0,997 3	0,997 2	0,997 2	0,997 3	0,997 6
6	0,992 6	0,994 4	0,996 6	0,997 4	0,997 5	0,997 3	0,997 2	0,997 1	0,997 2
7	0,993 2	0,993 5	0,995 9	0,997 1	0,997 4	0,997 4	0,997 3	0,997 2	0,997 1
8	0,994 0	0,992 9	0,995 1	0,996 6	0,997 3	0,997 5	0,997 4	0,997 3	0,997 2
9	0,994 7	0,992 5	0,994 4	0,996 1	0,997 0	0,997 4	0,997 5	0,997 4	0,997 3
10	0,995 3	0,992 4	0,993 8	0,995 5	0,996 6	0,997 2	0,997 4	0,997 5	0,997 4
11	0,995 5	0,992 4	0,993 3	0,994 9	0,996 2	0,996 9	0,997 3	0,997 5	0,997 5
12	0,995 3	0,992 6	0,992 9	0,994 4	0,995 7	0,996 6	0,997 1	0,997 4	0,997 5
13		0,992 8	0,992 6	0,994 0	0,995 3	0,996 3	0,996 9	0,997 2	0,997 4
14		0,993 2	0,992 5	0,993 5	0,994 8	0,995 9	0,996 6	0,997 1	0,997 3
15		0,993 6	0,992 4	0,993 2	0,994 4	0,995 5	0,996 3	0,996 9	0,997 2
16		0,994 0	0,992 4	0,992 9	0,994 0	0,995 1	0,996 0	0,996 6	0,997 0
17		0,994 4	0,992 4	0,992 7	0,993 7	0,994 8	0,995 7	0,996 3	0,996 8
18		0,994 7	0,992 6	0,992 5	0,993 4	0,994 4	0,995 3	0,996 1	0,996 6
19		0,995 0	0,992 7	0,992 4	0,993 1	0,994 1	0,995 0	0,995 8	0,996 4
20		0,995 3	0,992 9	0,992 4	0,992 9	0,993 8	0,994 7	0,995 5	0,996 1
21		0,995 4	0,993 2	0,992 4	0,992 7	0,993 5	0,994 4	0,995 2	0,995 9
22		0,995 5	0,993 4	0,992 4	0,992 6	0,993 3	0,994 2	0,994 9	0,995 6
23		0,995 5	0,993 7	0,992 5	0,992 5	0,993 1	0,993 9	0,994 7	0,995 4
24		0,995 3	0,994 0	0,992 6	0,992 4	0,992 9	0,993 7	0,994 4	0,995 1
25			0,994 2	0,992 7	0,992 4	0,992 8	0,993 4	0,994 2	0,994 9
26			0,994 5	0,992 8	0,992 4	0,992 6	0,993 2	0,994 0	0,994 7
27			0,994 7	0,993 0	0,992 4	0,992 5	0,993 1	0,993 7	0,994 4
28			0,994 9	0,993 2	0,992 4	0,992 5	0,992 9	0,993 5	0,994 2
29			0,995 1	0,993 4	0,992 5	0,992 4	0,992 8	0,993 4	0,994 0
30			0,995 3	0,993 6	0,992 6	0,992 4	0,992 7	0,993 2	0,993 8
31			0,995 4	0,993 8	0,992 7	0,992 4	0,992 6	0,993 0	0,993 6
32			0,995 5	0,994 0	0,992 8	0,992 4	0,992 5	0,992 9	0,993 5
33			0,995 5	0,994 2	0,992 9	0,992 4	0,992 4	0,992 8	0,993 3
34			0,995 5	0,994 4	0,993 0	0,992 4	0,992 4	0,992 7	0,993 2
35			0,995 5	0,994 6	0,993 2	0,992 5	0,992 4	0,992 6	0,993 0
36			0,995 3	0,994 7	0,993 3	0,992 6	0,992 4	0,992 5	0,992 9
37			0,995 2	0,994 9	0,993 5	0,992 6	0,992 4	0,992 5	0,992 8
38				0,995 0	0,993 7	0,992 7	0,992 4	0,992 4	0,992 7
39				0,995 2	0,993 8	0,992 8	0,992 4	0,992 4	0,992 6
40				0,995 3	0,994 0	0,992 9	0,992 4	0,992 4	0,992 6

3.4 Control charts and tests

Control charts and tests can be made for meter factor, K -factor or relative error, depending on the type of application (see 2.2.5).

3.4.1 Quality of meters

Meters which are proved in a centralized proving station should have performance characteristics which are sufficiently stable in terms of time and throughput to achieve a good repeatability.

3.4.2 Frequency of proving

The frequency of proving may be a function of time or a function of total volume metered. The meter should be proved as soon as one of these two limits is reached.

The meter should be re-proved if there is any defect in metering, even if no limit has been reached.

3.4.2.1 *Re-proving as a function of time*

The meter-factor drift is usually on the order of 0,1 % per year. The time interval between two consecutive provings should be judiciously chosen in order that the proving will be significant.

The time interval is mainly based on the operational experience of the meter, usually six months to one year even if the meter has not been used.

3.4.2.2 *Re-proving as a function of volume*

A re-proving of the meter is also required in terms of the volume measured by the meter. The limit to this volume before re-proving is based on the experience of the meter's behaviour as indicated by the control charts.

3.4.3 Control charts and tests corresponding to any meter

The meter-factor variations of a meter from one proving to another can be used to monitor the meter.

If the following criteria are met, the meter can be used; if not, an investigation of the meter is necessary.

- a) The difference between $E_{\max}$ and $E_{\min}$ of the new calibration curve should be less than 0,5 % (see Figure 7).
- b) The difference between the old and new curves should be less than 0,1 % (see Figure 8).

3.4.4 Control charts and tests via polynomials

The meter-factor variation analysis for an individual meter is evaluated by the use of the polynomials $MF = f(Q/v)$ or with control charts (see Figure 9 and Figure 10). The following criteria should be met.

- a) The difference between $MF_{\max}$ and $MF_{\min}$ of the new calibration curve should be less than 0,5 (see Figure 9), that is:

$$200 \frac{(MF_{\max} - MF_{\min})}{(MF_{\max} + MF_{\min})} \leq 0,5$$

- b) The random uncertainty of the polynomial (see Annex E) should be less than $\pm 0,1$ %.
- c) The maximum difference calculated from the old and new polynomials should be less than 0,1 %.

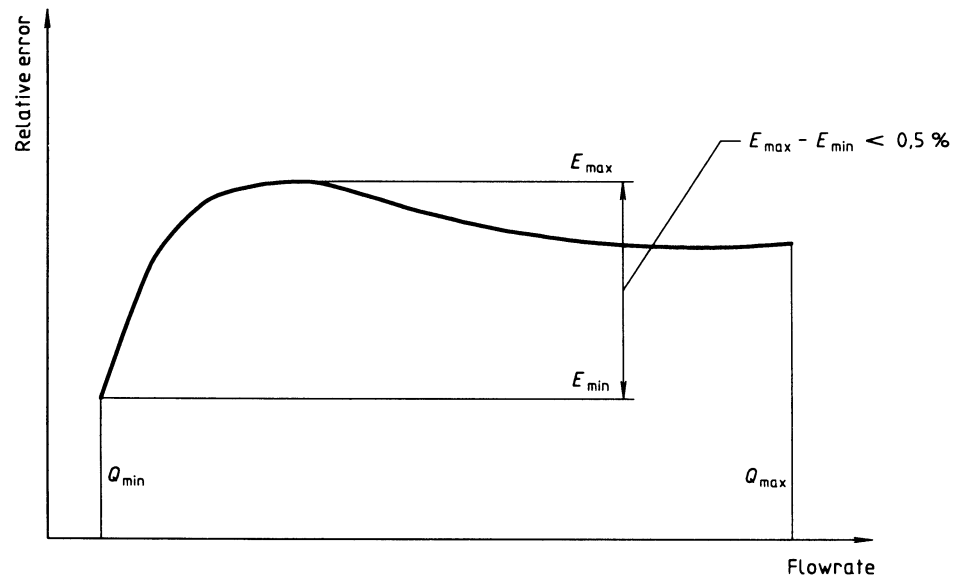


Figure 7 — Control chart No. 1

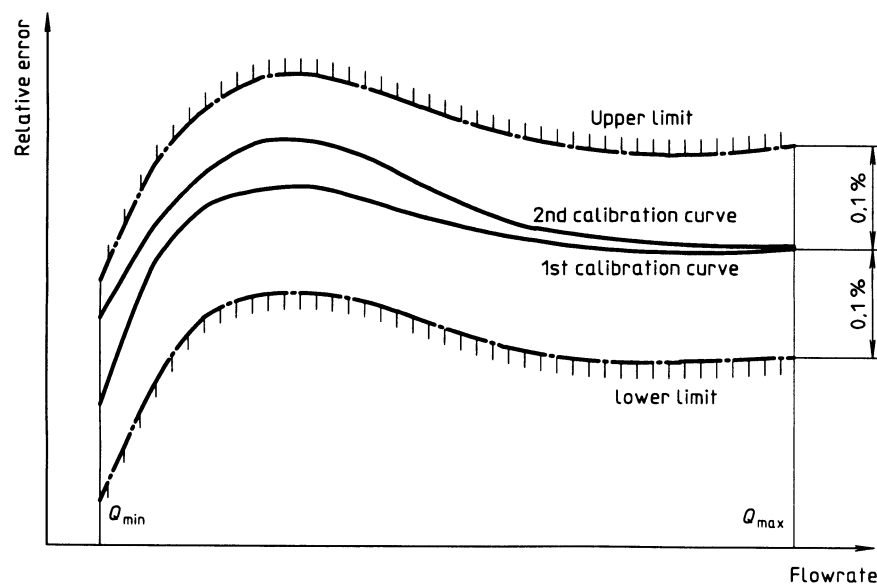
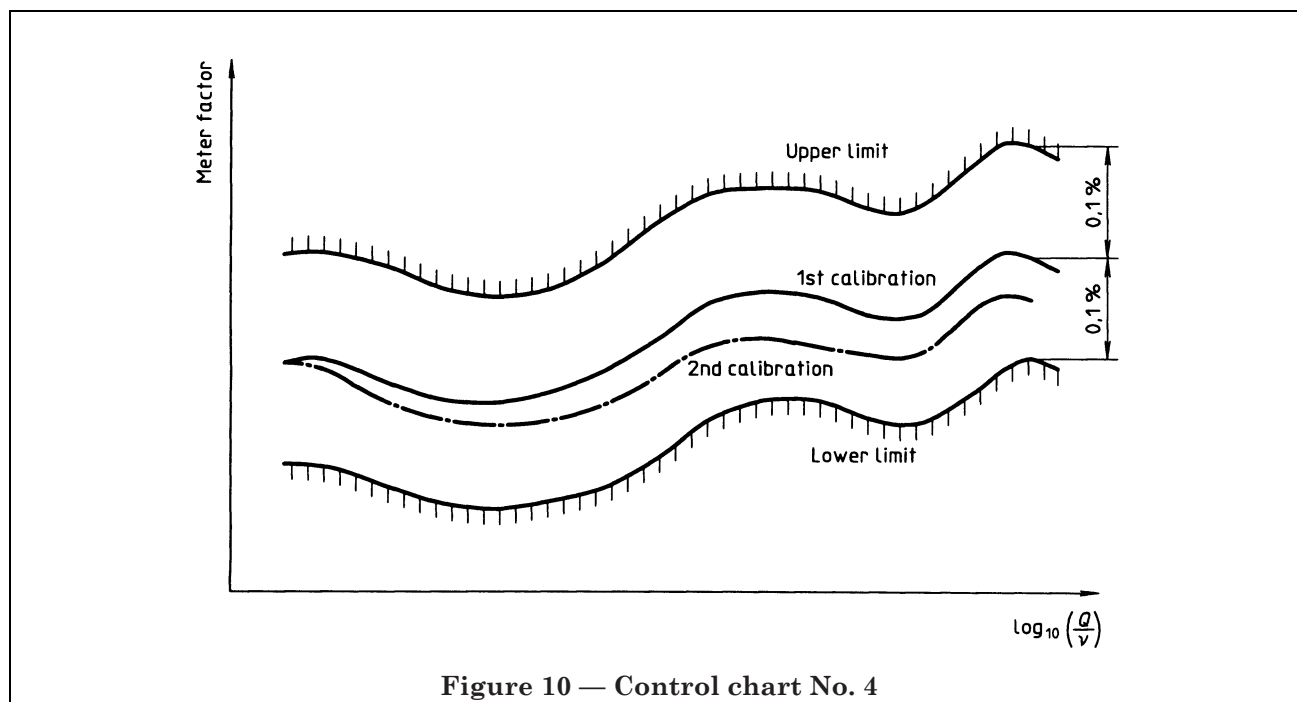
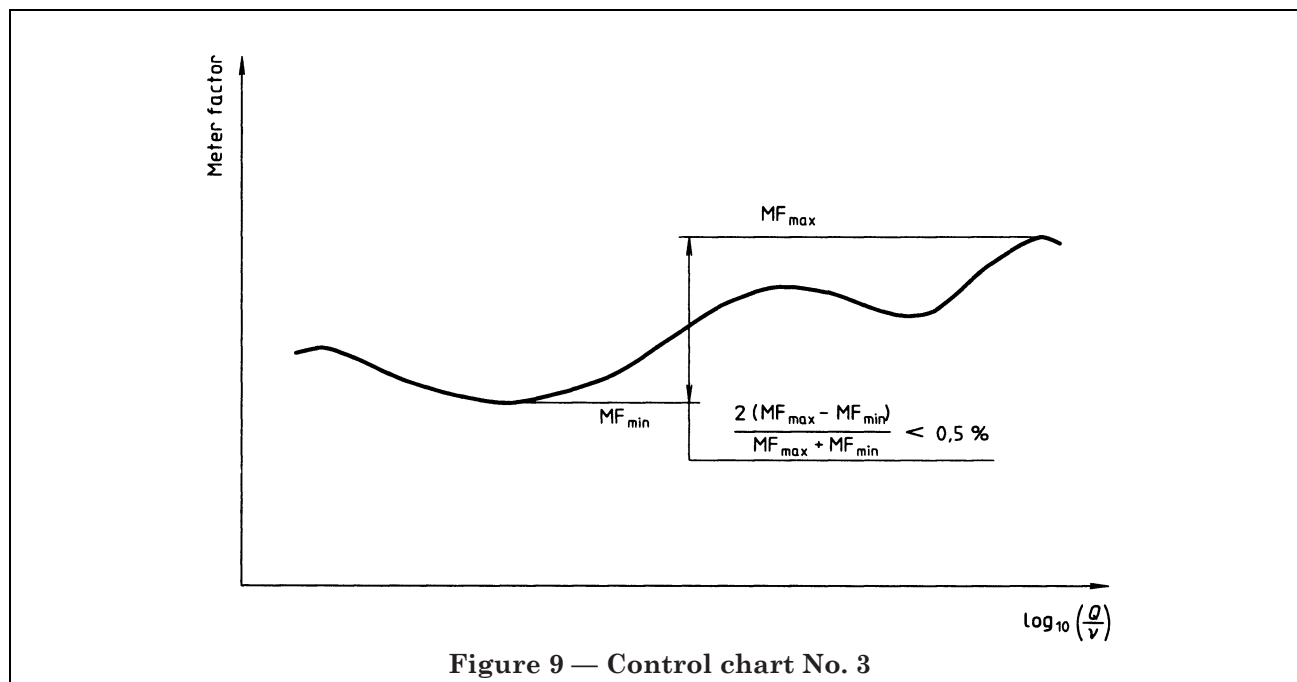


Figure 8 — Control chart No. 2



3.4.5 Control charts via direct matrix

The meter-factor variation analysis for an individual meter is made directly with the matrix. The following criteria should be met.

- See 3.4.4 a).
- The maximum difference between the old and new meter-factor values corresponding to the same inputs (Q , v) should be calculated. This difference should be less than 0,1 %.