Working paper

Role of measurement and calibration

in the manufacture of products for the global market

A guide for small and medium-sized enterprises

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna, 2006

This publication is one of a series of guides resulting from the work of the United Nations Industrial Development Organization (UNIDO) under its project entitled "Market access and trade facilitation support for South Asian least developed countries, through strengthening institutional and national capacities related to standards, metrology, testing and quality" (US/RAS/03/043 and TF/RAS/03/001). It is based on the work of UNIDO consultant S. C. Arora.

PREFACE

In the globalized marketplace following the creation of the World Trade Organization, a key challenge facing developing countries is a lack of national capacity to overcome technical barriers to trade and to comply with the requirements of agreements on sanitary and phytosanitary conditions, which are now basic prerequisites for market access embedded in the global trading system. The World Trade Organization has adopted two important agreements in these areas: the Agreement on Technical Barriers to Trade and the Agreement on Sanitary and Phytosanitary Measures (both available at http://www.wto.org). With a view to meeting this challenge, developing countries need significant technical assistance to develop institutional infrastructure related to standards, metrology, testing and quality in order to be an able partner in the global trade regime.

With a view to developing national capacity among the South Asian least developed countries, the United Nations Industrial Development Organization (UNIDO) has implemented a project entitled "Market access and trade facilitation support for South Asian least developed countries, through strengthening institutional and national capacities related to standards, metrology, testing and quality". The project was financed by the Government of India and the Norwegian Agency for Development Cooperation.

To facilitate understanding of the complex subject of standards, metrology, testing and quality, a number of small guides, as listed below, have been developed as part of the project. These guides are available free of charge to small and medium-sized enterprises and other interested users.

Role of standards

Product quality

Role of measurement and calibration in the manufacture of products for the global market

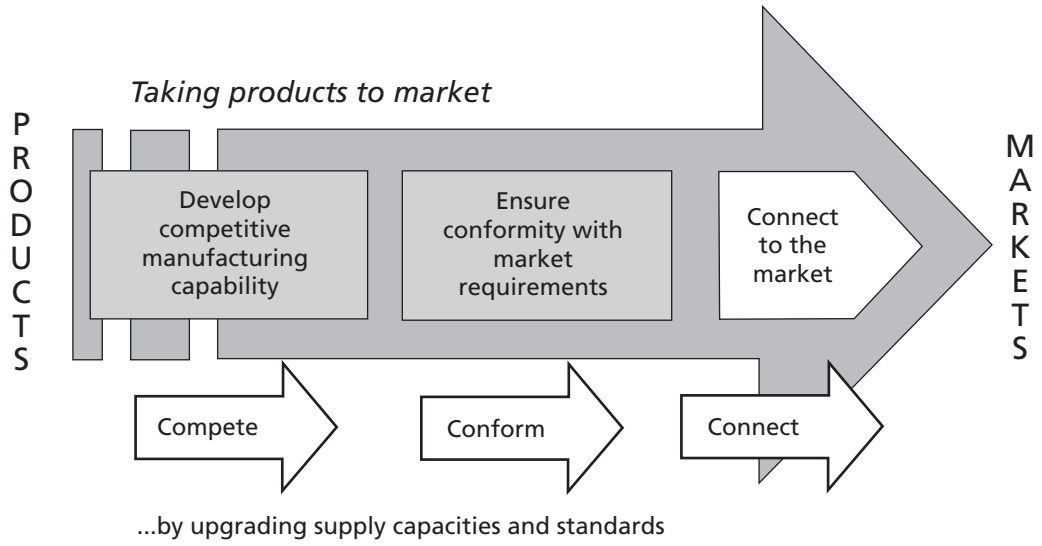
The purpose of the present guide is to assist small and medium-sized enterprises and other interested users to understand in simple terms the role of measurement and calibration in the manufacture of products for the global market. Chapter 8 of the guide also briefly covers the accreditation of testing and calibration laboratories.

UNIDO 3Cs approach addressing developing country concerns

A strategic response:

UNIDO has developed a strategic approach to help developing countries to overcome trade participation constraints and to achieve a palpable increase in exports:

- COMPETE: removing supply-side constraints and developing competitive manufacturing capability
- CONFORM: developing and ensuring product conformity with technical and market requirements
- CONNECT: enhancing integration with and connectivity to markets



COMPETITIVENESS: activities under this heading are oriented towards the removal of supply-side constraints, the promotion of the manufacture of products with high export potential and the provision of assistance related to:

- **Developing productive capacities**
  - Developing a conducive policy environment for investment and private sector development
  - Identifying key export areas facing supply-side constraints and value chain analysis
  - Upgrading industrial structures and mechanisms for value addition
  - Advising on product design, technology, upgrading and quality control
  - Establishing technology support institutions to improve technology acquisition
  - Improving business efficiency and performance, especially quality management
  - Introducing energy-saving, cleaner technologies, minimizing waste and utilizing by-products

- **Enhancing capacity to meet international standards and client quality and safety requirements**
  - Introducing a legal framework for consumer protection
  - Ensuring access to requirements via WTO enquiry points
  - Advising on food safety requirements, HACCP, TBT/SPS requirements, ISO 9001/14001
  - Ensuring compliance with labelling and packaging requirements
  - Introducing SME subcontracting and partnership exchanges

CONFORMITY: activities under this heading are oriented towards promoting conformity with market requirements and securing a larger share in export markets, focusing on:

- **Upgrading conformity assessment infrastructure**
  - Establishing the requisite legal and regulatory framework for conformity
  - Establishing recognized standards, accreditation, certification and inspection schemes
  - Developing internationally recognized and harmonized conformity structures
  - Upgrading laboratories and supporting international accreditation
  - Establishing international calibration chains for measurement and precision manufacture

- **Creating an environment conducive to export promotion**
  - Creating an enabling environment for foreign direct investment
  - Establishing national investment promotion agencies
  - Developing export support policy and export promotion infrastructure
  - Introducing export support services and trade information services
  - Linking to global supply chains and export consortia and cluster development

CONNECTIVITY: activities under this heading are carried out in cooperation with other agencies and oriented towards supporting developing countries in their efforts to acquire the technological and institutional capacities they need to implement WTO agreements and participate fully in the new rules-based trading system. The focus is on:

- **Integrating with the international trade framework and rules**
  - Sensitizing developing countries to WTO rules and facilitating WTO accession
  - Enhancing negotiating capacities and promoting policies for the settlement of disputes
  - Adhering to notification requirements

- **Harmonizing customs procedures and transport mechanisms**
  - Improving port and harbour operations and handling procedures
  - Streamlining registration and documentation requirements
  - Improving pre-shipment inspection and facilitating customs clearance

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OCCASION

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The later years

English foot-pound-second system

An Anglo-Saxon system of measurement was originally followed in England until the Norman Conquest in 1066. At that time, length was the main unit of measurement being used. For short lengths, barleycorn and the inch were used as units. The inch was originally defined as 3 grains of barleycorn laid end to end, or as the width of a thumb. It is interesting to note that in many languages, the word for inch was also the word for thumb. For measuring longer lengths, such as for measuring land, the *gyrd* (or rod) was used. This was equal to 20 "natural feet".

Before the Norman Conquest, volume measures such as the *amber*, *mitta*, *sester* and *coomb* were used in England. It is possible that the amber was close in volume to the Roman amphora of 6 gallons, but these early measures are not known to any level of accuracy and some of them varied with the product being measured. The English system of weights and measures was influenced greatly by the Romans and, through them, the Greeks. The roman-based measurement system was introduced after the Romans conquered England, from the middle of the eleventh century. However, in England units of measurement were not properly standardized until the thirteenth century. Even then, three different measures of a gallon (for ale, wine and corn) were standardized only in 1824.

The foot-pound-second system of units was a scheme for measuring dimensional and material quantities. The fundamental units were the foot (ft) for length, the pound (lb) for weight and the second (s) for time.

One foot represents a length of 12 inches; it was originally approximately equal to three hand widths or two thirds of a cubit. Today, however, a foot is considered to be 0.3048 metres, where the metre (m) is the fundamental unit of length in the international system of units.

One pound is the force that produces an acceleration of 32.1740 ft per second squared (32.1740 ft/s^2) when applied against a known standard mass. The acceleration of 32.1740 ft/s^2 is approximately the value of the earth's gravitational acceleration at a latitude of 45 degrees north.

As the years went by, the foot-pound-second system of measurement slowly lost ground against the metric system. Although the United Kingdom of Great Britain and Northern Ireland and the United States of America were following the FBS system, they found that more and more countries were adopting the metric system. This started creating technical problems for them in the field of international trade. Gradually, these two States also decided to adopt the metric system. However, although adopted in law, a portion of trade and industry in both these States still follows the old foot-pound-second system.

French metric system

In 1790, in the midst of the French Revolution, the National Assembly of France requested the french academy of sciences to "deduce an invariable standard for all the measures and all the weights".

The unit of length decided upon was the metre. This name was derived from the Greek word *metron*, meaning a measure. The metre was defined as being one ten-millionth part of a quarter of the earth's circumference. Measures for capacity (volume) and mass were to be derived from the unit of length. Thus, a system evolved in which the basic units of the system were related to each other. It was also decided that the larger and smaller versions of each unit were to be created by multiplying or dividing the basic units by 10 and its powers. Calculations in the metric system could therefore be performed simply by shifting the decimal point. Thus, the metric system was a "base-10" or decimal system. The weight of three cubic decimetres of distilled water at 4°C was adopted as the kilogram (kg). The litre was defined in terms of the kilogram.

The metric system, however, was not initially accepted with much enthusiasm. However, after France made its use compulsory in 1840, adoption by other States occurred steadily. The standardized character and decimal features of the metric system made it well suited to scientific and engineering work. Consequently, by an act of Congress in 1866, the United States made it "lawful throughout the United States of America to employ the weights and measures of the metric system in all contracts, dealings or court proceedings."

In 1875, an international treaty—the Convention of the Metre—set up well-defined metric standards for length and mass and established a permanent machinery to recommend and adopt further refinements in the metric system. A total of 17 States, including the United States, signed the Convention, which is also known as the Metre Convention. By 1900, a total of 35 States, including the major nations of continental Europe and most of South America, had officially accepted the metric system.

In the metric system, initially the centimetre was the unit of length while the gram was the unit of mass and the second was the unit of time. Thus, the early metric system was also known as the CGS system of units. For industry and trade, however, the units were MKS, standing for metre, kilogram and second.

The Metre Convention established the General Conference on Weights and Measures as the permanent machinery to maintain and improve upon the metric system. The Conference is an assembly of delegates from all the States that have signed the Metre Convention. The first meeting of the Conference was held in 1889 and it continues to be held once every four to six years.

The present world

The constant endeavours of the General Conference on Weights and Measures to improve upon the metric system resulted in the addition of further units of measurement. The ninth Conference, held in 1948, added the ampere (a) as the fourth unit

in the metric system, which then came to be known as MKSA system. In 1954, the tenth Conference defined two more units, the kelvin (k) as the base unit of thermodynamic temperature and the candela (cd) as the base unit of luminous intensity. Thus, the era of the International System of Units comprising the metre, kilogram, second, ampere, kelvin and candela began.

The eleventh Conference, held in 1960, redefined the metre in terms of wavelengths of light. It also gave the new metric system the official symbol of SI, taken from the French (Système international d' unités), as the International System of Units of measurement.

Finally, the fourteenth Conference, held in 1971, added a seventh base SI unit, the mole (mol), as the unit of the amount of substance. Thus, the present modern version of the SI metric system has seven base units, from which all other units of measurement are derived. The seven base units are defined in chapter 3 under the section entitled "Absolute standards".

With scientific and technological advancement over the years, the definition of these seven base units has been changing. Today, only the kilogram remains a unit based on an artefact or a physical object, the prototype kilogram kept near Paris. All the other units are defined in terms of wavelength and time, which can be measured and reproduced with a high degree of accuracy and precision.

References

1. National Standards Commission, Australia, Leaflet No. 6 (October 2002).

2. General information section of the website of the Department of Weights and Measures, Brockton, Massachusetts, United States of America.

3. National Institute of Standards and Technology, United States of America, *Specifications, Tolerances, and Other Technical Requirements for Weighing and Measuring Devices* (Handbook No. 44, 2002 Edition), available from http://www.nist.gov.

4. Website of the General Conference on Weights and Measures at http://www.bipm.fr/en/convention/cgpm/.

2 SELECTION OF MEASURING INSTRUMENTS

The measuring instrument is the most important part of the measurement process and the selection of the instrument therefore has to be done carefully. If the selection is not correct, the result of the measurement may give a wrong indication, thereby leading to an incorrect decision.

Selection criteria

The selection of measuring instruments depends on the measurement to be performed. Generally, three characteristics are considered; these are:

- The range and magnitude of the parameter to be measured and the accuracy of the measurement (the instrument should have the range to cover effectively the range of the parameter).

- The resolution of the measuring instrument should be smaller than the minimum unit of measurement of the parameter.

- Lastly, and most importantly, the accuracy or uncertainty of the measuring instrument should comply with the accuracy requirement of the parameter to be measured.

For example, if a process temperature of 100°C is being measured, the range of the temperature indicator should be such that it can measure not only 100°C, but also temperatures above and below that value. Suppose the following thermometers are available:

(a) 0-99°C *(b)* 0-199°C *(c)* 0-99.9°C *(d)* 0-199.9°C

From the range specification it is clear that the thermometers at *(a)* and *(b)* have a resolution of 1°C, while those at *(c)* and *(d)* have a resolution of 0.1°C. For measurement of the above parameter, i.e. 100°C, the thermometers at *(a)* and *(c)* above are not suitable, since these do not have the required range. The choice is therefore between *(b)* and *(d)*. This would again depend on the tolerance specified for the task. If the tolerance is ± 1°C, then the thermometer at *(d)* above should be selected. If, on the other hand, the parameter to be measured is 100° ± 10°C, then the thermometer with a range of 0-199°C would be sufficient for the measurement.

The third important criterion for the selection of a measuring instrument is the accuracy of measurement. The following table indicates the accuracy:

Parameter to be measured	*Accuracy of measurement*
100° ± 10°C	± 3°C
100° ± 1°C	± 0.3°C

The selected thermometer, when calibrated, should exhibit an accuracy that complies with the desired accuracy of measurement as demonstrated above. Alternatively, if the supplier of the thermometer provides a valid calibration certificate, the selection is easier.

From the above explanation, it is clear that unless the parameter to be measured is adequately defined, it is not possible to make a proper selection of the measuring instrument.

Understanding accuracy in measurement

In order to select the correct measuring instrument, the implications of instrument accuracy on the measurement data and the effect it has on decisions taken based on the data must be clearly understood.

If the accuracy of a measuring instrument is ± 1, this means that the value displayed on the instrument would be considered the correct value so long as the actual value of the measurement is within ± 1 of the actual value. In other words, if 10 is the reading displayed on a measuring instrument while making a measurement and if ± 1 is the accuracy of that instrument, then the actual value could be anywhere between 9 and 11, including either 9 or 11. Thus, the expanded value of the measurement can be considered as 11. Instead of direct algebraic addition, however, a better projection is that instead of 11, the expanded value is $\sqrt{(10^2 + 1^2)} = \sqrt{(101)} = 10.05$. Thus, the original value of 10 has now been expanded to 10.05. This is based on the statistical theory of root sum squares.

So now, instead of 11, the original value becomes 10.05 based on the accuracy of the measuring instrument. Thus, the expansion of 10 to 10.05 works out to $100 \times (10.05\text{-}10)/10 = 0.5$ per cent. It is therefore clear that when a ratio of 10:1 is maintained, the original value undergoes an expansion of 0.5 per cent in its magnitude.

Thus, if the specified tolerance on a parameter is 10 and the measuring instrument used to perform that measurement has an accuracy of 1, then the tolerance would undergo an expansion of 0.5 per cent. It would now become 10.05. So, even if all the readings are within the tolerance of 10, we run a risk of 0.5 per cent for false acceptance or false rejection, in particular for those readings which are on the borderline of the tolerance level.

Similarly, if the specified tolerance level on a parameter is 4 and the measuring instrument has an accuracy of 1, then the effect on the tolerance based on the root sum square principle is $\sqrt{(4^2 + 1^2)} = \sqrt{(17)} = 4.123$, and the percentage expansion of the tolerance becomes $100 \times (4.123\text{-}4)/10 = 3.1$ per cent.

In the same manner, it can be shown that when this ratio is 3:1, the effect on the tolerance is 5.4 per cent. The international standards set out in International Organization for Standardization ISO 10012 and American National Standards Institute/National Conference of Standards Laboratories of America ANSI/NCSL Z540-1-1994 state that this effect of accuracy on the measurement results should be as small as possible. It should preferably be one tenth, but should not be more than one third. This is mainly because a risk of up to about 6 or 7 per cent is considered small. However, when this ratio becomes small, the effect or the risk becomes quite large.

For example, when this ratio is 2:1, the expanded tolerance and hence the risk becomes 11.8 per cent. If the ratio is 1:1, the risk becomes 41.4 per cent.

Thus, it is advisable to maintain a ratio of 3:1 when selecting a measuring instrument.

A few examples

Example 1. Measurement of pressure (in kilograms of force per square centimetre)

	Parameter to be measured	*Pressure gauge selected*
Range	7.5 ± 1.0 kgf/cm^2	0 – 10.0 kgf/cm^2
Resolution	Preferably 1/10 of the tolerance	0.1 kgf/cm^2
Accuracy	Minimum 1/3 of the tolerance	± 0.25 kgf/cm^2

Example 2. Measurement of piston diameter

	Parameter to be measured	*Micrometer selected*
Range	17.75 ± 0.05 mm	0 – 25.000 mm
Resolution	Preferably 1/10 of the tolerance	0.001 mm
Accuracy	Minimum 1/3 of the tolerance	± 0.004 mm

While for effective measurement resolution of the measuring instrument should theoretically be one tenth of the tolerance and the accuracy of the instrument should be a minimum of one third of the tolerance, in practice selection is done based on what is generally available in the market. The selection of the instruments shown in the above examples is based on that consideration.

More on instrument selection

Selection criteria, as mentioned above, should generally be followed when procuring new instruments. However, in many cases the measuring instruments are already available. In such situations, action as described below should be taken.

(a) First, the parameter being measured should be examined to check whether the tolerance and the accuracy have been stated. Next, the measuring instrument should be checked to see whether the range and the resolution are appropriate for the measurement. Lastly, the accuracy of the instrument should be checked to see whether it satisfies the specified requirement. In cases where the accuracy of the measurement is

not specified, the instrument's accuracy should be examined to see if it is better than one third of the tolerance. If it is, then the instrument selection was appropriate.

(b) If, however, the measuring instrument's accuracy is more than one third of the tolerance of the parameter, then either of the following actions should be taken:

(i) Replace the instrument with an appropriate one, if the present system of measurement is affecting the quality of the product resulting in rejection or rework at the subsequent stage of production;

(ii) Review the specified tolerance if the existing measurement system does not affect the product quality. This means that perhaps the close tolerance specified is not needed and hence the tolerance could be increased to accommodate the accuracy of the instrument.

References

1. International Organization for Standardization, "Measurement management systems: requirements for measurement processes and measuring equipment" (ISO 10012:2003).

2. American National Standards Institute/National Conference of Standards Laboratories, "Calibration laboratories and measuring and test equipment: general requirements" (ANSI/NCSL Z540-1-1994).

3 CALIBRATION OF MEASURING INSTRUMENTS

The need for calibration

Measurement is vital in science, industry and commerce. Measurement is also performed extensively in our daily life. The following are some examples:

- Measurements for health care, such as measuring body temperature with a clinical thermometer, checking blood pressure and many other tests;
- Checking the time of day;
- Buying cloth for dresses;
- Purchase of vegetables and other groceries;
- Billing of power consumption through an energy meter.

Accuracy and reliability of all such measurements would be doubtful if the instruments used were not calibrated. Calibration ensures that a measuring instrument displays an accurate and reliable value of the quantity being measured. Thus, calibration is an essential activity in any measurement process.

What is calibration?

According to the International Organization for Standardization publication entitled *International Vocabulary of Basic and General Terms in Metrology* (published in 1993 and known as VIM), calibration is the set of operations that establish, under specified conditions, the relationship between values indicated by a measuring instrument, a measuring system or values represented by a material measure, and the corresponding known values of a measurand (the parameter that is being measured; see also chapter 9 below for a fuller explanation of the term "measurand").

Understanding of calibration is not complete without understanding traceability. In the above definition, the known values of the measurand refer to a standard. This standard must have a relationship vis-à-vis the calibration.

> *Traceability: The concept of establishing valid calibration of a measuring standard or instrument by step-by-step comparison with better standards up to an accepted national or international standard.*

Essentially, calibration is a comparison with a higher standard that can be traced to a national or international standard or an acceptable alternative.

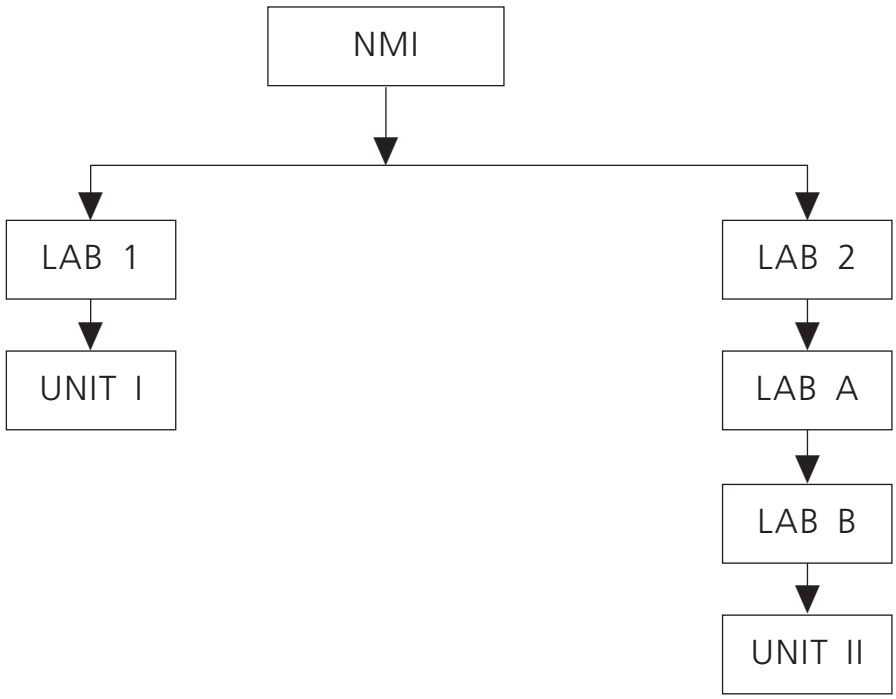
Measurement traceability

In most cases, we compare two or three measurements of the same parameter to check reliability and reproducibility of the measurement. A measurement must be traceable to the acceptable standard for it to be compared. Even if it is a single measurement, traceability of the measurement is still very important.

A measuring instrument's reading should be accurate in terms of the physical unit of measurement. The physical unit of measurement, in turn, should be traceable to the ultimate fundamental unit through calibration.

The following diagram gives an example of a traceability chain.

Figure I. Traceability chain



In the above case, unit 1 has had its measuring instruments calibrated by laboratory 1, whose master standards have been calibrated by the National Measurement Institute (NMI) of the country. Unit 2, on the other hand, has had its measuring Instruments calibrated at laboratory B, which has had its standard calibrated from laboratory A. Laboratory B's standards have traceability to the NMI through laboratory A and laboratory 2. Thus, both unit 1 and unit 2 have traceability to the NMI. However, error in the measurement process leading to calibration of the measuring instruments of unit 1 and unit 2 as a result of the traceability factor would be different. While there is no restriction on the number of steps that can be taken in the traceability chain,

uncertainty in measurement becomes the limiting factor. Chapter 4 provides more detail on this subject of uncertainty.

What is a standard?

> *Standard: A standard is a material measure or physical property that defines or reproduces the unit of measurement of a base or derived quantity.*

However, a standard also needs to be checked against a higher standard to establish its accuracy and traceability. Since the same argument would hold good even for the higher standard, this hierarchy of standards must lead to a level above which comparison is not possible.

Hierarchy of standards

The comparison of standards stops with the absolute or fundamental standard. Once that fact is understood and accepted, it is not difficult to ensure comparison of the next-level standards.

> *Fundamental or absolute standard: One whose value has been established without recourse to another standard of the same quantity.*

> *International standard: One recognized by international agreement as the basis for fixing the values of all other standards of the given quantity.*

> *National or primary standard: One which establishes the value of all other standards of a given quantity within a particular country.*

> *Secondary standard: One whose value has been established by comparison with a primary standard.*

> *Working standard: A secondary standard used to verify measuring instruments in places such as factories, shops, etc.*

By international agreement reached amongst the various standardization bodies of the world, there are seven absolute standards. These are:

Quantity	*Unit*	*Symbol*
Length	Metre	m
Mass	Kilogram	Kg
Time	Second	s
Electric current	Ampere	A
Temperature	Kelvin	K
Substance	Mole	mol
Luminous intensity	Candela	cd

In addition, there are two supplementary standards, which are:

Quantity	*Unit*	*Symbol*
Plane angle	Radian	rad
Solid angle	Steradian	sr

All the other standards are derived from the base units. Some of these are listed below:

Quantity	*Unit*	*Symbol*	*Formula*
Frequency	Hertz	Hz	S^{-1}
Force	Newton	N	$M.kg/s^2$
Pressure	Pascal	Pa	N/m^2
Energy	Joule	J	Nm
Power	Watt	W	J/s
Electric potential	Volt	V	W/A

Sandards, however, do not exist for many parameters. While some of these are engineering parameters, a large number of parameters are concerned with chemical and pharmaceutical measurements. In such cases, valid calibration is performed against reference standards, reference material, certified reference material or consensus industry standards. These alternative standards are explained below.

Reference standard: the best locally available standard from which measurements made at a location are derived.

Reference material: material sufficiently homogeneous and stable with respect to one or more specified quantities, used for the calibration of a measuring system, for the assessment of a measurement procedure, or for assigning values and measurement uncertainties to quantities of the same kind for other materials. A reference material can be in the form of, for example, a pure or mixed gas, in liquid, solid or suspension form.

Certified reference material: reference material accompanied by an authenticated certificate, having for each specified quantity a value, measurement uncertainty and stated metrological traceability chain.

Absolute standards

Definitions of the seven absolute standards are given below. The year within parentheses indicates the last revision or the agreement date.

Second (1967): The duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom.

Metre (1983): The length of the path travelled by light in vacuum during the time interval of 1/299792458 of a second.

Ampere (1948): The constant current that, if maintained in two straight parallel conductors of infinite length and of negligible cross-section, and placed 1 metre apart in a vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newtons per metre of length.

Kilogram (1901): The mass of the international prototype, which is in the custody of the International Bureau of Weights and Measures at Se'vres, near Paris.

Kelvin (its 90): The fraction 1/273.16 of the thermodynamic temperature of the triple point of water.

Candela (1979): The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 1012 hertz and has a radiant intensity of 1/683 watt per steradian in that direction.

Mole (1971): The amount of substance of a system which contains as many elementary entities as there are atoms in 0.12 kilogram of carbon atom.

More about calibration

Calibration fulfils two objectives:

- It determines accuracy of the measured data
- It provides traceability to the measurement

Calibration: Calibration is essentially the comparison, under specified conditions, with a higher standard, which is traceable to a national or international standard, or an acceptable alternative.

A higher standard means:

- A higher accuracy/uncertainty
  (a ratio of 10:1 is preferable, but it should not normally be less than 3:1.)
- A better resolution
  (the standard's resolution should preferably be better by a 10:1 or 5:1 or 2:1 ratio.)

The ratio mentioned above refers to the test accuracy ratio. The ratio should be as large as economically viable since the higher this ratio, the lesser is the measurement decision risk.

Test accuracy ratio:

$$TAR = \frac{\textit{Uncertainty of unit under calibration}}{\textit{Uncertainty of standard}}$$

In accordance with ISO 10012:2003, the test accuracy ratio should be ≥ 3:1, while ANSI/NCSL Z540-1-1994 specifies this ratio as ≥ 4:1. The test accuracy ratio today is commonly known as the test uncertainty ratio, since accuracy is considered a qualitative measure and not a quantitative one. Thus, instead of quantifying the accuracy of a measuring instrument, we use the term uncertainty to quantify this parameter. However, for ease and convenience of understanding, the term accuracy will be used in this publication.

Some examples of calibration of common parameters

Measuring instruments for common parameters are the micrometer, the voltmeter, the pressure gauge, the temperature indicator, the weighing balance, the volumetric flask, etc. Brief methods of calibration of some of these instruments are described below.

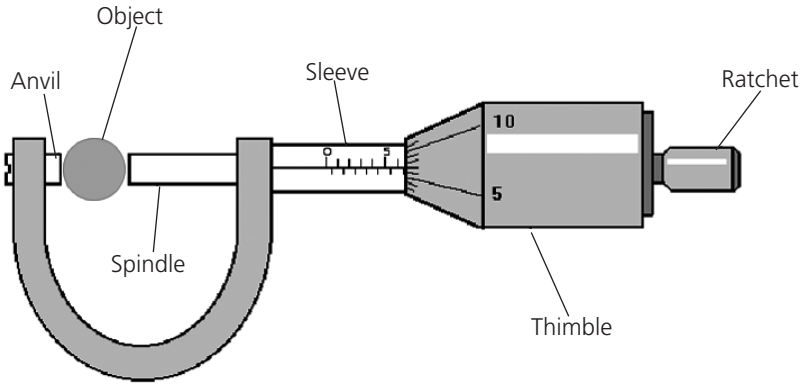
External micrometer

An external micrometer of a range of 0-25 mm with a resolution of 0.01 mm is shown below. The size of an object is measured on the scale together with the vernier scale readings of the thimble. Although checking of the scale accuracy is the main calibration parameter, there are three other parameters as well. These are:

- "Zero" error with the micrometer in the fully closed position;
- Flatness of the measuring surfaces, i.e. of the anvil and the spindle;
- Parallelism between the measuring surfaces.

Flatness and parallelism are checked with the help of calibrated optical flat and optical parallel devices using a monochromatic light source. Error of measurement is checked at 10 points using calibrated slip gauges.

Figure II. External micrometer



The table below shows the requirement of a micrometer generally specified in international standards.

Parameter	*Requirement (microns)*
Flatness of measuring surfaces, i.e. anvil and spindle	1.0 (maximum)
Parallelism of measuring surfaces, i.e. between the anvil and the spindle	± (2 + A/50)
Zero error	± (2 + A/50)
Error of measurement	± (4 + A/50)

Note: "A" equals the lower limit of the measuring range in mm; for a 0-25 mm size micrometer, A=0. Calibration points for checking error of measurement in a micrometer are fixed. These are: 2.5, 5.1, 7.7, 10.3, 12.9, 15.0, 17.6, 20.2, 22.8 and 25.0 mm. Irrespective of the micrometer size, these calibration points remain the same. Micrometers can also have digital readouts, but the method of calibration would be the same as described above.

Voltmeter

Voltmeters can use alternating or direct current and can be analogue or digital. Generally, calibration of these meters is done by injecting a known or a programmed quantity from a standard source at a few points covering the entire range of the voltmeter. These standard sources, in turn, are calibrated from a higher-level laboratory with traceability to national or international standards. During calibration, the standard input is varied to the readability of the unit under calibration. This is because the standard has a better resolution than the unit. The difference between the standard input and the value shown on the unit under calibration is the error or uncertainty of the measuring instrument.

Pressure gauge

Pressure gauges can be calibrated by two methods. In the first method, a dead weight tester is used, where a pressure is first created through the piston and cylinder arrangement and then the same is balanced against calibrated weights. In this method, the balanced pressure is required to be corrected for the effect of:

- Acceleration due to gravity ("g");
- Temperature;
- Air buoyancy.

In the second method, a pressure comparator is used in which a standard pressure gauge and the unit under calibration are connected in series, so that at any given pressure the readings of both the gauges can be observed.

In both cases, pressure at a certain point should be allowed to stabilize for 5 to 10 minutes before noting the readings.

Temperature indicator

A temperature measuring system normally comprises:

- A sensor/thermocouple;
- A compensating cable;
- An indicator/scanner.

It can also be a composite unit such as a mercury-in-glass or an alcohol thermometer. In both cases, calibration consists of creating a stable temperature through a heating source and comparing the temperature reading of the unit under calibration and a standard thermometer. The heating unit could be a constant temperature bath or a dry block, having openings for insertion of the standard thermometer and the unit under calibration. The stability of the heating unit is very important. First, it should be ensured that the constant temperature bath or the dry block furnace gives stable readings on the master or standard temperature indicator. Thereafter, the stability of the unit under calibration should be checked. Readings at different calibration points should be taken only after this has been done.

Volumetric flask

Calibration is done by weighing the volume of distilled water contained in the flask and then estimating the volume from the known value of the density of distilled water. However, for proper calibration, the effect of temperature on densities of water, air and balance weights should be considered. Also, the calibration results for volume are normally reported at a standard temperature of 20°C, for which the coefficient of thermal expansion of water is used for correction.

The volume of the flask is given by:

$$V_{20} = (I_L - I_E)\ Z$$

Where:

V_{20} = volume at 20°C
I_L = weight of weighing flask with water
I_E = weight of empty weighing flask
Z = factor that depends on the density of the air, the density of the water and the balance weight
= approximate unity under normal barometric pressure

Since the weights are taken at a temperature of T°C, correction is applied to bring the same to 20°C.

$V_T = V_{20} [1 + \alpha (T - 20)]$

Where:

V_{20} = Volume at 200°C
V_T = Volume at T°C
α = Coefficient of volume expansion of water

For commonly used borosilicate glass: $V_T = V_{20} [1+ 0.00001 (T - 20)]$
For soda-lime glass: $V_T = V_{20} [1+ 0.000025 (T - 20)]$

From the above formulae, the volume at T°C can be calculated.

Calibration in analytical measurements

In analytical chemistry, calibration has two components:

- Calibration of measuring instruments;
- Calibration of the analytical method.

Calibration of measuring instruments is performed and measurement traceability is established to SI units in the manner explained above for thermometers, volumetric flasks, etc.

The value indicated by a measuring instrument in an analytical method could be, for example:

- The optical density of an atomic absorption spectrophotometer;
- The intensity of current delivered by a flame photometer;
- The integral of a peak in arbitrary units for a high pressure liquid chromatograph.

The above signal cannot be related directly by calculation to the concentration of the entity assayed. It is determined from the relationship of the concentration versus the signal given by a certified reference material. In the absence of a certified reference material, a reference material with an assigned value reached by consensus can be used. (certified reference material was defined above under section “Hierarchy of standards”.)

Some of the available sources of certified reference materials for different applications are listed below. The list is not, however, comprehensive.

- National Institute of Standards and Technology, United States (http://www.nist.gov)
- Laboratory of Government Chemists, United Kingdom (http://www.lgc.co.uk)

- National Physical Laboratory, India (http://www.nplindia.org)

- The New Brunswick Laboratory is the United States federal certifying authority for nuclear reference materials (http://www.nbl.doe.gov/htm/crm.htm)

- The Sigma-Aldrich Group, Germany, the United States and the United Kingdom (Sigma, Aldrich, Fluka, Supelco, Riedel-de Haën) for reference material used in analytical chemistry (http://www.sigmaaldrich.com/Brands/Fluka_Riedel_Home/Analytical/Certified_Reference_material/EMPA_BAM.html)

- SPEX CertiPrep certified reference materials (e-mail at CRMSales@spexcsp.com)

- Starna® products, from Optiglass Limited, the United Kingdom (e-mail at starnabrand@optiglass.co.uk)

Deciphering a calibration certificate

When a calibration certificate is received, it should be checked and assessed in the manner described below before using the instrument for measurement. Such checking should be performed on a certificate received for an existing instrument that has been sent for calibration or when buying a new instrument.

- First the certificate must correlate with the instrument. This is confirmed through matching the serial or identification number of the instrument with the number on the certificate.

- Then, the instrument's range and resolution must be examined to see whether these fulfil the measurement requirements. For example, to make a measurement of temperature of 160.5°C, the range of the measuring instrument should be 0 to 199.9°C. The resolution of the instrument should be 0.10°C

- The next parameter to be checked is the instrument's accuracy. The accuracy of the instrument or the maximum error reported on the certificate should meet the specified required accuracy of the measurement. However, when checking the accuracy of the instrument, the uncertainty of measurement should be considered. For example, if the required accuracy of measurement is ± 1.50°C, then the maximum error reported on the certificate plus the measurement uncertainty should be within that value. If the accuracy of the instrument or the maximum error is stated as ± 1.20°C, the uncertainty of measurement associated with this value must be added. As long as the stated uncertainty of measurement on the calibration certificate is $\leq$ 0.30°C in this case, the instrument is considered to comply with the accuracy requirement.

- From the above, it is clear that if the measurement uncertainty is not stated on the calibration certificate, no judgement can be made about the suitability of the instrument.

Using the knowledge

Understanding calibration and traceability can help individuals in many ways. Some of these are mentioned below:

- Manufacturing organizations using measuring instruments will better understand the need for calibration and would be able to perform some of the minor calibrations in-house.

- When an organization is outsourcing its calibration, it would be able to ensure that such calibrations are performed correctly by monitoring the test accuracy ratio.

- Where standards traceable to SI units are not available, organizations could work towards ensuring traceability of their measurements to either a certified reference material or a reference material. Calibrations for instruments performing analytical measurement would be carried out against these materials.

- A person working in a laboratory that is preparing for accreditation under ISO/IEC 17025, would be able to appreciate the importance of traceability and could work towards ensuring traceability of all the measurements being performed.

References

1. International Organization for Standardization, *International Vocabulary of Basic and General Terms in Metrology*, 2nd ed. (1993).

2. International organization for Standardization, "Measurement management systems: requirements for measurement processes and measuring equipment" (ISO 10012:2003).

3. American National Standards Institute/National Conference of Standards Laboratories, "Calibration laboratories and measuring and test equipment: general requirements" (ANSI/NCSL Z540-1-1994).

4 RELIABILITY OF MEASUREMENT

Whenever measurements are made, it is with the objective of generating data. The data is then analysed and compared with requirements so that an appropriate decision can be taken, such as to accept, rework or reject the product. However, unless the measurement data is reliable, decisions based on such data cannot be reliable either. Consequently, these actions contribute enormously to the cost of quality a manufacturer has to bear.

Characteristics of data reliability

For measurement data to be reliable, measurement should be:

- Accurate
- Precise
- Reproducible

> *Accuracy: The closeness of the agreement between the result of a measurement and a true value of the measurand.*

For example, when the accuracy of a micrometer with a range of 0-25 mm and a least count of 1 µ is stated as ± 4 µ, it means that if this micrometer gives a reading of 20.255 mm, the actual or true value of the measurand can be 20.255 mm ± 4 µ, i.e. between 20.251 and 20.259 mm.

> *Precision: The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. Precision is also called repeatability.*

For example, if the above micrometer is used to measure the diameter of a steel pin a number of times at a certain point and the values of 20.253, 20.252, 20.250, 20.251 mm are obtained, then the precision or the repeatability of the measurement can be stated as 0.003 mm (20.253 – 20.250 mm).

> *Reproducibility: The closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.*

For example, if the above steel pin is measured for its diameter at three different locations (at the shop floor, at the laboratory and at the customer's premises) and if the values obtained are 20.255, 20.251 and 20.260 mm, then the reproducibility of the measurement can be stated as 0.009 mm (20.260 – 20.251 mm).

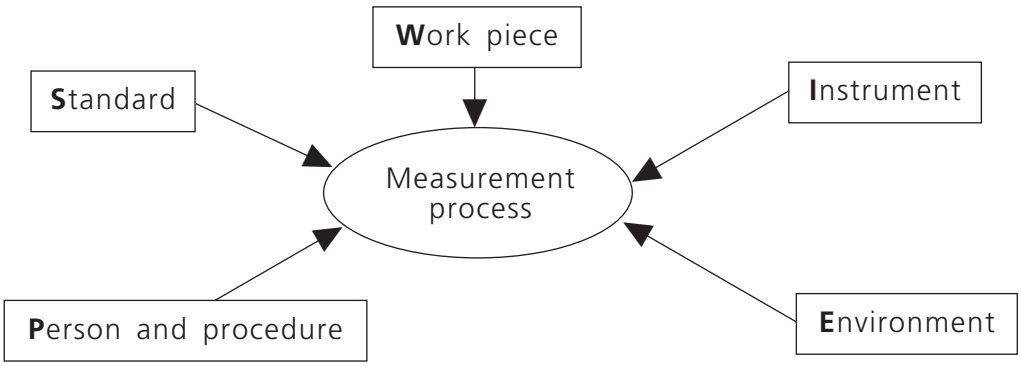
When making any measurement, it is normal practice to repeat the measurement in order to ensure that the data generated is repeatable.

It is also important to make sure that the data generated is reasonably accurate by taking care to use measuring instruments that are calibrated. Then, when the same measurement is made by a customer, who may either be internal or external, the data should be close to the figures generated by the manufacturer, that is to say the data should be reproducible. It is only then that the data that has been generated is considered reliable.

Variation in the measurement process

Even when all the factors in a measurement process are controlled, repeated observations made during precision measurement of any parameter, even under the same conditions, are rarely found to be identical. This is because of the inherent variation in any measurement process due to the following five basic metrology elements:

Figure III. Variation in the measurement process



A brief explanation of the reason for the variation resulting from each of these five factors is given below.

Standard. There are different levels of standard in the traceability chain in order to provide measurement traceability. Each of these standards, in turn, introduces some variation. Factors affecting the standard refer to this variation.

Work piece. No work piece is absolutely stable. There is always an inherent instability in any material or substance. However small the instability might be, this gives rise to variation in the measurement process.

Instrument. All measuring instruments have a stated accuracy or uncertainty. No instrument can measure the true value of the parameter. Thus, the accuracy or uncertainty of the measuring instrument contributes to the variation in the measurement.

Person and procedure. Factors affecting person and procedure stem from the fact that no two human beings' visual judgement is identical. Also, different methods of measurement—the procedure— would give rise to variation.

Environment. The environment plays an important role in any process of measurement. It might be possible to correct the effect of a few environmental conditions, such as temperature and height above mean sea level, to some extent. There are, however, quite a few environmental conditions for which there is no correction factor. Environmental conditions would, therefore, give rise to some variation in every measurement process.

Considering the first letter of each factor (shown in bold in the above figure), these factors are collectively known as SWIPE. Total variation due to SWIPE is also known as "uncertainty in measurement", which quantifies the reliability of the measurement data. The smaller the uncertainty, the more reliable the data.

Measurement uncertainty

Estimating the measurement uncertainty needs:

- A thorough knowledge about the measurement process and its sources of variation;
- The accuracy and precision of the measurements performed;
- Integrity of the persons involved in the measurements and calculations.

Based on a detailed understanding of the measurement, each component of uncertainty that contributes to the measurement uncertainty is represented by an estimated standard deviation, termed as "standard uncertainty", or "U_i".

After identifying and estimating the individual standard uncertainties, these are combined by the square root of the sum of the squares, based on the law of propagation of uncertainty.

Combined standard uncertainty would be, $UC = \sqrt{U_1^2 + U_2^2 + U_3^2 + [...] + U_n^2}$

The final value of the measurement uncertainty, known as "expanded uncertainty", is then determined by multiplying the combined standard uncertainty by a coverage factor. In accordance with international standards and practice, the coverage factor is defined as k = 2 for a 95 per cent confidence level and k = 3 for a 99 per cent confidence level.

The measurement uncertainty in a calibration situation should be one third or less than the accuracy of the instrument under calibration. In a test situation, where compliance to specification is required to be given, the measured value expanded by the estimated measurement uncertainty should not exceed the limit of specification.

For example, if a micrometer with a range of 0-25 mm and a resolution of 1 µ (0.001 mm) has a specified accuracy of ± 4 µ, then the measurement uncertainty of the calibration process should be ≤ 1.33 µ (1/3 of 4 µ).

Measurement system analysis

Another method of estimating the variation in the measurement process is to analyse the measurement system and calculate the gauge repeatability and reproducibility. This involves designing an experiment in which three or four appraisers (operators) perform measurements on three or more samples using the same measuring instrument. Three sources of variation are thus identified and quantified. These are:

- Gauge (instrument) variation (repeatability)
- Appraiser (operator) variation (reproducibility)
- Process variation (part-to-part variation)

The variation in the results of each type of measuring and test equipment system is then analysed. The objective is to find out whether the variation in the measured data is the result of variation in the product or the measurement system.

Based on the analysis of variation, the following conclusions are normally drawn:

- If the percentage gauge repeatability and reproducibility value is less than 10 per cent, the measurement system is acceptable.
- If the percentage gauge repeatability and reproducibility value is between 10 per cent and 30 per cent, the measurement system may be accepted depending upon the importance of the parameter being measured.
- If, however, the percentage gauge repeatability and reproducibility value is above 30 per cent, the measurement system needs improvement.
- If repeatability is large compared to reproducibility, the instrument or gauge needs maintenance or replacement.
- If reproducibility is large compared to repeatability, the appraiser (operator) needs better training and/or the instrument needs recalibration.

The following example illustrates the importance of variation in the measurement process in terms of decision-making.

The diameter of a piston pin was found to be 50.75 mm against the specified requirement of 50.00 ± 0.50 mm. Prima facie, the product does not meet the specification and should be rejected. However, before taking this decision, it would be advisable to ascertain whether the outlier quantity of 0.75 mm is actually the variation in the product, i.e. the piston pin, or if it comprises a substantial quantity of variation resulting from the measurement system.

As explained above, measurement system analysis and gauge repeatability and reproducibility provide this information, so that the decision taken is the correct one.

Coefficient of variation

In analytical measurement, the variation in the measurement process and hence the generated data is stated as a coefficient of variation. The coefficient of variation, or percentage coefficient of variation, is also a measure of the precision of the measurement process.

Consider that a standard cholesterol sample of 200 milligrams per deciliter (mg/dl) is tested in an automated instrument twice a day for 10 days and the data generated are as follows:

198, 197, 201, 204, 200, 201, 199, 197, 197, 199, 200, 203, 199, 198, 197, 196, 196, 199, 196 and 202 mg/dl.

The average value of the above data is $\mu = 198.95$ mg/dl ≈ 199 mg/dl and the standard deviation is $\sigma = 2.35$ mg/dl.

The percentage coefficient of variation = $100 \times (s/\mu) = 1.18\%$

The smaller the coefficient of variation, the lesser the variation and the better the precision.

Conclusions

Now that we know that SWIPE affects all measurement, a measured value would not be accepted as 100 per cent correct unless attempts are made to quantify the variation in the measurement process. This would be true in particular in the case of precision measurements, which have a close tolerance. The following examples explain this:

- Consider a calibration situation involving a thermometer whose range is 0-99.9°C, whose resolution is 0.1°C and for which the manufacturer's stated accuracy is ± 0.5°C. If this thermometer during calibration gives a reading of 50.3°C against a standard of 50.0°C, then apparently the displayed value is within the specified accuracy, i.e. within 50.0 ± 0.5°C. However, bearing in mind the existence of SWIPE, the variation in the measurement needs to be estimated. Suppose that

variation or the uncertainty associated with this measurement is ±0.30 C, then the displayed valued can be 50.3 ± 0.3°C, i.e. it can be anywhere between 50.0 to 50.6°C. But according to the stated accuracy, the displayed value should be 50.0 ± 0.5°C, i.e. between 49.5 and 50.5°C. Therefore, in this case it cannot be said that the instrument is showing a measurement within the stated accuracy.

- In a test situation, consider a piston pin whose diameter is specified as 25.5 ± 0.5 mm. If on measurement, a value of 25.2 mm is obtained, apparently the measured value is within the specified tolerance. However, before accepting the measured value the effect of variation on the measurement process should be estimated. If the uncertainty associated with this measurement is ± 0.2 mm, then the measured value is 25.2 ± 0.2 mm, which is within the specified limits, and the piston pin can be considered to be meeting the specification. If, on the other hand, the measurement uncertainty is ± 0.3 mm, then the measured value becomes 25.2 ± 0.3 mm, which does not comply with the specified limits. In this case, the measured value of the piston pin cannot be considered to be meeting the specification. From the above examples, it is clear that for measurement data to be reliable, the amount of variation due to SWIPE in measurement must be known. If the variation in the measurement process is substantial, then by designing experiments, it should be possible to ascertain the cause, i.e. whether the variation is due to the operators or the measuring instrument. Thereafter, attempts should be made to improve the measurement system so that the variation is minimized.

References

1. International Organization for Standardization, *Guide to the Expression of Uncertainty in Measurement* (1993, revised 1995), available from http://www.iso.org.

2. DaimlerChrysler, Ford and General Motors, *Measurement System Analysis Reference Manual*, 3rd ed. (2002).

5 HANDLING MEASURING INSTRUMENTS

Handling and storage of measuring instruments is very important for the measurement process. If handling and storage of such instruments is not appropriate, even a robust one may malfunction or may give erroneous output. To ensure proper handling and storage, a system approach is the most suitable.

A system for managing measuring instruments comprises not only handling and storage but other elements as well, such as unique identification, safeguarding against adjustments and training. These elements are discussed briefly below to provide guidance for implementing such a system.

Unique identification of the measuring instrument

After the measuring instrument is selected for a particular measurement or measurements, it should be identified with a unique identification number, so that it can be referred to and identified throughout its life in the measurement system. The number can be one inscribed on the instrument by the manufacturer or can be assigned by the user organization in accordance with its system. A unique number means that if the instrument is replaced with a new one, the identification number would not be the same. For example, suppose in a process industry there are five pressure gauges, numbered PG/01, PG/02, PG/03, PG/04 and PG/05. If the pressure gauge identified as number PG/04 is damaged and is replaced by a new gauge, the identification number on the replaced gauge would not be PG/04 but PG/06. The advantage of a unique numbering system is that the history of the instrument (data on range, resolution, accuracy, calibration, repair, maintenance, etc.) remains unique to that instrument alone.

Handling

It is common sense to say that all measuring instruments should be handled carefully. However, because of the varied nature of their shape, size, robustness, accuracy and method of operation, handling of instruments needs to be paid special attention. Normally, an instrument should be handled in the manner specified by the manufacturer. Sometimes, operational instructions contain steps on how an instrument should be handled.

A measuring instrument should be handled in such a way that the instrument:

- Is not damaged through improper holding or slippage and fall during usage;
- Does not lose its accuracy and fitness for use;
- Does not become dirty and need frequent thorough cleaning.

Sometimes, improper handling of an instrument is a source of risk and hazard to the operator of the instrument. In such cases, additional precautions should be taken for handling the instrument. One of the ways proper handling of instruments can be ensured is to appropriately train all the operators of the instrument.

Examples of proper handling include:

- A micrometer should be opened gently in a lateral manner to the required size using both hands. It should never be opened by holding the thimble vertically and rotating the spindle like a child's toy.
- A steel scale should not be held horizontally by one end. This may give rise to permanent sag to the scale due to cantilever action.
- A slip gauge block should never be held with bare fingers as this gives a thermal shock to the gauge. This is because the gauge is used at a temperature of about 20 ± 1.5°C while the human body temperature is around 38°C. Such handling should always be with gloved hands.
- A weighing balance after calibration should be handled in such a way that it is not displaced from its set position.

Safeguarding against adjustment

Many instruments with digital panel meters have built-in potentiometers for adjustment during calibration. The potentiometers after calibration should be sealed so that accidental or otherwise adjustment, which would invalidate the calibration, is prevented. This sealing, however, does not apply to those instruments which are required to be set to "zero" before use. Safeguarding against adjustment is not only required for the hardware of an instrument, it is also necessary for the software. Safeguarding software is generally done in accordance with the advice of the software developer. However, some simple steps should be followed while handling and operating software-driven measuring instruments. No unauthorized floppy disks or CD-ROMS should be inserted in such a measuring instrument. In fact, untrained or unauthorized persons should not be permitted to maintain, handle or operate software-controlled measuring instruments.

Storage

While handling is important, storage and preservation of a measuring instrument is equally important for it to continue to give reliable readings. Whenever an instrument is not in use, it must be stored in such a manner that there is no doubt about its accuracy and fitness when used the next time. For this, it is necessary to ensure that during storage, the instrument does not suffer any physical damage. Nor should environmental conditions be allowed to affect it during storage. The following aspects should be considered while deciding on storage of a measuring instrument:

- The manufacturer's instructions on storage and preservation;
- Prevention of mechanical shock and vibration;
- Locking of movable parts of the instrument, where possible;
- Covering of inlets and other holes to prevent ingress of dust;
- Using anti-static covers for the instrument;
- Use of moisture absorbent materials such as silica gel in the storage case or container of the instrument.

Maintenance of records

All the above activities for maintaining a system of storage and handling of measuring instruments require documents as support. Procedures may be developed for performing some of the activities. Formats may be necessary to record observations. Examples of documents and records needed for maintaining the system include:

- Records of unique identification of measuring instruments;
- The manufacturer's booklet of instructions on handling, storage and operation;
- Procedures for handling and storage of specific instruments;
- Safety instructions for operators of instruments;
- Training notes for operators;
- Calibration reports;
- Records of breakdown, repair and maintenance of instruments.

There could be other records and documents as well. These documents and records should be maintained appropriately so that they can be easily retrieved as and when needed. These records form valuable sources of information for taking decisions regarding the utilization of measuring instruments.

Training

Since it is people who are going to store and handle the measuring instruments, the individuals involved should be provided with suitable training. This training should be in line with the following elements:

- Training should be given to all newly recruited personnel in a laboratory;
- Training should be given on all the above elements of the system;
- Trainers could be the senior laboratory personnel, professional trainers or experts from the instrument manufacturers or suppliers;
- Such training should not be a one time affair but should be conducted periodically.

References

1. ISO 10012:2003, on "Measurement management system: requirements for measurement processes and measuring equipment".
2. ANSI/NCSL Z540-1-1994, on "Calibration laboratories and measuring and test equipment: general requirements".

6 INTERVALS AND SOURCES OF CALIBRATION

The need for recalibration

Calibration of a measuring instrument ensures that the value displayed by the instrument is both accurate and repeatable with respect to a traceable standard. However, once calibrated, it cannot be assumed that the instrument would continue to give accurate and repeatable results for all time to come. Thus, recalibration of the instrument is necessary to estimate its deviation from a reference value or standard and to ensure that the deviation is acceptable for the measurement over time.

Recalibration is also necessary under the following two conditions:

- When the instrument undergoes routine maintenance;
- When the instrument goes out of order and is repaired;

The purpose of a periodic calibration, therefore, is:

- To estimate the reference standard's or measuring instrument's deviation from a reference value and the measurement uncertainty associated with that deviation;
- To reassure that the measurement uncertainty can continue to be achieved with the reference standard or measuring instrument.

However, although frequent calibration would fulfil the above objective, the high cost involved in calibration also has to be considered. Thus, determining the appropriate periodicity of calibration, which balances the risk and cost, becomes an important activity in measurement.

Factors influencing recalibration

There are a number of factors that influence the time period between calibration of a measuring instrument. The important factors are:

- Accuracy/uncertainty of measurement;
- Risk of a measuring instrument going out of tolerance when in use;
- Type of equipment;

- Tendency to wear and drift;
- Manufacturer's recommendations;
- Extent and severity of use;
- Environmental conditions, e.g. temperature, vibration, radiation, etc.;
- Trends in data obtained from previous calibration records;
- Recorded history of maintenance and servicing;
- Frequency of cross-checking against other reference standards or measuring devices;
- Handling and storage arrangements and associated risk;
- Degree to which the serving personnel has been trained.

If the accuracy/uncertainty of the measurement is small, and if the risk of out-of-tolerance is high, then the measuring instrument needs more frequent recalibration. A similar situation would be the case for an instrument that has a tendency to wear and drift and is in use almost all the time. If, on the other hand, an instrument is robust in construction, is used only once in a while, is stored in proper environmental conditions and is subject to frequent verification against a reference standard, then the instrument need not be recalibrated as frequently.

Periodicity of calibration

Periodicity of calibration generally would be finalized based on recorded investigation. This means that calibration results of an instrument must be monitored over time and, depending on the drift it exhibits, the time period between recalibration can be decided. However, this is possible only after a few recalibrations. How should the initial recalibration interval be fixed?

The initial decision to determine the calibration interval is based on the following factors:

- Recommendation of the instrument manufacturer;
- How frequently and severely the instrument is expected to be used;
- The influence of the environment;
- Maximum allowable variation of the measurand;
- The uncertainty of measurement required.

Such a decision should, however, be made by a person with experience of measurement and who is knowledgeable about calibration of the instrument. This experience and knowledge would help in estimating the length of time an instrument is likely to remain within tolerance after calibration. However, clearly there cannot be one universal method of determining the calibration periodicity for all types of measuring instruments.

As a rule of thumb, to start with the following periodicity could be considered:

Detail of instrument/material	*Periodicity*
Pressure/vacuum gauges, working grade	6 months
Pressure/vacuum gauges, test grade	12 months
Mechanical measuring instrument used on shop floor	6 months
Mechanical measuring instrument used in laboratory	12 months
Electrical meters	12 months
Weighing balance	12 months
Weight box	12 months
Hardness testers	12 months
Temperature measuring system	12 months
Precision laboratory glassware, e.g. pipettes, burettes, volumetric flasks	Initially on commissioning
Length, pressure and voltage standards	24 months
Mass and temperature standards	12 months
Reference materials	24 months

Review of calibration intervals

Once the initial calibration is decided, it is necessary to evolve methods to review this interval so that neither the risk of the instrument being out of calibration nor the cost involved increases.

A number of such methods have been documented in international standards. Two such methods that are commonly followed are discussed below.

"Staircase" or calendar-time method

Each time an instrument is calibrated on a routine basis, the subsequent interval is extended if it is found that the accuracy of the instrument is within, say, 80 per cent of the tolerance band that is required for measurement. If, however, the calibration report shows that the instrument's accuracy is between 80 and 100 per cent of the tolerance band, then the calibration interval is reduced. As previously mentioned, only competent persons should decide the quantum of extension or reduction of the interval. In this method, each instrument is treated separately and records maintained accordingly. When there are a large number of instruments, keeping track of individual instruments may become difficult.

Control chart method

This method employs a statistical quality control technique. Significant calibration points are chosen and the results are plotted against time. When sufficient data is generated, standard deviation (σ) is calculated. The control limit of the drift in the instru-

ment's accuracy would then be estimated to be within plus or minus 2 standard deviations, i.e. within ± 2 σ. Once these control limits are fixed, subsequent calibrations should exhibit maximum drift within these limits for the instrument to be considered in tolerance. From these figures, the optimum interval can be calculated.

The calendar-time method can easily be applied provided the instruments are individually monitored. The value of 80 per cent is not a sacrosanct figure and can be modified by competent persons. The control chart method can be followed for such of the instruments that could be in service for a long time, so that effective data generation as well as data monitoring is possible.

Sources of calibration

It has already been shown how calibration of a measuring instrument affects the reliability of measurement made by that instrument. From the above paragraphs, it is also understood that calibration is not a one-time activity for a measuring instrument. Because of these reasons, calibration is considered a sacrosanct measurement and it should be obtained only from competent sources. The following are some of the sources that should be considered for selecting a calibration laboratory.

- First preference should be given to a calibration laboratory that is accredited under ISO/IEC 17025. A list of such laboratories is available from the website of the accrediting body of a particular country. Since most countries having a system of laboratory accreditation are members of either the organization known as International Laboratory Accreditation Cooperation (ILAC) or the Asia Pacific Laboratory Accreditation Cooperation (APLAC), the address of a particular country's accrediting body's website can be obtained from the website of either ILAC (http://www.ilac.org) or APLAC (http://www.aplac.org). When selecting the laboratory, the laboratory's scope of accreditation should be examined to see whether the laboratory has the capability of calibrating a particular measuring instrument.

- The next laboratory in order of preference would be a laboratory that has applied for accreditation or a laboratory that is certified under the ISO 9001:2000, on "Requirements for a quality management system".

- If there are no calibration laboratories in either of the above categories, then selection of the laboratory should be based on an assessment under the following criteria:

  Traceability of the standard.

  Correct test accuracy ratio. This is the ratio of the calibration standard's accuracy with respect to the stated accuracy of the measuring instrument under calibration. This ratio should be a minimum of 3:1.

  Details of the actual value in the report. The values observed on the measuring instrument against the standard values should be stated on the report, so that the user of the instrument knows how much deviation exists between the displayed reading and the corresponding standard value.

Measurement uncertainty.

Availability of trained manpower.

Market reputation.

- If it is decided to perform in-house calibration, it is advisable to ensure that the above criteria are complied with.

References

1. International Organization of Legal Metrology, "Guidelines for the determination of recalibration intervals of measuring equipment used in testing laboratories" (document D10, currently being revised), see the website of Deutsches Akkreditierungssytem Prüfwesen GmbH at http://www.dap.de/95doc/DAP-TM-08.pdf.

2. International Organization for Standardization, "Measurement management systems: requirements for measurement processes and measuring equipment" (ISO 10012:2003).

3. Website of the Hong Kong Laboratory Accreditation Service at http://www.itc.gov.hk/en/quality/hkas/hoklas/about.htm.

7 INTERNATIONAL ORGANIZATIONS

There are many international organizations working towards harmonization of measurement-related activities. Foremost amongst these is the International Committee for Weights and Measures, the highest authority on metrology in the world. It comprises the following seven organizations:

- International Bureau of Weights and Measures, France
- International Electrotechnical Commission, Switzerland
- International Federation of Clinical Chemistry and Laboratory Medicine, France
- International Organization for Standardization, Switzerland
- International Organization of Legal Metrology, France
- International Union of Pure and Applied Chemistry, United Kingdom
- International Union of Pure and Applied Physics, Sweden

Collectively, these seven organizations govern nearly all measurements made in the world today. Thus, any directive or decision given by the International Committee for Weights and Measures is binding on all aspects of measurement.

Principal international organizations

Brief details about these organizations are given in the following paragraphs. However, for more details, please visit the respective website of the organizations, which are given under the references below.

International Bureau of Weights and Measures

The task of the International Bureau of Weights and Measures is to ensure worldwide uniformity of measurements and their traceability to the International System of Units. It does this with the authority of the Metre Convention. The Metre Convention is a diplomatic treaty which gives authority to the General Conference on Weights and Measures, the International Committee for Weights and Measures and the International Bureau of Weights and Measures to act in matters of world metrology, in particular concerning the demand for measurement standards of ever increasing accuracy, range and diversity, and the need to demonstrate equivalence between national measurement standards. This diplomatic treaty, originally signed by 17 States in 1875, at the time of publication has 51 member States and operates through a series of Consultative

Committees, whose members are the national metrology laboratories of the member States of the Convention, and through its own laboratory work.

The International Bureau of Weights and Measures has its headquarters in France and carries out measurement-related research. It takes part in and organizes international comparisons of national measurement standards and it carries out calibrations for member States.

International Electrotechnical Commission

The International Electrotechnical Commission is the leading global organization that prepares and publishes international standards for all electrical, electronic and related technologies. These serve as a basis for national standardization and as references when drafting international tenders and contracts. Through its members, the Commission promotes international cooperation on all questions of electrotechnical standardization and related matters, such as the assessment of conformity to standards in the fields of electricity, electronics and related technologies.

The charter of the Commission embraces all electrotechnologies including electronics, magnetism and electromagnetism, electro-acoustics, multimedia telecommunication, and energy production and distribution, as well as associated general disciplines such as terminology and symbols, electromagnetic compatibility, measurement and performance, dependability, design and development, safety and the environment.

International Federation of Clinical Chemistry and Laboratory Medicine

The International Federation of Clinical Chemistry and Laboratory Medicine is a professional organization with its headquarters in France, serving a worldwide network of clinical chemists and laboratory physicians. Programmes and concepts developed by the Federation are intended to enable clinical laboratories to be operated efficiently, with a high standard of professional and technical competence. This, in turn, provides benefit to patients and value to society, taking into account changing economies and health-care systems and the globalization of suppliers of equipment and services. Continuous education is the means that allows people working in diagnostic laboratories to adapt their established skills and to implement the vision of clinical chemistry and laboratory medicine as the bridge between basic and applied science and clinical care. At present, the Federation has 77 States as full members.

International Organization for Standardization

The International Organization for Standardization is a network of the national standards institutes of 148 States, on the basis of one member per country, with a central secretariat in Geneva, Switzerland, that coordinates the system.

The International Organization for Standardization was created in 1946, when delegates from 25 States met in London and decided to create a new international organization, of which the object would be “to facilitate the international coordination and unification of industrial standards”. The new Organization officially began operations on 23 February 1947.

The International Organization for Standardization always uses ISO as the acronym of its name, taken from the Greek word *isos* meaning "equal". Therefore, whatever the State, whatever the language, the form used in the symbols for standards produced by the Organization is always ISO. The ISO 9000 and ISO 14000 families are among the Organization's most widely known and successful standards ever.

The International Organization for Standardization has produced a wide range of standards in the area of measurement, in terms of both testing and calibration. Some of the prominent measurement topics in which the Organization has produced standards are medical equipment; testing of water quality; measurement of pollutants such as noise, shock and vibration; assessment of protection levels against fire, radiation and explosion; safety testing for domestic appliances and children's toys; and testing in mechanical, electrical, electronic, chemical and non-destructive fields. The Organization regularly takes up contemporary measurement-related subjects and works towards developing standards for test methods. In addition, ISO has done major work in the area of measurement management systems, which has culminated in the publication of ISO 10012. The Organization is thus a valuable source of reliable and authentic information for all measurement-related subjects.

International Organization of Legal Metrology

The International Organization of Legal Metrology is an intergovernmental treaty organization whose membership includes States that participate actively in technical activities and States that join the Organization as observers. It was established in 1955 in order to promote the global harmonization of legal metrology procedures and has its headquarters in France. Since that time, the Organization has developed a worldwide technical structure that provides its members with metrological guidelines for the development of national and regional requirements concerning the manufacture and use of measuring instruments for legal metrology applications.

International Union of Pure and Applied Chemistry

The International Union of Pure and Applied Chemistry serves to advance the worldwide aspects of the chemical sciences and to contribute to the application of chemistry in the service of mankind. As a scientific, international non-governmental and objective body, the Union can address many global issues involving the chemical sciences.

The Union was formed in 1919 by chemists from industry and academia in the United Kingdom, where it has its headquarters. The Union has been recognized as the world authority on chemical nomenclature, terminology, standardized methods for measurement, atomic weights and many other critically evaluated data. It is an association of bodies, known as national adhering organizations, which represent the chemists of different member States.

International Union of Pure and Applied Physics

The International Union of Pure and Applied Physics was established in 1922 at Brussels with 13 member States. Its mission is to assist in the worldwide development of physics,

to foster international cooperation in physics and to help in the application of physics towards solving problems of concern to humanity.

The Union carries out this mission by sponsoring international meetings; fostering communications and publications; encouraging research and education; fostering the free circulation of scientists; promoting international agreements on symbols, units and nomenclature; and cooperating with other organizations on disciplinary and interdisciplinary problems. Currently, the Union has 46 member States. With its headquarters in Sweden, the Union functions through 7 working groups and 19 commissions.

Other international organizations

Eurachem

Eurachem is the international organization that provides a focus for analytical chemistry and quality-related issues in Europe. Eurachem was established in 1989 and, together with the organization known as Cooperation on International Traceability in Analytical Chemistry, it has been working with the objective of establishing a system for the international traceability of chemical measurements and the promotion of good quality practices. It provides a forum for the discussion of common problems and for developing an informed and considered approach to both technical and policy issues. Although primarily concerned with analytical measurements in Europe, Eurachem guidelines form a valuable reference for analytical work throughout the world.

One of Eurachem's important publications, Quantifying Uncertainty in Analytical Measurement, produced jointly with the Cooperation on International Traceability in Analytical Chemistry, provides the basis for estimation of uncertainty in chemical measurements.

European Cooperation for Accreditation

The organization known as European Cooperation for Accreditation was formed in June 2000 by combining two European organizations in order to improve cooperation among the various accrediting bodies of Europe. These two former organizations were the European Accreditation of Certification and the European Cooperation for Accreditation of Laboratories, concerned with certification bodies or with laboratories. The European Cooperation for Accreditation covers the following activities:

- Testing and calibration
- Inspection
- Certification of management systems
- Certification of products
- Certification of personnel
- Environmental verification under the European Union Eco-Management and Audit Scheme regulations

As part of the above activities, the European Cooperation for Accreditation has developed and published a number of standards in the field of calibration and testing.

Publications on measurement

There are a number of publications and documents available on measurement-related topics. Some of the important documents are listed below.

European Accreditation Cooperation

Calibration of stylus instruments for measuring surface roughness (EA–10/01)
Calibration of gauge block comparators (EA–10/02)
Calibration of pressure balances (EA–10/03)
Coordinate measuring machine calibration (EA–10/05)
Extent of calibration for cylindrical diameter standards (EA–10/06)
Calibration of oscilloscopes (EA–10/07)
Calibration of thermocouples (EA–10/08)
Measurement and generation of small AC voltages with inductive voltage dividers (EA–10/09)
Guidelines on determination of pitch diameter of parallel thread gauges by mechanical probing (EA–10/10)
Guidelines on the calibration of temperature indicators and simulators by electrical simulation and measurement (EA–10/11)
Guidelines on the calibration of temperature block calibrators (EA–10/13)
Guidelines on the calibration of static torque measuring devices (EA–10/14)
Guidelines on the calibration of digital multimeters (EA–10/15)
Guidelines on the calibration of electromechanical manometers (EA–10/17)
Guidelines on the estimation of uncertainty in hardness measurement (EA–10/16)
Expression of the uncertainty of measurement in calibration (EA–4/02)
Guidelines on the expression of uncertainty in quantitative testing (EA–4/16)

International Laboratory Accreditation Cooperation

Traceability of measurements (ILAC – G 2)
Guidelines for the selection and use of reference materials (ILAC – G 9)

Eurachem/Cooperation on International Traceability in Analytical Chemistry

Quantifying uncertainty in analytical measurements (QUAM: 2000)

International Organization for Standardization

Guide to the Expression of Uncertainty in Measurement (1993, revised 1995)
Measurement System Analysis Reference Manual (3rd edition, 2002)

American Association for Laboratory Accreditation

Guide for the estimation of measurement uncertainty in testing (July 2002)

The above list, however, is not comprehensive. Some of the documents can be downloaded free of charge from the respective websites given in the references below. Others, however, are sales documents and can be obtained from the respective organizations.

Conclusions

Measurement is critical in evaluating quality and safety. Correct methods of measurement together with the use of the appropriate instrument and environmental conditions, determine the reliability of the measurement data. The above organizations provide a valuable source of information for measurement methods, instruments, standardization and calibration for all measurements performed for quality and safety assessments. Most of these organizations also have facilities for seeking the opinion of experts. Thus, enterprises aspiring to set up a good testing and measurement facility can obtain a great deal of assistance from these organizations, not only for measurement-related subjects but also on system-related topics on management of good measurement practice.

References

1. Website of the International Bureau of Weights and Measures at http://www.bipm.fr.
2. Website of the International Electrotechnical Commission at http://www.iec.ch.
3. Website of the International Federation of Clinical Chemistry and Laboratory Medicine at http://www.ifcc.org.
4. Website of the International Organization for Standardization at http://www.iso.ch.
5. Website of the International Organization of Legal Metrology at http://www.oiml.org.
6. Website of the International Union of Pure and Applied Chemistry at http://www.iupac.org.
7. Website of the International Union of Pure and Applied Physics at http://www.iupap.org.
8. Website of Eurachem at http://www.eurachem.ul.pt.
9. Website of the European Cooperation for Accreditation at http://www.european-accreditation.org.
10. Website of the United Kingdom Accreditation Service at http://www.ukas.com.

8 LABORATORY ACCREDITATION

Accreditation and its benefits

> *Accreditation: A procedure by which an authoritative body gives formal recognition that a body or person is competent to carry out specific tasks. Laboratory accreditation is a method by which the test reports issued by laboratories can be certified as reliable.*

Formal recognition of the competence of a laboratory by an accreditation body in accordance with international criteria has many advantages:

- Better control of laboratory operations due to the existence of an in-built quality assurance system and technically competent manpower.
- Increased confidence in testing and calibration data and personnel performing the work.
- Savings in terms of time and money due to reduction or elimination of the need for re-testing of products, which is a technical barrier to international trade.
- Users of accredited laboratories will enjoy greater access for their products, in both domestic and international markets, when those products have been tested by accredited laboratories, thus facilitating overcoming technical barriers to trade.

Accreditation of a laboratory is granted in two broad areas. These are:

- Fields of testing
- Fields of calibration (or measurement)

Examples of fields of testing are:

- Chemical testing
- Electrical testing
- Mechanical testing
- Non-destructive testing
- Optical, photometric and radiometric testing

- Thermal testing
- Clinical testing
- Food testing

Examples of fields of calibration (or measurement) are:

- Dimensional calibrations (or measurement)
- Pressure calibrations (or measurement)
- Force calibrations (or measurement)
- Electrical calibrations (or measurement)
- Thermal calibrations (or measurement)
- Acoustic calibrations (or measurement)
- Accelerometry calibration (and/or measurement)

There could be more fields. All of the above fields may have subcategories for their applications in various technical sub-disciplines.

The accreditation process in brief

Laboratory accreditation is granted in accordance with the requirements of ISO/IEC 17025:1999. In addition, every accreditation body has also laid down specific criteria based on the discipline of tests or calibrations.

ISO/IEC 17025 specifies a total of 24 requirements, grouped under management requirements and technical requirements. The management requirements include 14 elements, while the technical requirements include 10 elements.

The specific criteria prescribed by accreditation bodies is discipline-specific. For example, in both chemical testing and clinical laboratories, a documented waste management programme must be laid down and followed. These laboratories are also required to have a documented health and safety programme for both the laboratory personnel and visitors to the laboratory. Another example is the special requirement to monitor environmental conditions for mechanical calibration laboratories, where temperature plays a vital role in laboratory test results. Similarly, an inter-locking Faraday cage is an essential specific criterion in a high-voltage testing laboratory.

The process of laboratory accreditation is much more rigorous than the certification process under ISO 9001:2000. Apart from compliance with the management require-

ments, accreditation assesses the technical competence of the infrastructure and human resources and the reliability of the test and calibration results. The assessment team for accreditation comprises a technical expert in each of the disciplines for which accreditation is applied for. These technical experts, among other things, observe actual tests or calibrations being performed by the laboratory personnel to assess their proficiency.

The accreditation of the applicant laboratory does not totally depend on the recommendation of the assessment team. Apart from the quality management system, a great deal of emphasis is placed on the various technical requirements, including the authorized signatory of the test and calibration reports. An accreditation committee comprising experts in the field of the concerned discipline deliberates upon the findings and recommendations of the assessors and only after this committee's satisfactory recommendation, is accreditation granted. Accreditation is normally granted for a period of three years with yearly monitoring.

With very few exceptions, only one authorized body in a State grants accreditation of laboratories.

International cooperation in laboratory accreditation

The organization known as the International Laboratory Accreditation Cooperation (ILAC) allows international cooperation between the various laboratory accreditation schemes operated throughout the world. Founded in 1978 as a conference, ILAC was formalized as a cooperation body in 1996 when 44 national bodies signed a memorandum of understanding in Amsterdam, the Netherlands.

The efforts of ILAC to further develop the cooperation body resulted in 44 laboratory accreditation bodies (ILAC members) of 36 States signing the multilateral, Mutual Recognition Arrangement in August 2003. In accordance with this Arrangement, test reports issued by a laboratory accredited by a member of the Arrangement are acceptable to all other partners. In international trade, non-acceptance of test reports by importing States is a technical trade barrier. With the signing of the Arrangement, this barrier is diminishing.

ILAC is an international cooperation mechanism among the various laboratory accreditation schemes operated throughout the world. In Europe it is the European Cooperation for Accreditation and in the Asia and Pacific region it is the Asia Pacific Laboratory Accreditation Cooperation that work in harmony with ILAC for regional cooperation. Currently there are 30 member States of the European Accreditation Cooperation and 19 full members of the Asia Pacific Laboratory Accreditation Cooperation through their national accreditation bodies. Both of these regional bodies have Mutual Recognition Arrangements among their members along similar lines as for the ILAC.

The objectives of all the three international and regional bodies are to develop a global network of accredited testing and calibration laboratories that are assessed and recognized as being competent by one of the respective signatory accreditation bodies

described above. The signatories have, in turn, been reviewed by their peers and shown to meet the respective criteria for competence. The ultimate aim is to increase the use and acceptance by industry as well as Governments of the results from accredited laboratories, including results from laboratories in other countries. This would finally remove one of the technical barriers to international trade. Further details about the members of the accreditation cooperation bodies can be obtained from their websites mentioned under the references below.

More about laboratory accreditation

All accreditation bodies have published directories of accredited laboratories, which give details of the individual laboratory's test and calibration parameters, its measurement range and capability, address and contact details. A prospective user can locate an appropriate laboratory through the directory, which normally is also available on the website of the accrediting body. This facility is particularly useful for importers, who can select an accredited laboratory in the exporting country for testing products before their physical import.

Accreditation can be granted to the following facilities:

- Permanent laboratories
- Field laboratories
- Mobile laboratories
- In-house laboratories of an organization that are open or partially open to others
- In-house laboratories of an organization that are not open to others

Many organizations obtain accreditation for their in-house laboratory so that the test and calibration results issued by the laboratory are more reliable. This also gives confidence to their customers regarding test data and product quality.

Conclusions

Laboratory accreditation can help organizations broadly in three different areas.

- *Availability of reliable test and measurement data*. In-process quality control involves alteration or improvement of process parameters based on test and measurement data. When this data is received from an accredited laboratory, whether in-house or from an external laboratory, the actions taken based on the data become both reliable and economical as the need for repeated checks is eliminated.

- *Help in improving domestic trade*. The customer's acceptance of a test report issued by an accredited laboratory would be much more likely than for a report from a non-accredited laboratory. This will also save money at the customer's end by removing the need for rechecking.

- *Help in improving international trade*. The global trend is towards a free market with no trade barriers. Normally, all importers resort to checking of products for quality and safety prior to acceptance in the importing country. This is because of the importing State's regulations and also the lack of reliability of the exporter's test certificate. This duplicate testing is considered a technical trade barrier and could be eliminated through the use of accredited laboratories.

References

1. International Organization for Standardization, "General requirements for the competence of testing and calibration laboratories" (ISO/IEC 17025:1999).

2. Website of the International Laboratory Accreditation Cooperation organization at http://www.ilac.org.

3. Website of the Asia Pacific Laboratory Accreditation Cooperation at http://www.aplac.org.

4. Website of the European Accreditation Cooperation at http://www.european-accreditation.org.

9 DEFINITION OF TERMS

Different terms used in the measurement process are defined in the present chapter, together with additional information where necessary. Additional terms, where required, are defined and explained in the respective sections.

Measurement

> *Measurement: is the assignment of numbers to material things to represent the relations among them with respect to particular properties.*

The process of assigning numbers is defined as the "measurement process".

- The measurement process is the set of operations to determine the value of a quantity.

- A process is an integrated set of activities that uses resources to transform inputs into outputs. In the case of measurement, the requirement or the objective of measurement is the input, while the method employed is the activity that uses the measuring instrument and operator as the resources, to give the output.

The value assigned is defined as the "measurement value".

- It is also known as the measurand or the result of a measurement value attributed to a measurand, obtained by measurement.

- For example when we measure the diameter of a steel rod by a micrometer, the value of the diameter, say 22.55 mm, is the measurand.

Metrology

> *Metrology: is the science of measurement.*

- *Metro* and *logy* are Greek words meaning "measurement" and "science", respectively. According to some historians, metrology started in 2750 B.C., in ancient Egypt, with the building of the pyramids.

- Today, metrology is defined as the science of measurement for the determination of conformance to technical requirements including the development of standards and systems for absolute and relative measurement.

There are different specialized areas of metrology. Some examples are:

- *Dimensional metrology*, which deals with measurement of length and angle.
- *Mass metrology*, which deals with measurement of mass.
- *Illumination metrology*, which deals with measurement of light.
- *Chemical metrology*, which deals with all types of measurement in chemistry.
- Legal metrology is another specialized area, which deals with mandatory measurements in a State to ensure that correct quantities are given against their monetary values in everyday trade. These relate, in particular, to volume, length and mass. Each country has a legal metrology department, which ensures compliance through periodic verification and surveillance of measuring instruments of all traders and business outlets.

Metrological confirmation

Metrological confirmation: is the set of operations required to ensure that measuring equipment conforms to the requirements for its intended use.

- Metrological confirmation generally includes calibration or verification of the measuring instrument for its accuracy, labelling for its identification and, where required, sealing to avoid unauthorized adjustment. It also includes documented evidence of the requirements of the instrument's intended use for range, resolution, maximum permissible errors, etc. These requirements are not specified in product requirements and should, therefore, be carefully considered for good measurement practice.

Accuracy

Accuracy: is the closeness of the agreement between the result of a measurement and a true value of the measurand.

- *Example 1.* When the accuracy of a micrometer with a range of 0-25 mm and a least count of 1 μ is ± 4 μ, it means that if this micrometer gives a reading of 20.255 mm, the actual or true value of the measurand can be 20.255 mm ± 4 μ, i.e. between 20.251 and 20.259 mm.
- *Example 2.* The accuracy of a pressure gauge with a range of 0-16 kgf/cm^2 and a least count of 0.5 kgf/cm^2 is 1.5 class. This means that any value (say 10.5 kgf/cm^2) exhibited by this pressure gauge would refer to a true value of 10.5 ± 0.24 kgf/cm^2.

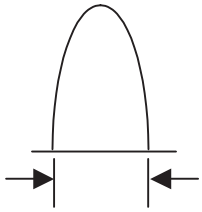
- However, later we would see that since true value is a theoretical concept, "accuracy" becomes a qualitative concept.

Precision

- Precision is the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

- These conditions are called repeatability conditions and include the following:

Figure IV. Repeatability



Repeatability

- The same measurement procedure

- The same operator or appraiser

- The same measuring instrument, used under the same conditions

- The same location

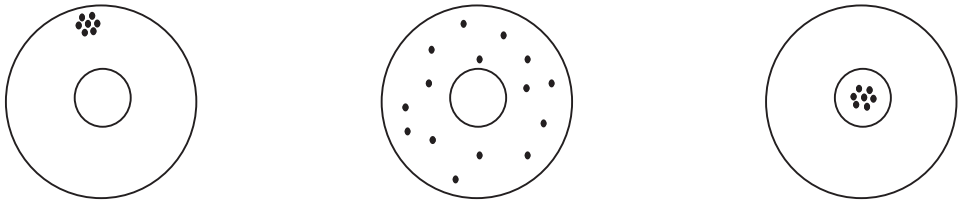
- Repetition over a short period of time

- Precision is also called repeatability.

Example. When the repeatability of a pressure gauge is stated as ± 0.25 per cent, it means that the repeat measurement by the gauge would give the readings within ± 0.25 per cent of the measured value.

Joseph Juran, the quality guru, explained the difference between accuracy and precision with the help of the following pictures. Consider the outer circle as a target and the smaller inner circle as the bullseye. In case 1, all the shots are missing the bullseye but are clustered around a particular point. In case 2, all the shots are dispersed around the target and missing the bullseye, but the average of the shots would have hit the bullseye. In case 3, as is evident, all shots hit the bullseye.

Figure V. Accuracy and precision



Case 1	Case 2	Case 3
Case 1 is an example of precise but not accurate	Case 2 is an example of accurate but not precise	Case 3 is an example of both precise and accurate

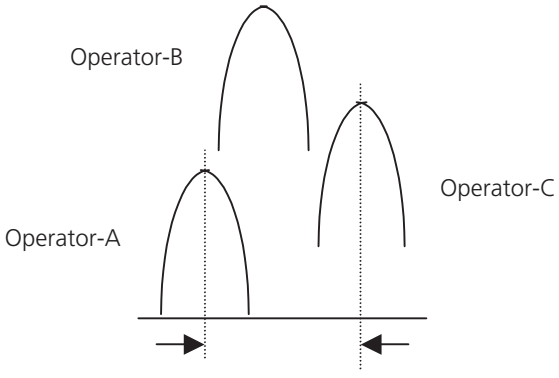
Reproducibility

Reproducibility: is the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

The changed conditions of measurement may include:

- Different measurement principle
- Different method of measurement
- Different operator or appraiser
- Different measuring instrument
- Different reference standard
- Different location
- Different conditions of use at a different time

Figure VI. Reproducibility



- *Example*. If measurement of the diameter of a steel pin by a particular micrometer by three operators gives values as 15.56, 15.75 and 15.63 mm, then the reproducibility of this measurement is 0.19 mm.

Least count

Least count: is the least or the minimum value of a unit that can be read in an instrument or displaying device.

- *Example 1.* A voltmeter with a measuring range of 0 to 750 volts can display a minimum value of 1 volt. The least count of the voltmeter is 1 volt.

- *Example 2.* A micrometer having a measuring range of 0-25 mm can display a minimum reading of 1 μ with the help of a built-in vernier scale. The least count of the micrometer is 1 μ or 0.001 mm.

Resolution

Resolution: is the smallest difference between indications of a displaying device that can be meaningfully distinguished.

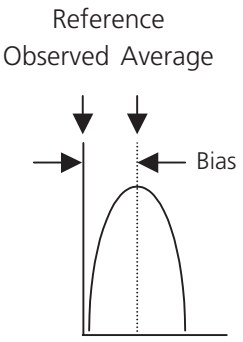
As the definition suggests, if it is possible to meaningfully distinguish between the two adjacent 1 volt displays and read 0.5 volts, 0.5 volts is the resolution of the voltmeter. However, in almost all cases, unless the operator is an expert, resolution and least count are considered one and the same thing. It will be seen below that the measurement process always has an inherent variation. By trying to distinguish between the least counts, further variation may be added to the measurement process, which perhaps should be avoided.

Bias

Bias: is the difference between the observed average of measurements and the reference value.

- *Example*. If the diameter of a stainless steel pin is measured on the shop floor as 12.345, 12.355, 12.352, 12.343 and 12.350 mm and if the diameter of the pin measured in a precision laboratory gives the value as 12.3500 mm, then the bias is calculated as 12.3500 – 12.349 = 0.001 mm. The laboratory result of 12.3500 mm is considered as the reference value while 12.349 mm is the average of the 5 measurements of the pin on the shop floor.

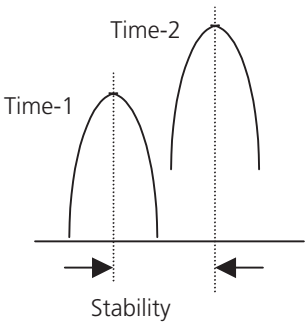
Figure VII. Bias



Stability

Stability: is total variation in the measurement system obtained with a measurement system on the same master part for the same characteristic over an extended time period.

Figure VIII. Stability



- *Example*. If the accuracy of a pressure gauge is found to vary from ± 0.3 per cent to ± 0.5 per cent over a period of six months, then the pressure gauge's stability may be considered to be ± 0.5 per cent.

Uncertainty

Uncertainty: is the parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand.

- It is an expression of fact that, for a given result of measurement, there is not one value but an infinite number of values dispersed about the result, with a varying degree of credibility.

- Example. when we say the diameter of a pin is 12.53 mm ± 0.04 mm, it means that the actual or true value of the pin diameter lies anywhere between 11.49 and 12.58 mm. In other words, the measured diameter of the pin is 12.53 with an associated uncertainty of ± 0.04 mm.

Confidence level

Confidence level: is the probability expressed in a decimal or percentage that the true value lies within a specified range of values.

- *Example:* A 95 per cent confidence level means that an event will occur 95 out of 100 times. Combining this concept with the example under the definition of uncertainty above, when we say that the pin diameter is 12.53 mm ± 0.04 mm under a confidence level of 95 per cent, it means that if we measure the pin diameter 100 times, then in 95 of those times the value would lie between 11.49 and 12.58 mm.

Test accuracy ratio

Test accuracy ratio (also known as test uncertainty ratio): is defined in a calibration situation as:

$$TUR = \frac{\textit{Specified uncertainty (accuracy) of the instrument under calibration}}{\textit{Uncertainty (accuracy) of the standard}}$$

- *Example:* If the accuracy of a voltmeter under calibration is 0.5 per cent and it is calibrated against a standard having an accuracy of 0.1 per cent, then the TUR is 5:1.

- Here, the accuracy and uncertainty have been used to mean the same characteristics, for ease of understanding. However, since accuracy is considered a qualitative measure and not a quantitative one, today the term uncertainty is used to quantify the accuracy.

- Test uncertainty or the accuracy ratio can be viewed as a measure of risk in decision-making based on measurement data. This risk pertains to either false acceptance or false rejection of the product based on measured value. The higher the ratio, the lower the risk.

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3. International Organization for Standardization, *International Vocabulary of Basic and General Terms in Metrology*, 2nd ed. (1993).

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